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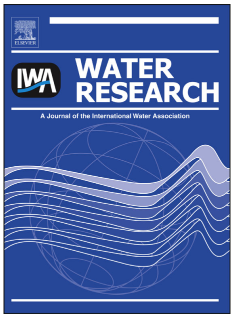

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Impacts of residence time during storage on potential of water saving for grey water recycling system

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Abstract

Grey water recycling has been generally accepted and is about to move into practice in terms of sustainable development. Previous research has revealed the bacteria re-growth in grey water and reclaimed municipal water during storage. However, in most present grey water recycling practices, impacts of water quality changes during storage on the system's performance and design regulation have not been addressed. In this paper, performance of a constructed wetland based grey water recycling system was analysed by taking the constraint of residence time during storage into account using an object based household water cycle model. Two indicators, water saving efficiency (*WSE*) and residence time index (*RTI*), are employed to reflect the system's performance and residence time during storage respectively. Results show that *WSE* and *RTI* change with storage tank volumes oppositely. As both high *WSE* and *RTI* cannot be achieved simultaneously, it is concluded that in order to achieve the most cost-effective and safe solution, systems with both small grey and green tanks are needed, whilst accepting that only relatively modest water saving efficiency targets can be achieved. Higher efficiencies will only be practicable if water quality deterioration in the green water tank can be prevented by some means (e.g. disinfection).

Key words:

Grey water recycling, residence time, storage tank, water quality degradation, water saving

1. Introduction

Grey water is defined as the water which is slightly contaminated by human activities and may possibly be reused after suitable treatment, for example, water from a washing machine, shower, bath etc. The reclaimed water or the treated grey water is termed as green water in this paper. Grey water recycling is emerging as an internal part of water demand management, promoting as it does the preservation of high quality fresh water supplies as well as potentially reducing the pollutant in the environment. The principle of domestic grey water reuse is to replace all or some of the non-potable water demand by reclaimed water. The general use of treated grey water in a household context mainly includes toilet flushing and/or garden watering. This paper focuses on the toilet flushing. In the last decade, grey water recycling practices have been reported in many countries (Asano and Levine, 1996; Fittschen and Niemczynowicz, 1997; Kayaalp, 1996; Nolde, 2000; Smith et al., 2000; Yang et al., 2006).

1.1 Grey water characterisation

As grey water arises from domestic washing operations, it varies in quality according to, amongst other things, geographical location, demographics and level of occupancy (Al-Jayyousi, 2003). Taking BOD as an indicator, its value has been reported between 33-466 mgl^{-1} in the literature (Al-Jayyousi, 2003; Prathapar et al., 2005; Gross et al., 2007). It has been noticed that the BOD in grey water from hand basin is slightly smaller than the one from combined sources (bath, shower, etc.) (Jefferson et al., 2000) and the quality of grey water varies with time during a day (Al-Jayyousi, 2003). Further to this, available evidences have shown changes of grey water quality during storage. Jefferson et al. (2000) reported that a 50% reduction in BOD over a 4 hours period could be achieved. However, longer residence time in storage tank can encourage bacteria re-growth and lead to degradation of water quality. Dixon et al. (2000) conducted an experiment to examine the change of grey water quality during storage and observed obvious increases of BOD and DO after initial decrease in the sedimentation period. Therefore, the quality of grey water fed into treatment device is expected to be various not only because of the different sources and time of grey water generated, but also the changes of quality during storage.

In terms of healthy concern, a key question or objective in domestic grey water recycling is to ensure the green water complies with relevant standards. This may be accomplished both by choosing robust and effective treatment and limiting grey water degradation during storage by rational design. This paper will mainly focus on the latter topic. On the other hand, the concept of grey water recycling is to reduce potable water demand by replacing non-potable demand with green water in term of water demand management and sustainable development. From this point of view, the objective of grey water recycling is to save as much potable water as possible. These two objectives may interact, or even conflict each other. Their interaction/confliction should be explored to increase the understanding and confidence in implementation of grey water recycling. Rational design can then be undertaken based on these understandings to ensure the great achievement of both objectives in recycling practices. This will be discussed in this paper.

1.2 Treatment technologies

Researchers have reported the application of several technologies for grey water treatment. Both strengths and constraints in implementation of these technologies have been recognized. Sand filtration plus disinfection represents the most common technology used for domestic grey water recycling in the UK (Jefferson et al., 2000). The treated grey water from this kind of system has been noticed remaining high in organic load and turbidity, which thereby limit the effectiveness of the chemical disinfection process. Membrane systems offer a permanent barrier to suspended particles greater than the size of membrane material, which can range from 0.5 μm of microfiltration membranes down to molecular dimensions for reverse osmosis. The key factor constraining the viability of membrane systems is the fouling of the membrane surface by pollutant species. This has been reported by many researchers. For example, Nghiem et al. (2006) and Oschmann et al. (2005). Meanwhile, the energy demand for membrane systems is high (Jefferson et al., 2000). Biological treatment and physical treatment can effectively remove different species. The benefits of biological and physical treatments are combined in processes such as membrane bioreactors (MBR). However, high cost implications have meant that this kind of treatment is more suitable for large scale of recycling scheme than single house.

As a low-cost technology, constructed wetland has recently gained much attention in grey water treatment. Experiences in Central America (Dallas et al., 2004), Middle East (Gross et al., 2007) and the UK (Frazer-Williams et al., 2008) showed that high averaged removal rate can be achieved provided appropriate hydraulic retention time is given. In this project, therefore, a constructed wetland based grey water recycling system is chosen to investigate the impact of residence time in storage tanks on the system's performance.

1.3 System configuration

Although different system configurations have been reported in practice, a grey water recycling system generally includes: a grey water storage tank, a treatment unit and a green water storage tank. For the system investigated in this project (Figure 1), it also has the similar system configuration. The grey water tank is connected to appliances, which consumes potable water and produces grey water. By collecting the grey water, the grey water tank stores and feeds it to the constructed wetland, where the green water is produced. The constructed wetland was placed outside of house. The constructed wetland is linked with the green water tank. The green water tank then collects and serves green water to non-potable water demand, for example, the toilet flushing. The design of grey water recycling system is a site-dependent problem. The storage tanks can be either placed underground or on the loft in terms of specific circumstance and the user's preference. Pumps may be employed to facilitate the flows between treatment device, storage tanks and toilet cistern when gravity flow is not a choice. For the purpose of simplification, in this project, the grey water recycling system is simulated in a common sense, i.e. no specific implementation situation was considered, only the main parts of the system (storage tanks, treatment device and toilet cistern) and the dynamic flows among them were simulated.

(Figure 1 here)

Although practices of grey water recycling system have been implemented widely, most published literatures mainly focused on reporting the performance of existing systems (for example, Jeppesen, 1996; Al-Jayyousi, 2003; March et al., 2004; Ghisi and Mengotti de Oliveira, 2007). Few attentions have been focused on the impacts of system configuration on potential of water saving. Especially, no attempt has been made to investigate this problem by taking the water quality degradation during storage into account. This paper concentrates on the analysis of potential of water saving from water quality point of view.

2. Methodology

2.1 The household water cycle model

The household water cycle model adopted in this project was developed on a MATLAB (Simulink) platform. It accounts for the production and storage of grey water and green water, and the water balance between compartments, for example, the water supply and the water demand. The allocation of water sources to water demands is facilitated by a '*first comes, first served*' rule. This refers that the water request will be satisfied according to its appearing sequence. The model operates at 10 minutes time step which is determined by the data availability. The household water cycle model was designed with the capacity of coping with any type of treatment system operating modes. However, complicated management strategy is required to facilitate intermittent operating mode. Therefore, in this paper, for the purpose of simplification, continuous operating mode is assumed for the operation of constructed wetland.

2.2 Input data

The input data required by the household water cycle model are the water use profile information for each appliance. To understand the performance of grey water recycling system at different situations (for example, peak and non-peak uses of toilet; different water use manners on weekdays and weekend), it is necessary to assess its behaviour over an extended period, ideally to cover its expected lifetime. However, in practice, it is hard to source this kind of data. Therefore, in this project, a Monte-Carlo method was adopted to generate water use profile time series data covering 10 years period at a time step of 10 minutes. The parent data uitilised in the Monte-Carlo method was derived from a large-scale survey conducted by Water Research Centre UK (WRc) to investigate water consumption trends in different parts of the UK. In this survey, flow meter and data logger were used to identify flow charcatersitics and classify water-use events, which can be the use of toilets, showers, baths, internal and external taps, washing machines and dishwashers (Ton That, 2005). The system is capable of recording every 10ml of water used at 1 second intervals for periods up to 2 week. In this research, water profile data from 100 three-person households was employed. Figure 2 shows, by average, a three-person household requires 369.11 litres water per day, in which 103.99 litres for toilet flushing, 39.91 litres for washing machine, 55.56 litres for bath, 50.70 litres for shower and 118.95 litres for tap uses. 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 3 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 4 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 4 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.

(Figure 2,3,4 here)

2.3 Residence time distribution

The residence time (*RT*) in a storage tank is calculated according to the '*first in first out*' (FIFO) algorithm (Walski et al., 2003). In the FIFO algorithm, the first volume of water to enter the storage tank as inflow is the first to leave as outflow. In the household water cycle model, each parcel of water is noted with the times entering and leaving the storage tank. The difference between these two times indicates the period the water staying in the tank and is therefore the *RT*, which is calculated at each time step and has a precision down to 10 minutes. The probability of a *RT* is accounted by dividing the number of its appearance over the whole running period (10 years in this case) with the total number of appearance for all *RT*s. Residence time distribution (*RTD*) refers to the curve of the probability against its corresponding *RT* (illustrated in Figure 5). The *RTD* describes the probability and range of *RT* of water in the storage tank.

(Figure 5 here)

2.4 Performance indicators

Two indicators are employed to evaluate the system's performance. One is from quality aspect, the residence time index. The other is from quantity aspect, the water savings efficiency.

The time range of a *RT* for the question under discussion is defined as target range (*TR*). Previous research has recommended that the *RT* in a grey water tank should not be beyond 48 hours to avoid the significant water quality degradation (Dixon et al., 2000). No similar research has been conducted for green water. However, experience from reclaimed municipal water suggests green water quality degradation during storage is expected (Narasimhan et al., 2005). For simplification, therefore, a 0 to 48 hours *TR* was adopted both for grey water and green water. To evaluate to what extent *RT* is within the *TR* (0 to 48 hours), a residence time index (*RTI*) is introduced, calculated as the ratio of the integral of *RTD* over the *TR* to the one over the whole range (Figure 5). A *RTI* value of 0 means no *RT* is in the range of 0 to 48 hours, while 1 indicates that all water leaving the storage tank as outflow stays in the tank less than 48 hours. The greater the *RTI* is, the better the storage tank performs in terms of avoiding water quality degradation.

$$RTI_{TR} = \frac{\int_{TR} RTD \quad dRT}{\int_{WR} RTD \quad dRT} \qquad (2)$$

in which RTI_{TR} refers to the *RTI* for the target period of *TR*; *TR* is the target range up to 48 hours; *WR* is short for the whole range of retention time.

Water saving efficiency (*WSE*) is defined as the percentage of potable water saved by reusing grey water. It reflects to what extent the toilet demand is satisfied by non-potable water. A higher *WSE* means more potable water is saved.

$$WSE = 100 * \frac{\sum_{t=1}^{T} W_t}{\sum_{t=1}^{T} D_t} \qquad (3)$$

Where:

T = Run duration

W_t = Amount of non-potable water used for toilet flushing

D_t = Toilet water demand

3. Model simulation and discussions

By feeding the input data series into the household water cycle model, the water dynamics in household water cycle over 10 years time was simulated. The attention was paid on the impacts of storage tank and treatment capacity on the potential of water savings with consideration of limitation for residence time. Model simulation for a three-person household was taken as an example for demonstration purpose.

3.1 The *RT* in grey and green water tanks

The function of grey and green water tanks is to deal with the synchronicity between water sources and demands. In this paper, the treatment is assumed to operate in a continuous mode, which implies that the outflow from the grey water tank and the inflow to the green water tank are continuous and at a constant rate. Meanwhile, the inflow to the grey water tank and the outflow from the green water tank are dependent on the grey water production and toilet water demand respectively, and they are at intermittent patterns. So, unlike a typical treatment reactor, which has a *RT* dictated solely by flow rate (for a given reactor volume), this *RT* will be more complex giving both varying tank volumes and intermittent supply/demand.

The *RTD* is the reflection of the comprehensive interactions between inflow and outflow rates and patterns, and the volume of storage tank. In order to provide an insight to these interactions, the investigations of the impact of tank volume on *RT* for both grey and green water tanks are conducted in two types of analyses: *offline* analysis and *online* analysis.

In the *offline* analysis, the inflow and outflow of the grey and green tanks keep unchanged while the tank volumes vary. The relationships of *RTD* and $RTI_{0\text{-}48}$ with tank volume are focused. The interactions and impacts from other system components are not considered. Thus, the *offline* analysis offers a static snapshot understanding of the *RT* during storage. For the green water tank, the outflow is toilet water demand and the inflow is related to the treatment capacity. For the grey water tank, the inflow is grey water production from household water consumptions and the outflow is determined by the water request from treatment device, which is also related to the treatment capacity. An arbitrarily given treatment capacity value is adopted here.

In the *online* analysis, the *RT* during storage is investigated by taking the system component interactions into account. For example, when the *RT* of a green water tank is under investigation, not only the impacts of volume of the green tank, but also the volume of grey water tank are considered. This reflects the situation in a real system. Therefore, the *online* analysis provides a more systematic understanding of the *RT*. It should be noted that the value of inflow to green water tank or the outflow from the grey water tank might not be the same as the treatment capacity because the grey water demand of the treatment device may not be always satisfied in the *online* analysis. The actual value, not the potential treatment capacity is adopted in the *online* analysis, while the potential treatment capacity is used in the *offline* analysis.

3.1.1 The green water tank

The results of the *offline* analysis for the green water tank are given in Figure 5. It presents the *RTD* of a 50 litres green water tank with an inflow of 0.7 litres per 10 minutes, which corresponds to a treatment capacity of 100 litres per day, and the *RTD* of a 200 litres green water tank with the same inflow rate. As shown in Figure 6 (chart A), for the 50 litres tank, most water flowing out of the green water tank (excluding overflow) resided 0 to 10 days in the tank. The median value of the *RTD* is accounted as 1.88 days. The $RTI_{0\text{-}48}$ is calculated to be 0.60 according to equation 2. For the 200 litres tank, the median value of *RTD* and the $RTI_{0\text{-}48}$ are 3.12 days and 0.43 respectively. It is observed that the increase of storage tank volume results in a longer residence time, and therefore, a reduced $RTI_{0\text{-}48}$. This is also revealed in chart B, in which the $RTI_{0\text{-}48}$ curve for tank size from 0 litres to 1000 litres with the same inflow rate is displayed.

(Figure 6 here)

Chart C in Figure 5 shows the result of the *online* analysis. It is clear that both the green and the grey water tank volumes impose impact on the $RTI_{0\text{-}48}$ of the green water tank. It decreases with increasing of grey and green water tank volumes. However, the $RTI_{0\text{-}48}$ is more sensitive to the green water tank volume. It is also noticed that very slight impact is imposed on the $RTI_{0\text{-}48}$ by the size of grey water tank when the green water tank is relatively small (for example, less than 150 litres). This is because the adoption of threshold treatment capacity values. The household model operates at a 10 minute time scale and a 'spill after yield' assumption. In the model, the amount of grey water to spill is calculated after serving the treatment device in each time step. When the grey water tank volume is rather small, the grey water generated in the household is more prone to spill. The difference between available grey water tank capacity and the grey water production in each time step is termed as amount to potentially spill (APS) in the case of the former is smaller than the latter. When the grey water tank is small, its 'buffer' function in adjusting the inflow and the outflow is not significant. At this circumstance, the more the APS uptaked by the treatment device (i.e. the bigger the treatment capacity), the more grey water would be possibly reused. For a recycling system with a small grey water tank, the highest *WSE* might appear when the treatment capacity is big enough to uptake all APS. This results in a large threshold value of treatment capacity. The difference between grey water in APS and in the grey water tank is that the latter can last beyond the current time step in the tank, while the former will spill if it is not uptaked in the current time step. When a bigger grey water tank is employed (more grey water can then be supplied from the grey water tank), a relatively small treatment capacity may be required to produce the same amount of green water as the situation of small grey water tank with large treatment capacity. For both situations, when the green water tank is small, more than enough (compared to the green water tank volume) green water can be produced. Different from the grey water tank, in which outflow is continuous and the APS can be uptaked by the treatment device, the outflow from the green water tank is intermittent (determined by the toilet water demand) and APS will be more possible to spill rather than to be uptaked by toilet cistern. Therefore, the *RTI*s of small green water tanks, as shown in chart C, will be rather steady regardless the volume of grey water tank.

3.1.2 The grey water tank

The results of the *offline* analysis for the grey water tank are shown in Figure 7. Chart A in Figure 7 presents the *RTD*s of 50 and 200 litres grey water tanks with 100 litres per day treatment capacity. The median value of the *RTD*s and the $RTI_{0\text{-}48}$s for 50 litres tank and 200 litres tank are: 0.25 days and 1, 1.64 days and 0.95 respectively. It is clearly shown that the grey water is more prone to reside longer in a bigger grey water tank for a given treatment capacity. The $RTI_{0\text{-}48}$ decreases with increasing grey water tank volume. This is also reflected by chart B in Figure 7, which depicts the changes of $RTI_{0\text{-}48}$ with various grey water tank volumes for a given treatment capacity. Chart B also suggests that, for a given treatment capacity, the $RTI_{0\text{-}48}$ of grey water tank remains 1 for the grey water tank volume up to a specific threshold value (for example, for treatment capacity 100 litres per day, the threshold value for grey water tank is about 190 litres (chart B in Figure 7)). The $RTI_{0\text{-}48}$s for grey water tanks which are smaller than the threshold value are expected to be 1. A smaller $RTI_{0\text{-}48}$ will be yielded for grey water tank which is bigger than this threshold. This turning point indicates the maximum grey water tank volume which a specific treatment capacity can ‘digest’ in terms of residence time up to 48 hours. The turning point for a bigger treatment capacity is expected to be higher.

(Figure 7 here)

The results of the *online* analysis are presented in chart C in Figure 7. It is observed that both grey and green water tank volumes have impact on the $RTI_{0\text{-}48}$ of the grey water tank. However, grey water tank volume is more influential on the value of $RTI_{0\text{-}48}$. It should be noticed that similar to the investigation for the green water tank, the threshold treatment capacity values are adopted in the *online* analysis for the grey water tank. The contour for $RTI_{0\text{-}48} = 1$ indicates a front that any combination of grey and green water tank volumes below it can lead to the residence time of grey water during storage is statistically lower than 48 hours given the adoption of threshold treatment capacity.

3.2 Relationship of potential *WSE* with grey and green water tanks

Figure 8 shows *WSE* versus treatment capacity for 200 litres grey and green water tanks. It clearly indicates that *WSE* is maximised at a threshold treatment capacity of 200 litres per day for this configuration. Beyond this point, efficiency slowly declines regardless the increasing of treatment capacity. This effect is produced by the complex interactions between water supply and demand in relation to the filling of the two tanks, remembering that the green water tank has the potential for mains top up if it cannot supply the requested demand. For given volumes of grey and green water tank volumes, a bigger treatment capacity means more grey water could be treated into green 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 green water tank and deficit of grey water. By iterating this calculation for any combinations of grey and green tanks in a reasonable range, the relationship of potential *WSE* with grey and green tank volumes can be explored. This is performed from two aspects: volume based analysis and quality based analysis. In the volume based analysis, the interaction between system performance and storage tank volumes are only investigated from water quantity aspect. The treatment device is assumed to be robust enough to cope with low quality grey water. It is also assumed that the quality of green water reaches the relevant standards and regulations before being consumed. In the quality based analysis, the relationship of grey and green water residence times during storage and their implications on water quality degradation are taken into account.

(Figure 8 here)

3.2.1 Volume based analysis

In the volume based analysis, the system was assessed by taking just the quantity balance between water supply and demand into account. A range of different configurations was evaluated, based on both grey and green water tank volumes up to 1000 litres, and treatment capacities up to 1000 litres per day. Result of this analysis is presented in Figure 9. It is observed that potential *WSE* increases with increasing total volume of grey and green water tank. For a given grey/green water tank volume, the *WSE* also increases with increasing green/grey water tank volume. However, the increase is not symmetrical. For a given green water tank size, impact of grey water tank volume changing on *WSE* is small. Whereas in the converse case, for a given grey water tank size, impact of changing green water tank volume on *WSE* is significant. The figure clearly indicates the relative importance of the green tank volume in terms of achieving high *WSE*. The figure clearly indicates the relative importance of the green tank volume in relation to the grey water tank. For the same total volume, a higher *WSE* is expected for the combination with a greater size of green water tank. For example, for 800 litres total storage volume, the combination of 700 litres grey + 100 litres green yields 60 % *WSE* (point *a* in Figure 9), 400 litres grey + 400 litres green gives 76 % *WSE* (point *b*), while 87 % *WSE* is expected for the combination of 100 litres grey + 700 litres green (point *c*).

(Figure 9 here)

3.2.2 Quality based analysis

For the quality based analysis, the same configurations as the ones in the volume based analysis are adopted. Results are shown in Figure 10. Chart A in Figure 10 presents the contours of *WSE* and $RTI_{0\text{-}48}$ (for the grey tank) for different grey and green water tank volumes. It indicates that the residence time in the grey water tank is prone to be longer than 48 hours when both grey and green water tanks are large (as shown in the top right area in chart A). This implies that special attention should be paid in sizing storage tanks for a recycling system employing less robust treatment device like constructed wetland discussed in this paper, whose removal performance is sensitive to inflow grey water quality. Although the $RTI_{0\text{-}48}$ of grey water tank imposes some influence on the system performance, a high *WSE* (i.e. over 85%) can still be accomplished theoretically by choosing rational grey and green water tanks given the $RTI_{0\text{-}48}$ of the green water tank is also satisfactory. For example, a combination of relatively big green water tank and small grey water tank can promote both high *WSE* and low residence time (as shown in the bottom right area in chart A).

(Figure 10 here)

Chart B in Figure 10 shows the relationships of *WSE* and $RTI_{0\text{-}48}$ (green) with grey and green water tank volumes. Opposing relationships are observed, such that higher grey and green water tank volumes lead to higher *WSE* but lower $RTI_{0\text{-}48}$. In terms of water demand management, an objective to save as much potable water as possible is generally pursued. The volume based analysis implies that a high *WSE* (i.e. over 85%) can be achieved with reasonable configurations (sizes – grey: 150 litres and green 650 litres, point *a* in chart B). However, for this configuration, the $RTI_{0\text{-}48}$ for the green water tank is 0.3. Currently, there are no standards for $RTI_{0\text{-}48}$, but in the interim if a value of 0.5 is suggested as a reasonable target figure, chart B clearly indicates it is not possible to achieve both an $RTI_{0\text{-}48}$ = 0.5 and *WSE* = 85 %, whatever size tanks are used. If an $RTI_{0\text{-}48}$ standard of 0.5 is needed, a *WSE* of no greater than 65 % is possible based on a small green water tank (150 litres).

4. Discussion

A basic concern in grey water recycling is that the green water quality is good enough for non-potable purpose use and complies with relevant standards and regulations. Previous studies have revealed the water quality degradation of grey water and municipal reclaimed water during storage. This might decrease the effluent quality of treatment device. Furthermore, the quality of grey water produced varies with time due to different sources (for example, quality of grey water from bath is different from washing machine). This imposes more uncertainties and variabilities on quality of influent grey water to treatment device. Therefore, methods should be taken to ensure that the grey water is to be treated before its quality degrades to unacceptable level. In other words, residence time less than a certain value (48 hours in this work) as a criterion should be taken into account in system design. Similar consideration applies to green water tank to ensure the green water to be supplied for toilet before quality degrades to unacceptable level.

The *RTI* is introduced in this paper to assess the probability of water residing in a storage tank over a certain period. From the analysis for grey and green water tanks, it is observed that the $RTI_{0\text{-}48}$ is related to the volume of storage tank, inflow and outflow patterns. For the same volume of grey and green water tanks, differences in feature of *RTD* and value of $RTI_{0\text{-}48}$ are observed. For example, the $RTI_{0\text{-}48}$s for 200 litres grey and green water tanks are 0.95 and 0.34 respectively (Figures 6 and 7). The shapes of *RTD* also show opposite trends (charts A in Figures 6 and 7). In the grey water tank, the probability of grey water flowing out (not spilling) immediately after flowing in ($RT \infty 0$ hour) is rather small and it is more prone to reside for a while. However, in the green water tank, the green water is more prone to flow out immediately although the overall probability of residing over 48 hours is bigger than the one for a grey water tank with the same volume ($RTI_{0\text{-}48}$ grey 200 litres = 0.95 or $RTI_{over\ 48}$ = 0.05; $RTI_{0\text{-}48}$ green 200 litres = 0.34 or $RTI_{over\ 48}$ = 0.66). This attributes to the different patterns of inflow and outflow of the storage tank. In the grey water tank, the inflow is the production of grey water in a household, which is intermittent and might be with high flow intensity over a short time period (for example, the use of bath and shower). The outflow is the water request from treatment device, which is continuous and with relatively low flow intensity. This results in that the grey water produced in the current time step is more possible to flow out afterwards.

However, the situation for a green water tank is opposite, in which the inflow (green water production) is continuous and with relatively flow intensity and outflow is intermittent (toilet water request) and with relative high flow intensity (Assuming 1 toilet event with 9 litres water request in a 10 minute time step, the flow intensity is 9 litres per 10 minutes. For comparison, the flow intensity for a 100 litres per day treatment device is about 0.7 litres per 10 minutes). This explains why the probability of $RT \infty 0$ hour for green water tank is high (chart A in Figure 6) and the probability of $RT \infty 0$ hour for grey water tank is low (chart A in Figure 7).

The residence times of water in grey and green water tanks are investigated both with *online* and *offline* situations in this paper. The former assumes the storage tank is isolated from the system except for the adoption of real inflow for grey water tank (grey water production) and outflow for green water tank (toilet water request) and ignores the interaction between grey and green water tanks, and the treatment device. It provides a static snapshot on the relationship of *RT* with the volume of storage tank and representative inflow and outflow patterns. The latter investigates the *RT*s by taking the dynamic interactions between treatment capacity, grey and green water tanks. The relationship of *RT* with grey and green water tank volumes for a system with optimal design is explored. It reveals the systematic influence on *RT* of grey and green water. The finding from the *offline* analysis provides an insight to the understanding of *RT* due to volume of storage tank and flow patterns. The finding from the *online* analysis offers a systematic understanding of relationship of *RT* with system configurations and assist in revealing the constraint of *RT* in system design and potential water saving.

In the investigation for the impact of system configuration on potential of water saving, the quality based analysis reveals the impacts of *RT*s on the potential of water saving. Small values of $RTI_{0\text{-}48}$ are observed for big grey and green water tanks in achieving high *WSE*. However, it is still possible to achieve both high *WSE* and $RTI_{0\text{-}48}$ (for the grey tank) by rational system design for a recycling system with less robust treatment device theoretically given the $RTI_{0\text{-}48}$ (for the green tank) is satisfactory. More significant influence of $RTI_{0\text{-}48}$ (for the green tank) on *WSE* is noticed. Although no standard for $RTI_{0\text{-}48}$ (for the green tank) value is currently available, results from quality based analysis show that the *WSE* is inevitably reduced to pursue to higher RTI_{0-48} (for the green tank). It is also suggested that a combination of ‘big grey’ and ‘small green’ be employed to achieve a higher RTI_{0-48} (for the green tank) without trading off the *WSE* (chart B in Figure 7). This does not conflict with the finding from the volume based analysis, in which a combination of ‘big green’ and ‘small grey’ is recommended. In the volume based analysis, this conclusion is drawn on the condition of the same total volume of storage tank and in terms of water saving. However, in the quality based analysis, it is concluded to aim a better RTI_{0-48} (for the green tank) and the total volume of storage tanks are not the same.

(Figure 11 here)

The discussion above indicates that the adoption of 0 to 48 hours *TR* can significantly reduce the potential of potable water saved in a grey water recycling system. Figure 11 demonstrates that a broader *TR*, *RT* less than 4 days (96 hours) in the green water tank, can increase the potential of water saving by 16% for a grey water recycling system with the same configurations. In most present grey water recycling practices, the green water normally serves the toilet demand without further treatment. Therefore, target range of less than 2 days residence time is adopted in this project. The main concern of grey water recycling in terms of water demand management is to save as much potable water as possible, provided the water quality is satisfied. Result from above discussion shows that the main constraint to the percentage of potable water saved is the *RT* in the green water tank. Therefore, solutions should be sought to tolerate longer *RT* without compensate the quality of green water significant to achieve a higher water saving efficiency. A possible answer to this might be to introduce another treatment or disinfection option, between green water tank and toilet cistern.

5. Conclusions

1. This paper explores the potential of water saving for a constructed wetland based grey water recycling system by taking the residence time of water during storage tank into account. The dynamics of water cycle in a household over 10 years is simulated using an object based model at a 10 minutes time step. Results from the investigation of removal performance for different qualities of grey water suggest that attention

should be paid in prohibiting degradation of grey water during storage for a constructed wetland based water recycling system. This conclusion may also apply to other grey water recycling system with less robust treatment technologies.

2. Analysis for the residence time in grey and green water tanks indicates that *RTD* and *RTI* are dependent on the volume of storage tank, inflow and outflow patterns. Results from the volume based analysis reveal that the *WSE* increases with increasing storage tank volumes. For a given total storage volume, greater *WSE* can be achieved by using greater volumes of green tank. Therefore, system configurations using larger green and smaller grey tanks are recommended in practice provided a suitable treatment strategy is employed. The quality based analysis has highlighted that although larger volume tanks produce higher water saving efficiencies, smaller volume tanks are needed to secure good water quality. Indeed water saving efficiencies of greater than approximately 60 % cannot be safely achieved.

3. As both high *WSE* and *RTI* cannot be achieved simultaneously, it is concluded that in order to achieve the most cost-effective and safe solution, systems with both small grey and green tanks are needed, whilst accepting that only relatively modest water saving efficiency targets can be achieved. Higher efficiencies will only be practicable if water quality deterioration in the green water tank can be prevented by some means (e.g. disinfection). In this research, the effect of temperature on deterioration in storage tank is not considered. It is suggested that its impact should be included in future research.

Acknowledgement

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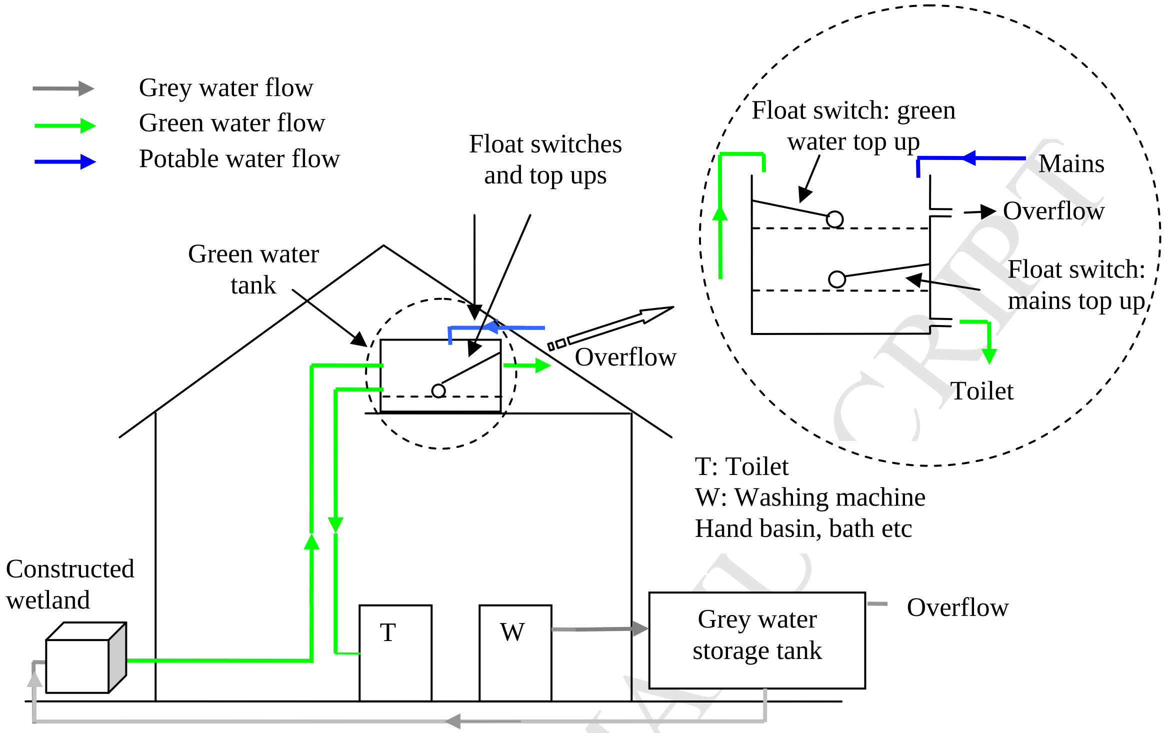
Grey water flow
Green water flow
Potable water flow
Float switches and top ups
Green water tank
Overflow
Float switch: green water top up
Mains
Overflow
Float switch: mains top up
Toilet
T: Toilet
W: Washing machine
Hand basin, bath etc
Constructed wetland
T
W
Grey water storage tank
Overflow

Figure 1

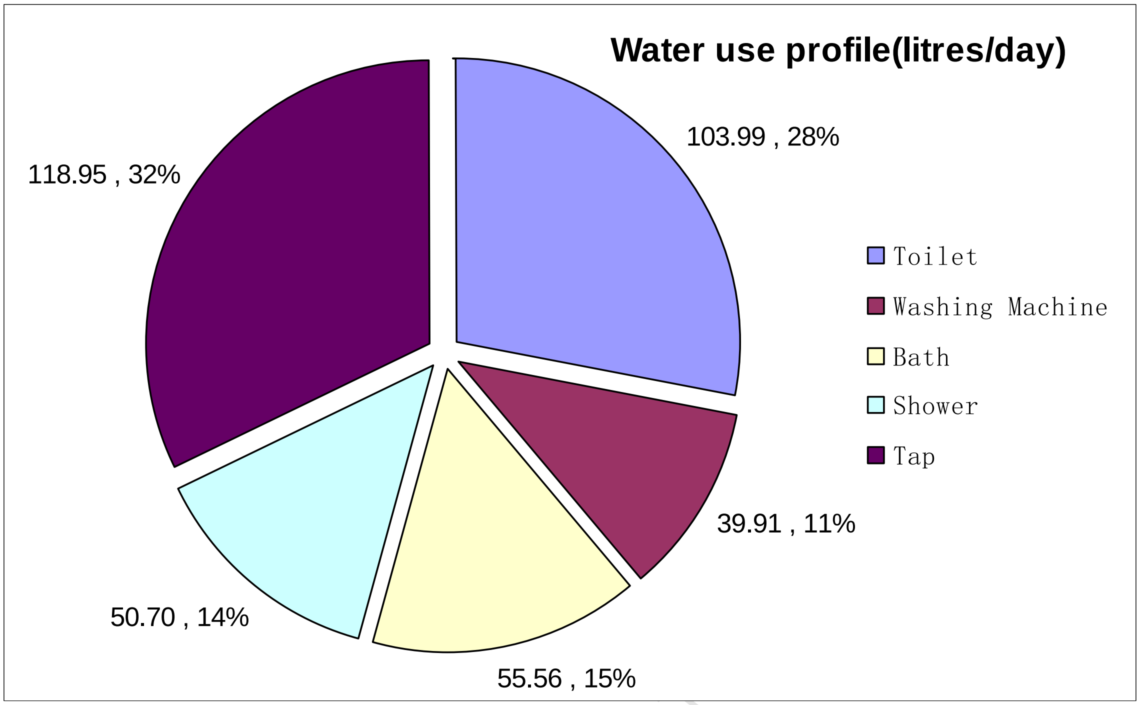
Water use profile(litres/day)
103.99 , 28%
118.95 , 32%
39.91 , 11%
50.70 , 14%
55.56 , 15%
Toilet
Washing Machine
Bath
Shower
Tap

Figure 2

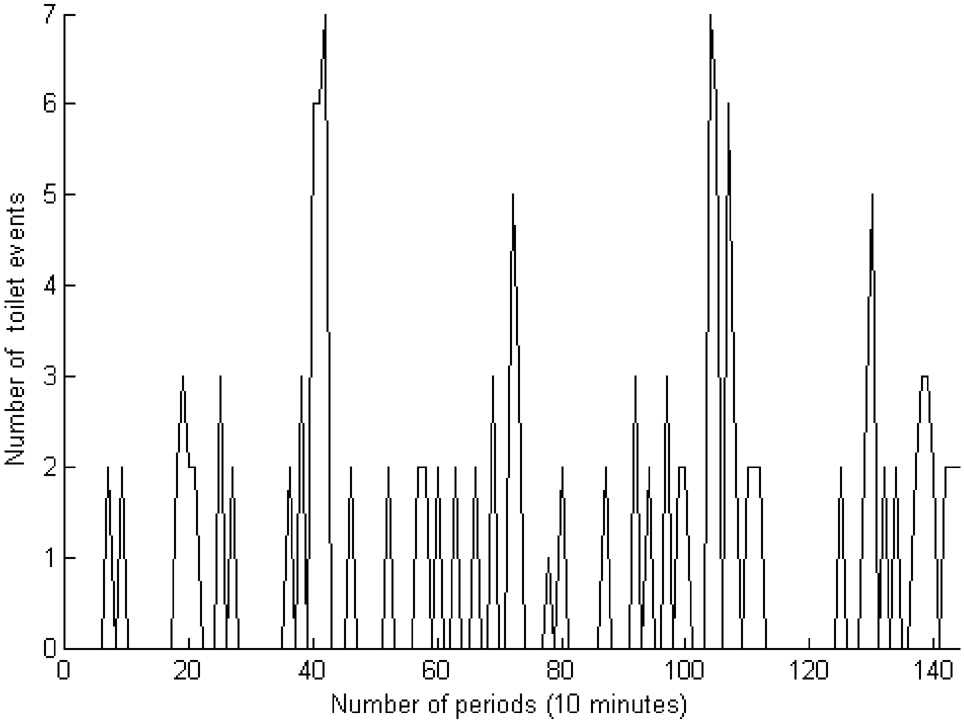
Number of toilet events
0
1
2
3
4
5
6
7
0
20
40
60
80
100
120
140
Number of periods (10 minutes)

Figure 3

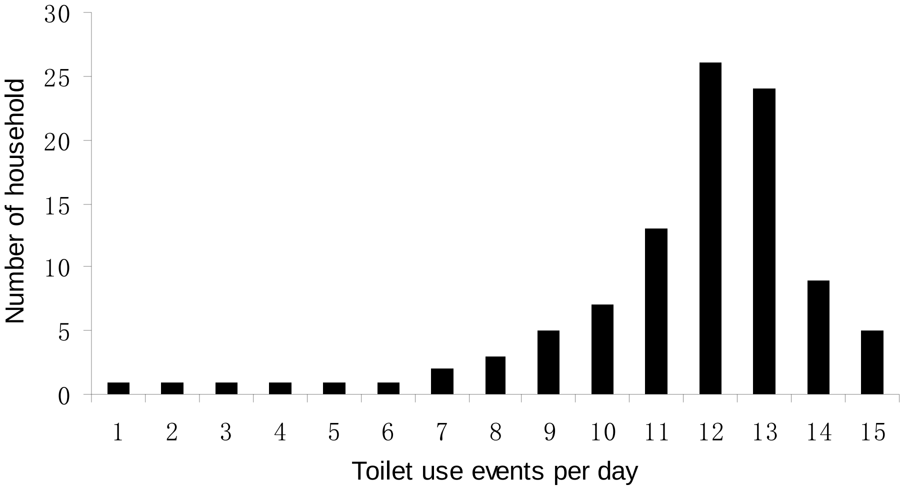
30
25
20
15
10
5
0
Number of household
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Toilet use events per day

Figure 4

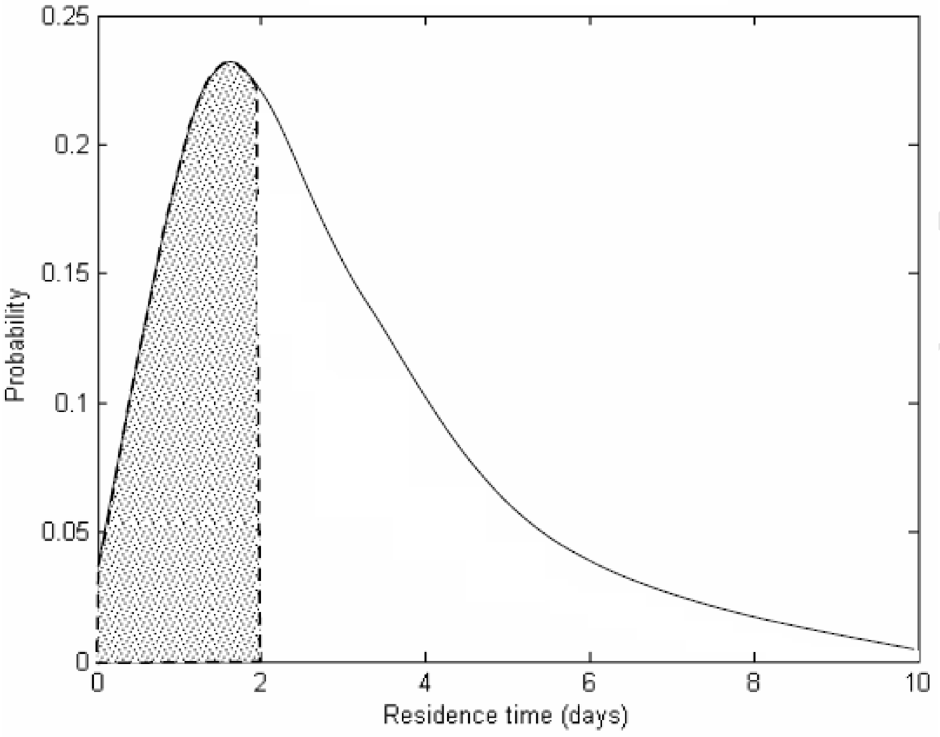

Figure 5

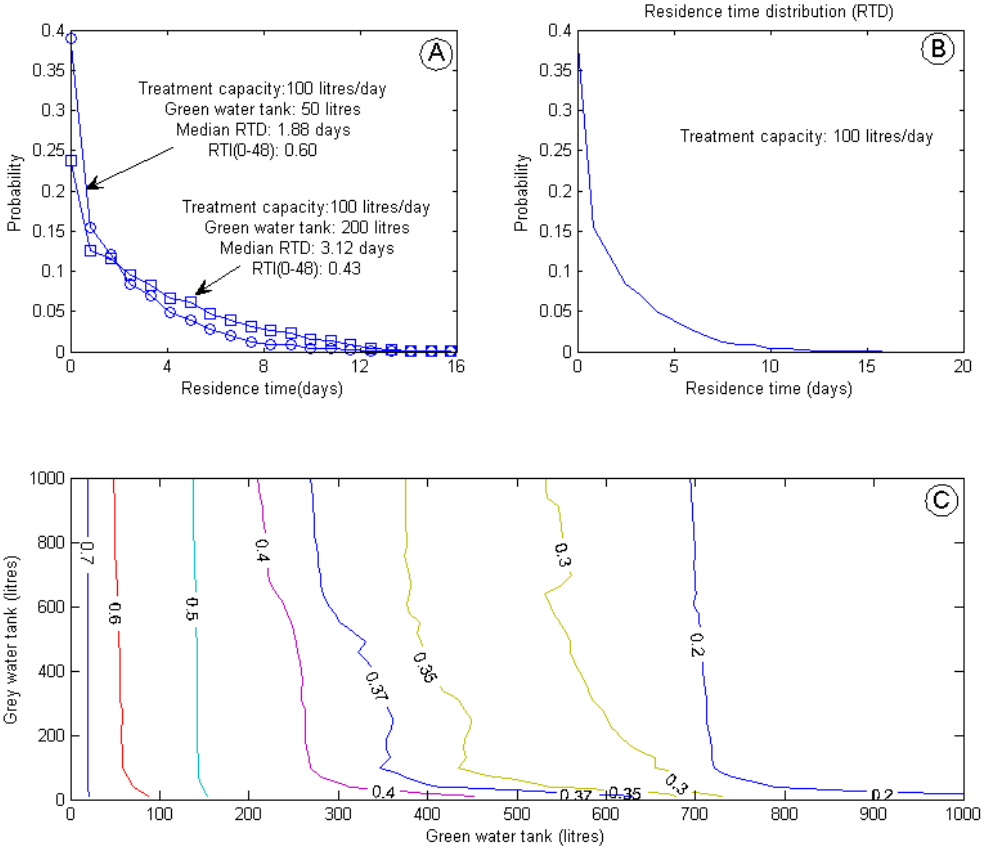
Ⓐ
Probability
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
4
8
12
16
Residence time(days)
Treatment capacity:100 litres/day
Green water tank: 50 litres
Median RTD: 1.88 days
RTI(0-48): 0.60
Treatment capacity:100 litres/day
Green water tank: 200 litres
Median RTD: 3.12 days
RTI(0-48): 0.43
Residence time distribution (RTD)
Ⓑ
Probability
Treatment capacity: 100 litres/day
0
5
10
15
20
Residence time (days)
Ⓒ
Grey water tank (litres)
1000
800
600
400
200
0
0
100
200
300
400
500
600
700
800
900
1000
Green water tank (litres)
0.7
0.6
0.5
0.4
0.37
0.35
0.3
0.2

Figure 6

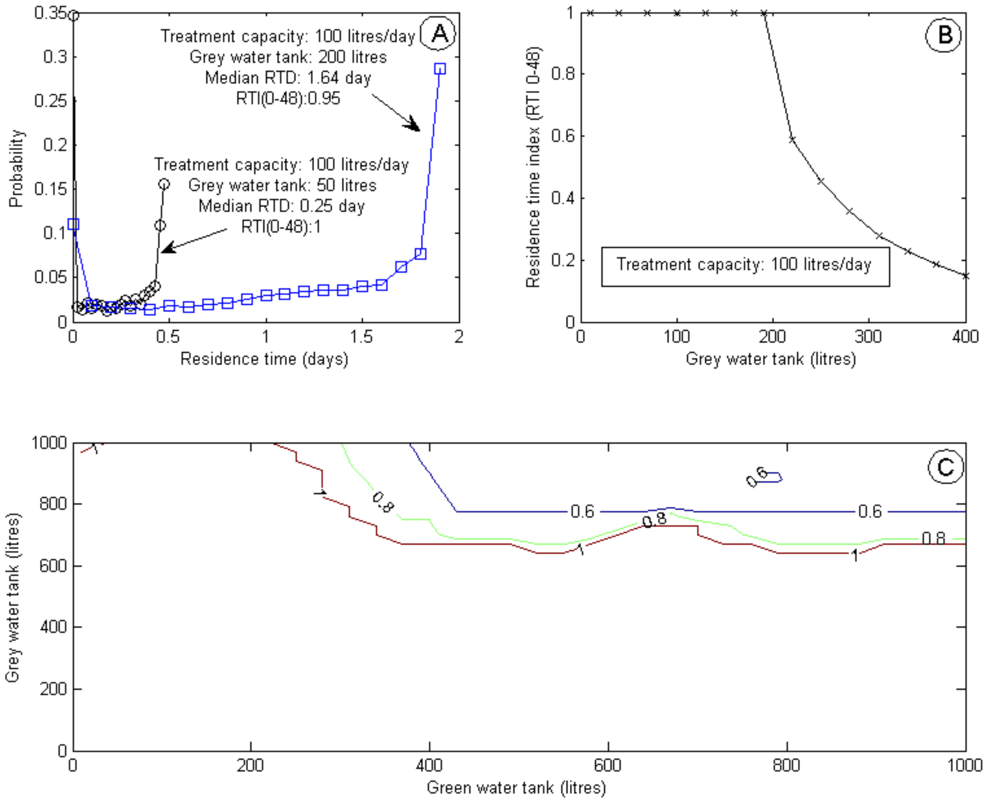
A
Probability
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
0.5
1
1.5
2
Residence time (days)
Treatment capacity: 100 litres/day
Grey water tank: 200 litres
Median RTD: 1.64 day
RTI(0-48):0.95
Treatment capacity: 100 litres/day
Grey water tank: 50 litres
Median RTD: 0.25 day
RTI(0-48):1
B
Residence time index (RTI 0-48)
1
0.8
0.6
0.4
0.2
0
0
100
200
300
400
Grey water tank (litres)
Treatment capacity: 100 litres/day
C
Grey water tank (litres)
1000
800
600
400
200
0
0
200
400
600
800
1000
Green water tank (litres)
1
0.8
0.6
0.6
0.8
0.6
0.8
1
1
0.6
0.8

Figure 7

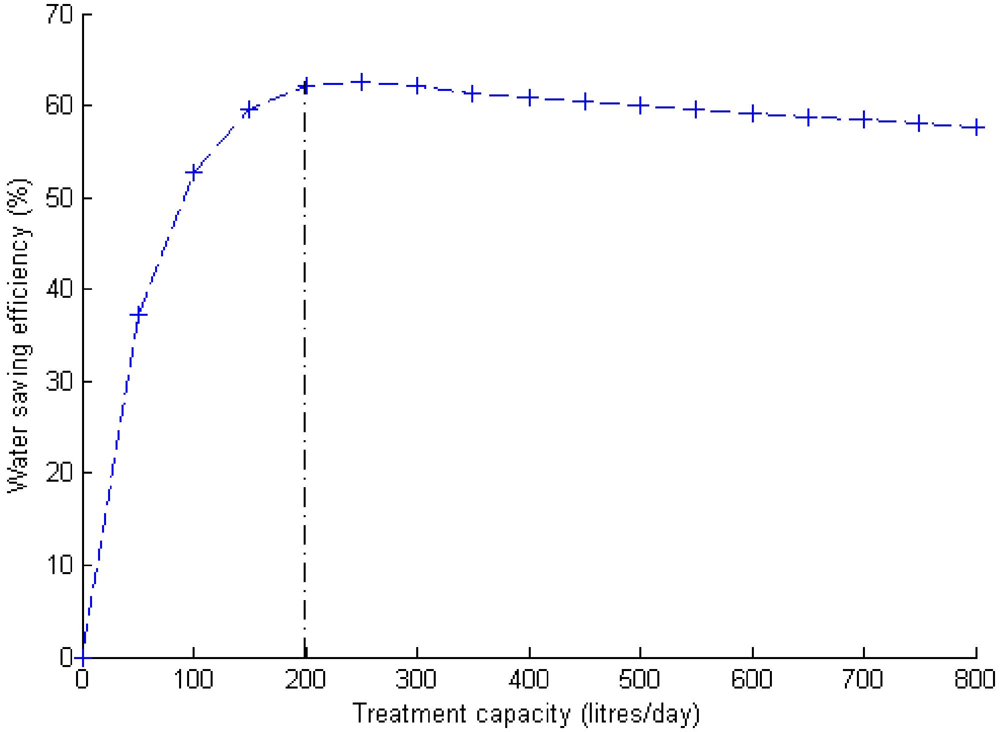
Water saving efficiency (%)
Treatment capacity (litres/day)
0
10
20
30
40
50
60
70
0
100
200
300
400
500
600
700
800

Figure 8

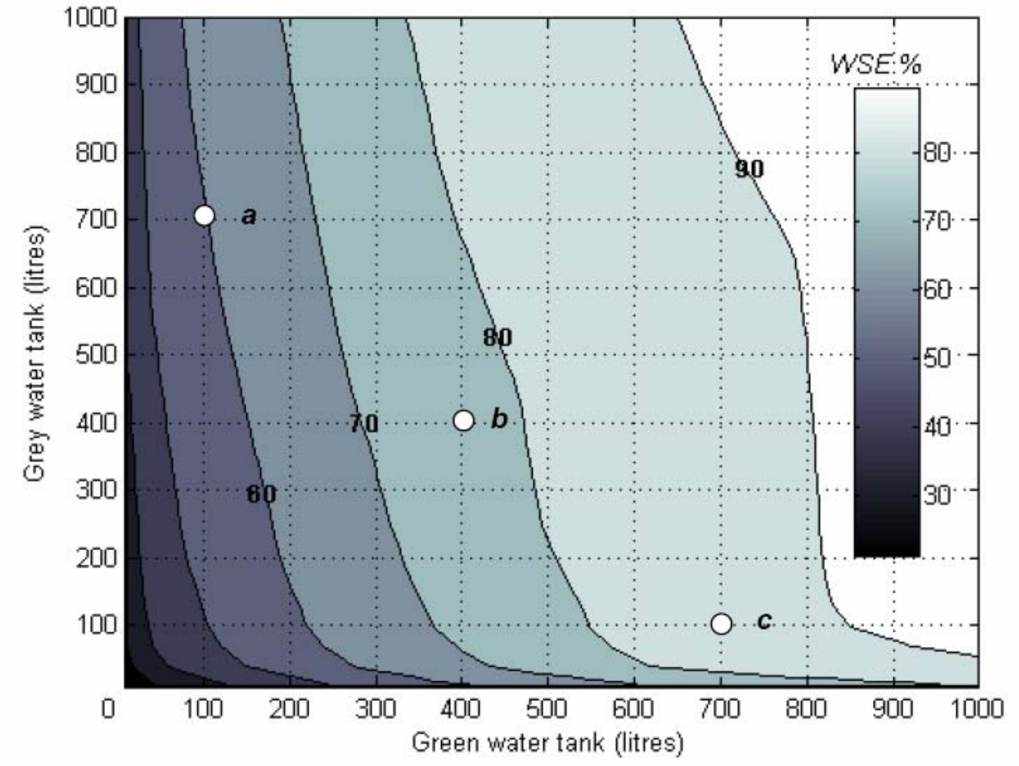
WSE:%
80
70
60
50
40
30
90
80
70
60
a
b
c
1000
900
800
700
600
500
400
300
200
100
0
100
200
300
400
500
600
700
800
900
1000
Grey water tank (litres)
Green water tank (litres)

Figure 9

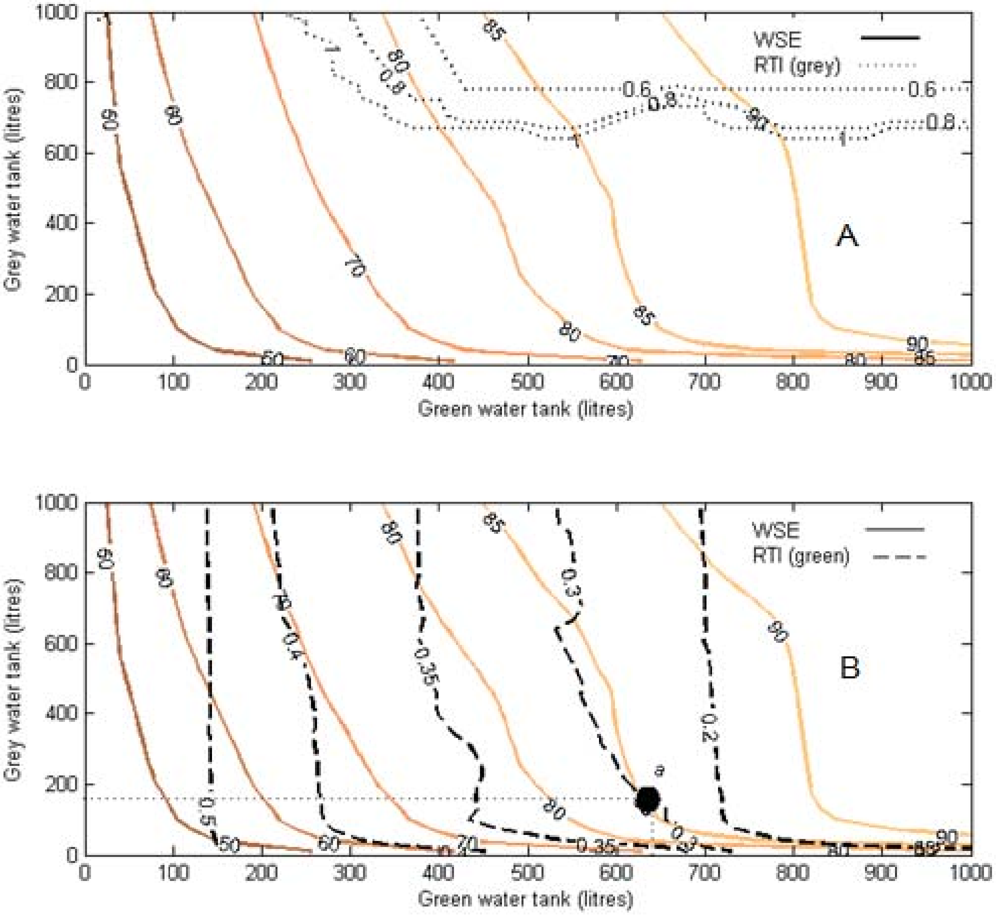
A
WSE
RTI (grey)
Grey water tank (litres)
Green water tank (litres)
0
100
200
300
400
500
600
700
800
900
1000
50
60
70
80
85
90
0.6
0.8
1
B
WSE
RTI (green)
0.5
0.4
0.35
0.3
0.2
a

Figure 10

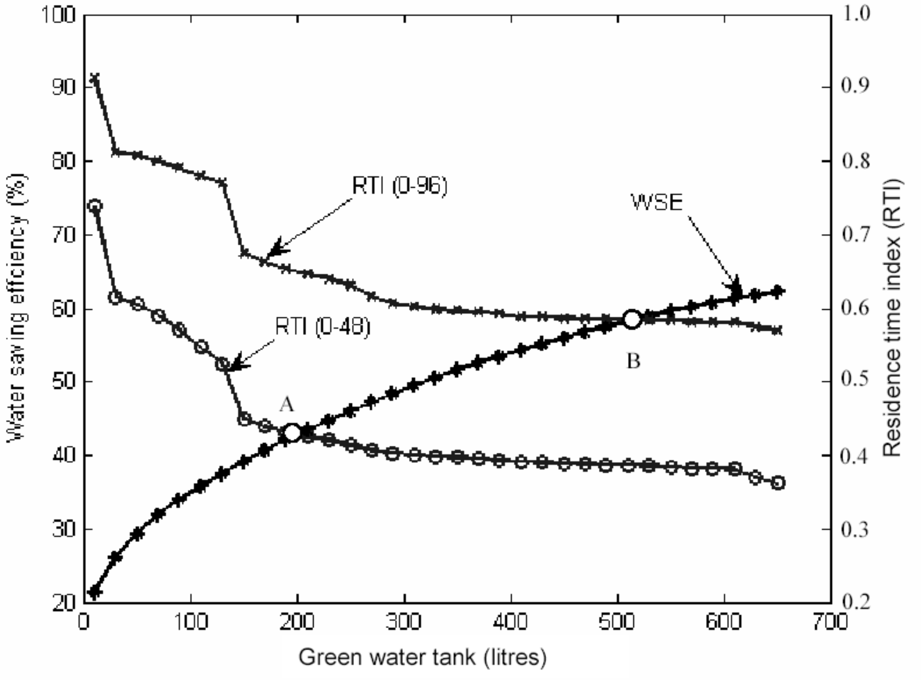
Water saving efficiency (%)
Residence time index (RTI)
Green water tank (litres)
RTI (0-96)
RTI (0-48)
WSE
A
B
100
90
80
70
60
50
40
30
20
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0
100
200
300
400
500
600
700

Figure 11