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Evaluation of the current state and perspective of wastewater treatment and reuse in Qatar

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ABSTRACT

In Qatar, many freshwater resources have already been depleted due to the overconsumption as a result of the population and economic growth. Moreover, due to the lack of sufficient sewage treatment infrastructure, Qatar is facing a daily problem in treating the wastewater. Dumping untreated sewage effluents (SE) contaminates groundwater resources and worsens the current water status in the country. On the other hand, treated SE (TSE), which is estimated at about 0.75 million m^3/d, could be one of the main sources of fresh water which can be used in agriculture and industry and even as a source of drinking water in Qatar. Qatar uses only about 27% of TSE in growing fodder (25 million m^3/y) and landscape irrigation (1 million m^3/y) while about 73% of the total TSE is discharged to septic lagoons to dry or percolate into groundwater (70 million m^3/y) and runoff (0.5 million m^3/y). Qatar can better utilize its TSE in several applications by further treating the produced TSE. In this paper, a review on the current state and a perspective into the wastewater treatment and reuse in Qatar is presented. Moreover, the main aspects, which should be considered while making a decision on reusing the treated SE in Qatar, are also addressed.

Keywords: Sewage effluents; Wastewater treatment; Reuse of treated sewage effluents

1. Water scarceness and resources of fresh water in Qatar

More than 97% of the water on earth is salt water and less than 1% of the earth's water is freshwater [1]. Unfortunately, this freshwater is not evenly distributed among the world; according to the World Health Organization (WHO), more than 1.1 billion people do not have access to safe drinking water while 2.6 billion lack of sanitized water [1].

The freshwater resources in the Gulf cooperation council (GCC) countries, is less than 1% of the total available freshwater around the world, while the population of these countries comprises around 6% of the world's population [2]. In the GCC countries, the average annual capacity of freshwater from renewable resources (such as infiltration) is estimated to be 453 m^3 per capita [3]. This is far below the bottom line of water poverty which is reported by WHO at 1,000 m^3 per capita per year [4]. Apart from some parts in Saudi Arabia, Oman and UAE, the majority of the GCC countries are essentially arid regions with scarce rainfall and no rivers or significant surface freshwater resources. More than 60% of the water demand in this region is met by the non-renewable groundwater which has already been depleted [3]. Table 1 lists the threshold values which are used to classify the water stress status within a region.

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Table 1
Threshold values: water stress within any region (cubic meters per year) [5]

Characteristic	Threshold	Situation
Water surplus	>10,000	Sustainability of water after fulfilling the needs of all aspects of the economy
Water abundant	>4,000–10,000	Able to cater to the needs of all sectors of the economy and also for the future
Adequate water stress	>1,700–4,000	Water sufficient to meet the present needs of the economy
	<1,700	The economy or human health may be harmed due to lack of proper drinking water, health and sanitation
Chronic water scarcity	<1,000	Frequent Water shortages both short term and long term
Absolute water stress	<500	The region completes its water supply by desalting seawater and over exploiting aquifers
Minimum survival level	<100	Water supply for industry and commercial purpose is compromised so as to fulfill demand for all other uses
Water stress	>20%	Severe water supply problems – Reusing waste water, overexploiting aquifers (by 2–30 times), desalinating seawater

Being located in the deserted Arabian Peninsula, Qatar has one of the world's lowest rainfall levels with an average annual of around 80 mm [6]. Moreover, Qatar has a natural evaporation rate of 2,000 mm/y; hence, freshwater supplies are extremely limited (no surface freshwater resources such as: rivers, springs, etc.,) [6]. More than 36% of the water consumption in Qatar comes from groundwater which is used mainly for agricultural irrigation [7]. Table 2 gives a breakdown of the groundwater consumption in Qatar in 2009. The groundwater resources are extracted recklessly at rates which far exceed the natural replenishment levels which resulted in a massive drop in water table and increase in the contamination and salinity level of the groundwater. In 2009, the annual extraction rate of groundwater was estimated at 248 million m^3 which accounts for about five times the annual natural freshwater recharge (50 Mm^3/y) which comes from infiltration and groundwater flow within aquifers from the Kingdom of Saudi Arabia. In 2012, the annual extraction rate of groundwater was estimated at 400 Mm^3/y which is almost seven times the replenishment rate [8]. Furthermore, the total annual renewable freshwater per capita has decreased from 47 m^3 in 2006 to only 27 m^3 per capita in 2015 [9]. The annually groundwater extraction level in Qatar has skyrocketed reaching over 800% of its renewable water resources [1].

Qatar relies mainly on desalination to provide about half of the country's need of freshwater and about 99% of freshwater for municipal use to drive the socioeconomic activities in the country [8]. Nowadays, there are eight gas-fired water desalination plants in Qatar, which produce about 327 million imperial gallons per day (MIGD). Moreover, the country has announced the commission of Qatar's largest desalination plant at Umm al Houl which is located in the southern part of Doha and will start production between 2017 and 2018. The $3.15 billion-worth plant will have a total daily production capacity of water around 135.6 million imperial gallons. In addition to that, Qatar has awarded $500 million contract to Mitsubishi Company to construct the first reverse osmosis (RO) desalination plant in Qatar. The plant will have a production capacity of 36 MIGD and is expected to start production by the end of 2016 [10].

In general, to produce 1 cubic meter of water, multistage flash distillation (MSF) units in Qatar require about 12 kWh thermal energy and 3.5 kWh electrical energy [11]. In fact,

Table 2
Breakdown of groundwater withdrawal in Qatar in 2009 [12]

Well site use	Rate (m^3/d)	Rate (Mm^3/y)	Percentage of total (%)
Farm	866,435	226	90.9
Municipal	35,677	9.3	3.7
Domestic	38,114	9.9	4.0
Industrial	13,070	3.4	1.4
Total	953,296	248.7	100

in 2011, the water and power production in Qatar has been found to constitute about 52% of the domestic natural gas consumption and 9.8% of the total gas production, which is equivalent to 15.3 billion m^3 of natural gas [13]. The total cost of energy subsidization paid by the government to freshwater producers through desalination is estimated at $5.02 billion. The high costs paid to subsidize the total cost of production and consumption of water in the country places a colossal pressure on the government as these funds can be used in other sectors such as health, education, research, etc.

Also there are many negative environmental impacts associated with desalination as a result of the massive amounts of fuel burned (energy intensive process) and the relatively low efficiency of the desalination even with combined power generation (about 62% of the energy supplied to the desalination plants is wasted in the form of cooling water or flue gases [14]). Some other environmental aspects associated with desalination plants include: (i) seawater intake, which harms marine environment by impingement and entrainment; (ii) rejected brine of high level of heat, salts, anti-foulants, anti-scalants and other chemicals [15]; (iii) the low tidal waves in the Arabian Gulf, that do not facilitate discharged contaminants and (iv) high atmospheric emissions of SO_x, NO_x, and CO_x gases [16].

In 2014, the average daily consumption of water in Qatar was reported by the sole distributor of water and electricity in the country, Qatar general electricity and water company (Kahramaa), to be around 595 L per capita [17]. Moreover, the total annual production rate of freshwater from Qatari thermal desalination plants have reached 437 million m^3 in 2012 compared to 312 million m^3 in 2008 with an approximate increase rate in the consumption of about 40%. Furthermore, the number of customers leaped from 167,540 to 241,204 over the same period with an average annual growth rate of 9.3% [17]. This means that it takes about only seven to 8 years to double the current consumption of water which is one of the highest growth rates around the world. Keeping in mind that not only the current consumption of water is enormous but also a high population growth rate (due to the increase in the economic and industrial activities) makes the forecasted water demand reach a value at which demand will overtake supply and thermal desalination will not be able to secure a reliable production of fresh water. Fig. 1 shows the annual water production and forecasted demand from 2009 till 2030. As seen in this Figure, the water demand will increase very steeply causing a serious water deficiency and the year 2020 will witness a serious water deficiency in the order of 40 million m^3 [7]. The main reason behind the expected drop in the water production at 2020 is a result of decommissioning of Ras Abo Fontas desalination plant which is expected to reach the end of its technical life by 2020. In the following years, the water production will remain as is while the demand will increase up to a level where the deficiency will reach about 70 million m^3 or about 15% of the water production in 2030.

On the other hand, treated sewage effluents (TSE), which is estimated at about 0.75 million m^3/d, could be one of the main sources of water which can be used in agriculture and industry and even as a source of drinking water in Qatar. The use of TSE to supply even a small fraction of the country's need in fresh water will help reduce the tremendous costs the country spends to produce fresh water and will enable Qatar become less dependent on desalination.

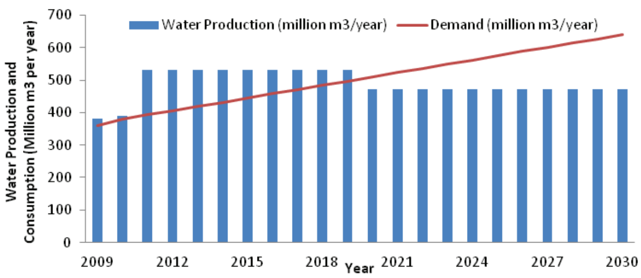

Fig. 1. Water production and demand in Qatar between 2009 and 2030 [7].

Table 3
The current and future WWTPs in Qatar [19]

Plant	Completion year	Design Flow Capacity (m^3/d)	Completion year	Design flow capacity (m^3/d)	Completion year	Design Flow Capacity (m^3/d)	Completion year	Design Flow Capacity (m^3/d)
Sailiyah	2008	13,5000	2013	175,000		175,000		175,000
Naijah	2006	106,000	2013	180,000		180,000		180,000
Industrial Area	2006	12,000	2013	24,000	2016	48,000		48,000
Al Khore	2008	5,000		5,000	2016	10,000		10,000
Al Dhakhirah		1,600	2013	3,200	2019	42,000	2030	56,000
Doha North			2013	243,000	2016	324,000		324,000
Al Shamal		150	2013	750	2015	7,500	2030	22,500
Jumeliyah	540	2014	2020			2020		2,020
North Camp		300	2014	540		540		540
Shahaniyah		810	2013	1,350		1,350		1350
Al Khareeb	2005	60						
Aum Sllal	2006	1,500						
Total				634,860		790,410		819,410

2. Current status of SE treatment in Qatar

In Qatar there are 12 waste water treatment plants (WWTPs) with a daily capacity of about 0.79 million m^3. Table 3 lists the current and future projects of WWTPs along with their capacity. Table 4 shows the treatment level of Qatari WWTPs in 2012. The typical characteristics of the influent wastewater along with the TSE (effluent) are also tabulated in Table 5.

3. Current status of TSE reuse in Qatar

In Qatar, the ratio of TSE to total production of WW is very low (14.8%); this shows the amount of work which needs to be done in order minimize the percolation of WW into GW. Table 6 tabulates the amounts of wastewater (produced, treated and reused) in some countries in the MENA region. In Qatar, both the ratio of TSE to total production of WW and the ratio of reused TSE to produced TSE are quite low: 14.8% and 65.5%, respectively especially when compared to other countries in the MENA region. The breakdown of the four reuse applications in Qatar is depicted in Fig. 2.

Table 4
Treatment level of Qatari WWTPs [18]

Treatment level	Production (m^3/d)	Percentage (%)
Tertiary treatment	335,000	50
P and N removal	175,000	26
Disinfection	159,400	23.7
Secondary treatment	2,000	0.3

Table 5
Characteristics of influent and effluent water from Doha South Sewage Treatment Works [20]

Parameter	Influent	Effluent
pH	7.18	7.16
BOD (mg/L)	156	1
TDS (mg/L)	1,643	
TSS (mg/L)	166	0.3
COD (mg/L)	395	19
DO (mg/L)		7.1
Salinity (mg/L)	806	1,028
Electrical Conductivity (µS/cm)	1,643	2,093
TKN (mg/L)		4.6
NH_3 (mg/L)		1
Po_4^{-3} (mg/L)	8.5	1
Aluminum (mg/L)	0.037	<0.001*
Arsenic (mg/L	0.001	0.001
Boron (mg/L)	0.208	0.234
Cadmium (mg/L)	<0.001*	<0.001*
Chromium (mg/L)	0.002	<0.001
Cobalt (mg/L)	<0.001	<0.001*
Copper (mg/L)	0.005	0.002
Iron (mg/L)	0.330	0.259
Lead (mg/L)	<0.001*	<0.001*
Manganese (mg/L)	0.021	<0.001*
Mercury (mg/L)	0.004	<0.001*
Nickel (mg/L)	0.004	0.003
Zinc (mg/L)	0.006	0.008
Fecal Coliform (CFU/100 mL)		0

*Concentration was below the detectable limit. The detectable limit for ICP-MS is 1 ppb (0.001 mg/L) to 5 ppm (5 mg/L).

Table 6
Amounts of SE (produced, treated and reused) in some countries in the Middle East and North Africa region [21]

Country	Total wastewater produced (10^9 m^3/y)	Volume of treated wastewater (10^9 m^3/y)	Volume of treated water reused (10^9 m^3/y)
Saudi Arabia	0.73	0.652	0.166
Bahrain	0.0449	0.076	0.0163
Egypt	3.76	2.971	0.7
United Arab Emirates	0.5	0.454	0.248
Iraq	0.575	0.098	0.0055
Jordan	0.117	0.111	0.102
Kuwait	0.25	0.239	0.078
Oman	0.098	0.037	0.0023
Qatar	0.444	0.066	0.043
Yemen	0.074	0.046	0.06

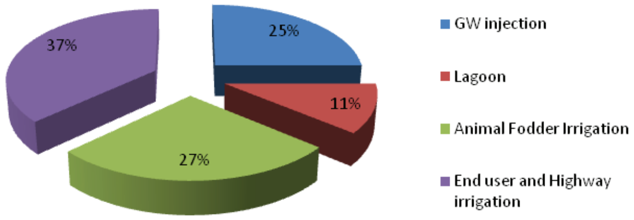

Fig. 2. Current reuse rates of TSE in Qatar [7].

As shown in Fig. 3, out of the TSE produced, which is estimated at 96 million m^3/y, Qatar uses only about 27% of TSE in growing fodder (25 million m^3/y) and landscape irrigation (1 million m^3/y) while about 73% of the total TSE is discharged to septic lagoons to dry or percolate into groundwater (70 million m^3/y) and runoff (0.5 million m^3/y) [7]. Moreover, the untreated wastewater in Qatar has been reported at about 110 million m^3/y and leakage of untreated SE in the network pipelines is estimated at about 20 million m^3/y [7]. This untreated wastewater will most probably leak to the groundwater aquifer, contaminates the scarce groundwater resources and make them unsuitable for human consumption. The large volume of TSE which are dumped in septic lagoons and untreated wastewater indicate that there is lots of work to be conducted to improve the wastewater infrastructure in Qatar. The possible solution to these problems is improving quality and better TSE utilization, which would relieve the water stress in the country.

As shown in Fig. 2, the TSE produced from Qatar WWTPs is mainly used for irrigation and landscape. Table 7 lists the standards set by the Ministry of Environment (MoE) in Qatar for irrigation and landscape applications. Recently, Qatari Public Work Authority (Ashghal) has set new standards for TSE produced from WWTPs (Table 8), which are more strict in terms of total nitrogen and total dissolved solids (TDS) for the sake of widening the uses of TSE beyond landscape irrigation to other industrial processes like construction projects, concrete and district cooling facilities.

Currently, the use of TSE in Qatar is estimated at about 30% of the municipal water; the government's aim is to increase it above 50% with tertiary level treatment to all WWTPs. In this sense treatment of SE up to some advanced level can produce fresh water that is pure enough to be used within the industrial (such as cooling, processing, etc.) and urban (e.g., recreational activities) applications to increase the percentage of TSE reuse.

The MoE in Qatar has issued a directive that requires energy and industry sectors in Qatar to work toward zero liquid discharge (ZLD) of process wastewater by December 2016 [22]. The reuse of treated industrial wastewater has been long used in industry and is now practiced by many industries in Qatar. The energy and industry sectors in Qatar has recycled about 24.5 million m^3 of water in 2013 [23]. Qatar Fertilizer company (QAFCO) has stated that it has a plan to reuse 90% of its process wastewater for irrigation in addition to other applications [24]. The world's largest liquefied natural gas producer (Qatar Gas) has announced signing several engineering projects to recycle up to 70% of its wastewater [25]. Qatar FEUL (or Woqood) is downstream oil storage, distribution and marketing company has announced the

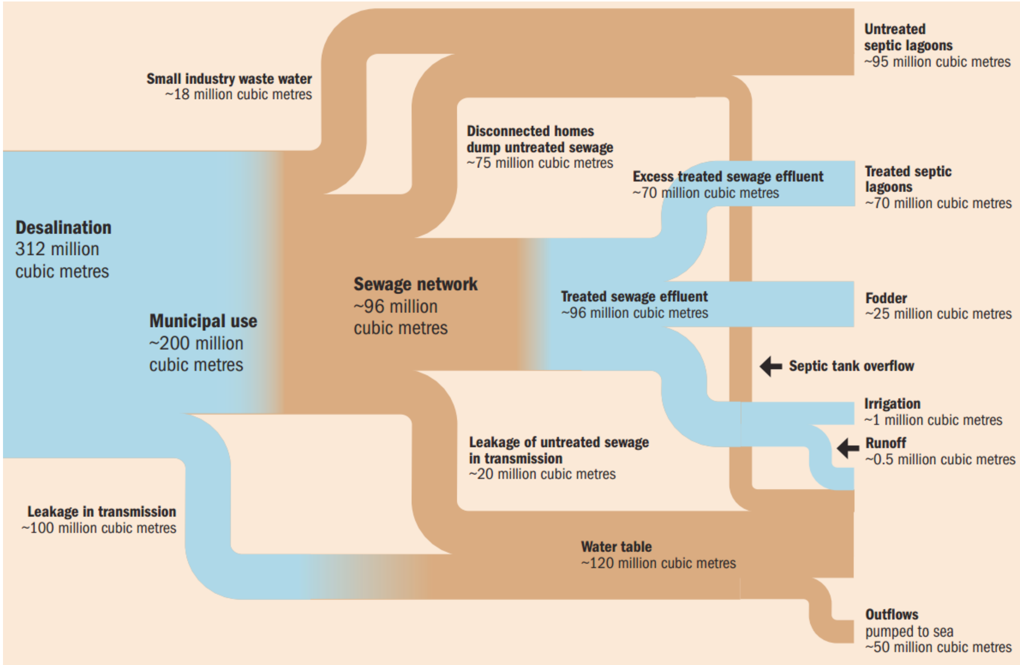

Fig. 3. Breakdown of the water and sewage production in Qatar [7].

Table 7
Standards set by the Ministry of Environment for TSE used in irrigation and Landscape [26]

Parameter	Limits	
	For irrigation	For landscape
1. Physical test		
TDS (mg/l)	2,000	2,000
TSS (mg/l)	50	–
pH	6–9	6–9
Floating particles	–	–
2. Inorganic maters		
Ammonia as N (NH_4^+) (mg/l)	15	15
Chloride (mg/l)	0.1	0.1
Cyanide (CN) (mg/l)	–	0.2
Dissolved Oxygen (DO) (mg/l)	>2	>2
Fluoride (F) (mg/l)	15	15
Phosphate as P (PO_4^{-3}) (mg/l)	30	30
Sulphate (SO_4^{-2}) (mg/l)	400	400
Sulfide (S^{-2}) (mg/l)	0.1	0.1
BOD_5 (mg/l)	10	50
TKN as N (mg/l)	35	35
COD (mg/l)	150	150
3. Organic matters		
Oil and Grease (mg/l)	10	10
Phenols (mg/l)	0.5	0.5
Total organic carbon (mg/l)	75	75
4. Biological test		
Total coliform (MPN/100 ml)	2.2	2.3
Egg parasites (mg/l)	<1	<1
Worm parasites (mg/l)	–	–

Table 8
Qatar's TSE Standards set by Public work authority [27]

Standard effluent criteria	Current standard	Future standard
Suspended solids	5 mg/l	5 mg/l
BOD	5 mg/l	5 mg/l
COD	50 mg/l	50 mg/l
pH	6–9	6–9
Ammonia	1 mg/l	1 mg/l
Phosphate	1/2 mg/l	2 mg/l
Total nitrogen	10 mg/l	5 mg/l
Dissolved oxygen	2 mg/l (min)	2 mg/l (min)
Chlorine (free residual)	0.5–1.0 mg/l	0.5–1.0 mg/l
Turbidity	2 NTU	2 NTU
Total dissolved solids	2,000 mg/l	500 mg/l
MPN of faecal coliform per 100 ml	0.0	0.0
Intestinal nematodes (No. of eggs per 1 L)	<1.0	0.0
Enteric viruses [No. of plaque forming unit (PFU) per 40 L]	<1.0	<1.0

reduction of the consumption of water in the automatic car wash by recycling up to 90% of the water used in cleaning [22,28]. Furthermore, Qatar steel has successfully managed to increase its recycle rate of blow-down water by four-folds compared to the recycle rate in 2012 (28,665 m^3) [29].

Qatar Fuel additives Company (QAFAC) has lowered the water consumption in 2014 by about 22% by recovering and reusing about 125,615 m^3 of water from the flue gas. Moreover, QAFAC has also reused 47% of the recycled sanitary wastewater in irrigation [30]. ORYX GTL, gas to liquid production plant, has stated that reuse of 80% of the treated industrial wastewater (1.38 million m^3) in cooling tower make-up, landscape irrigation and fire extinction has been successfully achieved in 2012 [22,31].

Moreover, TSE is estimated to play a major role in the district cooling industry in Qatar. According to Ashghal, district cooling is expected to use about 73 million m^3/y which is almost 17% of the total demand of TSE in 2020 [32]. Moreover, the approved directive of water resources committee (PWRC) in 2014 states that the use of potable water for cooling purposes is prohibited by the law of Qatar. TSE is the optimum substitute to potable water; according to Kahramaa, about 39 million m^3/y can be saved in 2023 if district cooling industries use TSE rather than potable water. Some of the other possible uses of TSE in Qatar are: sanitary flushing [22], make-up water for fire-fighting training exercise [33], sand washing [22] and non-potable use in construction field (such as concrete mixing) and road works [34].

4. Motivations behind the utilization of the TSE

As discussed above, from an environmental and socioeconomic perspective and due to the large number and capacity of the thermal desalination plants in the GCC region, a clean and environmentally-friendly approach should be found which would reduce some of the drastic effects of the desalination industry in the region and release the existing water stress. There are several key issues which must be taken into account in order to drive decision makers in Qatar to reuse TSE:

- The utilization of TSE has become extremely urgent due to the scarcity of freshwater resources and the negative impacts associated with the constant reliance on desalination to produce freshwater in Qatar.
- The use of TSE in agriculture, industry and for indirect potable reuse has been practiced long time ago all over the world [35]. Usually the produced water is of high quality and it can replace other freshwater resources such as groundwater.
- Apart from the environmental and socioeconomic effects associated with reducing the reliance on desalination as a source of freshwater in Qatar, TSE can also be used as a source of freshwater in addition to its storage as a strategic reservoir in order to increase the storage capacity of freshwater in Qatar and lower the depletion of Qatari groundwater aquifers. Each of these points will be discussed below.
- The utilization/reuse of TSE is going to have several social, economic and environmental benefits on the state of Qatar as it would reduce the government's spending on freshwater production, which in turn would enhance the development of agriculture, industry, education and health sectors in the country.

4.1. TSE as source of freshwater

Usually purification of SE consists of primary, secondary and tertiary treatment [36]. Primary treatment aims to separate the floating and suspended solids from the influent wastewater. This treatment comprises of some sort of screening in order to separate gross solid particles in addition to a sedimentation process which employs gravity to eliminate the existing suspended solids [37]. This treatment is also known as to as "mechanical treatment," despite the use of some chemicals are often used to speed up the sedimentation process. In secondary or biological treatment, microorganisms are introduced into wastewater in order to consume the organic contaminants [36]. Settling tanks are then used to reduce the content of the suspended solids in the wastewater [37]. Tertiary treatment is the last cleaning process which aims to remove the viral and bacterial content in addition to the inorganic continent of the water (such as nitrogen, phosphorous, etc.,). This treatment process aims to enhance wastewater quality prior to its reuse, recycle or discharge to the environment [36].

The further treatment of SE to produce water of a potable level quality involves a three-step purification process, which starts with microfiltration and ultrafiltration to remove the remaining solids, followed by reverse osmosis treatment and ends up with water disinfection with ozone, ultraviolet light or hydrogen peroxide [38]. Once the produced water is disinfected, it is pumped in an "environmental buffer," such as an underground aquifer or surface water reservoir, where it is stored for some time [39]. This step is intended to assuage public anxiety regarding the human consumption of potable-level TSE [39]. Once this water is pumped out of the storage reservoir, it is then passes through the typical water purification process just like any other drinking water resource in order to meet the required standards of water quality suitable for safe human consumption [39]. Fig. 4 depicts a schematic presentation of SE treatment process to produce water of a potable level quality adopted by many water treatment plants all over the world. The quality of the produced water is exceptionally high and as reported by NEWater (Singapore), it exceeds the requirements set by the United States Environmental Protection Agency (USEPA) and the WHO guidelines [40].

Unquestionably, the fixed and operating cost of freshwater production by SE treatment must be feasible and comparable to the cost of freshwater production via desalination. In fact, the cost of producing freshwater from SE has been estimated in Singapore and USA (Orange County, California) and has been found to be way less than that of desalination. In Singapore, the cost of producing potable water by SE treatment is around \$0.22/m^3 [41]. The cost of treating 1 m^3 of wastewater in Orange County (California USA) has been reported by the Orange county treatment plant to be around \$0.72 [42]. The wastewater treatment plant in Orange County has also reported that treating SE up to potable level, followed by pumping the treated water into the aquifer and

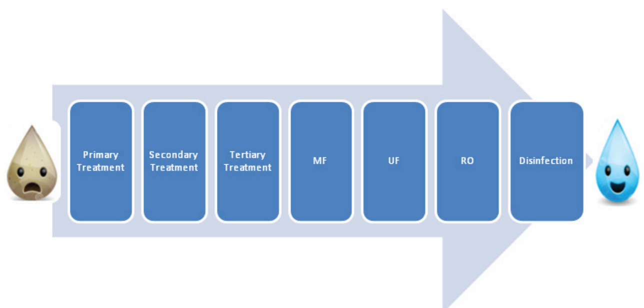

Fig. 4. Treatment of SE up to potable-level quality.

then using it for indirect potable reuse to supply freshwater for two families (each family consists of four members) for a year costs around \$800–\$850, whereas the cost of supplying the equivalent amount of freshwater by desalination has been estimated at \$1,200–\$1,800 [42]. Since 2008, Orange country treatment plant has been supplying potable water for around 850,000 people at a daily rate of 70 million gallons (0.27 million m^3/d). It is expected that the daily production of the plant will be around 85 million gallon at its full capacity [42]. Taking into account the cost of desalted fresh water in Qatar at about \$2.74/m^3 (with subsidized gas prices), the cost of freshwater production in Qatar is about 12.5 and 3.8 times higher than the cost of freshwater production by SE treatment in Singapore and USA, respectively.

The reuse of TSE to augment the supply of water in Qatar must be seriously considered as to avoid the occurrence of the expected gap in water demand which will place the existing economic and industrial activities at risk. By providing an advanced treatment of TSE, the treated water is pure enough to be used in a variety of applications ranging from indirect potable reuse, agriculture, industry, etc. For example, in Singapore , about 6% of the production of NEWater (75,700 m^3/d) is used for indirect potable reuse [40]. The state of California has been applying this technology in Orange County since 2008. The purified treated water has been pumped and retained into an aquifer and kept for about 6 months before being withdrawn as a source of freshwater [43]. TSE constitutes about 20% of the inflow into the Virginia Occoquan Reservoir, which provide potable water for over 1.2 million people in Washington, D.C. [44]. Indirect potable reuse has also been applied in Pasadena (California), Payson (Arizona) and Veurne (Belgium) [45].

The usage of TSE in agriculture has been long applied overall the world. For example, wastewater reuse has been implemented in California since the 1890. Over 200 wastewater treatment plants in California have been treating wastewater and producing about 0.759 million m^3 per day of freshwater which is used to grow more than 20 food crops [46]. In Qatar, the reuse of highly purified TSE in agriculture, domestic sector and industry could save massive costs, which can be used for investment in agriculture, industry, educational and health sector in the country.

4.2. Underground aquifers and storage of TSE

The current freshwater storage capacity of the Qatari desalination plants does not exceed 2 d; meaning that any interruption in the production could seriously hinder the social, economic and industrial activities. The state of Qatar has recently announced the investment in the freshwater storage sector by constructing a US \$4.67 billion-worth project which can act as a backup supply of desalinated freshwater with an estimated storage capacity of 7 d. The storage facility with a capacity of 2.3 billion MIGD consists of several mega reservoirs connected by 183 km pipeline connecting the northern (Ras Laffan) and southern (Ras Abo Fontas) desalination plants in Qatar [47]. The aim of this strategic project is to increase the water security in the country by storing water in several concrete reservoirs located at different locations such as Abu Nakhla, Um Salal, Um Baraka, Al-Thumama and Rawdat Rashid [17].

Both the depletion in the groundwater reserves (and the consequent increase in the salinity and contaminants level) and the storage of freshwater (to increase water security) can be overcome by what is known as aquifer storage and recovery (ASR) approach. With ASR the aquifers are used as strategic long-term storage systems which can store up to billions of cubic meters and later used to recover the stored water. ASR has been used in USA since 1984 for water storage, including storage potable level TSE. Between 1992 and 1994, the possibility of implementing ASR in Qatar by injecting desalted water in Rus and Umm er-Radhuma formation had been studied [48]. It was found that ASR can be successfully implemented to store water in both Rus and Umm er-Radhuma formation. Furthermore, in 2002, two pilot plant tests have been carried out in Abu Dhabi (Madinet Zayed) and (Al Shwieb area) to store 2.5 MIGD of desalinated water and a full feasibility study has been conducted and showed that both pilot plants exhibited recovery efficiency of about 85% [48]. Missimer et al. [49] have investigated the possibility of applying ASR in the GCC and the Middle East and North Africa region. They found that when mega storage capacities are required, conventional ground-storage are not economically feasible and ASR can offer an economically-feasible storage capacity when desalinated water is stored [48]. The storage of TSE should be implemented in Qatar as it provides cost-effective strategic water storage units which can be used as a source of drinking water.

It should be noted that salinity level of the Qatari groundwater has been rapidly increasing as a result of the huge groundwater withdrawal and saltwater intrusion [49]. Table 9 lists the change in the salinity and area underlain by freshwater and brackish water in Qatari aquifers between 1971 and 2009 whereas Fig. 5 shows the corresponding salinity level change between 1971 and 2003. Increasing the salinity level of the groundwater contaminates groundwater and makes them unsuitable for human or agricultural consumption. Both the Rus and Ummer Rhaduma aquifers, which are used to supply freshwater in Qatar, have a salinity level of 500 to 3,000 mg/l. This salinity level has been found to increase toward the sea reaching a value of 10,000 mg/l close

Table 9
The change in the salinity and area underlain by freshwater and brackish water in Qatari aquifers between 1971 and 2009 [12]

Area/percentage	Salinity level		
	TDS <1,000 mg/l	TDS <2,000 mg/l	TDS <3,000 mg/l
1971, area (km^2)	1,683	2,368	2,890
Percentage of country area in 1971	15	21	25
2009, area (km^2)	186	897	1,782
Percentage of country area in 2009	2	8	16
Percentage of 2009 to 1971, area	16	43	66
Projected year to reach zero area	2,018	2,037	2,056
Years remaining	4	13	42

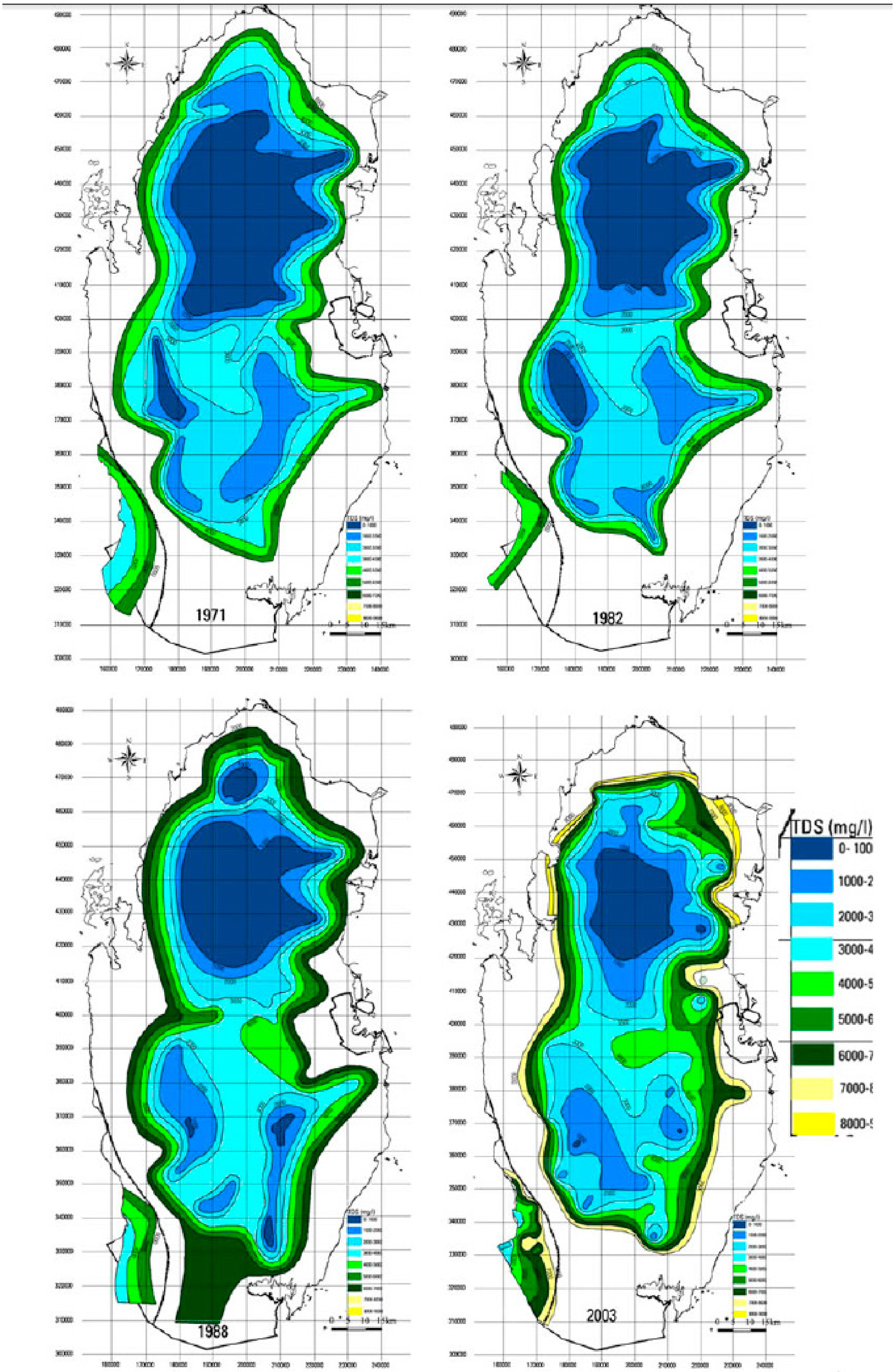

Fig. 5. Change in salinity of groundwater in Qatar between 1971 and 2003 [12].

to the coasts [49]. It is worth-pointing out here that irrigation water with a TDS ranging between 1,500 and 3,500 mg/l is considered harmful to plants whereas water at TDS of 3,500 is completely unsuitable for irrigation [8]. Fig. 6 shows the TDS iso concentration map of Qatar which clearly shows the unsuitability of many groundwater aquifers in Qatar for agriculture. This increase in salinity is not only caused due to the over pumping of groundwater by farmers but also due to salt intrusion which is the movement of saline water into freshwater aquifers (due to reduction of the pressure of the groundwater wells as a result of over pumping) which results in contaminating fresh groundwater.

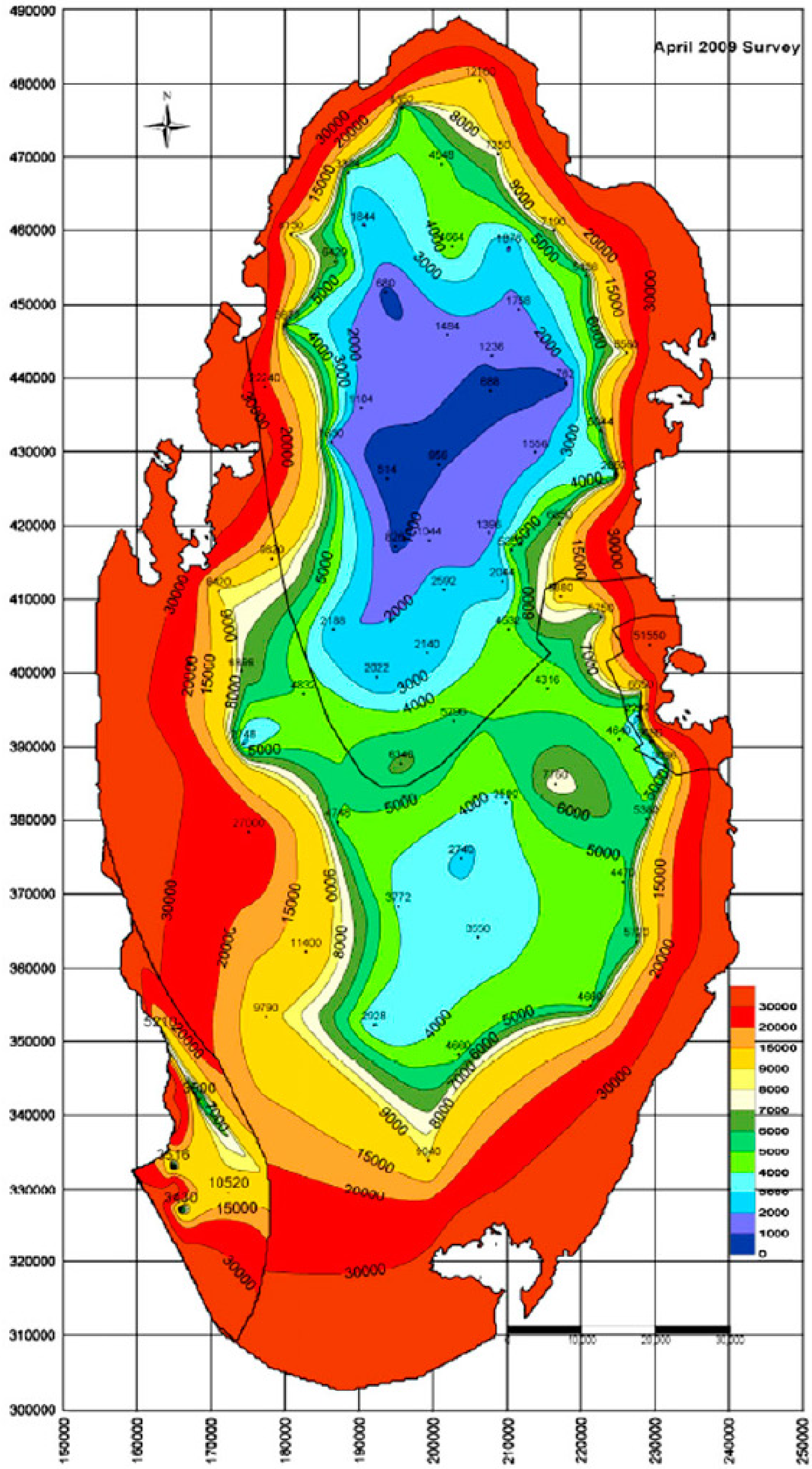

Fig. 6. TDS iso concentration map of Qatar [12].

One of the most commonly used solution to this problem is the recharge of freshwater wells with freshwater to increase the well pressure and stop the intrusion of saltwater or seawater. This has been practiced by many countries around the world. For example, at least half of the TSE in Orange County (California) is pumped into groundwater aquifers to prevent salt intrusion while the remaining half is used for indirect potable reuse [43].

The reuse of TSE to stop the seawater intrusion in the GCC region has already been applied in real life since 2003. This reuse application was applied in Oman for the sake of stopping the seawater intrusion on the coasts of Oman which is estimated to cost the country about $280 million, abandon about 6,000 ha and lose some 20,000 irreplaceable jobs [50]. Since 2003, Omani government has started TSE reinjection projects to treat and reinject about 20,000 m^3/d in the coastal wells in Salalah plain to combat the intrusion of seawater. Dhofar, one of the main WWTPs in Oman, is currently injecting in the coastal aquifers 9,000 m^3 of the 20,000 m^3 treated [51].

Similarly, TSE could be used to prevent the depletion of groundwater and reduce its salinity level in Qatar by pumping part of TSE into the already-depleted groundwater aquifers. This treatment will definitely be less costly when compared to desalination as reported by Qatar National Development Strategy which stated: "Qatar could make far more extensive use of recycled water, which is a quarter as expensive to produce as desalinated water" [7].

5. Conclusion

The discussed aspects have showed that reusing TSE would lead to a variety of positive benefits in the social, environmental and economic sectors in Qatar. The presented review has indicated that reuse of TSE is economically feasible and the water production cost is way less than desalination cost. Not only cost-wise but also environmentally, the SE treatment to produce freshwater would help minimize the environmental impact of desalination plants, reduce the contamination of groundwater by untreated waste waters and lower the saltwater intrusion into freshwater wells. The production of potable-level TSE would supply Qatar with freshwater which can be used in agriculture, industry and for indirect potable reuse. This would also reduce the consumption of energy and significantly mitigate the high current expenditure on freshwater production by seawater desalination. These aspects should be taken into account by decision makers in order to increase the water security in the country.

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