

Review

Reclaimed wastewater for agriculture irrigation in Qatar

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Highlights

- The real challenge of using treated wastewater in Qatar for crop production is social.
- The highly treated domestic wastewater could be a real water resource for irrigation.
 - Technical and economic calculations show minimum risks associated with reuse.
- The findings are extremely important to similar arid countries where water is absent.
- Reuse may achieve food security, combat desertification and improve life conditions.

Abstract

Qatar, one of the world's poorest countries in terms of fresh water resources, has the highest water consumption per capita in the world (>500 L/day/person). The country is completely dependent on seawater desalination to meet local demands. Limited and overexploited groundwater resources (GW) are used for crop irrigation; however, due to increasing population, Qatar imports over 95% of all food. Qatar's high volume of wastewater is currently treated using advanced technologies, often to the tertiary level. The quality of the treated wastewater (TWW) achieved allows for the water to meet standards for irrigation use; however, social factors currently inhibit this practice. This paper uses scientific, economic and technical evidence to show that TWW is a valuable and safe resource for crop irrigation that poses minimal risk to the soil, GW, and crops and is a key factor towards Qatar's food security. Content targets the scientific community, public and policy makers.

Keywords: Treated wastewater reuse; water scarcity; desalination; food security; Qatar

INTRODUCTION

Qatar is one of the world's poorest countries in terms of natural freshwater resources[1]. There are no rivers, very limited rainwater, and limited replenishment of groundwater (GW), about 58 Million cubic meters per year ($\text{Mm}^3\text{yr}^{-1}$). The GW is overexploited with a reported abstraction increase from $56.2 \text{ Mm}^3 \text{ yr}^{-1}$ in 1976 to $300 \text{ Mm}^3 \text{ yr}^{-1}$ in 2014. Qatar's total water withdrawal in 2013 was $800 \text{ Mm}^3 \text{ yr}^{-1}$. Freshwater withdrawal includes $414.382 \text{ Mm}^3 \text{ yr}^{-1}$ (53.6% of the total withdrawal) comes

from desalted seawater (DW) and $257.2 \text{ Mm}^3 \text{ yr}^{-1}$ (32.4% of total withdrawal) from GW abstraction[2]. Water withdrawal originating from treating wastewater (WW), sometimes called treated sewage (TSE) was $108 \text{ Mm}^3 \text{ yr}^{-1}$ (14% from total withdrawal) (Figure 1). Qatar utilizes its wealth of natural gas (NG) and oil production in urbanization and securing improved urban drinking water supply and sanitation services, which have reached 100% of Qatar's population since 2006.

Figures 2a, 2b and 2c show the history of GW withdrawal. It shows GW pumping increased from $51.2 \text{ Mm}^3 \text{ yr}^{-1}$ in 1976 (little less than replenishment rate) to $248.7 \text{ Mm}^3 \text{ yr}^{-1}$ in 2009. Figure 2a shows a decrease in

Figure 1: Water uses and water losses in 2011 [4]

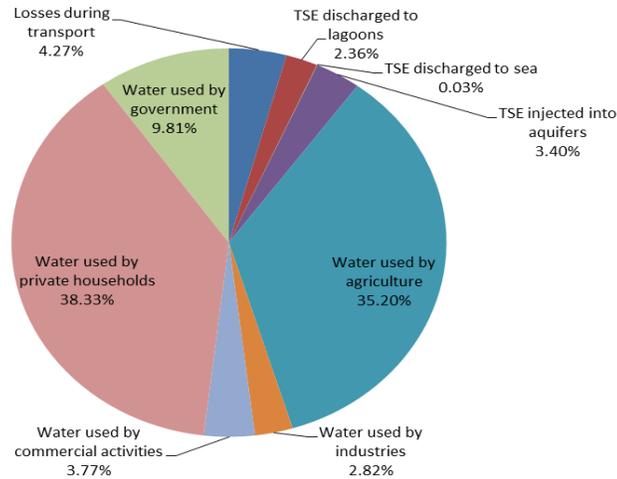
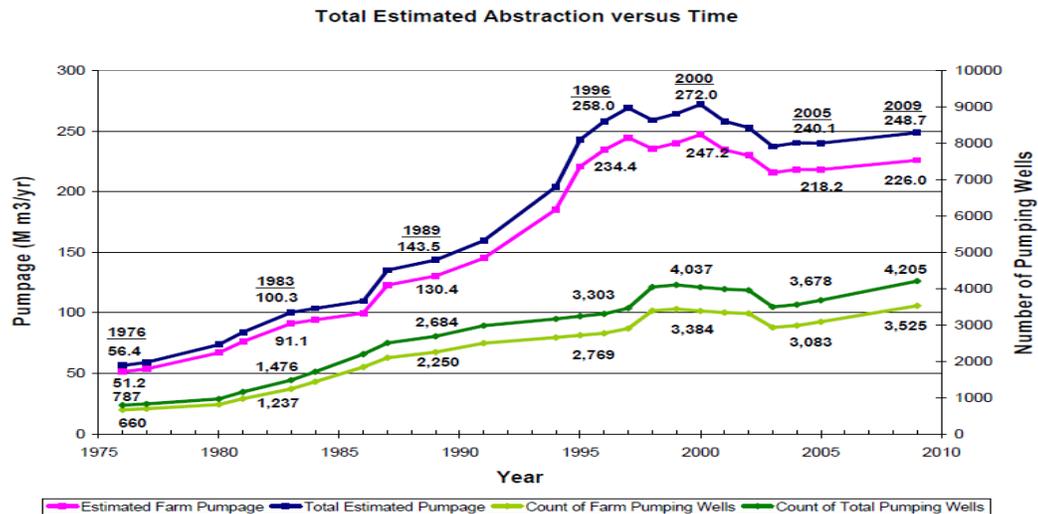


Figure 2a: Qatar farming and total GW abstraction, and number of wells from 1977 to 2009[3]



areas with underlying freshwater and brackish water (BW) suitable for irrigation. Water with total dissolved solids (TDS) between 1500-3500 mg L⁻¹ may be hazardous to the irrigation of several crops, while at TDS = 3500 mg L⁻¹ water is unsuitable for irrigation.

Concerning GW, a report issued by Qatar’s Ministry of Environment (MoE) in 2009 predicted that the predicted year for the area with underlying freshwater of TDS < 1000 mg L⁻¹ to reach zero is 2018, and that for low salinity of TDS < 2000 is 2037, and that for TDS < 3000 is 2056[3]. Many land farms have already been abandoned in Qatar due to the deterioration of GW quality. Of all groundwater abstractions 92% are for agricultural purposes, and the remaining 8% are for domestic, municipal, and industrial uses [4].

Qatar’s water is becoming increasingly scarcer with GW overexploitation, population increase at a high rate,

and more need for food productions. As DW is extremely expensive and GW is depleted, treated municipal WW should be fully utilized for agriculture irrigation after proper treatment and control. Nitrogen (N) and phosphorus (P) contents of WW can reduce or eliminate the needs for synthetic fertilizers. Saudi Arabia (SA) and Jordan have national policies to reuse all treated WW effluents [5]. WW reuse for agriculture would help the country to continue farming and promotes food security. Reclaimed WW is available year-round, allows multiple cultivation cycles, typically increases with population growth, and has a much lower cost than DW.

Waste Water (WW) and its Treatment in Qatar

By law in Qatar, WW should be treated before being reused or disposed in the surrounding area (e.g.

Figure 2b: Area underlain by fresh water (<1000 mg L⁻¹) and good brackish water (2000-3000 mg L⁻¹) in North Qatar, 1971-2008[3]

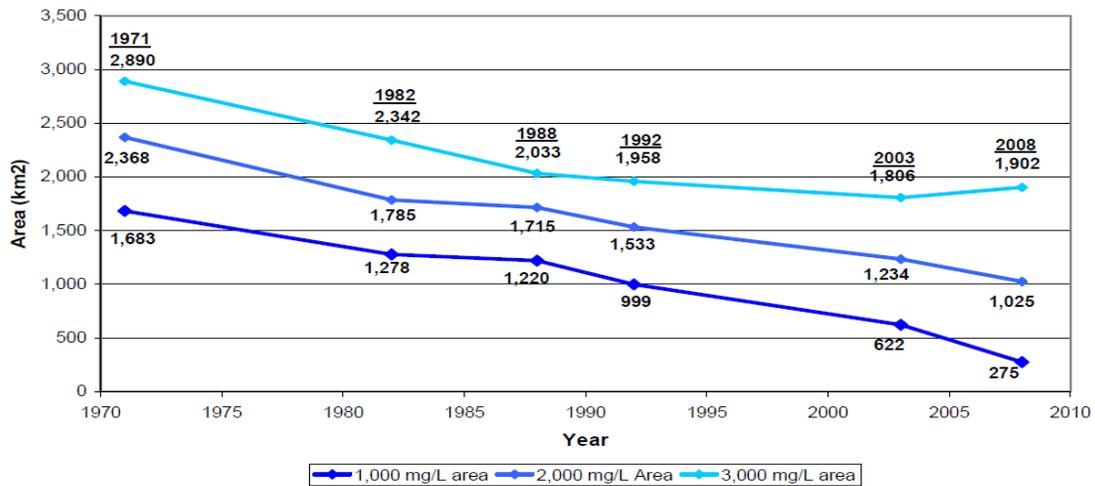


Figure 2c: Groundwater balance (Adapted from [4])

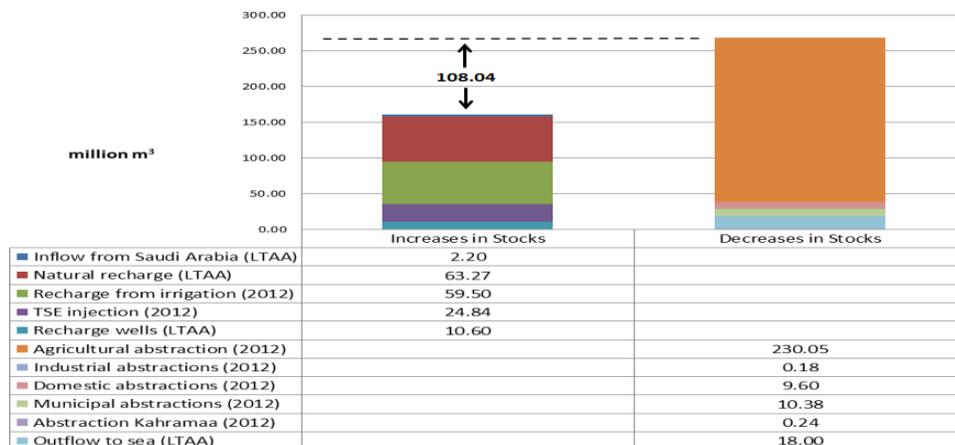


Figure 3: Effect of high contents of carbon, nitrogen, and phosphorous, toxicity and carcinogenicity due to heavy metals on the receiving water

High Content of C, N, P



receiving water or land). This is done by lowering the WW harmful contents to the extent that the environment would not be negatively affected. Qatar's Public Work Authority

(Ashghal) is responsible for treating the WW by building and running wastewater treatment plants (WWTPs). The WW harmful contaminants include organic materials, pathogens, nutrients, and synthetic chemicals. High content of organic matters or nutrients can lead to O₂ depletion in receiving water or eutrophication[6]. A list of several Qatar WWTPs names and capacities (in m³ day⁻¹) is given [7]:

- Saililyah of (135 000 m³ day⁻¹) commissioned in 2008, and was expected to reach 175 000 m³ day⁻¹ in 2013
- Najjah (106 000 m³ day⁻¹) capacity, commissioned in 2006, and was expected to reach 180 000 m³ day⁻¹ in 2013
- Lusail (60 000 m³ day⁻¹) [8].
- Doha North (234 000 m³ day⁻¹) was expected in 2013, and is expected to increase to 234 000 m³ day⁻¹ in 2016 [9]. Doha North is the largest, and is under-construction WWTP.
- Doha industrial area (12 000 m³ day⁻¹) commissioned in 2006, was expected to reach 24 000 m³ day⁻¹ in 2013, and 48 000 m³ day⁻¹ in 2016.

Figure 4a: Design capacity per treatment type of urban wastewater treatment plants in Qatar (Adapted from [10])

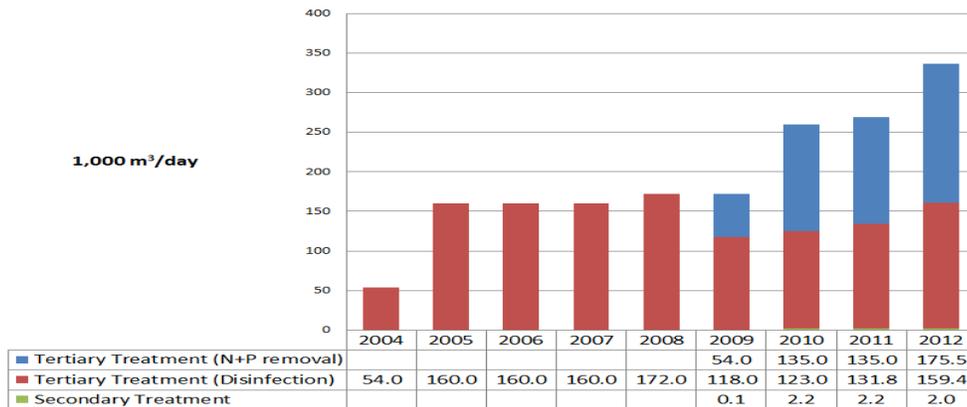
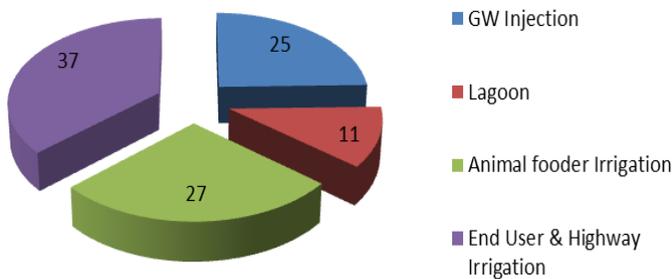


Figure 4b: Current Treated Effluent Rate and Distribution [7]



- Alkhor ($5000 \text{ m}^3 \text{ day}^{-1}$) capacity, expected to reach $10\,000 \text{ m}^3 \text{ day}^{-1}$ in 2016

- Al Thakhira ($1600 \text{ m}^3 \text{ day}^{-1}$), was expected to be ($3200 \text{ m}^3 \text{ day}^{-1}$) in 2013, and is expected to increase to $42\,000 \text{ m}^3 \text{ day}^{-1}$ is planned to add in 2019.

These numbers gave a total capacity of $352\,860 \text{ m}^3 \text{ day}^{-1}$ [8]. There are also small projects in Al Shamal, Jumeliyah, North Camp, Shahaniyah, Al Khareeb, and AumSallal.

The total treated wastewater (TWW) capacity is expected to reach $634\,860 \text{ m}^3 \text{ day}^{-1}$ ($231.7 \text{ Mm}^3 \text{ yr}^{-1}$) in 2013, $790\,410 \text{ m}^3 \text{ day}^{-1}$ ($288 \text{ Mm}^3 \text{ yr}^{-1}$) in 2016, and $819\,410 \text{ m}^3 \text{ day}^{-1}$ ($299 \text{ Mm}^3 \text{ yr}^{-1}$) by 2030 [7]. So, the current TWW capacity is almost equal or slightly higher than the GW used presently for agriculture. This means that utilizing the TWW in agriculture can double agricultural production and raise Qatar’s food self-sufficiency from 5.47% to more than 10%.

Nagy [4] reported that in 2012 most of WW, $335\,000 \text{ m}^3 \text{ day}^{-1}$, are treated to a tertiary level, with $175\,500 \text{ m}^3 \text{ day}^{-1}$ with P and N removal, $159\,400 \text{ m}^3 \text{ day}^{-1}$ for just disinfection, and $2000 \text{ m}^3 \text{ day}^{-1}$ for secondary treatment, Figure 4a.

The current treated effluent reuse applications are: GW injection (25%), animal fodder irrigation (27%), end user and highway irrigation (37%), and disposed to lagoon (11%), see Figure 4b [7].

Part of the TWW in Qatar is reused for irrigation of animal fodder. Qatar is already one of twenties countries using the largest volumes of TWW in agriculture - about $80\,000 \text{ m}^3 \text{ day}^{-1}$. This is a small amount compared to those of Saudi Arabia ($595\,000 \text{ m}^3 \text{ day}^{-1}$), Kuwait ($432\,000 \text{ m}^3 \text{ day}^{-1}$), UAE ($200\,000 \text{ m}^3 \text{ day}^{-1}$), Israel ($767\,000 \text{ m}^3 \text{ day}^{-1}$), and Libya ($110\,000 \text{ m}^3 \text{ day}^{-1}$) [10]. In Qatar, TWW is about 30% of municipal water and this ratio would be soon more than 50% and is treated to tertiary levels. The proposed standard for treating effluent WW for reuse as given by Ashghal is shown in Table 2 [7].

Reuse of WW in Agriculture: An Overview

Water reuse in agriculture should be an important component of the national integrated water resources management strategy (IWR) and a part of the national strategy for sustainable water management [1]. Some of the terms used in relation to TWW reuse for agriculture irrigation are mentioned below.

Untreated WW: Municipal WW collected from homes and public buildings, including: (1) Black water (excreta, urine and associated sludge) coming from toilets, (2) Grey water coming from less polluted sources such as washing hands/face, drinking, bathing, and heating and cooling, and (3) Grey water coming from kitchen water,

Treated waste water (TWW): Collected municipal or industrial WW can be treated physically, biologically, and chemically in WWTPs to reduce its pollution or health hazardous substances before its disposal.

Reclaimed water or recycled water: Reclaimed water or recycled water is TWW with specific conditions that can be used for beneficial purposes, such as irrigation, cooling, flushing, etc.

Table 1: Proposed standards for treated effluent WW for reuse[7]

Standard effluent criteria	Proposed standard	Future standard	Basis of compliance
Suspended Solids	5 mg L ⁻¹	5 mg L ⁻¹	90%
BOD	5 mg O ₂ L ⁻¹	5 mgO ₂ L ⁻¹	90%
COD	50 mgO ₂ L ⁻¹	50 mgO ₂ L ⁻¹	90%
pH	6 - 9	6 - 9	90%
Ammonia	1 mg L ⁻¹	1 mg L ⁻¹	90%
Phosphate	1/2 mg L ⁻¹	2 mg L ⁻¹	90%
Total Nitrogen	10 mg L ⁻¹	5 mg L ⁻¹	90%
Dissolved Oxygen	2 mg L ⁻¹ (min)	2 mg L ⁻¹ (min)	90%
Chlorine (Free Residual)	0.5-1.0 mg L ⁻¹	0.5 – 1.0 mg L ⁻¹	90%
Turbidity	2 NTU	2 NTU	90%
Total Dissolved Solids	2000 mg L ⁻¹	500 mg L ⁻¹	90%
MPN of Fecal Coliform per 100 ml	0.0	0.0	90%
Intestinal nematodes (no. of eggs per l	< 1.0	0.0	95%
Enteric Viruses (no. of plaque forming unit/40 liters)	< 1.0	<1.0	90%
Guardia (no. of cysts per 40 liters)	< 1.0	<1.0	90%

Table 2: Guideline for interpretation of water quality¹[18]

Potential Irrigation Problem	Units	Degree of Restriction on Irrigation		
		None	Slight to Moderate	Severe
Salinity (affects crop water availability)²				
EC _w	dS m ⁻¹	<0.7	0.7 - 3.0	> 3.0
TDS	mg L ⁻¹	< 450	450 - 2000	> 2000
Infiltration (affects infiltration rate of water into the soil; evaluate using EC_w and SAR together)³				
SAR	0 - 3	> 0.7	0.7 - 0.2	< 0.2
	3 - 6	> 1.2	1.2 - 0.3	< 0.3
	6 - 12	and EC _w =	1.9 - 0.5	< 0.5
	12 - 20	> 2.9	2.9 - 1.3	< 1.3
	20 - 40	> 5.0	5.0 - 2.9	< 2.9
Specific Ion Toxicity (affects sensitive crops)				
Sodium (Na) ⁴				
surface irrigation	SAR	< 3	3 - 9	> 9
sprinkler irrigation	meqL ⁻¹	< 3	> 3	
Chloride (Cl) ⁴				
surface irrigation	meq L ⁻¹	< 4	4 - 10	> 10
sprinkler irrigation	meq L ⁻¹	< 3	> 3	
Boron (B)	meq L ⁻¹	< 0.7	0.7 - 3.0	> 3.0
Miscellaneous Effects (affects susceptible crops)				
Nitrate (NO ₃ -N)	mg L ⁻¹	< 5	5 - 30	> 30
Bicarbonate (HCO ₃)	meq L ⁻¹	< 1.5	1.5 - 8.5	> 8.5
pH		Normal Range 6.5 - 8.4		

¹ Adapted from FAO (1985)²EC_w, means electrical conductivity, a measure of the water salinity, reported in deciSiemens per meter at 25°C (dS m⁻¹) or in millimhos per centimeter (mmhcm⁻¹); both are equivalent.³ SAR is the sodium adsorption ratio; at a given SAR, infiltration rate increases as water salinity increases.⁴ For surface irrigation, most tree crops and woody plants are sensitive to sodium and chloride; most annual crops are not sensitive. With overhead sprinkler irrigation and low humidity (< 30 percent), sodium and chloride may be absorbed through the leaves of sensitive crops.

Grey water: Water generated from households and other sectors (e.g. mosques) and not connected to a sewerage system can be treated and used under controlled conditions for irrigation of home gardens and trees. It consists of more than 50% of residential wastewater (like effluent of washing machines). Undigested or partially digested slurry or solid that

results from the storage or treatment of black-water in so-called on-site sanitation systems is called fecal sludge.

Wastewater usages: WW or TWW can be re-used directly or indirectly. In direct use of untreated WW, the WW from a sewage outlet is directly disposed on land where it is used for cultivation. In addition, direct use of

Table 3: Recommended water quality criteria for irrigation[15]

Constituent	Long-Term Use mg L ⁻¹	Short-Term Use mg L ⁻¹	Remarks
Aluminum	5	20	Can cause non-productiveness in acid soils, but soils at pH 5.5 to 8.0 will precipitate the ion and eliminate toxicity.
Arsenic	0.1	2	Toxicity to plants varies widely, ranging from 12 mg L ⁻¹ for Sudan grass to less than 0.05 mg L ⁻¹ for rice.
Beryllium	0.1	0.5	Toxicity to plants varies widely, ranging from 5 mg L ⁻¹ for kale to 0.5 mg L ⁻¹ for bush beans.
Boron	0.75	2	Essential to plant growth, with optimum yields for many obtained at a few-tenths mg L ⁻¹ in nutrient solutions. Toxic to many sensitive plants (e.g., citrus) at 1 mg L ⁻¹ . Usually sufficient quantities in reclaimed water to correct soil deficiencies. Most grasses are relatively tolerant at 2.0 to 10 mg L ⁻¹ .
Cadmium	0.01	0.5	Toxic to beans, beets, and turnips at concentrations as low as 0.1 mg L ⁻¹ in nutrient solution. Conservative limits recommended
Chromium	0.1	1	Not generally recognized as an essential growth element. Conservative limits recommended due to lack of knowledge on toxicity to plants.
Cobalt	0.05	5	Toxic to tomato plants at 0.1 mg L ⁻¹ in nutrient solution. Tends to be inactivated by neutral and alkaline soils.
Copper	0.2	5	Toxic to a number of plants at 0.1 to 1.0 mg L ⁻¹ in nutrient solution.
Fluoride	1	15	Inactivated by neutral and alkaline soils.
Iron	5	20	Not toxic to plants in aerated soils, but can contribute to soil acidification and loss of essential phosphorus and molybdenum
Lead	5	10	Can inhibit plant cell growth at very high concentrations.
Lithium	2.5	2.5	Tolerated by most crops at concentrations up to 5 mg L ⁻¹ ; mobile in soil. Toxic to citrus at low doses - recommended limit is 0.075 mg L ⁻¹ .
Manganese	0.2	10	Toxic to a number of crops at a few-tenths to a few mg L ⁻¹ in acidic soils.
Molybdenum	0.01	0.05	livestock if forage is grown in soils with high levels of available molybdenum.
Nickel	0.2	2	Toxic to a number of plants at 0.5 to 1.0 mg L ⁻¹ ; reduced toxicity at neutral or alkaline pH
Selenium	0.02	0.02	Toxic to plants at low concentrations and to livestock if forage is grown in soils with low levels of selenium.
Tin, Tungsten, & Titanium	---	---	Effectively excluded by plants; specific tolerance levels unknown
Vanadium	0.1	1	Toxic to many plants at relatively low concentrations.
Zinc	2	10	Toxic to many plants at widely varying concentrations; reduced toxicity at increased pH (6 or above) and in fine-textured or organic soils.
pH	6		Most effects of pH on plant growth are indirect (e.g., pH effects on heavy metals' toxicity described above).
TDS	500 - 2000 mg L ⁻¹		1000 mg L ⁻¹ , TDS in irrigation water can affect sensitive plants. At 1000 to 2000 mg L ⁻¹ , TDS levels can affect many crops and careful management practices should be followed. Above 2000 mg L ⁻¹ , water can be used regularly only for tolerant plants on permeable soils.
Free Chlorine	<1 mg L ⁻¹		Concentrations greater than 5 mg L ⁻¹ causes severe damage to most plants. Some sensitive plants may be damaged at levels as low as 0.05 mg L ⁻¹ .

TWW occurs when TWW is used for agriculture or other irrigation or recycling purposes. This requires storage and conveyance infrastructures to transport effluents from WWTPs directly to the site of application.

In indirect use of untreated WW, this water can be diluted with other water. Indirect TWW or untreated urban WW occurs for example, when water is injected first into a groundwater aquifer and then abstracted by farmers for agriculture. Moreover, TWW used for agricultural irrigation can be used to irrigate food crops that are intended for

human consumption or to irrigate crops that are either processed before human consumption or not consumed by humans.

Quality of Reclaimed TWW for Irrigation: Key Constituents

TWW is already reused (or reclaimed) in Qatar, [Figure 4b](#), for artificial GW injection, animal fodder irrigation, and highway irrigation. This water can also be reused for

Figure 5: Treatment technologies are available to achieve any desired level of water quality



irrigation of agricultural land besides other applications such as: landscape irrigation, urban and industrial uses, and recreational purposes with degree of treatments that suit each application. Figure 5 shows that according to the stages of WW treatment, the effluent of primary treatment (sedimentation) cannot be reused. The effluent of secondary (biological treatment) can be reused for surface irrigation of non-food crop irrigation provided it should have some quality measures such as pH between 6-9, BOD less than or equal to $30\text{MgO}_2 \text{ L}^{-1}$, total suspended solids (TSS) less than or equal to 30, total fecal coliform less than or equal to 200/100 mL, and salinity less than $1 \text{ mgCl}_2\text{L}^{-1}$ [11].

The effluent of tertiary (with P and N removal, disinfection and other advanced technologies) with chemical coagulation, filtration, and disinfection treatment can be applied to landscape and Golf course irrigation, toilet flushing, vehicle washing, food crop irrigation, unrestricted recreational impoundment, and indirect potable reuses.

The suitability of TWW reuse in agriculture irrigation depends on the key constituents of the TWW. The Food and Agriculture Organization [12], recommended TWW quality for irrigation, as shown in Table 2. The recommended water quality criteria for irrigation are given in Table 3.

The TWW reused salinity is one of the main factors affecting both the crops and the soil. The salinity expressed by EC_w, electrical conductivity reported in deci-Siemens per meter (dS m⁻¹) at 25 °C or total dissolved solids expressed in mg L⁻¹. It is noticed that: mg L⁻¹ = milligrams per liter; also, mg L⁻¹ ~ 640 x EC in dS m⁻¹. TWW of TDS < 500 mg L⁻¹ has no detrimental effect on soil, and of 500 < TDS < 1000 water can affect sensitive plants, and for 1000 < TDS < 2000 can badly affect many crops. Salt accumulation in soil depends on the TDS of the TWW and the rate at which salts are removed by leaching.

Chlorine is used for TWW disinfection, and chlorine residual in mg L⁻¹ of less than 1 mg L⁻¹ has no bad effect on plants, but at higher than 5 mg L⁻¹ cause severe damage to most plants. Moreover, sodium absorption

ratio (SAR) is affecting the soil and should be checked as shown in Table 2. The SAR is related to the sodium ions in irrigated water. When the reuse TWW has excess sodium ions, it negatively affects the soil. When sodium ions are present in soil above certain values relative to total dissolved salts dispersed in soil, they reduce the water and air infiltration rates into the soil. The SAR is the most reliable index of the sodium hazard of irrigation water, and is defined by:

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}}$$

The ion concentrations in the SAR definition are expressed in meqL⁻¹.

Nitrogen (N), phosphorus (P), and potassium (K) are nutrients minerals (called primary macronutrients). They are usually lacking in soil due to their uptake by plants to grow and survive; and usually added to soil as manure or synthetic mineral fertilizers. In addition, secondary macronutrients such as calcium, magnesium, and sulfur are needed for growing crops. N helps plants in rapid growth, increases seed and fruit production, and is usually applied as a fertilizer. P has an important effect on rapid growth and for blooming and root growth. These nutrients can be obtained from application of reclaimed water, so there is an added value in using reclaimed TWW. However, in light of ever-increasing regulatory requirements for nutrient removal to address loads to receiving streams, N and/or P are often removed in municipal WWTPs such as in Qatar.

Comparison of the quality of WWTPs tertiary WW effluents based on the proposed standards given by Ashghal (Table 1), and FAO recommendation for unrestricted use of TWW for agriculture, shows that more treatment is needed to lower the TDS of tertiary treated WW effluent from Qatar's WWTPs from 2000 mg L⁻¹ (Table 1) to 450 mg L⁻¹ (Table 2).

Micronutrients needed to grow crops include boron, copper, iron, chloride, manganese; molybdenum, and zinc, but in small quantities as given in Table 3. These are added as required for plant growth, but their concentration increase beyond the required amounts can be toxic.

Quality of Reclaimed TWW for Agriculture: Health Risks

The use of WW in agriculture can be risky from a health point of view, mainly due to its harmful constituents such as pathogens, i.e. disease-causing organisms that are usually present in untreated or partially treated (and to some level in TWW). Many excreta-related diseases can be spread by WW reuse in agriculture to workers in the WW-irrigated fields and those consuming WW irrigated foods, especially when eaten uncooked.

Municipal WW consists of mainly water (around 99.9%), and small amounts (concentrations) of constituents (suspended and dissolved organic and inorganic solids).

Table 4: Major constituents of typical domestic wastewater[13].

Constituent	Concentration, mg L ⁻¹		
	Strong	Medium	Weak
Total solids	1200	700	350
Dissolved solids (TDS)	850	500	250
Suspended solids	350	200	100
Nitrogen (as N)	85	40	20
Phosphorus (as P)	20	10	6
Chloride ¹	100	50	30
Alkalinity (as CaCO ₃)	200	100	50
Grease	150	100	50
BOD ₅	300	200	100

The constituent concentration, increases with decreasing the water consumption per capita. Table 4 shows the levels of the major constituents of strong, medium, and weak domestic WW[13]. Qatar high municipal water consumption per capita categorizes its WW constituents as weak.

The main constituents of municipal wastewater are:

- Pathogens
- Organic matter
- Nutrients (Nitrogen, Phosphorus, Potassium)
- Inorganic matter (dissolved minerals)
- Toxic chemicals

Some of these constituents (based on concentration and time of exposure) can be harmful to persons as they cause diseases by ingestion or contact.

Pathogens are classified as viruses, bacteria, protozoa and helminthes (Table 5) [14]. The viruses are highly contagious entero-viruses (*polio*, *echo*, *coxsackie*), hepatitis A and E, and a range of viruses causing diarrhea and gastroenteritis. Viruses are the smallest pathogens that can pass through filtration and be detected in drinking water. The bacteria include harmless and pathogenic coliforms, *salmonella*, *shigella*, and *enterococci*, and cause waterborne diseases such as typhoid, dysentery, cholera and other gastrointestinal illnesses. The protozoan pathogens are single-celled eukaryotic parasites. They survive as cysts outside their host, the most common being *Giardia lamblia* and *Cryptosporidium*.

High concentrations of excreted pathogens such as viruses, bacteria, helminthes eggs, and fecal coliforms are contained in WW, and at levels indicated in Table 4, and can survive for long periods as shown in Table 5[15]. The relative health impact of pathogenic agents is given in Table 6.

Pathogenic bacteria in WW have lower levels than the coliform group of bacteria, and are much easier to identify and enumerate (as total coliforms per 100 mL). *Escherichia coli* are the most widely adopted indicator of fecal pollution and they can also be isolated and identified simply, with their numbers usually being given in the form of fecal coliforms (FC)/100 mL of WW. A brief overview of the wastewater constituents, parameters, and

possible impacts are given in Table 6. These pathogens have the potential to cause disease when transmitted to humans in sufficient quantities. Intestinal nematodes pose the highest degree of risk of infection while bacteria pose low risk. Viruses exhibit the lowest risk[16].

The greatest concern when using WW for agriculture is due to the pathogenic micro- and macro-organisms. Comprehensive relative impacts of pathogenic constituents (Plant food nutrients, suspended solids, Pathogens, biodegradable and stable organics, dissolved inorganic substances, heavy metals, hydrogen ion concentrations, and residual chlorine in tertiary treated WW) on growing crops, human risk, discharging environment, and on soil are given in Table 7[17].

Helminthic diseases caused by *Ascaris* and *Trichuris* spp. are endemic in the population around the world where raw untreated WW is used to irrigate salad crops and/or vegetables are eaten uncooked. Numerous viruses may infect the intestinal tract and be passed in the feces, whereupon they may infect new human hosts by ingestion or inhalation.

Some information on the pathogens listed in Table 5 is given here [16]. The helminthes Ova and the parasitic worms are unlike external parasites such as lice and fleas that live inside their host. They live and feed off of living hosts, receiving nourishment and protection while disrupting their hosts' nutrient absorption, causing weakness and disease. They can live inside humans as well as other animals. Approximately 3 thousand million people globally are infected with helminthes. Because of their high mobility and lower standards of hygiene, school-age children and immune-compromised people are particularly vulnerable to these parasites.

The Nematodes are one of the most diverse of all animals. Nematode species are very difficult to distinguish; over 28 000 have been described, of which over 16 000 are parasitic. Nematodes have successfully adapted to nearly every ecosystem from marine to fresh water. Their many parasitic forms include pathogens in most plants and animals (including humans).

Coliforms include genera that originate in feces -"Fecal Coliforms" (e.g. *E. Coli*) as well as genera not of fecal origin - "Coliforms" (e.g. *Enterobacter*, *Klebsiella*, *Citrobacter*). The assay is intended to be an indicator of fecal contamination; more specifically of *E. coli* which is an indicator microorganism for other pathogens that may be present in feces. Presence of fecal coliforms in water may not be directly harmful, and does not necessarily indicate the presence of feces [18].

To prevent the transmission of communicable diseases, the WHO guidelines require that:

For restricted irrigation, no more than one viable human intestinal nematode egg per liter in the irrigated water [19].

For unrestricted irrigation, besides no more than one viable human intestinal nematode egg per liter, also no more than 1000 fecal coliform bacteria per 100mL.

Unrestricted irrigation, on the other hand, refers to all crops grown for direct human consumptions. These

Table 5: Occurrence and survival of pathogens[14].

	size [μm]	Common conc. In domestic sewage [number/100mL]	Infectious dose N_{50}	Usual survival time [days]		
				In Sewage	In Sewage	On Crops
Viruses	0.01 – 0.3	$10^2 - 10^4$	1 - 10	<50	<20	<15
Bacteria	0.2-10	$10^7 - 10^{10}$				
Faecal coliforms		$10^5 - 10^8$	106-1010	<30	<50	<15
<i>Salmonella</i>		$10^2 - 10^4$		<30	<30	<30
<i>Shigella</i>		$10^0 - 10^3$	10-20	<10	<10	<5
Protozoa	10-50 Cysts:4-6	$10^0 - 10^5$	1-20	<15	<15	<2
Helminthes	mm-cm eggs: 35- 70	100-103	1-10	months	months	<30

Table 6: Relative health impact of pathogenic agents[13].

Risk	Risk	Helminthes	
High (high incidence of excess infection)		(<i>Ancylostoma</i> , <i>Ascaris</i> , <i>Trichuris</i> and <i>Taenia</i>)	
Medium (low incidence of excess infection)	Risk	Enteric	Bacteria
		(<i>Cholera vibrio</i> , <i>Salmonella typhosa</i> , <i>Shigella</i> and possibly others)	
Low (low incidence of excess infection)	Risk	Enteric viruses	

include those eaten raw (e.g., lettuce, salads, cucumber etc.), and irrigation of sports fields and public parks, known as Category C. The recommended microbiological quality guidelines for wastewater use in agriculture are given as follows:

For category A reuse condition of Irrigation of crops likely to be eaten uncooked, sports fields, and public parks where Workers, consumers, public are exposed, the Intestinal nematodes(arithmetic mean no. of eggs per liter should be less than 1 (<1), and the Faecal coliforms (geometric mean no. per 100 mL) should be less than 1000 (<1000).

Similarly for category B reuse condition of irrigation of cereal crops, industrial crops, fodder crops, pasture and trees, where workers only are exposed, the Intestinal nematodes(arithmetic mean no. of eggs per liter should be less than 1 (<1), and no standard is recommended for Faecal coliforms. For category C reuse condition of Localized irrigation of crops if no exposure occurs, no applicable standards for intestinal nematodes(arithmetic mean no. of eggs per liter) or faecal coliforms[13].

Benefits of Using TWW for Agriculture

TWW is already available for recycling to farmers, or for releasing into aquifer recharge. The cost involved is much less than using desalted seawater (DW) for agriculture, or continue abstraction and desalination of GW (almost brackish). The latter means more mining of fossil water. Using TWW for agriculture is the best available solution, economically and environmentally. By

not directing the TWW for agriculture, many farmers will abandon their farms and the food security problem will worsen.

The alternatives to reuse TWW, other than in agriculture, are very limited, and the TWW is disposed of in lagoons or to the sea. The reuse of TWW enables GW to be used in new purposes such as expansion of irrigated farming, or for various environmental purposes. The major types of benefit that can be expected from the reuse of TWW are avoiding both the capital and recurrent cost of pumping GW, saving the cost of fertilizers as organic matter, N and P left in WW benefit the productivity of crops. In addition, TWW is a reliable source that is available all times.

While the WWTP are available for tertiary level treatment in Qatar, adjustments to an existing WWTP would be minimal. The real cost for using the TWW for agriculture is for installing new infrastructure for distributing the treated effluent from the WWTP to the irrigation areas (pipes, tanks, reservoirs, pumps, etc.) and recurring costs entailed (power for pumping, cleaning, etc.). The real cost of not using TWW for agriculture would be apparent from knowing the degree of food self-sufficiency in Qatar.

Growing Food in Qatar

Qatar's agricultural land in square kilometers (km^2) is shown in Figure 6a. The total cultivated area (arable land and area under permanent crops) in 2004 was 6322 ha (about 0.6% of total Qatar area), including 67 ha of greenhouses. The total area of arable land (annual crops + temp. fallow + temp. meadows) was 2651 ha, which

Figure 6a: Agriculture land in Qatar [14]



Figure 6b: Land areas occupied by the main agriculture products

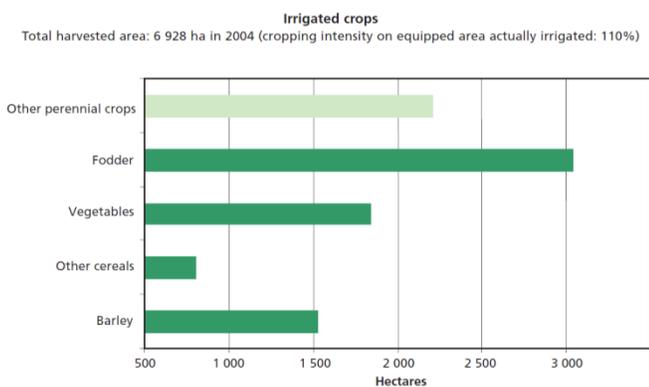
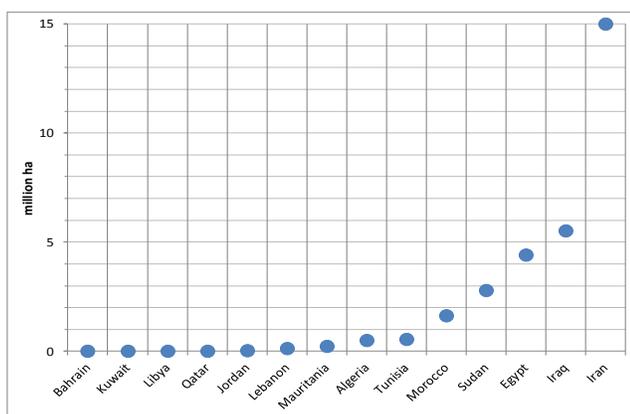


Figure 7: Irrigation potential, selected countries (2012) [23]



includes 1190 ha of vegetable crops and 1461 ha of field crops. The area under permanent crops amounts to 3412 ha and comprises 1478 ha of perennials and forage crops and 1934 ha of fruit trees. The land suitable for irrigation is 52 128 ha and most of it is classified as having marginal suitability for irrigation. All cultivated

areas are irrigated thus representing 12.1% of the land suitable for irrigation. The share of agriculture in gross domestic product (GDP) is 0.1%, [20, 21].

The long-term average water precipitation (long-term average) is 80 mm y⁻¹. The internal renewable water resources (long-term average) are 56 Mm³ yr⁻¹, with total actual renewable water resources of 58 Mm³ yr⁻¹. This gives total actual renewable water resources per capita as (for 2 M population) 29 m³ y⁻¹.Ca⁻¹.

The area of Qatar's agriculture land is given in Figure 6a[22]and the land area for the products is given in Figure 6b.

Irrigation potential of selected countries in the Middle East shows that Qatar, Libya, UAE, and Kuwait have the least land in 2012.

Qatar's food production is very limited. The 2012 food production reported by the UN Food and Agricultural organization (FAO) is given in Table 8a [23].

Table 8a gives the total production is 93 134 metric tons (MT) and cost \$M 54 902. The Arab Agriculture statistic yearbook [4]reported the following data in 2011:

- Rural population (77 000) to total Population (1 732 000) ratio is 4.44%.
- Agriculture labor (17 290) to total labor (1 277 450) ratio is 1.35%.
- Cultivated area (29 200 ha) to total area (1 143 000 ha) ratio is 2.54%.
- Permanent crop area is 2600 ha, seasonal cultivated area 10500 ha, uncultivated area 16 000 ha.
- Gross Agricultural Product (\$M162.09) to Gross Domestic Product (\$M171476.10) ratio is 0.095%.
- Per Capita Agricultural Product (\$93.55) to total per capita GDP (\$98963.65) ratio is 0.095%.
- Modern irrigation area is 280 ha.

The data of the Arab Agriculture statistic yearbook on Qatar's agriculture productions is given in Table 8b, and are compared with those given by the government's authorities, given between brackets.

Therefore, the total agriculture production is 114 790 metric tons (MT).

Modern irrigation area is 280 ha.

Livestock, poultry, and fish production:

Number of slaughtered sheep and goats 105420x20 average kg per head = 2108 ton, while production is 560 ton

- Number of slaughtered sheep and goats 105 420x20 average kg head-1 (560 ton)
- Production of camel meat _____ 2160 ton
- Production of poultry meat _____ 3650 ton
- Production of milk _____ 15890 ton
- Production of eggs _____ 37 800 ton
- Production of fish _____ 4030 ton
- Production of nitrogen fertilizers _____ 2908 200 ton (the highest in all Arab countries) Production of phosphate fertilizers (no data).
- Agricultural and food imports in 2011: Food (\$M 1451.81), agriculture (\$M1555.06), and total import (\$M 20924.52).

Table 7: Pollutants and contaminants in wastewater and their potential impacts through agricultural use[17]

Pollutant Constituent	Parameter	Impacts
Plant food nutrients	N, P, K, etc	<ul style="list-style-type: none"> - Excess N: potential to cause nitrogen injury, excessive vegetative growth, delayed growing season and maturity, and potential to cause economic loss to farmer - Excessive amounts of N, and P can cause excessive growth of undesirable aquatic species. (eutrophication) - nitrogen leaching causes groundwater pollution with adverse health and environmental impacts
Suspended solids	Volatile compounds, settle-able, suspended conditions and colloidal impurities	<ul style="list-style-type: none"> - Development of sludge deposits causing anaerobic conditions, - Plugging of irrigation equipment and systems such as sprinklers
Pathogens	Viruses, bacteria, helminthes eggs, fecal coliforms etc.	<ul style="list-style-type: none"> - Can cause communicable diseases (discussed in detail later)
Biodegradable organics	BOD, COD	<ul style="list-style-type: none"> - Depletion of dissolved oxygen in surface water - Development of septic conditions - Unsuitable habitat and environment - Can inhibit pond-breeding amphibians - Fish mortality - Humus build-up
Stable organics	Phenols, pesticides, chlorinated hydrocarbons	<ul style="list-style-type: none"> - Persist in the environment for long periods - Toxic to environment - May make wastewater unsuitable for irrigation
Dissolved inorganic substances	TDS, EC, Na, Ca, Mg, Cl, and B	<ul style="list-style-type: none"> - Cause salinity and associated adverse impacts - Phytotoxicity - Affect permeability and soil structure
Heavy metals	Cd, Pb, Ni, Zn, As, Hg, etc.	<ul style="list-style-type: none"> - Bio accumulate in aquatic organisms (fish and planktons) - Accumulate in irrigated soils and the environment - Toxic to plants and animals - Systemic uptake by plants - Subsequent ingestion by humans or animals - Possible health impacts - May make wastewater unsuitable for irrigation
Hydrogen ion Concentrations	pH	<ul style="list-style-type: none"> - Especially of concern in industrial wastewater - Possible adverse impact on plant growth due to acidity or alkalinity - Impact sometimes beneficial on soil flora and fauna
Residual chlorine in tertiary treated WW	free and combined chlorine	<ul style="list-style-type: none"> - Leaf-tip burn - Groundwater, surface water contamination (carcinogenic effects from organic chlorides formed when chlorine combines with residual organic compounds) - Greenhouse effect

Water needed for agriculture irrigation and food production represents a major share of total water withdrawal. While 2-4 liters per day is required drinking per capita, 3000 liters is required to raise the food per capita. Table 9 gives the main food import to Qatar with the equivalent virtual water.

The total main food import is 1 610 040 MT. This is to be compared with the production of 93 134 MT, representing 5.47% of total consumption, or 5.47% self-sufficiency.

The above data indicate that the total virtual water of the imported food is $6222 \text{ Mm}^3 \text{ yr}^{-1}$ (about $3111 \text{ m}^3 \text{ y}^{-1} \cdot \text{Ca}^{-1}$), which is about 25 times the water use in agriculture in Qatar (both GW and TWW). The present agriculture food growing can be sustained only if the low salinity abstracted GW can be desalinated, say by Reverse Osmosis (RO). The energy consumed by RO depends on the water salinity, which is much lower for the GW than seawater. The safe yield of groundwater, which is only $58 \text{ Mm}^3 \text{ yr}^{-1}$, and the present abstraction of about 250 Mm^3

Table 8a: Food and Agricultural commodities production [24].

Rank	Commodity Flag	Production (Int \$1000)	Production (MT)
1	Meat indigenous, chicken	13943	9789
2	Dates	11155	21843
3	Meat indigenous, sheep	5583	2051
4	Meat indigenous, goat	3858	1610
5	Eggs, hen, in shell	3574	4309
6	Tomatoes	3313	8964
7	Milk, whole fresh goat	2282	6800
8	Milk, whole fresh cow	2184	7000
9	Milk, whole fresh sheep	2142	5500
10	Milk, whole fresh camel	1773	5200
11	Pumpkins, squash and gourds	1281	7303
12	Meat indigenous, cattle	913	338
13	Eggplants (aubergines)	718	3358
14	Onions, dry	477	2270
15	Vegetables, fresh nes	409	2169
16	Maize, green	352	850
17	Cauliflowers and broccoli	309	1289
18	Cabbages and other brassicas	249	1665
19	Chillies and peppers, green	201	428
20	Lettuce and chicory	186	398

Table 8b: Qatar's agriculture production with data taken from [24].

	Cultivated area, ha	Productivity, kg ha ⁻¹	total production, ton
Wheat	10 (11)	3000 (2280)	30 (26)
Barley	180 (178)	3000	540 (535)
Maize	90	12556 (1225)	1130 (1130)
Vegetables	2000	16765	33530 (33528)
Tomatoes	290 (288)	29793 (30000)	8640
Onion	90 (86)	24667 (26000)	2220 (2223)
Water melon	10 (13)	12 000 (9540)	120 (124)
Melons and cantaloupes	80 (83)	9375 (9000)	750 (751)
Eggplant	140 (144)	25786 (25000)	3610 (3608)
Cauliflower	110 (115)	1545 (12000)	1380 (1376)
Pumpkin	(143)	9375 (20000)	750 (2852)
Sweet Pumpkin	(17)	25786 (22020)	3610 (370)
Lettuce	(115)	1545 (13000)	1380 (399)
Mulokhia	(21)	14583 (11980)	1750 (248)
Radish	(28)	14600 (15000)	730 (426)
Carrots	10 (7)	8000 (12000)	80 (84)
Broad beans, green	30 (20)	1000 (7500)	30 (148)
Okra	80 (75)	3750 (4000)	300
Fruits	2550	481.08 (2500)	21 380 (21554)
Dates	2370 (2366)	431.12 (8700)	20 700 (20696)
Citrus (lemon only)	100 (101)	25.11	280
Protected agriculture	130		11
Grapes (1550 trees)	4		
Pomegranates	(14)		
Mulberries	(13)		
Almond	(44)		

yr⁻¹ are not sustainable unless the aquifer storage and recharge (ASR) is applied, with WW treated to potable condition before its injection to aquifers. The total TWW capacity is expected to reach 634 860 m³ day⁻¹ (231.7 Mm³ yr⁻¹) in 2013, and 790 410 m³ day⁻¹ (288 Mm³ yr⁻¹) in 2016, and planned to be 819 410 m³ day⁻¹ (299 Mm³ yr⁻¹) by 2030 [7]. Therefore, the current TWW capacity is

almost equal or little higher than the GW used presently for agriculture. This means that utilizing the TWW in agriculture can double the agriculture production, and raises the country self-sufficiency from 5.47% to more than 10%.

Reuse of drainage water under Doha city (20 Mm³ yr⁻¹) of TDS in the range of 7 g L⁻¹ for irrigating salt-tolerant

Table 9: Qatar's main food imports in 2011, their specific virtual water, and self-sufficiency [25]

Item	Q in 1000 ton	Ton kg ⁻¹	Virtual water Mm ³	% Self sufficiency
Cereals (total)	468.97	0	0	0.37
Wheat and flour	150.28	1.6	240.448	0.02
Maize	13.7	0.71	9.727	7.62
Rice	134.18	3.4	456.212	0.00
Barley	127.76	1.91	244.022	0.42
Potatoes	42.94	0.287	12.324	0.05
Pulses (total)	14.95	1.754	26.222	0.00
Vegetables (total)	113.22	0.2	22.644	22.89
Fruits (total)	136.3	0.5	68.15	13.67
Sugar(refined)	41.11	0.318	13.073	0.00
Fats & oils(total)	55.81	3.83	213.752	0.00
Meat (total)	133.42		0	10.77
Red meat	38.96	15.415	600.568	8.68
Poultry meat	94.46	43.25	4085.395	11.60
Eggs	20.31	4.9	99.519	16.59
Milk and dairy products	130.28	1.000	130.28	22.65
Fish	23.67			37.30

crops, as suggested by FAO [15], or to be treated to irrigation requirements, a practice used in Kuwait. The long-term strategy should include ASR in the northern aquifer. Building infrastructure to supply the TWW for existing or new farm should be a priority in the time being.

CONCLUSION

Groundwater, mainly used for agriculture in Qatar, is overexploited, depleted, and its quality is deteriorating. The land with an underlying groundwater of total dissolved solids less than 1000 mg L⁻¹ (suitable for agriculture) is expected to disappear by 2018. To continue farming, the growing capacity treated wastewater should be utilized for agriculture irrigation. The treated wastewater key constituents affecting agriculture, as well as the health risks involved, have been addressed and should be considered in a dynamic monitoring strategy. The food import and production are presented to show the reasons for securing more water for growing more food. The findings of this study could be applied to all similar countries and mainly the countries of the Arabian Gulf.

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