OPPORTUNITIES AND CHALLENGES FOR TREATED WASTEWATER REUSE IN THE WEST BANK, TUNISIA, AND QATAR

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ABSTRACT. *Harsh environment, severe aridity, and climate change create chronic water shortages in the Middle East. Technical challenges, socio-economic factors, and competing uses of water have escalated the difficulties in water planning at national and institutional levels. This research identifies opportunities and challenges associated with wastewater treatment systems and the potential for wastewater reuse in the West Bank, Tunisia, and Qatar through the following objectives: (1) identify the factors associated with successful and unsuccessful reuse schemes, (2) compare treated wastewater quality with end use application of treated wastewater, and (3) identify the governance and social challenges preventing the use of treated wastewater, specifically in agricultural applications. Water quality analyses and consultations with farmers, local stakeholders, and water and agriculture experts were conducted. Opportunities and challenges for treated wastewater reuse in agriculture are identified as the proximity of the treatment facility to agricultural areas, water quality, and motivation of farmers. With proper maintenance and appropriate monitoring, the modest (natural) treatment facilities in the West Bank and secondary treatment technologies in Tunisia are capable of producing effluent safe for use in production of certain agricultural products; however, in Qatar, despite massive investments in producing high-quality treated wastewater using advanced treatment technologies, there is little demand. Water policies, laws and acts, and action plans are urgently needed to be coupled and integrated for implementation.*

Keywords. *Arid lands, Food security, MENA, Wastewater treatment, Water reuse.*

Several global trends dictate the need for research in the area of treated wastewater irrigation. As the world population increases and more affluent lifestyles are assumed, global wastewater production is also increasing. This is particularly true in regions of intense development, such as the Persian Gulf. For example, more than 10 times as much wastewater is currently treated in Qatar than in 2004 (Sheierling et al., 2010). Global demand for crop calories is also expected to increase by 100% between 2005 and 2050 (Ray et al., 2013). These factors combine to place increased pressure on already strained global freshwater resources. Increasing global wastewater production and food demand highlight an opportunity for better management through the reuse of treated municipal wastewater in global agricultural production, particularly in regions of the world suffering from acute water shortages, such as the Middle East and North Africa (MENA).

Despite the logic of connecting treated municipal wastewater with the agricultural sector, several known limitations are associated with treated wastewater irrigation. Public and farmer perceptions of the practice are varied and often misinformed; policies dictating treated wastewater irrigation range from prohibitively strict to unenforced; the cost of connecting urban population centers where wastewater is produced to rural areas where agriculture is practiced is quite high; some public health risks are well understood (e.g., pathogens, heavy metals) and others are not yet fully known (e.g., pharmaceutical compounds, wastewater treatment by-products); and other factors such as degradation of the environment by soil salinization and groundwater degradation, lack of commitment by decision makers to enact comprehensive water and wastewater management policies, disparity between water pricing and actual water cost, a general societal preference for freshwater over treated wastewater, and the unreliability or lack of wastewater-related datasets are just some of the limitations associated with this practice (Lazarova and Bahri, 2005; Jiminez and Asano, 2008; Qadir et al., 2010; Maliva and Missimer, 2012; Shomar, 2013; Sato et al., 2013). Despite these challenges, there are also several known benefits of irrigation with treated wastewater, including improved water

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and food security, potential for decreased synthetic fertilizer inputs, and protection of sensitive coastal and riparian areas by preventing direct discharge of wastewater to surface waters.

Most national policies for treated wastewater reuse are based either on California's policy for wastewater reuse or on the World Health Organization (WHO) Guidelines of Safe Wastewater, Greywater, and Excreta Use (WHO, 2006). The implementation of policies like that of California, which are stricter and require disinfection as part of the wastewater treatment process, can be too costly for less-developed countries with only primary or secondary treatment of wastewater (Blumenthal et al., 2000). The criteria for treated wastewater reuse are generally based on two factors: (1) the occurrence of potentially toxic substances, and (2) the occurrence of pathogens. Other limitations may also be included in reuse policies, including types of crops to be irrigated, type of irrigation scheme to be used, restrictions on contact with farm workers and the public, days between last irrigation and harvest, and frequency of monitoring of water quality. Depending on the capacity and priorities of governments, policies may be in the form of recommended guidelines or national law.

This research focused on communities in the West Bank (Palestinian Territories), Tunisia, and Qatar (fig. 1). These three locations have distinct political and economic situations: the West Bank struggles under marginalized conditions, Tunisia is considered a regional success story for wastewater reuse, and Qatar is a wealthy country with its own unique development challenges. Together they tell a story about the motivating factors, opportunities, and challenges associated with treated wastewater irrigation across the MENA. Studies in the West Bank (e.g., Fatta, 2004; Haddad and Mizyed, 2003; Shaheen, 2003; Shomar et al., 2004, 2010), Tunisia (e.g., Bahri and Brissaud, 1996; Martijn and Redwood, 2005), and Qatar (e.g., Al-Zubari, 1998; Shomar et al., 2014) all point to wastewater reuse in agriculture as a means to address the challenges of wastewater disposal, treatment, and food and water security. This research identifies opportunities and challenges associated with wastewater treatment systems and the potential for reuse through the following objectives: (1) identify the factors associated with successful and unsuc-cessful reuse schemes, (2) compare treated wastewater quality with end use application of treated wastewater, and (3) identify the governance and social challenges preventing the use of treated wastewater, specifically in agricultural applications.

Methodology

Identifying Factors for Successful Reuse of Treated Wastewater

Household and farm-level opportunities and challenges associated with treated wastewater irrigation were identified by conducting consultations with farms and households engaged in agricultural production. Through review of published surveys related to the use of reclaimed water, and following the guidance of local partners, a common set of interview questions was developed for all three study locations. Due to the nuances of how water is managed, the specific technologies employed in each location, and the farmers' experiences with water reuse, guiding questions were modified in accordance with each population interviewed. In compliance with an institutional review board (IRB) approved protocol for research with human subjects, over several weeks in 2013, 20 heads of households in the study communities in the West Bank and 13 farmers associated with the study locations in Tunisia participated in consultations (semi-structured interviews) with the researcher and a translator. Participants were known entities to the local partners; they were either beneficiaries/end users of water reuse projects or neighbors of users. In Qatar, differences in the way in which agriculture is practiced (farms are typically owned by wealthy landowners and operated by hired labor) led to the researcher conducting consultations with seven experts, including researchers, community organization leaders, and ministry staff in the fields of water, agriculture, and food security. Questions focused on current irrigation practices, sources of irrigation water, crops grown, the value placed on various sources of irrigation water, satisfaction with services provided by organizations working in the water and agriculture sectors, and ways in which the household receives information about public services, including information about agricultural extension.

Figure 1. Map of study locations.

To understand the situation at a national level, entities responsible for developing wastewater reuse policy and monitoring its implementation were identified, and their representatives participated in IRB-approved consultations (semi-structured interviews). These individuals included municipality representatives, government officials, academicians, and wastewater treatment plant operators. Participants described their specific roles and responsibilities related to treated wastewater reuse in agriculture, opportunities and challenges they observed with regard to this practice, trends in regional and national water and agriculture, and specifics about the operation and maintenance of the facilities included in this study. Policy documents for each study location were obtained through literature review or from the policymakers themselves. Policies (whether in the form of national laws or guidelines) were reviewed and compared across various parameters (table 1).

Comparing Water Quality versus End Use Application

Influent and effluent samples were collected from each treatment facility. Unless otherwise noted in the results (table 3), samples were grab samples taken over a few days during the irrigation season. In some cases, it was possible to obtain 24 h composite samples, or historical datasets were made available to the researcher. Samples were taken in June in the West Bank, in October in Tunisia, and in July in Qatar.

The methods of analysis and the parameters analyzed from the collected samples depended on the capacity of the local laboratory. In general, pH, BOD_5, COD, EC, TKN, NO^{3-}, NH_3, PO_4^{3-}, and fecal coliform counts were obtained in local laboratories using the best available methods. For all locations, more stable analytes, including metals, phosphate, and other elements (aluminum, arsenic, boron, cadmium, chromium, cobalt, copper, iron, lead, manganese, mercury, nickel, and zinc), were analyzed from samples collected in 15 mL vials, acidified to pH < 2, and chilled and transported to Purdue University in accordance with standards for sampling, preservation, storage, and shipping of wastewater samples (APHA, 2005; USEPA, 2011). Samples were filtered with Whatman Grade 1 cellulose filter paper either in the field or at the laboratory prior to analysis with a Perkin-Elmer ELAN DRC-e inductively coupled plasma mass spectrometer (ICP-MS).

Wastewater treatment technologies and the quality of water produced were considered along with the end use of treated effluent to evaluate whether the level of wastewater treatment was appropriate, excessive, or insufficient. Operational costs of the treatment facility were also compared with the value added to the treated effluent.

Identifying Governance and Social Challenges

Visits to farms and households, and discussions with farmers, heads of households, and key stakeholders served to identify key issues related to public perception, adoption, project implementation and management, evaluation and monitoring, and capacity of the entities providing oversight of treated wastewater irrigation. Interviews with farmers and heads of households highlighted unique challenges from the end-user perspective, while interviews with experts and local government provided a regional and national perspective.

Facility Descriptions

This section describes the wastewater treatment facilities at each study location and their associated treated wastewater reuse schemes, as applicable. The scale of these facilities varies from urban to rural, from cities to villages,

Table 1. Criteria and maximum limits for irrigation with treated wastewater for crops consumed by humans.

	WHO[a]	California[b]	West Bank[c]	Tunisia[d]	Qatar[e]
Type of regulation	Guidelines	Law	Guidelines	Law	Law
Year established	1989	1978	2003	1975	2004
Code	-	T-22	ICS 13.030	NT 106.02	-
Minimum treatment required	Stabilization ponds[f]	Disinfection	Stabilization ponds	Stabilization ponds	Disinfection
Main treatment processes	Stabilization ponds or equivalent	Oxidation, clarification, filtration, and disinfection	Stabilization ponds or equivalent	Stabilization ponds or equivalent	Oxidation, clarification, filtration, and disinfection
Analytes					
BOD_5 (total) (mg L^{-1})	-	-	60	30	10
Suspended solids (mg L^{-1})	-	-	30	30	50
Turbidity (NTU)	-	2	-	-	-
pH	-	-	6 to 9	6.5 to 8.5	6 to 9
Conductivity (dS m^{-1})	-	-	-	7.0	-
Dissolved O_2 (mg L^{-1})	-	Present	>1	-	>2
Total coliform (MPN per 100 mL)	-	2.2[g]	-	-	2.2
Fecal coliform (MPN per 100 mL)	1000	-	1000	-	-
Helminths (eggs per 100 mL)	1	-	-	<1	<1
Residual available Cl (mg L^{-1})	-	Present	-	-	0.1
Salinity	-	-	SAR < 5.83	-	-
Metals	-	-	Yes	Yes	-

[a] WHO (2006).
[b] Spray irrigation (California EPA, 2014).
[c] Low-quality irrigation (Palestinian Ministry of Agriculture, unpublished).
[d] Angelakis et al. (1999).
[e] Qatar Ministry of Environment (unpublished).
[f] Stabilization ponds in series, with adequate retention time.
[g] Not to exceed 23 MPN per 100 mL in a single test, once per month.

Table 2. Wastewater generated, treated, and used in study locations.[a]

	West Bank	Tunisia	Qatar
Population in 2013	2,338,361[f]	10,937,521[b]	2,042,000[b]
Total water withdrawals[c]			
Volume (km^3 $year^{-1}$)	0.094[d]	2.85	0.444
Reporting year	2009	2001	2005
Agricultural water withdrawals[c]			
Volume (km^3 $year^{-1}$)	0.033[e]	2.165	0.262
Reporting year	2010	2000	2005
Wastewater generated[f]			
Volume (km^3 $year^{-1}$)	0.03[e]	0.287	0.055
Reporting year	2010	2009	2005
Wastewater treated			
Volume (km^3 $year^{-1}$)	0.002[e]	0.226	0.117
Reporting year	2010	2010	2012
Treated wastewater used			
Volume (km^3 $year^{-1}$)	0[e]	0.068	0.047
Reporting year	2010	2010	2007

[a] Except as otherwise noted, data were taken from the FAO Aquastat database (http://www.fao.org/nr/water/aquastat/main/index.stm).
[b] CIA (2014).
[c] Includes freshwater withdrawals, desalinated water produced, and direct use of treated wastewater.
[d] World Bank (2011).
[e] PWA (2012).
[f] Annual volume of domestic, commercial, and industrial effluents, and storm water runoff, generated within urban areas.

and from advanced treatment technologies to low-tech household systems. Each site was selected in consultation with local partners based on the facilities' potential to be part of a treated wastewater reuse scheme for agricultural production. In Tunisia and Qatar, the facilities selected were representative of the wastewater treatment technologies employed throughout the country. In the West Bank, the local partner encouraged a focus on decentralized wastewater treatment systems that were more likely to be integrated into a reuse scheme. An overview of the population, water withdrawals, and wastewater production in each location is provided in table 2.

West Bank, Palestinian Territories

The West Bank relies solely on groundwater from wells, springs, and an allotment from the Israeli Water Company (Mekorot) to meet domestic, agricultural, and industrial water demands. In 2011, the quantity of water available to the West Bank totaled 139.6 million cubic meters (Mm^3), with 88.3 Mm^3 going to domestic uses and most of the remainder allocated to agriculture (PWA, 2012). This figure does not account for harvested rainwater used for irrigation or household purposes. Bearing in mind the World Health Organization's recommendation of 150 L $capita^{-1}$ d^{-1}, the supply of water for domestic purposes in the West Bank is at a 128.2 Mm^3 deficit (PWA, 2012). About 5% of the population of the West Bank is not connected to a municipal water network, and about 60% of the population is not connected to a wastewater collection network (PCBS, 2011).

The occupation and governance of the West Bank contributes to an unstable economy, hinders the installation of infrastructure, blocks access to advanced technologies, and limits control over water and wastewater resources (Selby, 2003; Zahra, 2001). The Israeli government controls the planning and permitting of water projects in the West Bank. This reality, combined with a lack of coordination and cooperation with local authorities, results in projects that are often delayed, canceled, or have funding withdrawn.

The water and sanitation sector in the West Bank is supported by a combination of the Palestinian Water Authority and non-governmental organizations, and projects are funded largely by foreign aid. The West Bank has a total of seven wastewater treatment plants in Al-Bireh, Ramallah, Jenin, Tulkarm, Hebron, and East and West Nablus. The new East Nablus and Al-Bireh activated sludge plants are the only plants operating properly, while other systems are considered to be operating with moderate or poor efficiency due to overloading and poor management (PHG, 2008a). For the 60% of the population not connected to one of these wastewater treatment plants, they rely on septic tanks or cesspits to collect their household wastewater. Cesspits present significant risks to public and environmental health. Most cesspits in the West Bank are constructed without an impermeable base, which allows wastewater to infiltrate into the ground and contribute to pollution of groundwater. These pits also attract disease vectors, can be a source of foul odor, and may overtop when they are not evacuated regularly. Overtopping has obvious environmental and public health concerns, and it creates social problems, as overland flow of wastewater may end up on a neighbor's property. Paying a vacuum truck to empty a 5 m^3 cesspit may cost as much as 100 NIS (28 USD), which is not within the budgets of many households.

Treated wastewater irrigation has gained little traction in the West Bank as a result of mixed levels of public and farmer acceptance and political constraints on water use (Faruqui et al., 2001; Al-Sa'ed and Mubarak, 2006). Guidelines for treated wastewater irrigation have been developed by the Palestinian Ministry of Agriculture and Palestinian Standards Institute. Two household-level gray water treatment units and a village-level wastewater treatment system were selected for this study.

Gray Water Treatment Units

Two gray water treatment units (GWTUs) in the communities of Kharbatha al-Misbah (population 3,345) and Deir Qaddis (population 2,283), located 12 to 15 km west of Ramallah, were selected for evaluation (PCBS, 2013). In these communities, the Palestinian Hydrology Group (PHG), with financial support from international donors and in-kind support from the beneficiaries, has installed a total of eight household-level GWTUs, serving 81 individuals.

Approximately 500 household-level GWTUs have been installed in the West Bank and Gaza. Although design features and capacity may vary, most units installed in the region use gravity to allow gray water (water from the shower, sinks, laundry, and kitchen) to pass from the house through a conduit into a multistage treatment unit with chambers for suspended solids settling, anaerobic degradation by upflow through a gravel medium, and sometimes "polishing" through a gravel, sand, or activated charcoal filter (PHG, 2008b). A schematic of the unit generally installed by PHG is provided in figure 2. This unit operates similarly to a continuous-flow reactor and can process about 1 m^3 of gray water per day (i.e., as raw water is added from the house, product water is collected in tank 5). The only energy consumed by this system is for a small pump that moves water from the

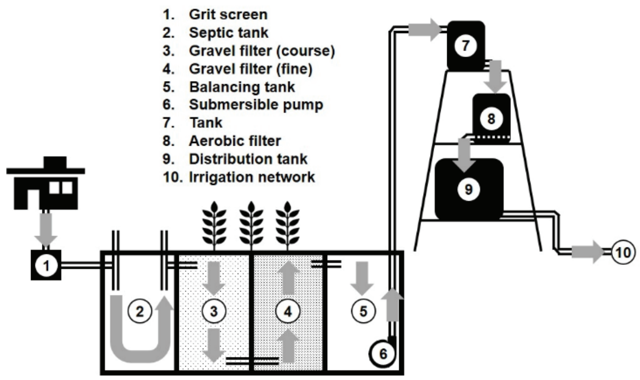

Figure 2. GWTU schematic (not to scale; adapted from PHG, 2008b).

anaerobic tank to the polishing phase, as shown in figure 2. These units are favorable in the West Bank because the cost per unit is low, the technology is simple to maintain and operate, the amount of land required is relatively small, no building permits are required for construction, and separation of gray water from black water reduces cesspit evacuation costs. A primary concern about decentralized wastewater management is water quality monitoring. These units are maintained by homeowners, so it is impossible to ensure that the unit is operating as intended, producing an effluent suitable for irrigation, and that users are employing safe handling practices. These challenges present a risk to both public and environmental health (McIlwaine and Redwood, 2010).

For this particular system, a special sample collection methodology was employed. To obtain a composite influent sample, the inlet pipe was disconnected from the treatment unit and diverted into the bottom of a 150 L barrel. An overflow pipe was connected to the top of the barrel to allow any gray water in excess of the barrel volume to enter the treatment unit. After approximately 24 h of collection, the water in the barrel was agitated, and a sample was taken. The gray water remaining in the barrel was dumped into the inlet of the treatment unit. The following day, a grab sample of effluent was collected from the final stage of treatment. The process was repeated three times over six days.

Bani Zeid Wastewater Treatment System

West Bani Zeid Municipality (total population 6,483) is located 27 km northwest of Ramallah. In 2004, the municipality, with support from the Palestinian Hydrology Group, constructed a wastewater treatment system to serve 100 houses in its first phase of construction. The system provides secondary treatment through a combination of an upflow anaerobic sludge blanket (UASB), two sedimentation chambers, and four constructed wetland cells planted with reeds. As of 2013, the system only had one operating constructed wetland cell and was connected to only 48 houses, processing approximately 40 m^3 d^{-1} of wastewater. The treatment system is not currently part of any wastewater reuse scheme, and effluent from the wetland cell is discharged into the wadi (ephemeral stream) below the system; however, a local olive oil cooperative has indicated interest in promoting irrigation with the facility's effluent among its members. The original design criteria for the Bani Zeid wastewater treatment system were as follows:

Upflow anaerobic sludge blanket (UASB):
- Influent COD: 1500 mg L^{-1}
- Effluent COD: 300 to 450 mg L^{-1}
- Design flow: 45.5 m^3 d^{-1} (100 connections, approx. 650 persons, assuming domestic water consumption of 70 L $capita^{-1}$ d^{-1}).

Constructed wetland:
- Design flow: 80 m^3 d^{-1}
- Influent BOD: 200 mg L^{-1} (assuming no UASB)
- BOD loading rate: 55 kg ha^{-1} d^{-1}
- Hydraulic loading rate: 0.047 m^3 m^{-2} d^{-1}
- Hydraulic retention time: 5 days
- Water depth: 40 cm
- Area: 0.18 ha per cell (four cells designed, only one constructed)
- Plant type: reeds
- Effluent BOD: 20 mg L^{-1}.

TUNISIA

Access to clean drinking water is nearly universal in Tunisia, and 90% of Tunisia's approximately 11 million people have access to improved sanitation facilities (WHO, 2013), with 84.2% of the population connected to one of the nation's 61 wastewater treatment facilities (Tunisia, 2013). About 33% of freshwater in Tunisia comes from surface water sources, while the remainder is from groundwater (FAO, 2016). Since 1965, Tunisia has been engaged in reusing wastewater in order to take pressure off groundwater resources susceptible to saltwater intrusion and has developed policies regulating how treated wastewater can be used, including a set national price per cubic meter (Shaheen, 2003). Wastewater infrastructure is managed by the Tunisian National Agency for Water and Sanitation (ONAS). Wastewater reuse in Tunisia is regulated by the 1975 Water Code, subsequent decrees and standards issued in 1989, and a list of crops and requirements for wastewater reuse projects released in 1994 and 1995, respectively. In brief, it is not permissible to irrigate vegetables that might be consumed raw (limiting reuse primarily to trees, forages, industrial crops, and landscaping), and all reuse projects must be approved and monitored by the Ministry of Agriculture, the Ministry of Environment and Land Use Planning, and the Ministry of Health (Angelakis et al., 1999; Bahri and Brissaud, 1996). Two wastewater treatment facilities in southern Tunisia and their associated agricultural areas were selected for evaluation based on their accessibility and history of effluent being reused in agriculture.

Gabès City Wastewater Treatment Plant and Dissa Agricultural Area

The Gabès City Wastewater Treatment Plant receives 20,000 m^3 d^{-1} of municipal wastewater from Gabès City (2004 population 116,323) (Tunisia, 2013). The facility, managed by ONAS, offers secondary wastewater treatment through an activated sludge wastewater treatment plant with an inlet screen, grit removal, aeration chambers, and clarifiers. Under normal circumstances, sludge would be removed regularly; however, following the Tunisian revolution of 2010-2011, the treatment plant did not receive this routine maintenance, and the treatment efficiency has decreased as a result. During the revolution, the laboratory and some of the equipment at the facility were vandalized, and historical records were destroyed by fire. Despite these challenges, the facility continues to operate, and a portion of the effluent is pumped to the Dissa Agricultural Area, located 8 km northwest of Gabès City, for irrigation purposes.

Dissa is a government project that was intended to increase employment and opportunities for irrigation with treated wastewater. Dissa is composed of twenty-four 8 ha plots, which are rented to participants in the project. When the project began in 1999, participants were offered a government loan equivalent to 29,000 USD, which came with a number of stipulations on the kinds of agricultural activities that should be undertaken at Dissa. Today, Dissa is essentially a failed project. Many of the original participants are renting their land to other tenants, and overall agricultural production is on the decline. Farmers cited poor project management, lack of a drainage network, lack of windbreaks, poor soil quality, and lack of water and electricity on site as some of the most significant challenges. Furthermore, many of the participants motivated by the government loan were formerly employed in the services industry and lacked experience in agriculture.

El Hamma Wastewater Treatment Plant and El Hamma Agricultural Area

The El Hamma Wastewater Treatment plant receives 2,000 m^3 d^{-1} of municipal wastewater from the city of El Hamma (2004 population 34,835) (Tunisia, 2013). The plant is managed by the same authority as the Gabès City plant (ONAS) and is of a similar design, i.e., providing secondary treatment through the use of activated sludge. The sludge is regularly removed and dried in sludge drying beds and then landfilled. The plant is located farther from a center of population than the Gabès City plant, so it has not been subject to as much scrutiny or vandalism, but the operation and maintenance of the plant still suffered following the revolution.

A portion of the effluent from this treatment facility is made available for farmers in an adjacent agricultural area. The El Hamma agricultural area differs from Dissa in that the lands are privately owned by farmers, and the El Hamma agricultural area is not part of any government project. Farmers at El Hamma are motivated by the opportunity to use the relatively inexpensive treated wastewater to produce fodder for their livestock or to sell at local markets. The El Hamma agricultural area also benefits from proximity, as most of the farms are within sight of the wastewater treatment plant.

Qatar

Qatar is an oil-rich and water-poor country with an aggressive goal to become 40% self-sufficient in food production (Shomar et al., 2014; Doha News, 2014). Qatar's population has experienced extraordinary growth over the last decade. Despite this growth, the country has managed to maintain an impressive level of infrastructure. Access to clean drinking water and improved sanitation are both universal, and within the major population center of Doha, 95% of the buildings are connected to a sewage network (Qatar, 2005). Desalinated water fulfills nearly all the water demand in Qatar, while agricultural demand is fulfilled through a mix of groundwater, desalinated water, and treated wastewater. About 67% of treated domestic wastewater in Qatar is delivered free-of-charge to Doha for irrigation of landscapes (50%) and to commercial farms for irrigation of fodder crops (17%), while the remainder is used in groundwater injection (21%) and discharged into a lake at Abu-Nakhla (Amer and Abdel-Wahab, 2009; Qatar, 2005, 2014). The Qatar Ministry of Environment regulates and sets standards for treated wastewater irrigation.

Doha South Sewage Treatment Works

Doha has two major wastewater treatment facilities and some additional smaller treatment plants that serve industrial operations and outlying areas. Both major wastewater treatment facilities (Doha South Sewage Treatment Works and Doha West Sewage Treatment Works) are activated sludge plants, constructed in the late 2000s, that use membrane filtration and chlorine disinfection. Doha South Sewage Treatment Works (STW) is under full operation and maintenance (O&M) of a French company (Degremont). Doha South STW can process approximately 200,000 m^3 d^{-1}, and the treatment processes include all levels (primary, secondary, tertiary, and selected advanced steps such as ultrafiltration and sand filters).

Results and Discussion

A summary of the water quality analyses conducted for each research location is provided in tables 3 and 4. An overview of the characteristics of each wastewater treatment facility is presented in table 5. Through analysis of water quality and stakeholder consultations, a number of successful and unsuccessful approaches to treated wastewater irrigation were identified. Each location had its own unique experience and motivation for reusing treated wastewater. Despite these unique situations, some shared factors that led to the success or failure of a wastewater reuse scheme included proximity of the treatment facility to agricultural areas, water quality, and proper motivation. These factors have implications for project design, project management, public health, environmental health, cost of operation, and technology selection.

Proximity

Decentralization of wastewater treatment with GWTUs can be an economical solution to sanitation for rural and peri-urban areas. Advocates for decentralization of wastewater treatment claim that the opportunities for reuse are greater when wastewater treatment is closer to potential locations of application, rather than being transported to a centralized treatment facility (Parkinson and Tayler, 2003). However, decentralization poses some challenges and risks in that it puts the responsibility of management and monitoring of treated wastewater quality on a household or municipality that may not have the training or capacity to handle these responsibilities. In this study, close proximity between wastewater treatment facilities and reuse locations is a factor for success.

Table 3. Summary of wastewater quality and respective standards for treated wastewater reuse.

	pH	BOD_5 (mg L^{-1})	COD (mg L^{-1})	EC (µS cm^{-1})	TKN (mg L^{-1})	NO_3^- (mg L^{-1})	NH_3 (mg L^{-1})	PO_4^{3-} (mg L^{-1})	FC (cfu 100 mL^{-1})
West Bank									
Standard[a]	6 to 9	60	150	NS	NS	40	15	NS	1000
Kharbata al-Misbah GWTU									
Influent (*n* = 3)[b]	5 to 6	470 to 867	1873 to 1170	2380 to 2640	-	0.93 to 1.02	6.0 to 30.5	-	2.02E7 to 2.92E6
Effluent (*n* = 3)	7	35 to 183	70 to 287	3050 to 3690	-	13.0 to 21.2	38.1 to 51.1	-	1.067E3 to 3.76E6
Deir Qaddis GWTU									
Influent (*n* = 3)	5 to 8	642 to 867	1537 to 3273	2540 to 4090	-	<0.05 to 0.69	4.9 to 30.9	-	8.76E6 to 8.34E7
Effluent (*n* = 3)	7	204 to 444	403 to 1673	2560 to 3050	-	<0.05 to 0.83	25.8 to 33.6	-	2.44E5 to 9.55E5
Bani Zeid WWTS									
Influent (*n* = 4)	7	177 to 807	606 to 2420	3090 to 3620	-	<0.05 to 5.74	91.1 to 148.9	-	5.68E6 to 4.32E7
Effluent (*n* = 4)[c]	7	60 to 133	220 to 337	3600 to 3870	-	<0.05 to 11	128.8 to 145.2	-	1.52E5 to 3.00E5
Tunisia									
Standard[d]	6.5 to 8.5	30[e],[f]	90[e],[f]	7000	NS	NS	NS	NS	NS
Gabès City WWTP									
Effluent (2004)[g]	-	2.5 to 5.9	17.1 to 44.9	-	2.2 to 3.9	4.1 to 37	-	2.2 to 49.3	2.00E2 to 6.50E2
Effluent (2013) (*n* = 4)	7	31.0 to 60.0	46.5 to 139.4	4520 to 4420	-	0 to 14.6	-	8.20 to 10.44	-
El Hamma WWTP									
Effluent (*n* = 2)	7 to 8	20.0 to 20.8	223.9	5120 to 5140	-	23.5 to 39.0	-	3.6 to 4.5	1.19E6 to 2.10E6
Qatar									
Standard[h]	6 to 9	10	150	NS	NS	NS	15	30	2.2
Doha South STW									
Influent (*n* = 1)	7.18	156[i]	395[i]	1643	-	-	-	8.5[i]	-
Effluent (*n* = 1)	7.16	1[i]	19[i]	2093	4.6[i]	-	-	1[i]	0[f]

[a] Standard for "low-quality" treated wastewater irrigation (Palestinian Ministry of Agriculture, unpublished); NS = no standard exists.
[b] *n* refers to the total number of samples collected (also the number of days over which samples were collected).
[c] This facility was rehabilitated shortly after these samples were taken.
[d] Standards derived from 1975 Water Code, and subsequent decrees and standards issued in 1989; NS = no standard exists.
[e] 24 h composite sample.
[f] Except with special authorization.
[g] Adapted from Meftah (2004).
[h] Qatar Ministry of Environment (unpublished); NS = no standard exists.
[i] Average quality as reported by Doha South STW (unpublished).

Table 4. Summary of heavy metal concentrations in collected samples.

	Aluminum (mg L^{-1})	Arsenic (mg L^{-1})	Boron (mg L^{-1})	Cadmium (mg L^{-1})	Chromium (mg L^{-1})	Cobalt (mg L^{-1})	Copper (mg L^{-1})	Iron (mg L^{-1})	Lead (mg L^{-1})	Manganese (mg L^{-1})	Mercury (mg L^{-1})	Nickel (mg L^{-1})	Zinc (mg L^{-1})
West Bank													
Standard[a]	5	0.1	0.7	0.1	0.1	0.05	0.2	5	0.2	0.2	0.01	0.02	2
Kharbata al-Misbah GWTU													
Influent (*n* = 3)[b]	0.447 to 1.330	0.002	0.170 to 0.256	<0.001	0.005 to 0.011	<0.001 to 0.001	0.025 to 0.095	0.931 to 2.420	0.004 to 0.029	0.064 to 0.083	<0.001 to 0.003	0.013 to 0.009	0.268 to 0.385
Effluent (*n* = 3)	0.014 to 0.438	0.014 to 0.018	0.227 to 0.244	<0.001	0.004	0.002	0.006 to 0.012	1.550 to 1.780	0.002 to 0.004	0.072 to 0.091	<0.001 to 0.002	0.013 to 0.014	0.015 to 0.028
Deir Qaddis GWTU													
Influent (*n* = 3)	0.448 to 2.360	0.002	0.177 to 0.409	<0.001	0.005 to 0.008	<0.001	0.021 to 0.075	0.610 to 0.689	0.007 to 0.008	0.042 to 0.072	<0.001	0.008 to 0.013	0.883 to 1.700
Effluent (*n* = 3)	0.205 to 0.619	0.002	0.288 to 0.318	<0.001	0.003 to 0.005	<0.00 to 0.001	0.002 to 0.017	0.980 to 4.240	0.002 to 0.005	0.052 to 0.060	<0.001	0.008 to 0.012	0.072 to 0.299
Bani Zeid WWTS													
Influent (*n* = 4)	0.432 to 0.872	0.001 to 0.002	0.219 to 0.270	<0.001	0.003 to 0.004	<0.001	0.017 to 0.038	0.579 to 1.370	0.004 to 0.009	0.064 to 0.092	<0.001	0.007 to 0.012	0.221 to 0.352
Effluent (*n* = 4)	0.196 to 0.286	0.002 to 0.003	0.247 to 0.255	<0.001	0.003	<0.00 to 0.002	0.006 to 0.038	0.696 to 0.918	0.002 to 0.005	0.092 to 0.100	<0.001	0.007 to 0.009	0.043 to 0.075
Tunisia													
Standard[c]	NS	0.1	3	0.01	0.1	0.1	0.5	5	1	0.5	0.001	0.2	5
Gabès City WWTP													
Effluent (*n* = 4)	<0.001 to 0.008	0.005 to 0.007	0.528 to 0.550	<0.001 to 0.007	<0.001	<0.001	0.003 to 0.013	0.693 to 0.798	<0.001 to 0.002	0.070 to 0.075	<0.001	<0.010 to 0.013	0.024 to 0.233
El Hamma WWTP													
Effluent (*n* = 2)	0.046 to 0.055	0.007	0.428 to 0.440	<0.001	<0.001	<0.001	0.007 to 0.022	0.047 to 0.049	0.001	0.047 to 0.049	<0.001	0.010 to 0.012	0.031 to 0.038
Qatar													
Standard[d]	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Doha South STW													
Influent (*n* = 1)	0.037	0.001	0.208	<0.001	0.002	<0.001	0.005	0.330	<0.001	0.021	0.004	0.004	0.006
Effluent (*n* = 1)	<0.001	0.001	0.234	<0.001	<0.001	<0.001	0.002	0.259	<0.001	<0.001	<0.001	0.003	0.008

[a] Standard for "low-quality" treated wastewater irrigation (Palestinian Ministry of Agriculture, unpublished); NS = no standard exists.
[b] *n* refers to the total number of samples collected (also the number of days over which samples were collected).
[c] Standards derived from 1975 Water Code, and subsequent decrees and standards issued in 1989.
[d] Qatar Ministry of Environment (unpublished).

Table 5. Wastewater treatment technologies, associated costs, and characteristics.

Plant and Technology	Year Built	Design Capacity (m^3 d^{-1})	Actual Flow (m^3 d^{-1})	No. of Connections (No. of persons)	Cost to Construct (USD)	Source of Capital	Energy Consumption	Applications of Treated Wastewater
West Bank								
Kharbata al-Misbah GWTU (gray water treatment unit)	2012	1	1	1 (11)	$2,900	Palestinian Hydrology Group (foreign grants), in-kind labor	20 W m^{-3} [a]	Home gardens (100%)
Deir Qaddis GWTU (gray water treatment unit)	2012	1	1	1 (12)	$2,900	Palestinian Hydrology Group (foreign grants), in-kind labor	20 W m^{-3} [a]	Home gardens (100%)
Bani Zeid WWTS (inlet screens, UASB, and constructed wetland)	2004	45.5	20[a]	48 (300[a])	$65,000	Palestinian Hydrology Group (foreign grants), Palestinian Water Authority	None	Discharged to wadi (100%)
Tunisia								
Gabès City WWTP (inlet screens, activated sludge, and clarifier)	1995	17,260	20,000	20,182 (30,565)	$4,112,362	Government	-[b]	Tree and fodder crops (30%) and industry (10%)
El Hamma WWTP (inlet screens, activated sludge, and clarifier)	2004	4,060	5,000	7,046 (8,333)	$2,277,616	Government	-[b]	Tree and fodder crops (60%)
Qatar								
Doha South STW (inlet screens, grit removal, SBR with activated sludge, sand filtration, ultrafiltration, and chlorination)	1960 (expanded in 2006 and 2013)	200,000	200,000	-[b]	$350,000,000[a]	Government	0.2 kWh m^{-3} [a]	Landscape (60%) and groundwater injection (40%)

[a] Approximate figure calculated using records available from facility or best available information.
[b] Data not available.

For the households in the West Bank that use GWTUs, due to the lack of sanitation infrastructure in rural Palestinian communities, the alternative for these households would be discharge or disposal of gray water. Treatment and reuse of gray water, despite its potential risks, presents an opportunity for increased water security, nutrient recycling, and increased environmental protection over direct discharge. In these households, gray water is collected, treated, and reused at the same location. Water losses are minimal because of the short conveyance distance, and there is increased transparency and confidence in the treatment process. Furthermore, given the political restrictions placed on water and sanitation projects in the West Bank, small-scale, household-level reuse seems to hold the most opportunity for success.

The El Hamma agricultural area in Tunisia is a successful example of treated wastewater reuse, and part of that success may be attributed to proximity. At El Hamma, the agricultural area is adjacent to the wastewater treatment facility; as a result, little additional infrastructure is required to connect the treated wastewater source with croplands. In contrast, farmers at the Dissa agricultural area, which is 8 km from the Gabès City treatment plant, claimed that they often experienced ten or more days in a row without irrigation water as a result of operation and maintenance issues. Close proximity decreases the infrastructure necessary for conveyance and results in fewer operation and maintenance challenges, decreases costs, and increases the likelihood of uninterrupted delivery of water.

In Qatar, the primary consumers of treated wastewater are industrial farms and companies that maintain the landscaping around Doha. Wastewater treatment facilities are relatively far from the locations where the effluent is used, so treated effluent is typically transported by tanker truck. The relatively low cost of energy in Qatar makes this option viable, and because the consumer is a municipality or company, rather than individuals, perception and transparency in the wastewater treatment process is less of an issue.

WATER QUALITY

While the agricultural sector is generally more forgiving than others when it comes to water quality, poor water quality is linked with concerns about farmworker and crop safety, sustainability of agricultural practices, perception, and suitability of cultivation of certain crops. As a result, water quality is a significant factor for determining whether a treated wastewater irrigation scheme will be successful. As shown in table 3, the performance of the Palestinian and Tunisian facilities is outside of the national standards for several parameters; however, one parameter, i.e., high electrical conductivity (EC), represents a significant challenge associated with treated wastewater irrigation. While the EC levels do not exceed the Tunisian national standard (7,000 $\mu S\ cm^{-1}$), and no standard for salinity is specified by Palestinian guidelines, an EC level greater than 3,000 $\mu S\ cm^{-1}$ may impose a severe restriction on crop yield (Ayers and Westcot, 1985). At several of the study sites, EC increased in the effluent water. While the sample sizes are too small to make firm conclusions, an increase in temperature between influent and effluent, accumulated salts in the treatment facility, and/or increases in ion concentrations may be the cause of this increase. None of the treatment facilities included in this study was designed to treat for salinity, so special management practices may be needed to mitigate high salinity and ensure successful crop production.

In Tunisia, the salinity may be due in part to the degraded infrastructure between the municipal connections, treatment facilities, and agricultural areas, which allows intrusion of salt water into the system. As water quality has only been consistently monitored at the exit of the wastewater treatment plants, and not on site at Dissa or El Hamma, it is unclear how long salinity levels have been elevated. Farmers at the Dissa and El Hamma agricultural areas indicated some challenges in growing certain types of crops, particularly pomegranates and olive trees. High salinity of the treated wastewater, combined with the lack of drainage networks at the farms, may explain these difficulties. Similarly, in the West Bank, there has been no regular monitoring of system performance or effluent quality at the Bani Zeid wastewater treatment system since its installation; at the time of sampling, only minimal maintenance had been conducted. Since that time, a full rehabilitation has been carried out on the facility. The high salinity at Bani Zeid is likely a result of extremely concentrated influent wastewater (due to water scarcity and household conservation practices in the West Bank) and an inability of the treatment system to remove salinity.

While the quality of effluent from the Tunisian and Palestinian treatment facilities represents a challenge for reuse, the effluent from Doha South STW highlights a significant opportunity. This facility is well managed and, as is evident in table 3, produces a consistently high-quality effluent suitable for a number of applications.

Motivation

Consultations with heads of households, farmers, stakeholders, and experts at each study location provided insights into the perceptions of treated wastewater reuse in each context, as well as the factors motivating (or discouraging) farmers toward the practice. Nowhere was the challenge of participant motivation more obvious than at the Dissa Agricultural Area in Tunisia. Dissa was conceived under a strict model: participants were provided with land, access to treated wastewater, and large bank loans and were required to buy specific items (irrigation conduit, alfalfa seed, pomegranate trees, livestock supplies, etc.). Furthermore, many of the participants selected for the project had no experience in agriculture but were instead out-of-work factory employees or originally worked in service industries. At the time of this study, many farmers had abandoned the project, and many of the original participants were unable to repay their initial bank loans. Given that Dissa was a somewhat experimental project for treated wastewater reuse on arid lands, participants with some demonstrated agricultural aptitude should have been selected for the project, rather than those motivated primarily by the bank loan. In contrast, farmers at the El Hamma Agricultural Area own their land and are not part of any government project or initiative for reuse. The farmers at El Hamma are motivated by the opportunity to work in agriculture and use a relatively inexpensive source of water to produce fodder and tree crops.

In the West Bank, the reuse of wastewater is motivated by need and economics. Freshwater supplies in the West Bank are limited, and water is relatively expensive, so alternative sources of irrigation water are sought in order to have a sufficient quantity of water for a home garden. In addition, for families not connected to a sewer system, reuse of gray water correlates to a savings in wastewater pumping costs. In contrast, there is very little motivation for treated wastewater reuse in Qatar. Being a wealthy country with expectations for a high standard of living, there is a societal preference for fresh or desalinated water rather than reusing treated wastewater in agriculture.

Comparing Water Quality versus End Use Application

For all locations, treated wastewater quality was compared with local standards for agricultural reuse (table 3) to determine if the effluent is suitable for irrigating agricultural production. Heavy metal concentrations (table 4) were well below standard limits and below detectable limits (<0.001 mg L^{-1}) for many analytes.

In the West Bank and Gaza, household GWTUs have been promoted as an economical means to reduce flows into household septic tanks or cesspits and provide an alternative source of irrigation water for Palestinian household gardens. Studies have found that processing water through GWTUs in this way can decrease the concentration of suspended solids, chemical oxygen demand, biochemical oxygen demand, total nitrogen, and fecal coliforms (Al-Hamaiedeh and Bino, 2010; Al-Jayyousi, 2003). However, no monitoring of water quality is conducted for the GWTUs due to the lack of financial resources among the municipalities and organizations involved in water and sanitation to run a water quality monitoring program for gray water and total wastewater effluent. Effluent from both of the GWTUs included in this study exceeded the limits for irrigation with treated wastewater set by the Palestinian Ministry of Agriculture for fecal coliforms, BOD_5, COD, total suspended solids, and ammonia (table 3). This treated gray water is used on home gardens to produce vegetables; however, no adverse health effects or impacts on crop quality were noted by the household members during consultations. In fact, these households enjoyed an improved economic situation because they were able to sell their vegetables in local markets. The health risk indicated by the presence of fecal coliforms seems to be mitigated by the use of drip irrigation and washing or cooking of the produce harvested from the home gardens.

Tunisia's policies for reuse of treated wastewater in agriculture seem to be well matched with the country's wastewater treatment capacity. With a return to the high standards in the water sector that existed prior to the 2010-2011 revolution, and continued agricultural extension to farmers, we expect that treated wastewater receiving secondary treatment will play an important role in the production of tree and fodder crops in Tunisia.

To address sanitation challenges, engineers and developers must select a wastewater treatment technology that is appropriate for the local community, considering the local environmental conditions and technical constraints as well as the unique political, economic, and social factors that may impact how wastewater is managed, valued, and perceived. The exceptional quality of Qatar's treated wastewater is indicative of the country's energy-based economy. Qatar can afford to install the best wastewater treatment facilities with little concern for construction or operating costs. While the demand for treated wastewater is low, and relatively little treated wastewater is reused in agriculture, societal pressures require that the national public works authority provides the best wastewater treatment possible. The high level of treatment and associated costs in Qatar and other Persian Gulf countries sets an unrealistic standard for the rest of the region. Poorer countries in the MENA, which are struggling with water scarcity and food security issues, need more modest and economical solutions for water, sanitation, and food production. Undoubtedly, a modern, community-scale mechanical wastewater treatment facility would provide more reliably safe effluent than household GWTUs in the West Bank, but given the local political and economic constraints, the latter technology is an appropriate solution.

Identifying Governance and Social Challenges

The negative perception of treated wastewater is a significant obstacle to increasing the adoption of treated wastewater irrigation. Whether the water is found to be safe or not, farmers are frequently misinformed or lack knowledge about the use of treated wastewater in agriculture. As a result, many misconceptions have been perpetuated about the risks and benefits associated with the practice. Furthermore, across all study locations, there is a concern that treated wastewater is unsafe and/or that the authorities in charge of water and sanitation services cannot be trusted to deliver treated wastewater that is safe for use in agriculture. This issue of trust is most prevalent in locations where there is a greater uncertainty about the future of the government, such as in the West Bank, where the government lacks complete authority, and in Tunisia, which was led by a transitional government at the time of this study.

A troubling mismatch was noted between the capacity for oversight and the motivation for use among the study locations. In the West Bank, for example, local constraints on water availability motivate the need for treated wastewater irrigation, and households generally accept this reality. Hundreds of household GWTUs have been installed throughout the West Bank, but essentially no oversight is provided for this practice of gray water reuse because there is limited capacity within the government and civil organizations to monitor the quality and application of this water. In contrast, Qatar has significant capacity to provide oversight of treated wastewater reuse, but there is no motivation to use the high-quality treated wastewater within the agricultural sector because of the country's economic capacity to produce water.

National priorities and the capacity to provide oversight of wastewater treatment and reuse activities have consequences for the quality and breadth of data available about wastewater production, collection, treatment, and reuse. As is evident in the results of this study, access to reliable and comprehensive data is a challenge because such data are not collected or reported regularly, or the entities in charge of maintaining the datasets are unwilling to make them public. Without access to wastewater-related data, it is difficult for policy and decision makers to reach informed decisions about the potential of treated wastewater reuse.

Conclusions and Recommendations

The use of treated wastewater and other reclaimed water will be increasingly important in the study locations and across the arid regions of the world as the growing population and climate variability increase the pressure on traditional water resources. Based on the surveyed examples in the West Bank and Tunisia, there is a demonstrated technical capacity for reusing treated wastewater (or gray water) in agricultural production, and there is a basic public acceptance of the practice. Qatar provides a contrasting perspective in that the public is reluctant to adopt treated wastewater as an alternative to freshwater, despite the high quality of the treated effluent and the huge public expenditures dedicated to water production and wastewater management in the country. This study confirms that, under proper maintenance and monitoring conditions, most of the wastewater treatment facilities evaluated are capable of producing effluent that is safe for use in certain types of agricultural production; however, the risks to public and environmental health, particularly salinity and decentralized management and monitoring, cannot be ignored. In addition, daily and seasonal variability in water quality should be taken into account. Water sector policies, national and local governance, health considerations, and perception of farmers and consumers are critical factors in determining the viability of treated wastewater reuse in any location.

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