Impact of system factors on the water saving efficiency of household grey water recycling

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Abstract

A general concern when considering the implementation of domestic grey water recycling is to understand the impacts of system factors on water saving efficiency. Key factors include household occupancy, storage volumes, treatment capacity and operating mode. Earlier investigations of the impacts of these key factors were based on a one tank system only. This paper presents the results of an investigation into the effect of these factors on the performance of a more realistic 'two tank' system with treatment using an object based household water cycle model. A Monte-Carlo simulation technique was adopted to generate domestic water appliance usage data which allows long term prediction of the system's performance to be made. Model results reveal the constraints of treatment capacity, storage tank sizes and operating mode on percentage of potable water saved. A treatment capacity threshold has been discovered at which water saving efficiency is maximised for a given pair of grey and treated grey water tank. Results from the analysis suggest that the previous one tank model significantly underestimates the tank volumes required for a given target water saving efficiency.

Key words

Grey water recycling, household water cycle, sustainability, water saving efficiency

Introduction

In a world of increasing population, urbanisation and consumption, prudent management of water resources has never been more important. One element of a water conservation strategy is that of grey water recycling, in which used water from the bathroom hand basin, shower and bath is recycled for toilet flushing and/or gardening watering. Treated grey water represents water whose quality is sub-drinking standard, but is suitable for uses such as garden watering or toilet flushing. Domestic grey water recycling has found some applications in the drier parts of developed countries such as Australia [1] and the USA [2] and more niche markets in Germany [3], Netherlands [4], Greece [5], Canada [6] and Sweden [7]. In Australia, dual pipe system for potable water and treated grey water is commonly installed in new development buildings in recent years [8]. In Tokyo, grey water recycling is mandatory for buildings with a floor area over 30,000 m^2 or with the potential to reuse at least 100 m^3/day [9] and there have been other 'keynote' applications at large scale elsewhere (e.g. the London Millennium Dome, in which around 500 m^3 of water per day was reclaimed to flush toilets and urinals on the site [10]. In developing countries, in order to tackle water shortage problem, grey water reuse has become a preferred choice [11-13].

An important reason for the lack of widespread adoption of household grey water recycling is the financial viability of the system [14-15]. This is linked in part to the amount of water that can be saved by such systems, which in turn is linked to their design. Critical factors must be the configuration and volume of water storage tanks, and the throughput or capacity of any treatment used. Strangely, this has received relatively little attention in the literature. For example, in Friedler and Hadari's example of implementation of grey water reuse for multiple flats, two storage tanks of 1m^3 each were selected, without specific reference to the building size [16]. Two storage tanks with size of 4.0 m^3 and 4.5 m^3 were employed in a grey water reuse system serving 81 rooms in a hotel [17]. Furthermore, Ghisi and Mengotti de Oliveira determined the size of treated and grey water tank sizes simply according to the daily toilet water demand and grey water production [18]. In Ghisi and Mengotti de Oliveira's example, the authors argue that '*The daily production of grey water in houses A and B is 239.8 and 170.1 litres, respectively. Therefore, a grey water tank of 250 litres would suffice. As for the daily grey water demand for toilet flushing, it is 174.8 litres in house A and 62.2 litres in house B. Such a demand is lower than the grey water production in both houses. Therefore, treated grey water tanks of 250 litres were adopted in both houses.'*. Therefore, a full understanding of the impacts of system factors on the amount of water that can be saved and the determination of system configuration is desirable.

Probably the most comprehensive analysis of grey water system design and performance has been undertaken by Butler and co-workers [19-20]. This has also formed the basis of UK advice on system sizing [21]. In this work, a simple grey water recycling system configuration was analysed, consisting of domestic appliances and a single grey water storage tank only. It was found that the percentage of potable water (for toilet usage) displaced by non-potable water, for a given household size, was directly (although non-linearly) related to grey water storage tank volume [19]. A system storing 100 to 200 litres was found to be optimal for a family of five persons, giving over 90% toilet flushing water displacement. However, on further reflection it now seems these values may be optimistic, for the following reasons:

- no treatment device was modelled. This effectively assumes an infinite treatment capacity.

- no non-potable water tank was modelled. This effectively assumes treated grey water is fed into the toilet cistern directly.

Thus there is a need to represent the system more comprehensively and to re-evaluate potential water savings in the light of this development. This paper introduces a new model developed to allow this evaluation and systematically re-assesses the potential for water savings in such systems.

Household water cycle model

To carry out this assessment, a new model of the household water cycle has been developed using an object-based approach. An object is a formal and simplified representation of a real world entity or phenomenon, abstracted and viewed as a black box, that can receive external requests or stimulation and perform corresponding responses by invoking its internal methods. An object is typically composed of an interface, which facilitates the interaction with other objects, a method library, which represents the functionality the object has, and a property table, which indicates the object’s attributes. The object’s attributes and methods are neither visible from the outside of the object nor accessible by other objects. They are encapsulated and private. Communication between objects is only facilitated through their interfaces [22].

In the household water cycle context, the elements of the system, ‘water source’ (e.g. mains water supplier, non-potable water), ‘water use’ (e.g. hand basin, toilet and shower), ‘treatment unit’ and ‘sink’ (e.g. downstream sewer) are all viewed as self-contained objects that encapsulate specific attributes and behaviours and can interact with other objects by exchanging water quantity and quality information. A storage tank, for example, is treated as a source object. The household water cycle is then conceptualised as a combination of water source, water use, treatment and sink objects. Construction of the object-based model consists of specifying and populating each object’s interface, method library and property table, and establishing the data communication between objects. In this work, the household water cycle model was constructed on a MATLAB (Simulink) platform and the property table is managed in Excel.

Two methods have been used to calculate the dynamics of water storage tanks: ‘spill before yield’ and ‘spill after yield’ [23]. ‘Spill before yield’ indicates that, in the modelling process, overflow takes place *before* satisfying water demand in each time step. 'Spill after yield' assumes that overflow occurs *after* satisfying the demand. 'Spill before yield' generated more conservative estimates of system performance when compared to those predicted by the 'spill after yield' rule [24]. In the household water cycle model, the storage tanks aggregate the inputs and outputs in 10 minute time steps using the 'spill after yield' concept. If the tank volume is exceeded, then excess is discharged to waste (i.e. sink). If sufficient water is not available in the treated grey water tank to meet demand, mains potable (white) water supply makes up the difference.

The performance of the reuse system is evaluated in terms of water saving efficiency (*WSE*), defined as the percentage of white water saved by reusing grey water. The *WSE* reflects to what extent the toilet demand is satisfied by treated grey water.

$$WSE = 100 * \frac{\sum_{t=1}^{T} W_t}{\sum_{t=1}^{T} D_t} \quad (1)$$

Where:

T = Run length

W_t = Amount of treated grey water used for toilet flushing

D_t = Toilet water demand

The benefit of such a modelling approach and this model in particular, is its transparency, flexibility, adaptability and speed/ease of coding. For example, the inclusion of a new appliance type can be achieved without revisiting the model code, making it straightforward to simulate the household water cycle with different system specifications and configurations.

System configuration

A domestic grey water reuse system is typically composed of a primary tank, which stores the grey water and provides inflow to the treatment unit; a treatment unit, which treats the grey water up to a certain quality to comply with relevant standards and a secondary tank, which stores and provides treated grey water to satisfy toilet water demand. A mains top up mechanism is typically included in the treated grey water tank to ensure continuity of supply at all times. A schematic illustration of such a system is given in figure 1. In this work, use of grey water for garden watering is neglected and attention focused on toilet flushing only. Two float switches are typically employed in the grey recycling system to facilitate the top up of treated grey water and white water (see inset to Figure 1). This mechanism is simulated in the household water cycle model, whereby white water top up, is only triggered when enough water to supply toilet demand is not available.

(Figure 1 here)

The process efficiency of the treatment unit is not specifically represented in this work; rather it is assumed that the reclaimed grey water produced is good enough for toilet flushing purposes. Also, it is assumed that no water is lost during the treatment process. Thus, the treatment device is general and not pointed to any specific technique although the capacity or throughput of the treatment unit is specified.

Data pretreatment

In order to make useful observations for the performance of a water reuse system, it is necessary to assess its behaviour over an extended period. Ideally, it should be evaluated over its expected lifetime. Typical data requirements are frequency of use and volume per use for all relevant appliances, throughout the day. However, it is hard to source this kind of water use profile data over a long period. Therefore, in this project, the Monte-Carlo method was applied to generate the large data set required, based on the data available. This method uses random numbers to index cumulative probability distributions made up from the frequency and/or volume of water use by each appliance and generates a time series of appliance events that have the same statistical properties as the parent data set. It is assumed that each appliance water use event is statistically independent.

The data used in this study was obtained from a large-scale survey conducted by WRc to investigate water consumption trends in different parts of the UK. The data collection procedure involved installation of a consumption monitoring system outside each participating household. The system consisted of a flow meter and data logger capable of recording every 10ml of water used at 1 second intervals for periods up to 2 week. The logged consumption data was processed using the Identiflow software [25]. This identifies flow charcatersitics and classifies water-use events, as one of: toilets, showers, baths, internal and external taps, washing machines and dishwashers. A sub sample of this data set was assembled consisting of water usage data over 7 consecutive days from 16 households in England [26]. The data was regrouped into 10 minute time steps and classified according to occupancy ranging from 1 to 5 people. For each occupancy, a cumulative probability distribution of frequency of water used by each appliance was assembled for each ten minute interval. Distributions of water use events in terms of time and household were examined. Spatial and temporal differences of water use event were found. Taking toilet flushing as an example, Figure 2 shows the cumulative number of toilet use event in every 10 minutes interval during a day (144 intervals) for the 100 households. Except for the morning and evening peak uses, toilet flushing is featured as a randomized event. Figure 3 displays the distribution of number of toilet use event and household numbers, which reveals that most households (79 households) use 10-14 times of toilet per day. It is also noticed from Figure 3 that 8 households use less than 7 times of toilet per day, which might be because of less people living in. In generating water use profile time series data using Monte-Carlo method, spatial and temporal differences were taken into account to represent the differences of water use event in term of time and household.

(Figures 2,3 here)

Model simulation runs

A 10-year dataset was derived as input into the household water cycle model. Given the flexibility of the model and the interest in re-evaluating water saving efficiency for more realistic configurations, a scenario-based approach was used (five in all) based on varying the key factors of storage tank number and volume, treatment capacity, treatment operating mode and dwelling occupancy.

Scenario 1 is designed to investigate the water cycle for a single (grey water) tank system. Scenarios 2, 3, 4 and 5 are designed to analyse the water dynamics in two tank (grey and treated grey) systems. In each scenario, the values of one or two factors were changed while the others kept as default values. Unless stated otherwise, default values are: grey water tank volume = 50 litres; treated grey water tank volume = 100 litres; treatment operating mode = continuous; household occupancy = 3 people. The configuration of factors in each scenario is summarized in Table 1.

(Table 1 here)

Two types of treatment operating mode were considered: continuous and intermittent. The former reflects the treatment device operating at a constant production rate over 24 hours. In the latter situation, the device operates part-time designed to be consistent with the peak uses of toilet in the morning and evening periods.

Results and discussion

Scenario 1: Single tank system --- without treatment device constraint. Scenario 1 is designed to investigate the relationship between water saving efficiency and grey water tank volume without treatment capacity constraint for a 'one tank' system. The treatment device is assumed to have an unlimited capacity and perform in a continuous mode. With this assumption, it is deemed that grey water can be treated and utilised immediately when a toilet water demand occurs. Therefore, no treated grey water tank is required. This actually represents an extreme system situation and is the same as the one investigated in [19]. In the model simulation, the grey water tank size was allowed to vary from zero to 100 litres. The average water saving efficiency (over the 10 year period) for different grey water tank sizes is shown in figure 4. As expected, efficiency increases with volume, but at a declining rate. Thus, the percentage of potable water saved is more sensitive to grey water tank volume when it is relatively small, i.e. in the range of 0 to 50 litres. For the three-person household under discussion (with a daily toilet demand of 94 litres), a 20 litre grey water tank saved 67% of toilet water demand, 40 litres 87% and 60 litres 92% respectively. These findings are consistent with results reported in [19] in which a similar relationship between water saving efficiency and grey water tank volume was obtained.

(Figure 4 here)

Scenario 2: Two tank system --- treated grey water tank volume. The relationship between water saving efficiency and treated grey water tank size in a 'two tank' system was investigated in scenario 2. A default value of 50 litres was adopted for the grey water tank volume. Results are presented in figure 5. It was found that the impact of treated grey water tank volume is similar to the findings for the grey water tank in scenario 1. This is reflected in three aspects. First, for a given treatment capacity, water saving efficiency increases with increasing volume of treated grey water tank, but the rate of increase weakens with increasing volume of tank up to an asymptote. Second, the water saving asymptote value is directly related to the treatment capacity. Third, given appropriate treatment capacity, grey and treated grey water tank volumes, it is possible that 100% of toilet water demand can be satisfied by treated grey water.

(Figure 5 here)

Scenario 3: Two tank system --- treatment capacity. As previously suggested, treatment capacity can have a significant impact on grey water reuse system performance. When the treatment capacity is low (for example, 20 litres per day, shown in figure 5), a maximum water saving efficiency of just 20% can be reached regardless how big the treated grey water tank is. Within a certain range (up to 140 litres per day, see figure 5), the maximum water saving efficiency increases with increasing treatment capacity. However, beyond 140 litres per day (figure 5), performance is hardly affected, particularly at higher treated grey water tank volumes.

Figure 6 shows water efficiency versus treatment capacity for a range of grey and treated grey water tank volumes. It clearly indicates that water saving efficiency is maximised at a threshold treatment capacity of 200 - 350 litres per day for these configurations in scenario 3. Beyond this point, efficiency slowly declines or keeps static regardless the increasing of treatment capacity. This effect is produced by the complex interaction between water supply and demand in relation to the filling of the two tanks, remembering that the treated grey water tank has the potential for mains top up if it cannot supply the requested demand. Whether the water saving efficiency keeps constant or declines beyond the threshold point is dependent on the interactions between grey and treated grey water tank volumes, treatment capacity, grey water production and toilet water demand. For given volumes of grey and treated grey water tank volumes, a bigger treatment capacity means more grey water could be treated into treated grey water. However, it might also result in less grey water to be actually reused for toilet flushing because a bigger treatment capacity can encourage overflow from the treated grey water tank and deficit of grey water. Other pairs (grey and treated grey) of storage tank volumes in the range of 0 to 200 litres have also been analysed and it was found that a threshold point exists for each pair.

Apart from the existence of a treatment threshold, it is also observed that the increasing trend is greater than the decreasing trend on each side of the threshold point. This explains why the water saving efficiency curves corresponding to a treatment capacity from 160 litres per day to 280 litres per day are closely overlain in figure 5, while curves for treatment capacity below 80 litres per day are well spaced.

From Figures 5 and 6, it is clear that the relationships of water saving efficiency with grey and treated grey water tank sizes and treatment capacity is quite complicated. No simple equations are available to express their relationships. Based on the findings from Figure 5 and Figure 6, the pair of grey and treated grey water tanks sizes corresponding to the treatment capacity at the threshold are recommended in system design to achieve a maximum system saving efficiency. Meanwhile, the family plots in Figure 6 can be utilised for system design. When a targeted water saving efficiency is specified, the treatment capacity and tank sizes can be determined according to Figure 6.

(Figure 6 here)

Scenario 4: Two tank system --- treatment operating mode. In scenarios 2 and 3, the treatment device is assumed to operate at a constant production rate. This is not, of course, consistent with the pattern of toilet water demand. In scenario 4, the treatment device is set to operate intermittently to mimic the morning and evening peak uses of the toilet noted in previous studies [27]. For comparison purposes, two intermittent modes were considered: intermittent and continuous modes. In the intermittent mode, the treatment device is set to operate at two intervals: from 6:00 to 9:00 and from 18:00 to 21:00. For each mode, a constant production rate is adopted during operating time periods. To facilitate easy comparison, the same treatment capacity, 94 litres per day, which is determined by the actual toilet water demand per day (three person household), was applied to all operating modes. Results from the model simulation are displayed in figure 7, in which it is shown that the water saving efficiency corresponding to the intermittent operating mode is about 4% higher than for continuous mode. It indicates that the better the treatment operating schedule fits with the actual demand, the greater the water saving efficiency. In practice, for some treatment techniques, the intermittent mode is difficult or impossible to implement. However, this comparison indicates that the operating mode of the treatment device does or could play a role in the performance of grey water reuse system in principle, and the more flexible the treatment operating mode is, the smaller storage tank volumes are required to achieve a certain water saving efficiency.

(Figure 7 here)

Scenario 5: Household occupancy. It has been previously reported [28] that increasing occupancy is linked with decreasing per capita water consumption. This result is broadly confirmed by the data adopted in this project (Table 2). Similar patterns were observed in the variation of water saving efficiency with occupancy and storage volumes. In addition, results indicate that volume of total storage tank required increase with increasing occupancy. Total storage tank required per capita shows an opposite trend with increasing occupancy. This finding applies to all household occupancies except for three person household (Table 2). The tank volumes required for a target *WSE* is dependent on the total amount of toilet demand, the water consumption water profile, and the pattern of water consumption for each appliance in a household. All these factors vary spatially and temporally. For example, the percentages of water consumption for toilet flushing (*Pwc*) for different household occupancies are shown in Table 2, which shows a variance from 18% to 41% for different household occupancies. For three person households, the averaged toilet demand contributes to 22% of household water consumption, while 33% for two person households, although the total household water demand for three person household is higher than the one for two person households. In terms of replacing toilet water demand with treated grey water, a bigger *Pwc* indicates that more water will be required for toilet flushing; therefore, a bigger total tank volume will be required to cope with this demand. This explains why the grey and treated grey water tanks required for the same target *WSE* for three person households is smaller than the one for two person households.

(Table 2 here)

Previous study suggested that a system storing 100 litres can achieve over 90% of potable water saved for a household with less than 5 people according to the analysis for a one tank based model with unlimited treatment capacity [19]. This work, however, better represents a real system with a second treated grey water tank and limited treatment capacity included. For a target water saving efficiency of replacing 80% of toilet water demand with treated grey water, the required water tank volume(s) from both models are presented in table 3, from which it is clear that Dixon et al.'s model underestimates the required tank volume significantly, justifying this reanalysis work.

(Table 3 here)

In general, grey water can be reused for toilet flushing, garden watering and even for cloth washing after suitable treatment. From the aspect of household water cycle modelling, the main differences between these water uses are demand patterns. The frequencies and amounts of water required during a single use event are different. For the purpose of simplification, only toilet flushing is considered in the modelling process in this paper. However, this simplification does not reduce the model's capability. In a situation where garden watering and cloth washing are main usage of reclaimed water, the household water cycle model can be easily modified to cope with. Meanwhile, the nature of the toilet flushing facilities is overlooked in the model and generalised as a single flush with 9 liters water. In practice, dual flush toilets, low flush toilets and toilets fitted with a recycled hand washing basin have been installed in some areas. For the first two types of toilets, the model can be applied without modification. However, the third type of toilet is not suitable for the model because no treatment is required for this kind of toilet.

This paper mainly focuses on the physical aspect of grey water reuse systems and its impact on the potential for water saving. Based on this, tank size and treatment capability design rules are presented for the sake of achieving the greatest water saving efficiency. However, the actual amount of water saving might also depend on social and economic factors since they impose significant influence on the willingness to embrace grey water reuse. The perception of grey water reuse may vary from region to region and culture to culture. In some areas, people might think it is unacceptable to reuse grey water from their neighbour's household although treatment and disinfection have been applied. Meanwhile, drinking water price is also a key factor. In some areas, household customers do not have a water meter installed and water price is low compared with other living costs. There is no financial incentive for these occupants to consider saving water. The installation and running costs are also important factors. Therefore, to promote implementation of grey water reuse, further investigation should be undertaken in the fields of drinking water pricing strategy, perception of reclaimed water and cost-effective technology development.

Conclusions

The impact of key factors on the performance of a water reuse system were investigated by simulating the water cycle process in a household using an object-based modelling method. The water dynamics within the household over 10 years based on a time step of 10 minutes was simulated using Monte-Carlo simulation- derived data. Results show that the water saving efficiency of a grey water recycling system is linked to dwelling occupancy, storage tank volume and treatment capacity and operating mode. The performance of ‘one tank’ and ‘two tank’ systems was also compared. It can be concluded that:

- The object-based household water cycle model works well in practice. Model simulations for one and two tank systems suggest that it is more flexible and extendable compared with earlier models. Model simulation results for the ‘one tank’ system are consistent with the findings in previous studies.
- Treatment capacity and storage tank volumes both impose impacts on water saving efficiency for a ‘two tank’ system. Generally, the bigger the storage tank, the more potable water can be saved. The rate of increase is greatest at lower volumes and beyond this range the gains reduce. Water saving efficiency is sensitive to low treatment capacity. When the treatment capacity is greater than a specific threshold, efficiency slowly declines with increasing of tank volume. The value of this threshold has been found to be a function of the volume of the storage tanks used, the treatment operating mode and treatment capacity.
- It was observed that the nearer the operating mode approaches the actual toilet water demand pattern, the higher water saving efficiency can be achieved.
- Houses with higher occupancy levels require larger storage tanks and treatment capacity than lower occupancies for the same water saving efficiency. However, volumes of storage tanks required per capita decrease with increasing occupancy.
- Dixon et al.’s one tank model significantly underestimates the tank volume required for a given water saving efficiency compared to the results from the model in this work.
- In addition to a system’s physical properties, social and economic factors also impose

significant impact on the amount of water to be saved. Further investigation should be undertaken in these fields.

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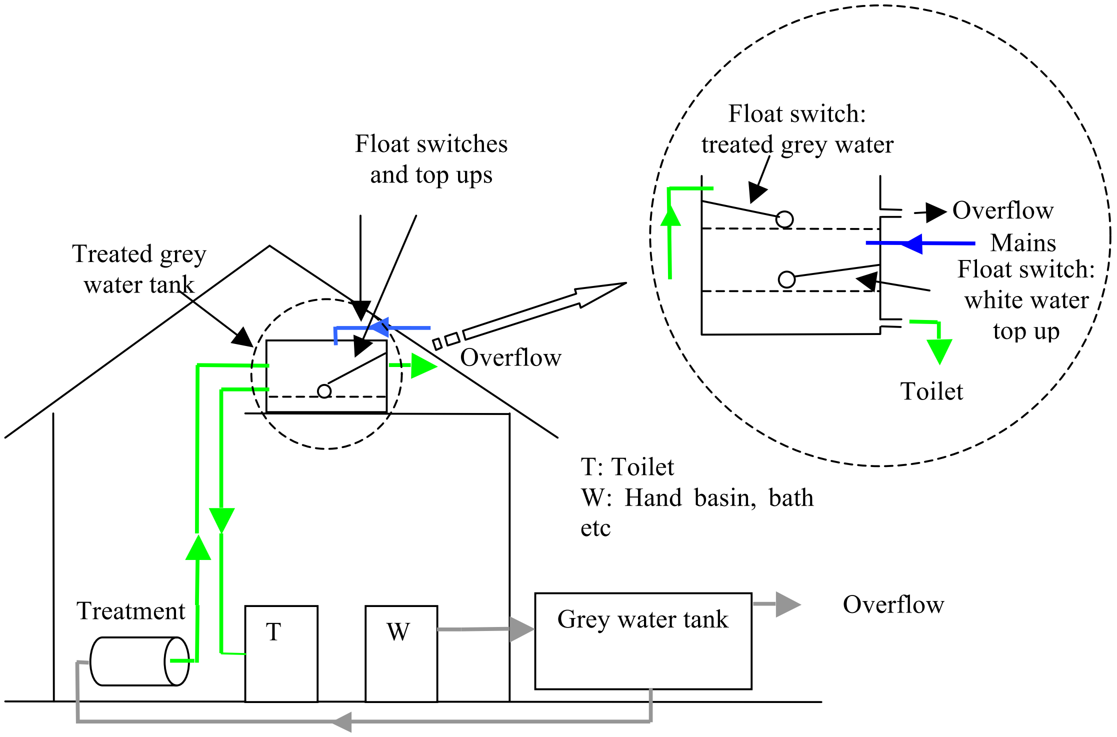
Float switches and top ups
Treated grey water tank
Overflow
Float switch: treated grey water
Overflow
Mains
Float switch: white water top up
Toilet
T: Toilet
W: Hand basin, bath etc
Treatment
T
W
Grey water tank
Overflow

Figure 1

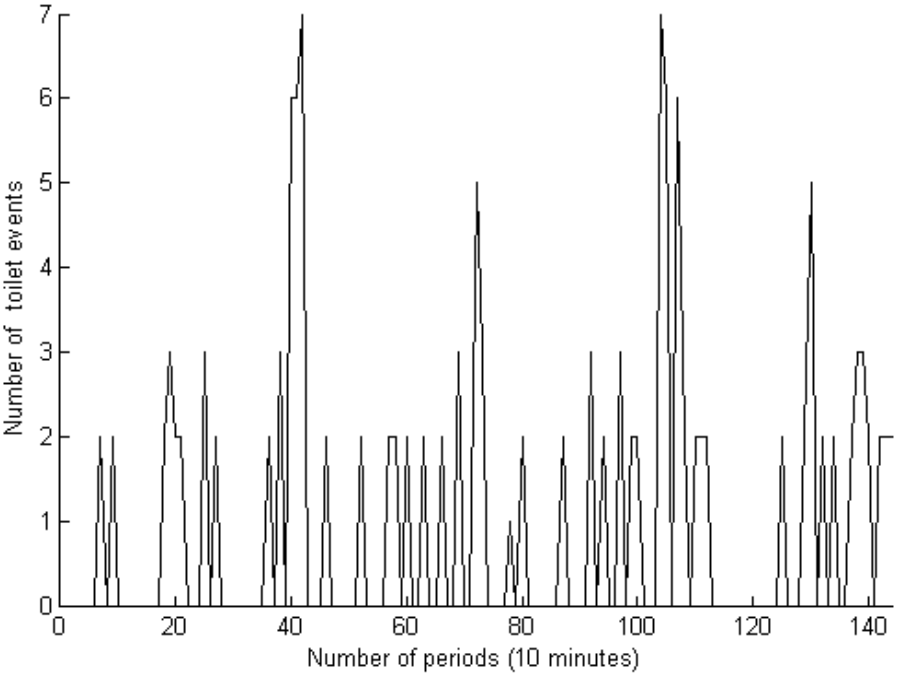
Number of toilet events
0
1
2
3
4
5
6
7
0
20
40
60
80
100
120
140
Number of periods (10 minutes)

Figure 2

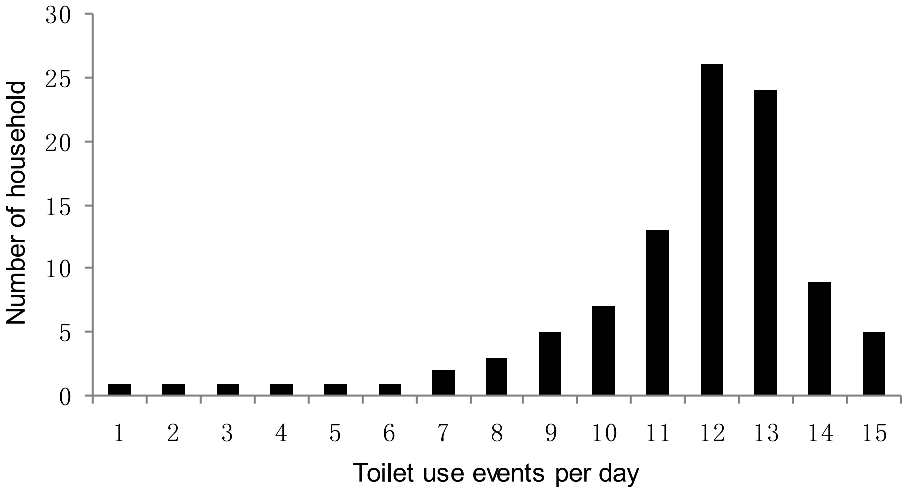
0
5
10
15
20
25
30
Number of household
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Toilet use events per day

Figure 3

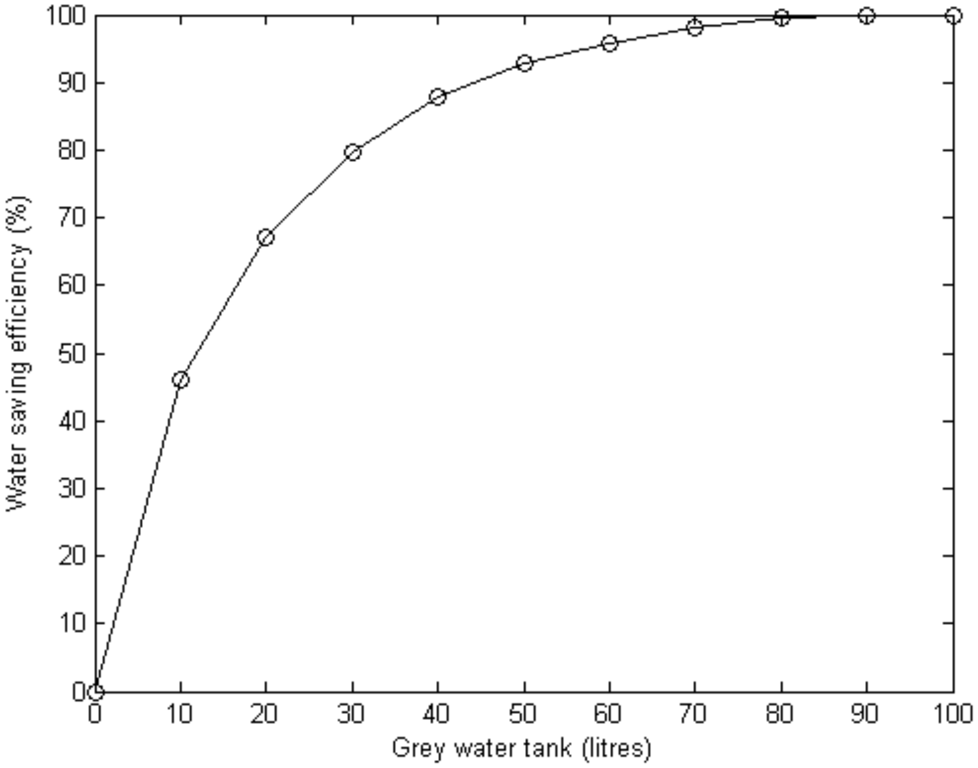
Water saving efficiency (%)
Grey water tank (litres)
0
10
20
30
40
50
60
70
80
90
100
0
10
20
30
40
50
60
70
80
90
100

Figure 4

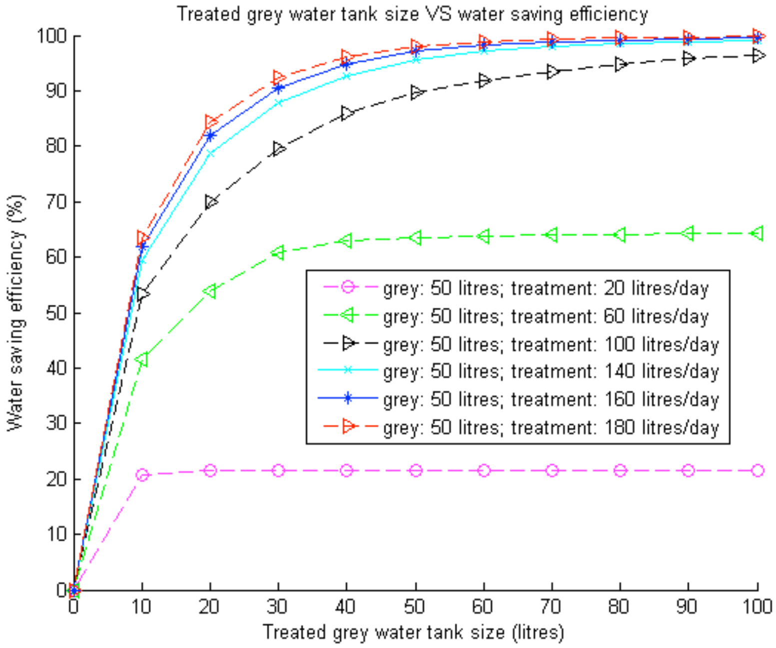
Treated grey water tank size VS water saving efficiency
Water saving efficiency (%)
Treated grey water tank size (litres)
0
10
20
30
40
50
60
70
80
90
100
grey: 50 litres; treatment: 20 litres/day
grey: 50 litres; treatment: 60 litres/day
grey: 50 litres; treatment: 100 litres/day
grey: 50 litres; treatment: 140 litres/day
grey: 50 litres; treatment: 160 litres/day
grey: 50 litres; treatment: 180 litres/day

Figure 5

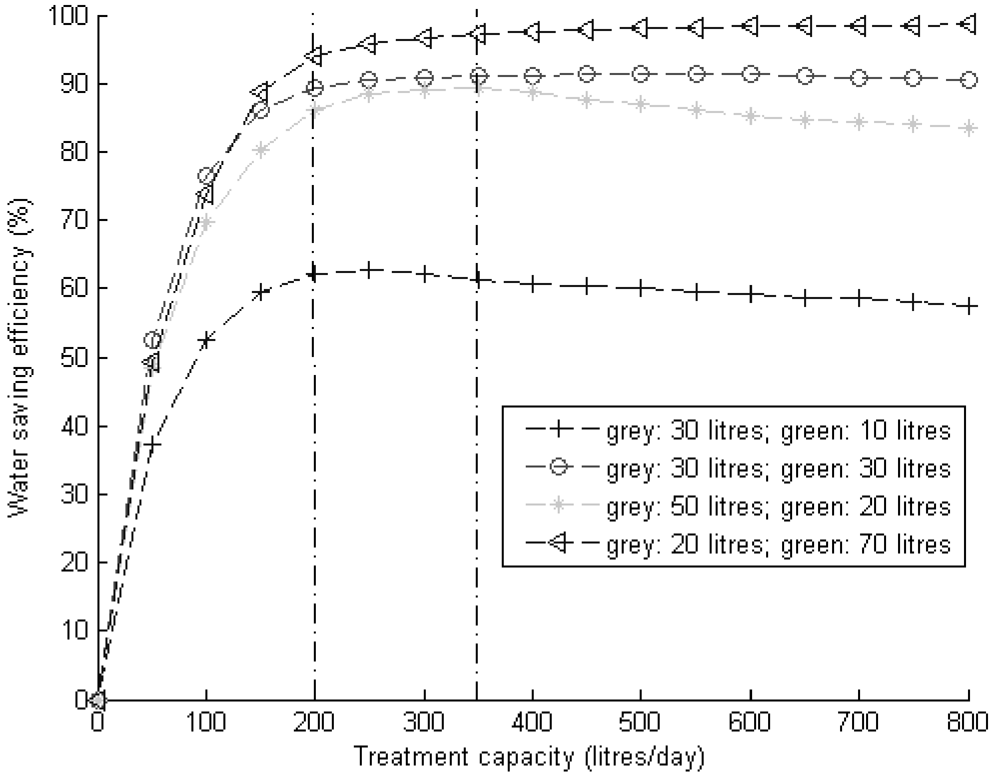
Water saving efficiency (%)
0
10
20
30
40
50
60
70
80
90
100
Treatment capacity (litres/day)
0
100
200
300
400
500
600
700
800
grey: 30 litres; green: 10 litres
grey: 30 litres; green: 30 litres
grey: 50 litres; green: 20 litres
grey: 20 litres; green: 70 litres

Figure 6

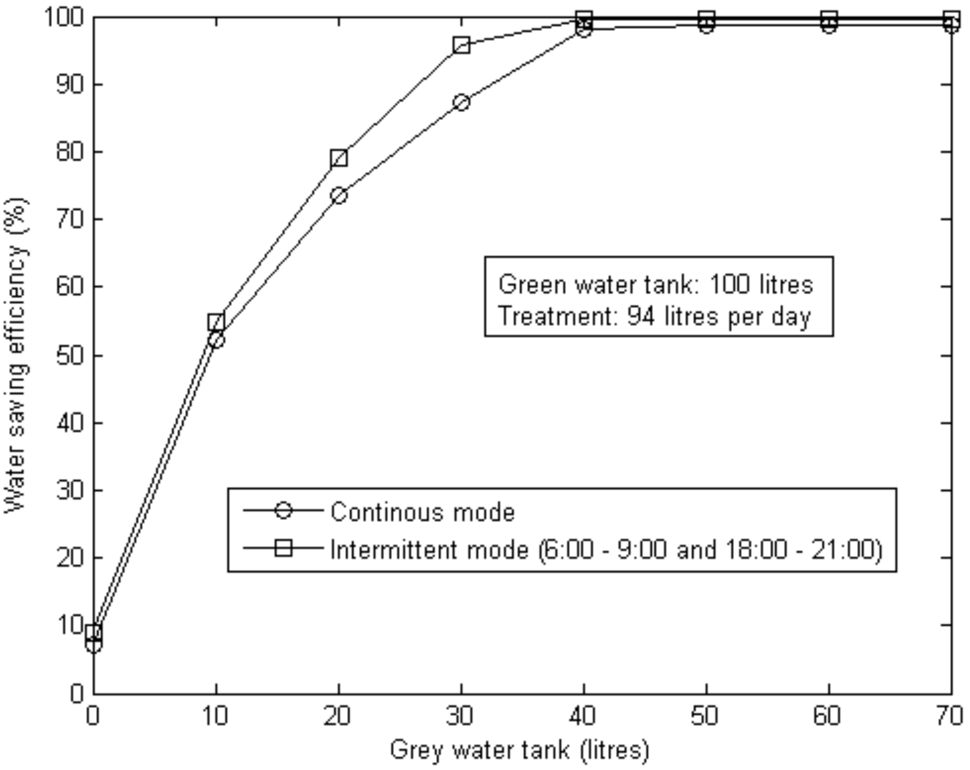
Green water tank: 100 litres
Treatment: 94 litres per day
Continous mode
Intermittent mode (6:00 - 9:00 and 18:00 - 21:00)
Water saving efficiency (%)
Grey water tank (litres)
0
10
20
30
40
50
60
70
80
90
100
0
10
20
30
40
50
60
70

Figure 7

	Grey water tank volume	Treated grey water volume	Treatment capacity	Treatment operating mode	Household occupancy
Scenario 1 One tank system: without treatment device constraint	Change	N/A	Infinite	continuous	3 people
Scenario 2 Two tank system: treated grey water tank	50 liters	Change	Change	continuous	3 people
Scenario 3 Two tank system: treatment capacity	50 liters	100 liters	Change	continuous	3 people
Scenario 4 Two tank system: treatment operating mode	50 liters	100 liters	94 liters	Change	3 people
Scenario 5 Two tank system: household occupancy	Change	Change	Change	continuous	Change

Table 1