Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2017.21246

70 (2017) 70–85
September

A review of Qatar's water resources, consumption and virtual water trade

Mohamed Alhaj[a], Sayeed Mohammed[b], Mohamed Darwish[c], Ashraf Hassan[c,*], Sami G. Al-Ghamdi[a,*]

[a]*Division of Sustainable Development, College of Science and Engineering, Hamad Bin Khalifa University, Doha, Qatar, Tel. +974 50563476; email: mohabkitalhaj@hbku.edu.qa (M. Alhaj), Tel. +974 44542833; Fax: +974 44540281; email: salghamdi@hbku.edu.qa (S.G. Al-Ghamdi)*

[b]*Progressive Vellore Organization, Vellore, Tamil Nadu, India Tel. +974 66852665; email: sayeed@progressivevellore.org*

[c]*Qatar Environment and Energy Research Institute, Hamad Bin Khalifa University, Qatar, Tel. +974 66402650; email: darwish738@gmail.com (M. Darwish); Tel. +974 44545887; email: ahassan@hbku.edu.qa (A. Hassan)*

Received 17 April 2017; Accepted 19 July 2017

ABSTRACT

Qatar is an arid land with very scarce natural freshwater resources. Its groundwater resources are limited and are being heavily depleted by inefficient irrigation methods and the growing population. As a result, Qatar relies primarily on desalination of seawater. Accurate assessment of water resources, consumption levels and virtual water trade is the first step in formulating an effective water resources management policy. This paper, hence, reviews the renewable and non-renewable water resources and the disaggregated consumption trends as well virtual water trade in Qatar. The total groundwater produced internally is 56 Mm^3/year and its consumption rate is 250 Mm^3/year which is mainly dominated by farms. The agricultural sector consumes 91% of all renewable water resources in Qatar. The total desalination capacity is 1.4 Mm^3/d which is primarily from thermal desalination plants. Water consumption rate is 200 m^3/capita/year. Regarding virtual water trade, it was found that Qatar is a net virtual water importer and imports an average of 1.35 billion m^3/year of virtual water. The per capita water footprint is 1,554 m^3/capita/year. We recommend that the water conservation efforts in Qatar should follow an integrated approach taking into account supply as well as demand side management.

Keywords: Water resources; Desalination; Water withdrawals; Virtual water; Qatar

1. Introduction

Qatar is a small peninsula located at the north eastern side of the Arabian Peninsula on the Arabian Gulf (latitude: 25.300 N and longitude: 51.5167 E). It has a land area of 11,610 km^2 and a population of 2.675 million [1,2]. Qatar has the highest gross domestic product (GDP) per capita in the world; $93,397 (2014). Its GDP is $211.8 billion (2014) and comes largely from the revenue of natural gas (NG) exports, as Qatar has the third largest NG reserve in the world. Qatar landscape is mainly arid and desert-like, with high temperatures, very little rainfall and sandstorms being very common. The geographical position and climate features of Qatar have made it very vulnerable in terms of water security.

Qatar is one of the poorest countries in terms of freshwater sources. This is primarily due to little annual rainfall and lack of rivers and lakes. Qatar relies on groundwater (GW), desalted seawater (DW) and treated wastewater (WW) to meet its water demands. The bulk of domestic water consumption comes from desalination plants because the GW resources are very limited. Desalination is a very energy intensive process and with the increasing consumption patterns, a lot of stress is put on the current desalination plants. Qatar has stated in its National Development Strategy 2011–2016 (QNDS) that one of its main objectives is to provide clean water and ensure its sustainable use. Further, the QNDS has emphasized its goal of "setting

* Corresponding author.

policies and regulations for the government to align consumption and supply over time while protecting water quality" [3].

In line with achieving this goal, this review paper will discuss the current water situation in Qatar in terms of available renewable water resources (RWRs), GW resources, water consumption sources and patterns, water desalination plants and Qatar's water footprint as represented by the trade of virtual water. The aim of this review is to highlight the main causes of water resources exploitation and then suggest effective water conservations policies and strategies.

2. Water resources

2.1. Annual rainfall

The RWRs in Qatar are very limited due to low rainfall amount; with an average of 40–80 mm/year. A recent study by the Gulf organization for research and development estimated the annual rainfall at Doha International Airport for the period of 1962–2011 to be 76.6 mm [4]. Further, the natural evaporation rate is high: 2,000 mm/year [5].

Fig. 1 shows the monthly average rainfall and temperature profile in Qatar. Rainfall mainly occurs between October and May and is concentrated in the Northern and central regions of the country. There are 28 monitoring stations throughout Qatar that collect weather data such as precipitation, humidity and temperature. By observing the long-term trend for rainfall in Qatar, we can deduce that rainfall mainly occurs in November to May. Further, the Ministry of Development Planning and Statistics (MDPS) reported that between 2008 and 2013, the total precipitation was less than the long-term average [7]. In fact, in 2013, rainfall amount was only 55% of the long-term average.

2.2. Groundwater resources

The main RWR in Qatar is groundwater which is recharged by rainfall. GW can be recharged either directly (e.g., during heavy rainstorms) or indirectly as surface runoff. In the latter case, GW is mainly recharged by an indirect mechanism "through run-off from surrounding catchments and the pounding of water from the depression floor" [8]. The Food and Agriculture Organization of the United Nations (FAO) has estimated the amount of GW produced internally in Qatar to be 56 million m^3/year (Mm^3/year) in 2014 [8]. This is equivalent to 24.8 m^3 of water per capita which is very much below the water poverty line (1,000 m^3/capita/year) and also the international average (6,000 m^3/year/capita) which are the standards given by the World Health Organization (WHO). Some recent studies have highlighted that the per capita share is expected to decrease to 22 m^3 by 2050 because of the increasing population and hence water demand [9].

GW recharges two main aquifers; the Rus aquifer located in the Northern part of Qatar and is composed of chalky limestone and the Abu Samra aquifer in the Southern Western region that is composed of granular limestone rocks. The incoming GW from Saudi Arabia (SA) contributes to Abu Samra aquifer recharge. The salinity level in the Rus aquifer is in the range of 500–3,000 mg/L of total dissolved solids (TDS) and in the Abu Samra aquifer (and other aquifers in the southern regions) the TDS is 4,000–6,000 mg/L [8]. Apart from the GW wells, there are 292 wells managed by the Qatari water and electricity Corporation (Kahramaa) to supply water for emergencies, army forces and travel outlets.

Regarding the emergency water storage capacity, Kahramaa has been increasing the capacity since 2009. By 2013, the strategic capacity was sufficient for 4 d and there are plans to increase this to 7 d by 2018 through the "water mega reservoirs" project. Kahramaa intends to commission five mega reservoirs in phase 1 to achieve a 7 d supply which would meet the demand up until 2026. Moreover, an additional five mega reservoirs will be built in phase 2 of the project to match the demand expected in 2036. Fig. 2 shows the current water reservoirs and storage days and the expected increase in storage capacity.

The total annual recharge for GW comes from rainfall, inflow from SA (through the Abu Samra aquifer), irrigation recharges and recharge wells. Recharge to aquifers comes from treated sewage effluents (TSE) injection (59%), rainfall (39%) and inflow from Saudi Arabia (1%) [7]. This leads to an annual sum of 56 Mm^3/year which accounts for 28% of the available water in Qatar. Recent statistics by the Ministry of Environment indicated that there has been an acute reduction in the percentage of land where freshwater is available. In 1971, 15% of the area of Qatar was underlain by freshwater. However, this ratio has dropped to only 2% by 2009 [11].

Fig. 3 shows a drastic reduction in the areas underlain by GW of low TDS between 1971 and 2009. This has occurred because of high water withdrawal rates that exceeded the replenishment rate. The Qatari Ministry of Environment has also highlighted that since 1970, the land area underlain by freshwater and brackish water (1,000–3,000 mg/L) has been reducing sharply as shown in Fig. 4. GW is currently being rapidly depleted. For example, in 2009, the withdrawal rate was between 400 and 444 Mm^3 that was around seven times

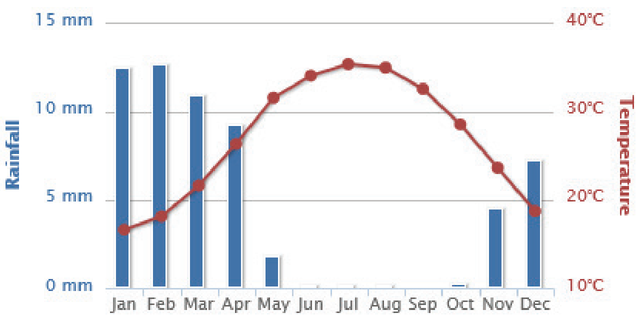

Fig. 1. Average monthly rainfall and temperature in Doha between 1990 and 2009 [6].

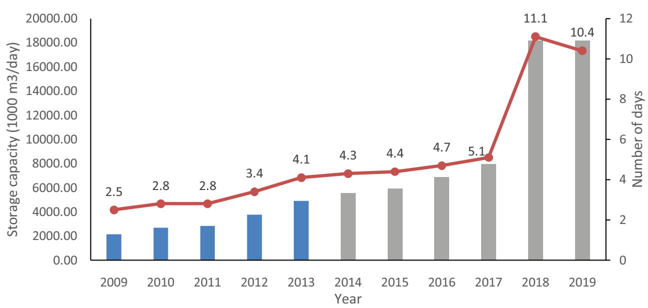

Fig. 2. Water reservoir capacity and number of days of storage [10].

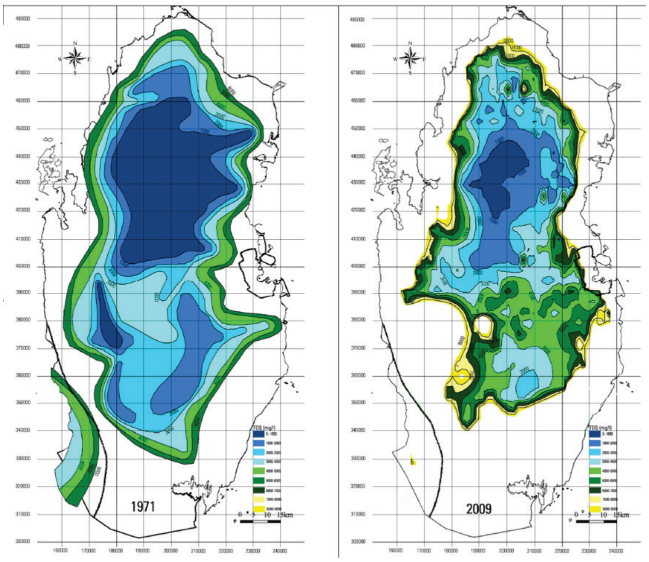

Fig. 3. Total dissolved salts (TDS) in groundwater between 1971 and 2009 [11].

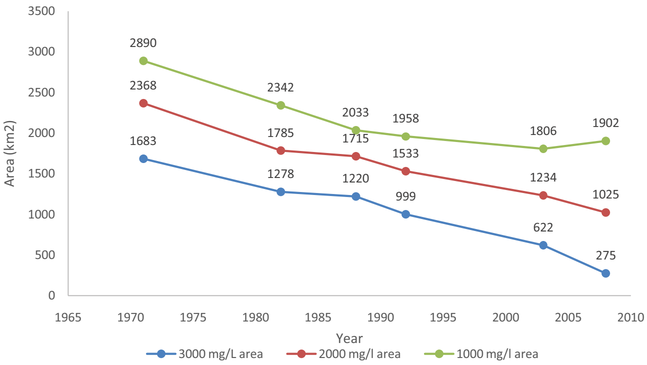

Fig. 4. Land area (in km^2) underlain by freshwater and brackish water between 1970 and 2010 [11].

the replenishment rate of groundwater resources [5]. If this trend continues, then groundwater reserves will be depleted entirely in a few years.

Recent studies indicate that the land area underlain by GW of TDS less than 1,000, 2,000 and 3,000 mg/L has been reducing sharply and will eventually vanish in a period of less than 50 years [12]. These statistics show that Qatar is highly vulnerable to water shortages and that serious measures have to be implemented to solve the water problem.

Regarding Qatar's position in the region in terms of RWRs, Fig. 5 shows the RWRs per capita for the MENA region. As Fig. 5 shows, Qatar, and the Gulf Cooperation Council (GCC) region as a whole, has very few RWRs per capita as compared with countries in the region like Somalia and Mauritania. The figure shows the available RWRs have also been diminishing since 1992 up to 2011. This trend is similar in neighboring countries like Kuwait, UAE and Saudi Arabia.

Due to the minimal amount of GW, Qatar and neighboring countries in the region face severe water scarcity. Based on total freshwater sources and per capita share, Qatar is at

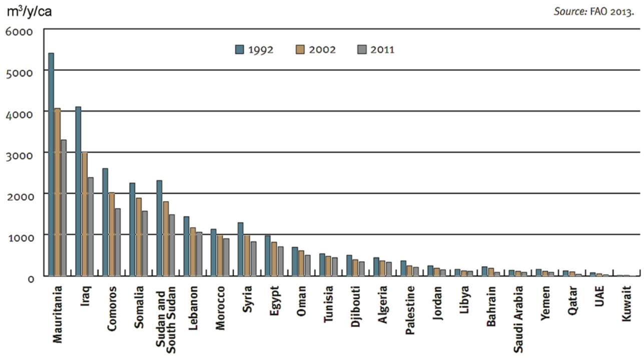

Fig. 5. Renewable water resources per capita in the MENA region for the period: 1992–2011 [13].

Table 1
Renewable water resources in GCC, Yemen, USA, UK, Germany and Iraq [14]

Country	Total renewable water resources (×10^9 m^3/year)	Renewable water resources per capita share (m^3/person/year)	Water status
Saudi Arabia	2.4 (2014)	81.72	Minimum survival level
UAE	0.15 (2014)	15.88	Minimum survival level
Oman	1.4 (2014)	356.6	Absolute water stress
Qatar	0.056 (2014)	25.57	Minimum survival level
Kuwait	0.02 (2014)	5.75	Minimum survival level
Bahrain	0.004 (2014)	86.31	Minimum survival level
Yemen	2.1 (2014)	84.1	Minimum survival level
USA	2,818 (2014)	9,514	Water surplus
Germany	107 (2014)	1,863	Water surplus
UK	145 (2014)	2,306	Water surplus
Iraq	89.86 (2014)	2,584	Water surplus

the minimum water survival level. Table 1 shows the water status of Qatar, GCC, Yemen, Iraq, Germany, UK and USA. In this table, the minimum survival level occurs at a per capita share of RWRs of less than 100 m^3/year. As this table shows, all countries in the GCC region are either at the minimum level or at absolute water stress (<500 m^3/year).

At the end of this section addressing Qatar's GW resources, it is useful to present the natural water balance for the whole country. The water balance for Qatar (net flow of renewable water) was reported by the MDPS in their "Water Statistics" report published in 2013. Table 2 shows the natural water balance for Qatar's aquifers for the period: 1990–2012 [7].

Table 2
Natural water balance of Qatar's aquifers (average annual values for the period: 1990–2012)

No.	Balance item	Million m^3/year	Reference
1	Recharge of aquifers from precipitation	63.3	[15]
2	Inflow from Saudi Arabia	2.2	[16]
3	Total RWRs	65.5	Calculation: 1 + 2
4	Outflow from aquifers to sea and deep saline aquifers	18	[15]
5	Average annual water balance	47.5	Calculation: 3 – 4

Table 3
Independent power and water producers in Qatar [18]

Water producer	Capacity (m^3/d)
Qatar Electricity and Water Company (QEWC)	
Ras Abu Fontas A	250,000
Ras Abu Fontas B	150,000
Ras Abu Fontas B2	131,818
Ras Abu Fontas A1	204,545
Ras Abu Fontas sub-total	736,364
Ras Laffan Power Company (RLPC)	
Ras Laffan A (RLPC)	181,818
Ras Laffan B (Q Power)	272,727
Ras Laffan C (Ras Girtas Power Company)	286,364
Ras Laffan sub-total	740,909
Total capacity	1,447,273

2.3. Water from desalination

Desalination is the process of desalting (or removing salt) from seawater and treating it to meet the required levels for potable water. Seawater generally has a salinity level of 35,000–45,000 ppm as TDS [17]. However, in the Arabian Gulf, seawater salinity exceeds 45,000 ppm, such as in the west of Qatar, and in some locations it reaches 60,000 ppm. International standards require that desalination systems reduce the salinity of seawater to 500 ppm or less. Usually, DW in Qatar has very low TDS (around 25 mg/L) due to the use of thermal desalting methods, and is blended with a small fraction of groundwater: 1% in the case of Qatar [5].

DW represented 60% of the total water withdrawal in Qatar in 2014. The use of desalination plants started in 1953 with a capacity of 680 m^3/d and by the end of 2014 there were seven desalination plants in Qatar with a total annual capacity of 495 Mm^3/year [18]. Combined together, the desalination plants in Qatar produce 1.5 Mm^3 of water per day [18]. Table 3 summarizes all the operating independent DW providers in Qatar in 2014.

Since 2010, the amount of the produced DW in Qatar has been increasing steadily due to the increase in population and water consumption per capita. Fig. 6 illustrates the increase in DW production from 2010 until 2014. The QNDS (2011–2016) has estimated an expected increase in water consumption through 2020 at 5.4% annually for Qataris and 7% annually for expats (QNDS). A report by Global Water Intelligence showed that Qatar's population has been increasing rapidly from 2000 to 2012 which lead to an increase in the cumulative water desalination plant online capacity [19].

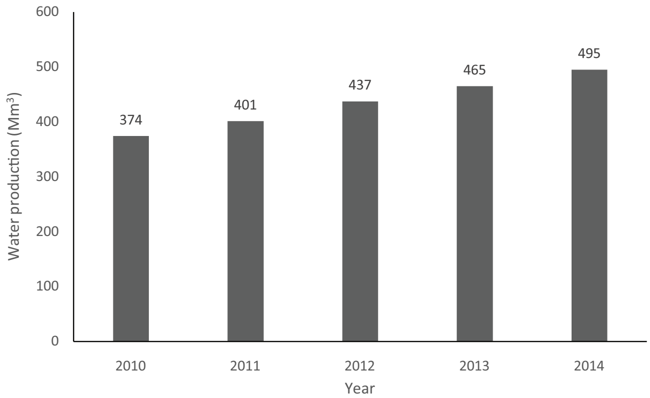

Fig. 6. Total water production from 2010 to 2014 [18].

In the 2014 annual report, Kahramaa has highlighted that there has been a constant increase in DW production from 2010 until 2014. The growth rate from 2010 to 2014 was 7.8%. As a result, Qatar Electricity and Water Company (QEWC) has made many plans to expand its network of desalination plants such as the expansion scheme for Ras Abu Fontas plant (A2) to produce 163,656 m^3 of freshwater per day. Future plans currently under negotiations include the construction of a water plant with a capacity of 621,438.2 m^3/d in Qatar economic zone, including 272,760 m^3/d using seawater reverse osmosis (SWRO) and 347,769 m^3/d using multistage flash (MSF). Moreover, Kahramaa in March 2015 has signed an agreement with QEWC to develop the Ras Abu Fontas desalination plant (A3) as an independent water project model. The new model will be an RO desalination plant with a capacity of 136 million L/d costing about $500 million. One of the largest water and power projects currently being constructed is the Umm Al Houl plant. The plant will produce 620,529 m^3/d of freshwater and 2,520 MW of electricity. The expected completion date for the project is July 2018.

The majority of desalination plants in Qatar are using thermally driven desalination processes especially the MSF process. In 2012, the estimated daily water production from thermally driven desalination plants was 1,771,638 m^3 while the RO desalination plants produced only 155,160 m^3 [19]. Qatar has abundant NG resources that have helped it to maintain the operation of its desalination plants and will continue to do so for at least 50 years. However, due to the severe shortage of RWRs in Qatar and the ever-increasing consumption, water security is becoming a very serious issue that must be addressed immediately. Currently used desalting methods have a number of inefficiencies and are vulnerable to "unforeseen" circumstances such as oil spills [5]. In addition, desalination plants can have a severe impact on the marine environment as discussed in detail in Darwish et al. [20]. Furthermore, increasing the desalination capacity by simply building more plants will only solve the water shortage temporarily and is not a sustainable solution in the long-term [21]. Increasing the desalination capacity also comes with an increased expenditure on fuel. Fuel costs in desalination plants account for as much as 70% of all costs. In 2010, the estimated fuel cost for desalination plant was $1.275 billion and this figure is expected to reach $2.55 billion before 2020 [5]. These facts are very alarming and indicate that a lot of effort has to be made to tackle this problem.

2.4. Treated wastewater

In Qatar, 12% of annual water withdrawals come from treated wastewater (TWW; also known as TSE) [18]. The Public Works Authority (Ashghal) is the government entity responsible for wastewater treatment. Ashghal produces 300,000 m^3 of TWW per day that is used for irrigation (70%), GW injection (22%) and the balance (8%) is discharged to lagoons [18]. In 2011, Qatar produced 444 Mm^3 of wastewater but only 14% of this was treated [22].

Ashghal operates a number of wastewater treatment plants (WWTPs) throughout Qatar. Table 4 shows all the WWTPs in Qatar from 2004 until 2013 and their respective capacities.

The improvements in wastewater treatment technologies were the reason behind the large increase in WWTP capacity. The total WWTPs annual capacity increased from 19.71 Mm^3 in 2004 to 233.65 Mm^3 in 2013. Fig. 7 shows WWTPs capacities based on the treatment method.

In their annual environmental statistics report for 2013, the Ministry of Urban Planning and Statistics has highlighted the major improvements in TWW in Qatar. Among the improvements is that since 2004, all WWTP can carry secondary treatment processes ensuring that organic waste is eliminated to a great extent. Secondary treatment is a biological treatment that uses anaerobic–anoxic–aerobic (AAA) methods to remove organic matter and nitrogen from WW. Further, in 2012, the urban WW treatment facility in western

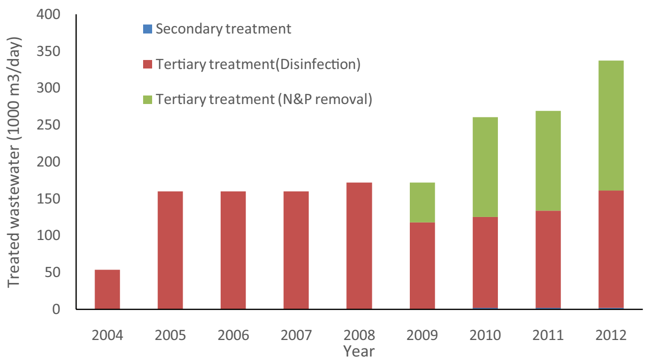

Fig. 7. WWTPs capacity based on treatment method [23].

Table 4
WWTPs in Qatar [23]

Year	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
WWTP	Treatment capacity (1,000 m^3/d)									
Al Dhakhira PTP							1.60	1.60	1.60	1.60
Al-Jamiliyah PTP							0.54	0.54	0.54	0.54
Al-Khor PTP								4.86	4.86	4.86
Al-Khuraib PTP										0.06
Al-Shamal							0.15	0.15	0.15	0.15
Barwa Al Baraha PTP									12.00	12.00
Barwa City STW									15.00	15.00
Barwa Mesaimeer PTP								1.50	1.50	1.50
Barwa Sailiya PTP								1.50	1.50	1.50
Barwa Village PTP								1.00	1.00	1.00
Barzan PTP						0.08	0.08	0.08		
Doha North STW										244.00
Doha South STW		106.00	106.00	106.00	106.00	106.00	106.00	106.00	106.00	106.00
Doha West STW	54.00	54.00	54.00	54.00	54.00	54.00	135.00	135.00	175.50	175.50
Duhail PTP							0.81	0.81	0.81	0.81
Industrial Area STW					12.00	12.00	12.00	12.00	12.00	12.00
Lusail STW										60.00
North Camp PTP							0.25	0.25	0.25	0.25
Ras Abu Fontas PTP							0.54	0.54	0.54	0.54
Shahaniya PTP							0.81	0.81	1.35	1.35
Umm Slal PTP							1.50	1.50	1.50	1.50
Total	54.00	160.00	160.00	160.00	172.00	172.08	259.28	268.14	336.09	640.16

Note: PTP – Package treatment plant; STW – Sewage treatment works.

Doha has started to carry tertiary treatment to the WW that removes nitrogen (N) and phosphorus (P). This facility is the largest in Qatar serving 900,000 people and treating 52% of all wastewater produced in Qatar. It has a peak capacity of 439,000 m^3/d of TWW. Water is treated in four stages in this plant [24]:

- Preliminary treatment using step screens and vortex degritters.
- Secondary treatment using the AAA method and biological nutrient removal.
- Tertiary treatment using advanced membrane filtration and UV technologies.
- Solid treatment where the following processes occur: sludge digestion, thickening and dewatering and wet sludge treatment.

This plant is the first of its kind in Qatar and will produce high-grade water supply for non-potable use.

Wastewater is one of the valuable water sources in Qatar and should be utilized in an efficient manner. One good example that is currently being used is groundwater injection with TSE. This is an effective mechanism as it helps in reducing the pressure on the limited water sources. However, there still remains a large quantity of wastewater that is not treated or not reused. Furthermore, the recovery of injected TSE is still an issue that has not been resolved.

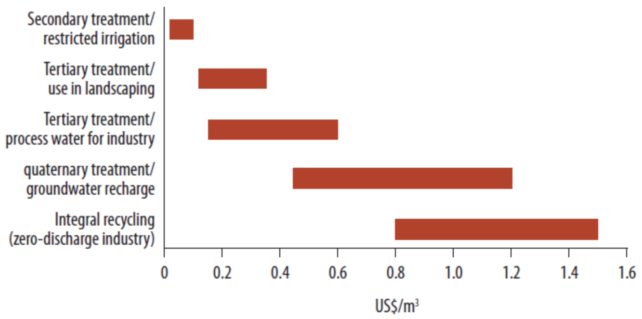

Fig. 8. Cost of wastewater treatment methods in MENA region [25].

The QNDS 2011–2016 has indicated that WWTP facilities should be significantly expanded since TWW is currently the only water source in excess. The QNDS has also emphasized that "Qatar lacks the infrastructure to deliver recycled water to every potential user" [3]. Partly because of this constraint, the supply of recycled water exceeds consumption, leaving about 40% of TSE to be dumped into vast septic lagoons, creating problems for nearby communities. The current sewage network must be improved and controls must be implemented on wastewater dumped into the sea. Treating WW may be expensive at the initial investment stage but it is much cheaper than DW production in terms of cost per m^3. Generally speaking, TWW costs only one-quarter of the cost of desalted water. In the GCC region, desalted water costs around \$3.3/m^3 for thermal desalination whereas the maximum cost for TWW is \$1.5/m^3 [5,25]. Darwish et al. [26] calculated the realistic costs of desalted water in Qatar which was \$2.04/m^3 for the MSF process. However, it should be noted that the unit cost of TWW varies with the treatment type and desired TWW final quality. Fig. 8 shows the cost variation for different treatment technologies for the MENA region. A study on the economics of supplying villages in western Saudi Arabia with water (for potable and non-potable use) from either TWW or SWRO desalination found that the cost of water from SWRO was \$2–5/m^3 plus conveyance costs. TWW costs were only \$0–0.5/m^3 plus conveyance costs. The authors concluded that TWW is a very cost-efficient method for reducing the cost of supplying water to remote villages [27]. In Kuwait, the cost of TSE was found to be \$0.66/m^3 compared with more than \$3/m^3 for thermal desalination [5]. These findings provide a great motive for using a larger amount of TWW to meet Qatar's water demand.

Table 5 summarizes for this section of the review the total water resources available in Qatar compiled from different sources.

Table 5
Total water resources in Qatar

Parameter	Value	Year	Source
Population	2,267,916	2014	The World Bank
Long-term average precipitation (mm/year)	74	2014	FAO
Long-term average precipitation volume (10^9 m^3/year)	0.8591	2012	FAO
Groundwater produced internally (10^9 m^3/year)	0.056	2014	FAO
Total internal renewable water resources (10^9 m^3/year)	0.056	2014	FAO
Groundwater: entering the country (total) (10^9 m^3/year)	0.002	2014	FAO
Total renewable water resources (10^9 m^3/year)	0.058	2014	FAO
Total renewable water resources per capita (m^3/capita/year)	25.57	2014	FAO
Improved water source, urban (percentage of urban population with access)	100	2015	The World Bank
Water produced from desalination plants (Mm^3/d)	1.48	2014	Kahramaa
Water produced from desalination plants (Mm^3/year)	495	2014	Kahramaa
Water produced from WWTP (1,000 m^3/d)	640.16	2013	Ministry of Environment
Water produced from WWTP (Mm^3/year)	108.26	2011	Ministry of Environment
Total water production (RWR + Desalination + WWTP) (Mm^3/year)	553.01	NA	
Total water availability per capita (m^3/capita/year)	243.84		

3. Water withdrawals

Water withdrawal and per capita consumption in Qatar are among the highest in the MENA region. This is a very startling fact because Qatar is one of the poorest countries in terms of RWRs. Over the past decades, consumption rates have been rising steadily with the increasing population and the subsequent increase in demand. Agricultural and domestic sectors are the main water consumers. GW resources are overexhausted and overexploited far beyond their regenerative potential by farming. On the other hand, the little public awareness about the importance of water conservation in the NG-rich state and the continued unsustainable use of water has made the per capita consumption among the highest globally at 222 m^3/capita/year [18]. It is worthy of mentioning here that calculation of parameters like per capita water consumption is not a straightforward task and can be achieved using different approaches. Hence, a number of estimates may exist for the same parameter. Fig. 9 shows the per capita water consumption in the MENA region in relation to each country's per capita GDP.

Fig. 9 shows that Qatar has the highest per capita water consumption in the MENA region after Bahrain. This is very surprising since Qatar has one of the smallest populations in the MENA region and also has a relatively small water desalination capacity (as compared with SA and Kuwait). However, by considering the world average of per capita water consumption, Qatar ranks 81st with an average of 385 m^3/capita/year according to FAO [8]. This ranking is a rough estimate because the AQUASTAT database from FAO did not provide the per capita value for the same year for all countries. Hence, there may be some variations if exact results from the same year were taken for all countries. Based on FAOs AQUASTAT database, the global average for per capita water consumption was calculated to be 486.5 m^3/person/year. This means that Qatar's per capita water consumption is below the global average. Nevertheless, water demand in Qatar is expected to continue increasing as forecasted by a number of studies [25,28,29]. Kahramaa stated that demand for water has grown at an average rate of 8.5% from 2008 to 2013 and is expected to continue growing at a rate of 6.3% from 2014 to 2019 [10]. Fig. 10 shows Kahramaa's statistics on demand for water and their future forecast.

3.1. Groundwater sources withdrawal

Groundwater in Qatar contributes to 28% of total water supplies and is estimated at 250 Mm^3/year [10]. The large majority of GW supplies are used for irrigation (91%) and the remaining is consumed by the homes, municipalities and industry [10]. Water consumption is high in the agricultural sector because water is given free to the farmers who only have to pay for the pumping systems. Moreover, the farming processes currently used are unsustainable and water-intensive because they rely on flooding fields with water that will eventually evaporate quickly because of the high evaporation rate in Qatar's climate [5]. Furthermore, continued exploitation of GW for irrigation may compromise the soil's structure and crop yield [30]. Fig. 11 shows an increase in the number of farms in Qatar that gives an indication of increased GW withdrawal. As an example, GW use increased

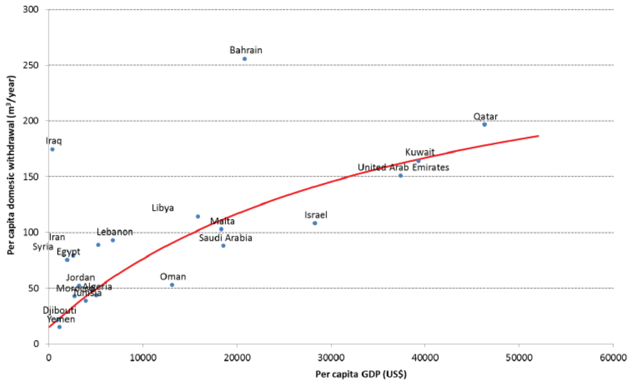

Fig. 9. Per capita water consumption in the MENA region (in 2010) vs. per capita GDP [28].

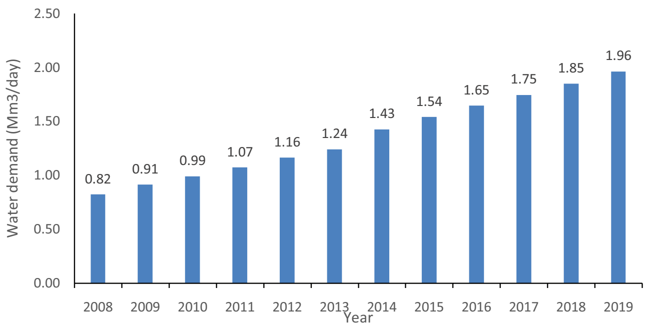

Fig. 10. Water demand from 2008 to 2019 [10].

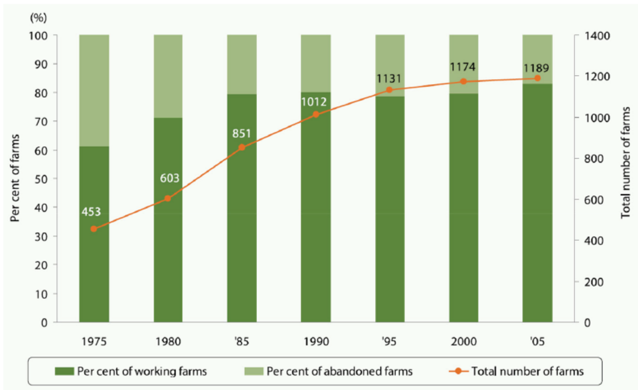

Fig. 11. Number of farms in Qatar from 1975 to 2005 [3].

from 185 Mm^3 in 2010 to 250 Mm^3 in 2014 [31]. In 2012 alone, Qatar's total water withdrawal was 400 Mm^3, out of which 236 Mm^3 (59%) was used by agriculture [9]. Water withdrawal by the agricultural sector in the same year was 407% of the total annual freshwater resources. Recent statistics given by the Ministry of Environment in October 2014 showed that current extraction of groundwater is 250 Mm^3/year while the recharge rate is only 56 Mm^3/year. This means that the extraction rate is nearly four times the recharge rate.

GW withdrawals in Qatar and the GCC region are extremely high and exceed the rate of replenishment of GW. This poses a serious threat to current GW reserves. Table 6

Table 6
GCC countries water demand, renewable GW, surface runoff and GW usage [31]

Country	Total demand ($\times10^6$ m^3/year)	Renewable GW ($\times10^6$ m^3/year)	Surface runoff ($\times10^6$ m^3/year)	Total RWRs ($\times10^6$ m^3/year)	GW usage ($\times10^6$ m^3/year)	Percentage of renewable GW to total RWRs (%)
Saudi Arabia	2,350	3,850	3,210	7,060	14,430	54.53
Kuwait	512	160	0.1	160.1	405	99.94
Bahrain	117	100	0.2	100.2	258	99.80
Qatar	190	58	1.4	86.4	185	98.38
UAE	750	130	150	280	2,650	46.43
Oman	151	550	1,470	2,020	1,644	27.23

Table 7
GW withdrawals in GCC countries as a percentage of annual freshwater resources [9]

Country	All uses (%)	Agricultural use (%)
Bahrain	344.8	155
Kuwait	4,500	2,500
Oman	92.3	82
Qatar	689.6	407
Saudi Arabia	987.5	869
UAE	2,666.6	2,213
GCC countries	740	633
Yemen	549.3	472

Table 8
Annual water consumption per capita [18]

Year	Cubic meters per person per year (m^3/person/year)			
	Based on total water production	Based on system input volume, including losses	Based on authorized consumption of system input volume, net of losses	Based on system input volume excluding real losses
2010	220	221	164	214
2011	228	229	182	211
2012	238	232	187	216
2013	227	222	176	208
2014	222	216	170	202

shows water demand in the GCC, renewable GW, surface run-off and GW usage. Table 7 shows water withdrawals as a percentage of annual freshwater resources for Qatar and the GCC.

Both Tables 6 and 7 clearly show that GW withdrawals in Qatar and the GCC region (with the exception of Oman) are much higher than the rate of replenishment. Hence, GW is severely overexploited. Exhausting the GW resources in this manner cause rapid depletion of GW and deterioration of water quality because as the water table falls, the water becomes saltier. Overall, we can conclude that GCC countries are heavily dependent on fossil GW which is non-renewable and not sustainable.

A recent study by Qatar Energy and Environment Research Institute (QEERI) about GW quality in Qatar has highlighted that "overexploitation of groundwater resources has led to seawater intrusion of the Qatari aquifers" [30]. The study has also pointed out that groundwater resources should be utilized in a more efficient manner because they can help to reduce dependency on seawater desalination. An example of inefficient utilization is the currently employed irrigation system in Qatar which increases soil salinity and leads to more desertification. It was also found that groundwater in Qatar has relatively high levels of molybdenum (Mo; mean = 26.9 μg/L) as compared with other regions in the world. It is believed that high concentrations of Mo may pose health risks to the local population.

3.2. Desalinated water withdrawal

Desalination provides most of the water consumed for all purposes in Qatar (except for agriculture). Although it is an energy-intensive and expensive process, yet it seems to be the only viable solution currently for securing Qatar's municipal's water demand. The per capita water consumption (from all desalination plants in Qatar) is given in Table 8 (adapted from Kahramaa). Kahramaa, however, has underlined that there is no internationally accepted water per capita consumption calculation and hence has provided this value by four different estimates.

3.3. Treated sewage water consumption

TSE is an important water source in Qatar for all demand sectors, except potable use. As emphasized earlier, improving the treatment methods for sewage water can reduce the water shortage in Qatar and is a good step in efficient water management. Fig. 12 shows the consumption of TSE from 2004 to 2012 by different sectors.

Fig. 12 shows that the largest percentage of TSE is used by the agricultural sector followed by the injection to aquifers. In 2011, TSE water withdrawal was 108 Mm^3 which accounted for 14% of total water withdrawal [32]. Fig. 13 shows the percentage of withdrawal from TSE by different sectors in Qatar in 2011.

It is anticipated that the withdrawal rate from TSE water will increase in the coming years and hence there are plans to expand the TSE capacity in Qatar to 288 Mm^3/year in 2016 and 299 Mm^3/year by 2030 [34].

3.4. Water withdrawals by the industry

Industries in Qatar, mainly petrochemicals, also withdraw large amounts of water for their processes. The main industries are petrochemicals and chemicals, refining industries, liquefied natural gas (LNG) plants, mining and minerals and oil and gas industries. Fig. 14 shows the major water consuming industries in Qatar in 2013 with their respective water consumption shares.

Power and utilities in Qatar like QEWC produce DW and then sell it to Kahramaa. Kahramaa in turn then distributes this water to the houses and industries. Some industries, however, produce on-site water for their process. The 2013 sustainability report produced by Qatar Petroleum Health, Safety and Environment Regulations and Enforcement Directorate General in the Ministry of Energy and Industry have given a comprehensive review of water consumption by the industrial sector in Qatar [35].

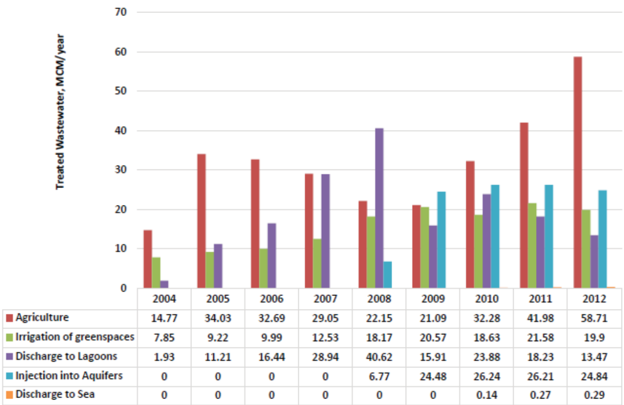

Fig. 12. TSE consumption in 2004–2012 [10].

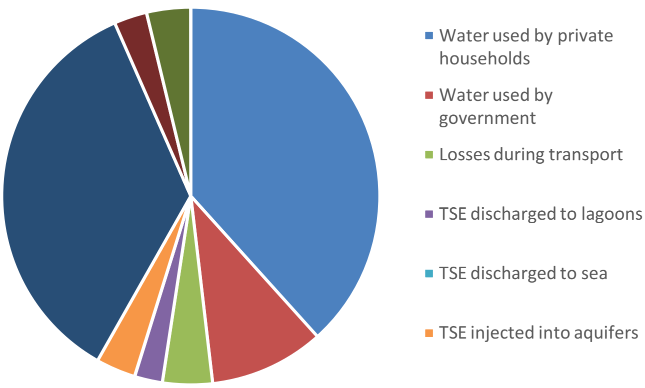

Fig. 13. TSE water withdrawal in 2011 [33].

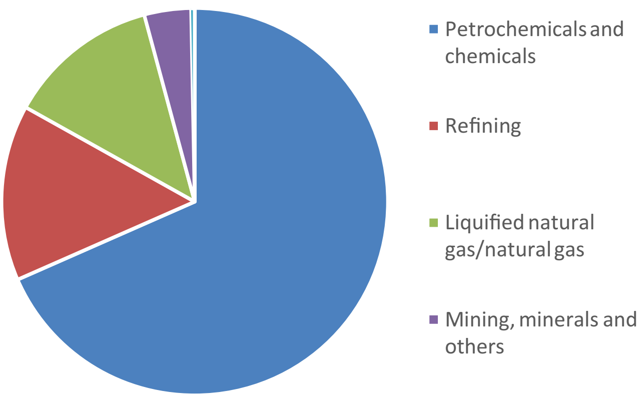

Fig. 14. Percentage water consumption by the industry sectors in 2013 [35].

In 2013, 25 companies in Qatar purchased 14.1 Mm^3 of water which marked a decrease of 2.2% compared with 2012 levels. These companies also generated 60.8 Mm^3 of on-site water: an increase of 88.7% compared with 2012 and was nearly four times the amount of water purchased. This large difference between on-site generated water consumption and water purchased from Kahramaa is because of the emergence of two new water-intensive petrochemical production lines that started operating in 2013. Table 9 shows the total water purchased from Kahramaa and on-site generation by 25 major companies in 2012 and 2013.

Petrochemicals industries consume the largest amounts of water in Qatar (68.4% of total water consumption by industries in 2013) while the oil and gas plants consume the least (0.3% in 2013). Table 10 shows the water consumption by sector in 2012 and 2013.

Tables 9 and 10 both show that water consumption by industry sectors has increased by 66.1%. Consumption is primarily dominated by the petrochemicals and refining industries. Table 9 further shows that the demand for water has been rising in most sectors from 2012 to 2013. The reason for this increase is the establishment of new plants especially in the petrochemicals sector. This sector has been growing steadily at a rate of 9.5% annually from 2003 to 2013 [36]. Moreover, in 2013, petrochemicals represented 42.6% of Qatar's manufacturing added value that was worth $8.4 billion. 9% of Qatar's non-oil GDP comes from the petrochemicals sector [36]. Hence, it is not surprising that it has a high water consumption level.

An important indicator of water consumption in the industry sector is water intensity. Water intensity is defined as the amount of water consumed per unit product. The water intensity profile for industries in Qatar is variable with some sectors experiencing an increase, some experiencing a reduction and others being stable. Water intensity is an important measure of the efficiency of production and hence it can be concluded that sectors where water intensity reduced have

Table 9
Freshwater purchased and generated on-site by 25 major industries in 2012 and 2013 [35]

Indicator	Comparable companies	Water consumed (m^3)		
		2012	2013	Change (%)
Freshwater purchased	25	14,409,602	14,096,410	–2.2
Water produced on-site	25	32,207,938	60,764,726	+88.7
Total freshwater consumed	22	42,510,301	70,588,542	+66.1

Table 10
Water consumption by industry sectors [35]

Subsector	Comparable companies	Water consumed (m^3)		
		2012	2013	Change (%)
LNG/NG	3	9,227,946	8,994,447	–2.50
Mining, minerals and other	3	2,758,056	2,761,389	0.10
Oil and gas (exploration and production)	6	195,597	210,570	7.7
Petrochemicals and chemicals	7	18,881,526	48,275,708	155.70
Refining	2	11,407,053	10,346,428	–9.30
Support services	1	40,124	0	–100

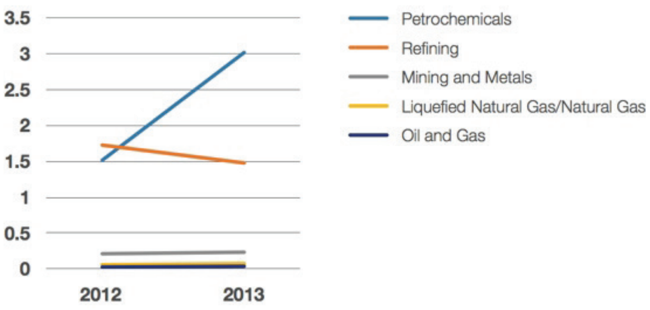

Fig. 15. Water intensity by sector in 2012 and 2013 [35].

implemented some form of water conservation or energy efficiency methods. Fig. 15 shows the water intensity by sector in 2012 and 2013. The units for the *y*-axis are m^3/ton of production.

The total water intensity for all industries increased from 0.21 m^3/ton of production in 2012 to 0.35 m^3/ton of production in 2013: 64% increase.

Wastewater discharged and recycled by the energy and industry sectors is another important parameter to be analyzed. The energy and industry sectors in Qatar have been actively working to reduce their water discharge to the sea to near zero levels. This is in accordance with the Ministry of Environment goal of zero liquid discharge by the end of 2016. To achieve this, a number of companies are trying to reuse wastewater in their processes or otherwise use it for irrigation. In addition, some companies are also working on monitoring the quality and temperature of wastewater discharged to the sea in accordance with the regulations of the Ministry of Environment. Moreover, the Qatar Petroleum Health, Safety and Environment Regulations and Enforcement Directorate General is currently engaging with the energy and industry sector to design and install a monitoring system for wastewater ejected to the sea. Unfortunately, there are very little data so far about amounts of wastewater discharged to the sea by the energy and industry sectors. Fig. 16 shows key figures about water discharge to the sea and to non-sea sinks like ponds and reinjection to wells.

Some companies in the energy and industry sectors have also reported recycling of water in their processes. In 2013, 24 Mm^3 of water was recycled as given in data from 15 companies in Qatar Petroleum (QP) Sustainability Report. Some companies made large improvements in the recycling of

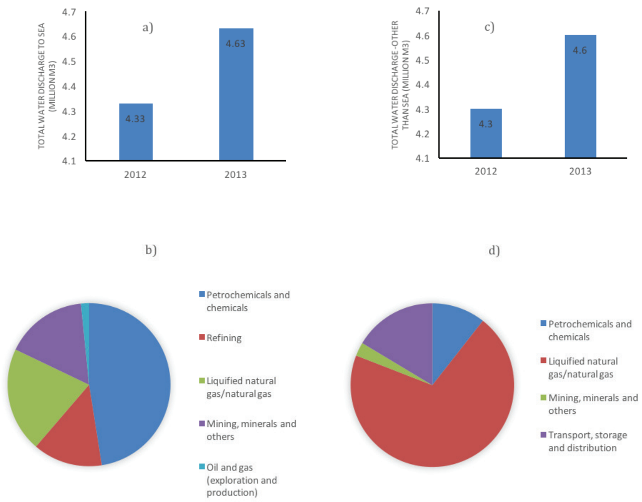

Fig. 16. (a) Water discharge to sea in million m^3. (b) Water discharge to sea as percentage per subsector. (c) Water discharge to other than sea sinks in million m^3. (d) Water discharge to other than sea sinks as percentage per subsector [35].

water such as Qatar Steel, Qatar Fuel Additives Company (QAFAC) and Qatar Fuel (Known as WOQOD) which had an increase of 150%, 86% and 60% in the volume of recycled water, respectively. Fig. 17 shows the percentage of water recycled by subsector in 2013.

In conclusion for this section of the review, we can highlight the following:

- Qatar has one of the highest per capita water consumption rates in the MENA region: 200 m^3/capita/year.
- Estimates for some water consumption parameters (like per capita consumption) are variable to a great extent. However, almost all sources indicate that Qatar has high water consumption rates.
- The agriculture sector is the most water demanding sector consuming about 91% of all RWRs and 35.2% of TSE.
- Unsustainable irrigation methods and the fact that water is free are the major reasons behind high water consumption in the residential and agricultural sectors.
- Groundwater is being severely exploited with the extraction rate four times the replenishment rate.

- Groundwater quality is also deteriorating because of salts from irrigation water being recycled and reasonably high levels of Mo (that may pose some health risks in the future).
- TSE is mainly utilized for agriculture and domestic purposes and is one of the key water sources for reducing water shortage in Qatar.
- Water consumption by industries is dominated by the petrochemicals and refining sectors (68.4% and 14.7% of the total, respectively).

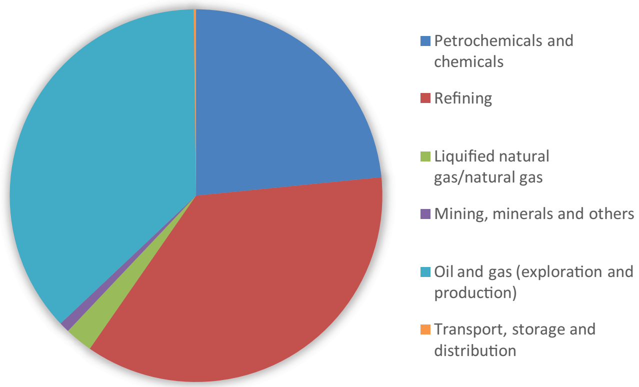

Fig. 17. Percentage of water recycled by subsector [35].

After presenting all of these statistics about RWRs, non-RWRs and water consumption by different sectors, it is useful to present the water balance for both natural and human-induced water sources. The entire water balance for Qatar is shown in Table 11.

4. Virtual water trade in Qatar

The concept of virtual water refers to the trade of "invisible" water associated with food imports and industrial commodities. Any country that has water scarcity has to rely on food imports to meet local demand especially for water-intensive products like sugar and cereals. Virtual water or water footprint is a major source of relief for countries with severe water shortages [37,38]. Analyzing a country's water footprint is vital when assessing national water needs and flows [39–42]. Qatar, being very poor in RWRs and having poor soil quality, is heavily dependent on food imports. Moreover, the agricultural sector in Qatar only contributes 0.1% of the GDP and 1.6% of total labor force [43,44]. Furthermore, only 6% of Qatar's area is suitable for agriculture and out of this, only 11,216 ha are used for cultivation. As a result, local food production is very low. In 2014, total domestic production (for human consumption) was 20 kilotons which represented only 13% of the local consumption [45]. This heavy dependence on food imports is reflected in the self-sufficiency ratio which

Table 11
Detailed water balance [7]

Water use balance 2013 (million m^3)	Water potentially available for use (million m^3)	Water uses and losses (million m^3)	Remarks
Desalinated water	453.21		System volume input of Kahramaa
Fresh groundwater abstraction	250.21		Agricultural, municipal, domestic and industrial wells. Data of 2012 used
Treated wastewater	151.22		Wastewater discharged by urban wastewater treatment plants
Wastewater discharged without treatment	18.04		Discharge of untreated wastewater to lagoons
Total water potentially available for use	872.68		Water available before losses
Wastewater discharged without treatment		18.04	
Losses of desalinated water		92.31	Total losses
TSE discharged to lagoons		35.391	
TSE discharged to sea		0.23	
TSE injected in aquifers		35.462	
TSE unknown destination		0.23	RO and discharge by tankers
Water used by agriculture		285.28	Groundwater and TSE
Water used by industries		19.18	Water supplied by Kahramaa and industrial wells
Water used by commercial activities		54.38	Water supplied by Kahramaa including big industrial complexes and hotels
Water used by private households		245.50	Water supplied by Kahramaa, domestic wells and municipal wells
Water used by government		88.67	Water supplied by Kahramaa and TSE for irrigation of green spaces
Total water uses and losses		872.68	

declined sharply over the past years. In the 1990s, the self-sufficiency ratio was 20% which dropped to 13% by 2015. Qatar has had a reducing trend of food self-sufficiency due to the rapid population growth and inefficient irrigation methods in farms [46]. Over the past years, water use in agriculture was very inefficient due to immense reliance on food imports. However, the recent new regulations by the Ministry of Environment have help limit GW withdrawals and many farms have started adopting efficient irrigation methods. In addition, water use per unit ton of agricultural produce has a reduced significantly in recent years. In 1995, 940 m^3 of water was required to produce 1 ton, whereas in 2013 this dropped to 437 m^3 only which indicates a nearly two times increase in water-use efficiency. We also estimated that the water use per agricultural GDP has halved in less than a decade from 1.04 m^3/unit GDP in 2005 to 0.56 m^3/unit GDP in 2013. These results show a significant improvement in water-use efficiency within Qatar. However, water allocation for agriculture is still a disputed issue in Qatar.

The accurate calculation of water footprint is an important assessment tool for formulating national policies that preserve the country's resources. In the case of Qatar, we calculated the virtual water flow using the methodology proposed by Hoekstra and Hung [47]. The virtual water flow is given by:

$$\mathrm{VW}_{\mathrm{flow}} = \mathrm{VW}_{\mathrm{exports}} - \mathrm{VW}_{\mathrm{imports}} \tag{1}$$

where

$$\mathrm{VW}_{\mathrm{exports}} = \sum_{p} \mathrm{VWC}_{p}^{z}(z,p,t) * \exp_{p}^{z}(z,p,t) \tag{2}$$

$$\mathrm{VW}_{\mathrm{imports}} = \sum_{p} \mathrm{VWC}_{p}^{y}(y,p,t) * \mathrm{imp}_{p}^{z}(y,p,t) \tag{3}$$

In Eq. (2), VWC_p^z is the virtual water content of product (*p*) in country (*z*) that is exported (for our case, *z* = Qatar). The other parameter: $\exp_p^z$ is the exported quantity of the product (*p*) at time (*t*). Similarly, in Eq. (3) the quantity VWC_p^y refers to the virtual water (blue water or green water) content for product (*p*) imported from country (*z*) at time (*t*) to Qatar. Blue water is surface water or groundwater used for crop production whereas green water is rainwater. The parameter imp_p^z is the quantity of product (*p*) imported at time (*t*). We also calculated the virtual water dependency (WD) which is the ratio of external water footprint to total water footprint. The virtual WD is given by Eq. (4).

$$\mathrm{WD} = \begin{cases} \dfrac{\mathrm{NVWI}}{\mathrm{WU} + \mathrm{NVWI}} \times 100 & \text{if NVWI} \geq 0 \\ 0 & \text{if NVWI} < 0 \end{cases} \tag{4}$$

WD represents internal water footprint and NVWI is the external water footprint. WD is a measure of the external WD of Qatar.

The aim was to calculate the virtual water flow and the WD for Qatar in 2015. In 2015, Qatar had a negligible amount of virtual water exports: <3,000 tons. In our analysis, we considered these food types: cereals, vegetables, fruits, flour (processed), sugar, meat and dairy products. These food types represent 80% of Qatar's food imports. We used references [48,49] to acquire data about the virtual water content for crop and animal product for different countries. We also used the agrifood import dataset from the foreign merchandise trade database which is co-managed by MDPS and General Customs Authority of Qatar.

Using the set of inputs outlined and Eqs. (1)–(4), it was found that Qatar is a net virtual water importer. A net virtual water importer is a country that imports more virtual water than it exports. For the period 1998–2015, Qatar had a total virtual water flow of 24.4 billion m^3 with an annual average of 1.35 billion m^3/year. Qatar's per capita water footprint is 1,554 m^3/capita/year. In 2015, 70% of Qatar water footprint for national consumption was external and only 30% was internal.

Cereals have the largest water footprint, accounting for 46%, followed by dairy 17%, meat 13%, vegetables 8%, fruits 6%, flour 5% and sugar 5%. Our results also show that Qatar's dependency on green water outweighs dependency on blue water. This is because most imported foods are from regions where crops are rain fed. It was also found that only 10% of the agricultural sector water demand comes from domestic water sources. Furthermore, Qatar's dependence on virtual water for food products escalated from 63% in 1998 to 90% in 2015. The virtual WD ratio is 68%. Southeast Asia is among the largest exporters of virtual water to Qatar especially for foods like wheat, rice and cereals. The largest exporters of green water to Qatar are India, Australia, Saudi Arabia, Pakistan and Brazil who account for 70% of total green water imports. As for blue water, 83% of Qatar's blue water imports come from India, Pakistan, Saudi Arabia, Egypt and Iran.

The results of this section substantiate previous works that quantified virtual water flows at a global or country scale [50,51]. In a research published by Hoekstra [51], the water footprint for humanity was calculated at a high resolution. Although the findings were only for the period 1996–2005, yet we can still draw a number of similarities with our results. The water footprint for consumption for Qatar which is 1,554 m^3/capita/year is higher than the global average of 1,385 m^3/capita/year as cited in the paper. It is interesting to note that in a more recent publication, the global average water footprint per capita was estimated as 1,780 m^3/capita/year [52]. This marks an increase of 28.5% from the value of 1,385 m^3/capita/year in 2005. Nevertheless, this figure (1,554 m^3/capita) is within the range given in Hoekstra [51] for developing countries: 550–3,800 m^3/capita. Moreover, from the same reference, we found that Qatar's water footprint for consumption per capita is higher than some developed countries like the UK (1,258 m^3/year). Hoekstra and Hung [53] estimated Qatar's net virtual water import as 49 Mm^3 and the WD as 17.8% for 1995. However, our results for the same year show a 10 times increase in net virtual water import (500 Mm^3) and an increase in WD to 55.4% in 1998. The difference between 1995 and 1998 in terms of population and food imports was minimal.

Regarding the uncertainties in this analysis, we only considered green water and blue water. Gray water was excluded and hence this affects the comprehensiveness of the results. However, considering the fact that on a global scale the gray water footprint only accounts for 15% of total water footprint as cited in Hoekstra [51], we believe that this will not affect the trend of our results. Further, we only considered the following food items: cereals, vegetables, fruits, flour (processed), sugar, meat and dairy products which form 80% of Qatar's food imports.

An analysis that covers all of Qatar's food imports will no doubt produce more reliable results. The merchandiser's database we used to quantify food imports was reorganized to group different types of the same food item together in one dataset. For example, different types of rice (milled, broken, etc.) were all grouped under one dataset: rice. We believe that this grouping will not adversely affect the overall virtual water trade. We also disregarded the virtual water for live animals. This is because it is difficult to determine whether the animal was at full age (ready for slaughtering) or still young to be raised in Qatar. This assumption will affect the total virtual water flow calculation. The agrifood import dataset co-managed by the MDPS is a dynamic one and is monthly updated. Hence, it is a highly reliable source for our analysis.

5. Policy implications and water conservation

It is important that Qatar adopts a number of water conservation initiatives to reduce the overexploitation of its water resources. The overexploitation of water resources can be attributed to four main reasons:

- Awareness about the need for water conservation and its immense importance for Qatar is not yet as widespread as it should be.
- The heavy subsidies given for water which does not encourage people to appreciate the value of what they are consuming. The fact that Qatari nationals (who consume by far most water) do not pay anything for water or electricity further leads to irresponsible water consumption habits.
- The use of inefficient water irrigation methods in agriculture consumes huge amounts of GW annually. Farmers should be made aware of water efficient irrigation methods such as hydroponics and brackish water treatment systems and mandated to use them.
- The use of treated domestic wastewater in productive sectors is an excellent water conservation method but has not yet been fully utilized.

Water conservation in Qatar is a national priority and all the statistics presented in this review highlight that a lot of effort has to be put to preserve RWR and non-RWRs. Conservation efforts should focus primarily on reducing demand in the domestic sector, introducing efficient irrigation methods in farms, reducing network leakage and introducing resilient water policies. It is always much easier and more economical to reduce water usage rather than build new water capacity.

One of the important recommendations of this review is carrying a comprehensive assessment study on the effect of climate change on RWRs in Qatar. This topic, unfortunately, has not been investigated in depth and there are several inconsistencies and research gaps. There are different estimates on the effect of climate change on water stress on a global scale [54]. Regarding the rise in sea levels, some studies suggested that the impact of climate change on sea level rise at the population of beaches is very small relative to many other regions globally [55]. There is a need to develop climate models that incorporate seawater desalination, groundwater and rainfall and observe how these parameters are affected by possible future climate change scenarios.

Our results highlighted the heavy dependence Qatar has on food imports to meet its local consumption demand. These results also have a number of key policy implications. Currently, virtual water trade has been absent from the national water policy in Qatar. Currently, the Qatari government has formed a committee to draft a new Water Policy Act. The Water Policy Act is a policy that aims to create an "integrated governance framework for water regulation" [3]. This new act, which is expected to come into effect by the end of this year will regulate water production, distribution, consumption and reuse. The allocation of GW for agriculture is the main priority as it is the main freshwater source in Qatar. Even though virtual water helps in identifying the water requirement in addition to domestic consumption, yet it is still difficult to make any impact on policymaking. The authors seriously doubt neither that virtual water will be integrated into the national water policy nor that there will be a shift in blue and green water imports from water-scarce countries. We believe that food trade will be based on economics and not virtual water content [39].

Nevertheless, policy-makers should still take into account virtual water trade as a major factor in achieving water and food security. Although Qatar has limited natural resources to produce significant amounts of food for domestic consumption, yet more improvements in water-use efficiency in the agriculture sector can still be implemented to preserve available GW. In fact, a number of farms have already started using technologies like hydroponics, greenhouses and brackish water treatment systems. GW real-time monitoring is also important in providing data for scientists to make better forecasts about GW reserves in Qatar. These are excellent initiatives and should be further supported by developing traditional practices of crop cultivation and irrigation.

Schyns et al. [50] carried an analysis on virtual water trade in Jordan and made a number of suggestions to solve Jordan's domestic water problems and external WD. These include:

- Increasing water availability through desalination powered by sustainable energy technologies such as solar or wind energies.
- Improving soil management to allow for greater storage of moisture which in turn increases yield.
- Applying a number of reforms in agriculture such as: growing drought-tolerant crops, increasing the cost of irrigation water, training farmers to adopt sustainable agriculture practices, etc.
- Rehabilitating the water distribution network to reduce leakage.

Regarding network leakage, estimates for Qatar are high: 30%–35% compared with an average of 18% for OECD countries. This costs Qatar annual losses of 1 billion QAR [3].

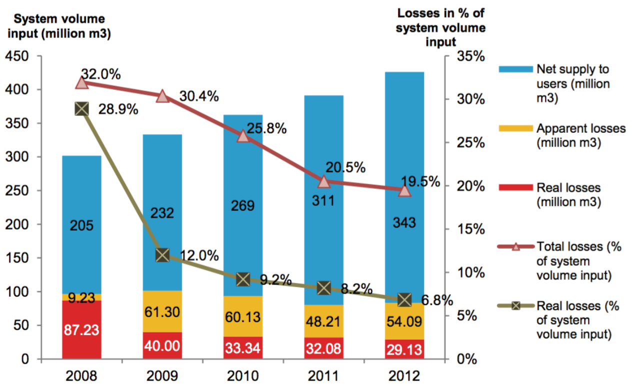

Fig. 18. Net supply and losses in the drinking water distribution network [7].

By directing a significant investment to improve water network efficiency, it is possible to recover millions of cubic meters of water annually. A reduction of 12% in network leakage will allow Qatar to recover 51 million m^3 of potable water annually. This is equivalent to providing water for 236,000 people for 1 year (assuming a per capita consumption of 216 m^3/year). Reducing network leakage should be made the priority at this stage for Qatar. A recent publication by the MDPS (2013) revealed that Qatar has indeed been reducing leakage in the drinking water distribution network since 2008. Losses in the water distribution losses are either real losses (physical water losses from the pressurized system) or apparent (unauthorized consumption such as theft). The total loss is the sum of real and apparent losses. Fig. 18 shows the real, apparent and total losses in the drinking water distribution network from 2008 until 2012. Fig. 18 clearly shows that real losses have decreased from 28.9% in 2008 to only 6.8% by 2012. This is a good indicator of the efforts of Kahramaa to reduce network leakage.

From the demand side, Kahramaa has implemented the Tarsheed campaign to increase public awareness about the need for water conservation. This campaign has currently implemented 22 projects which were publicized in 7 languages across different media channels. Among the initiatives was awareness to young children in schools about the importance of preservation of water. This campaign was currently implemented in 75 schools. Kahramaa has also built its own "awareness park" which previews different technologies for conserving water and electricity. From the regulatory side, Kahramaa has recently started charging water usage violation fines for improper use of potable water. This includes using potable water for washing cars or courtyards. The fines for such violations can go up to 20,000 QAR.

This study recommends, based on the literature, that in addition to current conservation efforts, water tariffs should be revised in Qatar for all residents. The new tariff should reflect the consumption quantities for all residents. When people are made to pay for their consumption, it is more likely for them to start conservation. However, determining the structure of the new water tariff requires a detailed economic analysis. Such an analysis should take into account supply/demand changes, the cost of water production and availability of subsidies. Qatar's unique case of having tremendous NG reserves, a small population and limited RWRs leads us to ask: should the new water tariff be comparable with European countries and the USA whose economy and demography are entirely different? In the case of Qataris, considering the high income per household, will including a water tariff even change their consumption habits? These are key questions requiring a thorough social study of people's behavior and motives for water conservation. Moreover, it is interesting to explore the driving forces for changing the water usage culture in the Qatari community. Lastly, the use of water efficient faucets, pipes and other water equipment should be made mandatory in homes.

6. Conclusion

This paper reviewed Qatar's water resources and consumption by different sectors. The study concluded that Qatar is one of the poorest countries in terms of freshwater sources due to little rainfall, rapid depletion of groundwater and high per capita water consumption. Annual rainfall is less than 80 mm, and the rate of evaporation is 2,000 mm/year. The amount of GW produced internally is 56 Mm^3/year which equates to a water share of 24.8 m^3/capita which is very low.

Water withdrawals from GW are much higher than the rate of regeneration indicating that GW resources will soon be exhausted. This is primarily due to heavy water withdrawals for farming and inefficient water irrigation methods. The review also found that Qatar is heavily dependent on desalination for meeting local water demands. DW constitutes 60% of total water withdrawals in Qatar. The agricultural sector is the most water demanding sector consuming about 91% of all RWRs and 35.2% of TSE. Groundwater quality is also deteriorating because of salts from irrigation water being recycled and the presence of reasonably high levels of Mo (that may pose some health risks in the future). TSE is mainly utilized for agriculture and domestic purposes but is one of the key water sources for reducing water shortage in Qatar. Water consumption by industries is dominated by the petrochemicals and refining sectors; 68.4% and 14.7% of the total industrial water consumed, respectively. We also concluded that desalination, although expensive and energy-intensive, is the only viable solution for Qatar currently. However, it is recommended to adopt the SWRO desalination process over thermal desalination because of its higher energy efficiency.

This paper also reviewed Qatar's water footprint by calculating the virtual water flow. It was concluded that Qatar is a net virtual water importer. On average, Qatar imports 1.35 billion m^3 of virtual water per year. This has important policy implications which should take into account virtual water trade as a major factor in achieving water and food security. The findings of this review highlight that great efforts must be put on the conservation of water resources. Conservation is highly effective as it targets the demand side and thus has the potential to reduce the impact on current water resources. A number of promising water conservation methods have been implemented by Qatar such as the TARSHEED campaign by Kahramaa and the recent regulations that impose fines on improper water usage in the domestic sector. Among its achievements is the implementation of district cooling and public parks irrigation using TSE. These initiatives should be further developed and monitored to create a sense of awareness and responsibility among Qatar's residents.

We recommend that the water conservation efforts in Qatar should follow an integrated approach taking into account supply as well as demand side management. The focus should be on minimizing demand as it less costly than building new water desalination capacities. Furthermore, TSE should be utilized more effectively and at a larger scale for non-potable use. Future work that will further complement this review paper will be to focus on integrated water resources management for Qatar and the structure of new water tariff. In addition, it will be highly important to focus on institutional and policy aspects of water resources management. More indepth research should be carried out to develop the SWRO process and reduce its water unit cost as well as optimize the feedwater pretreatment processes.

The review highlighted key questions about the effectiveness of imposing a revised water tariff in Qatar especially on Qataris and the important role of societal considerations in formulating a new water tariff. Moreover, comparisons between Qatar and other countries in terms of water tariff must take into consideration Qatar's unique situation: a small population and scarce RWRs. Demand side management and the use of efficient piping and water faucets are useful water conservation tools that should be adopted.

References

[1] The World Bank, World Development Indicators, 2014. Available at: http://databank.worldbank.org/data//reports.aspx?source=2&country=QAT&series=&period=# (Accessed February 2016).

[2] Ministry of Development Planning and Statistics, Qatar Population Number, 2017. Available at: http://www.mdps.gov.qa/en/pages/default.aspx (Accessed May 2017).

[3] Qatar General Secretariat for Development Planning, Qatar National Development Strategy 2011–2016, Doha, Qatar, 2011. Available at: http://www.mdps.gov.qa/en/knowledge/HomePagePublications/Qatar_NDS_reprint_complete_lowres_16May.pdf

[4] A. AlMamoon, N.E. Joergensen, A. Rahman, H. Qasem, Derivation of new design rainfall in Qatar using L-moment based index frequency approach, Int. J. Sustain. Built Environ., 3 (2014) 111–118.

[5] M.A. Darwish, Desalination Engineering, Balaban Desalination Publications, Hopkinton, 2015.

[6] The World Bank, Average Monthly Temperature and Rainfall for Qatar from 1960-1990, 2009. Available at: http://sdwebx.worldbank.org/climateportal/index.cfm?page=country_historical_climate&ThisRegion=Middle East&ThisCCode=QAT (Accessed April 2017).

[7] Ministry of Development Planning and Statistics, Water Statistics in the State of Qatar, Doha, 2013.

[8] Food and Agriculture Organization of the United Nations (FAO), AQUASTAT Database, 2015. Available at: http://www.fao.org/nr/water/aquastat/countries_regions/QAT/index.stm (Accessed April 2017).

[9] N. Saab, Ecological Footprint of Arab Countries, Beirut, Lebanon, 2012.

[10] Qatar Electricity and Water Corporation (Kahramaa), Efficiency of Water Resources Management for Various Consuming Sectors in Qatar, 11th Gulf Water Conference, Muscat, 2014. Available at: http://www.wstagcc.org/.../Qatar-water-management-efficiency.pdf

[11] A. Al-Muraikhi, Ground Water in Qatar, 10th Gulf Water Conference, Ministry of Environment, Doha, 2012. Available at: http://www.wstagcc.org/.../S3A_L6_GW_Qatar_Al-Muraikhi.pdf

[12] M.A. Darwish, H.K. Abdulrahim, Y. Mohieldeen, Qatar and GCC water security, Desal. Wat. Treat., 55 (2015) 2302–2325.

[13] United Nations Development Programme, Water Governance in the Arab Region, Managing Scarcity and Securing the Future, New York, 2010.

[14] Food and Agriculture Organization of the United Nations (FAO), Aquastat Database (n.d.). Available at: http://www.fao.org/nr/water/aquastat/water_res/index.stm (Accessed August 2016).

[15] Ministry of Environment, Studying and Developing the Natural and Artificial Recharge of the Groundwater Aquifer in the State of Qatar, Doha, 2009.

[16] DAWR – Department of Agricultural and Water Research, Groundwater Data and Balance, 2006. Available at: http://www.fao.org/nr/water/aquastat/data/wrs/readPdf.html?f=WRS_QAT_en.pdf (Accessed August 2016).

[17] G.N. Tiwari, R. Tripathi, Present status of solar distillation, Sol. Energy, 75 (2003) 367–373.

[18] Qatar General Electricity and Water Corporation (Kahramaa), Statistics Report, Doha, 2014.

[19] Global Water Intelligence, Contracted and Online Capacities with the Population Trend in Qatar, Oxford, 2013.

[20] M. Darwish, A.H. Hassabou, B. Shomar, Using Seawater Reverse Osmosis (SWRO) desalting system for less environmental impacts in Qatar, Desalination, 309 (2013) 113–124.

[21] M.A. Darwish, H. Abdulrahim, S. Mohammed, R. Mohtar, The role of energy to solve water scarcity in Qatar, Desal. Wat. Treat., 57 (2016) 18639–18667.

[22] S. Abdel-Dayem, D. Al Saiid, Water Reuse in the Arab World: From Principle to Practice, Wastewater Management in the Arab World Expert Consult, Dubai, UAE, 2011.

[23] Ministry of Development Planning and Statistics, Environmental Statistics Report 2013, Doha, 2013.

[24] K. Seghers, Online Article: Water Treatment Plants (n.d.). Available at: http://www.keppelseghers.com/en/content.aspx?sid=3027 (Accessed April 2017).

[25] The World Bank, Renewable Energy Desalination: An Emerging Solution to Close the Water Gap in the Middle East and North Africa, Washington, D.C., USA, 2012.

[26] M. Darwish, H. Abdulrahim, A.S. Hassan, Realistic power and desalted water production costs in Qatar, Desal. Wat. Treat., 57 (2015) 1–7.

[27] T.M. Missimer, R.G. Maliva, N. Ghaffour, T. Leiknes, G.L. Amy, Managed aquifer recharge (MAR) economics for wastewater reuse in low population wadi communities, Kingdom of Saudi Arabia, Water, 6 (2014) 2322–2338.

[28] W. Immerzeel, P. Droogers, W. Terink, J. Hoogeveen, P. Hellegers, M. Bierkens, R. Van Beek, Middle-East and Northern Africa Water Outlook, Wageningen, 2011.

[29] F. Trieb, Concentrating Solar Power for Seawater Desalination, Aqua-CSP Study Report, Stuttgart, Germany, 2007.

[30] N. Kuiper, C. Rowell, B. Shomar, High levels of molybdenum in Qatar's groundwater and potential impacts, J. Geochem. Explor., 150 (2015) 16–24.

[31] D. AlRukaibi, Water Resources of GCC Countries, 2010. Available at: http://www.ce.utexas.edu/prof/mckinney/ce397/Topics/Gulf/Gcc_2010.pdf

[32] B. Shomar, M. Darwish, C. Rowell, What does Integrated Water Resources Management from local to global perspective mean? Qatar as a case study, the very rich country with no water, Water Resour. Manage., 28 (2014) 2781–2791.

[33] M. Nagy, Structure and Content of the Environment Statistics Report 2013, Lessons Learnt and Data Shortcomings, Environment Statistics Work, 2013. Available at: http://www.qsa.gov.qa/eng/Activities/EnvironmentWorkshop2013/3_Report_Structure_MN.pdf

[34] K. El Emadi, G.A. Kerim, H. El Emadi, Public Works Authority Apply Sustainable Developments Concept with Sewerage Works, Qatar, 2014. Available at: http://wstagcc.org/en/wp-content/uploads/sites/2/2014/05/S6_L7_public-works-authority_Elemadi.pdf (Accessed April 2017).

[35] Qatar Petroleum Health Safety and Environment Regulations and Enforcement Directorate, Ministry of Energy and Industry, Sustainability in the Qatar Energy and Industry Sector, Doha, 2013.
[36] Gulf Petrochemicals and Chemicals Association, The Economic Benefits of Chemistry in Qatar, 2014. Available at: http://www.gpca.org.ae/qatar/ (Accessed April 2017).
[37] J.A. Allan, The Middle East Water Question: Hydropolitics and the Global Economy, I.B. Tauris, London, New York, 2002.
[38] T. Allan, Virtual Water: Tackling the Threat to Our Planet's Most Precious Resource, I.B. Tauris, London, New York, 2011.
[39] D. Wichelns, The role of "virtual water" in efforts to achieve food security and other national goals, with an example from Egypt, Agric. Water Manage., 49 (2001) 131–151. doi:10.1016/S0378-3774(00)00134-7.
[40] A.E. Ercin, M.M. Mekonnen, A.Y. Hoekstra, Sustainability of national consumption from a water resources perspective: the case study for France, Ecol. Econ., 88 (2013) 133–147.
[41] M.M. Aldaya, A.Y. Hoekstra, The water needed for Italians to eat pasta and pizza, Agric. Syst., 103 (2010) 351–360.
[42] A. Garrido, P. Novo, R. Rodriguez Casado, C. Varela-Ortega, Can Virtual Water "trade" Reduce Water Scarcity in Semi-Arid Countries? The Case of Spain, 2009, pp. 1–18. http://purl.umn.edu/51048.
[43] Ministry of Development Planning and Statistics, National Accounts Bulletin – 2015, Doha, Qatar, 2015.
[44] Ministry of Development Planning and Statistics, Labour Force Sample Survey – 2014, Doha, Qatar, 2014.
[45] Ministry of Environment, Agricultural Statistics Bulletin – 2014, Doha, Qatar, 2014.
[46] S. Mohammed, M.A. Darwish, Water footprint and virtual water trade in Qatar, Desal. Wat. Treat., 66 (2017) 117–132.
[47] A.Y. Hoekstra, P.Q. Hung, Globalisation of water resources: international virtual water flows in relation to crop trade, Global Environ. Change, 15 (2005) 45–56.
[48] M.M. Mekonnen, A.Y. Hoekstra, The green, blue and grey water footprint of crops and derived crop products, Hydrol. Earth Syst. Sci., 15 (2011) 1577–1600.
[49] M.M. Mekonnen, A. Hoekstra, The Green, Blue and Grey Water Footprint of Farm Animals and Animal Products, UNESCO-IHE Institute for Water Education, The Netherlands, 2010.
[50] J.F. Schyns, A. Hamaideh, A.Y. Hoekstra, M.M. Mekonnen, M. Schyns, Mitigating the risk of extreme water scarcity and dependency: the case of Jordan, Water, 7 (2015) 5705–5730.
[51] A.Y. Hoekstra, The water footprint of humanity, Proc. Natl. Acad. Sci. USA, 109 (2011) 3232–3237.
[52] I. Arto, V. Andreoni, J.M. Rueda-cantuche, Global use of water resources: a multiregional analysis of water use, water footprint and water trade balance, Water Resour. Econ., 15 (2016) 1–14.
[53] A. Hoekstra, P.Q. Hung, A Quantification of Virtual Water Flows Between Nations in Relation to International Crop Trade, IHE Delft Institute for Water Education, The Netherlands, 2002.
[54] G. Nelson, M. Rosegrant, J. Koo, R. Robertson, T. Sulser, T. Zhu, C. Ringler, S. Msangi, A. Palazzo, M. Batka, M. Magalhaes, R. Valmonte-Santos, M. Ewing, D. Lee, Climate Change: Impact on Agriculture and Costs of Adaptation, Washington, D.C., USA, 2009.
[55] N. Arnell, T. Wheeler, T. Osborne, G. Rose, S. Golsing, T. Dawson, A. Penn, A. Perryman, The Implications of Climate Policy for Avoided Impacts on Water and Food Security. Work Stream 2, Report 6 of the AVOID Program (AV/WS2/D1/R06), London, 2010.