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Water balance modelling of alternate water sources at the household scale

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ABSTRACT

Alternate water sources are being implemented in urban areas to augment scheme water supplied by a water utility to homes. These sources include residential wells, rainwater tanks and greywater systems. Greater water efficiency can be achieved when these systems are designed to match a water source to a given demand based on both water quantity and quality parameters. In this way the use of an alternate water source can be maximised and the use of the high quality scheme water minimised. This paper examines the use of multiple alternate water sources sequentially to supply the same demand point potentially optimising the use of all available water sources. It also allows correct sizing of such water systems and their components to reduce scheme water demand. A decision support tool based on water balance modelling was developed that considers such water options at the household scale.

Application of this tool to eight scenarios for both large and small house lots shows that using alternate water sources individually can result in significant scheme water savings. However by integrating these sources additional scheme water saving can be made.

Key words: alternate water sources, modeling, urban water, water balance, water system design

INTRODUCTION

Urban water supply (scheme water) is mostly provided by large centralised water treatment plants and distribution systems. With increasing costs of water and new technologies available, alternate water sources are being taken up by many households to augment the scheme water supply. These sources include self-supply ground water as well as piped ground water supply (also referred to as dual reticulation or third pipe), recycled wastewater via third pipe, rainwater harvesting and greywater reuse for irrigation. All of these alternate sources of water can provide significant volumes of water to households if designed correctly and if the supply is matched to demand both temporally and quality wise.

Often alternate water systems are not well designed. This usually results in an increase in the cost of the alternate water source through higher capital costs. There are two situations where this regularly occurs. The first is the installation of large rainwater tanks in areas with a Mediterranean climate with rainfall mainly in winter and a long dry summer. Simple calculations show that there is a strong diminishing return when the size of the rainwater tank is increased. This is because the tank is generally full in winter and empty in summer. The size of the tank will determine how long it takes for the tank to empty from that change from winter to summer. Therefore if the tank is two cubic meters bigger, then roughly speaking that is the extra volume of water per year that can be utilised. As such larger tanks will generally only yield a reliable supply of a few percent greater than a small tank. The increase in yield will rarely justify the capital expense.

The second common area where poorly designed alternate water sources provide increased costs is in sizing the application area for greywater irrigation fields. If the irrigation area is oversized extra expense has been incurred in irrigating a larger area than there is available greywater. Plants will not receive sufficient water and will suffer resulting in either plant death or the requirement for supplementary watering from another irrigation system again adding to the costs. If the field is undersized the plants will receive too much water and again may suffer or die. If the irrigation area is too small, sufficient treatment of the greywater will not occur as it will travel too rapidly through Perth's generally sandy soil profile.

For alternate water systems to be truly effective they must be designed well and this involves water balance calculations based on the both the supply and demand side otherwise the result will likely be an ineffective and expensive water system.

A study has been undertaken to assess the opportunities that alternate water sources can provide to reduce scheme water use and to determine where and when the best use of the alternate water source is. This study considers a new approach of using an alternate source of water as a backup to the primary alternate source of water and assesses the merits of this. A water balance model is used to assess water supply and demands based on water demand/consumption data and to determine the scheme water savings. By running a water balance model, it can be identified where scheme water can be saved in the home and which source is the best to use to achieve the greatest savings. This paper reports on the results of this study based on 8 case studies in Perth, capital city of Western Australia (WA).

METHODOLOGY

This study aimed to determine the volume of scheme water that could be saved by utilising available alternate water sources. A model was developed that allowed alternate water sources to be substituted for scheme water for inhouse and exhouse demands. These alternate sources were greywater, rainwater and groundwater.

For the purposes of this study greywater is the water from the bath, shower and washing machine and can be treated to a suitable quality for application for irrigation and toilet flushing. It is assumed that 100% of the greywater produced is available to meet demand. Rainwater is available when there is water stored in the rainwater tank which is generally only during the winter months. Groundwater is assumed to be available all year round. This is generally the case in Perth due to the superficial aquifer below much of the metropolitan area. This aquifer is widely used by householders (approximately 30% of homes have a bore) for the irrigation of gardens during the summer months and is recharged with rainfall during winter months.

Eight scenarios were chosen with each demonstrating differing methods of using alternate water sources as a substitute for scheme water. Scenario 6 is the most complex of the scenarios and the priority of water uses is shown in Figure 1. The other scenarios follow the same water use priority but are simplified. Four of these scenarios are based on actual projects in the Perth area and these are described further below. Scenario 1 represents only scheme water use. Scenarios 2 to 5 represent recently constructed land (real estate) developments where alternate water systems have been applied to homes throughout the

development. Scenario 6 utilises all three alternate water sources to back up each other depending on the water quality required for a particular demand. For example the primary water source for the toilet is rainwater but it is backed up by greywater and then groundwater (refer Figure 1). Scenario 7 represents what could be described as current best practice with rainwater used for all inhouse demands except for kitchen, bathroom and laundry faucets and greywater and groundwater are used for irrigation. Finally Scenario 8 is presented as the outcome of analysis of the water balance calculations for effective use of the alternate water resources. It takes the most effective elements of Scenario 6 and removes the ineffective elements resulting in a much simplified scenario that still demonstrates significant scheme water reductions without the complexity.

Input data

Inhouse water demands were the same for each scenario and are based on an end use water study on about 1000 Perth homes by Loh & Coghlan (2003) (DWUS) which showed an in house water demand of 155 litres per person per day (L/p/d). Washing machine use was 42 L, toilet use was 33 L, bath and shower use was 51 L, leaks was 5 L and taps (faucets) was 24 L per person per day. For this study, the taps component was divided into 8 L for bathroom, 6 L for laundry, 6 L for kitchen and 4 L for external taps per person per day. Hot water use was estimated to be 37 L/p/d and greywater produced is 93 L/p/d.

It is expected that since the time the study was conducted (1998–2001) average household water demands would have been reduced for a range of reasons some of which are described

in Byrne et al. (2008). The most significant of these has been the ongoing uptake of water efficient fixtures since that time.

The occupancy rate was set at a relatively high 4 persons per household compared to the Perth average of 2.5 in the Greater Perth region (ABS 2006). The key reason for this was to comply with the Western Australian Code of Practice for the Reuse of Greywater (CoP) (DoH 2005) which requires that the greywater irrigation field required for a home be sized to effectively irrigate the volume of greywater generated by the number of people equal to the number of bedrooms plus one. Three bedroom homes make up approximately 35% of all homes in Perth with only 24% of those having four or more persons living in them. Four bedroom homes make up approximately 50% of all homes in Perth and of these only 20% have five or more occupants (ABS 2006). These statistics demonstrate that the CoP produces a less than optimal design outcome for the majority of greywater system installations. (Note that for the purposes of his study, irrigation refers to the watering of residential gardens.)

The two housing lot sizes that were chosen were 800 m² and 350 m² with the only difference being the irrigable area. The larger lot size represents the old larger lots that were common until the 1980s, while the smaller lot size represent both newer development lot sizes and the older lots that are subdivided to produce two lots. (These lot sizes concur with Gray 2003).

The irrigable area is calculated using data from GHD (2005) which determined the proportional areas of different land surfaces for lots for zoning densities of between R20 (20 lots per hectare) and R160 (160 lots per hectare).

The irrigable area for the lot consisted of two zones for the modelling. The first zone is that allocated to the greywater system with the size as specified by the CoP. The second is the remainder of the irrigable area. For the first zone the irrigable area was calculated using the total household greywater production (L/hh/d) divided by an application rate of 10 mm/day. The area for zone 2 was determined by subtracting from this the zone 1 area. The result was that the zone 2 irrigable area for the 800 m² lot was 410 m² and the zone 2 irrigable area for the 350 m² lot is 100 m².

The grey water system was based on a fully occupied 3 bedroom home (4 occupants) producing 372 L/hh/d of greywater and therefore requiring an irrigation area of 37.2 m² at an application rate of 10 mm/d. The irrigation system was not turned off during the winter months but instead only irrigated when the plants required it. A crop factor of 0.5 was used to determine plant water requirements.

Historic daily rainfall data from Perth airport was used as the rainfall data set. The roof catchment area was 100 m² with catchment efficiency of 90%, an adsorption coefficient of 0.2 mm/event and a tank size of 2500 L. The tank was assumed empty at the beginning of the simulation as the simulation started in the summer month of January.

The water balance modelling tool

Using an occupancy of 4 persons per household and the water demands outlined in Table 1, a water balance modelling tool was developed to determine the water usage of each water sources for the eight case studies.

The tool used a daily time step to balance water demands with supply from the rainwater tank and greywater system. Groundwater and scheme water were modelled as providing a continuously available supply. The tool included a rainwater tank simulator which used actual daily rainfall data local to that area and catchment factors to establish volumes of roof runoff and therefore volumes of water in the rainwater tanks on any given day. The greywater system was modelled based on the Code of Practice for Greywater Reuse (CoP) which outlines expected greywater production volumes (this document also uses water use data from Loh & Coghlan (2003)) and gives guidelines for irrigation areas to utilise the water.

To fully model greywater irrigation demands would require additional information on soil type, crop factors and climate factors. However the CoP prescribes what irrigation areas are required regardless of the aforementioned factors. Since this prescribed area is predetermined, optimising this area would not reflect what could be achieved in a real life situation. However modelling showed that for a three bedroom home with 4 occupants, the crop factor could not exceed 0.5 in order for the greywater produced to satisfy summer plant water demands. If higher crop factor plants are used additional scheme water will be required to maintain healthy plants in this climate.

Actual scheme water savings generated by the greywater system were determined to be only the proportion of greywater required to effectively irrigate the area prescribed by the CoP or required by the toilet demand (as in Scenario 6) and not the total volume of greywater produced. This was because much of the greywater produced (about 55%) does not replace scheme water as the plants do not require additional watering during rainfall events and for the period after rainfall until the soil starts to dry out. There can also be a proportion of

greywater produced that flows to the sewer and does not make it to the irrigation field. This proportion is dependant on several factors but in particular the physical design of the greywater unit. A significant cause of sewer flow from greywater systems is overflow resulting from overloading of the system such as when a bath is emptied or when the filters are blocked. This grey water is therefore of no net benefit to this water balance and is not considered as scheme water savings. It does have other benefits such as recharging the aquifer and reducing the load on the centralised wastewater treatment plant.

Therefore any grey water generated in excess to plant (and toilet) requirements (particularly relevant in the wetter months) was not counted as scheme saving water. This excess water could be dispersed throughout the rest of the irrigable area however this would involve dual reticulation (cross connection with greywater is not permitted) and switching the greywater between the irrigation zones for each season. Because of this added complexity it was not considered as an option in this study.

Kitchen grey water was not included in the calculation due to the extra treatment required by the CoP to utilise this water adding additional cost to the system.

Currently greywater reuse inside the homes is not permitted in Western Australia. Changing this to allow greywater reuse for toilet flushing either as the primary source or as a back up to rainwater would result in significant volumes of scheme water potentially being saved. In other states of Australia this use is already approved. The source is either treated wastewater via third pipe or household scale greywater reuse units. Such greywater units capable of toilet

flushing are already approved for irrigation use in WA. The approval in WA is dependent on satisfactory validation trials from coliphage testing currently underway. This testing was not required in other states.

Scenarios

Seven scenarios were selected to be modelled based on existing land developments where the water regime described has been applied to all houses within the development. The eighth is a result of the modelling outcomes. No scenarios were considered that required high cost treatment of water in order to meet the water quality requirements of a particular demand. Each of the scenarios is described below and Table 1 outlines the water sources used for the water demands in each scenario.

Scenario 1: Business as usual – The water use in this scenario is based on a study performed by Loh & Coghlan (2003) looking at the breakdown of household water demands. Scheme water is assumed to be the only source for this case study.

Scenario 2: This development of approximately 1500 homes extracts ground water from communal bores and delivers it to all the homes through a piped system. This water is used to irrigate part of the household gardens, streetscapes and public open space (POS). The advertising material states that this development will reduce total water consumption by around 30% from typical metropolitan household usage when combined with the built-in water conservation measures and reduce potable water use by 56%.

Scenario 3: This development of 380 homes has a piped system for groundwater to irrigate part of the household gardens, streetscapes and POS. In addition greywater from each home

is used to irrigate the remainder of the yard. Water efficiency measures are built in to homes before they are handed over to the client.

Scenario 4: This development of 266 homes uses small rainwater tanks for toilet flushing and for cold water laundry use. It also uses a piped groundwater network for external household use. They propose an 84% reduction in scheme water as a result of these initiatives.

Scenario 5: No groundwater is used at this site. Instead each home has two rainwater tanks. One is used for the washing machine, toilet and taps while the other is used to supplement the greywater system to irrigate a food producing (productive) garden.

Scenario 6: Integrated model - Uses fit for purpose water sources such as those described in the other case studies. This integrated model differs from the previous scenarios by using another alternate water source as a first or second backup rather than relying on scheme water as the first backup. This scenario is demonstrated in Figure 1. The following scenarios are variations of this scenario.

Scenario 7: Based on current best practice where rainwater is used as the primary source for all inhouse demands except the taps, greywater is used for zone 1 irrigation and groundwater for zone 2 irrigation.

Scenario 8: This is a simplified version of scenario 6 where only the secondary sources of water that made a significant contribution to reducing scheme water use was retained. The main features of this scenario are that greywater was used to back up the rainwater for toilet flushing and that groundwater was used to backup the greywater for irrigation zone 1.

Technology

In order to effectively supply three or even four water sources to a single fixture such as is the case for the toilet in Scenario 6, a large amount of additional plumbing is required. This would result in the cost of the system being prohibitive to implement. In order to achieve Scenario 6 outlined in this paper, a new piece of technology is required. The technology would be an extension of existing technology that switches water supply between two sources based upon availability of either source to supply a fixture or fixtures. The technology has a preference to use one water source over the other so that only when the preferred water source is unavailable the second source utilised. This new technology would use the same process with the exception that more than two sources can be used. A method of setting preferences for the water sources would be required.

RESULTS AND DISCUSSION

Figure 2 shows the results of the modelling. All scenarios used the same volume of water but they sourced the water for each demand differently. Scenario 1 used only scheme as a source and therefore used the most scheme water of all scenarios whereas Scenario 6 used the least amount of scheme water as it had multiple backups for the water demands with scheme water the last to be utilised.

It can be seen in Figure 2a and d that groundwater use can easily substitute at least 50% of total water demand because it can supply the large exhouse water demands. Greywater use made up about 24% of the exhouse water use. This is not because the greywater was not available but because the plants in irrigation zone 1 required the total volume of greywater

produced only in the peak summer period. The remainder of the year the entire greywater volume was not required. This water could be used for toilet flushing as in Scenarios 6 and 8 or for irrigation of some of zone 2 in the cooler months reducing groundwater demand. Care needs to be taken though as peak summer zone 1 plant demand will require the majority of the greywater available and distributing the greywater further at this time will result in plant stress. This is demonstrated in Figure 3 where summer demand nearly matches the volume that can be supplied.

The best approach to reducing groundwater use would be to reduce the irrigable area and improve the ability of the garden to cope with less water. The modelled irrigable area of 410 m² for the large lots was bigger than the entire area of the small lots at 350 m² which is a significant area to irrigate at a crop factor of 0.5. Choosing low water use plants with an average crop factor of 0.3 or less would mean that a significant proportion of the groundwater could be saved.

Inhouse water use for Scenario 6 consists of a combination of all water sources. Most of the greywater and groundwater used internally is for toilet flushing with some groundwater used for exhouse taps. In Scenario 8 groundwater was not used in the home yet this only marginally increased the volume of scheme water used. This reiterates the above point that a good use of the extra greywater is for toilet flushing. The volume of greywater used in the toilet in Scenario 8 is 18.3 kL/a or 8% of total inhouse demand. This greywater is unusable in the wetter months for irrigation but can be utilised in the toilet presuming suitable treatment is achieved. There are currently two units approved in Western Australia capable of treating to this level.

For both large and small lots rainwater can significantly contribute to reducing inhouse scheme water use. Rainwater contributed about 24% of inhouse water use which is in line with other published data on rainwater use (e.g. Coombes & Lucas 2006¹/₄17% of total water use, Gray 2003¹/₄up to 30%).

The total scheme water savings for each scenario is presented in Tables 2 and 3. Of note is that inhouse savings are a minimum of 21% where rainwater is used internally. Scenario 7 which is seen as current best practice can reduce inhouse use by 24% however by backing up the toilet with greywater this saving can be increased to 33% as in Scenario 8. This represents a significant saving of scheme water.

CONCLUSIONS AND RECOMMENDATIONS

Current end use water data for Perth homes is now almost 10 years old and there is anecdotal evidence to suggest that in that time there have been significant changes to the volumes of water consumed by Perth residents due to behavioural and attitudinal changes and appliance water demands. As new data becomes available the results of the modelling will improve, resulting in a clearer picture of domestic water use and the opportunities to reduce scheme water consumption.

The current approach of implementing alternate water sources is generally limited to backing up rainwater for toilet and washing machine use with scheme water and the use of greywater for garden irrigation. This arrangement will reduce inhouse scheme water by 21% based on standard water use figures (scenario 4). This research has shown that significant improvement

in scheme water reduction can be achieved by selecting other ways to use alternate water sources. If all the water demands outlined were backed up with alternate water sources then 38% of internal scheme water use can be saved (Scenario 6). However this is a complicated system and is therefore not considered practical at this time (refer Figure 1). If rainwater was used for all non-potable inhouse demands backed up only by scheme water then 24% of inhouse scheme water use could be saved (Scenario 7).

However if the rainwater supply to the toilet was backed up by greywater then 33% of inhouse scheme water use could be saved (Scenario 8). This is nearly as good as the complicated Scenario 6 but without the expense and represents an extra 18 kL/hh/a of greywater that is not discharged to the sewer network or the ground but is reused and replaces scheme water.

The key advantage of greywater to toilet flushing is that this becomes a permanent year round water savings and reduction to sewer flow thereby in the long term and with wider take up leading to reduced demand on centralised infrastructure. With only seasonal reuse of greywater or treated wastewater (i.e. summer irrigation) there will not be a basis for reduced centralised infrastructure. This has particular relevance to wet weather sewer flows.

As technologies continue to improve in both efficiency and cost, and as both the consumer attitude and policy changes adapt to these technologies, more scenarios will inevitably become available for future analysis resulting in more opportunities to substitute high quality scheme water with fit for purpose water sources.

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Figure 1: Scenario 6 flow diagram. For toilet, for example, Rw is used first and only if necessary Gyw, then Gdw and finally scheme water. Where: HW ¼ hot water; Rw ¼ rainwater; Gyw ¼ greywater; Gdw ¼ groundwater; w/m ¼ washing machine; z1 ¼ zone 1 (greywater); z2 ¼ zone 2; Sw ¼ scheme water; Irr ¼ irrigation.

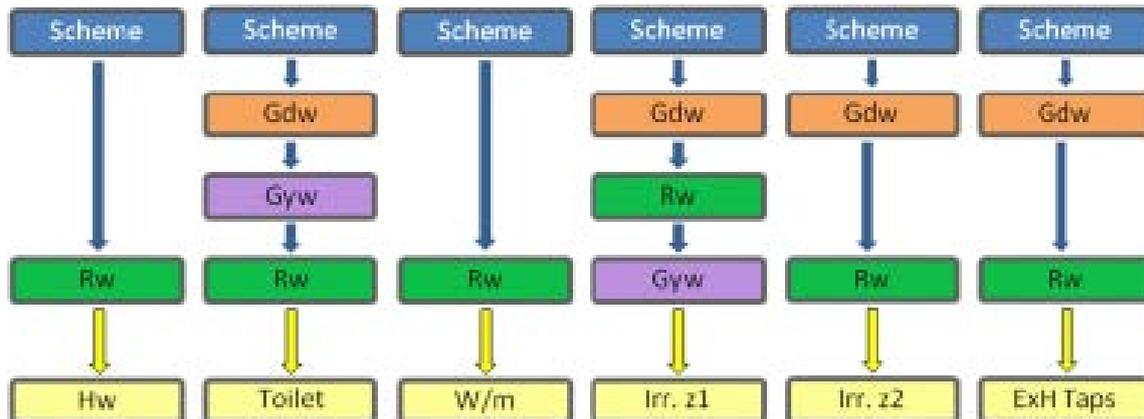


Figure 2: Modelling results.

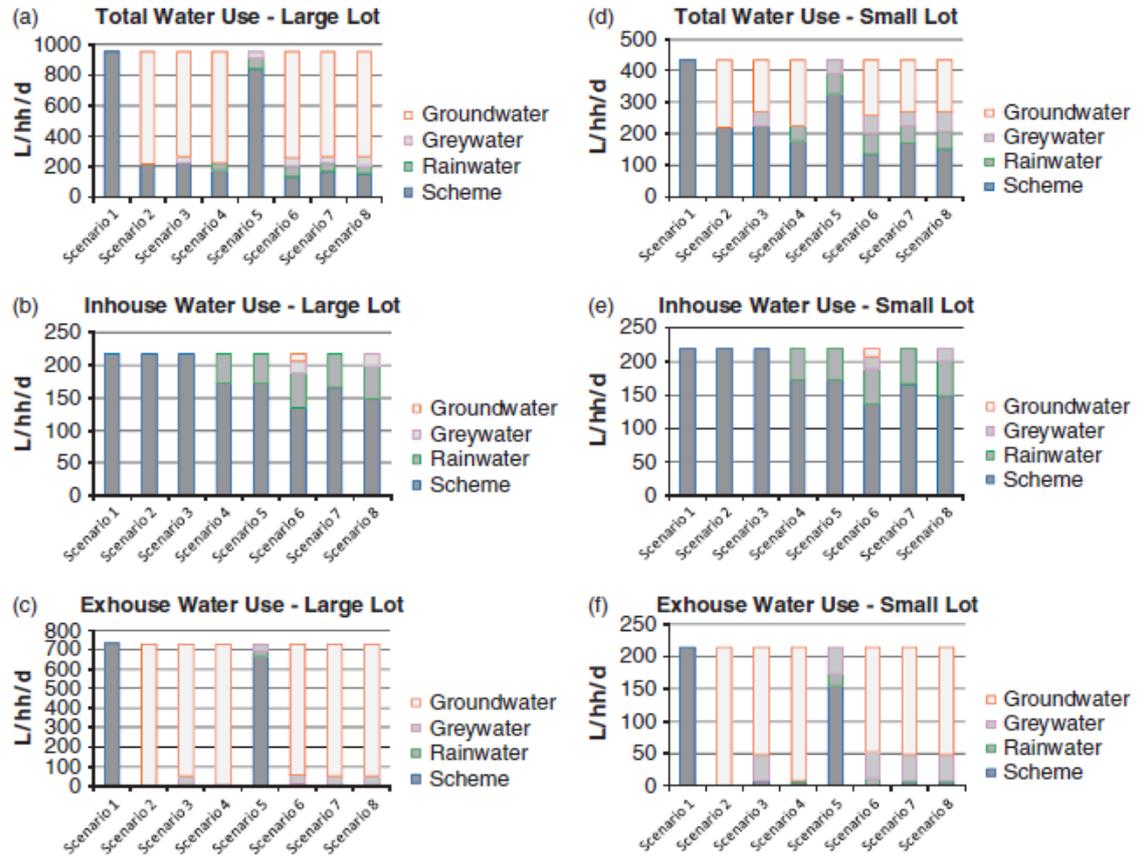


Figure 3: Demand and supply of greywater for irrigation.

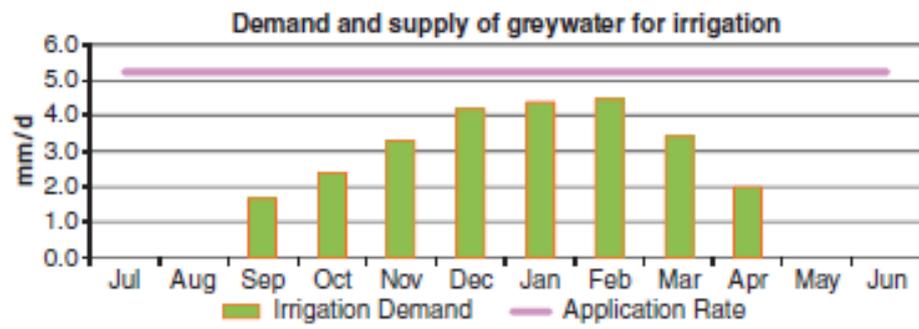


Table 2: Percentage scheme water reductions for large lots

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8
Total scheme water saved	0	77	76	81	11	86	82	84
Inhouse scheme water saved	0	0	0	21	21	38	24	33
Exhouse scheme water saved	0	100	99	99	8	100	99	99

Table 3: Percentage scheme water reductions for small lots

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8
Total scheme water saved	0	49	48	59	24	69	61	65
Inhouse scheme water saved	0	0	0	21	21	38	24	33
Exhouse scheme water saved	0	100	97	98	28	100	98	98