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Economic feasibility of on-site greywater reuse in multi-storey buildings

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Abstract

This paper analyses the economic feasibility of on-site greywater reuse in the urban sector. RBC- and MBR-based systems were selected as model systems for the economic analysis. The analysis showed that the investment costs of an RBC-based system consist of less than 0.5% of the price of a flat for buildings of more than 20 flats (five storeys). At a water price of 1.16 US$/m^3 and sewage charges of 0.3 US$/m^3, the RBC-based system became economically feasible when the building size reached seven storeys (28 flats). The on-site MBR-based system proved to be economically unrealistic, becoming economically feasible only when the building size exceeded 40 storeys. Cluster MBR-based systems, incorporating several buildings together, became feasible when the cluster size was four buildings or more (each 10 storeys high). A subsidy of 0.7 US$/m$^3_{\text{reused}}$ resulted in much smaller systems becoming economically feasible: four-storey buildings (16 flats) for the RBC system and two buildings for the cluster MBR system. The on-site MBR system (single building) remained unfeasible.

Keywords: Greywater reuse, Urban; Economic aspects; Decentralised reuse; On-site treatment; Cost benefit analysis; MBR; RBC

1. Introduction

Population growth coupled with ever-increasing urbanization, and in many cases a parallel rise in specific water demand, results in continuous growth of urban water demand in many regions around the world. Today many large urban areas, even in regions that were traditionally considered as water ample (Japan, Europe), suffer from water scarcity. This necessitates the development of additional resources, e.g., exploitation of more distant (surface water) and deeper (groundwater) sources, construction of new dams and long conveyance systems, and seawater desalination. Utilising these new sources usually entails high direct costs (construction, operation and maintenance), and is likely to result in high indirect

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(external) costs (increasing negative environmental effects). Therefore, lowering the overall urban water demand has recently become an important issue for water utilities and regulatory bodies. This could be achieved by a combination of different measures such as increasing the efficiency of water supply systems (lowering real losses), installation of water-efficient appliances, raising public awareness to water saving, and reusing water as a "new" alternative resource. When considering urban water reuse, on-site greywater reuse has the potential to play a significant role.

Indoor domestic water demand (excluding garden irrigation and other external uses) in developed countries usually ranges between 100 and 180 L/d per capita or 36–66 m^3/y per capita [1–6], comprising 30–70% of the total urban water demand. Besides minor quantities, most consumed water is transformed into wastewater, which can be classified into two major categories:

- Greywater: originating from all household "water-generating" appliances except toilets, comprising 60–70% of the in-house water demand.
- Blackwater: originating from toilets, comprising 30–40% of the in-house water demand.

In urban areas the most feasible greywater reuse option is for toilet flushing, which can reduce individual in-house net water demand by 40–60 L/d per capita. If this practice becomes widespread, a reduction of up to 10–25% in urban water demand can be achieved. For example, Friedler and Galil [7] showed that in 2023, with a 30% penetration ratio (i.e., 30% of houses having greywater reuse units installed), greywater reuse for toilet flushing in the domestic sector could save about 50 MCM/y in Israel (projected population 10×10^6). This consists of about 5% of the projected national urban water demand and equals the capacity of a medium-size seawater desalination plant. The authors further demonstrated that reaching 30% penetration in 20 years is realistic if the government would promote and encourage such a practice. Indeed on-site greywater reuse has been investigated extensively in the last decade, especially in the EU, Japan, USA and Australia. However, full-scale commercial systems are not very common [6,8–12].

Greywater, in contrast to common perception, may be quite polluted, and thus may pose health risks and negative aesthetics (i.e., offensive odour and colour) and environmental effects [1,13–16]. As a result, highly efficient and reliable conveyance, storage and treatment systems are required. Various treatment systems are reported in the literature varying in complexity and degree of treatment [12,13,17–20]. Friedler [15] demonstrated that since domestic greywater production is greater than its consumption (reuse for toilet flushing), it is possible — and preferable — to reuse only "light" greywater (i.e., the less polluted greywater streams originating from baths, showers and washbasins) and thus reduce treatment costs and possible adverse effects.

Most research to date has focused on the development and performance of different treatment and reuse units, whereas the economic aspects of greywater reuse have been scantily addressed. The goal of this paper is to perform an economic analysis of on-site greywater reuse systems, since unless proven to be economically feasible, greywater reuse practice will not become widespread. The analysis was performed on newly built houses where the greywater reuse system was installed during construction of the building (retrofit systems were not considered). The paper focuses on multi-storey residential buildings, which are typical to densely populated urban areas where the water saving potential is most significant on a regional/national scale.

2. Methods

2.1. Basic considerations

When performing an economic analysis of on-site greywater reuse, two distinct entities can be

Table 1
Greywater reuse — costs and benefits of individual consumers and the general public

Benefits	Costs
Individual consumer:	
• Money saving	• Network separation
Water bill	Collection: grey, black
Sewage bill	Supply: potable, treated greywater
	• Greywater treatment system
	Capital costs
	Operation and maintenance costs
	Monitoring costs
	• Treated greywater conveyance
	Energy
General public:	
• Water resources	
Development of new resources can be postponed	
• Water abstraction	
Less energy	
• Water treatment	
Less energy	
Fewer chemicals	
Existing plants: enlargement can be postponed	
Future plants: smaller	
• Water conveyance and distribution	
Less energy	
Existing systems: enlargement can be postponed	
New systems: smaller	
• Wastewater collection	• Wastewater collection
Less energy (force mains)	Lower flows, more blockages?
Existing systems: enlargement can be postponed	
New systems: smaller	
• Wastewater treatment plants (WWTP)	• Wastewater treatment plants
Lower pollutants loads (degradable pollutants)	Higher pollutants concentration (less dilution)
Less energy?	
Fewer chemicals	
Existing WWTP: enlargement can be postponed?	
New WWTP: smaller?	

identified differing in their share of costs and benefits (Table 1):

- Individual consumer — defined as an individual flat owner/tenant, a family living in a flat, a group of occupants living in the same multi-flat building, etc.
- The public in general — defined here as any of the following stakeholders: the general public, local authority, public water utility, private water company, central government, etc.

The individual consumer who uses less fresh water (as greywater is reused for toilet flushing) benefits from reduced water and sewage bills (sewage charges are usually proportional to water demand). On the other hand, the individual consumer carries the financial burden of paying the capital, operation and maintenance costs of the treatment and reuse system. The public does not pay for the on-site greywater reuse systems, while it benefits from the reuse practice of individual consumers: since individual consumers use less water, the costs of water (abstraction, treatment, conveyance and distribution) are bound to be lower, and it is the general public who pays these costs. The same is true for wastewater: lower discharges mean less expenditure on sewage collection and treatment. It should be noted that reduced flows in sewers may result in a higher frequency of clogging events in existing sewers. However, this problem should not be substantial since many (or even the majority of) existing municipal sewer systems are maintained close to or over their design capacity. Wastewater treatment plants might have difficulties in dealing with the higher concentrations of some pollutants (the loads of biodegradable pollutants will decrease while the loads of non-biodegradable ones will not change).

The above investment model is one of many possible models of cost-sharing between the individual consumer and general public. This is the most extreme cost-sharing model since the public does not share any costs with the individual consumer while it does share most benefits (all but reduced water and sewerage bills). As such, it forms a useful example for the purposes of this study.

The analysis performed addresses the direct costs and benefits to the individual consumer, while benefits (and costs) to the public in general are addressed indirectly through a subsidy policy as explained later.

The basic building-blocks of the analysis are "typical" multi-flat buildings. Data on these were derived from ICBS reports [21] and from the Ministry of Housing, which are: typical family size, 3.4 persons; one family per flat; four flats per floor; floor height, 3 m.

2.2. *Description of the on-site greywater treatment and reuse system components*

2.2.1. *Conveyance systems*

The conveyance system consists of three main components (Fig. 1): collection of raw greywater from each flat, conveyance of treated greywater to the storage tank (situated on the roof), and distribution of treated greywater from the storage tank to WC cisterns in each flat.

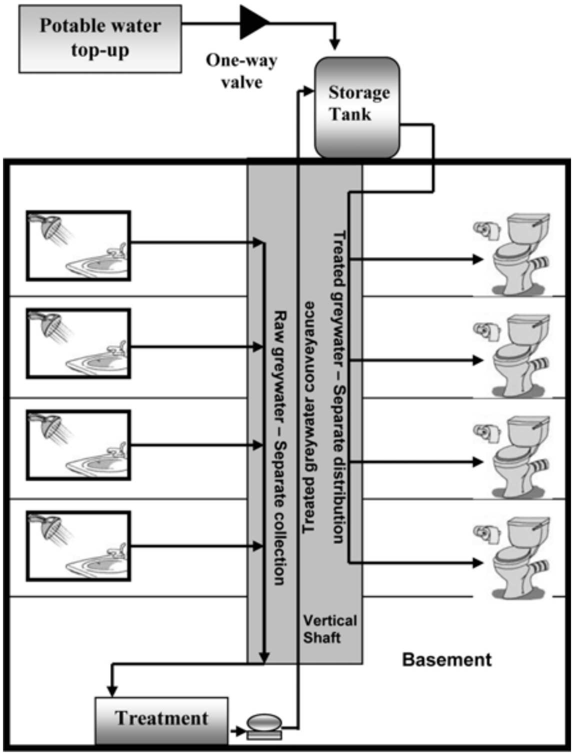

Fig. 1. Schematic layout of greywater collection and distribution.

Lateral pipes collect light greywater from its sources (bath, shower and washbasin) to a central vertical collector pipe. The extra costs associated with these laterals are low since most building standards require separate laterals for greywater and blackwater collection. Further, in most multi-storey residential buildings, bathrooms and WCs are situated near the vertical shaft/s of the building in order to reduce costs. In a typical "non-recycling" building greywater and blackwater collectors merge to one conduit in the vertical shaft. In a "greywater reusing" building, a separate pipe should be installed in the vertical shaft

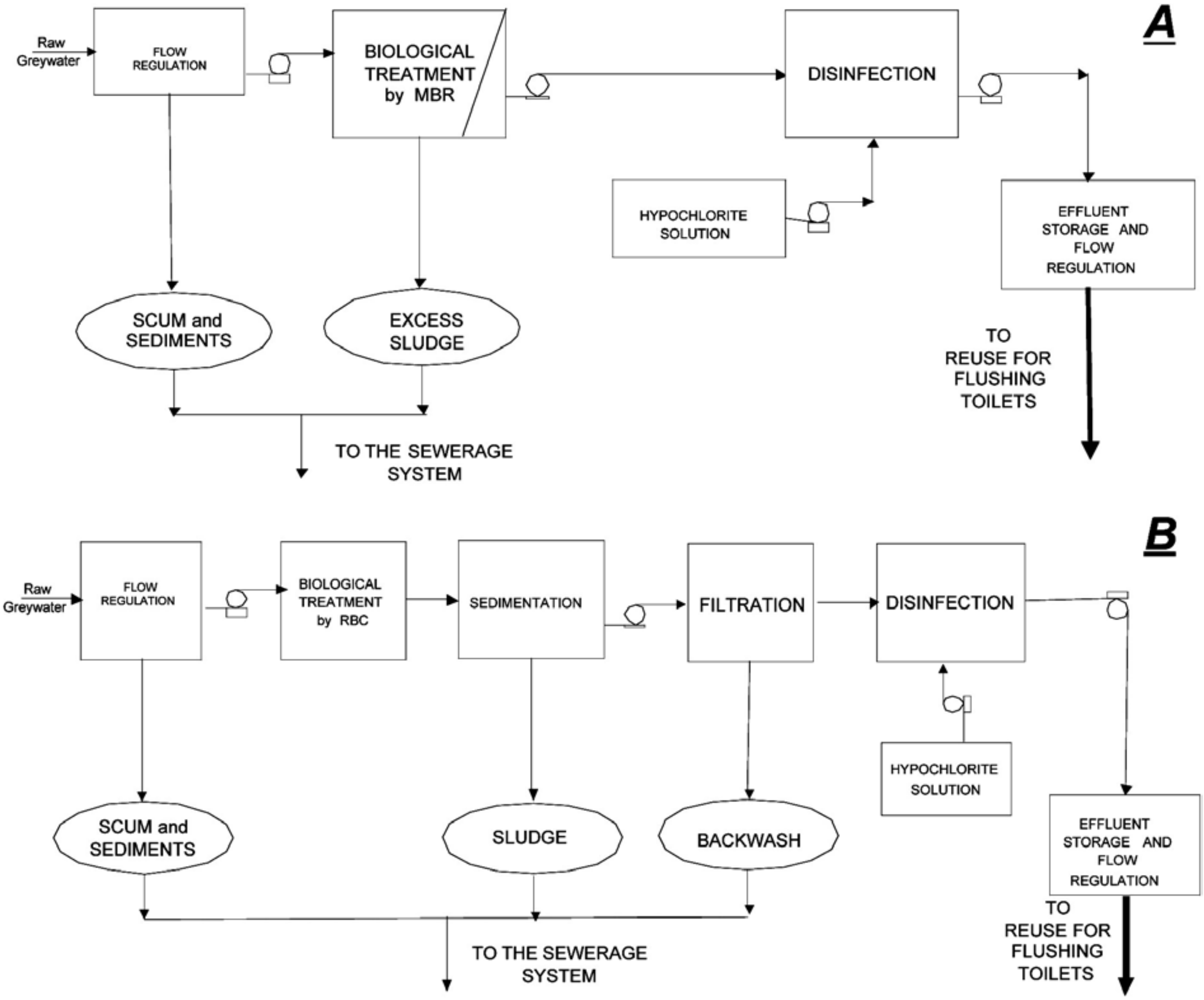

Fig. 2. Block diagram of the greywater treatment systems: A, MBR-based system; B, RBC-based system.

in order to convey raw greywater to the basement (or the entrance floor) where the treatment unit is situated. Treated greywater is then pumped to the top of the building to the storage tank and conveyed from there gravitationally through a separate pipe in the vertical shaft to the WC cisterns in each flat. Any shortage of treated greywater in the storage tank is topped up by fresh water through a one-way valve, and any excess is discharged through the blackwater collector of the building.

2.2.2. Treatment units

Two treatment technologies were selected to serve as models for the economic analysis (Fig. 2): a membrane bioreactor (MBR) system, which represents the latest generation of compact intensive wastewater treatment technologies; and a rotating biological contactor (RBC) system, which represents a well-proven, more extensive technology, especially suitable for small plants. The MBR unit consists of an equalisation basin (regulates flows, quality and temperature of the raw greywater), membrane bioreactor and a disinfection unit (chlorination). The RBC unit consists of an equalisation basin, RBC, and a sedimentation basin, followed by a disinfection unit (chlorine). In urban areas excess sludge, scum and sediments are discharged to the municipal sewer system.

Nolde [22] states that after 10 years of experience, RBC-based greywater reuse systems proved to be very reliable and produced high-quality effluent. Nolde [22] adds that MBR-based systems are starting to make their way into the field of on-site greywater treatment and reuse systems. Friedler et al. [17,23] also report that both RBC-based and MBR-based greywater treatment systems (pilot scale) were very reliable and consistently produced effluent of excellent quality.

2.3. Costs

2.3.1. Capital costs

Capital costs of all system components were received from leading manufacturers and distributors (who requested anonymity). These included the costs of the components plus installation. Where possible, regression analysis was performed on data acquired from various sources in order to derive a cost function to each component (Table 2). For storage tanks, RBC, and pumps, the best regression was obtained using a power equation (R^2= 0.94, 0.978, not applicable, respectively), while for the MBR unit the best regression was obtained using a logarithmic equation (R^2 = 0.868), suggesting higher sensitivity of cost to size in the low-size range. The following system components deserve further attention:

- Conveyance system: Based on the above discussion, it was estimated that additional 5 m of pipes are needed inside each flat (collect, distribute), and 9 m per floor (3×3 m: collect, convey to the rooftop storage, distribute to floors).
- Storage tanks: Fewkes and Ferris [24] showed that a 1 m^3 storage tank should be sufficient to regulate between raw greywater production and treated greywater consumption for toilet flushing for a large range of buildings sizes. Dixon et al. [4] demonstrated that as little as 0.15–0.2 m^3 storage is sufficient. In the system examined, two storage tanks of 1 m^3 each were selected, regardless of building size, one near the treatment unit for storing raw greywater and one on the rooftop for storing treated greywater prior to its reuse (Fig. 1).
- Chlorination unit: Information gathered from distributors of chlorination equipment revealed that for on-site greywater reuse, small chlorination units are suitable. The cost of these units is quite high, and does not vary with capacity (Table 2). Disinfection by UV irradiation should be less expensive. However, it does not allow for residual disinfectant and thus needs further investigation.
- Additional expenses: Ancillaries such as pipes, small devices, valves, fittings, etc. These are needed mainly in the treatment unit and were estimated at 15% of total cost.

2.3.2. Operation and maintenance (O&M) costs

O&M costs include costs of energy needed for treatment and conveyance, cost of labour (maintenance personnel), cost of disinfectant (chlorine), cost of preventative treatment of the MBR membranes, and costs of spare parts and repairs, with the following details:

- Labour: Based on experience from small wastewater treatment facilities, 1 h per week maintenance is required, at a rate of 20 US$/h.
- Disinfectant: Liquid chlorine disinfectant will be used (11%) at a price of 0.26 US$/L. Friedler et al. [17,23] showed that the chlorine demand of greywater effluent treated by either the RBC or MBR unit does not exceed 3 mg/L (satisfying 1 mg/L residual chloride after 1 h

Table 2
Capital costs of various components of the reuse system

Item	Cost basis	Units	Cost function	R^2	Data sources
Pipes	Length	US$/m	$C = 6 \cdot L$	—	[30]
Storage tanks	Volume	US$/m^3	$C = 144 \cdot V^{0.484}$	0.940	2 leading Israeli distributors[b]
Pump	Flow	US$/(m^3/d)	$C = 594 \cdot Q^{0.0286}$	—[a]	2 Israeli distributors[b]
MBR	Flow	US$/(m^3/d)	$C = 18{,}853 + 17{,}945 \cdot \text{Ln}(Q)$	0.868	3 international manufacturers[b]
RBC (incl. sed. basin)	Flow	US$/(m^3/d)	$C = 3{,}590 \cdot Q^{0.6776}$	0.978	Leading British manufacturer[b]
Chlorination	Unit	US$/unit	$C = 1{,}670$	—[a]	2 Israeli distributors[b]

[a] Not enough data points.
[b] Preferred not to reveal their identity.

contact time as required in various reuse standards). Thus, the yearly cost of chlorine solution can be expressed as:

$$C_{\text{chlorine solution}} = (\text{Chlorine dose}) \cdot (Q \cdot 8760) \cdot \frac{1}{X} \cdot \frac{1}{\rho} \cdot (\text{Unit cost}) = 62.11 \cdot Q \tag{1}$$

where $C_{\text{chlorine solution}}$ is the annual cost of chlorine solution [US$/y]; chlorine dose is 0.003 [kg/m^3] (3 mg/L); Q is the greywater flow [m^3/h]; X the fraction of chlorine in the chlorine solution [kg$_{\text{chlorine}}$/kg$_{\text{solution}}$] (solution contains 11% chlorine, thus $X = 0.11$); ρ is chlorine solution density [kg/L] (approximately 1 kg/L), with the unit cost 0.26 US$/L.

The right-hand side of Eq. (1) was obtained by inserting the above values into the middle section of the equation.

- Preventive maintenance of MBR membranes: Membranes require periodical preventive treatment with chemicals, the costs of which were assessed by a leading international manufacturer at 0.02–0.03 [US$/(m^3/y)]. The higher value was taken for the analysis.
- Energy: Consumed for the operation of the treatment units and for conveying treated greywater to the storage tank on the rooftop, at a cost of 0.11 US$/kWh (Israel Electric Corporation).

1. Treatment: A leading MBR manufacturer reported energy consumption of 1–1.5 kWh/m$^3_{\text{treated greywater}}$. A value of 0.5–0.75 kWh/m$^3_{\text{treated greywater}}$ (corresponds to 0.1–0.16 kWh/m$^3_{\text{reactor}}$) was calculated based on Davies et al. [25], who analysed the energy consumption of much larger treatment units (650–10,000 m^3/d). For the MBR unit, a value of 1.5 kWh/m$^3_{\text{treated greywater}}$ was used for calculating O&M costs.

Based on data from a leading British manufacturer, the following equation was derived for power consumption in the RBC (R^2 = 0.991):

$$\underline{P} = 42.2 \cdot e^{(0.1046 \cdot Q)} \tag{2}$$

where $\underline{P}$ is power consumption [W] and Q is the greywater discharge [m^3/d].

2. Conveyance: The pump that conveys treated greywater to the top of the building has to overcome elevation difference and the head loss is the pipes [Eq. (3)].

$$H_p = \Delta Z + \Delta H_f \tag{3}$$

where H_p is the head to be supplied by the pump [m]; ΔZ the elevation difference [m] and ΔH_f is the head loss in the conveyance pipe [m].

Each storey was considered to be 3 m high. Since the treatment units will be situated either in the basement of the building or on the entrance floor where usually there are no residential flats, an extra 3 m were added to all elevation calculations, e.g., for a four-storey building, the pump should overcome an elevation difference of 15 m (4×3 m + 3 m) and not 12 m. Head losses in the pipes were calculated by the Hazen–Williams equation:

$$\Delta H_f = 1.131 \times 10^9 \cdot \left(\frac{Q}{c_{H-W}} \right)^{1.852} \cdot D^{-4.87} \cdot L \quad (4)$$

where Q is the flow [m^3/h], c_{H-W} is the smoothness coefficient (assumed 130); D the diameter [mm] (assumed 1", 25.4 mm); and L is the length [m]. An additional 15% was added to the calculated values to account for local head losses.

Power required by the pump was calculated by:

$$\underline{P} = \frac{\gamma \cdot Q \cdot H_P}{\eta} \quad (5)$$

where $\underline{P}$ is the power required for pumping [W]; $\gamma = -\rho \times g$ [kg/($m^2 \times s^2$)] ; Q is the flow [m^3/s] and η is the pump overall efficiency (pump and engine together, assumed 75%).

- Spare parts and repairs: These were estimated at 2% of total investment costs per year.

2.4. Benefits

Benefits to individual consumers stem from reduced water and sewage bills. Potable water is charged in Israel on a per flat basis, at a stepwise differential price of (updated January 2005): 0.74, 1.04 and 1.45 US\$/(m^3/month) for the first 8 m^3/month, the next 7 m^3/month, and excess amounts of water consumed, respectively. Sewerage is charged in accordance with potable water consumption at a constant rate of 0.3 US\$/($m^3_{\text{potable water consumed}}$/month).

Considering a typical flat of 3.4 occupants (see basic considerations section, above) and average domestic water demand of 161 L/d per person, of which 55 L/d is used for toilet flushing [26], a typical flat consumes 16.7 m^3/month (with a total cost of 16.5 US\$/month, ~200 US\$/y), of which 5.7 m^3/month is for toilet flushing. Thus, when greywater is reused for toilet flushing, the first 1.7 m^3/month of saved water is worth 1.45 US\$/m^3, and the remaining 4 m^3/month is worth 1.04 US\$/m^3, with a weighted average cost of 1.16 US\$/(m^3/month). Adding sewage charges results in a total savings of 1.46 US\$ for each m^3/month of reused greywater. The annual benefit per flat stands at US \$100, of which, US \$79.5 is in water bills and US \$20.5 in sewage bills.

2.5. Method of calculation

The net annual costs saving due to greywater reuse is the sole means of paying back the capital investment. Eq. (6) describes the net annual saving:

$$R = R_{WS} - C_{O\&M} \quad (6)$$

where R is the net annual saving [US\$/y], R_{WS} the annual savings on water and sewage bills [US\$/y] and $C_{O\&M}$ are the annual O&M costs [US\$/y].

Eq. (7) serves as the basis for calculating the investment return period:

$$R = \left(\frac{i \cdot (1+i)^n}{(1+i)^n - 1} \right) \cdot C \quad (7)$$

where R is the annual payment [US\$/y], i the annual interest rate (currently 5.5%/y in Israel); n

is the investment return period and C are the total investment costs [US$].

Representing the investment return period in Eq. (7) as a function of capital costs, annual cost savings (R) and interest rate yield:

$$n = \frac{\log\left[\dfrac{1}{1-\left(\dfrac{C\cdot i}{R}\right)}\right]}{\log(1+i)} \tag{8}$$

Only when $R > C\cdot i$ is the expression inside the logarithm in the numerator positive, and the equation has a solution. This is logical since only when the net annual saving is greater than the annual interest paid on the capital costs is it possible to return the investment costs (this is the physically possible solution). However, in order to be economically feasible, the return period (n) has to be shorter than the serviceable life of the system. Since electro-mechanical equipment comprises a major part of the total capital costs, the serviceable life of the whole system was set at 15 years.

Based on the above data, assumptions and considerations, an economic analysis for each system was performed, the results of which are presented in the following section.

3. Results and discussion

The investment costs of the RBC- and MBR-based systems are very sensitive to the size of the system, especially in the low-size range (Fig. 3A and B). The specific investment costs (costs per flat) of the RBC-based system become lower than 1,000 US$/flat when the number of flats exceeds 10, while for the MBR system about 80 flats are needed in order to reach the same specific cost. This indicates that the MBR-based system is much more expensive than the RBC-based one. The proportional investment costs of the reuse system (cost of the system as a proportion of the cost of a flat), may be more important than its nominal costs. In order to assess the relative investment costs, three prices of residential flats were selected: US $100,000, US $150,000 and US $200,000 (based on the typical price range in Israel [21]). The analysis shows that the proportional investment costs of the RBC-based system are quite marginal, while the proportional costs of the MBR-based system are somewhat higher (Fig. 3C and D). For example, considering US $150,000 flats (average price in Israel), the proportional cost of an RBC-based system is less than 1% and 0.5% for a building of more than four and 20 flats (one and five storeys) respectively, while the MBR-based system proportional cost becomes lower than 1% and 0.5% only when the building consists of more than 40 and 120 flats, respectively (10 and 30 storeys).

The specific (cost per flat) O&M costs (conveyance, treatment and distribution) of the RBC-based system is reduced with increasing number of flats, while the specific income does not change with size, as it stems from reduced water demand of each flat, leading to reduced water and sewage bills (Fig. 4). It can be seen that, under the current water and sewage prices in Israel (1.16 + 0.3 US$/m^3), when the number of flats exceeds 10–12 (a three-storey building), the specific income becomes positive, and the system enters the region of a physically possible solution. For the MBR-based system (results not shown), the specific income becomes positive only when the number of flats exceeds 24–28 (a 6–7 storey building).

Under the current Israeli water prices, the RBC-based reuse system becomes economically feasible (return period <15 years) when the number of flats exceeds 26–28 (7-storey building, Fig. 5A). The figure further shows that for the water price in the US (0.51 US$/m^3 [27,28])—about half the Israeli price — the system becomes feasible only when the building is 19 storeys high (>76 flats), a size which is currently not very

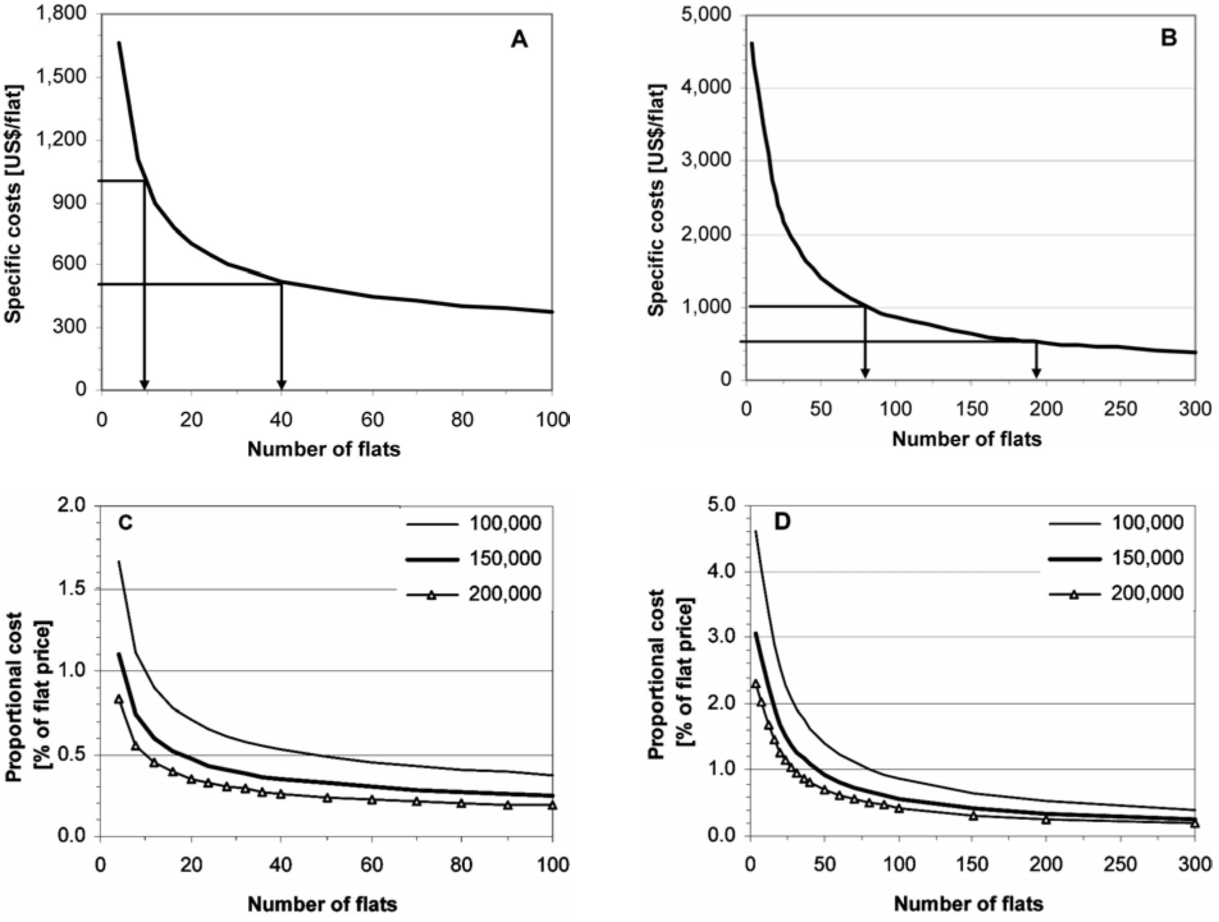

Fig. 3. Investment costs of the greywater treatment and reuse system. A, RBC specific costs; B, MBR specific costs; C, RBC proportional cost; D, MBR proportional cost.

common. Nevertheless, when the water price rises to 1.9 US$/m^3 (Germany [27,28]), the system becomes feasible when the number of flats exceeds 15 (~four storeys). This great variation demonstrates the high sensitivity of the economically feasible solution to water prices in the small-size systems range.

The MBR-based system becomes economically feasible (at Israeli water prices) only when the building is 38 storeys high (152 flats; Fig. 5B). This is, of course, currently quite an extraordinary height for residential buildings. Thus, at the current Israeli water price, MBR-based systems are not feasible on an on-site scale (single building), but rather on a cluster scale (incorporating several buildings together). Even at the German water price, the system is hardly realistic, becoming feasible only when the building is over 20 storeys high.

In order to investigate the economic feasibility of cluster MBR-based greywater reuse systems, an imaginary cluster of buildings was considered, the basic unit of which was a 10-storey-high building (40 flats). The difference between a stand-alone building and a building in a cluster lies in the need to convey raw greywater to the

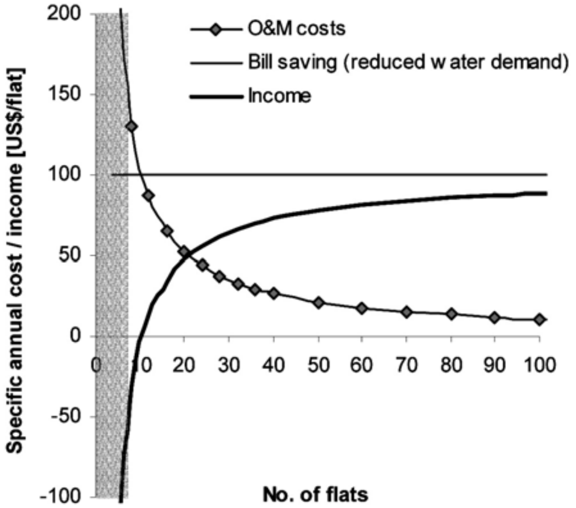

Fig. 4. Annual specific O&M costs and saving of the RBC system.

central treatment system and to distribute treated greywater to each building. It was assumed that each building needs an extra two 50-m-long pipes at a cost of 6 US$/m. The outcome of this analysis shows that a cluster of four buildings becomes economically feasible (Israeli current water price; Fig. 6), with a return period of 13.5 years. The return period decreases sharply to 4.9 years for a cluster of 10 buildings. The explanation of this phenomenon is that the specific investment costs of the treatment units decrease exponentially with cluster size, while the specific conveyance costs (investment and energy) remain almost constant with cluster size.

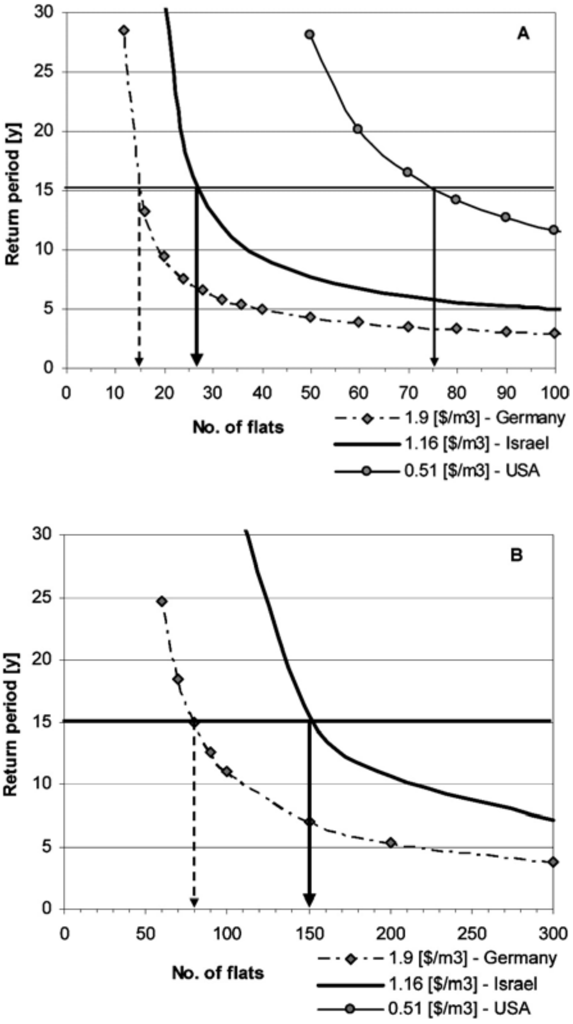

Fig. 5. Greywater reuse system return period under different water prices. A, RBC system; B, MBR system.

3.1. Subsidies and incentives

As discussed above (basic considerations section), it appears that the financial benefits that on-site greywater reuse offers on a regional/national scale may be much more significant than the benefit to the individual consumer. This is especially true in regions suffering from water scarcity. Thus, local and or national authorities may want to encourage individuals to install greywater reuse systems in order to enhance this practice. This can be done by various measures such as subsidies per m^3 of greywater reused, establishing a fund from which individuals can borrow money needed for the investment costs at interest rates lower than the market ones, reduced property taxes for greywater reusing buildings, etc.

To demonstrate the effects of such measures, Israel was selected as a case study country. In

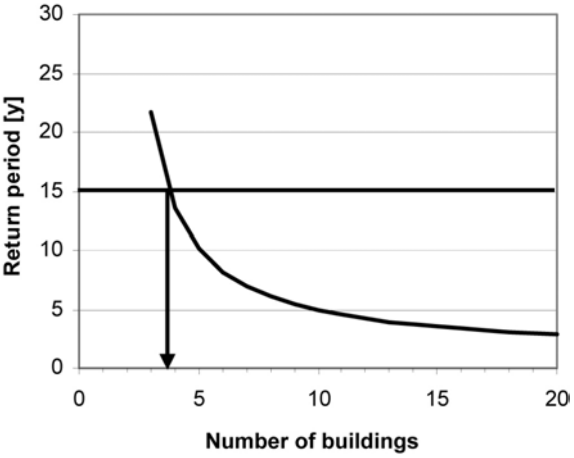

Fig. 6. Return period of a cluster MBR-based greywater reuse system.

order to alleviate its chronic water shortage, seawater desalination plants are being constructed, with a total projected capacity of over 300× 10^6 m^3/y. Greywater reuse will actually decrease the amount of water to be desalinated, thus the cost saving to the public equals the cost of desalinated water, which is estimated at 0.7 US\$/m^3 (75% production and 25% conveyance [29]). Thus, in order to reduce the total expenditure on water, the Israeli government can subsidise individual greywater reuse schemes by up to 0.7 US\$/m^3. This is a conservative value as the actual savings will probably be higher since factors such as costs of sewage collection and treatment (see Table 1) and external costs of seawater desalination (air and marine pollution, land cost) were not considered.

Adding a 0.7 US\$/m^3 subsidy to the economic analysis showed that the RBC-based system became economically feasible when the number of flats was equal to 16 (four-storey building, return period of 12.8 years), while the return period for a seven-storey building shortened from 15 to 6.4 years. The cluster MBR-based system became economically feasible when two buildings were serviced together (return period 14.3 years). The single building MBR-based system remained unrealistic in most circumstances, becoming feasible for a 20-storey-high building (return period 14.3 years).

4. Conclusions

This paper analysed the economic feasibility of on-site greywater reuse systems in new buildings in the urban sector, since a prerequisite for this practice to become widespread is its economic feasibility to the individual consumer.

Two distinct entities in the urban sector were defined: the individual consumer/s, and the public in general. The most extreme cost-sharing model is when the individual consumer exclusively pays for the system (and benefits from reduced water and sewage bills), while the public does not share any of the costs. At the same time, the public does share most benefits resulting from the reuse practice of individuals (positive consequences of overall reduction of water consumption and sewage flows).

Under this extreme model (not sharing any costs), the investment costs of an RBC-based system consist less than 0.5% of flat price (US \$150,000 in Israel) for building of more than 20 flats (five storeys). Such marginal extra costs (much less than other components of the building), emphasise the attraction of the system to entrepreneurs: For a minor cost increase (most of which will be passed over to the buyer), they get an “environmentally friendly image”, enabling them to sell “green” flats that sell better and for more, especially to the middle and upper-middle classes. The investment costs of the MBR-based systems were found to be about three times higher (1.7% of flat price for the same building size).

Considering a water price of 1.16 US\$/m^3 and sewage charges of 0.3 US\$/m^3, the RBC-based reuse system became economically feasible when the building size reached seven storeys (28 flats), while the on-site MBR-based system was proven to be economically unrealistic, becoming feasible only when the building size exceeded 37 storeys. Nevertheless, cluster MBR-based systems, incorporating several buildings together, was found to become feasible when the cluster size was four buildings (each 10 storeys high).

The return period was found to be very sensitive to building size and to the price of water, especially in the small size range. This is due to the fact that the specific cost of the treatment system (which is very sensitive to size) comprised a major part of the total investment costs, while the specific cost of the conveyance system (which does not vary much with size) comprised only a minor part of the total investment costs.

As mentioned, considering this extreme model the public benefits from the reduced overall water consumption and from reduced sewage flows, but does not carry any financial burden. Since these benefits could be substantial on a regional/national level, authorities may want to encourage individuals to install on-site greywater reuse systems.

To demonstrate this, a conservative subsidy of 0.7 US\$/m$^3_{\text{reused}}$ (cost of production and conveyance of desalinated seawater) was added to the economic analysis. Adding this subsidy resulted in much smaller systems becoming economically feasible. The RBC-based system became economically feasible when the building size was four storeys high (16 flats). A cluster of two buildings served by the MBR system became feasible with a return period of 14.3 years, while a cluster of 10 buildings has a return period of less than 3 years. This example clearly shows that greywater reuse in the urban sector becomes more attractive when a consensus on appropriate distribution of costs and benefits, risks and responsibilities is reached.

If on-site greywater reuse practice becomes widespread, the costs of the systems will obviously decrease, making them more appealing to individual consumers. This is especially true for the MBR-based systems which are an emerging technology dominated by few manufacturers and not widespread (particularly in the small size range).

The analysis demonstrated that on-site greywater reuse is a feasible solution for decreasing overall urban water demand, not only from an environmental standpoint, but also from economic profitability under typical conditions.

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