Wastewater reuse: potential for expanding Iran's water supply to survive from absolute scarcity in future

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ABSTRACT

Iran, like many parts of the world, suffers from water scarcity and is located in one of the most arid regions. This is not only due to the low rates of precipitation received, but also due to the increase in demand on water resources for municipal, agricultural, and industrial uses. Wastewater reuse has proven to be effective and successful in creating a new and reliable water supply. Also, it can meet environmental needs, sustainable development, and a viable economy. There are two strategies for reuse implementation: (1) a future oriented approach allows structured planning within a broader wastewater management master plan and gives the greatest flexibility for reuse; (2) the available effluent quality from existing treatment plants defines the possible reuse option. According to the present situation in Iran, the second strategy is more reliable in preserving the country from absolute scarcity in future. Thus, the objective of this article is to understand the hidden comprehensive potential of reuse in three major categories: agricultural, industrial, and municipal uses, according to the improvement in the Falkenmark indicator.

Key words | Falkenmark indicator, reuse, wastewater management, water scarcity

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INTRODUCTION

As populations increase and development calls for increased allocations of groundwater and surface water for the domestic, agricultural, and industrial sectors, the pressure on water resources intensifies, leading to tensions, conflicts among users, and excessive pressure on the environment (FAO 2007). In the past 20 years, many indices have been developed to quantitatively evaluate water resources' vulnerability (e.g., water scarcity or water stress). The Falkenmark indicator (FI) is perhaps the most widely used measure of water stress. It is defined as the fraction of the total annual runoff available for human use. Many countries have been surveyed and the water usage per person in each economy has been calculated. Based on the per capita usage in Table 1, the water conditions in an area can be categorized as: no stress, stress, scarcity, and absolute scarcity (Brown & Matlock 2011).

A major study, a comprehensive assessment of water management in agriculture, reveals that one in three people today face water shortages (CA 2007). If all the freshwater on the planet were divided equally among the global population, there would be 5,000–6,000 m^3 of water available for everyone, every year. As experts consider that people experience scarcity below a threshold of 1,700 m^3/person, this global calculation gives an impression of abundance. However, the world's freshwater resources are distributed very unevenly, as is the world's population. Many parts of the world suffer from water scarcity. This is not only due to the low rates of precipitation they receive, but also due to the increase in demand on water resources for domestic, agricultural, and industrial uses (National Research Council 2007). Many countries are already well below the threshold value. Iran, like several other countries, is an extreme case with renewable water resources of about 1,600 m^3/person per year (MOAJ 2013).

According to Iran's Ministry of Energy (MOE 2010), Iran is located in one of the most arid regions in the world. It has

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Table 1 | Water barrier differentiation proposed by Falkenmark (1989)

Index (m^3 per capita)	Category/condition
>1,700	No stress
1,000–1,700	Stress
500–1,000	Scarcity
<500	Absolute scarcity

a national population of 75 million and covers a total area of about 165 million hectares. The average annual rainfall is 250 mm, approximately one-third of the global average, while the rate of evaporation exceeds 2,000 mm annually. Approximately 90% of the country is arid or semi-arid and is located in the interior and far south, which is characterized by long, warm, and dry periods, lasting sometimes more than seven months.

Iran's use of wastewater is best described as unplanned and uncontrolled. With increasing restrictions on conventional water resource development and wastewater discharges, wastewater reuse has grown over the past decade, particularly in arid regions, as a technology that can promote sustainable, efficient, and appropriate water use (Maksimovic & Tejada-Guibert 2001). Reuse has become an essential tool in addressing both water supply and wastewater disposal needs. This growing dependence on reuse makes it critical to integrate reuse programs into broader planning initiatives. Agriculture is the main water withdrawal (Ww) sector, with 86 billion cubic meters (bcm) in 2004, which remains identical to the amount of water withdrawn compared to 1993 (around 92%). However, municipal and industrial Ww was 6.2 bcm and 1.1 bcm, respectively (in 2004). Estimates suggest the water levels in Iranian aquifers have declined by an average of nearly half a meter every year over the last 15 years (Tajrishy 2012).

According to the UN development program, the level of Iran's per capita water resources is predicted to fall to as little as 816 m^3 in 2025, down from 2,030 m^3 in 1990. It is clear Iran is facing an impending water crisis of staggering proportions. Thus, the objective of this article is to understand the hidden comprehensive potential of reuse in three major categories: agricultural, industrial, and municipal uses, to preserve the country from water scarcity in 2025 according to the predictions.

METHODOLOGY

In general, Iran has three major sectors where wastewater reuse can be utilized, including for agricultural, industrial, and municipal uses. To evaluate this more precisely, the quantity and quality of effluent in each sector according to government statistics and predictions in the year 2021 (1,400 in terms of solar year) are presented. Reuse projects can be implemented if all participants have a full perception of the present and future trends.

Agriculture

The most important role of reuse in agriculture is related to drainage water. Agricultural drainage water is the excess water removed from the soil surface and soil profile of cropland, either by gravity or artificial means. According to the Vice Presidency for Strategic Planning and Supervision report (MOE 2010), the total amount of water used in the agricultural sector in 2021 (1,400 solar) will have increased to 94.5 bcm, while the proportion of drainage water will be around 30 bcm.

Industrial

The theory of industrial wastewater reuse was developed in 1980 as a major economic–environmental factor in water resource management, and practiced according to the UN Conference on Environment and Development 1992 (United Nations 1992; Campiglio *et al.* 1994). Water demand (WD) for the industrial sector is 10–30% of total WD, and in developed countries amounts to 50–80% (Kretschmer *et al.* 2002). Industrial WD in Iran as a developing country is 1–3% of total WD (MOE 2010). Currently, the total amount of water used in the industrial sector is around 1.6 bcm and that will reach 2.1 bcm in 2021; the total wastewater produced from this sector will be 1.08 bcm.

Municipal wastewater

Reuse of municipal wastewater is more possible than for other wastewaters due to its characteristics. Production rate is dependent on the population and collection rate.

Currently, total produced wastewater (Pw) in this sector is 4.5 bcm and will reach 5.2 bcm in 2021 (MOE 2010). Three kinds of common secondary treatment in Iran are activated sludge, lagoon, and oxidation ditch.

DISCUSSION

Potential of agricultural drainage water reuse in Iran

Iran has the largest area equipped for irrigation and the most potential for expanding irrigation. Under the present situation, 82.5 bcm of water is utilized for irrigation of 9.13 million hectares of irrigated agriculture (FAO 2014). About 3.0 million hectares of these areas are under irrigation networks (main and secondary canals), 4.7 million hectares is irrigated by means of traditional networks, and less than 1.1 million hectares are under fully equipped networks or pressurized irrigation systems (Abbasi *et al.* 2015). The water drainage in this section will be 30 bcm in 2021. There are several factors in determining limits, usages, purification, and discharge of drainage waters that include the volume of drainage water, the concentration of chemicals in it, and its location (Akram *et al.* 2007). The most important factors that determine the quality of drainage water are: climate, soil type, agricultural practices, geology, hydrology, irrigation methods, and the quality of water used in irrigation (Ayers & Westcot 1994). One of the most important effects of reusing drainage water is salt accumulation, turning good soil into saline soil and contaminating local groundwater with salt. Contamination of soil and water may also occur due to the presence of high concentrations of some mobile nutrients and herbicides and pesticides in agricultural drainage water. Therefore, proper assessment of the quality of drainage water is important in deciding possible reuse routes. The main approaches for reuse of agricultural drainage water are shown in Figure 1.

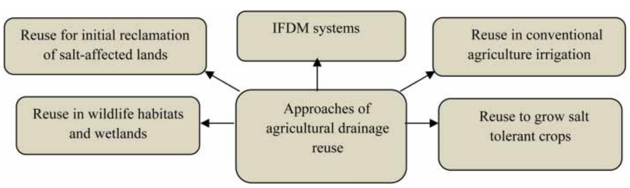

Figure 1 | Main approaches for reuse of agricultural drainage.

Drainage water can be reused in conventional agriculture or in saline agriculture, or in wildlife habitats and wetlands (Rhoades *et al.* 1992; Nasr & Zahran 2015); where the irrigation water is too saline to grow conventional agricultural crops, irrigation of halophytes might be considered. The maximum amount and kind of salt that salt-tolerant plants and halophytes can tolerate vary among species and varieties. Halophytes possess a special feature, as their growth is improved at low to moderate salinity levels (Goodin *et al.* 1999). One alternative developed over the last two decades involves sequential reuse of water on crops of increasing salt tolerance. This integrated on-farm drainage management (IFDM) system has evolved from an agroforestry-based phytoremediation concept to a combined approach utilizing multiple stages of plant growth followed by a final physical salt removal step (Cervinka *et al.* 1999). The IFDM system has been implemented in various forms at several sites, and has apparently been effective in avoiding toxic accumulations of salt in the root zones of the main production areas, and even in improving soil quality on previously salt affected lands (Cervinka *et al.* 2001).

Drainage water is normally of inferior quality compared to the original irrigation water. Adequate attention needs to be paid to management measures to minimize long-term and short-term harmful effects on crop production, soil productivity, and water quality at project or basin scale. The drainage water quality determines which crops can be irrigated. Highly saline drainage water cannot be used to irrigate salt-sensitive crops, but it can be used on salt-tolerant crops, trees, bushes, and fodder crops. A major concern in reuse applications is that drainage water from reused waters is often highly concentrated, requiring careful management.

Potential of industrial wastewater reuse in Iran

Construction and development of Iranian industrial wastewater treatment plants (WWTPs) are the same as in developed countries. According to the Iranian small industries and industrial parks organization report (ISIPO 2012), the first WWTP with a capacity of 1,700 m^3/day went into operation at Abbas-abad industrial park in 2005. Currently, about 37% of all industrial parks in Iran are equipped with

WWTPs and nearly 69% of all operational factories are connected to such treatment plants. Based on government data, the quantity of Ww and Pw for the present and future status of the industrial sector is presented in Table 2 (MOE 2010).

As illustrated, food, textile, chemical, and non-metallic mineral industries have more water consumption than other fields in both the present and future. Total industrial wastewater production is 0.668 bcm, 0.853 bcm, and 1.09 bcm in 2011, 2016, and 2021, respectively. The main quality parameters for some industrial wastewaters are shown in Table 3 (MOE 2010).

Treatment methods for industrial wastewater in Iran

Most processes used in the industrial WWTPs are biological (92.57%), of which 81.67% have a combination of aerobic and anaerobic units (Piadeha *et al.* 2014). For the main purpose of removing high biological oxygen demand (BOD) and chemical oxygen demand (COD) concentrations, integrated anaerobic/aerobic treatment systems are used for industrial wastewater treatment in Iran. This strategy compensates for the disadvantages of aerobic treatment units such as high energy consumption, high sludge production, and low organic loading rate (Chan *et al.* 2009). Up to now, around 20% of the total industrial treated wastewater in Iran has met the main parameters of the national effluent emission standards for irrigation purposes, including a pH between 6.5 and 8.5, BOD = 100 mg/L, COD = 200 mg/L, and total suspended solids (TSS) = 100 mg/L (Shaeri & Rahmati 2012) and, directly or by mixing with raw water, these effluents have been reused for landscape irrigation of industrial parks (ISIPO 2012). One of the best strategies for reuse of industrial wastewater is in eco-industrial parks by shifting the basis of industrial wastewater from a linear to a closed

Table 2 | Quantity of Ww and Pw in different industry fields

Year	2011		2016		2021	
Industry field	Ww (Mm^3)	Pw (Mm^3)	Ww (Mm^3)	Pw (Mm^3)	Ww (Mm^3)	Pw (Mm^3)
Food, beverage and tobacco	368.4	239.9	480.2	306.2	600.2	390.7
Textile, clothing and leather	180.1	96.7	229.9	123.5	293.4	157.6
Wood and timber services	5.7	4.7	7.3	6	9.3	7.6
Paper and printing	6.9	2.7	8.8	3.5	11.2	4.4
Chemical	262.6	110.4	335.2	141	427.8	180
Non-metallic mineral	250	190	390	152	407.2	163.6
Manufacturing of basic metals	111.5	39.1	142.4	50	181.7	63.7
Machinery and equipment	60.7	48.7	77.4	62.1	98.8	79.3
Power plants	43.8	6.7	55.9	8.6	71.4	10.9
Total	1,289.9	668.1	1,646.3	852.7	2,101	1,088.3

Table 3 | Quality parameters of food, textile, chemical, and metal industry wastewater in Iran

Main parameters		pH	Turbidity (NTU)	Alkalinity (Mg/L)	TSS (Mg/L)	BOD (Mg/L)	COD (Mg/L)
Food industry		8.7	195	369	473	1,412	1,494
Textile industry		6–13	61–87	500–800	100–5,000	100–4,000	150–10,000
Chemical industry	Pharmaceutical	6.5	175	128	315	300	580
	Cosmetic	10.3	175	138	315	300	580
	Paint	8.3	27,000	1,078	2,083	379	7,900
	Carton	10.2	7,675	1,260	47,980	26,750	94,160
Metal industry	Plating	6.7	9.5	170	41	15	61
	Color and glaze operation	10	138	580	26	40	80

loop system (Gibbs & Deutz 2005). Closed loop systems are obtained by installing proper WWTPs, which have been proposed by several studies (Gumbo *et al.* 2003; Visvanathan & Asano 2009; Adewumi *et al.* 2010; Bakopoulou *et al.* 2011). Advanced treatment units are necessary in order to completely treat the wastewater as a new water resource instead of fresh water (Piadeha *et al.* 2014).

Potential of municipal wastewater reuse in Iran

The main construction and development of municipal wastewater collection and treatment in Iran relates to the Islamic revolution period in 1978. Now, Iran, with 150 municipal WWTPs, covers 23 million inhabitants and the total collected wastewater is more than 3.5 million m^3/d. The actual total capacity of treated wastewater is 2.698 million m^3/d, with a nominal capacity of 3.802 million m^3/d, and 87 treatment plants with a total capacity of 1.598 million m^3/d are under construction (NWWE 2014). Based on government data (MOE 2010), the trends for produced municipal and rural wastewater to 2021 are shown in Figure 2. Typical main characteristics of BOD, COD, TSS, total Kjeldahl nitrogen (TKN), total phosphorus (TP), and fecal coliforms of municipal wastewater mixed with surface runoff, WWTP effluent, and output standards, published by the Iran Department of Environment for discharge and reuse of wastewater, are presented in Table 4 (Nasseri *et al.* 2008; MOE 2010).

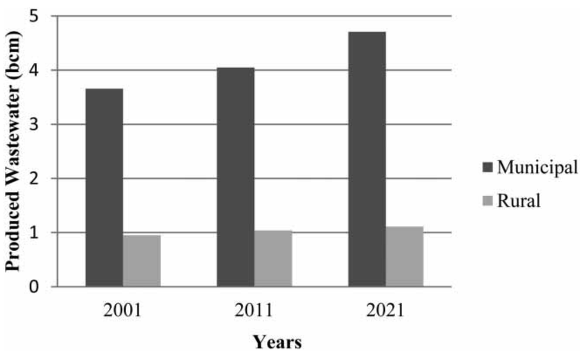

Figure 2 | Trend of produced municipal and rural wastewater.

Treatment methods of municipal wastewater in Iran

According to government data, activated sludge (AS), stabilization ponds (SP), and lagoon systems comprise 51%, 36%, and 13% of total WWTPs in Iran, respectively (MOE 2010). Table 5 presents the advantages and disadvantages of biological WWTPs' performance (Pescod 1992).

AS. AS is a widely used secondary process with a proven ability to remove a variety of micropollutants (Clara *et al.* 2005; Koh *et al.* 2009; Radjenovic *et al.* 2009; McAdam *et al.* 2010). However, meeting high nitrogen and phosphorus removal standards has proved to be challenging. Some WWTPs have successfully combined two processes, attached and suspended biomass, by adding biofilm carriers into the AS system (Ge *et al.* 2012; Zhang *et al.* 2014), so that high biomass concentrations can be obtained without overloading in the secondary clarifiers. Due to the presence of the biofilms, a long sludge retention time can be achieved for nitrifying bacteria (Randall & Sen 1996). Applying these modifications can direct AS systems towards sustainable reuse.

SP. Treatment in a waste SP is a natural process resulting from a complex symbiosis of bacteria and algae (Muñoz &

Table 4 | Main characteristics of wastewater mixed with surface runoff, and standards of discharge

Parameter	Unit	Wastewater + Surface runoff	Approved standards: Discharge into injection wells	Approved standards: Discharge into surface water	Approved standards: Agricultural reuse
BOD_5	Mg/L	60–220	30	30	100
COD	Mg/L	260–460	60	60	200
TSS	Mg/L	270–600	–	40	100
Total nitrogen	Mg/L	4–17	21	62.5	–
Total phosphorus	Mg/L	1.2–2.8	6	6	–
Fecal coliforms	MPN	10^5–10^6	400	400	400

Table 5 | Advantages and disadvantages of biological WWTPs' performance

Treatment systems Parameters	AS				SP	
	Conventional	Extended aeration	Oxidation ditch	Aerated lagoon	Aeration	Other
BOD removal	Average	Average	Good	Good	Good	Good
TSS removal	Good	Good	Good	Average	Average	Average
Virus removal	Average	Poor	Good	Average	Good	Good
Coliform removal	Poor	Average	Average	Average	Good	Good

Guieysse 2006). The pond systems provide a natural sustainable process for disinfection (Davies-colley *et al.* 2000; Craggs *et al.* 2004) without risk of by-products. Experience of full-scale plants has shown that a microbiologically safe effluent can be provided by this process (Mara & Pearson 1998). SP is also recommended for the treatment in order to reuse the effluent in agriculture and aquaculture because of its effectiveness in removing nematodes (worms) and helminth eggs (WHO 2006), while preserving some nutrients. If reuse is not possible, SPs may not be adequate for areas sensitive to eutrophication (Kayombo *et al.* 2004). Better removal of organic nutrients and suspended solids (SS) are obtained in the attached-growth waste stabilization ponds. However, correct operation and upgrading of this system in Iran can provide a good opportunity to reuse the effluents.

Lagoons. Wastewater lagoons are widely used worldwide where sufficient space is available, because they are a simple technology for wastewater treatment. Treatment lagoons can result in a significant reduction of fecal agents in the effluent through biological processes, but with considerable reductions in treatment cost (Oubrim *et al.* 2011). The major limitation of this type of treatment is the high effluent SS concentrations, mainly due to high concentrations of algal cells in the finished effluent. The presence of such algae can impose serious constraints on effluent reuse potential. Algae may be removed by several methods, but these are debatable as an economic strategy or from an operational practical point of view. Processes such as centrifugation, micro-straining, coagulation–flocculation, sand filters, and rock filters to scavenge algae from lagoon effluents have been discussed extensively in the literature (Kaya *et al.* 2007). Another method to increase the quality of lagoon effluent is the use of membrane technology. Upgrading of these systems in many arid regions of Iran may provide a good opportunity for wastewater reuse for agricultural purposes.

The effect of wastewater reuse on FI

As discussed earlier, the FI is used to show the water stress of a region. Table 6 shows the improvement in this indicator in Iran if reuse schemes are implemented. In fact, with four possible strategies (25, 50, 75, and 100% reuse) that the government can adopt for potential reuse in the three major sectors (agriculture, industry, and municipal), improvement in the FI is achievable. The quantity of WD, Pw, and country population (CP) are presented for 2021 (1,400 in terms of solar year) in Table 6, and the FI (m^3/year/capita) is calculated according to different strategies.

Table 6 | Improvement of FI according to different strategies

	WD (bcm)	PWW (bcm)	CP (M)	FI from 25% reuse (m^3/PCY)	FI from 50% reuse (m^3/PCY)	FI from 75% reuse (m^3/PCY)	FI from 100% reuse (m^3/PCY)
Agricultural	94.5	30	81	92.5	185	277.5	370
Industrial	2.1	1.08		3.3	6.6	9.9	13.2
Municipal	6.5	5.2		16	32	48	64
Total improvement of FI				111.8	223.6	335.4	447.2

CONCLUSION

As illustrated, Iran's location in one of the world's most arid regions, population growth, climate change, and economic development are causing a decrease in the FI scale regarding the World Health Organization warning about absolute water scarcity up to 2025. By considering the statistics, available water resources per capita will increase to 816 m^3 in 2025, down from 2,030 m^3 in 1990. In other words, the rate of water scarcity in Iran is 35 m^3/year/capita. This study has tried to describe the huge potential of reuse as a new water supply in three possible major categories: agriculture, industry, and municipal. Evaluation of the quality and quantity of these sectors showed that reuse is achievable for most Pws. If the reuse strategy is implemented completely (100% reuse), the new water supply provided from the agricultural, industrial, and municipal sector will be 370 m^3/year/capita, 13.2 m^3/year/capita, and 64m ^{3}/year/capita, respectively. Finally, an increment in the FI to 447 (m^3/year/capita) is achievable. Even with 100% recycling, there is still not enough water to lift Iran out of water stress ($FI = 447 + 816 = 1{,}263$ which is $<1{,}700$). When the FI is 1,263 (m^3/year/capita), Iran will still be under water stress, but that is better than a scarcity or absolute scarcity situation. However, to lift Iran out of water stress completely, some additional strategies must be implemented by governments. According to the information provided in this paper, these recommendations are as follows:

- Increase the number and quality of WWTPs.
- Development of municipal wastewater collection networks because of the huge amounts of missed wastewater (around 70% of the total Pw) that are removed through soil absorption systems (absorbed wells).
- Seawater desalination on a large scale thanks to the geographical position of Iran, which is located between the Caspian Sea and the Persian Gulf.
- Application of IFDM systems in the agricultural sector.
- Improvement of drainage and irrigation systems.

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