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Greywater Recycling Systems in Urban Mixed-Use Regeneration Areas: Economic Analysis and Water Saving Potential

Sara Zadeh [1], , Rachel Lombardi [2] Dexter Hunt [3]*and Christopher Rogers [4]

[1] Postgraduate PhD student / Department of Civil Engineering, College of Engineering and Physical Sciences, University of Birmingham, UK
[2] Associate Director of Business Development, International Synergies Ltd, Birmingham, UK
[3] Birmingham Research Fellow / Department of Civil Engineering, College of Engineering and Physical Sciences, University of Birmingham, UK
[4] Professor of Geotechnical Engineering / Department of Civil Engineering, College of Engineering and Physical Sciences, University of Birmingham, UK

E-Mails: sxm942@bham.ac.uk (S.Z.); d.r.lombardi@bham.ac.uk (R.L.); huntd@bham.ac.uk (D.H.); c.d.f.rogers@bham.ac.uk (C.R.)

* Author to whom correspondence should be addressed; Tel.: +44-121-414-3544

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Abstract: Greywater (GW) recycling for non-potable uses such as toilet flushing is a management strategy to meet urban water demand with substantial water saving. This paper proposes a system that collects GW from residential buildings and recycles it for toilet flushing in both residential and office buildings. The total cost and water saving of standard sanitation technology were compared with 5 other options requiring less or no potable water use in toilets. Scenarios compare: no GW, individual GW, and shared GW systems with and without low-flush appliances. Typical residential and office buildings in urban mixed-use regeneration areas in the UK were used for these analyses. The results implied that constructed wetland treatment technology with standard appliances is more economically and environmentally viable than other scenarios. By increasing the water and wastewater price, shared GW systems with and without low-flush appliances were viable options within highly water efficient domestic and office buildings.

Keywords: Constructed wetland, Greywater recycling, Low-flush toilet, Urban mixed-use development

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1. Introduction

Population growth, rapid urbanization, higher standards of living and climate change have led and will lead to continuous growth of urban water consumption (WWAP, 2009). International Water Management Institute (2002) projected that total urban water consumption will increase from 1995 to 2025 by 62%. Two approaches address current and future water demands in urban regions. The first is to develop additional local 'natural' supplies, for example: new dams and reservoirs, seawater desalination, importing water from greater distances, or deep groundwater abstraction (Surendran, 2001). In many cases, these additional sources are either unavailable or can be developed only at extremely high direct and indirect costs compared with existing water sources. The second approach is to reduce potable water demands by: (i) optimizing the existing water supply system (i.e. reducing leakage), installing water-saving devices, and/or changing public behaviour; (ii) water re-use; and (iii) water recycling (Hunt et al., 2006).

Greywater (GW) recycling is receiving increasing attention as part of an overarching urban water management plan. GW is defined as the wastewater from baths, showers, handbasins, washing machines, dishwashers and kitchen sinks, and excludes streams from toilets (Jefferson et al., 2004). Toilet flushing is a frequently cited GW application. Toilet flushing in a typical home accounts for approximately 30% of home water use, but reaches over 60% in offices.

There are numerous case studies of installed GW systems within individual family dwellings, multiple housing dwellings, multi-storey office buildings, and individual (multi-room) hotel buildings. The high volume of GW generation in residential buildings, which accounts for approximately 50%-70% of daily water consumption, is usually greater than the requirement for toilet flushing (20%-36%) (Lazarova et al., 2003). In contrast, the GW produced in commercial, retail and other non-residential buildings (from handbasins, which use 21% of daily water consumption) is substantially less than the demand for toilet flushing (43%-65%); hence the cost of the infrastructure and treatment equipment is unlikely to justify the long pay-back periods under current water pricing (Leggett and Shaffer, 2002; Memon et al., 2005).

This paper presents an innovative method to improve the efficiency of GW recycling through symbiosis; it shares GW in mixed-use developments between different users. The mixed-use development has perhaps the best potential for GW systems: because the accommodation buildings (such as residential buildings, hotels, student halls, etc.), produce more GW than they need, the excess can be reused in other types of building with higher demand and less production (such as offices or retail buildings). In this specific case, the GW generation from domestic dwellings and offices (and their respective demands) is optimised to make the system much more viable, economically and environmentally.

The total costs and water savings are compared across six different supply/demand scenarios. The scenarios cover both standard and high efficiency water toilets/urinals both with and without individual or shared GW recycling. The Net Present Value (NPV) of each scenario is calculated to compare the economic cost of each scenario. Two alternative treatment technologies for GW have been assumed in this study: Membrane Bioreactors (MBR) and Vertical Flow Constructed Wetlands (VFCW).

2. Methodology

2.1. Description of buildings

Typical multi-storey residential and office buildings within urban mixed-use regeneration areas in the UK were chosen for a general model. The typical residential building has 16 apartments per floor, 10 floors with 3m floor heights, an occupancy rate of 2.4 occupants per apartment, and a gross area of 22,000m^2. The typical office building in this study is a 7-storey building with 49 toilets and 12 urinals, and a gross area of 14,000m^2. It is assumed that the office and residential buildings are located within 90m of each other, and that both are connected to a municipal central water supply and wastewater treatment plant. The distances assumed in this study were derived from Birmingham Eastside mixed-use development, in which residential and office buildings are co-located.

2.2. Scenarios considered

Six scenarios were evaluated (Figure 1-3):

- The baseline Scenario 1 (Figure 1a) adopts a standard water system in which potable water from the municipal water treatment plant is used to flush standard toilets (6.0 litres per flush) and urinals (3.8 litres per flush), and the wastewater from flushing is conveyed to a wastewater treatment plant.
- In Scenario 2 (Figure 1b), low-flush toilets (4.8 litres per flush) and urinals (1.5 litres per flush) are adopted; supply and discharge infrastructure are unchanged from Scenario 1. Scenarios 3 and 4 model individual GW systems.
- In Scenario 3 (Figure 2a), GW is collected from showers (13 litre per minute) in the residential building and recycled for flushing standard toilets therein; in addition GW is collected from handbasins in the office building and recycled for flushing standard toilets and urinals therein. [Calculations show that GW collected from showers meets toilet flushing demand in selected residential buildings; GW from basins and baths is not required.]
- Scenario 4 (Figure 2b) adds low-flush appliances to Scenario 3.
- In Scenario 5 (Figure 3a), GW is collected from showers in the residential building and used for flushing standard toilets and urinals in both residential and office buildings.
- Finally, Scenario 6 (Figure 3b) adds high efficiency technologies.

Figure 1. Systems without GW recycling for typical residential and office buildings with **(a)** standard technologies (Scenario 1). **(b)** low-flush appliances (Scenario 2).

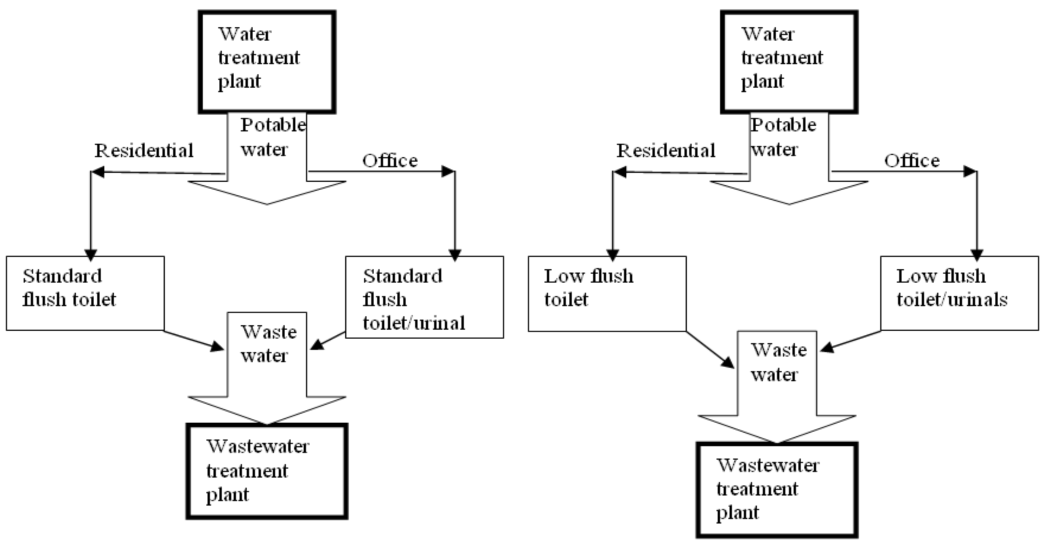


Figure 2. Individual GW systems for typical residential and office buildings with **(a)** standard technologies (Scenario 3). **(b)** low-flush appliances (Scenario 4).

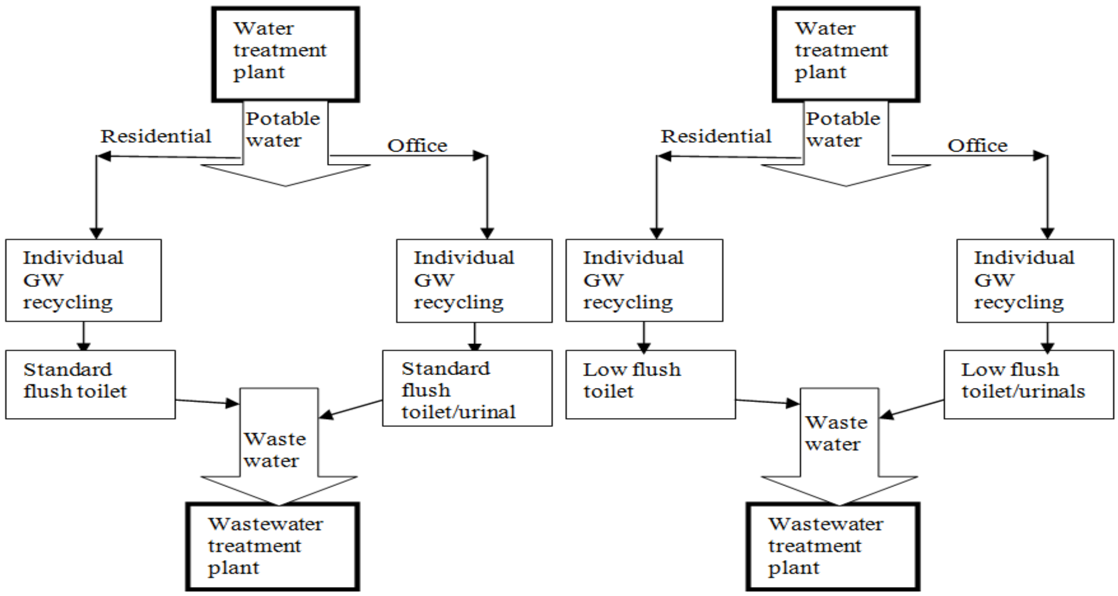
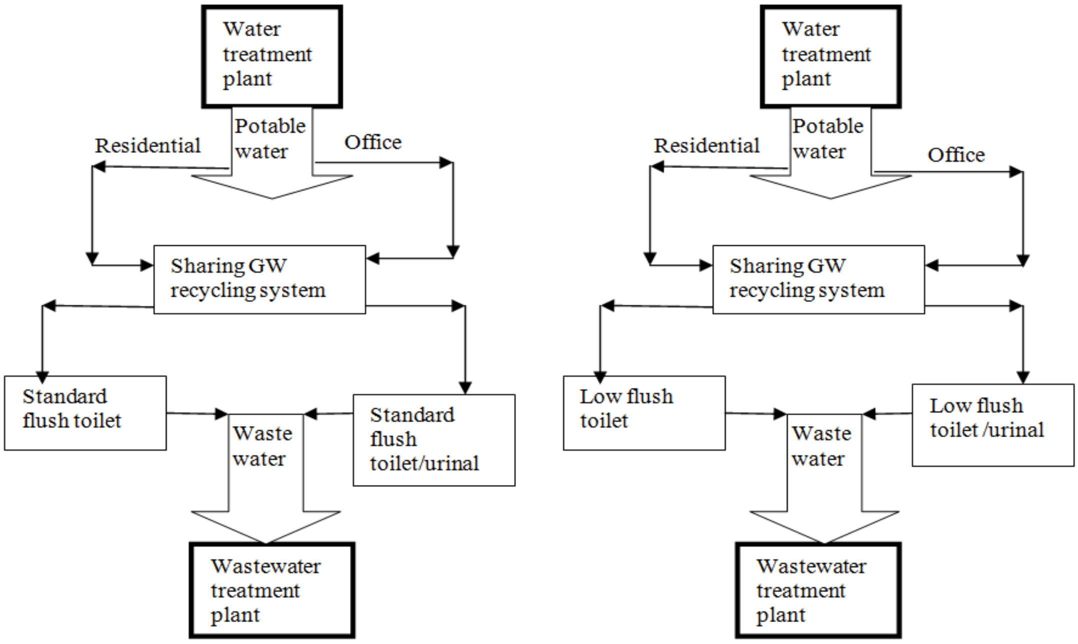


Figure 3. Shared GW systems for typical residential and office buildings with **(a)** standard technologies (Scenario 5). **(b)** low-flush appliances (Scenario 6).

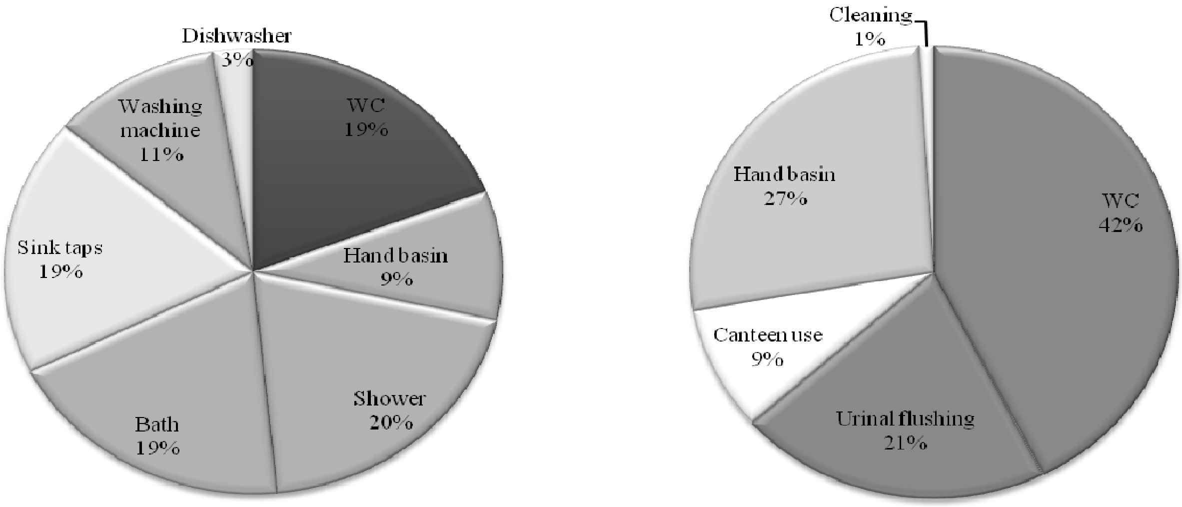


2.3. Standard assumptions across scenarios

Potable water demand within buildings is determined by the efficiency of the water using technology (micro-components) and user behaviour. Figure 4 illustrates the breakdown of micro-components for UK residential and office buildings. Potable water demand is estimated by assuming the average frequency of use and volume of water per use for each micro-component. Based on 7 previous UK studies, residential users flush between 3 and 8 times a day with an average of 4.6 (Roebuck, 2007). A study of water use in offices recognizes that the number of employees provides a better gauge of water consumption than the floor area (Thames Water, 2000). However, for the purpose of this study the number of employees has been assumed on the basis of the approximations based on British Council for Offices Guide 2000, which suggests an average floor area to employee within the UK of 15 m^2 (Wagget and Arotsky, 2006), and gender divided 50-50 (MTP, 2008). Females were assumed to use toilets three times a day; males were assumed to use toilets once a day and urinals twice a day (Anand and Apul, 2011). Assumptions about building size and occupancy can be adjusted to match actual conditions.

Handbasin taps are used 3 times a day per employee and run for 10 seconds each time. Cooking and drinking per employee uses 1 litre per day. For cleaning purposes, it is assumed that each toilet and urinal flushes twice and each handbasin runs for 5 seconds. The number of toilets, urinals and handbasins for office employees is assumed to be 1 per 25 males and 1 per 14 female employees, plus one extra one for persons with disability (MTP, 2008). Offices were assumed to be in operation 269 days per year.

Figure 4. Water use breakdown for **(a)** Residential (EA, 2008).
(b) Office (Wagget and Arotsky, 2006).



2.4. Potable water demand and wastewater estimation across scenarios

The total annual water demand for residential and office buildings without GW systems (Scenarios 1 and 2) is approximately 26 and 23 million litres, respectively (Table 1). A 9% reduction in potable water demand and a 7% reduction in wastewater generation were possible using low-flush appliances.

Residential buildings with individual GW systems (Scenario 3) require no potable water for toilet flushing. In office buildings the volume of GW is less than the demand; therefore 86% of the water needed for toilet flushing was potable. In these circumstances, individual GW systems can reduce potable water demand by 14% and wastewater generation by 17% (Table 1).

Table 1. Potable water demand and wastewater generation of all 6 scenarios

Scenario	*Potable water consumption (million litre /year)*	*Wastewater generation (million litre/year)*
1	25.66	24.58
2	23.43	22.90
3	21.75	20.85
4	20.37	18.99
5	18.33	16.38
6	18.27	14.16

Using low-flush fixtures with individual GW systems in each building (Scenario 4) can reduce the potable water demand and wastewater generation by up to 21% and 23%, respectively. Although applying low-flush appliances reduces the demand for flushing, office GW generation still does not meet their demand for flushing, and the shortfall is made up by potable water.

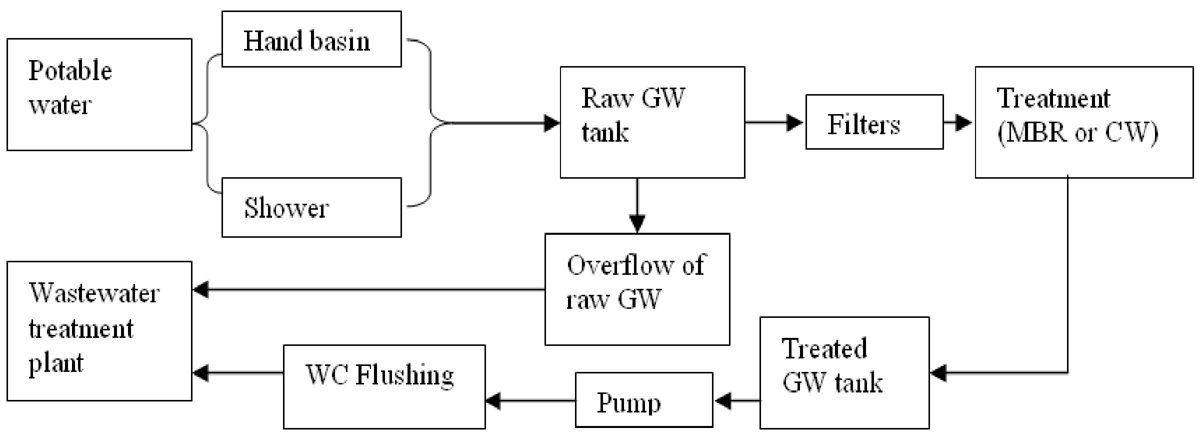
A shared GW system with standard fixtures (Scenario 5) can reduce potable water demand and wastewater generation by up to 29% and 30%, respectively compared to baseline (Scenario 1). The addition of efficient appliances has the same potable water saving as Scenario 5 and the lowest wastewater generation (45%) of all six scenarios.

2.5. Cost of water systems compared across scenarios

The total economic cost is a function of capital, operational and maintenance costs (Memon et al., 2005). The capital costs (Table 2) and maintenance costs (Table 3) of all inventory items were obtained from UK vendors; costs for water supply and wastewater disposal are based on 2011-12 UK tariffs (OFWAT 2011).

The capital cost for Scenarios 1, 3, and 5 includes the cost of supplying standard toilets/urinals. For Scenarios 2, 4, and 6, the capital cost includes the cost of low-flush appliances. Scenarios 3 to 6 require additional equipment for the GW systems (Figure 5).

Figure 5. Component parts of GW recycling system.



A concrete tank with inner lining is selected: the tank size is specified to meet the total volume of daily GW demand plus an extra 10% to accommodate loss in the treatment process (Memon et al., 2007; Ghisi and Oliveria, 2007). Filters are included to remove the solid particles such as hair and skin from the raw GW before it enters the treatment unit. The pump is located after the treated GW tank and delivers water from the tank to the toilet cisterns inside the buildings.

The distance between buildings and the treatment plant determines the length of the GW collection and distribution pipes, and thus factors into the capital cost of system. To estimate the pipe length, it is assumed that the tanks and treatment unit stand together in the middle of the residential and office buildings, 45 m distant from each. Doubling and tripling the distance between buildings and the treatment plant increases the capital cost of system by 2.2% and 4.3% respectively.

MBR consists of a compact unit which combines activated sludge treatment for the removal of biodegradable pollutants and a membrane for solid/liquid separation (Merz et al., 2007). MBR is commonly used in large buildings such as multi-storey buildings (Nolde, 1999; Friedler and Hadari, 2006), student accommodation (Surendran, 2001), stadiums (Merz et al., 2007) and communal residential buildings (Lazarova et al., 2003). The main barrier is its high energy requirement (1.4 KWh/m^3 of treated GW); (see Nolde, 1999; Freidler and Hadari, 2006; Mercoiret, 2008).

Constructed wetlands replicate natural wetlands to improve water quality through physical, chemical and biological treatment mechanisms (USEPA, 1999). The main barriers to implementing constructed wetlands are the land requirement, scarce in urban areas; and the cost of the system changes dramatically with the land area required. In the present study, the VFCW system was selected for GW treatment because it requires less space (1-2 m^2 PE^{-1}) than other construction wetland configurations and offers more appropriate and robust treatment (Frazer-Williams, 2007). Both Membrane Bioreactors (MBR) and Vertical-Flow Constructed Wetlands (VFCW) are appropriate to a UK setting (Jefferson et al., 2004; Pidou et al., 2007; Frazer-Williams, 2007; Li et al., 2009). The capital cost of these two treatment systems in each scenario is presented in Table 2. The operation and maintenance costs for all scenarios are shown in Table 3. The average current price of water (0.70 £/m^3) and wastewater (0.42 £/m^3) services in the UK were used (Memon et al., 2005).

Booster pumps are required to deliver treated GW from the tank to the toilets at the top of the building. The energy requirement for the pumps was estimated using the standard pump power equation:

$$P = \frac{\gamma . Q . H_p}{\eta} \quad (1)$$

where P is the energy delivered to pump (W), Q is the flow rate (m^3/s), η is the pump overall (mechanical and hydraulic) efficiency, assumed to be 65% (Cengel and Cimbala, 2005), γ is the specific weight of water (N/m^3), and H_p is the head supplied by the pump (m):

$$H_p = \Delta Z + \Delta H_f \quad (2)$$

where ΔZ is the elevation difference, equal to the height of the building's top floor plus the depth of buried pipe underground. ΔH_f is the head lost in pipes due to friction and varies according to the flow rate (Q) of the water, length (L) and diameter (D) of the pipe and material (C_{H-W}) of the pipe, which is calculated for each pipe in the building using the Hazen-Williams equation:

$$\Delta H_f = 3.134 \times 10^6 \left(\frac{Q}{C_{H-W}} \right)^{1.852} D^{-4.87} L \quad (3)$$

An additional 15% was added to the calculated values to account for local head loss in joints and fittings of piping (Friedler and Hadari, 2006).

Table 2. Capital costs compared across all 6 scenarios

Parameters	*Scenario 1*		*Scenario 2*		*Scenario 3*		*Scenario 4*		*Scenario 5*		*Scenario 6*	
Unit adopted	No. units	Price (£K)	No. units	Price (£K)	No. units	Price (£K)	No. units	Price (£K)	No. units	Price (£K)	No. units	Price (£K)
Standard toilet[1]	202	13.5			202	13.5	-	-	220	13.5	-	-
Low-flush toilet[1]	-	-	202	55.5	-	-	202	55.5	-	-	202	55.5
Standard urinal[1]	8	240	-		8	240	-	-	8	240	-	-
Low-flush urinal[1]	-		8	0.320	-	-	8	0.320	-	-	8	0.320
Tank[2]	-	-	-	-	4	0.861	4	0.836	2	0.854	2	0.738
Pump[2]	-	-	-	-	2	0.813	2	0.812	1	0.425	1	0.422
Filter[2]	-	-	-	-	2	0.800	2	0.800	1	0.400	1	0.400
Pipes[3]	-	-	-	-	-	5.6	-	5.6	-	4.2	-	4.2
MBR[4]	-	-	-	-	2	61.1	2	59.9	1	49166	1	45616
VFCW[5]	-	-	-	-	2	14.9	2	13.8	1	26398	1	19512
Total costs (MBR) £K	13.7		55.9		83.0		123.9		68851		107279	
Total costs (VFCW) £K	13.7		55.9		36.9		78.0		46083		81175	

1. Costs provides by Environment Agency, 2007, 2. Data from UK leading manufacturers, 3. Spon's ,2010, 4. Data from three international manufacturers (Friedler and Hadari, 2006), 5. Personal communication with UK construction wetland companies

Table 3. Potable water demand and wastewater generation of all 6 scenarios

Parameters	*Scenario 1*		*Scenario 2*		*Scenario 3*		*Scenario 4*		*Scenario 5*		*Scenario 6*	
Unit adopted	No. units (K)	Price (£K)	No. units (K)	Price (£K)	No. units (K)	Price (£K)	No. units (K)	Price (£K)	No. units (K)	Price (£K)	No. units (K)	Price (£K)
Annual potable water usage[1] (m^3)	25.6	17.9	23.4	16.4	21.7	152.2	21.7	14.2	18.3	12.8	18.3	12.8
Annual wastewater generation[1] (m^3)	24.6	10.3	22.9	9.6	20.8	8.7	20.8	7.9	16.4	6.9	14.1	5.9
Annual labour cost[2] (MBR)	-	-	-	-	-	0.172	-	0.172	-	0.172	-	0.172
Annual labour cost [2,5](VFCW)	-	-	-	-	-	1.033	-	0.992	-	1.193	-	0.947
Annual consumables[4,6] (MBR)	-	-	-	-	-	1.580	-	1.570	-	0.823	-	0.810
Annual consumables[5,6] (VFCW)	-	-	-	-	-	1.179	-	1.178	-	0.623	-	0.611
Annual operating electricity[1,4] (MBR)	-	-	-	-	-	1.385	-	1.272	-	2.563	-	1.888
Annual operating electricity[1] (VFCW)	-	-	-	-	-	0.018	-	0.014	-	0.044	-	0.026
Equipment replacement[4,3,6](MBR)	-	-	-	-	-	0.145	-	0.143	-	0.113	-	0.108
Equipment replacement[5] (VFCW)	-	-	-	-	-	0.087	-	0.085	-	0.090	-	0.049
Desludging for MBR every 3-6 year[4]						0.115		0.115		0.115		0.115

1. Author calculation; 2. Spon's, 2010; 3. Friedler and Hadari 2006; 4. FBR, 2005; Nolde, 1999; Mercoiret, 2008; 5. Personal communication with two UK CW companies; 6.BSI, 2009.

The variables used in this study to evaluate the GW system operational and maintenance cost are presented in Table 4. A design life of 15 years was assumed for both systems (Memon et al, 2005; Friedler and Hadari 2006). Replacement materials were assumed as follows: pumps were replaced after 10 years, filters every 5 years (Kirk and Dell'Isola, 1995), membranes for MBR after 10 years (Mercoiret, 2008) and the bed and plant for VFCW are rebuilt after 6 years.

Table 4. Variables for GW system operation and maintenance cost.

Parameter	*Description*	*Cost*
Labour	- Maintenance of collection and distribution systems, pump, storage tank and filter - Maintenance of treatment system	- Labour cost per hour - Hours required for inspection and maintenance
Consumables	- Water quality analysis monitoring purposes - Chemicals for membrane maintenance - Chemicals for disinfection	- Chemical and microbiological analysis - Frequency of analysis - Chlorine solution price
Energy	- Pumping (collection and distribution) - Energy demand for MBR	- Energy price per KWh - Energy demand for distribution
Equipment renewal & repair	- Replacement elements (pumps, pipes, valves and filters) - Replacement of MBR membrane - Rebuilding of CW bed and plant	- Replacement interval for equipment - Price of replacing equipment
Sludge management costs	- Desludging for MBR, dependent on rate of sludge production	- Desludging price - Desludging frequency

2.5.Economic analysis

Net Present Value (NPV) is the present value of an investment's future net cash flows minus the capital investment. It is customary to invest in projects with positive NPV.

$$NPV = \left(\sum_{n=1}^{n} \frac{C_n}{(1 + r/100)^n} \right) \quad (4)$$

where r =economic discount rate, n = life of the project (taken as 20 years), and C_n= cash flow of evaluated scenario minus the cash flow of Scenario 1 for year n.

The base case scenarios 1 and 2 used a 15-year lifetime, 6% discount rate (HM Treasury 2010), and the current average UK price of water and wastewater. The influence of changes in discount rates (from 0% to15%, to allow for comparison with previous work on rainwater harvesting systems; Anand and Apul (2011)), lifetimes of the system (10, 15 and 20 years) and changes in current water and wastewater prices were further investigated.

3. Results

The costs for all 6 scenarios (with and without MBR and VFCW technologies) over a lifetime of 15 years are shown in Table 5.

Table 5. Total cost of scenarios for typical residential and office building for a 15-year lifetime

Scenario / Cost (£K)	*No GW*		*MBR*				*VFCW*			
	1	***2***	***3a***	***4a***	***5a***	***6a***	***3b***	***4b***	***5b***	***6b***
Manufacturing cost	13.8	55.9	83.2	124.5	68.9	107.3	37.0	78.4	46.1	81.2
Annual Operational cost	28.3	26.0	27.0	25.2	22.3	20.9	26.2	24.5	21.6	20.4
Total operational cost	424.3	390.3	411.3	436.6	372.2	345.1	384.3	382.7	336.9	314.8
Total cost	438.4	446.1	494.4	561.1	441.0	452.4	421.4	461.1	386.5	399.4

The highest manufacturing costs are for those scenarios including low-flush appliances and MBR: Scenarios 4a and 6a. Scenario 1 has the lowest manufacturing costs, followed by scenario 3b (VFCW); introducing low-flush technologies (Scenario 2) raised the manufacturing cost by about 70%.

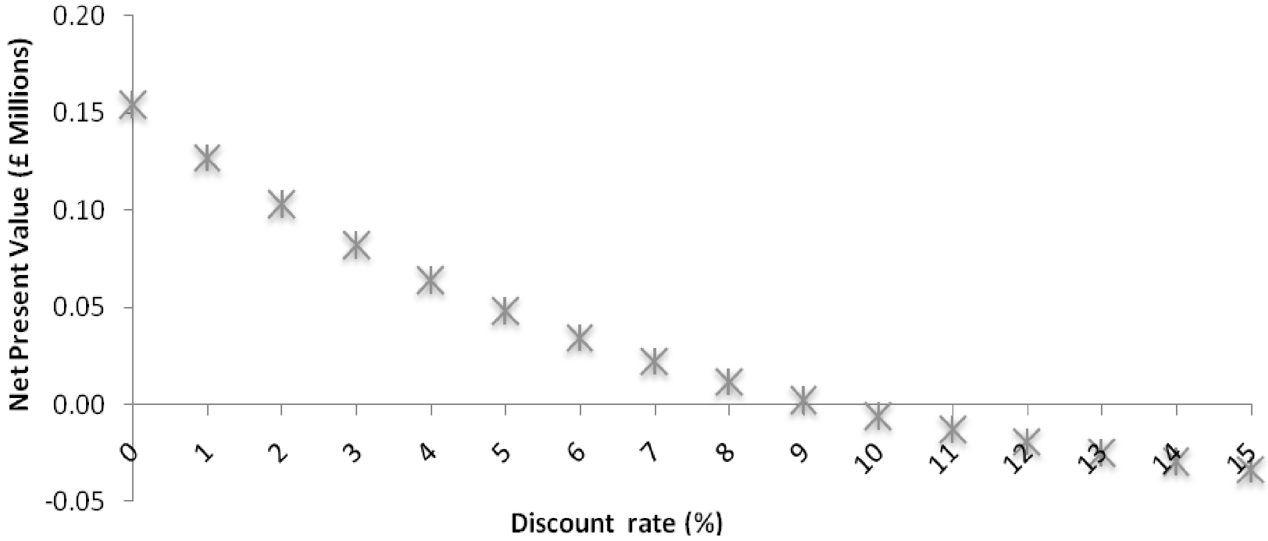
For Scenario 1, the annual operational cost was £28,285. Adding low-flush appliances (Scenario 2) lowers the operational cost about 8% due to reduced water usage. While the manufacturing cost of the GW recycling system was higher, the annual operational cost was slightly lower than for Scenarios 1 and 2. The initial cost of the treatment technology and pipes was the highest component of the GW recycling scenarios using both MBR and VFCW treatment options (Table 2).

At a 6% discount rate the 15-years NPV of Scenario 5b with VFCW treatment technology was the only scenario with a positive value compared with Scenario 1. Despite lower water and wastewater savings than Scenario 6b, the lower manufacturing cost of the standard toilets used in Scenario 5b resulted in positive NPV. The rest of the scenarios had negative NPV. Scenario 4b with low-flush appliances and individual GW recycling system produced the lowest NPV.

The cash flow of GW systems is sensitive to daily water consumption and water utility rates, and thus varies with location. The influence of design life for both GW technologies is simulated for 10, 15 and 20 years, at a discount rate of 6%. Other parameters remained unchanged. For all scenarios, the NPV increases with the increase in the design life.

The NPVs of all other scenarios remain negative for all discount rates between 0% and 15%. NPV decreased with increasing discount rate, and the difference in NPV among scenarios became less (Figure 6).

Figure 6. Variations in NPV with discount rate for Scenario 5b (VFCW treatment).

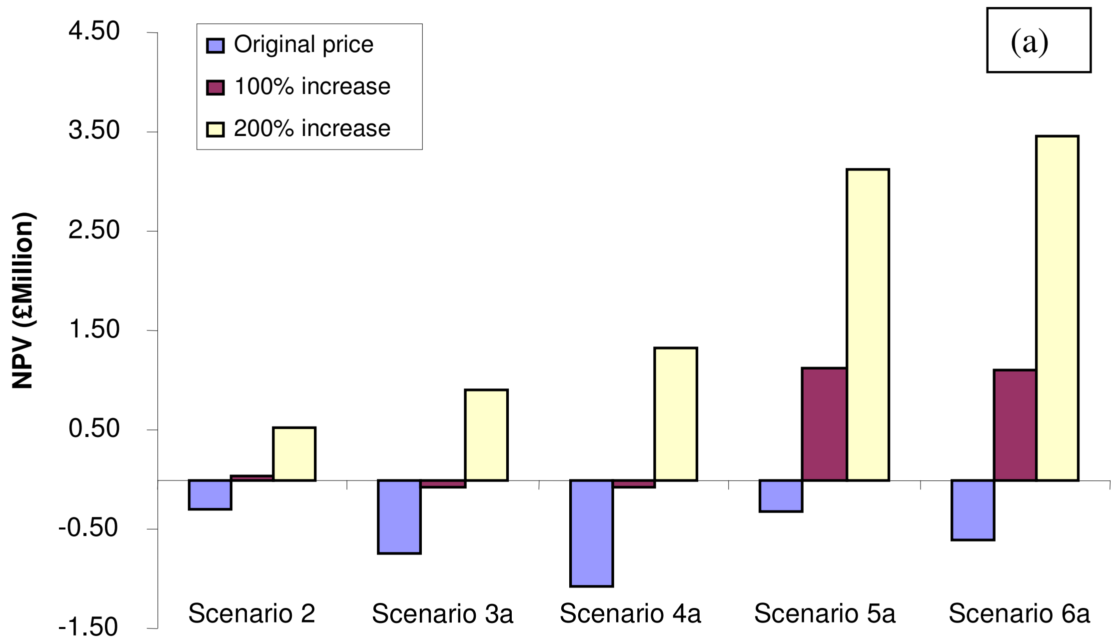


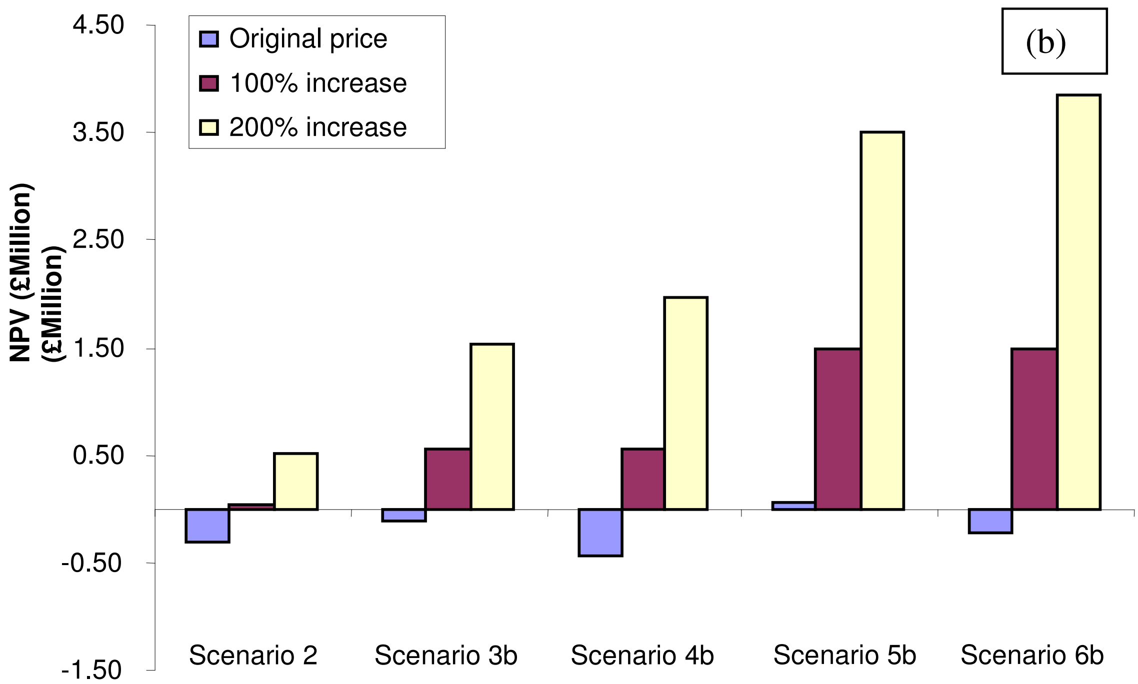
Water and wastewater prices have a significant influence on the NPV of scenarios through water saved during toilet flushing. The UK water price (0.70 £/m^3) (Memon et al., 2005) is about 50% higher than that of wastewater price (0.42 £/m^3). This relative pricing of water over wastewater is still experienced in parts of the UK (OFWAT 2011). In other parts of the world (e.g. Germany) and most of the water companies in UK, the price of wastewater is 50% higher (not lower) than that of water. A sensitivity analysis was conducted to explore the impact of the relative prices (water vs. wastewater) in selected scenarios. A further analysis increases both the price of water and waste water by 100% (water - 1.54 £/m^3 and wastewater - 2.27 £/m^3) and 200% (water - 3.08 £/m^3 and wastewater - 4.54 £/m^3). Other parameters were unchanged.

The result for a 15-year lifetime and 6% discount rate with 100% price increase is shown in Figure 7. Scenarios 5a and 6a (MBR) and Scenario 2 reach a positive NPV. The NPV for Scenarios 3a and 4a remains negative due to the water and wastewater saving being lower than the high manufacturing and operation costs of MBR.

With a 200% increase in water prices, the NPV of all scenarios (MBR and VFCW) becomes positive. With 100% increase in prices, the NPVs of the shared GW system scenarios (5 and 6) were very close, although the water and wastewater saving in Scenario 6 are offset by the high cost of low-flush appliances. A 200% increase in water and wastewater prices increases the NPV of Scenario 6 dramatically.

Figure 7. Comparing the NPV of scenarios with original water (and wastewater) prices and 100% and 200% increases in price **(a)** MBR **(b)** VFCW





4. Discussion

The water and wastewater services in UK deliver a very high quality service and are relatively inexpensive, compared to other countries. This makes it seem less important for investors to reduce water use. Should water and wastewater prices increase substantially, a shared GW recycling system, using either treatment option, should be considered in building design. The recent change in household water and sewage charge tariffs (OFWAT, 2011) substantiates the plausibility of doubling the wastewater price compared to water price, and of 100% increases in both.

As urban population grows, and rainfall patterns alter with climate change, the cost of water is expected to rise. Moreover, increasing pressure on the aging and deteriorating water and wastewater infrastructure will influence costs. Under such conditions, solutions that reduce water demand – such as greater use of GW – become more viable financially. Given that the utility service infrastructure created to support buildings typically has a design life of 20-40 years, adoption of systems that might be marginally more expensive now but deliver considerable benefits in the future should be seriously considered: possibly proving an immediate 'selling point' for the development, and a future means to avoid retrofitting costs.

5. Conclusions

This study compares the total costs of individual and shared GW recycling in mixed-use urban areas for the first time. Six scenarios were analysed for residential and office buildings representative of UK urban mixed-use regeneration areas, using two different treatment technologies. Economic analyses were conducted using NPV calculations. A sensitivity analysis was employed to determine the impact of discount rate, lifetime and costs of water and wastewater. GW recycling is not yet widely accepted in practice, partly because the low economic benefit, particularly in commercial buildings. Our findings showed that a shared GW recycling system can carry lower economic costs in high efficiency buildings. The same methodology can be extended to buildings with different uses, including hotels, educational facilities, commercial premises, and malls. The same methodology should be widely applicable by extension, with country-specific patterns of use.

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Conflict of Interest

The authors declare no conflict of interest

References and Notes

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