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Greywater reuse experience in Sharjah, United Arab Emirates: feasibility, challenges and opportunities

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ABSTRACT

In 2003, the Sharjah Electricity & Water Authority (SEWA) initiated a program mandating installation of greywater reuse (GWR) systems in large buildings in Sharjah to reduce demand for desalinated water. In this article, an assessment of the main challenges and opportunities experienced during implementation of the program is presented. Furthermore, the feasibility of GWR in Sharjah is analyzed for new and retrofitted multistorey buildings, hotels, schools and houses of worship. GWR for toilet flushing in Sharjah buildings proved financially beneficial to tenants on the account of owners, while GWR as makeup water in open HVAC cooling towers proved attractive to owners but not tenants. The lack of financial incentives to owners who were set to lose resulted in significant resistance to the program. Furthermore, insufficient planning prior to launching the program and inadequate coordination and follow up resulted in faulty installations, malfunctions and abandoned systems. As a result, SEWA changed the mandatory GWR requirements to optional in 2014 except for buildings with HVAC cooling towers. Overall, the number of GWR systems in Sharjah remained limited to about 200 installations serving a small fraction of the buildings stock in the city. Therefore, ample potential exists for increasing participation through a modified GWR policy that offers incentives and avoids the shortcomings identified during program implementation. The assessment presented in this study should provide valuable information to stakeholders involved in GWR programs, especially those involved in making decisions and formulating policies in developing countries.

Keywords: Greywater reuse; Sharjah City; United Arab Emirates; Greywater reuse policy; Assessment of greywater reuse program; Feasibility of greywater reuse

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1. Introduction

The demand for fresh water resources in urban areas is constantly increasing. Decentralized water management solutions that focus on conservation and use of unconventional water sources have gained increasing attention during the past few decades. Greywater reuse (GWR) and rainwater harvesting in buildings offer supplementary water sources [1–5] that can meet a significant portion of water demand. GWR provides an unconventional water supply alternative that can help reduce demand for fresh water resources, especially desalinated water. The interest in the GWR to reduce water consumption and enhance sustainability is steadily increasing worldwide [6–11].

Greywater (GW) is generated in households from washing, showering and bathing, and can amount to more than 40%–60% of residential water use [12–14]. GW is lightly contaminated compared with sewage and may be reused in and around buildings without the need for extensive treatment [15]. Therefore, GWR for non-potable purposes, such as toilet flushing, landscape irrigation, cooling, car washing, dust control and similar applications, may be feasible [16]. Many cities and towns around the world, especially in Australia and the United States (USA), have formal GWR programs [17–22]. GWR, however, is associated with many challenges [14,23,24]. Some challenges are common to all GWR programs; however, others are influenced by specific cultural, religious, socio-economic, governance, education and awareness, and population realities [25,26].

GWR can be an attractive option in the United Arab Emirates (UAE) and the region due to the scarcity of rainfall [27] and high dependence on desalination to meet demand for fresh water [28]. As such, water conservation in all sectors is high on the agenda of the water authorities in the UAE. Abu Dhabi, the capital of the UAE, introduced in 2011 a pearl rating system called “Estidama” to rank green buildings based on a variety of criteria, including water conservation [29]. The Premier Inn Hotel was the first entity in Abu Dhabi to receive permission to install a GWR system, which proved successful and reduced water consumption by about 24% [29]. Dubai city, UAE, also developed a rating system called “Sa’ffat” (palm fronds) in 2016 for both new and existing buildings to promote sustainability [30]. The rating system sets requirements for GWR in buildings, including installation of dual-plumbing, use of color-coded pipes, and avoidance of human contact. The Dubai Sa’ffat rating systems require 15% to 30% water savings from GWR to achieve golden and platinum ratings [30]. Sharjah city, UAE, was the first in the UAE and region to introduce GWR requirements for large water consumers back in 2003 [31]. The GWR program was initiated by the Sharjah Electricity and Water Authority (SEWA), with the program approved by the Executive Council of the Government of Sharjah [11].

With over 15 years of experience in GWR in Sharjah, SEWA dealt with a variety of challenges that required special attention and program modifications. As a result, significant experience was accumulated, which is highly relevant to those involved in setting policies and administering GWR programs. In this study, highlights of the challenges and opportunities associated with GWR in Sharjah are introduced and discussed. In addition, the article includes assessment of the feasibility of GWR in new and retrofitted multistorey buildings, hotels, schools, and houses of worship for cooling, toilet flushing and possibly irrigation. The assessment and analysis presented in this article should provide valuable information to stakeholders involved in GWR programs, especially those involved in making decisions and formulating policies and regulations in developing countries.

2. Potential for greywater reuse in Sharjah

According to SEWA, the water supply in Sharjah comes mostly from desalination (75%), groundwater (5%) and imported water (20%). The estimated residential water consumption by use, fixture, or appliance in Sharjah is as follows [31]: 26.7% toilet flushing, 21.7% laundry, 16.7 washing basins, 15.8% showering, 5.3% miscellaneous, and 13.7% loss. Clearly, the GW fraction, which includes water from laundry, washing basins and showers, is substantial and constitutes more than 50% of the overall residential water consumption. Therefore, the quantity of GW is adequate to support a GWR program in the city.

Residential buildings in Sharjah include multistorey residential, mixed residential/commercial and detached dwellings. The desert climate conditions and zoning realities is such that multistorey buildings in Sharjah are closely packed, mostly with no surrounding green spaces. As such, GW in such building can be used either for toilet flushing or as makeup water in HVAC open cooling towers. GWR for flushing toilets consumes about 30% of residential water use, which is significantly less than the available GW. On the other hand, HVAC cooling towers in high-rise buildings consume significant amounts of water and may use all available GW. Detached villas in Sharjah typically come with a small front and/or back yards. Such green spaces require daily irrigation, especially during the long and hot summer season. Such green spaces can benefit from irrigation with GW treated to a high standard.

In terms of potential water savings, a 10% saving from GWR requires participation of approximately a quarter of Sharjah residents. Currently, the GWR program in Sharjah serves less than 3% of the residents and therefore its impact is limited. However, the city is highly dependent on desalination and water conservation and GWR remain strategic long-term objectives from efficiency and sustainability points of view, but also to meet the ever increasing water demand in the city.

2.1. Sharjah’s GWR program

In 2003, and upon the initiative of SEWA, the Executive Council of the Government of Sharjah approved the Sharjah GWR program [31]. Implementation of the program started in 2004. The main objectives of the program were to [11]: (1) save potable water for domestic purposes; (2) reduce the load on the water distribution networks and sewage treatment plants in the city; (3) decrease the demand for potable water and the corresponding need to establish new costly desalination plants; (4) reduce the monthly consumption bill of consumers; and (5) contribute to pollution reduction resulting from energy-intensive water production and brine disposal. In order to protect public health and the environment, the program demanded that GW cannot: (1) be stored for long durations to avoid possible growth of microorganisms given the prevailing hot and humid weather conditions; (2) be used for irrigation by domestic planters; (3) be used for irrigation of plants or vegetables that are consumed raw; and (4) come in direct contact with humans.

The SEWA's 2003 program mandated GWR in a variety of building types, as shown in Table 1. The compulsory nature of the program faced significant implementation challenges and resistance from owners and as such it was scaled down and made voluntary in 2014, except for the categories identified in Table 1. The mandatory requirements were maintained on hotels and buildings that utilize GW in HVAC cooling towers as such installations proved successful and cost effective to owners. In fact, the owners of hotels and buildings with HVAC cooling towers who implemented GWR achieved significant financial benefits through savings in their water bills.

The Sharjah 2003 GWR program specified a set of minimum water quality requirements (Table 2) that apply to all GWR applications, including toilet flushing and cooling. However, the requirements did not specifically address water quality requirements for irrigation. In general, the Sharjah GWR water quality requirements are consistent with international practice [14,21,32].

During the early stages of the Sharjah GWR program, SEWA recommended two types of treatment systems, both of which include a series of treatment steps (Fig. 1), as follows: screening/straining; aerated holding/equalization tank with scum removal; filtration; activated carbon adsorption or ultrafiltration; and disinfection. Adsorption systems in Sharjah are mainly used in schools, mosques and laborer's accommodations, while ultra-filtration systems are used in high-rise residential buildings and hotels. Following many years of experience, SEWA preferred ultrafiltration systems. SEWA demands from owners to conduct and submit monthly water quality reports by approved third party laboratories to demonstrate meeting the required water quality. Moreover, SEWA deploys inspectors to ensure that the installed GW systems are functional and properly operated in terms of lack of foul odors and general cleanliness.

Table 2
SEWA's minimum treated GW quality requirements

Water quality parameter	Minimum requirement
Turbidity, NTU	≤2
pH	6–8
BOD_5, mg/L	≤10
COD, mg/L	≤50
TSS, mg/L	≤10
Total coliforms, MPN/100 mL	≤100
Fecal coliform, MPN/100 mL	≤5
Free chlorine, mg/L	0.5–1

Greywater treatment systems are typically placed in basements of buildings, but it is also possible to place such systems on the roofs [3,28], which may require adequate shading and containment. Operation and maintenance (O&M) of GWR treatment systems was identified as a major challenge as buildings' owners do not have qualify employees and delegation of O&M to a third party was considered an extra cost to owners who are not compensated for installation and operation of GWR systems.

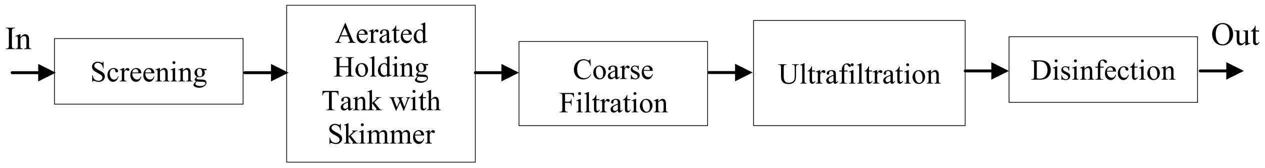
3. Challenges and opportunities of GWR in Sharjah

SEWA conducted series of inventories of the GW treatment systems installed in Sharjah between 2011 and 2019. The data in Fig. 2 show the numbers of installations reported between 2011 and 2019 compared with those reported in the literature [31] for 2011 and 2017. A noticeable change in the number of installed GW systems occurred between 2011 and 2017, then the numbers remained relatively unchanged at about 200 installations. In 2010/2011, SEWA's field audits revealed that about half of installed GWR systems were not working properly [31]. The main issues observed during the audit were related to faulty installation, use of cheap and ineffective systems, negative perception, lack of proper operation and maintenance, lack of performance monitoring, and

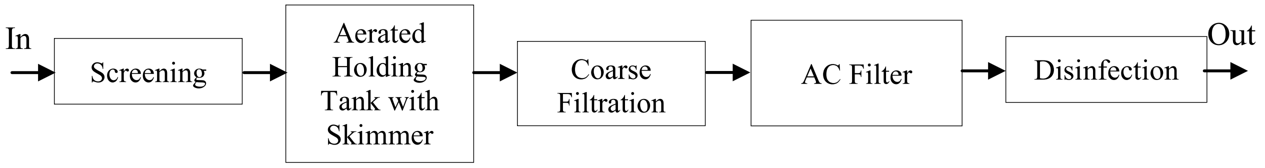
Table 1
SEWA's mandatory and optional GWR requirements

Facility	2003 Requirements	2014 Requirements
Places of worship	Mandatory	Optional
Shopping centers	Mandatory	Optional
Schools	Mandatory	Optional
Industrial facilities	Mandatory	Optional
Institutional government facilities	Mandatory	Optional
Car wash facility	Mandatory	Optional
Hotels and furnished apartments	Mandatory	Mandatory[a]
Mixed use commercial/residential buildings	Mandatory	Mandatory[a]
Laborer's accommodation	Mandatory	Optional

[a] In case cooling towers were utilized in the facility.



a) Ultrafiltration System



b) Activated Carbon Filter System

Fig. 1. SEWA's preferred GW treatment systems.

other issues [31]. The audit also revealed effective operations, especially those involving GWR for cooling in open HVAC cooling towers. During the early stages of implementation, GWR in Sharjah suffered major technical difficulties that included [31]: (1) inadequate design and installation of GWR infrastructure; (2) installation of inefficient systems without SEWA's approval; (3) insufficient experience of contractors and consultants; (4) intervention of owners and/or tenants by shutting down treatment systems to reduce cost and/or control foul odors; (5) lack of on-site inspection and supervision during installation, and (6) inadequate operation and maintenance of treatment systems.

Currently, GWR for toilet flushing in Sharjah is practiced in some schools and hotels but not in residential and mixed residential/commercial buildings. In multistorey buildings that have open HVAC cooling towers and GWR systems, GW is successfully used as makeup water. The GWR program was initially intended for new buildings and therefore there are no reported installations in older building retrofitted with GWR systems. Furthermore, the GWR program in Sharjah did not target detached residential dwellings and therefore, there is no reported GWR installation in detached dwellings.

3.1. Community perceptions

Treated wastewater is extensively used for landscape irrigation in green public spaces in Sharjah. The practice has not generally faced concerns from the community on cultural, religious, ethnic, or environmental grounds. In fact, and although wastewater is locally considered unclean and impure, religious scholars allow beneficial reuse of wastewater that is adequately treated to meet the quality requirement of its intended use [33]. However, GWR indoors and within premises are different than wastewater reuse outside in public spaces. In general, acceptance of GWR for toilet flushing or irrigation is of concern to Sharjah residents. For example, SEWA reported concerns associated with GWR for toilet flushing from residents of buildings based on perceptions, in addition to complaints related to bad smells emitted from treated GW or from basements where treatment systems are located. As Sharjah is revising its GWR policies and implementation practices, concerns related to improper use of treatment systems and poor operation and maintenance should be addressed. Furthermore, any revised policies should focus on building community education and awareness with regard to water conservation and GWR.

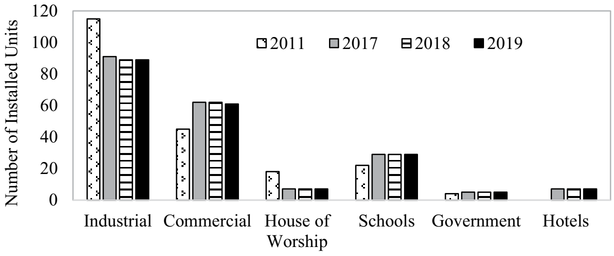


Fig. 2. Summary of GWR installations in Sharjah.

Owners' concerns relate to the cost of GWR and operational burden. Negative perceptions were enhanced by the fact that many mandatory GWR systems intended for toilet flushing ended up abandoned. On the other hand, successful GWR applications were not adequately promoted in the community. Owners and tenants, therefore, need education on the value of water conservation, including GWR. Furthermore, the legitimate concerns of owners who may not benefit from GWR should be addressed in any revised GWR policy. The financial feasibility of GWR to a variety of ownership situations is addressed in a following section.

3.2. Ownership and who pays/who benefits

Buildings' ownership and who pays for and who benefits from GWR had a major impact on compliance and interest in GWR in Sharjah. Owners of tenanted buildings do not pay for water, except in buildings that has central HVAC systems that use open cooling towers. Such cooling systems consume significant amounts of water that is paid for by owners. Owners in return pass the cost of central air conditioning to tenants in the form of extra rent. Due to constant need for air conditioning in Sharjah, which typically constitutes more than 70% of electricity consumption of households, tenants in Sharjah generally prefer to pay increased rent in exchange for free air conditioning. In buildings with central HVAC systems, GWR proved financially favorable to owners, as demonstrated in a following section. In building with split air conditioning, GW can be used for toilet flushing. However, the financial benefits of GWR for toilet flushing go to tenants but not to owners, unless owners offer free water to tenants and increase the rent accordingly. However, owners do not generally prefer to pay for water in exchange for moderate increase in rent as water consumption by tenants may spiral out of control.

The ownership situation proved to be a critical factor as it determined the share of owners and tenants of financial savings that can be realized from GWR. The majority of Sharjah residents are expatriates who live in rental units in multistorey buildings, mostly with no green spaces. The lack of green areas in multistorey buildings limits available GWR options to toilet flushing and/or cooling in central HVAC cooling systems. The current GWR policy in Sharjah provides no incentive to owners to install GWR systems for toilet flushing as owners pay for installation and operation and maintenance while their tenants benefits from savings in their water bills. Furthermore, tenants may be hesitant to live in buildings with GW used for toilet flushing out of health and religious concerns. As a result, all GWR installations for toilet flushing in residential buildings in Sharjah have been abandoned. On the other hand, owners of buildings with HVAC cooling towers who installed GWR systems for cooling achieved significant financial benefits in the form of savings in their water bills.

Owner-occupier buildings in Sharjah are mostly limited to detached residential dwellings. Most of such dwellings are occupied by UAE nationals rather than expatriates who until recently were not allowed to own free-hold properties. The UAE nationals are offered fresh water by the authorities at a reduced rate and therefore may not have enough incentive to install GWR systems. Furthermore, the current GWR policy in Sharjah does not address GWR for detached dwellings.

The population composition in Sharjah also impacts potential success of GWR in terms of community water use habits, education, participation, and acceptance of GWR. The World Bank [34] estimates the UAE population at 9.27 million in 2016 and 9.53 million in 2018. The majority of the population is male (about 70%) with about 88.5% expatriates and 11.5% UAE nationals. The majority of the population (about 60%) is from India, Pakistan, Bangladesh, Philippines, Iran, and Egypt [34]. In terms of ownership, the majority of owners are UAE nationals or investors from other Gulf countries. The recent freehold ownership allowance from expatriates limits ownership to certain areas and projects, and is mostly directed towards ownership of individual apartments or dwellings that are managed by investors. Overall, success of GWR in Sharjah requires provision of adequate incentives to owners, efficient enforcement to ensure protection of public health, and active education and awareness raising programs to enhance community acceptance and participation.

3.3. Governance of GWR programs

Another challenge that was faced by GWR in Sharjah is related to coordination between the various authorities that are involved, or should be involved, in managing GWR, such as SEWA, Sharjah Municipality (SM), and Sharjah Health Authority (SHA). In principle, SEWA is the main entity in charge of water supply and the initiator of the GWR program in Sharjah. On the other hand, SM is in charge of approving design and supervising construction of buildings, including installation of plumbing infrastructure. Moreover, SM is responsible for wastewater collection, treatment, disposal and reuse in the City. SHA is responsible for enhancing, improving and regulating the healthcare system in Sharjah. The current coordination between SEWA and SM in relation to GWR is as follows: when an owner wants to attain a building construction permit from SM, SEWA is assigned to review and attest plans for water supply, greywater collection and reuse, and GW treatment system. Therefore, SM does not approve construction permits without SEWA's approval. However, SEWA is not involved in supervising construction or approving GWR materials, suppliers, and contractors. As such, GWR faced challenges related to faulty installations and use of sub-standard materials and systems. In terms of health and community well-being, and although SEWA requirements are consistent with international practice in terms of protecting public health, SHA has not been involved in regulating GWR in Sharjah. Therefore, any revised GWR policy must involve partnership between the various concerned authorities, as well adequate coordination between all stakeholders.

4. Feasibility of GWR in Sharjah

The economic feasibility and who gains or loses proved to be critical factors in owners' acceptance of GWR in Sharjah. In this section, the economic feasibility of various GWR installations is assessed based on cost data received from SEWA. The assessment was prepared for the following cases: (1) 40-storey building with 250 apartments; (2) a school that consists of 160 classrooms; (3) a house of warship (mosque) that can accommodate 1,000 worshipers; and (4) a hotel with 165 guest rooms. The basic data used to assess the various cases are presented in Tables 3 and 4. In Table 3, the data needed to estimate GW generation and potential GWR are provided. In Table 4, the capacities, capital and O&M costs of treatment systems, together with costs of GW collection and distribution infrastructure are presented. Moreover, the feasibility analysis was extended to retrofitting existing buildings with GWR systems. It should be emphasized that the feasibility analysis presented in this article reflects the assumptions in Tables 3 and 4, which were provided by SEWA.

Various feasibility indicators were estimated based on a service life of $n = 15$ years for treatment systems and interest rate of $i = 4\%$. The indicators included: cost recovery factor (CRF); annual capital cost (ACC); cost recovery period (CRP); and net annual savings (NAS). The estimates also included capital cost (CC) and net annual running cost (NARC). The equations used to calculate the various indicators are listed below.

Table 3
Data used for analyzing feasibility of GWR in selected buildings in Sharjah

Cost item	Item	Value	
		Cooling tower	Toilet flushing
High-rise building	Number of stories	40	40
	Number of apartments	250	250
	People/apartments	5	5
	Water use (L/person/d)	300	300
	GW fraction of water use (%)	40	40
	Toilet flushing needs (L/person/d)	–	60
	Capacity of cooling tower (m^3/d)**	240	–
		Toilet flushing	
School	Number of classrooms	150	
	Student/class	30	
	GW generated (L/student/d)	18	
	Toilet flushing needs (L/student/d)	18	
		Toilet flushing	
House of Worship	Capacity (No. of worshipers)	1,000	
	Worshipers requiring ablution (%)	50	
	Number of prayers/d	5	
	Water for ablution (L/worshiper/pray)	6.5	
	Toilet flushing needs (L/worshiper/flush)	12	
		Toilet flushing	
Hotel	Number of rooms	165	
	Room capacity (guest/room)	3	
	GW generation (L/guest/d)	100	
	Toilet flushing needs (L/person/d)	60	

**Cooling tower working for 24 h at an efficiency of 60% of the chiller compressor.

Table 4
Cost and capacity of items used for estimating the feasibility of GWR systems

System	Component	Multi-story	Hotel	School	Mosque
Treatment system	Treatment type	UF System[a]	UF System[a]	AC System[a]	AC System[a]
	Capacity (m^3/d)	200	55	100	35
	Available GW (m^3/d)	150	50	86	16 or 33[b]
	Toilet flushing demand (m^3/d)	75	30	86	60
	Installed system cost (USD)	95,000	82,000	68,000	41,000
	O & M of system (USD/y)	14,000	13,000	13,000	9,000
GWR collection and distribution infrastructure	Installation cost (USD)	365,000	120,000	110,000	23,000
	Retrofitting cost (USD)	1,100,000	32,000	31,000	41,000

[a] UF = ultrafiltration system (Fig. 1a), AC = activated carbon system (Fig. 1b).
[b] Assuming 50% and 100% of worshippers perform ablution.

$$\text{NARC} = \text{Annual Water Cost Savings} - \text{Annual O \& M Cost} \tag{1}$$

$$\text{CC} = \text{Infrastructure Cost} + \text{Treatment System Cost} \tag{2}$$

$$\text{CRF} = \frac{i\left(1+i\right)^n}{\left(1+i\right)^n - 1} \tag{3}$$

$$\text{ACC} = \text{CC} \times \text{CRF} \tag{4}$$

$$\mathrm{CRP} = \frac{\mathrm{ACC} \times n}{\mathrm{NARC}} \tag{5}$$

$$\mathrm{NAS} = \mathrm{NARC} - \mathrm{ACC} \tag{6}$$

The available GW in the various establishments (multistorey building, hotel, school and mosque) constitutes 46%–93% of installed treatment systems' capacities (Table 4), while toilet flushing requires 38%–171% (Table 4). The available GW can fully meet the demand for toilet flushing in all buildings types in Table 4 except in the mosque. In case available GW exceeded flushing requirements, the feasibility analysis was extended to full utilization of available GW. In the multistorey building, for example, GWR for cooling can consume all of the available greywater.

The feasibility of GWR increases as the full capacity of the treatment system is utilized. The data in Fig. 3 present the economic feasibility of GWR as a function of the fraction of the maximum treatment system capacity. Assuming that O&M costs do not change with operational capacity, the NAS, which accounts for the annual cost of saved water, ACC and annual O&M costs, linearly increases as more GW is reused. Based on maximum GW generation and utilization in the various establishments studied, the data in Fig. 3 show that a minimum GWR capacity of 36% to more than 100% of treatment system capacity is needed to make the GWR feasible (i.e., NAS ≥ 0.0). For example, achieving positive net returns, or NAS ≥ 0.0, requires a minimum GWR of 36% in the 40-storey building fitted with GWR infrastructure, while toilet flushing requires 38% of the capacity and cooling can utilize the full capacity. Therefore, GWR for toilet flushing and cooling in the new building allows net positive returns, or NAS ≥ 0.0, with cooling being more feasible than toilet flushing. However, the extra cost of retrofitting a similar building increases the

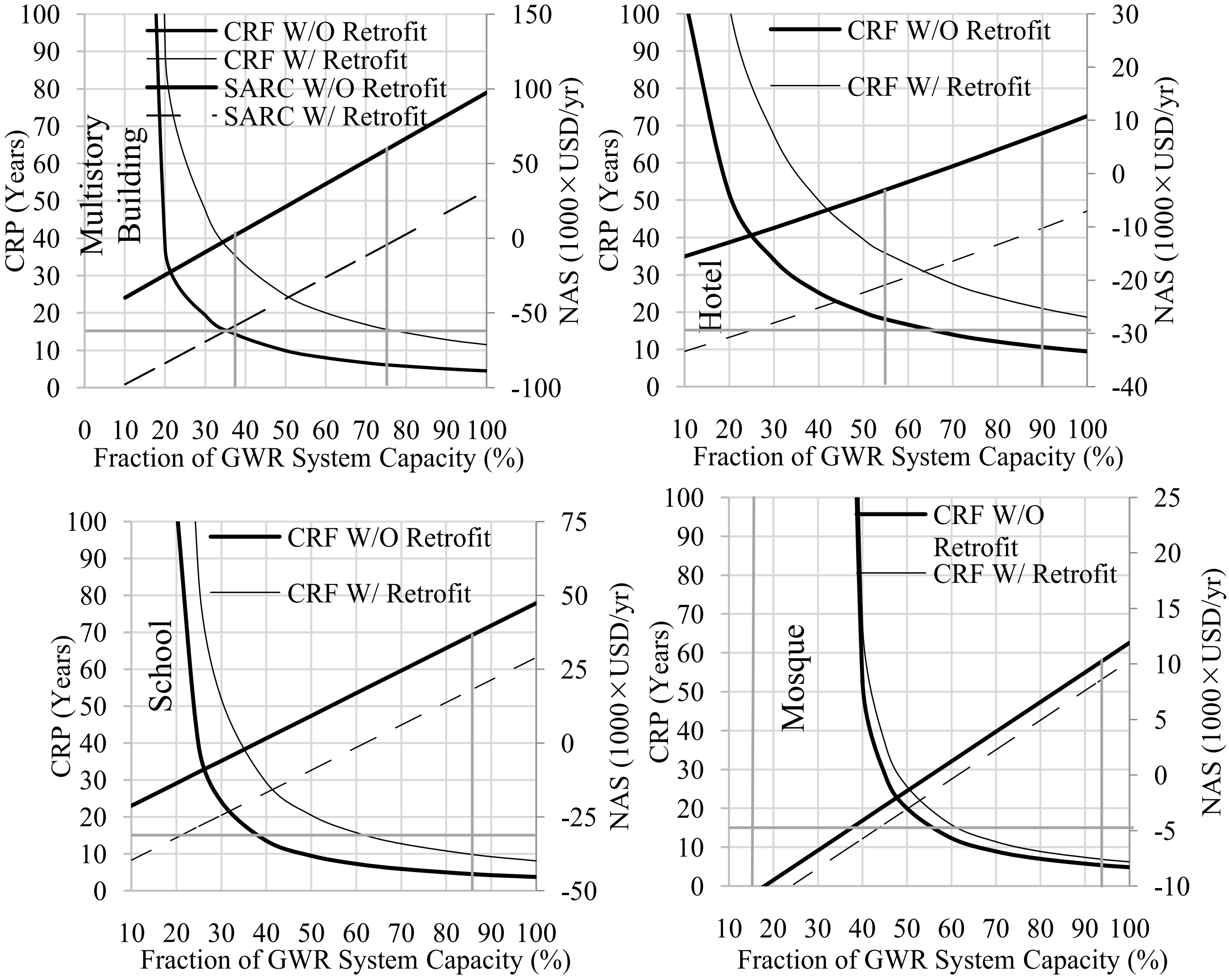


Fig. 3. NAS and CRP for partial GWR relative to maximum capacity of treatment system with operating points indicated by the vertical and horizontal dashed lines.

minimum GWR requirement to achieve positive returns to 78%, which is greater than available GWR capacity of 75%, and therefore positive returns cannot be achieved for a retrofitted building. Similarly for the hotel, the available GWR capacity of 90% exceeds the requirements for flushing (54%) and can be fully utilized for flushing and/or irrigation. However, positive returns require GWR capacity of more than 64%, which means that positive returns cannot be achieved if GWR is limited to toilet flushing. For the mosque and school, utilization of the maximum available GWR capacity can generate net positive returns, or NAS ≥ 0.0, and covers the cost of retrofitting.

The data in Table 5 summarize the results presented in Fig. 3 and show the NAS and CRP for the various possible GWR scenarios in the different establishments. As the capital cost was distributed over a period of 15 years, CRP values > 15 years indicate that annual water cost savings are more than annual O&M cost (i.e., negative annual running cost, or NARC < 0.0), which suggests that cost recovery is impossible. The analysis suggests that cost recovery within 15 years is generally possible for new buildings but not for retrofitted buildings, which require more than 15 years. The only case that shows impossible cost recovery at the cost rates used in the study is associated with low GWR capacity in the mosque as the annual water cost savings are less than annual O&M cost, NARC < 0.0. In terms of NASs, only new buildings can generate positive returns (NAS > 0.0), which are in this case in the range of approximately 2,000 USD to 60,000 USD.

The feasibility of GWR can be reduced through reducing the costs of GW collection, distribution and treatment infrastructure. One approach to achieve cost reduction is to limit the capacity of the infrastructure as needed by the specific GWR requirements. For example, available GW in the 40-story building (150 m^3/d; Table 3) exceeds demand for toilet flushing (75 m^3/d; Table 3) and therefore it is possible to use a 75 m^3/d treatment system and to collect GW only from part of the building (i.e., 50%). On the other hand, a cooling tower in the 40-storey building can consume all available GW (150 m^3/d) and therefore GW collection from all floors and a treatment system with minimum capacity of 150 m^3/d are needed. The data in Table 6 show feasibility analysis based on installation of GWR treatment systems and infrastructure that match demand. To simplify analysis, the costs of full capacity items used in the analysis in Fig. 3 were proportioned to reflect partial capacities. Clearly, the data presented in Table 6 show significant improvement in the feasibility of GWR for both new and retrofitted buildings, with NAS increasing and CRP decreasing.

The feasibility analysis presented so far does not indicate who gains and who loses among the stakeholders (owners,

Table 5
NAS and CRP for GWR in the different establishments based on infrastructure and treatment capacity proportional to GW utilization

Establishment	GWR	Water Savings (m^3/d)	NAS (USD/Year)	CRF (Years)	NAS (USD/Year)	CRF (years)
			New Building		Retrofitted Building	
Multistorey Building	Toilet flushing	75	2,000	14.3	–58,500	35.2[a]
	Cooling tower	150	5,900	6.2	–4,500	15.7[a]
Hotel	Toilet flushing	30	–3,300	18.4[a]	–21,200	36.4[a]
	Full GWR	50	7,600	10.6	–10,200	21.0[a]
School	Full GWR	86	37,000	4.5	18,600	9.7
Mosque	Users of GW	16	–10,400	–18.3[b]	–18,300	–23.5[b]
	Full GWR	33	10,000	5.5	8,400	7.0

[a]CRP > 15 years indicates GWR may be feasible for $n > 15$ years as NARC > 0.0. CRF was estimated based on $n = 15$ (Eq. (3)).
[b]CRP negative indicates impossible cost recovery as annual water cost savings are less than annual O&M cost (i.e., NARC < 0.0).

Table 6
NAS and CRP for GWR in the different establishments based on infrastructure and treatment capacity proportional to GW utilization

Establishment	GWR	Water savings (m^3/d)	NAS (USD/year)	CRF (year)	NAS (USD/year)	CRF (year)
			New building		Retrofitted building	
Multistorey building	Toilet flushing	75	36,500	4.5	12,000	11.5
	Cooling tower	150	73,000	4.5	24,000	11.5
Hotel	Toilet flushing	30	5,800	9.4	–3,800	18.6[a]
	Full GWR	50	9,000	9.8	–7,400	19.3[a]
School	Full GWR	86	40,900	3.8	25,000	8.1
Mosque	Users of GW	16	5,500	4.9	4,800	6.3
	Full GWR	33	11,000	4.9	9,600	6.3

[a]CRP > 15 years indicates GWR may be feasible for $n > 15$ years as NARC > 0.0. CRF was estimated based on $n = 15$ (Eq. (3)).

tenants, and SEWA). However, whether owners gain or lose is critical in terms of their interest in making investment in GWR systems. Table 7 summarizes the gain/loss positions of the various stakeholders involved. In case of GWR for toilet flushing in tenanted buildings, installing, and operating GWR systems results in major losses to owners and the benefits go to tenants. Of course, owners have the option of passing the cost to tenants through raising rent; however, the competitive rental market may not allow such an increase. In addition to the cost to owners, premises that implement GWR for toilet flushing suffer from negative perceptions, as tenants may not favor having treated water inside their homes out of health and cleanliness concerns. Tenants of building that implement GWR for toilet flushing can achieve significant water cost reductions, which serves as an incentive subject to strict operation and maintenance of treatment system.

The data in Table 7 show that GWR is highly feasible to owners of buildings in which GWR is used for cooling. The analysis also explains the difficulties faced by SEWA in implementing the compulsory GWR program for toilet flushing and one of the reasons behind modifying the requirements from being mandatory to optional, except for cooling purposes, which remained mandatory. It should be noted that all current operational GWR installations in Sharjah are for cooling, with all installations for flushing toilets abandoned by owners.

The cost/benefit analysis demonstrates that GWR for cooling offers significant economic advantage to owners of buildings who typically pay for water. Owners of such buildings can get GW for free from their tenants then use it, after treatment, to satisfy a significant portion of water demand at a faction of the cost of drinking water. In this case, tenants do not benefit but virtually lose as they serve as suppliers of raw GW to owners. Furthermore, tenants may be negatively affected in case of poor operation and maintenance of treatment systems.

Fig. 4 presents a record of the average monthly potable water and GW utilized to feed the cooling towers of a

Table 7
Sharing of costs and benefits of GWR between owners and tenants

Building type	Intended use	Who pays system cost	Who pays water cost for intended use	Who benefits	Who loses	SEWA loss & gain
High-rise building	Flushing toilet	Owner	Tenant	Tenant	Owner	• Potential loss of revenue
	Cooling tower	Owner	Owner	Owner	–	• Meeting water demand, reduced emissions, delayed investment in infrastructure
Hotel	Flushing toilet	Owner	Owner	Owner	–	
	Full GWR	Owner	Owner	Owner	–	
School	Full GWR	Owner	Owner	Owner	–	
Mosque	Flushing toilet	Owner	Owner	Owner	–	
	Full GWR	Owner	Owner	Owner	–	

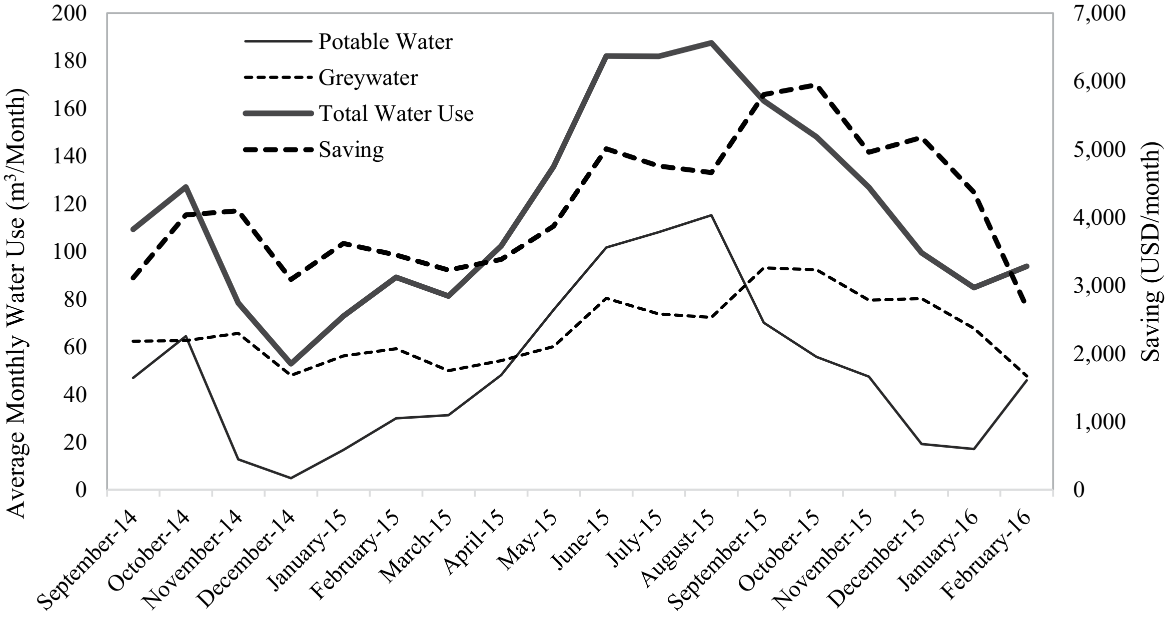


Fig. 4. Monthly average freshwater and GW utilization for cooling in a 40-storey building in Sharjah and monthly savings in water cost.

40-storey building starting September 2014 until February 2016. Moreover, the actual monthly savings due to GW recycling are presented. The data show seasonal variations in consumption; highest during summer (June to August) and lowest during winter (December to February). The total water use for cooling was in the range of 53 to 190 m^3/d. Out of total consumption, with GW supplying 40%–90% of the total water demand, with reported monthly savings in the range of 3,600–7,900 USD. The data also show that the maximum capacity of the treatment system maximum (200 m^3/d practical capacity) was only partially (22%–43%) utilized.

GWR reduces SEWA's revenues, however helps SEWA meet the increasing demand for desalinated water and delays investment in expansion of desalination capacity. Despite loss of revenues, SEWA needs to offer incentives to encourage increased participation and partially compensate owners of properties who may not benefit from GWR installations. Such benefits can be in the form of reduction of water connection fees, grants or loans, rebates and especially structured water charges. Currently, SEWA is working on producing a revised GWR policy and the issue of incentives is being considered carefully.

5. Impacts of GWR on energy and emissions

In addition to potentially achieving significant water savings, GWR can reduce energy consumption and emissions associated with desalination and conveyance of water. Energy consumption for desalination is reported in the range of 4.1–23.4 kWh/m^3, depending on the method of desalination [35–37]; 5 kWh/m^3 for reverse osmosis (RO) and 23.4 kWh/m^3 for flash desalinations (MSF). The average emissions associated with electricity generation in the UAE is reported to be 0.61 kg CO_2/kWh [38], and therefore emissions from desalination can be estimated to be in the range of 2.5–14 kg CO_2/m^3; 3.1 kg CO_2/m^3 for RO and 14 kg CO_2/m^3 for MSF. Greywater treatment requires energy and generates emissions, which is considered herein equivalent to the energy and emissions associated with wastewater treatment. Therefore, only the savings in energy and emissions associated with desalination are considered.

According to Sharjah Census in 2015, the city hosts around one million residents [39], with water consumption of about 0.3 m^3/person/d of which about 50% is GW. Fig. 5 presents an estimate of the range of desalination energy and emissions savings associated with various levels of GWR in Sharjah. Clearly, GWR can save significant amounts of energy and emissions. However, at the current level of participation in GWR, estimated to be less than 3% of the total water use, the impact is limited. Assuming that Sharjah can achieve 10% reduction in water consumption due to GWR, energy savings of 27.4–128.7 GWH/year, and emissions reduction of 17–76.6 KT CO_2/year may be achievable.

6. Conclusions

The GWR program in Sharjah faced a variety of challenges but also revealed opportunities for reducing demand on desalinated water. Analysis of Sharjah experience suggests that tenants and owners of buildings can financially gain or lose, and therefore future GWR policies must be carefully formulated to increase participation through incentives, education and awareness raising. GWR may reduce SEWA's revenues but helps SEWA meet increasing demand on desalinated water and delays needs to expand desalination and water infrastructure capacity. Therefore, and despite the challenges faced during the past years of implementation of GWR in Sharjah, SEWA remains committed to expanding the GWR program. Currently, a joint team from SEWA and the University of Sharjah (UoS) is working on developing a modified GWR policy.

The feasibility study presented in this article suggested that GW reuse in Sharjah is generally feasible for new buildings with CRP < 15 year. However, the benefits may not be adequately shared by tenants and owners. For retrofitted GWR installations in older buildings, the analysis suggest that CRP > 15 years. However, the feasibility of GWR in new and older buildings can be enhanced through limiting GWR

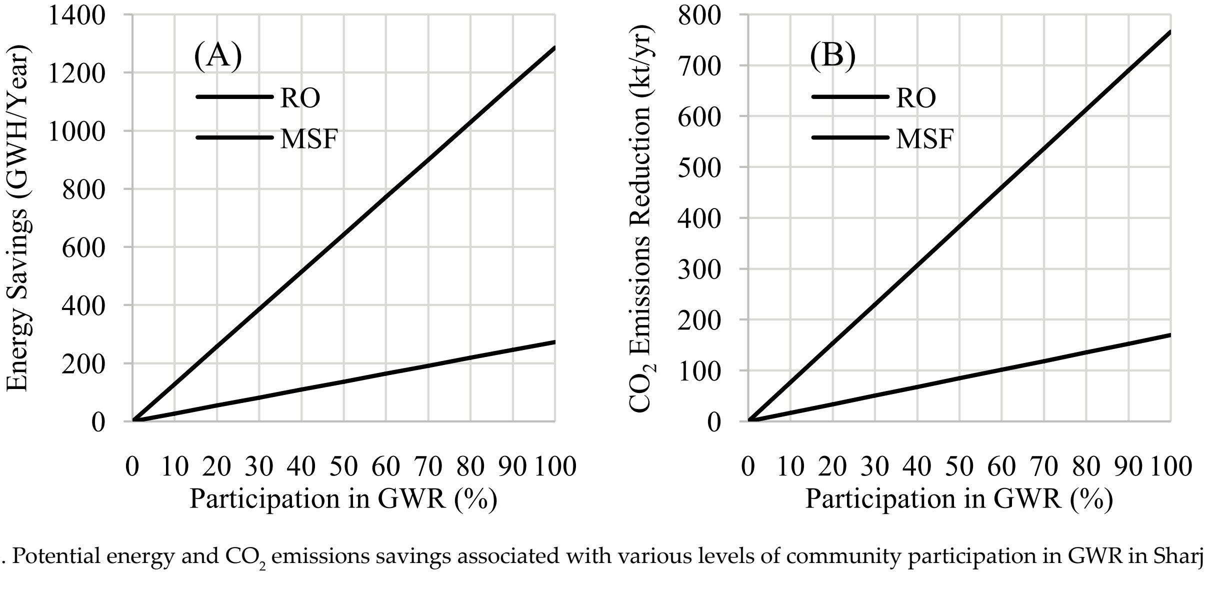


Fig. 5. Potential energy and CO_2 emissions savings associated with various levels of community participation in GWR in Sharjah.

infrastructure and treatment capacities to the minimum of available greywater or demand needed to satisfy intended use.

The results demonstrate that GWR in Sharjah can significantly reduce the impacts of desalination through reducing water demand, electricity consumption, and CO_2 emissions. The study provides valuable information on GWR for policy formulation and decision-making that is based on extended real-life experience.

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