Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2014.947782

55 (2015) 2302–2325
August

Qatar and GCC water security

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Received 13 March 2014; Accepted 16 June 2014

ABSTRACT

The significant wealth in natural gas and oil makes Qatar the country of the highest income per capita in the world. Meanwhile, Qatar is among the world's poorest countries in natural fresh water resources. The water scarcity severely limits agriculture food production. Agriculture in Qatar depends mainly on the over-exploited, depleted, and quality deteriorated ground water (GW). The use of GW for agriculture cannot be continued. Water scarcity is the main obstacle to achieve the food self-sufficiency. The possibility of using Qatar's abundant energy to generate desalted seawater or wastewater treatment for agriculture purposes is thought by many. This possibility is studied in this paper, along with the interdependent relation between water, energy, and agriculture (and thus food).

Keywords: Water resources; Groundwater; Wastewater; Desalination; Multi-stage flash; Reverse osmosis; Natural gas; Oil; Renewable energy; Food; Agriculture; Cereal

1. Introduction

The significant wealth in natural gas (NG) makes Qatar the country of the highest income per capita in the world. The fast economic growth created by the discovery and exporting of prime energy resources (oil and NG) resulted in rapid urbanization, population growth, and rising standard of living. These increase the water and energy demands and put pressures on the country's energy and water resources. Qatar's populations increased from 0.73 M in 2004 to close to 2.1 M in 2014 (Fig. 1, Qatar Population) [1]. The Qatar Statistics Authority reported that 2,035,106 people were estimated to be in Qatar as of 30 September 2013. This is compared with 0.62 M in January 2001, more than three times in 10 years. Water and power consumptions increased by the increase in population and standard of living, expressed by the gross domestic product (GDP). Qatar GDP increased from 43 Billion (B) USD in 2006 to 183.4 B-USD in December 2012 (Fig. 2, Qatar GDP) [2]. The GDP measures national income and output for a given country's economy. The GDP is equal to the total expenditures for all final goods and services produced within the country in a stipulated period of time.

Meanwhile, Qatar is in an arid land, one of the world poorest countries in natural freshwater resources. The acute water scarcity is resulted from:

(1) Low levels of rainfall (82 mm/year) with high rate of evaporation (2,000 mm/y), Figs. 3a and 3b.

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Presented at the Conference on Desalination for the Environment: Clean Water and Energy 11–15 May 2014, Limassol, Cyprus

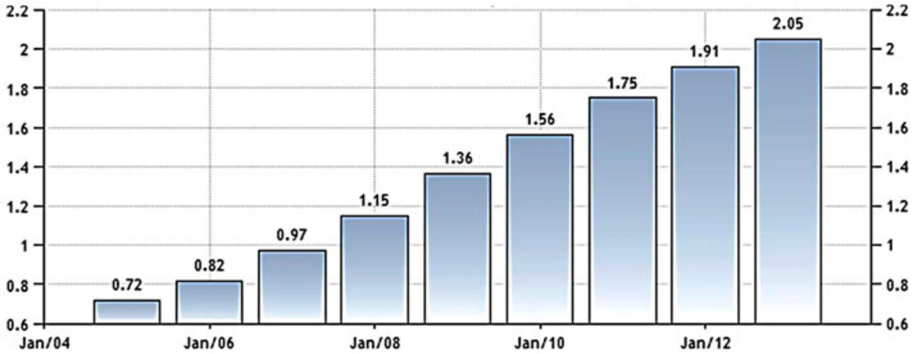

Fig. 1. Qatar historic population increase in millions of people [1].

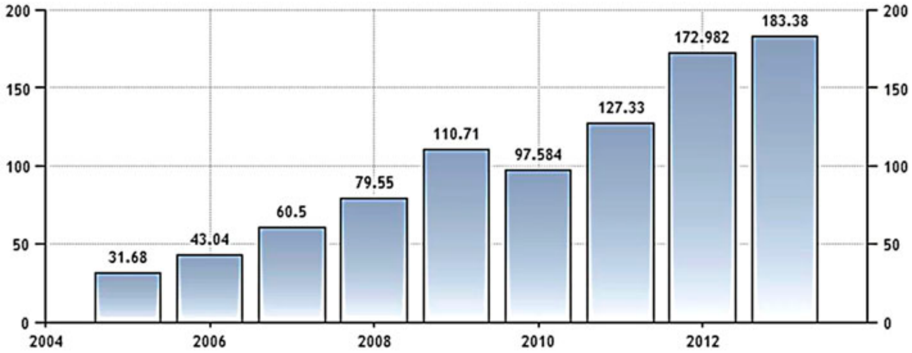

Fig. 2. Qatar's GDP history in billions of US dollars, Qatar GDP [2].

(2) Low Groundwater (GW) replenishment rate of 58 million cubic meters per year (Mm^3/y) (Fig. 4, Water Governance) [3].

The estimated population of 2.1 M in 2014 gives an average natural water resource of less than 29 cubic meters per year per capita ($m^3/y.ca$). This is far below the worldwide average of 6,000 $m^3/y.ca$, and the

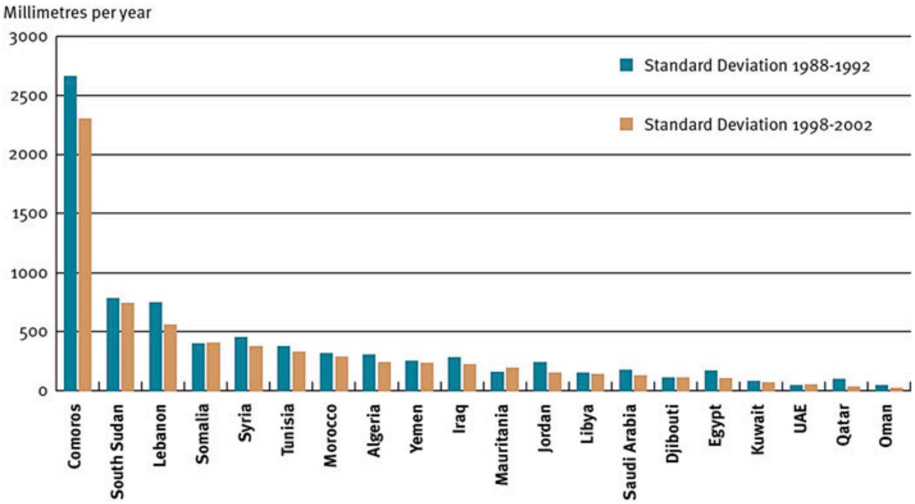

Fig. 3a. National rainfall index for Arab countries, standard deviations for 1988–1992 and 1998–2002 [3].

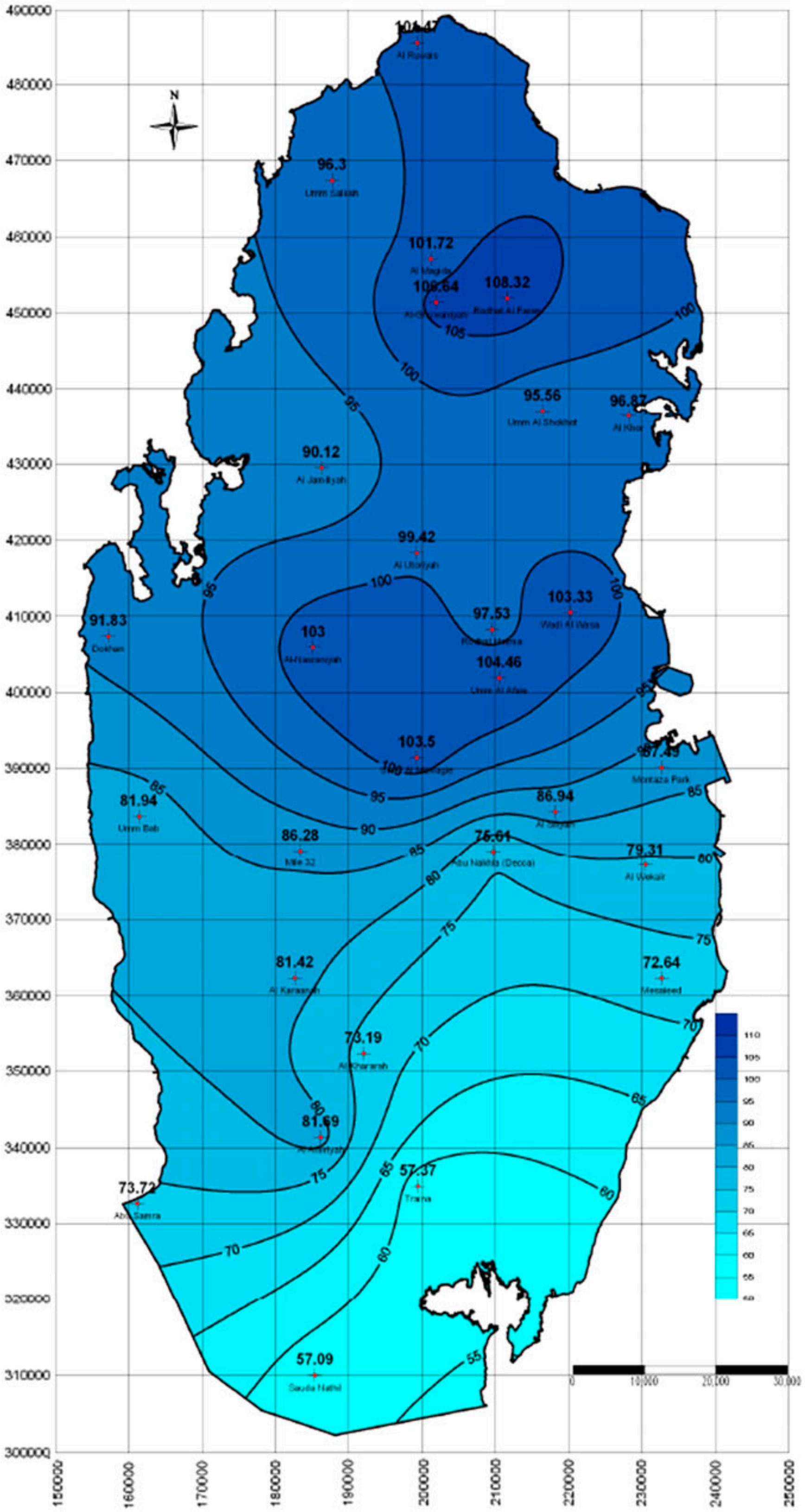

Fig. 3b. Average annual rainfall between 1989 and 2007.

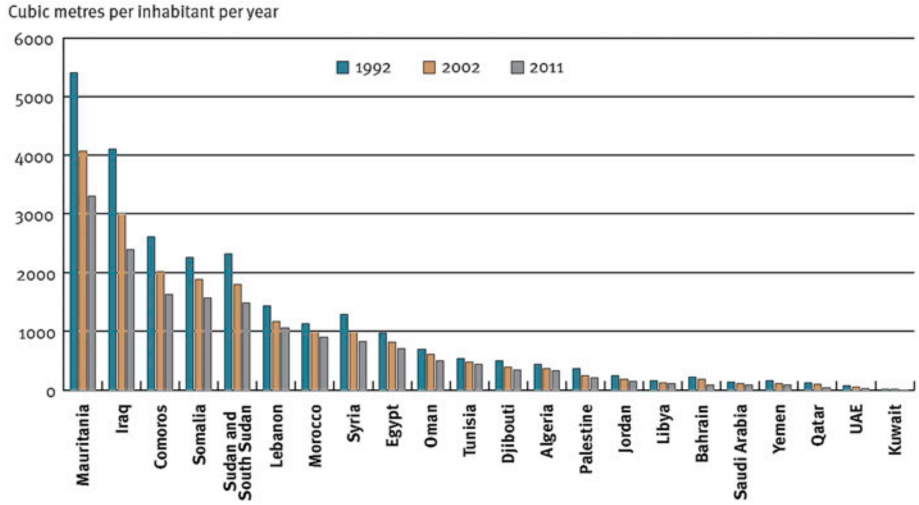

Fig. 4. Total renewable water resources, 1992, 2002 and 2011 in m^3/y.ca [3].
Source: FAO 2013.

recognized water poverty line of 1,000 m^3/y.ca, see Table 1 [4]. Fig. 4 shows that Kuwait, United Arab Emirates (UAE), and Qatar have the lowest annual renewable water sources per capita in all the Arab countries, and among the poorest in the whole world.

The rainfall index in Fig. 3a measures the variation of total annual precipitation from the long-term average for 1986–2000, FAO 2013.

Qatar water needs are far beyond its natural water resources. The severe water shortage impacts the national development, while endangers water and food securities, and environment. Desalted seawater (DW) is largely used to meet its water needs using the available NG as fuel to run the co-generation power-desalting plants. Qatar desalting capacity became one of the 10th highest in the world, as given in Table 2, Global Desalination Capacity, World Water [5].

DW accounts for about half the water used in the country, and account to almost all (99%) of municipal water requirement. Fig. 5 shows the present and projected desalting seawater capacity in Qatar as given by Qatar National Strategy 2012–2016 [6].

Desalination plants in Qatar are vulnerable to unforeseen conditions such as oil spills that can force desalting plants to shut down. This factor, besides the inefficiency of the used desalting methods, threatens the water security or requires large investments to ease shortages [1]. The continuous growing water demands are met by building more desalting plants, and more NG consumption. The desalination plants

Table 1
Threshold values: water stress within a region (cubic meters per year) [4]

Characteristics	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	>1,700–4,000	Water sufficient to meet the present needs of the economy
Water stress	<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 the demand for all other uses
Water stress	>20%	Severe water supply problems, reusing waste water, over-exploiting aquifers (by 2–30 times), desalinating seawater

Table 2
The top 10 seawater desalination countries by online capacity [5]

Country	Commissioned SW desalination capacity (m^3/d)
Saudi Arabia	9,170,391
UAE	8,381,299
Spain	3,781,314
Kuwait	2,586,761
Algeria	2,364,055
Australia	1,823,154
Qatar	1,780,708
Israel	1,532,723
China	1,494,198
Libya	1,048,424

capacity reached 325 million imperial gallons per day (MIGD), or 1.478 Mm^3/d in 2010, reported to be 1.9 Mm^3/d in 2013, and still there are plans to invest heavily in further desalination facilities.

Kahrama invested in water storage construction activity, undertaking a US$2.8 B (QR 11 B) reservoir project capable of holding seven days of DW as a backup for DW supply. The 1.9 B gallon 8.65 Mm^3 facilities will include a network of reservoirs connected by 183 km, 2.5 m wide pipeline linking the Ras Laffan desalination facility in Qatar's north and the Ras Abu Fontas plant in the south.

It is questionable that building more desalting plants is a sustainable solution to face the rising water demands in view of the substantial economic and environmental costs of desalination; the increase of the fossil fuel cost; even though, it is abundant now. Building more desalting capacity should not be the only solution to tackle water scarcity and to ensure the water security. Qatar water security is critical, and this is about ensuring every person reliable access to safe water at an affordable price to lead a healthy, dignified, and productive life, while maintaining the ecological systems that both provide and depend on water. Water security is further threatened by Qatar's harsh and fragile environment (high temperature, low rainfall, and low nutrient availability in the soil). Beyond meeting basic human needs, water is necessary for agriculture and for many industrial processes.

The Gulf Co-operating Countries (GCC) are following the same approach of building more desalting seawater plants, which is energy- and capital-intensive process to meet the rising water demands. While DW reduces pressure on water resources, it has negative air and marine environmental effects. This problem can be mitigated by water supply and demand managements.

In this paper, the conventional (GW) and nonconventional (DW and treated wastewater [TWW]) water resources are presented; and more sustainable solutions to solve Qatar water problem are discussed.

2. Qatar conventional water resources—ground water

Qatar's annual rain fall is low, about 82 mm/y, while natural evaporation rate is 2,000 mm/y, and thus rainfall is not a real water resource in Qatar (Figs. 3a and 3b). The GW is the main natural water resource in Qatar. The GW has low replenishment rate of 58 Mm^3/y. As of 2014, the average per capita is less than 29 $m^3/(y.ca)$. This is far below the worldwide

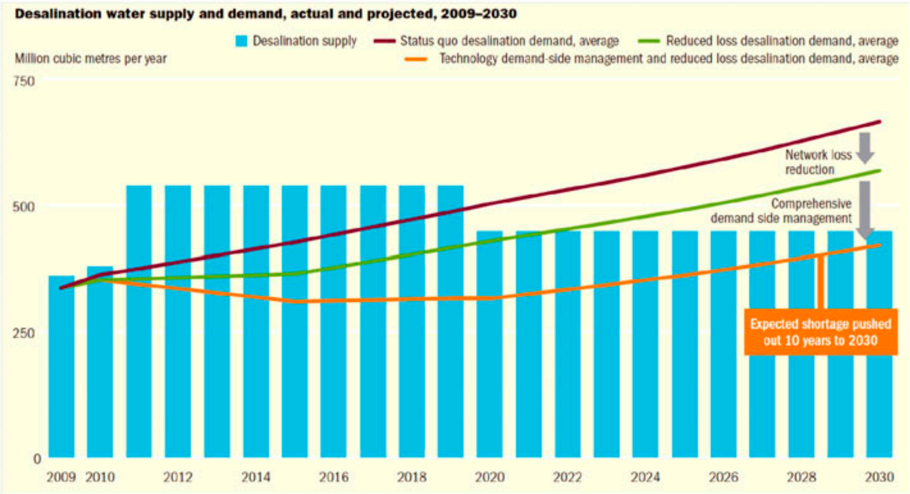

Fig. 5. Qatar desalination present and projected capacities, Qatar National Strategy 2012–2016 [6].

average of 6,000 m^3/y.ca, and recognized water poverty line of 1,000-m^3/y.ca, as given before. Table 1 classifies world regions according to the available renewable water resources, as regions with water surplus, water abundant, adequate water stress, water scarcity, absolute water stress, and minimum survival level. The table shows that the GCC region is within minimum survival level with renewable water resources less than 100 m^3/y.ca.

The annual 58 Mm^3/y estimated renewable water in Qatar and the 29 Mm^3/y.ca (in 2014) are far below the annual GW withdrawal rates. The withdrawals in 2012 were estimated by 400 Mm^3/y. These include 236 Mm^3/y for agriculture, 8 Mm^3/y for industry, and 156 Mm^3/y for domestic uses. The withdrawal increased from 56.4 Mm^3/y in 1976 to 100 Mm^3/y in 1983 to 272 Mm^3/y in 2000 to 248 Mm^3/y in 2009, and was reported as 400 Mm^3/y in 2012, (almost 7 times replenishment rate). Table 3 gives the GW withdrawal in 2009, and the specific use of these waters, MoE final GW report [7].

The historical GW withdrawal and the number of wells are given in Fig. 6. The over-abstraction beyond the replenishment rate drastically reduces the area underlain by fresh water (<1,000 ppm), and good brackish water (2,000–3,000 ppm) as shown in Fig. 7. The freshwater lens that is accumulated in the northern-central part of Qatar has declined in area, which represented 15% of the country's area in 1971 to become 2% in 2008. The fresh water lens in 2009 was approximately 11% of its size in 1971, and continues its shrinkage.

Table 3
Qatar 2009 GW withdrawal and its usage, MoE final GW report [7]

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

The total dissolved solids (TDS) in GW, based on the specific conductivity measurement is shown in Fig. 8. Historical TDS map from 1971 to 2003 is given in Fig. 9a, and for 2009 is given in Fig. 9b.

The areas of fresh water and GW that are suitable for irrigation are declining as shown in Fig. 7. Fig. 7 indicates that the total area of fresh water (TDS < 1,000) has reduced by nearly 80% between 1982 and 2008 (from 1,278 to 275 km^2). For the same period, the area of brackish water, with TDS between 1,000 and 2,000 ppm, has been reduced by nearly 45% (from 1,785 to 1,025 km^2), whereas the brackish water (TDS 2,000–3,000 ppm) has been reduced by 20%. Table 4 shows the changes in area underlain by fresh water and low salinity brackish water from 1971 to 2009. It shows that, based on current withdrawal, fresh GW

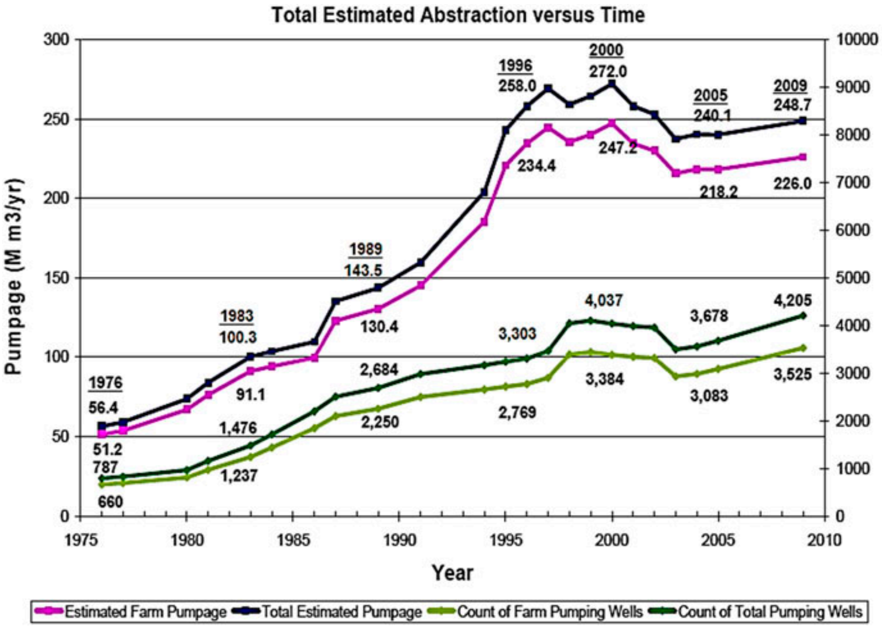

Fig. 6. Qatar farming and total GW abstraction, and number of wells from 1977 to 2009, MoE final GW report [7].

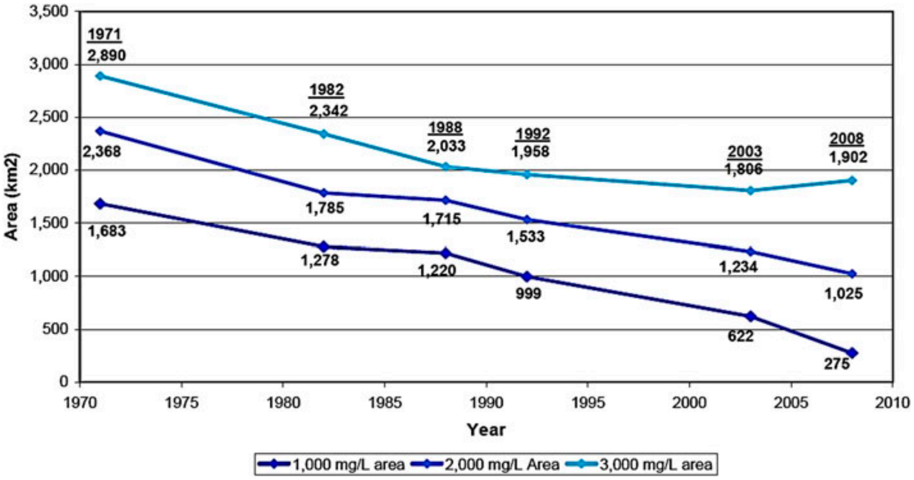

Fig. 7. Area underlain by fresh water (<1,000 ppm) and good brackish water (2,000–3,000 ppm) in North Qatar, 1971–2008, MoE final GW report [7].

will completely disappear within four years from now. Fig. 6 shows that the 1977 GW abstraction was almost equal to the natural replenishment rate with country's self-sufficiency by natural water resources in that year.

It is worth noticing that water with TDS between 1,500 and 3,500 ppm could be harmful to plants, while at TDS = 3,500 ppm, water is unsuitable for irrigation.

The main reason in Qatar for high GW withdrawal is that it is freely available for extraction. Farmers pay only pumping costs, and the prices of diesel and electricity are very little. The farmers are not feeling the urgency of water conservation and management. Consequently, the pressure on water resources continues, and the reserves of GW are steadily being reduced. This not only results in the depletion of GW resources but also in deterioration of water quality and the abandonment of some farms (Fig. 10). Since this water is later deployed for irrigation and other agricultural uses, it increases the salinity of the soil. Substantial parts of GW reserves show salinity levels above what is considered suitable for irrigation. The brine produced by certain farm processes is discharged back into the ground, raising the salinity of the remaining GW.

Fig. 9c shows the GW table potentiometric surface map in 2009; and Fig. 9d shows the change in water table level of the GW between 1980 and 2009. The figure shows that the water table in the North of Qatar is lowering due to over-exploiting of GW. However in South Qatar (around Doha), the water table is increasing due to leakage from Kahramaa's clean water distribution network and leakage from Ashghal's sewage collection network, see Fig. 11. Fig. 9c was created from the 1980 and 2009 potentiometric iso maps. Geo-statistical techniques were used to model the potentiometric surfaces of 1980 and 2009, and the change was then calculated.

The situations in the GCC are very similar as shown in Tables 5–7 [9], where GW natural resources are limited (far below the poverty line) and withdrawals are far beyond replenishment rates. The renewable water per capita (in m^3/y.ca) for several GCC were decreased between 2002 and 2010 as: 164 to 92 in Bahrain, 8–7 in Kuwait, 88–33 for Qatar, 102–87 in Saudi Arabia (SA), 51–20 in UAE, and 212–87 in Yemen [10]. This is mainly due to continuous population increase, for the same water resources.

SA suffers the biggest gap between renewable supply and demand: it has only 2.4 annual renewable water resources in cubic kilometers (km^3/y), yet they extracted 23.67 km^3/y. Many farms in Qatar and UAE stopped farming [11]. There are around 8,000 farms abandoned (or near abandoned) out of 24,000 farms in Abu Dhabi and the Western Region of the UAE, and Al Ain in UAE. Concerns have been growing about the amount and quality of GW.

The fossil GW is a finite and irreplaceable once being mined. Mining GW may be beneficial in the short term; but it is real loss in the longer term as this water should be considered as the country national wealth. The GW resources should be protected from excessive use by:

(1) Stopping mining of the GW.
(2) The use of GW for irrigation should be replaced by reclaimed wastewater (WW) of proper treatment for irrigation usage which is a common practice worldwide.

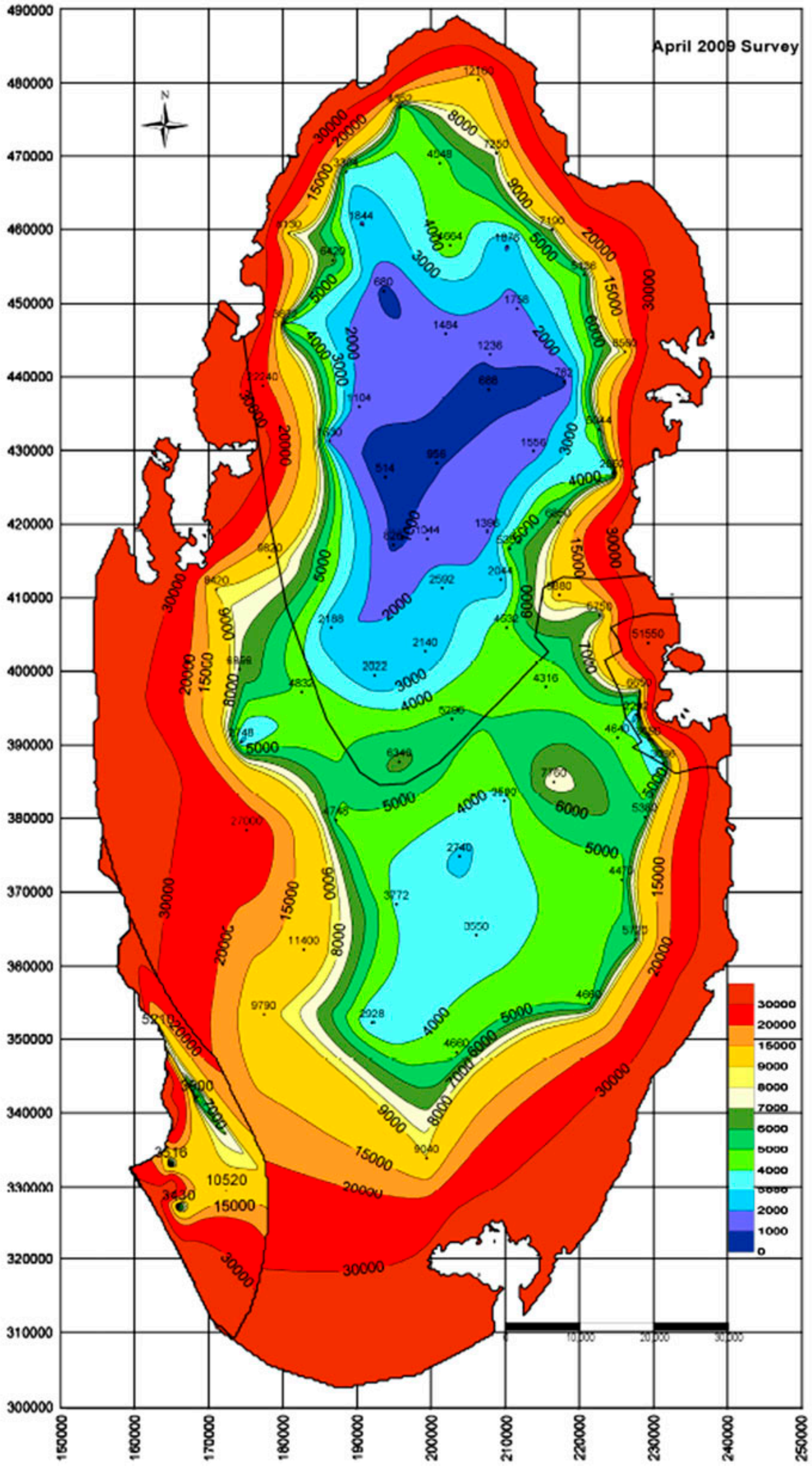

Fig. 8. TDS iso concentration map, MoE final GW report [7].

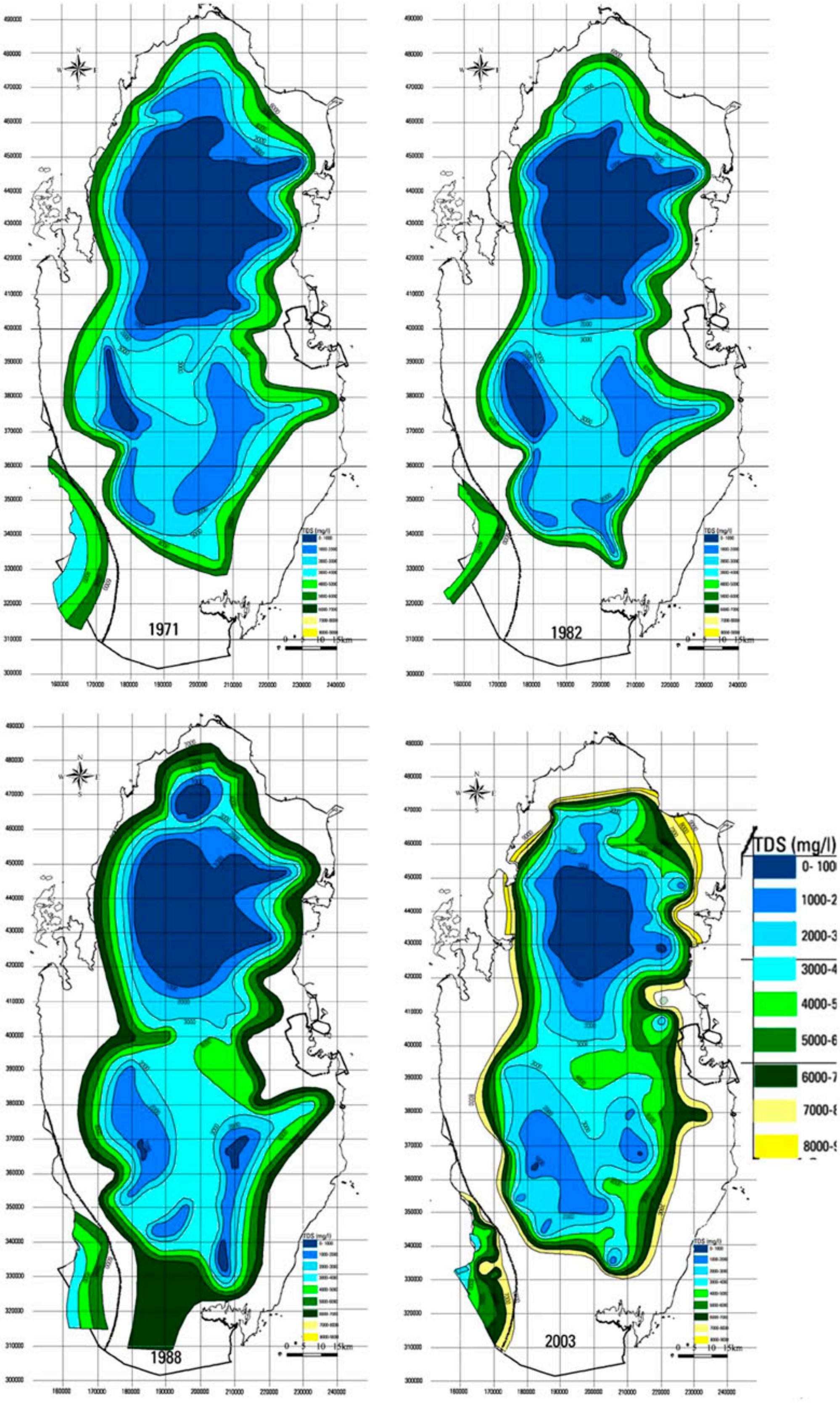

Fig. 9a. Historic TDS in ground water map between 1971 and 2003, MoE final GW report [7].

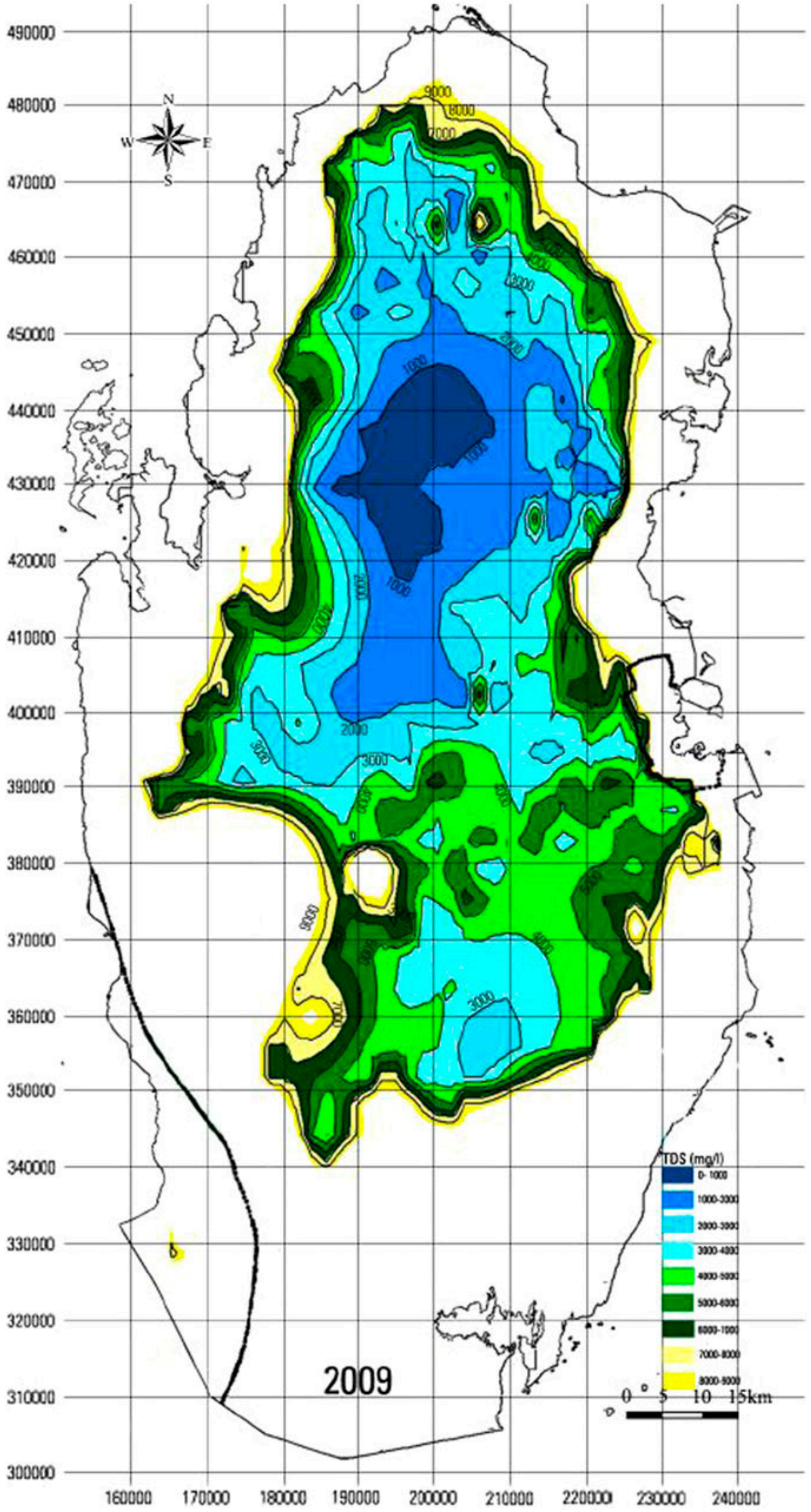

Fig. 9b. TDS in ground water map in 2009, Qatar GW Report [7].

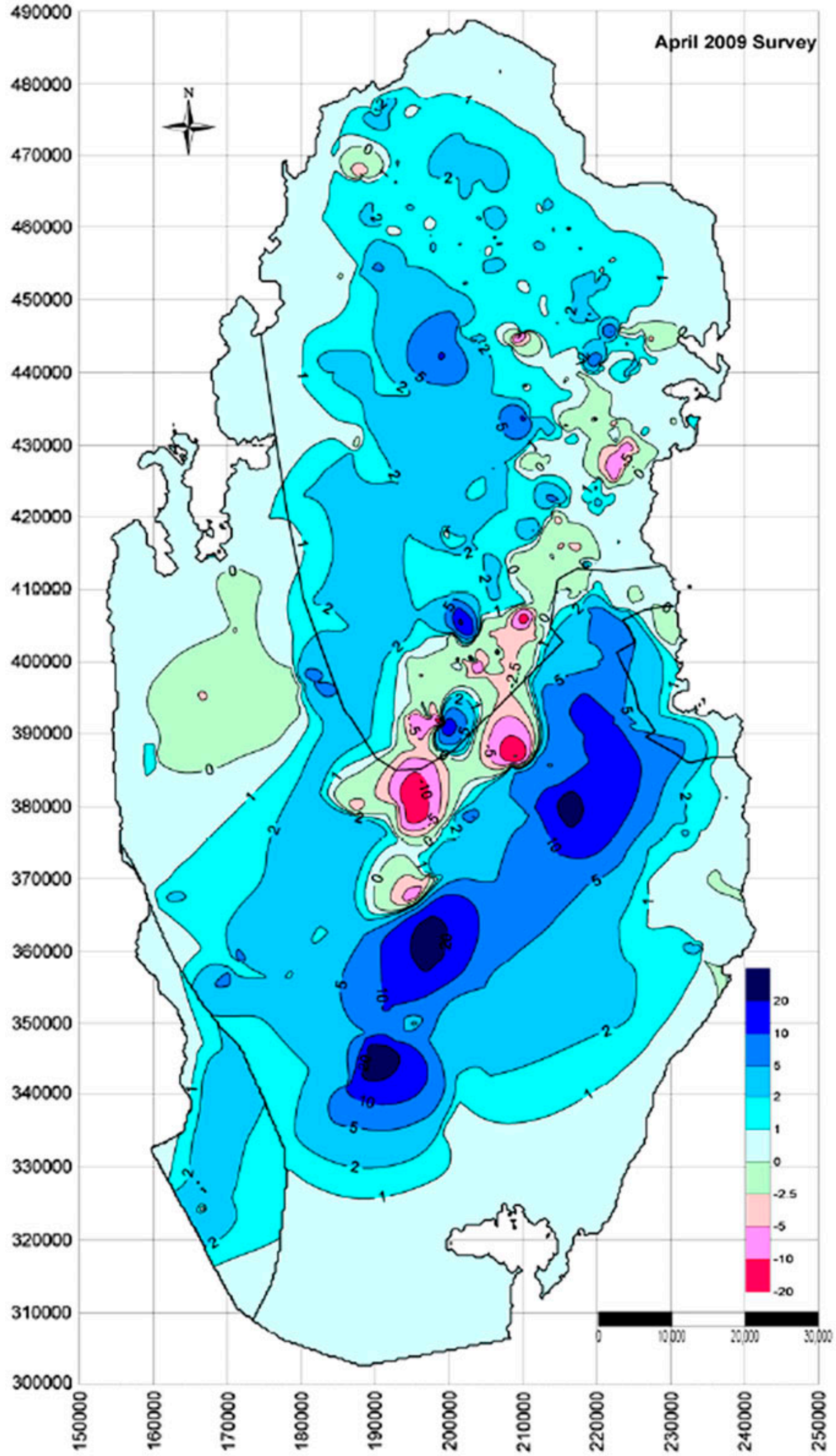

Fig. 9c. Potentiometric surface map.

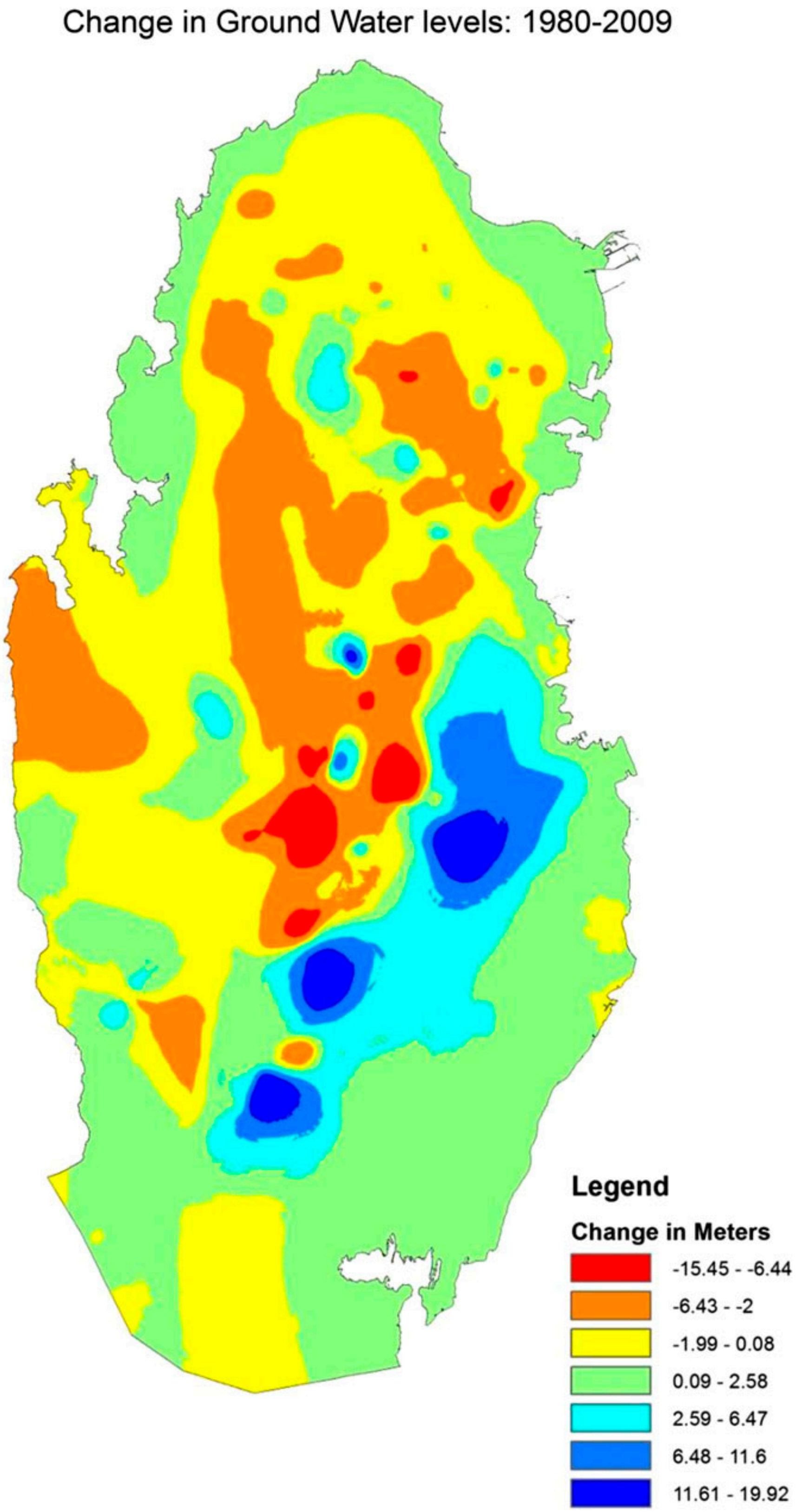

Fig. 9d. Change in GW level between 1980 and 2009. Source: Mohieldeen unpublished work [8].

Table 4
Changes in area underlain by fresh water and low salinity brackish water, 1971–2009, MoE final GW report [7]

	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
1971 % of country area	15	21	25
2009 area (km^2)	186	897	1,782
2009 % of country area	2	8	16
2009 % of 1971 area	16	43	66
Projected year to reach zero area	2018	2037	2056
Year remaining	4	13	42

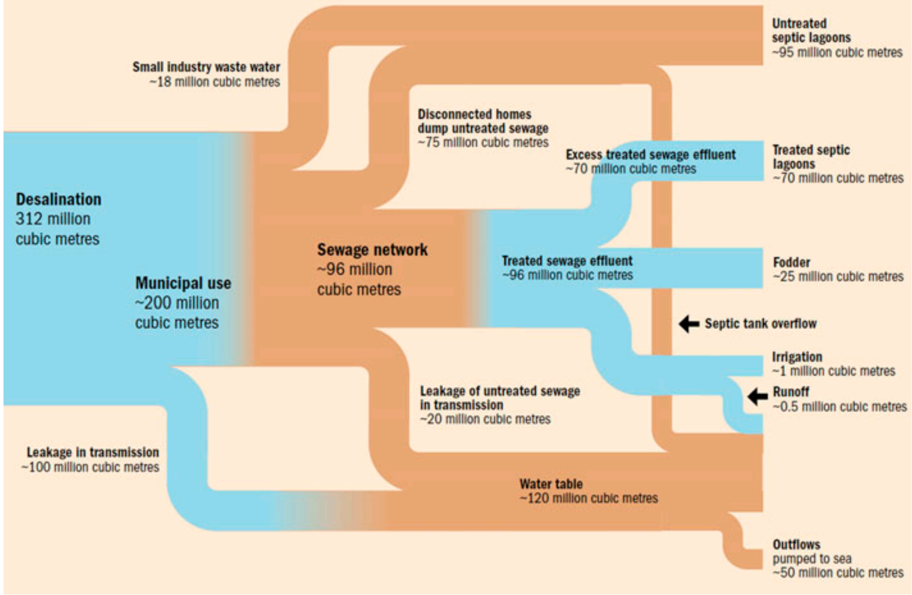

Fig. 10. Produced and wastewater leakage into the water table in 2008 [6].

The GW should be recharged to balance the water deficit by injected clean water (such as DW, or treated waste water of potable quality, and harvested rainfall). These waters can be used also as strategic water storage. GW aquifers can certainly provide natural strategic water storage. Recharging GW aquifers with reclaimed WW of potable quality is an approach to WW reuse that results in the planned augmentation of GW sources. The benefits of artificial recharge of GW utilizing WW include:

1. Stopping the decline of GW levels due to excessive GW withdrawal;
2. Protecting coastal aquifers against saltwater intrusion from the sea;
3. Storing water for future use; and
4. GW recharge also occurs incidentally/naturally in the process of municipal and industrial WW disposal via infiltration.

3. Non-conventional water resource (desalination)

Qatar scarcity of renewable water resources, escalating demands for water, and securing fresh-water mainly by DW are major challenges. Qatar annual DW production increased from 178 Mm^3/y in 2004 to 373 Mm^3/y in 2010, (almost doubled in six years or 14% annual increase) and is expected to reach 480 Mm^3/y in 2014. This is based on 6.5% average annual increase, Qatar National Strategy [6] expected annual increase of 5.4% for national and 7% for expatriates or 1.32 Mm^3/d. Qatar and all GCC are increasingly relying on desalting seawater, which is energy- and capital-intensive process. While DW satisfies fresh water demands, it is negatively affecting the environment. The high rate of consumed energy by desalination contributes highly to air and marine pollutions. The concentrate (at higher temperature and salt concentration compared with those of the Gulf)

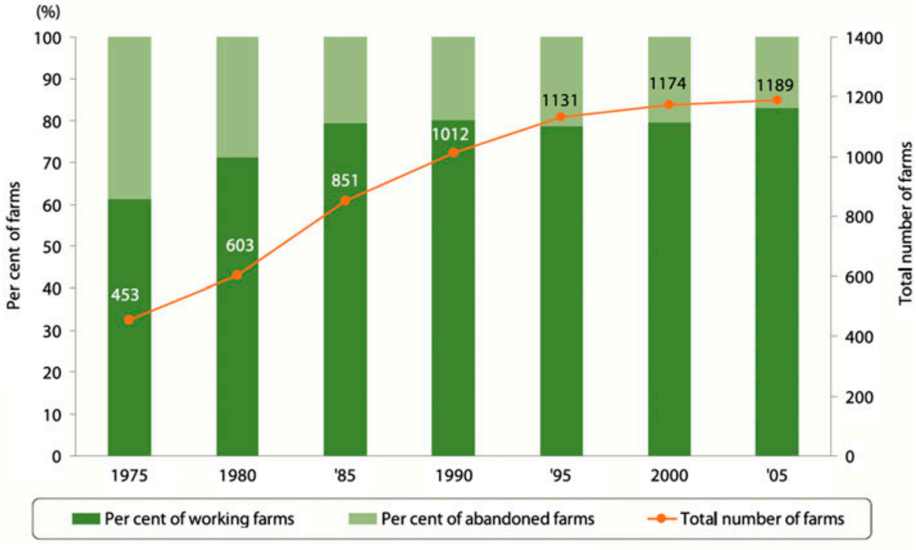

Fig. 11. Rising number of farms in Qatar with the proportion of abandoned farms stabilizing [6].

Table 5
Renewable water resources and per capita share in the GCC [9]

		Average annual share (m^3/capita)		
Country/sub-region	Natural water resources (M m^3)	2010	2030	2050
Bahrain	116	92	70	64
Kuwait	20	7	5	4
Oman	1,400	503	389	374
Qatar	58	33	24	22
Saudi Arabia	2,400	87	62	53
United Arab Emirates	150	20	14	12
GCC	4,144	95	68	59
Yemen	2,100	87	51	34
GCC and Yemen	6,244	92	61	47

Table 6
Water withdrawal and uses of natural water (2009) in GCC [9]

	Million m^3			
Country/sub-region	Withdrawal	Agriculture	Industry	Domestic
Bahrain	400	180	24	196
Kuwait	900	486	18	396
Oman	1,300	1,144	26	130
Qatar	400	236	8	156
Saudi Arabia	23,700	20,856	711	2,133
United Arab Emirates	4,000	3,320	80	600
GCC	30,700	26,222	867	3,615
Yemen	3,600	3,276	72	252
GCC and Yemen	34,300	29,498	939	3,863

Table 7
Water withdrawal in the GCC as percent of annual fresh water resources (2009) [9]

Country/sub-region	All uses (%)	Agriculture use (%)
Bahrain	344.8	155
Kuwait	4,500	2,500
Oman	92.3	82
Qatar	689.6	407
Saudi Arabia	987.5	869
United Arab Emirates	2,666.6	2,213
GCC	740	633
Yemen	171.9	156
GCC and Yemen	549.3	472

and chemical discharges to the marine environment are real threats to marine environment. These can decrease local biodiversity and harm the ecosystem. Moreover, a future rise in the highly saline Persian Gulf sea level is likely to affect natural in-land water resources and further salinized agricultural lands affecting local food security.

DW generated in the GCC has drinking water quality, and may be the only option to secure fresh water, although it is very expensive. Between 2000 and 2009, the desalting added capacity in the GCC was: 325 Mm^3/y in Qatar, 20,439 Mm^3/y in SA, 3,370 Mm^3/y in UAE, 763 Mm^3/y in Oman, 508 Mm^3/y in Kuwait, and 226 Mm^3/y in Bahrain [12]. Dependence on DW is on the rise as shown in Fig. 12 [13]. Presently, 25% of Saudi oil and gas production is used locally to generate electricity and desalt seawater; and this fraction can reach 50% by 2030 [14]. Table 8 gives the GCC estimated DW production in 2012 as 26.937 Mm^3/d. These include 17.245 Mm^3/d by the thermally operated plants used only in the GCC, namely, multi-stage flash (MSF), Fig. 13, and multi-effect thermal vapor compression (ME-TVC), Fig. 14, and 9.690 Mm^3/d by seawater reverse osmosis (SWRO), Fig. 15 as shown in Table 9 [15]. Table 9 gives also the annual cost in billion dollars per year ($B/y). The MSF and ME-TVC consume about four times the energy consumed by the SWRO. By considering the energy cost of the MSF (or the ME-TVC) as $2.4/$m^3$, and the SWRO as $0.6, (this will be explained later), the annual energy cost for DW generated by thermal processes in Qatar is $1.552 billion, and this can be reduced 75% to $0.388 B if the SWRO is used.

The ways to reduce the cost of producing DW are:

(1) First, the more energy efficient SWRO desalting system should be used in place of the predominantly used MSF, and ME-TVC systems.
(2) The use of relatively cheap NG fuel, compared with oil which is extensively used in Kuwait and SA.
(3) The DW quality is high, as well as its cost; and its use should be limited to cooking and drinking, while treated waste water should be used for application that do not need high water quality such as toilet flushing, gardening, etc.

4. Energy used to generate DW

4.1. Energy consumed by MSF desalting system

The calculation of energy consumed by the pre-dominantly used MSF system is shown here by practical example of 6 MIGD capacity MSF units operating in Kuwait. Thermally operated desalting plants such as MSF and ME-TVC require pumping energy for: extraction of seawater from the sea, moving streams inside the unit, brine discharge, and DW distribution. This is besides the need of thermal energy in the form of supplied steam at moderate pressure (2–3 bar). The considered MSF unit has distillate product (D), and is supposed to be supplied by steam (S) determined by the gain ratio, $D/S = 8$ and consumes 280 kJ of thermal energy/kg of

Table 8
The 2012 estimated daily desalted water production in the GCC [15]

Country	Thermal + SWRO + BW (m^3)	Thermal processes (m^3)	SWRO (m^3)	Thermal processes energy cost ($B/y)	SWRO processes energy cost ($B/y)
SA	13,530,973	5,426,131	5,479,792	4.753	1.200
UAE	9,753,024	7,411,069	2,209,065	6.492	0.484
Kuwait	2,134,253	1,461,136	275,254	1.280	0.060
Qatar	1,944,195	1,771,638	155,160	1.552	0.034
Oman	1,626,149	417,990	988,888	0.366	0.217
Bahrain	1,398,064	756,967	582,667	0.663	0.128
Total	30,386,658	17,244,931	9,690,826	15.107	2.122

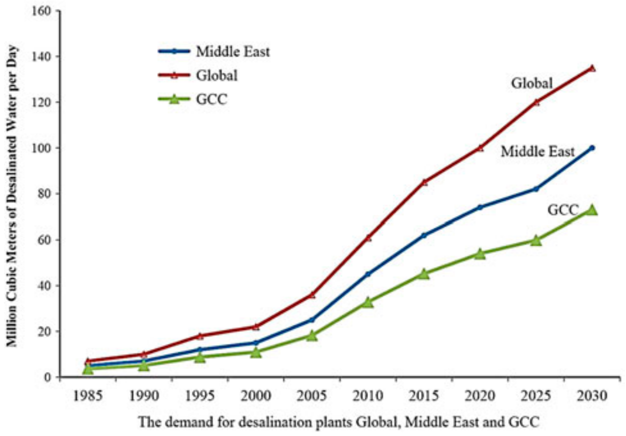

Fig. 12. Current and expected demands for DW in the GCC, Arab countries, and world [13].

Table 9
Nominal capacity and heads of used pumps, Darwish et al. [16]

Pump duty	Flow rate (l/s)	Head (m)	Motor rating (kW)
Re-circulating pump	4,200	73	4,100
Seawater cooling	2,675	25	890
Distillate pump	348	57	170
Condensate pump	45	114	90
Total power			5,250

distillate. The flow rates of the $D = 316$ kg/s (6 MIGD), consumed steam $S = 316/8 = 39.5$ kg/s, required cooling water is about $7.7\,D = 2{,}433$ kg/s, and the re-circulating stream = $12\,D$. The used pumps nominal capacity and heads are given in Table 10.

The nominal pumping energy used to produce 316 kg/s distillate is 5,250 kW, or 16.6 kJ/kg. The actual recoded consumed pumping energy is 14.4 kJ/kg, (4 kWh/m^3).

If the steam supplied to the MSF unit is at temperature $T_h = 127$°C (400 K), was supplied to a Carnot cycle operating between this high steam temperature and a low temperature $T_L = 47$°C (320 K), the average condenser temperature in the Gulf area, the Carnot cycle would have an efficiency defined by $\eta(\text{Carnot}) = (1 - T_L/T_h) = 0.2$. For an actual cycle, its efficiency would be little less than that of an ideal Carnot cycle.

So the real work equivalent to the 280 kJ/kg thermal energy supplied the MFS is: $280 \times 0.2 = 56$ kJ/kg (or 15.55 kWh/m^3). This is the equivalent of work of the 280 kJ/kg thermal energy supplied to the MSF unit. In practice this number reaches 16–18 kWh/m^3. So, the total equivalent work (for the heat supplied and pumping energy) is in the range of 20 kWh/m^3.

By taking the electrical energy cost is as \$0.12/kWh, the energy cost in \$/m^3 of MSF distilled water is \$2.4/m^3, and if this represents 80% of distilled water cost, the actual DW cost would be \$3/m^3.

The commonly used MSF units and the newer ME-TVC are very energy extensive, and their use should be stopped. They should be substituted by the more energy efficient SWRO desalting system.

4.2. *Energy consumed by SWRO desalting system*

In SWRO desalting system (Fig. 14), membranes are used to separate fresh water from saline feed water. Feed seawater (F) is pumped, after pretreatment, to semi-permeable membranes, that allow water, but not salt, to pass through the membranes. The pumped F should have much higher pressure than the osmotic pressure for freshwater to pass

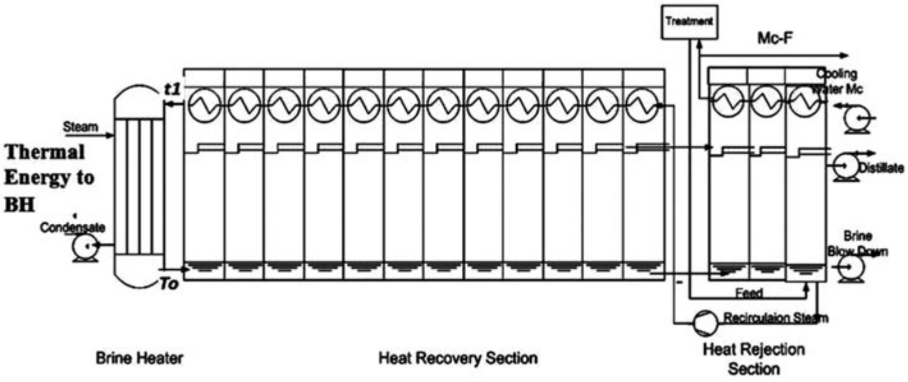

Fig. 13. Schematic diagram of an MSF unit consisting of n stages.

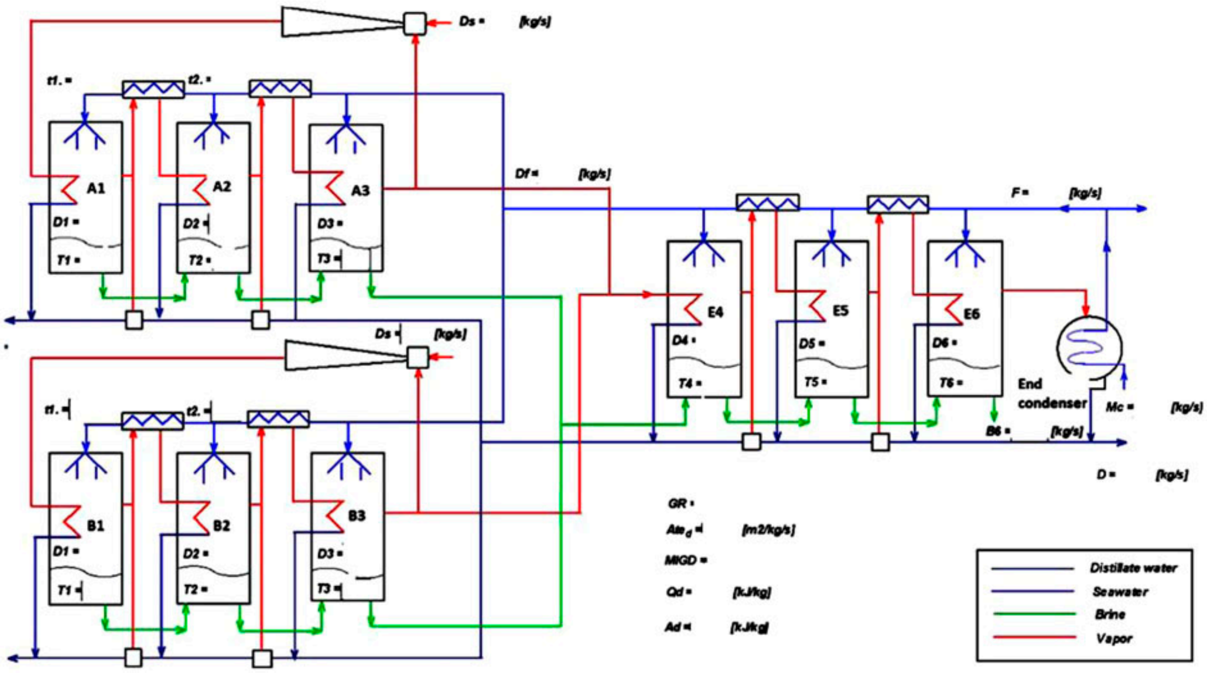

Fig. 14. Schematic diagram of a ME-TVC unit.

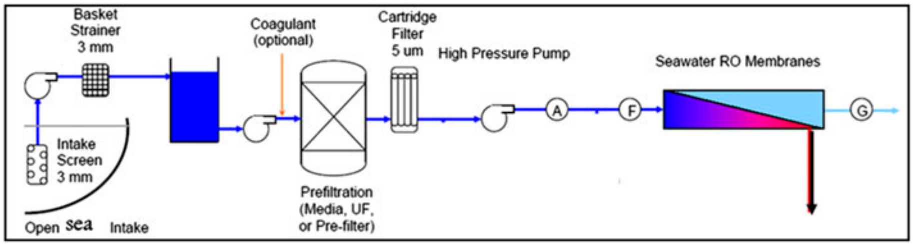

Fig. 15. Simplified reverse osmosis scheme without energy recovery system.

Table 10
Required feed water (F) applied pressure for several F's salinity [17]

Water source	Salinity (mg/l)	Pressure range (bar)
Brackish water	500–3,500	3.4–10.3
Brackish to saline	3,500–18,000	10.3–44.8
Seawater	18,000–45,000	44.8–82.7

through the semi-permeable membranes at reasonable rates, leaving the solid salt behind. Examples of applied pressures at different salinities are given in Table 11 [17].

The SWRO plants are very sensitive to feed water quality (salinity, turbidity, temperature, etc.), while other distillation technologies do not need high quality feed water demand. The increase of seawater salinity necessitates rising of feed water pressure to membranes and thus consumes more energy. High-turbidity feed water can cause fouling where membrane pores are clogged with suspended solids, and thus the SWRO needs extensive feed water pretreatment that brings the silt density index of the feed water to less than 5 for spiral wound membranes.

The energy consumed by the SWRO is calculated here for a typical example.

For $1\,\mathrm{m}^3/\mathrm{second}$ (s) of permeate (P), and 1/3 recovery ratio R defined by $R = P/F = 1/3$, the feed (F) would be $3\,\mathrm{m}^3/\mathrm{s}$.

For 70 bar applied feed pressure (P_f) (typical feed pressure for high salinity water in GCC) and 0.8 pump efficiency (η_p), the consumed feed pump energy is:

Table 11
Water withdrawal, wastewater produced, treated waste water, and reused TWW [18]

Countries	Total water withdrawal (10^9 m^3/ year)	Total wastewater produced (10^9 m^3/ year)	Volume of treated wastewater (10^9 m^3/year)	Volume of treated water reused (10^9 m^3/year)
Saudi Arabia	23.67 in 2006	0.73	0.652	0.166
Bahrain	0.3574	0.0449	0.076	0.0163
Egypt	68.3	3.76	2.971	0.7
United Arab Emirates	3.998	0.5	0.454	0.248
Iraq	66	0.575	0.098	0.0055
Libya	4.326	0.546	0.04	0.04
Jordan	0.941	0.117	0.111	0.102
Kuwait	0.913	0.25	0.239	0.078
Oman	1.321	0.098	0.037	0.0023
Qatar	0.55	0.444	0.066	0.043
West Bank and Gaza	0.418	0.05	0.03	0.00544
Yemen	3.4	0.074	0.046	0.06

$$\begin{aligned} W(\text{feed pump}) &= (F \text{ in m}^3/\text{s})(\Delta P \text{ in kPa})/\eta(\text{pump}): \\ &= 3 \times 7{,}000/0.8 = 26{,}250\,\text{kW}/(\text{m}^3/\text{s}) \\ &= 26{,}250\,\text{kJ/m}^3 = 7.29\,\text{kWh/m}^3 \end{aligned}$$

Energy recovered: the brine (B) flow rate becomes 2 m^3/s, and leaves the membranes at pressure slightly less than that of the feed, say 67 bar, and enters an energy recovery turbine of 0.9 turbine efficiency (η_t) would give work output.

$$\begin{aligned} W(\text{turbine}) &= (B \text{ in m}^3/\text{s})(\Delta P \text{ in kPa}) \times \eta(\text{turbine}): \\ &= 2 \times 6{,}700 \times 0.9 \\ &= 12{,}060\,\text{kW}\,(3.35\,\text{kWh/m}^3) \end{aligned}$$

So, the net feed water pump power = 7.29−3.35 = 3.94 kWh/m^3.

The SWRO consumed energy is almost 1.2 times the energy consumed by the feed water pump or 4.728 kWh/m^3.

This power consumption depends on feed water temperature, see Fig. 16, and the seawater salinity, which varies with time.

The energy efficient desalting SWRO should be the only method used for desalting seawater, as the specific energy consumption is in the range of 4–6 kWh/m^3, and thus the desalting cost is in the range of \$1–\$1.5/m^3. As an example, if the consumed energy by the SWRO is 5 kWh/m^3, and the specific electric power cost is \$0.12/kW, then this energy cost would be \$0.6/m^3. If the energy cost represents 50% of the total DW cost by the SWRO, then the DW cost is in the range of \$1.2/m^3. The high cost of producing DW by thermal technology is the reason behind its decreasing share, worldwide from about 55% in 2003 to 34.8% in 2012. This cost, as well the previous given MSF cost, does not include the heavy environmental cost to marine life, due to the disposal of very high salinity brine at temperature higher than that of the ambient seawater (≅10˚C). Moreover, the rejected brine is loaded with chemicals from the treatment process. Also, the cost of air pollution caused by burning fuel to produce the energy required for the desalting process is not included.

4.3. Recycled TWW

Municipal WW should be treated anyway before being disposed to sea or inland. Additional treatment is needed for this water to be reused (or reclaimed) in agriculture as example, or any other application. Water reuse combines the benefits of freshwater conservation, GW resource protection, and total water supply augmentation. Table 9 shows that limited amount of total withdrawal are treated in the GCC, [18], and more WW should be treated and reused.

Recycled water or TWW effluent is a guaranteed valuable water resource which grows with population growth, and its amount can be high percentage of domestic water use (up to 80% in Israel). In arid area like Qatar, it is a water source that should be fully utilized. The treatment cost to potable water quality for domestic water reuse (unlimited water use excluding

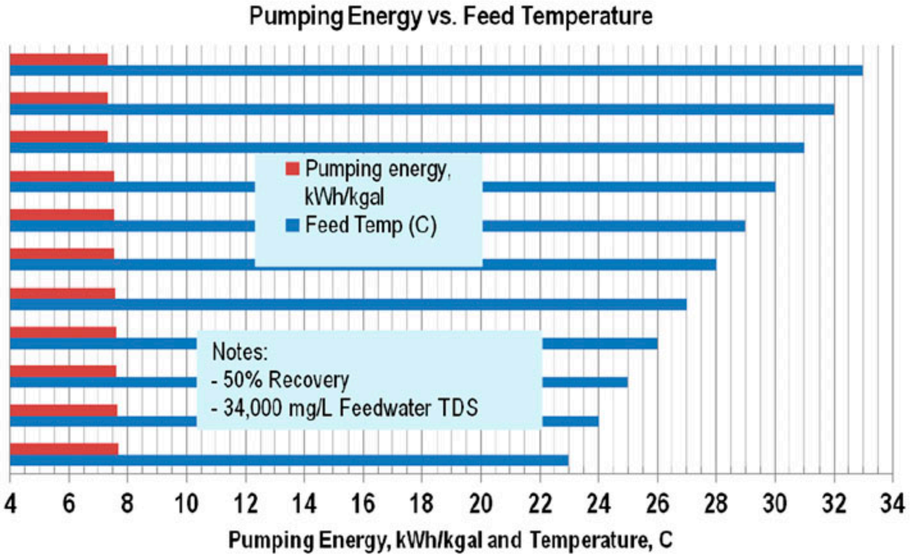

Fig. 16. Dependence of pumping energy (in kWh/kgal = 3.75 kWh/m^3) in SWRO on seawater temperature [17].

drinking) is lesser than that of desalting seawater. So, it is desirable here to treat all generated WW and reuse it. But, Qatar, for example, lacks the infrastructure to deliver recycled water to every potential user. Investments are needed to extend collection and treatment networks. Public campaign for the acceptance of recycled water is needed.

In Qatar, recycled TWW effluent accounts for only 14.9% of the water use. The TWW supply currently is more than demand, and about 40% of treated sewage effluent is discharged into septic lagoons. In Qatar, about one-third of municipal WW is treated (≅354,000 m^3/d or 129.4 Mm^3/y) and partially recycled. The two main TWW plants in Doha had reached between 140,000 and 150,000 m^3/d in 2005; at tertiary treatment level. The recycled TWW is used for the irrigation of few crops and landscaping. Extending the WW treatment of tertiary level of limited usage for irrigation to quaternary level (of potable water quality), using hyper-filtration (reverse osmosis) has opened the door to use the TWW as part of municipal water. This will improve the water security by not becoming completely dependent on the DW. DW production is vulnerable to oil spills, operation interruption, and so on.

The GCC should make far more extensive use of recycled water, which costs about one quarter of the DW, (Qatar National Development Strategy, 2011). Water demand for irrigation in the GCC can be satisfied by properly TWW; as the GW is limited and already exploited and depleted. TWW using tertiary level treatment of municipal WW was found to be adequate for irrigating ornamental plants and growing fodder. The recycled TWW may also be suitable for irrigating trees. However, more advanced treatment technology would be required for irrigating vegetables and other crops for human consumption, or for recharging GW aquifers.

Qatar was behind UAE and Kuwait in utilizing TWW as another water source, see Table 11. In Qatar, only 14.9% of the produced waste water is treated and only 65% of it is reused; while in UAE (and Kuwait), 91% (95.6%) of the produced waste water is treated and 55% (and 33%) of it is reused.

In Qatar, Doha North Sewage Treatment Plant is under construction [19]. It will have a peak capacity to treat WW up to 439,000 m^3/d and will be the largest WW treatment and reuse facility in Qatar (more than triple the capacity of the next largest) and one of the biggest in the Middle East. WW at the plant will be treated to the tertiary level. The project site is located some 22 km northwest of the city of Doha and will serve a population of over 900,000 people. The treated water will be recycled for irrigation and other non-potable needs. Development of TWW reuse should be motivated in the GCC because of the very low natural freshwater supplies. In addition, the depleted and deteriorated GW left no other water resource except TWW, as DW is very expensive.

Technically proven WW treatment and engineered purification processes already exist to produce water of almost any quality desired. The feasibility of using reclaimed water for irrigation is evaluated based on several factors including: salinity, trace elements, and water infiltration rates. Long-term soil exposure to reclaimed water results in increased deposits of nitrogen and phosphorus, while potassium, calcium, magnesium, and sodium tend to be more variable. Water reuse for agriculture and irrigation becomes an established water management practice in several water-stressed countries of the Arab region. It saves polluting the environment from untreated waste water discharge. The nutrients in TWW can reduce the need for applying chemical fertilizers, thereby reducing costs and potentially adverse effects associated with fertilizers. While costs vary according to quality and transportation expenditure, 1 m^3 of treated effluent costs $0.66 in Kuwait to bring TWW to potable condition, while a cubic meter of desalinated water costs by thermal system is above $3/$m^3$. However, health risks to consumers of agricultural goods produced from untreated or inadequately TWW. Also, GW can be polluted from infiltration of contaminated irrigation water.

5. Water and food

5.1. Food, arable land and water shortage

Qatar and all GCC rising population and economic expansion increase food demands. Besides the rise in population, the food consumption per capita is rising due to increased standard of living, see Fig. 17. The low domestic food production is due to water shortage and lack of arable land; insufficient to meet the gap between the consumed and produced food. The current percent of the arable to total area is 2.9% in Bahrain, 1.6% in Qatar, 0.8% in Kuwait, 0.1% in Oman, 0.8% in UAE, and 1.7% in SA [20]. This is compared with 18.4% in the US and 23.7% in the UK. SA leads the GCC in food production by producing cereals (mainly wheat), vegetables, fruits, and meat (poultry), and dairy products. The UAE, Qatar, and Kuwait produce mainly fruits, vegetables, and fish. In 2007, food production in the region totaled 11.2 million tons (Mt), compared with 37.2 Mt food import [20]. In 2010, the percentage of self-sufficiency in cereals were: 1.01% in UAE, 0% in Bahrain, 11.51% in SA, 4.31% in Oman, 0.52% in Qatar, 1.61% in Kuwait, and 22.92% in Yemen [21].

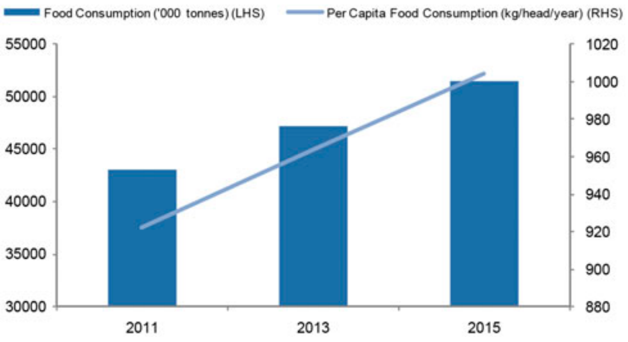

Fig. 17. GCC food consumption, per capita consumption [20].

The drives to produce more food over-exploit the scarce GW resources. The ratios of water used in agriculture to total water withdrawal in SA, UAE, Qatar, and Bahrain are shown in Fig. 18. Although of the high water withdrawal ratio used for the agriculture which adds less than 5% of GDP, The Economist [22].

In Qatar, as example, many farm stopped agriculture due to GW depletion. The GCC cost food imports in 2010 were $B25.8, and is estimated to be $B53.1 B by 2020. The historical food import in GCC is shown

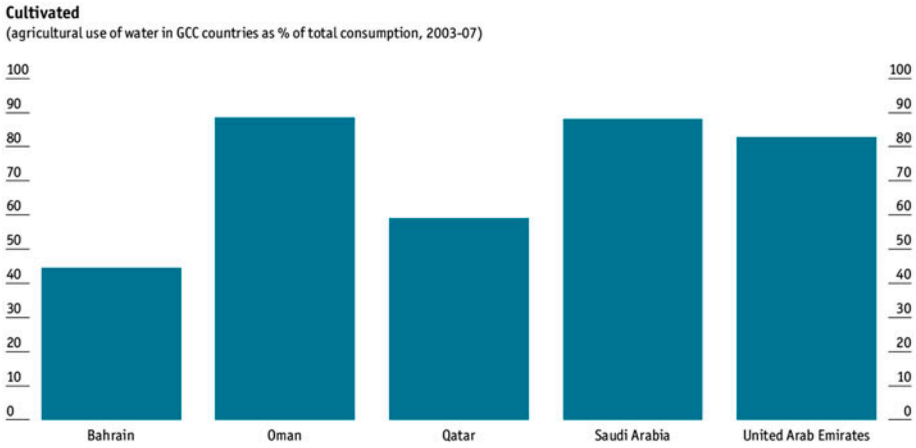

Fig. 18. Agriculture use of water in GCC as % of total water consumption, The Economist [22].
Source: Food and Agriculture Organisations, Aquastat.

in Fig. 19. Types of imported food to Qatar as example are given in Fig. 20. The estimated values for GCC imports by individual GCC countries are given in Table 12. This table shows that the cost of imports would increase more than 40% from 2010 to 2015. Soaring of food prices in 2007 and 2008 (Fig. 21), motivates GCC governments and private investors to explore wide-ranging purchases of agricultural land from all over the world.

Water scarcity makes domestic agriculture very costly. SA has announced that it will phase out domestic wheat production by 2016 in order to save water [23]. The GCC have taken initiatives to enhance domestic production, and at the same time to secure food imports through international agricultural investments.

The ratios of food imports to consumptions in 2007 are given in Table 13 that shows that all GCC were almost dependent for all its needs of wheat, rice, and pulses on import food, except SA which was dependent on its wheat production at 2007. Only Bahrain and Oman are exporting fish.

Despite all the GCC government efforts and support to increase local agriculture production through financial assistance and subsidies, the agricultural input to GDP in 2008 was 0.5% in Bahrain, 0.1% in Qatar, 0.3% in Kuwait, 1.4% in Oman, 0.9% in UAE, and 2.7% in SA [24]. Population percentage engaged in agriculture varies, and in the period of 1997–2006, it was 0.8% in Qatar, 1% in Bahrain, 1% in Kuwait, 4.6% in UAE, 9.1% in SA 9.1%, and 35.4% in Oman [24].

5.2. Water requirements for food

Production of food in the severely stressed water GCC region is a real challenge [25]. It is estimated that equivalent to more than 3,000 l is needed to grow food for one person per day; much more than what is needed for drinking (2–5 l) and for domestic purposes (20–300 l), Spiess [25]. The water needs in liters per kg

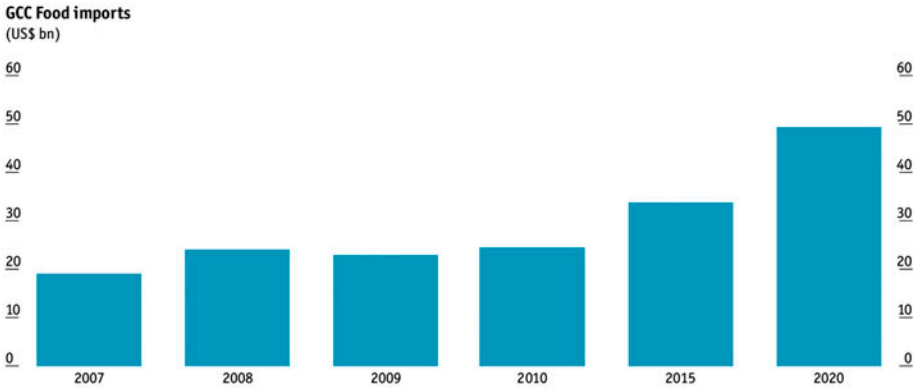

Fig. 19. The historical food import to the GCC, The Economist [23].
Sources: Individual country central banks, Economist Intelligence Unit long-term forecasts.

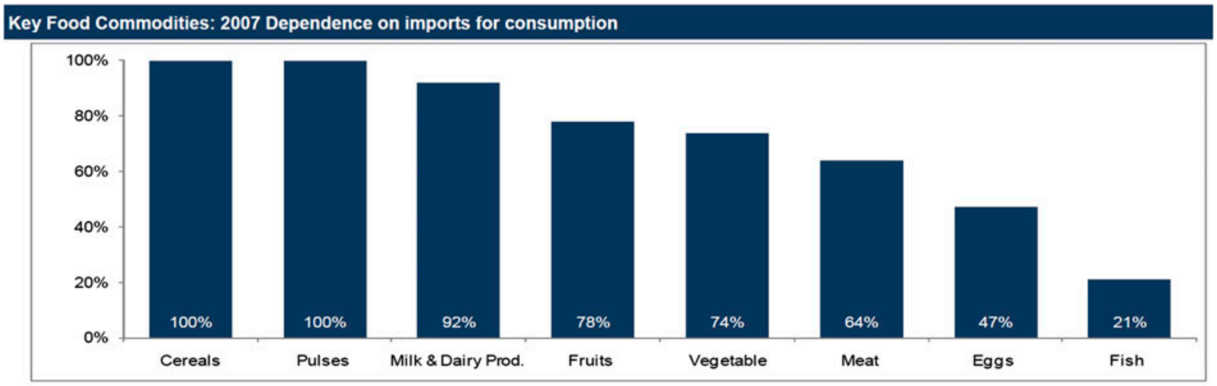

Fig. 20. Percent of food commodities depends on imports in 2007 [20].

Table 12
GCC food imports estimates (USD billion) [20]

Country	2010	2015E	2020E
Bahrain	0.7	1.1	1.6
Kuwait	2.3	3.6	5.3
Oman	2.1	3.3	4.8
Qatar	1.3	2.1	3.3
SA	16.8	24.5	35.2
UAE	3.6	5.5	8.4
GCC total	25.8	36.3	53.1

(l/kg) of some produce, as examples, are: 1,827 l/kg for wheat, 1,423 l/kg for barley, and 3,015 l/kg for olives. Producing dairy, meat, poultry, and other animal products can be even more water intensive, necessitating appreciable amounts of freshwater to grow feed, provide drinking water, and care for the animals. The water demand for raising one kg of beef (l/kg) is 15,415 l/kg on the average. The corresponding values are 10,412 l/kg for lamb, 3,265 l/kg of eggs, and 1,020 l/kg for milk. SA used about 3,000 m^3 of water for each ton of produced wheat, which accounts to three times the global norm [26]. Moreover, water needs are 500 l of water to produce 1 kg of potatoes, 1 l of water to produce 1 kg of vegetables, 4,000 m^3 to raise one cattle, 500 m^3 to raise one sheep or goat, 1 m^3 to produce one kg of pulses, roots and tubers, and 2 m^3 to produce 1 kg of palm oil.

Securing these prohibitively, high amounts of water needed to grow food are hard to achieve in the GCC. DW is very expensive to be used for agriculture. Most of the water used for agriculture in the GCC is withdrawn from GW aquifers and TWW. The GCC is using more water than what they have. The water used for agriculture in Qatar is given here as example [27]. The GW is accounting for about 36% of water use, predominantly in agriculture, but it is rapidly depleted. Many water wells ceased to provide the required water in terms of quantity or quality, and even the

Fig. 21. Food inflation rise after falling in 2009, Alpen Capital [20].

Table 13
Food imports as a proportion of consumption (2007) [24]

Country	Bahrain (%)	Kuwait (%)	SA (%)	Oman (%)	Qatar (%)	UAE (%)	GCC (%)
Wheat and flour	100	99	2	99	100	100	39
Maize	100	92	91	100	93	100	92
Rice	100	100	100	100	100	100	100
Barley	100	96	100	92	98	100	100
Potatoes	100	17	−2	76	100	91	19
Pulses (total)	100	100	100	100	100	89	98
Vegetables (total)	78	41	22	36	86	62	37
Fruits (total)	77	73	35	23	77	47	40
Meat (total)	62	62	44	73	89	80	56
Fish	−51	64	40	−74	36	29	16
Eggs	43	37	−4	53	63	62	19
Milk and dairy products	91	92	72	64	93	83	77

government prevented more exploitation. Recycled water, or treated sewage effluent, is the only water source in surplus in Qatar now. It is used mostly in irrigation, accounting for 14% of water use. Treated sewage effluent can play larger role in industrial processes, district cooling, and watershed management.

The GCC dependence on external markets to satisfy food needs makes them vulnerable not only to price variations and high food prices, but also to increasingly changing food policies of the exporting countries such as a blanket ban on the exports of certain food commodities. The GCC is trying to treat the symptoms of growing food insecurity by adopting new approaches. Food security is realized "when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life," FAO [28], and thus represents the emergence of food security as a social, cultural, and political construct. The UAE and SA are already developing arable lands and food processing units in several Asian and African countries in a bid to overcome the snowballing global food shortages.

Dependence on DW to produce food, coupled with the present methods of generating desalting seawater and current agriculture practice, will produce prohibitively expensive food products. Growing food needs both water and energy at much higher cost than the produced food. It is certainly not acceptable to produce one kg of potatoes by consuming $0.5\,\mathrm{m}^3$ of desalted water produced by MSF method at cost of $\$3.5/\mathrm{m}^3$. The same applies for meat, milk, wheat production, etc.

6. Conclusion

Qatar and the GCC region are facing acute water scarcity. The water problem in Qatar is more worsen by the very rapid increase in population, urban expansion, and consumed water. The increasing demand for food cannot be met by the scarce and dwindling conventional GW water resources. These conventional resources have already been over exploited by irrigation practices. The water problem should be solved by sustainable water management to cope with ever-increasing water demands. Securing DW by solar energy, aquifer recharge using recycled waste water, and the use of recycled water of better than tertiary-TWW for irrigation and other purposes are some of the sustainable solutions. In conclusions:

(1) Qatar is mining its fossil water reserve. This is should not only be stopped, but GW should be replenished by potable quality injected to aquifers to restore the GW resource, and use it as strategic water storage. DW and/or advanced TWW (both of potable quality) should be used to aquifer storage and recharge. The current storage capacity of DW to meet any emergency situation is limited to two days and will be extended to nine days. So, strategic water storage in aquifers is needed for months.

(2) Qatar is using the most inefficient desalting systems, namely MSF and ME-TVC. Additional of these systems should be stopped. Any new installed DW system should use the most efficient SWRO desalting system.

(3) Qatar should fully utilize its WW. It should be treated beyond its tertiary water quality (designed for disposable purposes), unrestricted water usage, say to potable water quality. This should replace the usage of GW for agriculture, and usage of DW for municipal water for non-drinking and cooking needs. Dual distribution system can be constructed: one for high quality system DW for drinking water and other high quality uses; and second for reclaimed water for agricultural irrigation, landscaping, and fire protection.

(4) Water pricing should reflect the real value of water. The government should not end up by subsidizing the depletion of an essential natural resource. Under-pricing or zero-pricing lowers the incentive to conserve water, and does not reflect the scarcity value of the water. Implementation of real cost, especially for water consumed beyond basic needs (that should be considered wasteful) is a mean for demand and water wastage management. This should not be in conflict with the right of all individuals to adequate, reliable, and affordable supply of potable water.

(5) Water efficiency in agriculture through water management and drainage and improved surface irrigation alongside drought–heat tolerant crop varieties (in parallel with improvements in plant breeding or genetic manipulation to reduce irrigation demand).

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