Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2019.24347

162 (2019) 1–13
September

Water desalination as an option to balance the water demand and supply equation of Jordan

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Received 12 August 2018; Accepted 26 April 2019

ABSTRACT

Jordan is facing an increasing and serious threat of water shortage while its population has almost doubled over the last decade. The adoption of nonconventional water supply technologies such as desalination is unavoidable. In this review, key facts of current water desalination status are highlighted, in the context of a comprehensive review of water desalination in Jordan in the past. Future needs are then discussed taking into consideration the potential of available water sources and economic drivers for the next generation. Performance of two existing desalination plants for drinking water purposes was evaluated. Due to current and projected water shortages, water desalination has a great potential to balance the water demand and supply equation in Jordan. This analysis suggests that Jordan will have to depend significantly expanding its desalination capacity for reliable water supply. However, it is recommended to combine non-conventional energy sources to power desalination to overcome the energy shortages facing this country.

Keywords: Desalination plants; Reverse osmosis; Brackish water; Seawater; Jordan

1. Introduction

The Kingdom of Jordan has an arid to a semiarid climate with limited fresh water resources and a short rainy season. The annual rainfall is less than 200 mm in most of the country. It is facing an increasing and serious threat of water shortages and has been ranked as the second water-poor country worldwide [1]. The annual per capita share from renewable water resources is currently less than 100 m^3.

Jordan's primary water resources are aquifers and surface basins; 12 ground water aquifers are identified [2]. However, most of the rainfall that feed these aquifers evaporates, leaving only 3.9% of annual precipitation to infiltrate and recharge the groundwater [3]. In addition, there are three major surface water resources, the Jordan River, the Zarqa River and the Yarmouk River none of which can be directly used due to their high salinity and contamination [4]. Water scarcity in Jordan is not only attributed to the limited water resources; it is also influenced by other factors, such as over draw of groundwater resources in response to increasing population demand. Jordan's population is expected to rise significantly; this increases pressure on the available limited water sources. The Jordanian department of statistics estimated population growth rate in Jordan during the period between 2004 and 2015 to average 5.3% [5]. As a result of conflicts in the region, Jordan is episodically

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receiving massive influxes of refugees, which usually exhort capricious demands on the available water. In recent years, the population of Jordan has increased from 6.99 million in 2011 to about 10.05 million in 2017 due to Syrian refugee influx [5]. Furthermore, the water's situation in Jordan is influenced by the fact that the major surface water resources are shared with neighboring countries, which already either diverted or stored behind dams. The situation is further complicated by recently frequent draught conditions that hit the country due to climate change.

Water scarcity has become chronic in Jordan since the early 1980s. Total demand on fresh water exceeds the available fresh water resources and changes the affordable supply. As for 2015, Jordan's demand on fresh water sources was 1,401 million cubic meters (MCM). This exceeded the total available water, which was about 992 MCM. Accordingly, Jordan is facing water deficit of about 409 MCM annually. According to the national water strategy 2016–2025, water demand will exceed the available water resources by more than 26% by the year 2025 [6]. To bridge the gap between supply and demand, integrated measures have been or must be adopted. These measures must improve the availability of fresh water sources ensuring their suitability and sustainability. Jordan has already started relying on non-conventional water resources or is considering the utilization of some in the near future. Among the non-conventional water resources are large-scale wastewater reuse (already widely implemented), water harvesting (only implemented at macro-scale), and desalination of both brackish (mainly implemented at small scale) and emerging seawater desalination. More than 92.6% of the treated wastewater, for all uses, is reused widely in agriculture, either directly or after blending with water from other sources. This reclaimed water contributes 14% of the Jordanian annual water budget [1]. The remaining option, for Jordan's water supply in the future, is believed to be desalination of brackish and seawater resources [3,7–9]. Desalination is successful in many oil producing countries bordering seawaters in the Middle East [10]. However, Jordan is an energy importing country and has paucity qualified and experienced personnel in the field of water desalination. Until the beginning of the current century, the water planners in Jordan have not given water desalination appropriate attention as a potential water supply [8]. Wide-scale desalination, as well as other alternative resources, has shown that the water deficit can be reduced from 400 MCM in 2015, to less than 100 MCM in 2025, as shown in Fig. 1.

Several studies investigated projections of saline water desalination in Jordan. However, most of these investigations were part of feasibility studies for different proposed projects. Therefore, a comprehensive image of water desalination in Jordan is still not clear. Mohsen [9] reviewed some aspects of water desalination in Jordan as a part of different water strategies to overcome water shortage. However, there is no comprehensive review that frames the overall situation or future perspectives for desalination in Jordan. Realizing the importance of desalination technology in addressing Jordan's water deficits, this review highlights key facts and figures of current water desalination and provide comprehensive review of water desalination in Jordan in the past and future, taking into consideration the potential of available water sources and economic drivers for the next generation

2. Role of desalination in Jordan water equation

Desalination of brackish water and sea water is being seriously considered to bridge the water gap in the kingdom of Jordan. Abu Qdais and Batayneh [8] assessed deficits between water supply and demand, and the potential role desalination may play during the period between 2000 and 2020. In 2000, water deficits were estimated to be 300 MCM when desalination capacity was only 86 MCM year^{-1}. The assessment was performed up to the year 2020 based on the following two scenarios: first scenario assuming a population growth rate of 3.3%, a second scenario assuming a reduction in population growth rate to 2.5%. These scenarios took into consideration, as well, the potential of Jordan's water resources after the introduction of two new major water conservation and transport projects, namely Al Wahda dam of 110 MCM year^{-1} and Disi pipeline of 100 MCM year^{-1}, in addition to enhancement of wastewater reuse. The study estimated that the deficit would reach 710 and 520 MCM year^{-1} according to the first and second scenarios by 2015, respectively. However, the study anticipated significant reduction in the deficits to 420 and to 220 MCM year^{-1} for the first and second scenario, respectively, by desalinating sea and brackish water.

Compared with the current figures in the National Water Strategy of Jordan, the deficit in the year 2015 was 409 MCM year^{-1}, which indicates that the first scenario proposed by Abu Qdais and Batayneh [8] was met, and can be attributed to the increased desalination capacity in Jordan as a result of constructing several plants with a net approximate capacity of 86 MCM year^{-1}. On the other hand, the second scenario was somehow optimistic, as the current water deficit is much higher than the estimated value. This can be explained by the fact that the study expected the Red–Dead Sea project would commence operation by the year 2010 and that Jordan will obtain 110 MCM from Al Wahda dam. Due to the lack of finances and political instability in the Middle East, the Red–Dead Sea project is not yet implemented, and Jordan did not get its share from Al Wahda dam because of the construction of several Syrian dams upstream of the Yarmouk River. The

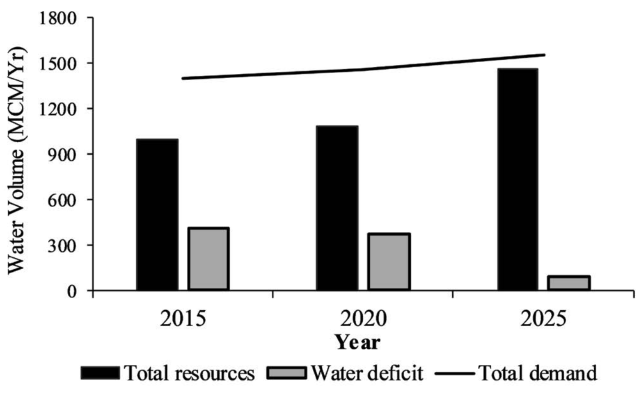

Fig. 1. Projected demand versus planned supply for Jordan (2015-2025).
Source: Adapted from Abu Qdais and Bataineh [8] and MWI [1].

situation was further complicated by the continuous influxes of the Syrian Refugees (about 1.5 million).

3. Seawater and brackish water availability for desalination

In Jordan, there are two main raw saline resources for desalination applications, namely seawater which is limited to the southern shoreline of 27 km on the Red Sea of the Gulf of Aqaba, and the brackish groundwater resources that are distributed in different groundwater basins throughout the country [11]. In addition to the brackish water available in different aquifers, there are 67 brackish springs distributed throughout the country. The groundwater basins, brackish springs in each ground water (GW) basin, the total annual discharge capacity of each basin springs, as well as, the average total dissolved solids (TDS) are shown in Fig. 2.

Japan International Cooperation Agency (JICA) classified brackish ground water resources in Jordan as renewable with a capacity of 55–60 MCM year^{-1}; nonrenewable/flowing with a capacity of 265–300 MCM year^{-1} and nonrenewable/stagnant with a total capacity of 24 billion m^3. The nonrenewable/flowing source which flows into the Dead Sea and Jordan valley was recognized as promising for brackish desalination development [12]. More than three trillion cubic meters of brackish water is stored in the groundwater aquifers including Ram Aquifer, Khrem Aquitard, Zarqa aquifer, Kurnub Aquifer, lower Ajlun Aquifer, Amman-Wadi Sir Aquifer, Wadi Araba Alluvial Aquifer and Rujam Aquifer. Table 1 shows the amount of water stored in each aquifer as distributed among different basins [13].

In 1995, Japan International Cooperation Agency (JICA) [14] proposed a brackish groundwater desalination project in Hisban/Kafrein area. Later, in 2004, JICA [12] proposed another brackish groundwater desalination project in Lajoun. Mohsen [9] indicated that a maximum of 80 MCM year^{-1} of brackish water can be available in Jordan valley with an average salinity of 3,000 ppm. Brackish water with salinity between 5,000 and 7,500 ppm in the South of Ghore between Dier Alla town and Dead Sea can provide about 60 MCM year^{-1} of drinking water. In addition, brackish water springs with a capacity of 10 MCM year^{-1} are distributed east and west of Jordan Valley [3].

4. Assessment of reverse osmosis desalination in Jordan

Using the analytic hierarchy process (AHP), Jaber and Mohsen [15] evaluated several non-conventional water resources as a potential supply of water in Jordan, such as wastewater treatment, water harvesting, importation of water

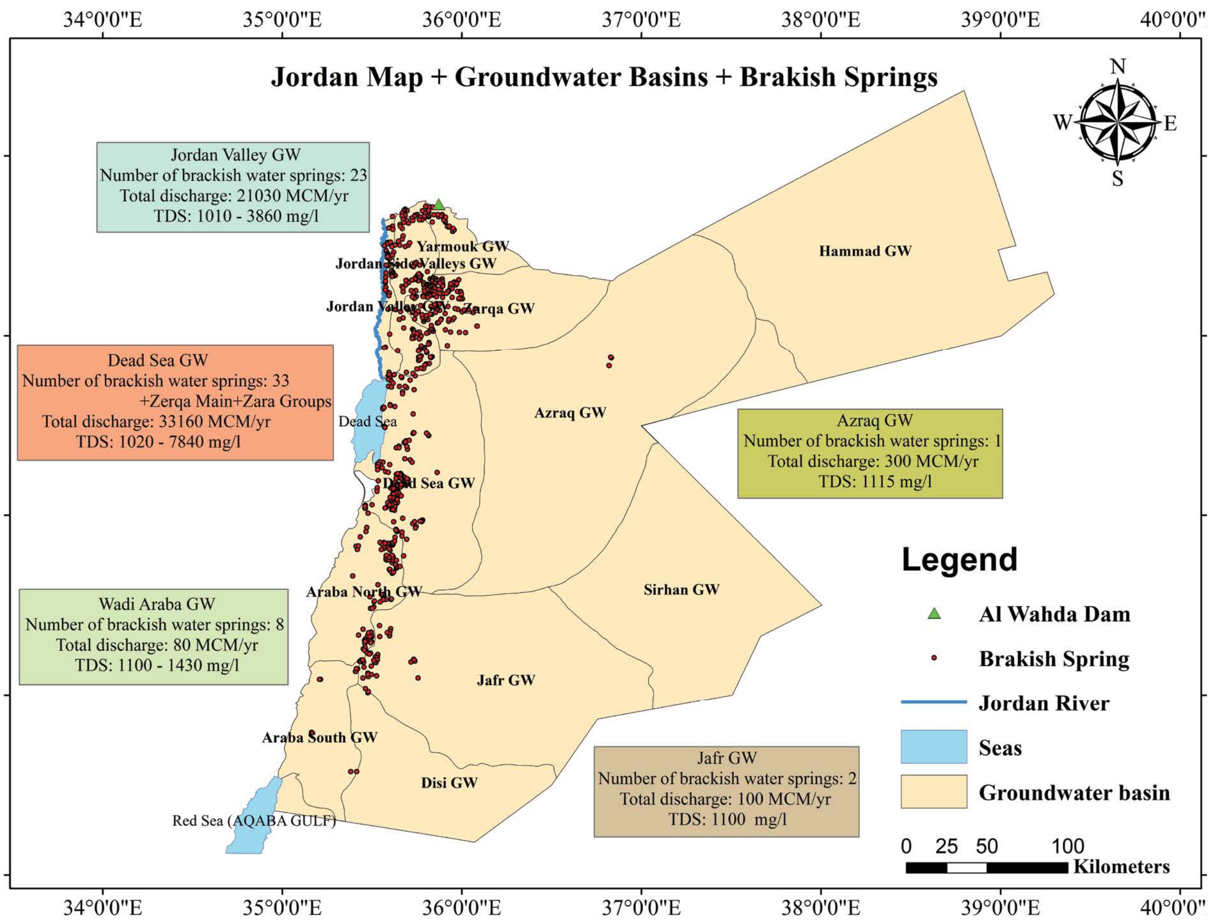

Fig. 2. Groundwater basins and brackish springs in Jordan.
Source: Adapted from USAID/DAI [13].

Table 1
Distribution of the total estimated quantity of brackish groundwater stored in the aquifers among the groundwater basins. The figures are billions of cubic meters [13]

Groundwater basin / Aquifer system	Azraq	Dead Sea	Hamad	Jafr	Jordan River	Sirhan	Southern Desert	Wadi Araba	Total
Ram	486.70	206.80	812.80	12.20	767.40	538.00	–	–	2,824.00
Khreim	–	–	111.70	88.20	–	11.10	1.70	–	212.70
Zarqa	7.90	0.07	18.89	–	5.90	0.33	–	–	33.09
Kurnub	41.78	6.10	31.17	12.40	31.19	24.60	–	–	147.24
A1–6	–	–	–	39.00	–	–	–	–	39.00
B2/A7	45.55	2.57	15.68	1.68	–	32.25	–	–	97.72
B4/B5	2.20	–	11.55	–	–	0.80	–	–	14.55
Alluvium	–	–	–	–	–	–	–	70.40	70.40
Total	584.12	215.54	1,001.79	153.48	804.48	607.08	1.70	70.40	3,438.6

and desalination. Among all the nonconventional resources, desalination was proved to rank as the highest advocated for alternative in terms of availability and reliability from the perspectives of economic, technical and environmental sustainability.

Several studies and projects were carried out to evaluate the feasibility of water desalination in Jordan. Desalination of seawater on the Red Sea was shown to be infeasible for municipal water supply, due to the relatively high cost. This was mainly attributed to the cost of energy import the seawater location in the far south of Jordan, away from the main centers of water demand (at the northern eastern and middle territories). However, a study that considered the application of desalination plants along the Red Sea shoreline, to meet the demand of industry and tourism, showed that seawater desalination might be feasible considering that those two sectors can afford the higher costs of the process [8]. Recently Jordan has seriously considered seawater desalination for drinking water purposes. A feasibility study conducted by a French firm – Coyne et Bellier – showed that the project of driving Red Sea water to the Dead Sea, can be feasible, and the study recommended that this pipeline conveyance should be combined with a high-level desalination plant [16].

Mohsen and Al-Jayyousi [7] showed that brackish water desalination was more competitive than seawater due to the relatively lower cost. Since brackish water resources are distributed in different places in the country, they suggested distributing medium size reverse osmosis (RO) systems at domestic and industrial levels. Abu Qdais and Batayneh [8] showed that desalination of brackish water might play a significant role in bridging the water gap and hence it might be a feasible option to augment the water supply status. The analysis conducted in this study illustrated that by applying the Ministry of Water and Irrigation (MWI) plan for water desalination, the expected future water deficits can be reduced. Afonso et al. [17] investigated the technical-economic feasibility of brackish water desalination by RO to produce potable water. The study was conducted by operating a pilot plant, where FilmTech RO membrane (SW 30-2521) was used. Brackish water samples were brought from Hussein thermal power station. The study revealed that, RO could remove organic and inorganic material from this brackish water, with salt rejection of more than 85%. In addition, from an economic point of view, the cost for producing potable water through RO was not excessively high (0.24$ m^{-3}). However, this study emphasized the importance of governmental contribution in financially supporting the capital cost. Mohsen and Al-Jayyousi [7] conducted a study to select the optimum desalination technology of brackish water in Jordan using the hierarchy process method. Their evaluation was based on technical, economic and environmental aspects. According to the study, RO was ranked the highest desalination process compared with other desalination processes such as multi-effect desalination, vapor compression, electrodialysis and multi-stage flash.

5. Past, present and future of desalination in Jordan

The MWI of Jordan decided not to accept the responsibility for operating desalination plants and to transfer this responsibility to the private sector (The World Bank) [18]. Some RO desalination units were established to facilitate industrial needs since the year 1980. These plants are located at Hussein Thermal Power Station, Oil Refinery, Pepsi Cola Co., Potash Co. and other small factories, and all together had a total capacity by 2010 of only 3.29 MCM $year^{-1}$ [3]. According to the water management study for Jordan, which was conducted in 1992 to help Jordan to meet its chronic crisis in water supply, there was almost no utilization of brackish water in 1990. Increase in the brackish water desalination capacity was expected to reach between 2 and 20 MCM $year^{-1}$ by the years between 2000 and 2015, respectively [19]. Until the early 2000, Jordan`s experience in desalination had been limited to industrial and agricultural uses. An evaluation of the World Bank [18] revealed that there are 10 seawater desalination plants with a total capacity of 5,500 m^3 d^{-1}, which are operating mainly for industrial purposes, and 30 brackish water desalination plants with a total capacity of 5,700 m^3 d^{-1} in the Jordan Valley (nine of these plants are for industry, while the rest are for irrigation purpose.

Jordan started seriously to consider desalination as an important option to overcome water shortage in the country since 2000. The desalination plants that have been constructed since 2000, and that are affiliated to the government are listed in Table 2 and their locations are shown in Fig. 3. Other private small scale desalination plants that are distributed throughout Jordan for industrial and agricultural applications are listed in Table 3.

Most of the desalination plants in Jordan are of sizes up to 3.6 MCM year^{-1}. This include 32% of small desalination plants with size less than 0.3 MCM year^{-1} and 58% of medium desalination plants with size between 0.3 and 3.6 MCM year^{-1}. The four plants with size more than 3.6 MCM year^{-1}, namely: KEMAPCO seawater desalination plant, Zarqa desalination plant, Abu Zeighan plant and Wadi Ma'in, Zara and Mujib desalination plant, represent only 10% of the total number of desalination plants, but contribute to 90% of the total capacity of desalinated water that can currently be supplied to the country.

As shown in Table 2, several small-scale desalination plants for drinking water purposes were constructed for the Yarmouk Water Company in Northern Jordan. Ruwaished wells (1 + 4) treatment plant was constructed in 2000 by local contractors, as the first water desalination project using RO. This plant was designed to improve the water quality of these wells, which suffer from high concentration of dissolved salts, iron, and sulfur and to achieve desalination capacity of 0.53 MCM year^{-1}. Later in 2008, another plant with desalination capacity of 0.53 MCM year^{-1}, was constructed to treat Ruwaished wells (6 + 7). RO desalination plants with approximately similar capacity such as Baptism site RO plant, Ein Sara desalination plant, Ghor Al-Safi plant, Al-Safawi plant and Kraymeh well treatment plant were constructed as well [20].

Under the umbrella of the Ministry of Water and Irrigation/Water Authority of Jordan, several large-scale desalination plants were constructed by local contractors based on BOT (build-operate-transfer) scheme such as Karameh Dam/TharetRamel RO plant (AquaTreat), Kryameh Plant (AquaTreat), Ein Sara Plant (AquaTreat), SWRO at Kemapco site (AquaTreat), Mashatel Faisal (Irshedat).

Zarqa groundwater desalination plant was inaugurated by the King Abdullah in 2001, and is operating at 5.26 MCM year^{-1} [18]. In 2002, the large project of Abu Zeighan was built at the village of Abu Zeighan, which is located in the Jordan Valley, 350 m below sea level. This plant treats ground water with a TDS content of 7,000 mg L^{-1} and it has a total capacity of 15.77 MCM year^{-1} (Yara Shahrouri, personal communication, October/24/2016). The WadiMa'in, Zara and Mujib desalination plant is currently the largest brackish water desalination plant with production capacity of 47 MCM year^{-1}. The agreement for this desalination plant between MWI and Water Authority of Jordan (WAJ) was signed in September 2003. The plant now receives water with salinity between 1,500 and 2,000 mg L^{-1} and it is supplying Amman with high-quality water [21]. Today, the desalination capacity for drinking water purposes in Jordan, which comes mainly from the above three mentioned desalination facilities, is estimated around 86 MCM year^{-1}. This is distributed as 6 MCM year^{-1} from Zarqa wells, 10 MCM year^{-1} from Abu-Zighan plant, 50 MCM year^{-1} from Zara-ma`in plant and 20 MCM year^{-1} from other sources [22]. Another large-scale desalination plant is the Al Karameh Dam Desalination Plant, which was constructed in 2009. The idea was for the raw water to be extracted from the surface water of Al Karameh dam with a maximum TDS of 18,000 ppm (Yara Shahrouri, personal communication, October/24/2016). The plant was to be executed in two phases. Phase one with a capacity of 1 MCM year^{-1} and Phase 2 with a capacity of 3 MCM year^{-1} to give a total of 4 MCM year^{-1}. The purpose was to supply desalinated water (<500 ppm TDS) for household drinking and agricultural purposes. It was a BOT contract with a concession period of 15 years. However, after the construction and operation of Phase 1 (capacity of 1 MCM year^{-1}) the Dam salinity increased to 25,000 ppm. Subsequently an alternative source of water was allocated – Thahret Al Ramel Well – and the existing plant was modified to accommodate the different water source (in quality and quantity) and the operation resumed in 2015 with a capacity of 0.87 MCM year^{-1}.

A total of approximately 90 MCM year^{-1} is produced annually in Jordan. This amount of desalinated water is essential in enhancing the gap between supply and demand; however, additional desalination capacity is still needed to meet the increasing demand on fresh water sources.

In 2014, Dabaan well plant was constructed in Mafraq with desalination capacity of 0.07 MCM year^{-1}. Al Mahasi desalination plant extracts water from three wells, Al Mahasi wells (5,6) and Baraka well (8), to produce 1.05 MCM year^{-1} of drinking water. Operation of this plant started in April, 2015 to supply desalinated water to approximately 4,100 residents in Al Ramtha's surrounding villages of Shajarah, Torrah and Emrawah, which have realized increasing numbers of Syrian refugees. Abu Thableh water treatment plant that, has a production capacity of 1.93 MCM year^{-1}, was moved from Abu Thableh and installed at Kufranja [20]. Thahret Al Ramel wells desalination plant was built in 2016 as a modification of Al Karameh Dam Desalination Plant. The new plant capacity is 0.87 MCM year^{-1}. As the first large sea water desalination plant for drinking water purposes installed in the country, Sea Water Desalination plant at Kemapco site was recently constructed and put into operation in Aqaba with a capacity of 4.38 MCM year^{-1}. The raw seawater has high salinity which reaches around 42,000 ppm and the produced water has TDS of less than 350 ppm. Water will be utilized by KEMAPCO (Arab Fertilizers & Chemicals Industries) and Aqaba Water Company (Yara Shahrouri, personal communication, October/24/2016).

Jordan's future plan is to increase the desalination capacity to about 150 MCM year^{-1}. Most of the additional water will be coming from desalination of the Red Seawater in the Gulf of Aqaba (70 MCM year^{-1}), 8 MCM year^{-1} from the Hisban project and 10 MCM year^{-1} from other areas [22]. The Hisban project was planned to be constructed between 2016 and 2018. This project is located in the Jordan Valley and it could generate 9–15 MCM year^{-1} [9]. A mega desalination project, the Red Sea–Dead Sea project (RSDSP), to link the Red sea with Dead Sea, was proposed as a part of the integrated master plan of the peace treaty between Israel and the Hashemite Kingdom of Jordan. The goal of the project is to reach an ultimate capacity of 850 MCM year^{-1} in 2060 [16]. The parties signed an agreement on 9 December 2013 to start the implementation of the initial phase of the project. The aim of phase one is to extract 190–300 MCM year^{-1}

Table 2
RO desalination plants that are affiliated to the government

Number	Plant name	Production capacity MCM year^{-1}	Treatment process	Location	Water resource	Constriction year	Owner
1	Ruwaished wells (1 + 4)	0.53	RO	Northern Badia	Brackish	2000	Yarmouk Water
2	Dier Allah	0.44	RO	Balqa	Brackish	2001	MWI/WAJ
3	Zarqa desalination plant	5.26	RO	Zarqa	Brackish	2002	Miyahuna
4	Al-Reesha desalination plant	0.31	RO	Aqaba	Brackish	2002	Aqaba Water
5	Omari Borders desalination Plant	0.18	RO	Zarqa	Brackish	2003	MPWH
6	Qatar	0.03	RO	Aqaba	Brackish	2003	Aqaba Water
7	Abu Zeighan plant	15.77	RO	Balqa	Brackish	2003	MWI/WAJ
8	Mobile unit (Mudawar)	0.31	RO	Maan	Brackish	2003	MWI/WAJ
9	Mobile unit (Ghor Al-Mazraa)	0.31	RO	Karak	Brackish	2003	MWI/WAJ
10	Mobile unit (shouneh 5)	0.31	RO	Balqa	Brackish	2003	MWI/WAJ
11	Al-Safawi plant*	0.48	RO	Northern Badia	Brackish	2003	Yarmouk Water
12	Ein Sara desalination plant	0.96	RO	Karak	Brackish	2005	MWI/WAJ
13	Ghor Al-Safi plant	0.79	RO	Karak	Brackish	2005	MWI/WAJ
14	Al-Karamah borders plant	0.18	RO	Mafraq	Brackish	2006	MPWH
15	Ghuwaibeh plant	0.13	RO	Karak	Brackish	2006	MWI/WAJ
16	WadiMa'in, Zara and Mujib	47	RO	Swemeh	Brackish	2006	Miyahuna
17	GhorFiFa	0.26	RO	Karak	Brackish	2007	MWI/WAJ
18	Ruwaished wells (6 + 7)	0.53	RO	Northern Badia	Brackish	2008	Yarmouk Water
19	Kraymeh R.O. desalination plant	0.88	RO	Jordan Valley	Brackish	2008	Yarmouk Water
20	Omari Plant	0.04	RO	Zarqa	Brackish	2008	MWI/WAJ
21	Zniya Plant	0.79	RO	Mafraq	Brackish	2008	Yarmouk Water
22	MashtalFasall desalination plant	2.63	RO	Jerash	Brackish	2010	Yarmouk Water
23	Karameh well 2	0.04	RO	Balqa	Brackish	2013	MWI/WAJ
24	Mahasi plant	1.05	RO	Ramtha	Brackish	2014	Yarmouk Water
25	Daba'an well plant	0.07	RO	Mafraq	Brackish	2014	Yarmouk Water
26	Zaqiq 1*	0.44	RO	Ajloun	Brackish	2014	Yarmouk Water
27	Salihyiat Al Naim	0.01	RO	Northern Badia	Brackish	2014	Yarmouk Water
28	ThahretRamel Well/modification of Al-Karameh Dam plant	0.87	RO	Balqa	Brackish	2015	MWI/WAJ
29	KEMAPCO seawater	4.38	RO	Aqaba	Sea	2017	Aqaba Water
30	Sabha well desalination plant	0.42	RO	Mafraq	Brackish	2017	Hashemite Fund
31	Kufranja water treatment Plant/previously TabaketFahel	1.54	RO	Ajloun	Brackish	2015/2017	Yarmouk Water
32	Haŝhemite University Plant	0.31	RO	Mafraq	Brackish	Under construction	Hashemite University
33	Abu thableh water treatment plant *moved from abuThableh and installed at Kufranja	1.93	RO	Jordan Valley	Brackish	2017	Yarmouk Water

WAJ: Water Authority of Jordan, MWI: Ministry of Water and Irrigation, MPWH: Ministry of Public Works and Housing Source: MWI/WAJ.
*Not in operation anymore: Yarmouk Water.

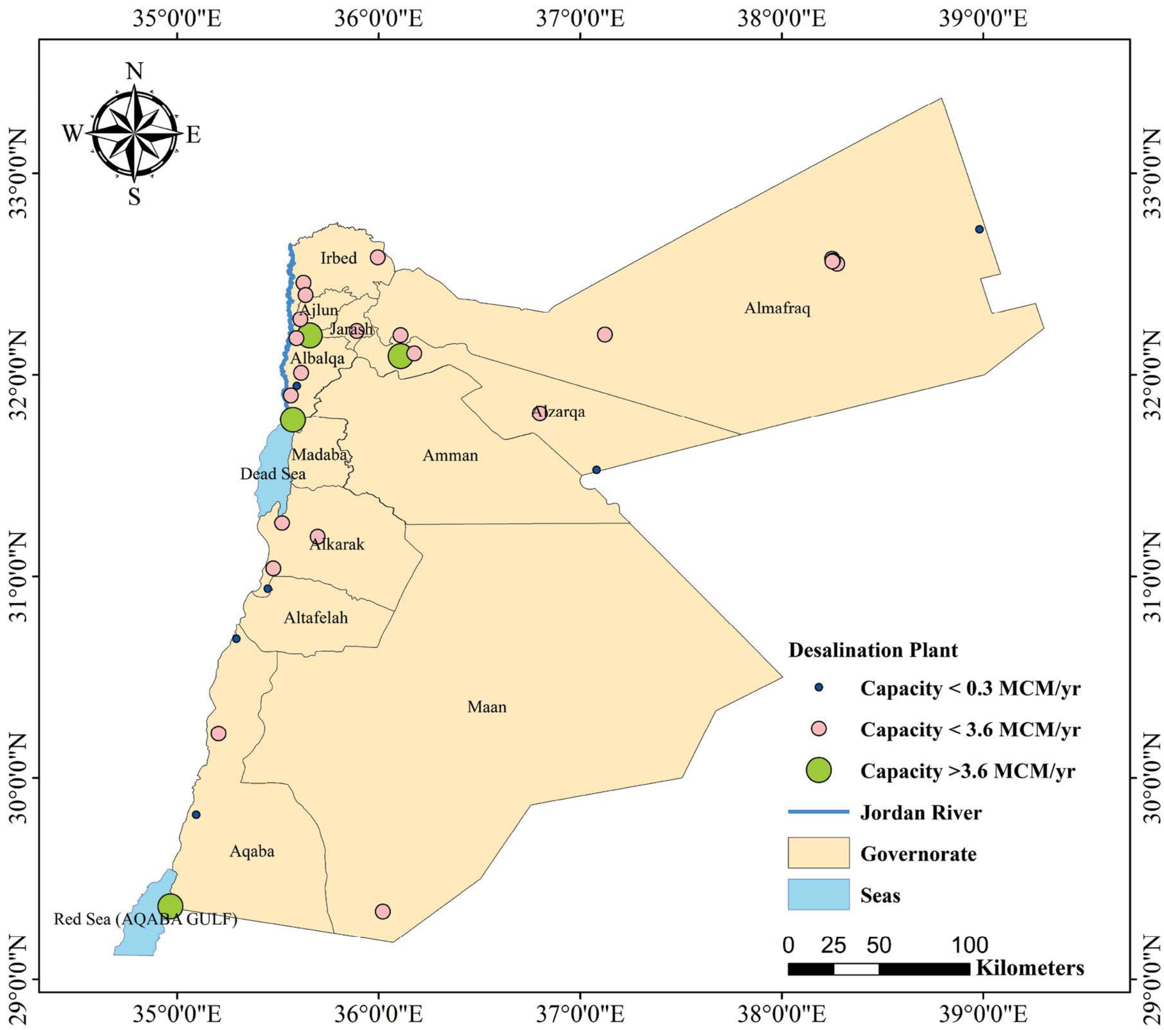

Fig. 3. Sites of desalination plants in Jordan.

Table 3
Some private-sector RO desalination plants

Number	Plant name	Production capacity MCM year^{-1}	Treatment process	Location	Water resource	Constriction year	Reference
1	Brewery industry	0.13	RO	Amman	Brackish	1979	Mohsen [9]
2	Jordan Petrol (4 units)	1.11	RO	Amman	Sea	1981	Mohsen [9]
3	Armorrebuild	0.15	RO	Amman	Brackish	1981	Mohsen [9]
4	SOM DATT group	0.22	RO	Azraq	River	1987	Mohsen [9]
5	Baptism Site RO plant-high salinity (55,000 ppp)	0.284	RO	Jordan Valley	Brackish	1999	AquaTreat
6	Movenpic Hotel RO plant	0.44	RO	Dead Sea	Brackish	2005	AquaTreat Group Internal document, 2016.
7	Jafer desalination plant	0.31	RO	Maan	Brackish	2007	AquaTreat Group Internal document, 2016.

from the Red Sea and produce about 65–85 MCM year^{-1} of desalinated water to supply Israel by 35–50 MCM year^{-1} and Aqaba with 30 MCM year^{-1}. In exchange, Jordan will be receiving 50 MCM year^{-1} of water from Israel to the northern part of Jordan [11,23]. The commercial operation of phase one is planned to be in 2018 (JVA) [24]. Based on the national water strategy 2016–2025, the purpose of the second phase of RSDSP is to produce 150 MCM year^{-1} by the year 2025. In addition, Jordan is planning its own version of the project, the Jordan Red Sea project, which aims to supply Jordan with 930 MCM year^{-1} of desalinated freshwater by 2045 [25].

According to the Jordanian national water strategy, Fig. 4 illustrates the projected changes in water resources and water demand through the years 2015–2025. Desalination will contribute sufficiently to the development in water resources, mainly the Red Sea–Dead Sea Project, which will supply a total of 235 MCM year^{-1} and improve water deficit by 6% when it goes online. Around 187.5 MCM will be generated by other projects such as Aqaba desalination plant project and projects for desalination of brackish water in Aghwar area and Badia.

6. Performance of two desalination plants as a case study

6.1. Wadi Ma'in, Zara and Mujib plant (the largest brackish water desalination plant in Jordan)

The WadiMa'in, Zara and Mujib (WMZM) desalination plant was initiated in 2001 to treat brackish water that comes from the following sources: The WadiMujib River, the Wadi Ma'in Zarqa River and the Zara hot spring. The plant has a total treatment capacity of 60 MCM year^{-1}, where 23 MCM year^{-1} is from Wadi Ma'in Zarqa River, 30 MCM year^{-1} from Wadi Mujib and 7 MCM year^{-1} from Zara springs. The plant is composed of nine RO trains. Membranes of two types are in use: type 1 (BW30–400FR) and type 2 (LE-400), with an area of 400 ft^2 [26]. Raw water is chemically pretreated by pumping the water into a mixer where chemicals are added to initiate coagulation and flocculation in the sludge blanket clarifier. Water then passes through Pulsatube clarifier and dual media filters to remove large quantities of small suspended particles. The last stage of the pre-treatment is achieved by passing the water through a five-micron cartridge filtration unit. RO systems operate at a conversion rate between 85% and 90%. Permeate then passes through a demineralization process and then disinfected with UV and chlorine application [21]. Fig. 5 shows the WMZM water treatment plant block diagram.

Mohsen and Gammoh [26] evaluated the plant's performance and operation since the plant started in August 2006 until April, 2008. During the first 150 d, the performance of the RO system was less stable and was characterized by lower recovery of 85%, low normalized differential pressure across the membrane, flow rate of 675 m^3 h^{-1} and high salt rejection. After 150 d of operation, the system started to be more stable with recovery rate over 85%. The overall performance of the system can be summarized as follows: the water production was 100,000 m^3 d^{-1} with a TDS value of 185 mg L^{-1}. The feed flow rate was 5,100 m^3 h^{-1} (less than the designed flow rate which was 6,000 m^3 h^{-1}). The differential pressure across the membrane was 2.31 bar. Yassin and Ghandour [21] showed that after 5 years of operation, the original membranes had not been replaced and the RO membrane performance kept sustainable levels throughout the operating years, but after that time some were replaced to keep optimum performance.

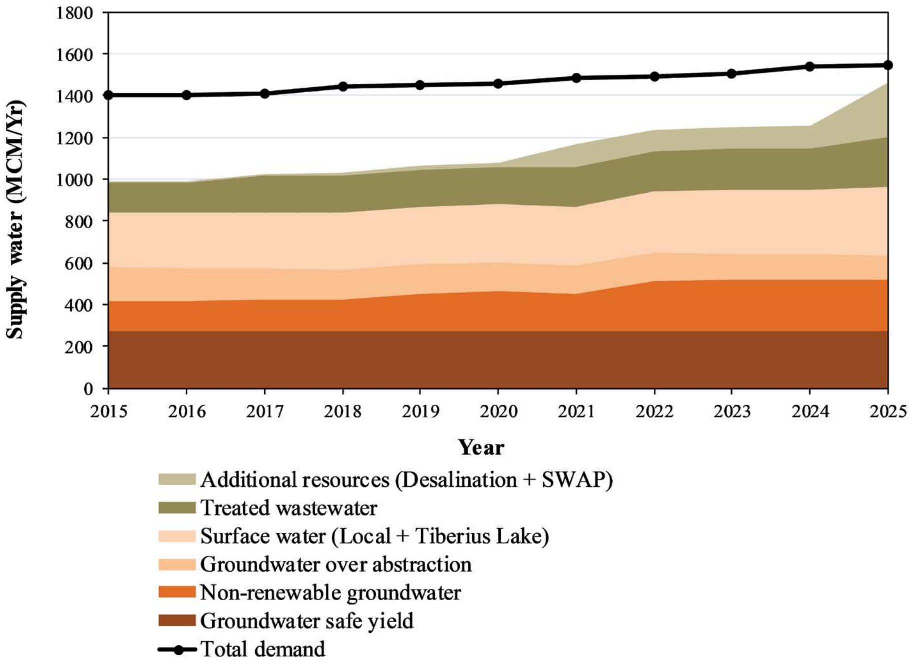

Fig. 4. Development of resources and projected demand in MCM year^{-1}.
Source: National water strategy 2016–2025 [6] with team analysis.

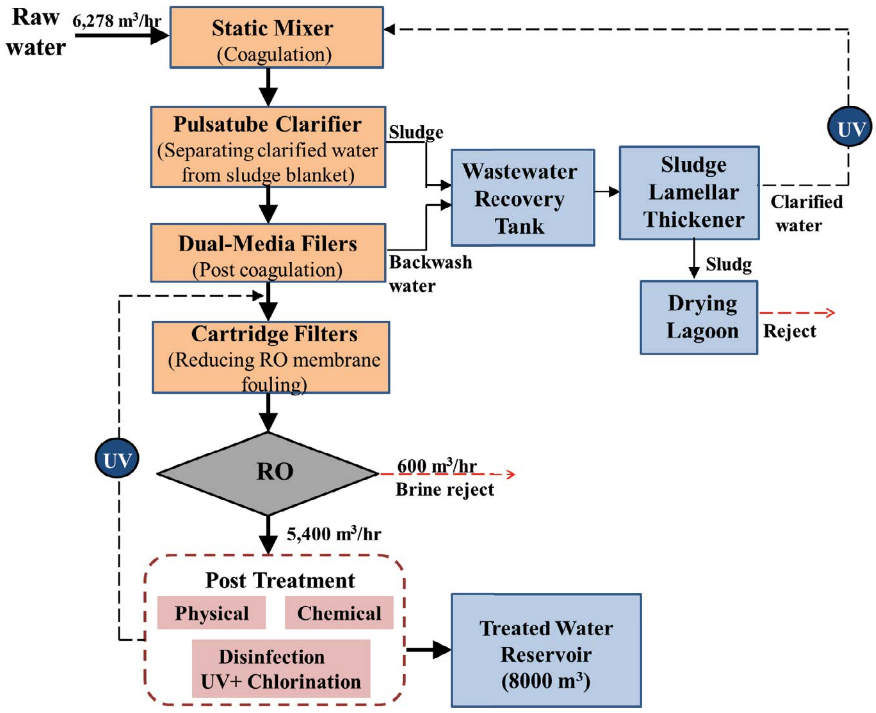

Fig. 5. WMZM Desalination Plant process.
Source: Adapted from Yassin and Ghandour [21].

6.2. Design, build, operate and transfer of a sea water desalination plant at Kemapco site in Aqaba (the largest sea water desalination plant in Jordan)

This plant is located in Aqaba and it is the first sea water desalination plant to be installed in Jordan with a capacity of 4.38 MCM year^{-1}. The plant was built as a BOT project and first operated in 2017. The desalinated water is purchased by KEMAPCO (Arab Fertilizers & Chemicals Industries) with total amount of 1.3 MCM year^{-1} and by Aqaba Water Company (AWC) with total amount of 3.1 MCM y^{-1}.

The plant employs pre-treatment technologies including media filtration, self-cleaning microfiltration and ultrafiltration. The inlet TDS is 44,000 ppm and the plant consists of a dual train surface water reverse osmosis then brackish water reverse osmosis to achieve the needed quality for both municipal and industrial usage. Feed water is first treated by rapid multimedia filtration, followed by micron self-cleaning filters followed by ultrafiltration. The plant had a compact design with a small foot print, less than 2,500 m^2.

The chemical pre-treatment includes dosing of acid, anti-scalant and anti-oxidant (for de-chlorination). The desalination plant is designed in two streams each with a permeate capacity of 2.2 MCM year^{-1}. Two-stage RO is conducted at an operating pressure of 68 bars and a total recovery rate of 39%. Effluent's TDS of less than 350 ppm. After the RO unit, post-chemical treatment is conducted through the addition of lime. An energy recovery system was installed to reduce the power consumption. Fig. 6 shows the plant-block diagram.

The plant has received global recognition due to its uniqueness – for its technical and commercial advancement. It was shortlisted by the Global Water Awards (GWA) for 2 years in a row. The Global Water Awards recognizes the most important achievements in the international water industry; rewarding significant initiatives in the water, wastewater and desalination sectors, moving the industry forward through improved operating performance, innovative technology adoption and sustainable financial models. In 2017, the plant was shortlisted with another three projects globally for the category "Water Deal of the Year" and again in 2018 it was shortlisted for "Industrial Desalination plant of the Year.

The main attraction of the plant is due to its local flavor. The whole project has been designed, engineered, 100% financed and operated by a local firm (AquaTreat). It is considered the first Sea Water Desalination plant in Jordan with the capacity of 4.38 MCM year^{-1} (500 m^3 h^{-1}, 12,000 m^3 d^{-1}) and located at Red Sea/Aqaba. It is a practical example of the advancement of private sector participation in the water sector as it is a BOT project with a concession period of 7 years. The BOT deal, as well as the plant itself, will work as a pilot for the anticipated Red Sea Dead Sea Project – as a path finder for seawater desalination in Jordan.

The implementation of the first sea water desalination project in Jordan highlights the financial and technical strengths of a secure entity to guarantee the supply of high quality water under performance based conditions. The plant serves both municipal and industrial needs. In less than one year of operation, it reduced Kempaco's cost of water by more than 40% and allowed AWC to transfer some of its wells water to Amman. The plant is performing as per contract and is giving the following results: TDS < 300 ppm; Cl < 180 ppm, and Na < 120 ppm (AquaTreat).

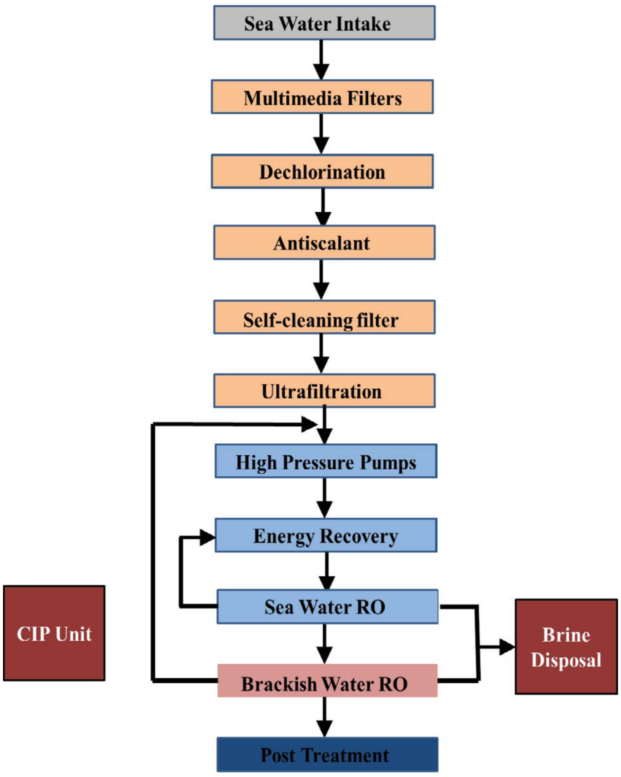

Fig. 6. KEMAPCO Sea Water Desalination Plant process.
Source: AquaTreat Group, Internal Document, 2016.

7. Non-conventional energy integrated desalination: a sustainable solution to overcome water shortages in Jordan

The availability of energy supply is important issue in the application of desalination. Most neighboring oil producing countries rely on fossil fuel to supply desalination plants with the required energy. Jordan is suffering from a lack of natural energy sources and most of oil and natural gas are imported. The Jordanian National Energy Strategy for 2007–2020 targeted a reliance on domestic energy sources from 4% to 40%. Jordan passed the Renewable Energy and Energy Efficiency Law to boost investment and allow citizens to sell electricity back to the national grid. By 2017, Jordan archived 7% share of renewable energy and it is anticipated to reach 10% by 2020 [27]. The current share, as well as the targeted share of renewable energy, is presented in Fig. 7 for each renewable energy sources of interest which are solar, wind, hydropower and waste to energy.

In order to make desalination more applicable in Jordan, large body of literature was devoted to study and evaluate the application of renewable energy in seawater or brackish water desalination.

Akash et al. [28] conducted a study to evaluate the integration of non-conventional energy technologies with desalination in Jordan. Four nonconventional technologies – solar, wind, hydropower and nuclear – were evaluated and compared by conducting a multi-criteria analysis using the analytic hierarchy process. Hydropower showed the highest priority to be applicable for both domestic and industrial sectors. Solar showed high potential for industrial applications. Wind technology might be applicable for domestic use. Solar and hydropower energy–desalination systems were shown to have higher potential compared with wind and nuclear energy. Wind can be utilized in only specific areas with consistently higher velocity.

The integration of water desalination with renewable energy sources can facilitate the penetration of renewable energies in the energy system of the country [29,30]. The results of these studies have shown that the application of desalination, especially in the case where desalination is combined with pump storage, could currently increase penetration of wind power to 32% and photovoltaic (PV) to 37%, while the overall penetration of renewable energy sources can reach 76% by 2050.

The published literatures concerning the application of the major three energy sources: solar, hydropower and wind, are discussed below.

7.1. Solar

Jordan lies between 29°11′ and 33°22′ N latitudes of the global sunbelts, which gives Jordan good access to solar energy. The daily solar radiation is about 5.5 kWh m^{-2} d^{-1} and the annual sunshine duration is estimated to be 2,900 h [31]. Jordan designed a comprehensive solar atlas, which is available to developers [32]. Solar-driven membrane desalination was the main topic of several studies [33,34].

Since the end of the last century, researchers in Jordan started to consider photovoltaic-powered reverse osmosis (RO-PV) system to facilitate RO desalination in Jordan. Gocht et al. [35] conducted a project to evaluate the technical feasibility and cost benefit of a small-scale brackish water desalination plant. The study proposed a discontinuously and transiently operating RO with a transmembrane pressure difference of 40 bar and with disc-tube-modules directly connected to a PV. In addition, the second phase of this study considered a pilot plant with a capacity of 40 m^3 d^{-1} and consists of RO desalination unit coupled with PV in Qatar village, south of Jordan. Qiblawey et al. [36] investigated the design and performance of PV-RO system, which was part of the ADIRA (autonomous desalination in rural areas) project funded by the European Commission. This system was installed in 2007 in Hartha Village in the northern part of Jordan for desalinating brackish water. Permeate production of 9.3 to 53 L h^{-1} with a salinity of less than 30 mg L^{-1} was achieved. Hrayshat [37] proposed a stand-alone RO-PV system and compared its application in 10 selected sites in Jordan; Tafila, Queira, H-4, H-5, RasMuneef, Mafraq, Hasa, DeirAlla, Baqura and WadiYabis. By referring to the daily solar radiation, duration of sunshine and the water salinity, a computer code in C++ was used to predict and compare the water production at the 10 sites. The most favorable sites were Tafila, Queira, RasMuneef, H-4, and H-5, amongst Tafila showed the highest annual water production and RasMuneef showed the highest water production during summer (May–September).

7.2. Wind

The highest potential for wind energy is in the northern and the southern parts of the country. In the northern part,

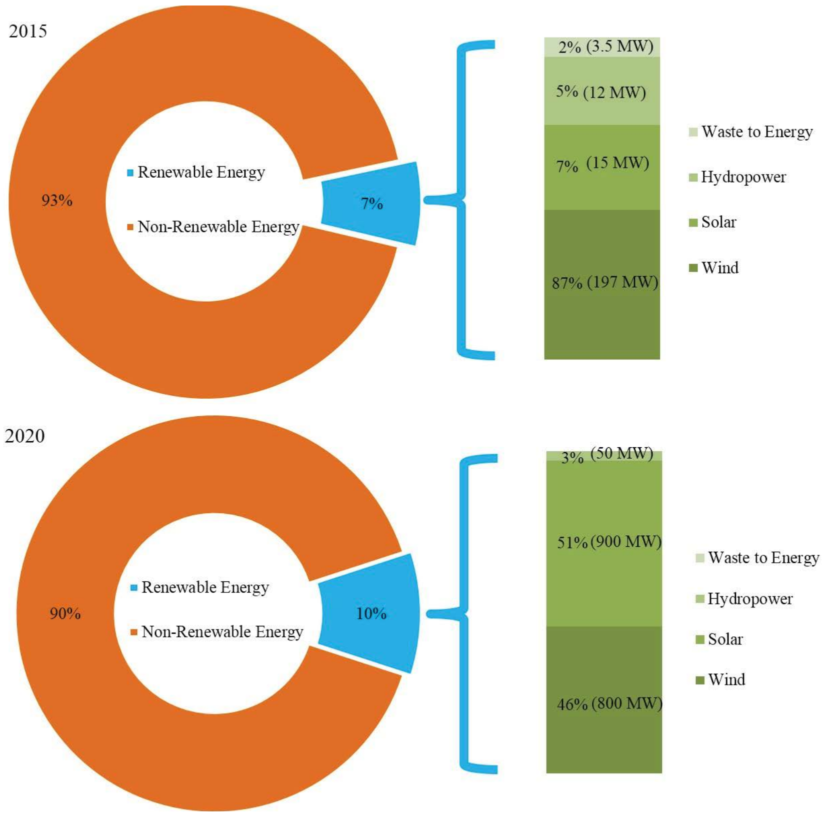

Fig. 7. Jordan energy capacity as well as the Renewable energy sources share in 2015 and as targeted for 2020.
Source: The Jordanian National Energy Strategy for 2007–2020 [27] and IRENA, Renewable Energy in the Arab Region 2016 [32] with team analysis.

Hofa and Fjeij are attractive sites. Wind speed of 7 m s^{-1} can be reached near Hofa [35]. Jordan designed a comprehensive wind atlas, which is available to developers [32]. The first wind farm in Jordan was in Ibrahimyya (close to Hofa) with a capacity of 320 kW. In the south, Wadi Araba is considered as an attractive site for wind energy harvesting. Currently, 800 MWs are generated annually from wind turbines in Jordan [32].

An early publication by Habali and Saleh [38] proposed a wind powered RO system to be applied in Jordan. The study estimated the cost of pumping and desalinating brackish water to be around 0.94 to 1.63$ m^{-3}, which was less than the cost of using conventional diesel based on the prices of that time. Mohsen and Akash [39] investigated 11 sites for the potential of wind powered water desalination; RasMuneef, Mafraq and Aqaba had the highest production of water and were considered to be favorable, H-5, Irbid and Maanwere considered promising, and the rest sites were considered poor. RasMuneef showed higher potential for water production than Mafraq and Aqaba. However, Mafraq and Aqaba showed higher production during the summer period when the need for water is higher. According to Mohsen [31], six sites have a wind speed higher than 7 m s^{-1} and these sites can have a potential application of wind energy for water desalination. These sites are Hofa, Kamsha, Aqaba, Tafila, Al-Reesheh and Al-Harir, where Tafila and Al-Harir showed the highest potential for water production of 2,660 and 3,074 m^3 d^{-1}, respectively.

Østergaard et al. [40] analyzed the effects of a large-scale desalination on the Jordanian energy system with introducing wind power into the energy system. The study revealed that RO assists the energy system as it contributed to the decrease in Critical Excess Electricity Production (CEEP) by approximately 15% and especially water storage can enhance the system's ability to integrate wind power.

7.3. Hydropower

Hydropower energy in Jordan is limited by relief and the lack of rivers, waterfalls and other surface water sources. Currently, there are two hydropower generating stations in Jordan, one in King Talal dam with a capacity of 5 MW and another at Aqaba with a capacity of 5 MW.

The RSDS project, which transfers water from the Red Sea to the Dead Sea though a 180 km pipeline, is an interesting option to exploit the 400-m height difference between the two seas to generate hydropower in the Jordan Valley area, and use this generated power to run RO system for desalinating some of the transferred water. Some studies focused on the importance of linking the two seas. Beyth [41] identified two goals of the Jordan Red Sea–Dead Sea project (1) an annual desalination of 800–850 MCM with 20–300 mg L^{-1} TDS (2). The Dead Sea level restoration at around 400 m below sea level (mbsl). By performing a mass balance estimates for that the amount of brine from the RO plant that can be discharged into the Dead Sea, would equal the amount of water evaporates considering a desalination capacity of 2,130 MCM of seawater per year [28]. Rabadi [23] indicated six components to be constructed for the Red Sea–Dead Sea project and estimated the capital cost of the first phase of the project to be around $950 million for an annual production of 65–85 MCM of desalinated water. Abu Qdais [11] studied the environmental impacts of the RSDS project on both Red and Dead seas.

7.4. Nuclear energy

Jordan's interest in nuclear energy goes back several decades. However, serious steps for the application of nuclear energy in Jordan have not taken place until the year 2007. In 2007 the nuclear law was modified and the Jordan Atomic Energy Commission (JAEC) and the Jordan Nuclear Regulatory Commission (JNRC) were established. In the same year a nuclear engineering program was launched in Jordan University of Science and Technology.

Jordan had chosen the nuclear energy option, because there are several uranium deposits on the country's territory. In Jordan it is possible to produce 30,900 tons of uranium from fields that were discovered in the central part of the country and 28,700 tons of uranium in the Hasa-Qatrana area. Furthermore, some of 100,000 tons of uranium are estimated to be produced as a by-product in phosphate deposits. Additionally, some uranium mineralization are also reported at Rweished near the Iraq borders (The world nuclear association site) [42].

In October 2013, Al-Amra site, which is 70 km east of Amman, was chosen as a suitable site where a nuclear power plant can be constructed. An agreement was signed between JAEC and Russia to build the Kingdom's first nuclear power plant. The plant will consist of two 1,000 MW reactors; the first is to be launched in 2023, and the second in 2025 [43].

Desalination plants were included in the nuclear cooperation agreement which was signed by Russia and Jordan and according to the Desalination and Water Reuse website it was reported that around 40% of the desalination plants, which will be established in Jordan, will use their energy from the nuclear plants.

8. Conclusions

Jordan is a country located in the Middle East that is suffering from chronic water scarcity. Currently, Jordan has been listed as the second poorest water country worldwide, where the demand on water exceeding the potential of the conventional water resources. Until recently, Jordan has not seriously considered the water desalination as a major source of water supply. Due to the limited shoreline of the country on the sea, Jordan has focused on desalination of brackish water that is available in several groundwater basins of the country. There are about 40 public and private desalination plants around the country, where 90% of the plants with a capacity less than 3.6 million m^3 $year^{-1}$. The only seawater desalination plant was recently put into operation in 2017 with a capacity of 4.38 MCM $year^{-1}$ and utilized for both drinking and industrial purposes. The country now working seriously to start the implementation of the Red–Dead Sea project, which is a regional desalination project that is expected – in case implemented – to augment the water supply of the country.

Water is not the only scarce resource in Jordan. The country is also lacking endogenous energy resources, where about 95% of the energy needs are imported. The absence of energy complicates the adoption of desalination and renders it an expensive option for water supply. As such, it is recommended to increase the share of renewable energy such as solar, wind and hydropower in the desalination process, in order to obtain a water with reasonable cost. The current review study indicates that desalination is a viable option to balance the water demand and supply equation of the country.

Acknowledgments

The authors highly acknowledged Eng. Muna Gharaibeh, the desalination department manager at Water Authority of Jordan, and Eng. Kefah Mrayyan, laboratories and quality director, Yarmouk Water Company for their helpful information and valuable discussion regarding desalination plants in Jordan, although they may not agree with all of the interpretations/conclusions of the paper. Also we thank Prof. Mark Hernandez (University of Colorado at Boulder, USA) for his diligent proofreading of this paper. Any opinions, findings and conclusions or recommendations expressed in this publication are those of the researchers and do not reflect the view of the organizations presented above. This work was supported in part by the USAID under grant No. PR&D 05-01.

References

[1] MWI (Ministry of Water and Irrigation), Jordan Water Sector: Facts and Figures 2017, Ministry of Water and Irrigation, Amman, Jordan, 2017. Available at: http://www.mwi.gov.jo/sites/en-us/Hot%20Issues/Jordan%20Water%20Sector%20Facts%20and%20Figures%202017.PDF.

[2] N.A. Hadadin, Z.S. Tarawneh, Environmental issues in Jordan, solutions and recommendations, Am. J. Environ. Sci., 3 (2007) 30–36.

[3] N. Hadadin, M. Qaqish, E. Akawwi, A. Bdour, Water shortage in Jordan — sustainable solutions, Desalination, 250 (2010) 197–202.

[4] M.F. Abu-Taleb, E. Salameh, Environmental management in Jordan: problems and recommendations, Environ. Conserv., 21 (1994) 35–40.

[5] Department of Statistics, Jordan, 2017. Available at: http://dosweb.dos.gov.jo/DataBank/Yearbook2017/Population.pdf.

[6] MWI (Ministry of Water and Irrigation), National Water Strategy of Jordan 2016–2025, Ministry of Water and Irrigation, Amman, Jordan, 2016. Available at: http://www.mwi.gov.jo/sites/enus/Hot%20Issues/Strategic%20Documents%20of%20%20The%20Water%20Sector/National%20Water%20Strategy(%202016-2025)-25.2.2016.pdf.

[7] M.S. Mohsen, O.R. Al-Jayyousi, Brackish water desalination: an alternative for water supply enhancement in Jordan, Desalination, 124 (1999) 163–174.

[8] H.A. Abu Qdais, F. Batayneh, The role of desalination in bridging the water gap in Jordan, Desalination, 150 (2002) 99–106.

[9] M.S Mohsen, Water strategies and potential of desalination in Jordan, Desalination, 203 (2007) 27–46.

[10] M. Nair, D. Kumar, Water desalination and challenges: the Middle East perspective: a review, Desal. Wat. Treat., 51 (2013) 2030–2040.

[11] H.A. Abu Qdais, Environmental impacts of the mega desalination project: the Red–Dead Sea conveyor, Desalination, 220 (2008) 16–23.

[12] JICA (Japan International Cooperation Agency), The Study on Water Resources Management in The Hashemite Kingdom of Jordan Final Report/Main Report Part-A "Master Plan", Ministry of Water and Irrigation, The Hashemite Kingdom of Jordan, 2004.

[13] USAID/DAI, Water Quality Improvement and Conservation Project, Technical Report, Assessment of Brackish Water, USAID, Amman, Jordan, 1998.

[14] JICA (Japan International Cooperation Agency), The study on brackish groundwater desalination in Jordan – Final Report (Summary and Main Reports), Ministry of Water and Irrigation, Amman, The Hashemite Kingdom of Jordan, 1995.

[15] J.O. Jaber, M.S. Mohsen, Evaluation of non-conventional water resources supply in Jordan, Desalination, 136 (2001) 83–92.

[16] Coyne et Bellier, Red Sea - Dead Sea Water Conveyance Study Program Feasibility Study, Final Feasibility Study Report Summary, Report No. 12 147 RP 05, 2014. Available at: http://siteresources.worldbank.org/EXTREDSEADEADSEA/Resources/5174616-1416839444345/RSDS-Summary_of_Final_FS_Report.pdf.

[17] M.D. Afonso, J.O. Jaber, M.S. Mohsen, Brackish groundwater treatment by reverse osmosis in Jordan, Desalination, 164 (2004) 157–171.

[18] World Bank, Seawater and Brackish Water Desalination in the Middle East, North Africa and Central Asia: Final report, Report 33515, 2004. Available at: http://large.stanford.edu/courses/2013/ph240/rajavi2/docs/33515.pdf.

[19] USAID/Jordan, A Water Management Study for Jordan. Project in Development and the Environment, Technical Report No. 4, USAID/Jordan Project No. 398-0365, Chemonics International Consulting Division Inc., Washington, D.C., 1992.

[20] Yarmouk Water, Water Supply: Desalination Plants, 2015. Available at: http://yw.com.jo/en/desalination-plants.

[21] A.Y. Yassin, I. Ghandour, Performance evaluation of five years operation experience of WMZM RO desalination plant, Desal. Wat. Treat., 52 (2014) 2939–2955.

[22] J. Klinger, N. Goldscheider, H. Hötzl, SMART - IWRM: Integrated Water Resources Management in the Lower Jordan Rift Valley; Project Report 2nd Phase, KIT Scientific Reports 7698, 2015.

[23] A. Rabadi, The Red Sea–Dead Sea desalination project at Aqaba, Desal. Wat. Treat., 57 (2016) 22713–22717.

[24] JVA (Jordan Valley Authority), Ministry of Water and Irrigation. RSDS - Phase I, Red Sea Desalination Project, Aqaba, 2014. Available at: http://www.jva.gov.jo/sites/en-us/RSDS/SiteAssets/summary4.aspx.

[25] JEAC (Jordan Atomic Energy Commission), White Paper on Nuclear Energy in Jordan: Final Report, Worley Parsons and Jordan Atomic Energy Commission, 2011. Available at: http://www.jaec.gov.jo/CMS/UploadedFiles/c18cbcac-92e9-481b-a781-498ca0bf7e9c.pdf.

[26] M. Mohsen, S. Gammoh, Performance evaluation of reverse osmosis desalination plant: a case study of Wadi Ma'in, Zara and Mujib Plant, Desal. Wat. Treat., 14 (2010) 265–272.

[27] MEMR (Ministry of Energy and Mineral Resources), Updated Master Strategy of Energy Sector in Jordan for the Period (2007–2020), Amman, Jordan, 2016. Available at: http://inform.gov.jo/en-us/By-Date/Report-Details/ArticleId/61/Updated-Master-Strategy-of-Energy-Sector-in-Jordan-for-the-Period-2007–2020-First-Part.

[28] B.A. Akash, O.R. AI-Jayyousi, M.S. Mohsen, Multi-criteria analysis of non-conventional energy technologies for water desalination in Jordan, Desalination, 114 (1997) 1–12.

[29] T. Novosel, B. Ćosić, G. Krajačić, N. Duić, T. Pukšec, M.S. Mohsen, M.S. Ashhab, A.K. Ababneh, The influence of reverse osmosis desalination in a combination with pump storage on the penetration of wind and PV energy: a case study for Jordan, Energy, 76 (2014) 73–81.

[30] T. Novosel, B. Ćosić, T. Pukšec, G. Krajačić, N. Duić, B.V. Mathiesen, H. Lund, M. Mustafa, Integration of renewables and reverse osmosis desalination – case study for the Jordanian energy system with a high share of wind and Photovoltaics, Energy, 92 (2015) 270–278.

[31] M.S. Mohsen, Potential for wind-powered desalination systems in Jordan, IJTEE, 1 (2010) 109–123.

[32] IRENA, Renewable Energy in the Arab Region: Overview of developments, International Renewable Energy Agency (IREA), Abu Dhabi, 2016. Available at: https://www.irena.org/DocumentDownloads/Publications/IRENA_Arab_Region_Overview_2016.pdf

[33] R. Olwig, T. Hirsch, C. Sattler, H. Glade, L. Schmeken, S. Will, A. Ghermandi, R. Messalem, Techno-economic analysis of combined concentrating solar power and desalination plant configurations in Israel and Jordan, Desal. Wat. Treat., 41 (2012) 9–25.

[34] F. Banat, N. Jwaied, M. Rommel, J. Koschikowski, M. Wieghaus, Performance evaluation of the "large SMADES" autonomous desalination solar-driven membrane distillation plant in Aqaba, Jordan, Desalination, 217 (2007) 17–28.

[35] W. Gocht, A. Sommerfeld, R. Rautenbach, T. Melin, L. Eliers, A. Neskakis, D. Herold, V. Horstmann, M. Kabariti, A. Muhaidat, Decentralized desalination of brackish water by a directly coupled reverse-osmosis-photovoltaic-system - a pilot plant study in Jordan, Renewable Energy, 14 (1998) 287–292.

[36] H. Qiblawey, F. Banat, Q. Al-Nasser, Performance of reverse osmosis pilot plant powered by Photovoltaic in Jordan, Renewable Energy, 36 (2011) 3452–3460.

[37] E.S. Hrayshat, Brackish water desalination by a standalone reverse osmosis desalination unit powered by photovoltaic solar energy, Renewable Energy, 33 (2008) 1784–1790.

[38] S.M. Habali, I.A. Saleh, Design of stand-alone brackish water desalination wind energy system for Jordan, Sol. Energy, 52 (1994) 525–532.

[39] M.S. Mohsen, B.A. Akash, Potentials of wind energy development for water desalination in Jordan, Int. J. Energy Res., 22 (1998) 683–690.

[40] P.A. Østergaard, H. Lund, B.V. Mathiesen, Energy system impacts of desalination in Jordan, Int. J. Sustainable Energy Plann. Manage., 1 (2014) 29–40.

[41] M. Beyth, The Red Sea and the Mediterranean Dead Sea canals project, Desalination, 214 (2002) 364–370.

[42] The world nuclear association site. Available at: http://www.world-nuclear.org/information-library/country-profiles/countries-g-n/jordan.aspx.

[43] Valdai Discussion Club Grantees Report, Prospects for Nuclear Power in the Middle East: Russia's Interests, 2016. Available at: http://ceness-russia.org/data/doc/REPORT_ENG_prospectsfornuclearpowerME.pdf.