

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

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10

11 Abstract

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

25

26 Key words:

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

28

29 1. Introduction

30 Grey water is defined as the water which is slightly contaminated by human activities and may possibly be
31 reused after suitable treatment, for example, water from a washing machine, shower, bath etc. The
32 reclaimed water or the treated grey water is termed as green water in this paper. Grey water recycling is
33 emerging as an internal part of water demand management, promoting as it does the preservation of high
34 quality fresh water supplies as well as potentially reducing the pollutant in the environment. The principle
35 of domestic grey water reuse is to replace all or some of the non-potable water demand by reclaimed water.
36 The general use of treated grey water in a household context mainly includes toilet flushing and/or garden
37 watering. This paper focuses on the toilet flushing. In the last decade, grey water recycling practices have
38 been reported in many countries (Asano and Levine, 1996; Fittschen and Niemczynowicz, 1997; Kayaalp,
39 1996; Nolde, 2000; Smith et al., 2000; Yang et al., 2006).

40

41 **1.1 Grey water characterisation**

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

55

56 In terms of healthy concern, a key question or objective in domestic grey water recycling is to ensure the
57 green water complies with relevant standards. This may be accomplished both by choosing robust and

58 effective treatment and limiting grey water degradation during storage by rational design. This paper will
59 mainly focus on the latter topic. On the other hand, the concept of grey water recycling is to reduce potable
60 water demand by replacing non-potable demand with green water in term of water demand management
61 and sustainable development. From this point of view, the objective of grey water recycling is to save as
62 much potable water as possible. These two objectives may interact, or even conflict each other. Their
63 interaction/confliction should be explored to increase the understanding and confidence in implementation
64 of grey water recycling. Rational design can then be undertaken based on these understandings to ensure
65 the great achievement of both objectives in recycling practices. This will be discussed in this paper.

66

67 **1.2 Treatment technologies**

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

82

83 As a low-cost technology, constructed wetland has recently gained much attention in grey water treatment.
84 Experiences in Central America (Dallas et al., 2004), Middle East (Gross et al., 2007) and the UK (Frazer-
85 Williams et al., 2008) showed that high averaged removal rate can be achieved provided appropriate

86 hydraulic retention time is given. In this project, therefore, a constructed wetland based grey water
87 recycling system is chosen to investigate the impact of residence time in storage tanks on the system's
88 performance.

89

90 **1.3 System configuration**

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

105

106 (Figure 1 here)

107

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

114

115 **2. Methodology**

116 **2.1 The household water cycle model**

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

126

127 **2.2 Input data**

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

142 for shower and 118.95 litres for tap uses. Distributions of water use events in terms of time and household
143 were examined. Spatial and temporal differences of water use event were found. Taking toilet flushing as
144 an example, Figure 3 shows the cumulative number of toilet use event in every 10 minutes interval during a
145 day (144 intervals) for the 100 households. Except for the morning and evening peak uses, toilet flushing is
146 featured as a randomized event. Figure 4 displays the distribution of number of toilet use event and
147 household numbers, which reveals that most households (79 households) use 10-14 times of toilet per day.
148 It is also noticed from Figure 4 that 8 households use less than 7 times of toilet per day, which might be
149 because of less people living in. In generating water use profile time series data using Monte-Carlo method,
150 spatial and temporal differences were taken into account to represent the differences of water use event in
151 term of time and household.

152

153 (Figure 2,3,4 here)

154

155 **2.3 Residence time distribution**

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

165

166 (Figure 5 here)

167

168 **2.4 Performance indicators**

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

171

172 The time range of a *RT* for the question under discussion is defined as target range (*TR*). Previous research
173 has recommended that the *RT* in a grey water tank should not be beyond 48 hours to avoid the significant
174 water quality degradation (Dixon et al., 2000). No similar research has been conducted for green water.
175 However, experience from reclaimed municipal water suggests green water quality degradation during
176 storage is expected (Narasimhan et al., 2005). For simplification, therefore, a 0 to 48 hours *TR* was adopted
177 both for grey water and green water. To evaluate to what extent *RT* is within the *TR* (0 to 48 hours), a
178 residence time index (*RTI*) is introduced, calculated as the ratio of the integral of *RTD* over the *TR* to the
179 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
180 indicates that all water leaving the storage tank as outflow stays in the tank less than 48 hours. The greater
181 the *RTI* is, the better the storage tank performs in terms of avoiding water quality degradation.

182

$$183 \quad RTI_{TR} = \frac{\int_{TR} RTD \, dRT}{\int_{WR} RTD \, dRT} \quad (2)$$

184 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
185 short for the whole range of retention time.

186

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

$$190 \quad WSE = 100 * \frac{\sum_{t=1}^T W_t}{\sum_{t=1}^T D_t} \quad (3)$$

191 Where:

192 T = Run duration

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

194 D_t = Toilet water demand

195

196 **3. Model simulation and discussions**

197 By feeding the input data series into the household water cycle model, the water dynamics in household
198 water cycle over 10 years time was simulated. The attention was paid on the impacts of storage tank and
199 treatment capacity on the potential of water savings with consideration of limitation for residence time.

200 Model simulation for a three-person household was taken as an example for demonstration purpose.

201

202 **3.1 The RT in grey and green water tanks**

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

210

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

215

216 In the *offline* analysis, the inflow and outflow of the grey and green tanks keep unchanged while the tank
217 volumes vary. The relationships of RTD and RTI_{0-48} with tank volume are focused. The interactions and
218 impacts from other system components are not considered. Thus, the *offline* analysis offers a static snapshot
219 understanding of the RT during storage. For the green water tank, the outflow is toilet water demand and
220 the inflow is related to the treatment capacity. For the grey water tank, the inflow is grey water production
221 from household water consumptions and the outflow is determined by the water request from treatment

222 device, which is also related to the treatment capacity. An arbitrarily given treatment capacity value is
223 adopted here.

224

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

233

234 **3.1.1 The green water tank**

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

244

245 (Figure 6 here)

246

247 Chart C in Figure 5 shows the result of the *online* analysis. It is clear that both the green and the grey water
248 tank volumes impose impact on the RTI_{0-48} of the green water tank. It decreases with increasing of grey and
249 green water tank volumes. However, the RTI_{0-48} is more sensitive to the green water tank volume. It is also

250 noticed that very slight impact is imposed on the RTI_{0-48} by the size of grey water tank when the green
251 water tank is relatively small (for example, less than 150 litres). This is because the adoption of threshold
252 treatment capacity values. The household model operates at a 10 minute time scale and a ‘spill after yield’
253 assumption. In the model, the amount of grey water to spill is calculated after serving the treatment device
254 in each time step. When the grey water tank volume is rather small, the grey water generated in the
255 household is more prone to spill. The difference between available grey water tank capacity and the grey
256 water production in each time step is termed as amount to potentially spill (APS) in the case of the former
257 is smaller than the latter. When the grey water tank is small, its ‘buffer’ function in adjusting the inflow and
258 the outflow is not significant. At this circumstance, the more the APS uptaked by the treatment device (i.e.
259 the bigger the treatment capacity), the more grey water would be possibly reused. For a recycling system
260 with a small grey water tank, the highest WSE might appear when the treatment capacity is big enough to
261 uptake all APS. This results in a large threshold value of treatment capacity. The difference between grey
262 water in APS and in the grey water tank is that the latter can last beyond the current time step in the tank,
263 while the former will spill if it is not uptaked in the current time step. When a bigger grey water tank is
264 employed (more grey water can then be supplied from the grey water tank), a relatively small treatment
265 capacity may be required to produce the same amount of green water as the situation of small grey water
266 tank with large treatment capacity. For both situations, when the green water tank is small, more than
267 enough (compared to the green water tank volume) green water can be produced. Different from the grey
268 water tank, in which outflow is continuous and the APS can be uptaked by the treatment device, the
269 outflow from the green water tank is intermittent (determined by the toilet water demand) and APS will be
270 more possible to spill rather than to be uptaked by toilet cistern. Therefore, the $RTIs$ of small green water
271 tanks, as shown in chart C, will be rather steady regardless the volume of grey water tank.

272

273 **3.1.2 The grey water tank**

274 The results of the *offline* analysis for the grey water tank are shown in Figure 7. Chart A in Figure 7
275 presents the $RTDs$ of 50 and 200 litres grey water tanks with 100 litres per day treatment capacity. The
276 median value of the $RTDs$ and the RTI_{0-48} s for 50 litres tank and 200 litres tank are: 0.25 days and 1, 1.64
277 days and 0.95 respectively. It is clearly shown that the grey water is more prone to reside longer in a bigger

278 grey water tank for a given treatment capacity. The RTI_{0-48} decreases with increasing grey water tank
279 volume. This is also reflected by chart B in Figure 7, which depicts the changes of RTI_{0-48} with various grey
280 water tank volumes for a given treatment capacity. Chart B also suggests that, for a given treatment
281 capacity, the RTI_{0-48} of grey water tank remains 1 for the grey water tank volume up to a specific threshold
282 value (for example, for treatment capacity 100 litres per day, the threshold value for grey water tank is
283 about 190 litres (chart B in Figure 7)). The RTI_{0-48} s for grey water tanks which are smaller than the
284 threshold value are expected to be 1. A smaller RTI_{0-48} will be yielded for grey water tank which is bigger
285 than this threshold. This turning point indicates the maximum grey water tank volume which a specific
286 treatment capacity can ‘digest’ in terms of residence time up to 48 hours. The turning point for a bigger
287 treatment capacity is expected to be higher.

288

289 (Figure 7 here)

290

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

298

299 **3.2 Relationship of potential *WSE* with grey and green water tanks**

300 Figure 8 shows *WSE* versus treatment capacity for 200 litres grey and green water tanks. It clearly indicates
301 that *WSE* is maximised at a threshold treatment capacity of 200 litres per day for this configuration. Beyond
302 this point, efficiency slowly declines regardless the increasing of treatment capacity. This effect is
303 produced by the complex interactions between water supply and demand in relation to the filling of the two
304 tanks, remembering that the green water tank has the potential for mains top up if it cannot supply the
305 requested demand. For given volumes of grey and green water tank volumes, a bigger treatment capacity

306 means more grey water could be treated into green water. However, it might also result in less grey water to
307 be actually reused for toilet flushing because a bigger treatment capacity can encourage overflow from the
308 green water tank and deficit of grey water. By iterating this calculation for any combinations of grey and
309 green tanks in a reasonable range, the relationship of potential *WSE* with grey and green tank volumes can
310 be explored. This is performed from two aspects: volume based analysis and quality based analysis. In the
311 volume based analysis, the interaction between system performance and storage tank volumes are only
312 investigated from water quantity aspect. The treatment device is assumed to be robust enough to cope with
313 low quality grey water. It is also assumed that the quality of green water reaches the relevant standards and
314 regulations before being consumed. In the quality based analysis, the relationship of grey and green water
315 residence times during storage and their implications on water quality degradation are taken into account.

316

317 (Figure 8 here)

318 **3.2.1 Volume based analysis**

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

333

334 (Figure 9 here)

335

336 3.2.2 Quality based analysis

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

349

350 (Figure 10 here)

351

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

362

363 4. Discussion

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

374

375 The *RTI* is introduced in this paper to assess the probability of water residing in a storage tank over a
376 certain period. From the analysis for grey and green water tanks, it is observed that the RTI_{0-48} is related to
377 the volume of storage tank, inflow and outflow patterns. For the same volume of grey and green water
378 tanks, differences in feature of *RTD* and value of RTI_{0-48} are observed. For example, the RTI_{0-48} for 200
379 litres grey and green water tanks are 0.95 and 0.34 respectively (Figures 6 and 7). The shapes of *RTD* also
380 show opposite trends (charts A in Figures 6 and 7). In the grey water tank, the probability of grey water
381 flowing out (not spilling) immediately after flowing in ($RT \infty 0$ hour) is rather small and it is more prone to
382 reside for a while. However, in the green water tank, the green water is more prone to flow out immediately
383 although the overall probability of residing over 48 hours is bigger than the one for a grey water tank with
384 the same volume (RTI_{0-48} grey 200 litres = 0.95 or $RTI_{over\ 48} = 0.05$; RTI_{0-48} 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
385 water tank, the inflow is the production of grey water in a household, which is intermittent and might be
386 with high flow intensity over a short time period (for example, the use of bath and shower). The outflow is
387 the water request from treatment device, which is continuous and with relatively low flow intensity. This
388 results in that the grey water produced in the current time step is more possible to flow out afterwards.
389

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

397

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

410

411 In the investigation for the impact of system configuration on potential of water saving, the quality based
412 analysis reveals the impacts of RT s on the potential of water saving. Small values of RTI_{0-48} are observed
413 for big grey and green water tanks in achieving high WSE . However, it is still possible to achieve both high
414 WSE and RTI_{0-48} (for the grey tank) by rational system design for a recycling system with less robust
415 treatment device theoretically given the RTI_{0-48} (for the green tank) is satisfactory. More significant
416 influence of RTI_{0-48} (for the green tank) on WSE is noticed. Although no standard for RTI_{0-48} (for the green
417 tank) value is currently available, results from quality based analysis show that the WSE is inevitably

418 reduced to pursue to higher RTI_{0-48} (for the green tank). It is also suggested that a combination of ‘big grey’
419 and ‘small green’ be employed to achieve a higher RTI_{0-48} (for the green tank) without trading off the WSE
420 (chart B in Figure 7). This does not conflict with the finding from the volume based analysis, in which a
421 combination of ‘big green’ and ‘small grey’ is recommended. In the volume based analysis, this conclusion
422 is drawn on the condition of the same total volume of storage tank and in terms of water saving. However,
423 in the quality based analysis, it is concluded to aim a better RTI_{0-48} (for the green tank) and the total volume
424 of storage tanks are not the same.

425

426 (Figure 11 here)

427

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

440

441 **5. Conclusions**

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

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

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

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

463

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468

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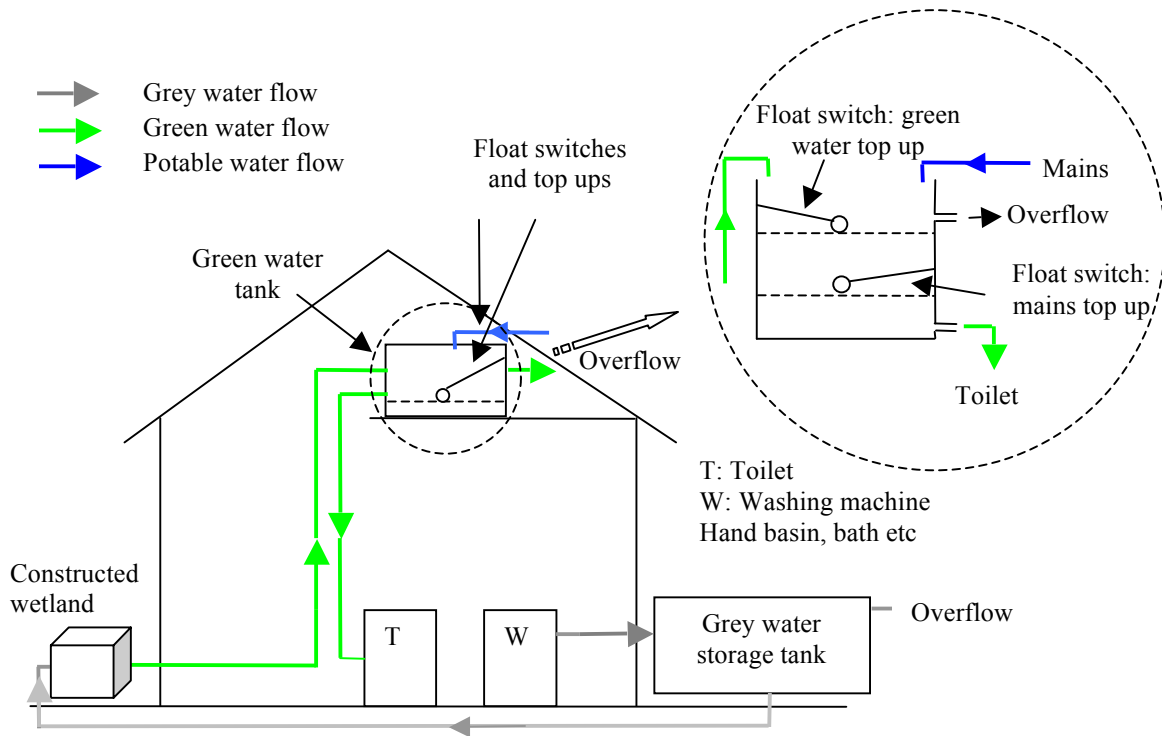
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530 Figure 1

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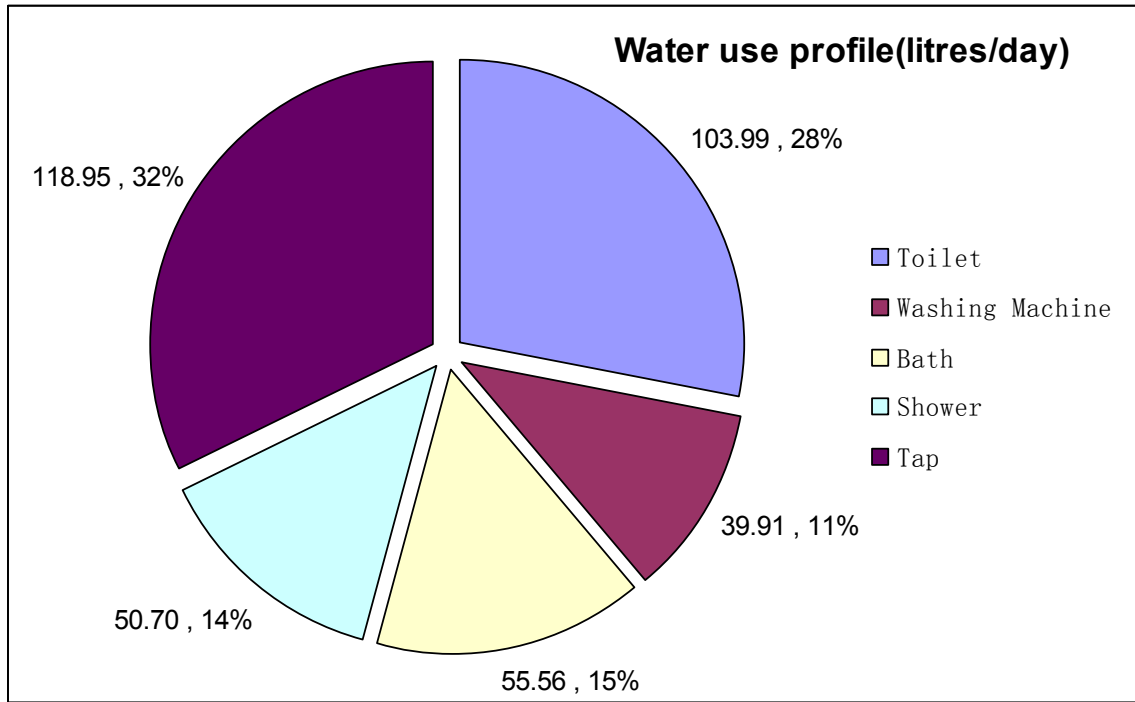
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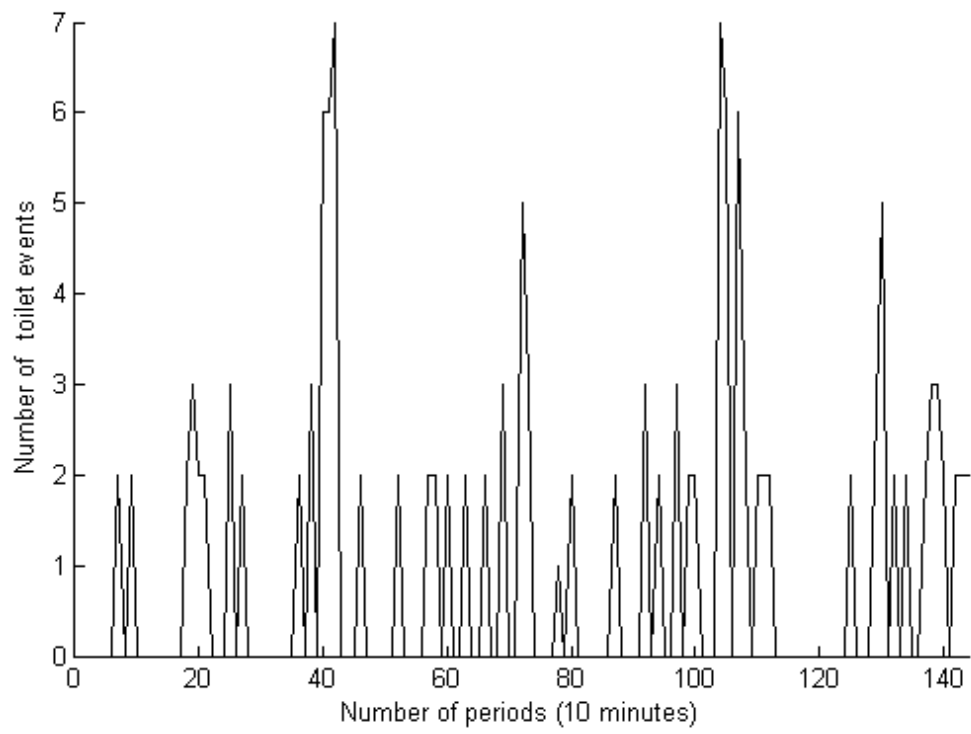
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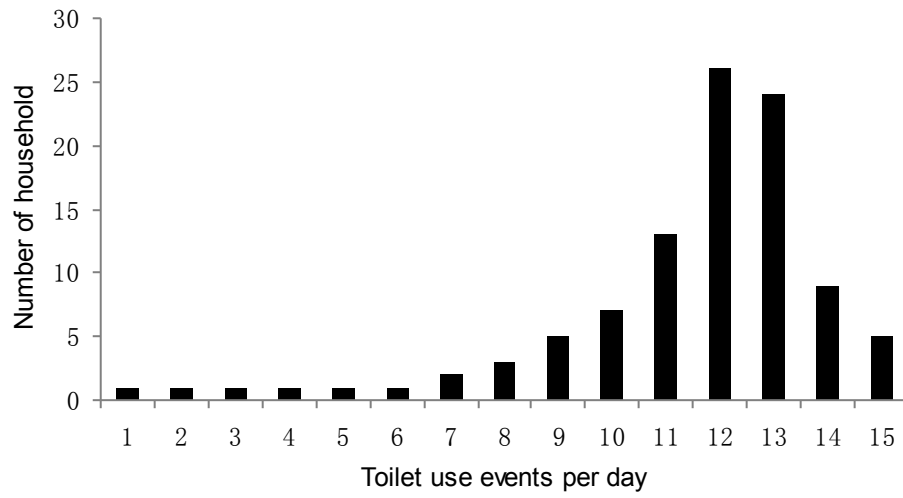
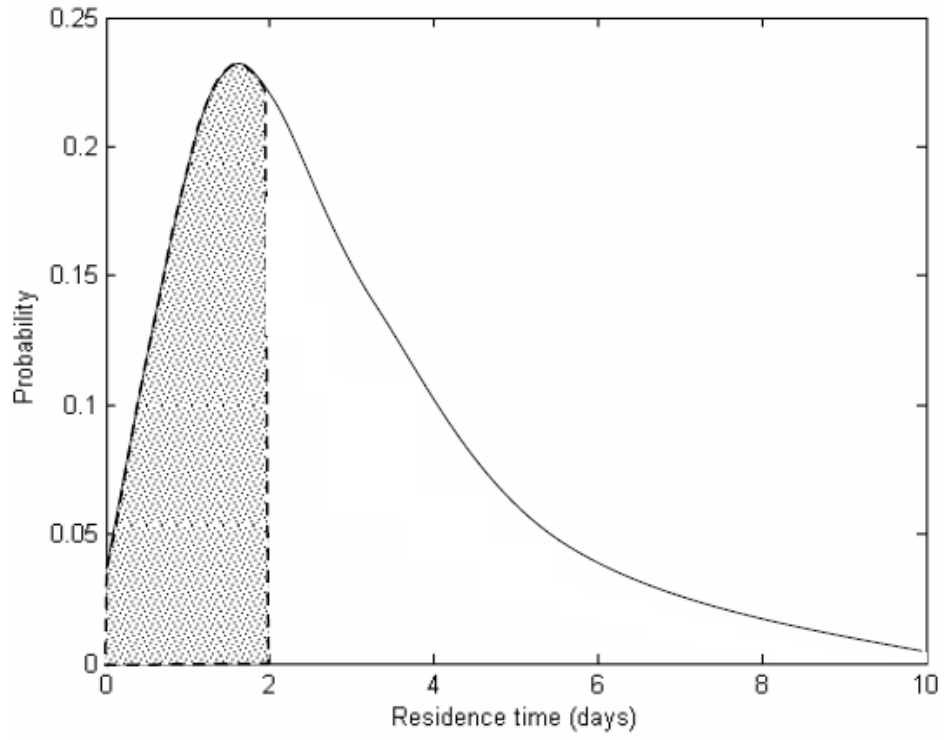


Figure 4

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605 Figure 5

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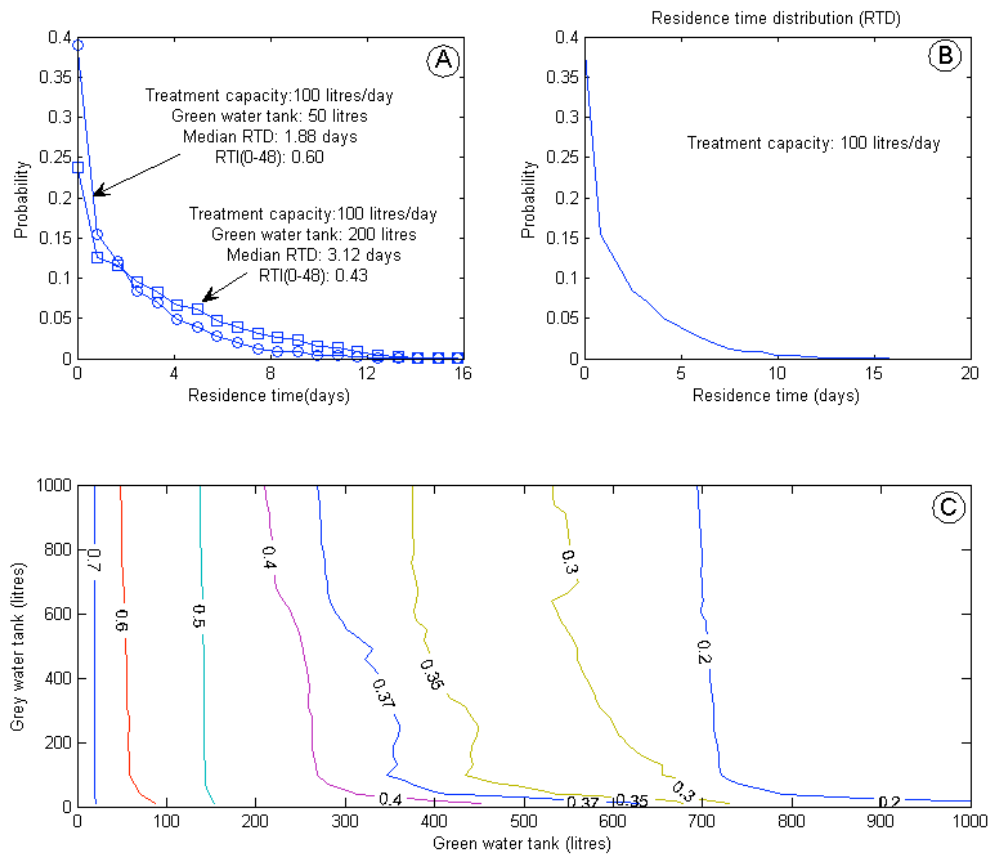
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619 Figure 6

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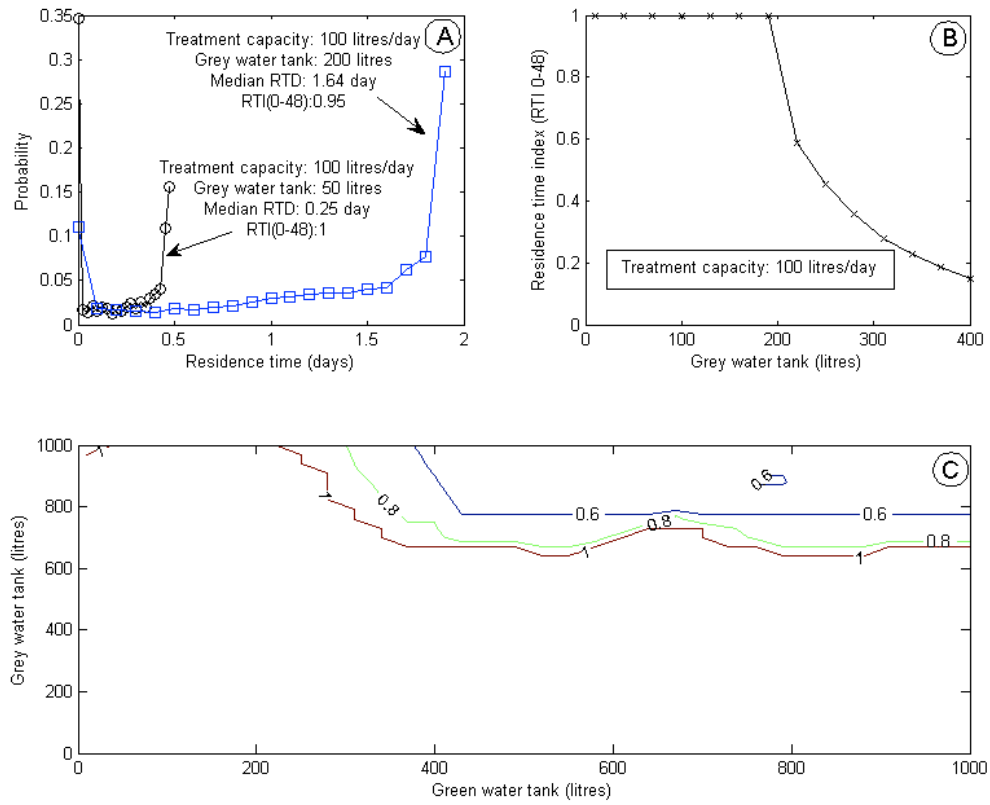
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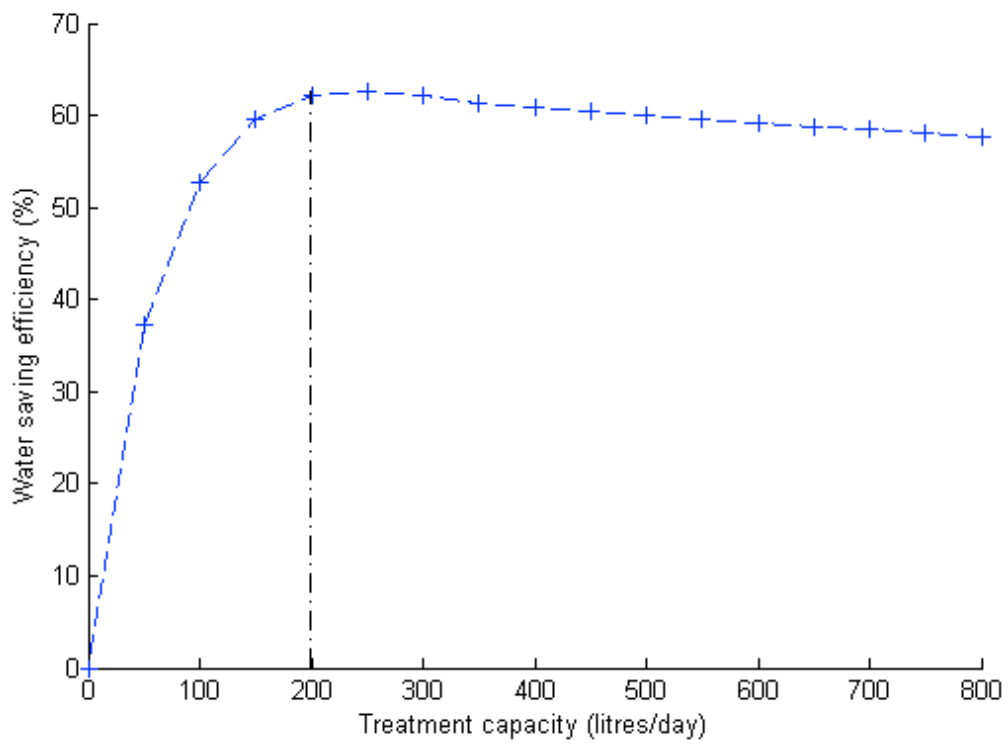


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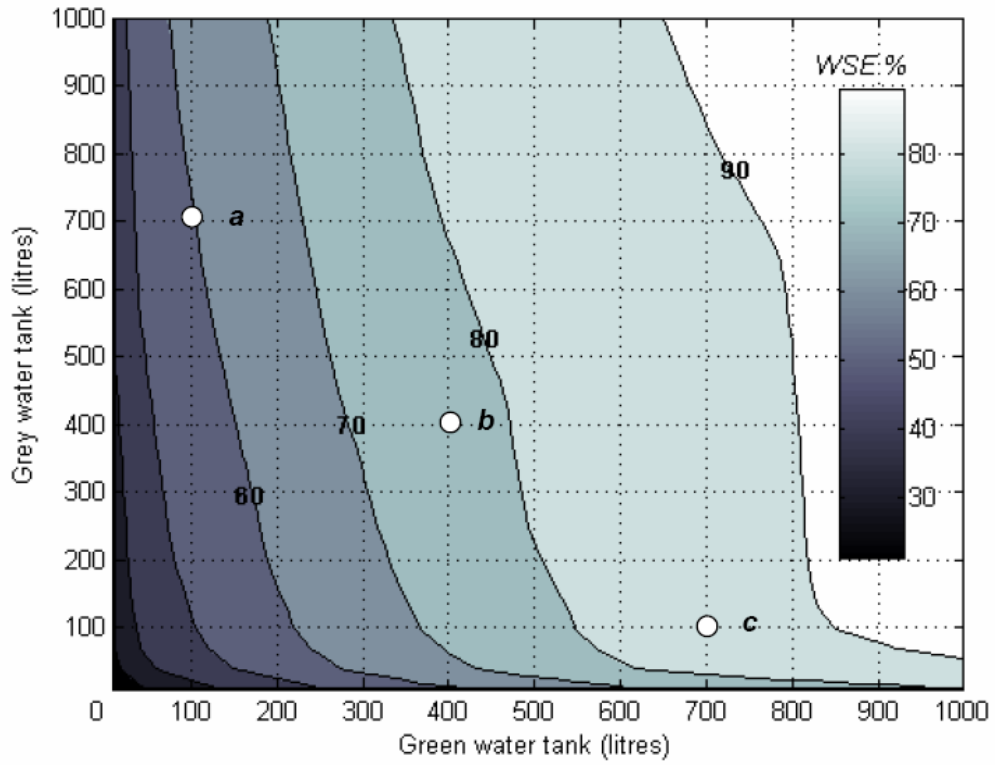
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640 Figure 8



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644 Figure 9

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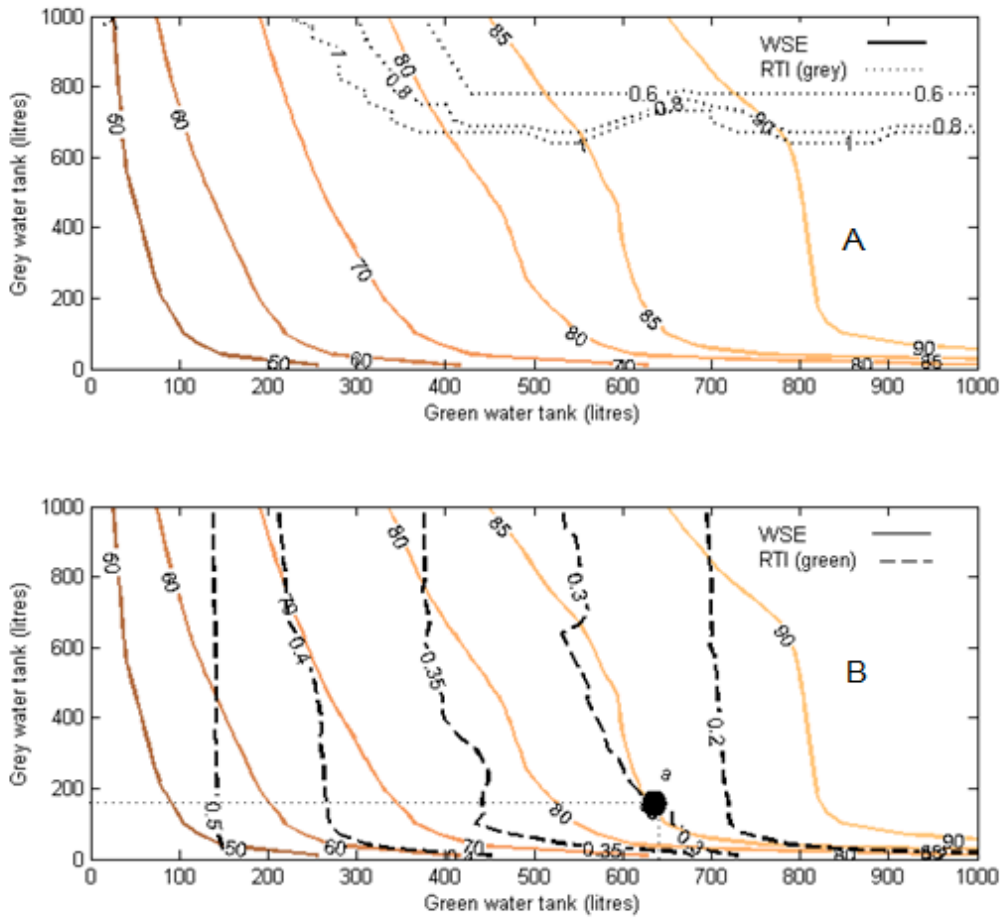
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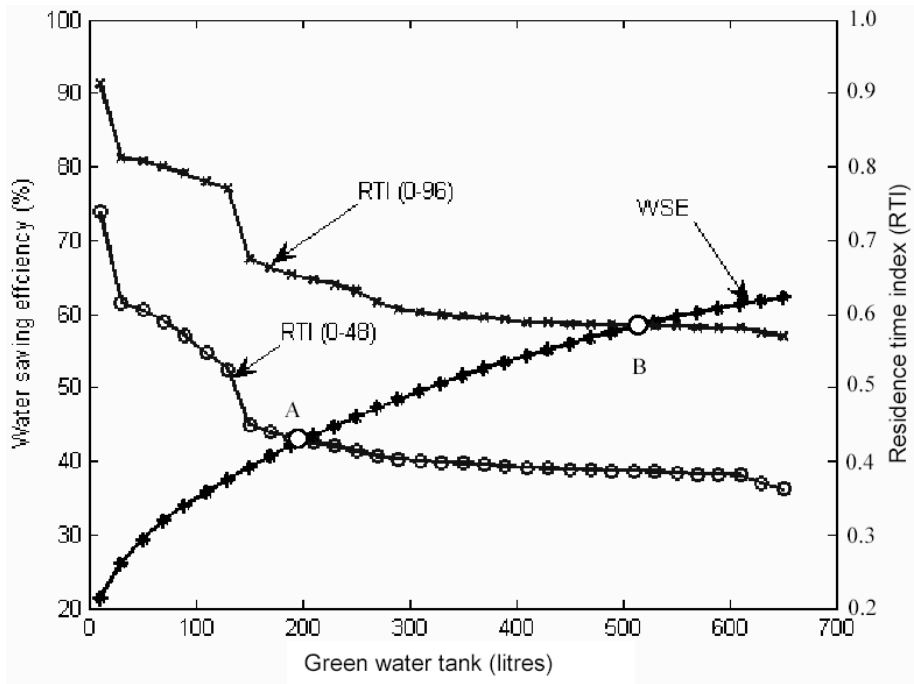
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671 Figure 11

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688 Figure 1 Illustration of grey water recycling system

689 Figure 2 Water use profile data for three-person households

690 Figure 3 Distribution of toilet use event in terms of time

691 Figure 4 Distribution of toilet use event in terms of household

692 Figure 5 Illustration of residence time distribution

693 Figure 6 Results for residence time of green water: *online* and *offline* analyses

694 Figure 7 Results for residence time of grey water: *online* and *offline* analyses

695 Figure 8 Relationship of *WSE* and treatment capacity

696 Figure 9 Relationship of *WSE* and system configuration: volume based analysis

697 Figure 10 Relationship of *WSE* and system configuration: quality based analysis

698 Figure 11 Impacts of target range on *WSE*

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