Feasibility and impact of greywater recycling in four types of buildings in Sharjah, United Arab Emirates

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Abstract. Greywater (GW) recycling and reuse is an important approach for conserving water and meeting the demand of the growing population. However, the success of greywater reuse (GWR) depends on process feasibility and impacts. In this study, the feasibility and impact of GWR installations in four types of buildings (high rise residential building, school, hotel and house of worship) in Sharjah, United Arab Emirates, were assessed. The study included economic assessment as well as assessment of impacts in terms of CO₂ emissions and energy consumption over time. The GWR options included use of GW, as applicable, for toilet flushing or as make-up water in open air conditioning cooling towers. The results from the study indicate that GWR is feasible for the various types of buildings and applications assessed and that it can lead to significant reductions in water consumption, CO₂ emissions and energy consumption. However, buildings owner’s share of financial savings is a key factor in deciding interest in installing and operating GWR systems.

1. Introduction
Rapid urbanization and population growth around the world have resulted in an overexploitation and contamination of freshwater resources. This has especially placed a severe stress on the limited water sources in the arid and semi-arid regions, such as the United Arab Emirates. Therefore, in order to ensure long term sustainability and meet the demand of the growing population, it is critical adopt water conservation strategies such as water use reduction, wastewater and greywater recycling and reuse, and rainwater harvesting [1–2]. Greywater reuse (GWR) is an approach which has potential to reduce freshwater consumption through point source treatment and recycling of the generated greywater [3] that can be reused for several applications, including toilet flushing, irrigation and car washing [4].

Greywater is wastewater generated from baths, shower, washing machine, dishwashers, as well as hand basin excluding toilet wastes [5], and generally accounts for 50-80% of the total generated domestic wastewater [6]. The main environmental and public health concerns with reuse of greywater is the presence of pathogenic and macro- and micro-pollutants [7]. Therefore, selection of appropriate treatment technology is critical in producing water of acceptable quality. To this end, various physical,
chemical, and biological treatment approaches can be adopted. Physical treatment methods, such as filtration, are easier to adopt and operate at point sources compared to other approaches. For instance, granular activated carbon (GAC), which has a high surface area and low production cost, is capable of removing organic material from greywater [8]. On the other hand, ultrafiltration (UF) membranes are effective in the removal of suspended solids, surfactants and microbial pollutants [9]. Sharjah is one of the seven emirates of the United Arab Emirates located in the arid region with an average rainfall intensity of 110 mm/year [10]. Sharjah is dependent on groundwater and seawater desalination for supplying water for domestic, commercial, and industrial applications. However, desalination is expensive, consumes significant amounts of energy, generates high greenhouse gases (GHG) emissions and the produces brines in need of disposal [11]. Furthermore, and according to projections by the Sharjah Electricity and water Supply Authority (SEWA), the water demand in Sharjah is expected to exceed the available supply this year 2020. To help meet the water demand, SEWA initiated in 2003 (implementation started 2004) a compulsory greywater reuse program in Sharjah, which was changed to a voluntary program afterwards. Currently the program is optional for several building categories in Sharjah, with ultrafiltration (UF) membrane and granular activated carbon (GAC) adsorption being the recommended treatment technologies. Example performance of GAC and UF systems similar to those used in Sharjah are shown in table 1.

![Table 1. Treatment capacities of selected greywater treatment systems.](image)

| Technology                                            | COD removal (%) | BOD removal (%) | TSS removal (%) | Turbidity removal (%) | Total Coliform removal (%) | References |
|-------------------------------------------------------|-----------------|-----------------|-----------------|-----------------------|----------------------------|------------|
| Screening + holding tank + filtration + GAC + Cl₂ disinfection | 31.4            | -               | 55.5            | 53.8                  | 100                        | [12]       |
| Screening + holding tank + filtration + UF + Cl₂ disinfection | 72.3            | 65.2            | -               | 100                   | 100                        | [13]       |

Studies on the feasibility of implementing GWR are growing but remain limited. For example, a study evaluated the feasibility of applying membrane bioreactor (MBR) for greywater treatment in a single household. It was found that the system was not financially feasible when high quality effluent is required [6]. Another study carried out a feasibility assessment using MBR in multi-story building. The study proved that the number of floors required to collect greywater is a key factor in identifying the feasibility of such system [1]. Another GWR study, which involved using filtration, reported financial feasibility through considering health impact and nutrient recovery as additional savings [14]. Additionally, pilot scale MBR inside a small hotel indicated that 7 years of operation was required to recover the GW reuse system cost [15]. Moreover, an assessment was conducted for single household GW system using filtration and carbon adsorption. The system achieved a payback period of 4 years of operation [16]. This study represents a contribution to assess the feasibility and impact of greywater recycling in four types of buildings in Sharjah, United Arab Emirates.

2. Methodology
In this study, greywater reuse installations in four types of buildings; a high rise building, a hotel, a school and a house of worship, were assessed based on data provided by SEWA (table 2). The residential tower assessed consists of 244 apartments with 652 flushing tanks in which a 200 m³/d system was installed. The hotel has a capacity of 165 rooms with 180 flushing tanks and greywater is treated using 55 m³/d system. The school has 150 classrooms with 150 flushing tanks and the GW is treated using a 100 m³/d treatment system. The house of worship has 35 m³/d treatment system and can accommodate around 1000 worshippers along with 15 flushing tanks.
Table 2. Basic description of the four types of buildings.

| Description | High rise building | Hotel | School | House of worship |
|-------------|--------------------|-------|--------|------------------|
| Building information | 244 Apartments 652 Flushing tanks | 165 Rooms 180 Flushing tanks | 150 classrooms 150 Flushing tanks | Medium size 15 Flushing tanks 1000 worshippers |
| Number of users | 1220 residents | 495 guests | 4500 students | |
| Type of GWR treatment system | UF* | UF* | GAC** | GAC** |
| Capacity of installed GWR treatment system | 200 m$^3$/d | 55 m$^3$/d | 100 m$^3$/d | 35 m$^3$/d |

*Screening + holding tank + filtration + Ultra Filtration (UF) + Cl$_2$ disinfection  
**Screening + holding tank + filtration + Granular Activated Carbon (GAC) + Cl$_2$ disinfection

Schematics of the two types of treatment technologies implemented in the four types of buildings are shown in figure 1 (a), and (b). The granular activated carbon system consists of a screen followed by an aerated holding tank, a filtration unit, GAC unit, and a chlorination unit, figure 1 (a). Disinfection is mandatory in Sharjah and SEWA requires maintaining a minimum of 1 mg/L residual chlorine in treated greywater. The UF system is similar to the GAC system except for the replacement of the GAC by the UF membrane unit, figure 1 (b). SEWA adopted a set of water quality requirements, table 3, and SEWA requires owners of greywater systems to submit monthly reports documenting water quality assessed by licensed laboratories to ensure compliance with the requirements.

The whole-life cost (WLC) model was used for assessing the feasibility of implementation of greywater reuse in the four types of buildings [17]. The relevant model equations are as follows:

\[
TC_{o&m} = C_{o&m}(1 + r_{o&m}t)W_S
\]

\[
TC_{elec} = C_{elec}(1 + r_{elec}t)W_S
\]

\[
TC_W = C_W(1 + r_Wt)W_S
\]

\[
TC_{swg} = C_{swg}(1 + r_{swg}t)W_S
\]

\[
TC_{Ann} = TC_{o&m} + TC_{elec} - TC_W - TC_{swg}
\]

\[
TC_{WL} = TC_{cap} + \sum_{i=1}^{l} \frac{TC_{Ann}}{(1 + i)^t}
\]

Where $TC_{o&m}$ is total operation and maintenance cost, $TC_{elec}$ is total electricity consumption cost, $TC_W$ is total cost of water, $TC_{swg}$ is total cost of sewage disposal, $TC_{Ann}$ is total annual cost, and $TC_{WL}$ is net present value of whole life cost (NPV). The assumption and parameters used in the study is illustrated along with remaining equations abbreviation.

Greywater can be recycled and used for flushing toilets, landscape irrigation, and cooling in open cooling towers. However, some reuse options are not available for certain categories of buildings. High rise buildings, city hotels, schools and houses of worship usually do not have open areas in need for landscape irrigation. Furthermore, houses of worship are usually cooled using split-air-conditioning units and do not use central HVAC units. Therefore, the analysis presented in this study...
is for the two possible greywater applications in the four types of buildings selected in this study, namely toilet flushing and cooling. The reduction in CO$_2$ emissions and energy consumption were based on the reduced quantity of water acquired from reverse osmosis (RO) plant. Generally, RO consumes 5 kWh/m$^3$ of treated water coupled with 3.1 kg CO$_2$ emissions/m$^3$ based on the average emission of electricity production in UAE (0.61 kg CO$_2$/kWh) [18]–[19]. The quantity of produced water was used to assess the reduction of both emissions and energy for both reuse applications.

Table 3. SEWA minimum requirements for greywater reuse [18]–[19].

| Water parameter               | Minimum requirements |
|-------------------------------|----------------------|
| COD (mg/L)                   | ≤ 50                 |
| BOD (mg/L)                   | ≤ 10                 |
| TSS (mg/L)                   | ≤ 10                 |
| Total coliforms MPN/100 mL   | ≤ 100                |
| Fecal coliforms MPN/100 mL   | ≤ 5                  |
| Free chlorine (mg/L)         | 0.5-1                |
| Turbidity (NTU)              | ≤ 2                  |
| pH                            | 6-8                  |

Figure 1. Treatment systems used in the four types of buildings: (a) granular activated carbon system; and (b) ultrafiltration system.

3. Results & discussions

3.1. General considerations

In assessing feasibility of greywater reuse systems, it is essential to consider who pays and who benefits from greywater reuse (table 4). Building owners currently pay for the installation of greywater systems in addition to the operation and maintenance costs. Cost cutting is a major incentive for voluntarily installing greywater reuse systems. Owners of private hotels and private schools can benefit from feasible greywater installations while owners of high rise residential buildings may not benefit from savings achieved from greywater reuse unless they can pass the cost to their tenants through rent increase, which is not a favorable option. Another consideration that determines the feasibility of greywater reuse relates to the amount of greywater than can be reused. Typically, open cooling towers require more water than can be
produced through recycling greywater, however toilet flushing usually requires less than available greywater. Public acceptance is also a major hinderance to the adoption of greywater reuse. Inspections showed some objections due to the release of unpleasant odors resulting in public health concerns. Public acceptance is mainly influenced by education and understanding the importance of water conservation. Thus, challenges in terms of public acceptance are directly affected by the efficiency of systems operation [18]–[19].

Table 4. Applicability of greywater reuse options to establishments and who pays & benefits.

| GWR option   | High rise buildings | Houses of worship | Schools | City hotels |
|--------------|---------------------|-------------------|---------|-------------|
|              | Applicable          | Who pays/ benefits | Applicable | Who pays/ benefits | Applicable | Who pays/ benefits |
| Cooling towers | Yes                | owner pays & benefits | No     | Yes          | *Private - owner pays & benefits | Yes |
| Flushing toilets | Yes               | Owner pays/ tenants benefits | Yes   | Public Building | *Public - public cost | Yes |

*The option may be available for some schools.

3.2. Economic assessment of greywater installations

The details of the capital and operational costs of the four greywater reuse systems, based on information, provided by SEWA, are presented in table 5. The total infrastructure cost included both supply and installation of treatment system cost coupled with the cost of water collection and plumbing system distribution. The total infrastructure cost was computed as 315000, 143300, 148300, 64000 USD for high rise building, hotel, school, and house of worship, respectively. Similarly, the total operational cost included both maintenance and electricity consumption costs.

Table 5. Capital and operating costs of GW installation in the four types of buildings.

| Cost description                        | High rise building | Hotel   | School  | House of worship |
|-----------------------------------------|--------------------|---------|---------|------------------|
| Cost of supply & installation of treatment system (USD) | 133000             | 33800   | 61300   | 18500            |
| Cost of collection & distribution plumbing system (USD) | 182,000            | 109500  | 87000   | 45500            |
| Total infrastructure cost (USD)         | 315000             | 143300  | 148300  | 64000            |
| Annual cost of preventative maintenance and service (USD/Y) | 8200               | 7200    | 8200    | 4900             |
| Electricity consumption (USD/Y)         | 6500               | 5700    | 6500    | 4100             |
| Total operational cost (USD/Y)          | 14700              | 12900   | 14700   | 9000             |

The WLC model was used to conduct the feasibility for each type of building based on the applicability of GW reuse application within the unit. Cooling tower option was not available in house of worship as determined in table 4. The school scenario required equal volume of GW for both applications and thus either applications could be applicable. The high rise building and hotel showed variation in the required GW between toilet flushing and cooling tower. The different parameters implemented in the WLC model are presented in table 6.
Table 6. Parameters for assessing greywater reuse for four types of buildings in Sharjah.

| Description                              | Symbol  | High Rise Building | Hotel     | School     | House of worship |
|------------------------------------------|---------|--------------------|-----------|------------|-----------------|
| Capacity of treatment system             | GW<sub>Cap</sub> | 73,000            | 73,000    | 20,075     | 20,075          | 36500           | 12775           |
| Treatment system water efficiency system (%) | WE<sub>FF</sub> | 80                | 80        | 80         | 80              | 80              | 80              |
| Available GW (m<sup>3</sup>/Y)           | GW<sub>AV</sub> | 55000             | 55000     | 18068      | 18068           | 29565           | 11863           |
| GW for flushing/cooling (m<sup>3</sup>/Y) | W<sub>S</sub>   | 26,718            | 55,000    | 10841      | 18068           | 29565           | 11863           |
| Annual increase in O&M cost (%)         | r<sub>m&s</sub> | 0                 | 0         | 0          | 0               | 0               | 0               |
| Annual increase electricity rate (%)    | r<sub>elec</sub> | 0                 | 0         | 0          | 0               | 0               | 0               |
| Annual increase water rate (%)          | r<sub>w</sub>   | 0                 | 0         | 0          | 0               | 0               | 0               |
| Annual increase sewage disposal rate (%) | r<sub>swg</sub> | 0                 | 0         | 0          | 0               | 0               | 0               |
| Annual discount rate (%)                | i         | 4                 | 4         | 4          | 4               | 4               | 4               |
| Cost of maintenance & service (USD/m<sup>3</sup>) | C<sub>o&m</sub> | 1.12              | 0.55      | 2.44       | 1.47            | 1.01            | 1.52            |
| Cost of electricity (USD/m<sup>3</sup>) | C<sub>elec</sub> | 0.095            | 0.095     | 0.095      | 0.095           | 0.095           | 0.095           |
| Cost of water (USD/m<sup>3</sup>)       | C<sub>w</sub>   | 2.1               | 2.1       | 2.1        | 2.1             | 2.1             | 2.1             |
| Cost of sewage disposal (USD/m<sup>3</sup>) | C<sub>swg</sub> | 0.3              | 0.3       | 0.3        | 0.3             | 0.3             | 0.3             |
| Useful life of system (Y)               | t         | 1-20              | 1-20      | 1-20       | 1-20            | 1-20            | 1-20            |

The economic feasibility of the high rise residential building revealed that during first year of operation, the system was not financially feasible for both reuse applications. However, the cooling tower was expected to achieve profit after 5 years of operation and up to the design life of the system with maximum NPV of 1.27 M USD. The toilet flushing application showed less profit compared to the cooling tower with maximum NPV of 0.36 M USD. Additionally, toilet flushing gained non-feasibly NPV after 5 years and turned to profit after 10 years of operation as shown in figure 2 (a). Furthermore, due to the usage of system capacity above GWR requirements within the high rise building, the system capacity was suggested to be reduced depending on the reuse application by 50% and 10% for the flushing and cooling, respectively. The modification resulted in enhancing the maximum useful life profit up to 1.29 M USD and 0.44 M USD for the toilet flushing and cooling.
tower, respectively as shown in figure 2 (b). Additionally, due to the fact that, building owner will pay for installing the system, and tenants will benefit from the reduction of water bills, a rental increase of 250 USD/Y should be adopted for each flat within the building. Furthermore, the cooling tower application will reflect the benefits directly on the owner and thus no incentive was required.

The hotel analysis in figure 3 (a) showed different trends compared with high rise building for toilet flushing application. It was predicted that for toilet flushing, the hotel required up to 15 years of operation to produce a profit of 2000 USD only and increased to 34000 USD at the maximum design life of the project. However, the cooling tower application gained a higher profit after 15 years of operation at 0.19 M USD. Additionally, 10 years of system operation for cooling tower yielded 0.10 M USD, which was higher than the maximum profit obtained through the toilet flushing application. The hotel system also required modification of the system capacity to increase the resulted profit for toilet flushing only. The system capacity was suggested to be reduced by 30% and provided a maximum profit of 65000 USD after 20 years of operation as follows in figure 3 (b). The modification for cooling tower reuse was not required as 90% of system capacity was being utilized. The benefits of the system installing will induce benefits for the owners and it can be noted that hotel with GW reuse systems should not increase the room rental rate.

Furthermore, the forecasting of school and house of worship scenarios resulted in a maximum NPV of 0.62 M USD and 0.20 M, respectively (figure 4 (a), and (b)). The school owner will directly be influenced by the projected benefits whether it is public or private ownership. The benefits of house of worship will be directed to the governmental sector. The modification of both system capacities was not required as around 80% of each system was being utilized for GWR applications.

**Figure 2.** Economic feasibility of GWR in the high rise building for flushing toilets and cooling: (a) Based on installed system capacity, which exceeds demand for GW; and (b) reduced treatment system capacity to match demand for greywater.

**Figure 3.** Economic feasibility of GWR in the hotel for flushing toilets and cooling: (a) Based on installed system capacity, which exceeds demand for GW; and (b) reduced treatment system capacity.
to match demand for greywater.

Figure 4. Economic feasibility of GWR in the school and house of worship (a) School; and (b) house of worship.

3.3. *Impact assessment of greywater recycling on CO₂ emissions and energy consumption*

The high rise building was estimated to reduce CO₂ emissions by 168 to 3355 Ton CO₂ and energy consumption by 275 to 5500 MWh using cooling tower (CT) application (figure 5 (a)). The hotel analysis (figure 5 (b)) revealed that a maximum reduction in CO₂ emissions of 1102 Ton compared to 661 Ton were predicted using CT and toilet flushing (TF) applications, respectively. Additionally, the school scenario (TF/CT) application showed higher reduction in both CO₂ emissions and energy consumption compared to the house of worship (figure 5 (c), and (d)). Moreover, the reduction of emissions and energy could be increased dramatically when GWR will be implemented in all residential buildings, hotels, schools, houses of worship within Sharjah and even on the UAE scale. The reduction of energy consumption ranged between 54 to 5500 MWh depending on building type, reuse application, and useful life of the system.
Figure 5. Projected reduction in energy consumption and CO\textsubscript{2} emissions for: (a) high rise building; (b) hotel; (c) school; and (d) house of worship.

4. Conclusion
The economic feasibility of different building categories located in Sharjah city was carried out through whole life cost (net present value) approach. The maximum NPV from cooling tower application was obtained in the high rise building scenario. The obtained results provided noticeable reduction in CO\textsubscript{2} emissions and energy associated with RO plant water production. Additionally, a rental increase of 250 USD/Y was required to provide building owners with incentives as a compensation of GWR system cost. The reduction of system capacities was essential in new buildings depending on the GWR requirements.

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