ENVIRONMENTAL IMPACTS OF GREYWATER USE FOR IRRIGATION ON HOME GARDENS

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ABSTRACT

This study focuses on the feasibility and environmental impacts of using raw domestic greywater from laundry and bathroom after only primary treatment, e.g. coarse filtration for irrigating lawns and gardens. The use of greywater for landscape irrigation requires careful management, especially in regions with sandy soils and shallow groundwater levels. There is the possibility that excessive nutrients and other contaminants will leach into surrounding water bodies. This has been a major concern with greywater use in ecologically sensitive environments, such as on the Swan Coastal Plain of Perth, Western Australia. Proper management is essential to ensure environmental risks from greywater irrigation are avoided.

The main purpose of the first stage of the study was to develop a new zero-tension lysimeter (ZTL) as a leachate sampler in a greywater irrigation plot. The new ZTLs were tested to compare the quantity and quality of leachate collected with that from the conventional pan lysimeter, in a pilot-scale study. The results indicate that the new lysimeter designated as ZTL (N1), was effective at collecting leachate and was suitable to install at household sites. The lysimeter ZTL (N1) design offers significantly improved performance, was cost-effective and required limited effort to install using an auger, which also minimizes soil disturbance. Since the lysimeter was practical and inexpensive it was established to facilitate the monitoring of greywater irrigation.

The second stage of the study was to monitor the use of primarily treated greywater by using diversion system from bathrooms and laundries at four Perth houses: two houses at the Bridgewater Lifestyle Village (BWLV), one each at White Gum Valley and Hamilton Hill. Each house had different characteristics: different house types, occupants, cleaning product preferences and presence, or not, of household pets. Water use activities, soil and vegetation were monitored and were sampled for physical and chemical characteristics. Groundwater samples at the BWLV site were also collected. This site has 389 houses with a greywater diversion system installed in each, is located close to the Peel-Harvey estuary and a wetland, and has a shallow aquifer. Monitoring results showed that the groundwater samples were within the ANZECC guidelines. Greywater quality showed high variability depending on water consumption by washing machines, use of detergents and fabric softeners, as well as individual lifestyles. Land activities such as fertilizers and pets were expected to contribute to high amounts of nutrients in the leachate. Mulching and fertilizer used by householders in conjunction with greywater irrigation improved the function of soil and condition of plants.

The third stage of the study was to determine the effects of raw laundry and bathtub greywater irrigation on the growth of couch grass (*Cynodon dactylon L.*) sod on a sandy soil in a 24-week study, from October 2009 to March 2010. In Perth, the use of greywater is significant during these months as rainfall is at its lowest and irrigation demand at its highest. Couch grass is a common lawn used in Western Australia with excellent drought tolerance, water efficiency and relatively low maintenance requirements. Three irrigation treatments were applied using a modified aquarium tank: (i) 100% scheme water as a control (TW), (ii) untreated full cycle laundry water (LGW), (iii) untreated bathtub water (BGW). Salts and nutrients Na, Cl, P, Ca, Mg, K, B, Zn and Al were chosen for measuring because they are dominant constituents in greywater and have a beneficial role in turf grass growth. Their dynamics and mass balance were assessed by measuring the irrigation (input) and leachate (output) volumes and concentrations of element concentration in both input and output water of the tank. Irrigation using LGW and BGW in sand resulted significant leaching of some Mg and Al beyond the 30cm root-zone depth. The mass balance showed an increased amount of stored Na, Cl, P and K in the soil at the end of the study. The accumulation of salts and nutrients in the soil has resulted in the infiltration rate, K, gradually declining.

The final stage of the study was to investigate further the significant reduction of K in the tank test. Another soil hydraulic property, capillary rise (P_c), was also measured. The soil samples were collected from greywater-irrigated plots at the case studies and the tank test, as mentioned previously. In addition, the study examined the changes in soil properties from the use of an anionic surfactant, *linear alkylbenzene sulphonate* (LAS) which is known to be the main ingredient in detergent formulation. A commercially available surfactant-based wetting agent to alleviate water repellency in household gardens was also considered. Irrigation with raw laundry and bathtub greywater, application of LAS and a wetting agent made a significant reduction on infiltration rate, K, and on P_c. At the case study sites, the changes were difficult to quantify owing to various land activities that influenced the result.

The results of the extensive experimental on-site program indicated that the use of primarily treated greywater is a viable option to conserve water for irrigation during times of drought and water restrictions. The sustainable use of raw greywater would vary with specific site conditions and householder practices. Soil and plant quality parameters are significantly affected after continuous irrigation with greywater. This is mainly determined by the management regime of greywater irrigation and its composition. In addition, continuous irrigation with greywater may lead to accumulation of salts, plant nutrients and some nutrients beyond plant tolerance levels. Therefore, these concerns should be essential components of any management plan for greywater irrigation. On the other hand, plant growth, soil fertility and productivity can be enhanced with properly managed greywater irrigation, through increasing levels of plant nutrients and soil organic matter. It is suggested that proper management of greywater irrigation with periodic monitoring of soil fertility and quality parameters are required to ensure successful and safe long-term use of greywater for irrigation. The adequate assessment of any environmental risks will require further research.

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CHAPTER 1

INTRODUCTION

1.1 THE NEED FOR GREYWATER REUSE

The world's freshwater sources are threatened by climate change. Scientists around the world agree that recent climatic changes occurring globally are the result of human activities (Parry *et al.*, 2007). Rising global temperatures lead to an intensification of the hydrological cycle and heightened risks of more extreme and frequent floods and drought. By the early 21st century, there are already acute water shortages in large parts of Australia, Asia, Africa, and the United States. In Perth, Western Australia (WA), winter rainfall has declined by 15% since 1975, reducing run-off into metropolitan dams and estuaries by more than 50% (Barron, 2008). This has resulted in extremely high water demand between the growing city and nature requirements.

With water restrictions in place, people are looking for ways to reduce their water consumption. According to the Perth Domestic Water Use Study (Loh and Coghlan, 2003), water used outside the house typically makes up between 50 and 80% of total household water usage. Strategies and programs are being established to promote water as a precious resource, incorporating the smart and efficient use of it, one aim being to "ensure that all available non-potable wastewater is being used appropriately" (WA Govt., 2007). This, combined with an increasing community interest in water conservation, has led to recycling of wastewater. The *State Water Plan WA* set a target of recycling 20% of its wastewater by 2012, the current level being 12.5%. Among these strategies, greywater has gained attention as a resource, owing to its low level of contamination compared to blackwater, because of the exclusion of toilet water. Moreover, greywater enables water provision to be 'climate independent'.

The common definition of greywater is as wastewater derived from the bathroom and laundry but not the toilet. Greywater includes kitchen wastewater (DOH, 2010), but it may pose an unacceptable risk from pathogens contamination (Casanova *et al.*, 2001), unless it is treated before reuse DOH (2010). It has been found that if all wastewater from all possible sources is recycled a significant amount of fresh water can be saved (DOH, 2010; Jeppesen, 1996). Such savings may also be made to wastewater discharge to council sewers (Radcliffe, 2006). The need to apply fertilizer to gardens and lawns may be partly satisfied by greywater (WHO, 2006). In Jordan, using greywater has become a component of a poverty alleviation strategy (Faruqui and Al-Jayyousi, 2002; Bino *et al.*, 2010).

Greywater use for irrigation is recognized around the world in many countries, indeed as early as the 19th century in Santa Barbara, USA (Al-Zu'bi and Al-Mohamadi, 2008). Although studies have shown greywater could be used for irrigating edible crops -- tomato (Misra *et al.*, 2010; Al-Zu'bi and Al-Mohamadi, 2008); lettuce, carrots, peppers (Finley *et al.*, 2009); silverbeet (Pinto *et al.*, 2010) and for household lawns and gardens (Al-Jayyousi, 2003), studies on its interaction with the environment are limited. Still, the leaching of salts and other chemicals from greywater sourced from the laundry has been examined (Misra and Sivongxay, 2009).

On the basis on what is known to date, use of greywater has been considered to have potential as a water management option for the countries with inadequate fresh water supplies. It has therefore been promoted as a strategy to address water scarcity.

1.2 CHALLENGES OF SUSTAINABLE IRRIGATION WITH GREYWATER

A major problem with the use of greywater for irrigation is the widespread use of it, untreated, for watering the lawn and garden. The WA Code of Practice of the use of greywater specifies that untreated greywater can be applied manually, by using a bucket to collect water from the bath or shower or by a diversion system to water lawns and gardens, without a permit from the council (Maxey, 2005; DOH, 2005, 2010). Greywater regulation has been developed mainly to safeguard public health. Despite the regulations, the increasing use of greywater on gardens has become unsustainable (Maimon *et al.*, 2010), because of the increasing number of household chemicals (Eriksson *et al.*, 2009).

The use of unknown quantities and combinations of chemically complex cleaning products from the negligent homeowner causes excess salts, nutrients and pollutants in soils. For instance, Carden *et al.* (2007) reported that soil salinity increased as a result of long-term disposal of greywater in a non-sewered area in South Africa. The infiltration, hydraulic conductivity and aggregate stability of the soils have been affected (Misra and Sivongxay, 2009). In addition, the disposed contaminants into waterways or leaching into shallow aquifer may adversely affect the environment. The heavy usage of chemical pollutants, for example, boron from laundry detergents, can be toxic to plants while surfactants can alter soil properties if highly concentrated (Redwood, 2010). Synergistic effects may also occur when a plant receives unacceptable levels of nutrient for plant growth, leading to the imbalance of nutrients.

Conditions such as dry continents and sandy soils pose particular challenges for water and nutrient management for plants, because of the relatively low water-holding and nutrient-retention capacities of these substrates. There is concern with the long-term sustainability of the dedicated irrigation areas due to high P loading, which can be up to 120 kg P/hectare/year (Beal *et al.*, 2008) and the high salinity of greywater (Al-Hamaiedeh and Bino, 2010; Wiel-Shafran *et al.*, 2006). Furthermore, the imbalance of greywater irrigation and rainfall with high evapotranspiration rates and insufficient biological uptake for decomposition may possibly leach the excess nutrients or constituents to the groundwater and waterways.

Having established that greywater can be an effective resource for irrigating lawns and gardens but pose an environmental threat under certain circumstances, this dissertation commences by identifying the major elements that are causing environmental deterioration.

1.3 SCOPE AND AIMS OF THE RESEARCH

The aim of this thesis is to investigate:

The effects of the use of either primary treated or raw greywater on soil and plants.

The objectives of this study are to:

- establish an effective lysimeter to measure the migration of nutrient and chemical constituents from greywater irrigation in household gardens, and
- assess the greywater effluent quality, chemical characteristics of soil and plants and possible leaching of nutrient in the soil in case studies of four different types of household in Perth, Western Australia, and
- evaluate, through a soil tank test, the potential effect of three different types of irrigation water: tap water (TW), laundry greywater (LGW) and bathtub greywater (BGW), on the soil and on the growth of turf grass, and
- determine, the efficiency of the use of wetting-agent-based surfactant through the soil hydraulic conductivity measurement as affected from greywater irrigated soils.

1.4 THESIS STRUCTURE

The above objectives have been studied through three major experiments and one year monitoring four case studies, which are elaborated in the following chapters.

Chapter 2 is a review of the current literature, describing major environmental problems when reusing greywater.

Chapter 3 is the establishment of sampler prototype, conducted in a pilot study, to use as a monitoring tool in household gardens irrigated with greywater. This chapter attemps to answer with some certainty the following question:

Can a zero tension lysimeter or leachate sampler be improved in design so that it can be installed in house gardens with a minimum of soil disturbance and be large enough to collect a representative sample?

Chapter 4 gives the results of a monitoring campaign which investigated the variability of greywater quality from four different houses, the effects on the soil and plants, and leachate collection using lysimeter. This chapter attemps to answer with some certainty the following questions:

Are the variety of chemicals, preferences of householders and greywater maintenance systems reflected in the chemical quality of greywater, are the chemicals harmful to plants, and do they build up in the soil as a result of greywater irrigation?

Is there any potential effect of greywater that will be detrimental to the shallow groundwater?

Chapter 5 describes the tank experiment which seeks clear answer to whether or not constituents in raw greywater from laundry and bathtub accumulate in soils in sufficient quantities to harm turf grass, or are transported below the root zone to groundwater. This chapter attempts to answer with some certainty of following question:

Will a turf grass that is irrigated with raw greywater remain healthy? What are the changes in plant and soil chemistry properties?

Chapter 6 is a further investigation of soil hydraulic conductivity based on the significant finding of its reduction during the tank experiment in Chapter 5.

Chapter 7 is a general discussion on the significant effects of using greywater on soil and plants and limitations to greywater irrigation.

Chapter 8 contains the conclusions and recommendations for further research based on the present findings.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The UN's climate change panel (IPCC) stated that the world's current population of about 6.6 billion is forecast to rise by 2.5 billion by 2050. As human population increases, the need for water also increases in domestic, agricultural, industrial and urban sectors. Consequently, water or “Blue Gold” is widely predicted to be a critical resource. In 2009, the symposium on water security organized by the World Water Organization warned that two-thirds of the world's population will face water shortage by 2025 (Grey and Connors, 2009). This is partially attributed to climate change where dry seasons are prolonged, less rainfall is recorded and events of extreme droughts become more common in certain areas around the globe. These patterns have significant impacts on the availability of water.

The terrifying consequences of a global water shortage could be mitigated by implementing a wise water management policy. As a result, it becomes necessary to assess the potential of reusing treated wastewater to cope with the supply of and demand for potable water. In Australia, wastewater reuse is not a novelty and has been receiving increasing attention since the early 1990s, when new water policies and resource protection legislation were adopted (Radcliffe, 2006). In countries experiencing arid and semi-arid climates, wastewater reuse is becoming necessary as a supplement to existing water sources. Most large-scale reuse schemes are in Israel, South Africa, and arid areas of USA, where alternative sources of water are limited (Asano, 1998). However, the quality of wastewater reuse has raised concern with regards to public health risk within the community. This, along with the cost of the system has always been hotly debated among researchers, politicians and institutions and is possibly limiting the further uptake of this technology.

However, there is a general consensus that the health risk from greywater use is much lower than from household wastewater, since it comes from light wastewater sources such the laundry, bathtub and shower. California, for example, has been using treated greywater for subsurface irrigation for many years, and has yet to show any health problems associated with its use (Vigneswaran and Sundaravadivel, 2004). In Australia, scarce water availability in some regions of Victoria has prompted the interest in bathroom and laundry greywater recycling for garden irrigation (EPA, 2008) and the efficiency of this system has been tested (Christova-Boal *et al.*, 1996; Namdarian, 2006).

Maintaining a reliable source of greywater use is important for ongoing success and livelihood in communities. Improving water resource development and management is a critical factor for meeting the Millennium Development Goals (MDG) (Madungwe and Sakuringwa, 2007). Greywater reuse will benefit the economy and social fabric by providing a water supply for non-potable uses. This chapter will review the environmental effects associated with the use of greywater for household irrigation, and its application as a feasible option for plant irrigation.

2.2 WATER SCARCITY

Water scarcity currently affects many regions of the world. For example, in Tannoura, Lebanon, women in particular have suffered severe water stress, since they are in charge of water collection over long distances and carry heavy containers to provide for their family's water needs (Allen *et al.*, 2010). In water-rich countries, urbanization and industrialization have frequently led to contaminated and deteriorated surface water and groundwater such that these countries are unable to meet the ever-increasing water demands. In arid and semi-arid regions, where the human populations are constantly subjected to water stress, wastewater reuse has played a major role in meeting domestic and irrigation demands. In most Australian cities, water restrictions have been in place since 2003 and water efficiency programs implemented as an attempt to sustain water supplies (www.mdbc.gov.au). Thus, in spite of seeming abundance, water scarcity is endemic in most parts of the world.

Indeed, uncertainty with regards to climate change is the biggest challenge in assessing future water supply. Man-made activities affecting climate change on water resources can already be seen. In the global arena, IPCC has classified that the area of land as 'very dry' and it has more than doubled since the 1970s (Parry *et al.*, 2007). This has often been accompanied by greater flooding events in the mid-high latitudes and longer and more frequent droughts in parts of Asia and Africa. All of these factors affect the balance between the demand for and supply of water.

2.3 GREYWATER AND ITS REUSE POTENTIAL

In countries with large sources of capital, manipulating of existing supplies to cope with water stress often occurs. For instance, desalination technology has been documented in UAE, Israel, Australia, Cyprus and in the US. In Singapore, desalination is projected to meet 30% of water demand in order to fulfil the country's future needs after the long-term water supply agreement with Malaysia expires in 2061 (Hock and Kesavapany, 2006). Dual reticulation systems have been observed where recycled water is used as an alternative water supply in residential areas. The Rouse Hill project in New South Wales is the largest residential dual reticulation wastewater reuse scheme in Australia (Pigram, 2006). According to Sinclair *et al.* (2010), an evaluation of public health concluded that the reuse of recycled water was quite safe. However, major obstacles are the high energy consumption required coupled with the need for specialized and expensive infrastructure, which has prevented further implementation. These factors result in the cost of delivering recycled water to be higher than the cost of water itself (Crase, 2008).

Redwood (2010) pointed out that the simplest way to conserve water is by optimizing wastewater derived from home sources. Less energy and chemical costs are some advantages of on-site greywater reuse. Greywater provides a consistent resource as constant amounts of greywater are generated from the laundry, shower, laundry tub and bathtub in household's daily routine, independently of the weather. Birks *et al.* (2003) observed up to 36% of individual household water consumption was saved by fitting a greywater recycling system in five single houses in Aylesbury, UK. In Israel, using Rotating Biological Contactor

(RBC)-based greywater reuse systems in multi-storey buildings became economically feasible only when the building size exceeded eight storeys (Friedler and Hadari, 2006).

2.4 GREYWATER REUSE FOR IRRIGATION

The main municipal application of centralized wastewater reclamation and distributed water reuse are agricultural land, golf courses and urban landscape irrigation. The practice of reclaiming wastewater is common in the US. An estimated 2.6 billion gallons of water per day (9.8 Gl/day) is reused in the US (Miller, 2006). In Israel, more than 70% of its treated wastewater is reused for agricultural irrigation (Jimenez and Asano, 2008). In water-scarce countries like Saudi Arabia, Cyprus, and Jordan, wastewater reuse is now part of their overall water irrigation plan. Even countries that are not typically considered to be scarce in water, such as the UK, Canada, Japan and Germany, are also at the forefront of centralized wastewater reuse technology implementation (Jimenez and Asano, 2008).

Decentralized greywater use for irrigation is a growing practice in individual homes, clusters of homes, or isolated industries and institutional facilities. In 2009, California modified its plumbing code to allow the reuse of certain types of greywater in households (California, 2009). Australia is the most progressive country in terms of greywater policy. This dry continent not only promotes greywater reuse but provides rebates for systems that recycle greywater from showers, laundry troughs, baths and sinks to irrigate outdoor plants (DOH, 2010). In Jordan, the use of greywater in poor rural areas in Tufileh can save 44% of the family expenditure on irrigating home-grown garden produce. Some families generate additional income by selling surpluses (Faruqui and Al-Jayyousi, 2002; Bino *et al.*, 2010). In sub-Saharan Africa, the role of greywater recycling provides supplementary nutrients, assisting plant growth and helping the landscape to flourish (Madungwe and Sakuringwa, 2007).

Raw greywater and primary treated greywater are more often used to irrigate lawns or ornamental gardens. DOH (2005) recommends that greywater use should be avoided on acid-loving plants, as most greywater is slightly alkaline owing to the presence of soaps and detergents. For crop irrigation, the reuse of greywater after some treatment is recommended. Studies have suggested that plant growth is improved when using irrigated greywater, instead of scheme water (Misra *et al.*, 2010; Pinto *et al.*, 2010; Finley *et al.*, 2009). For example, the use of treated greywater in the Karak project in Jordan has proved to be suitable for crop irrigation. Results showed that the chemical properties of treated greywater from households on irrigated olive trees and vegetable crops was not detrimental (Al-Hamaiedeh and Bino, 2010). However, as pointed out by Novotny *et al.* (2010), the nutrient value of greywater is generally lower than plants require for optimal growth, therefore certain plants might adding commercial fertilizers to defy the purpose of greywater reuse.

Mulch basin, its role in greywater irrigation

In greywater practice, the use of mulch is important as a direct composting system. A mulch basin is usually a donut shaped pit that circles a tree or shrub and is filled with mulch. Mulch is usually made from wood chips but can be composed of a variety of organic material such as manure, grass clippings, leaves, hay and straw. Mulches serve as good medium for the conservation of soil moisture and the moderation of soil temperature. Generally, mulch covers greywater so that any particles like lint, hair, etc. cannot clog small holes as shown in **Figure 2.1**. Hair, lint and other small organic particles are composted in the mulch.

Therefore, it is highly recommended to provide mulch (Hemenway, 2009; Ludwig, 2004) when using greywater for irrigation. This system is Art Ludwig's (Oasis Designs www.oasisdesign.net, retrieved on 25 July 2009) preferred method of delivering raw greywater as there is no risk of clogging irrigation systems, hair and lint simply becomes compost, there is no need for filters and hence cleaning filters. Namdarian (2007) added that the mulch acts as a sponge, soaking up the water and then slowly releasing it; it also acts as a medium for good nutrient-consuming bacteria.

Figure 2.1. Topped mulch when using greywater (purple driplines)

2.5 LAUNDRY AND BATHROOM GREYWATER QUALITY

Generally, laundry greywater contains high chemical concentrations as a result of detergents and soiled clothes (Na, PO_4, B, surfactants, NH_4^+, and N) and is high in suspended solids (SS), lint, turbidity and oxygen demand. Common washing powders contain Na salts as bulking agents (up to 30%), which generate saline greywater. A typical detergent may contain surfactants, builders, enzymes, fabric whiteners, and bleaches. **Table 2.1** shows the main ingredients of a laundry detergent along with their functions and weight percent.

Table 2.1. Typical ingredients in laundry detergents (Roesner, Qian *et al.*, 2006)

Group	Functions	Component	Weight Percent in Liquid Detergents	Weight Percent in Powdered Detergents
Surfactants	Binding hardness cations (mainly calcium and magnesium) and form micelles that help to remove hydrophobic stain	Anionic (LAS, AS, AES)	15 – 30	15 – 25
		Nonionic (AE)	0 – 15	0 – 5
Builders	Breakdown large water-insoluble molecules into smaller	Zeolite	–	20 – 30
		Citrate	0 – 10	0 – 5
		Polycarboxylate polymers	–	0 – 3
		Carbonate	–	8 – 25
		Sodium Silicate	–	1 – 3
Sodium Sulfate	As a filler		–	10 – 25
Enzymes	Removing starch-based stains (amylase), some are used in removing oil and grease (lipase)		0 – 1.5	0 – 3
Fabric Whiteners	Enhance the Brightness of light-colored fabrics		0 – 0.5	0.1 – 0.5
Dye binders	Maintain fabric colour		–	–
Bleach	Kill germs and act as a whitening agent	Percarbonate	–	0 – 5
		Activator	–	0 – 5

Bathroom wastewater (hand basin, shower and bath) is considered to be the least contaminated type of greywater with soap being the most common chemical contaminant. Although soaps are usually biodegradable, Madungwe and Sakuringwa (2007) stated that soaps contribute pollutants to the water, such as sulphates and chlorides which causes scum formation in hard water; some of which persist for considerable time before biodegrading completely. Other chemicals originate from toothpastes, hair dyes, shampoos and cleaning chemicals.

The chemical and physical quality of greywater compared with raw sewage is shown in **Table 2.2**. The high variability of greywater quality is due to factors such as source of water, water use efficiencies of appliances and fixtures, individual habits, products used (soaps, shampoos, detergents) and other site specific characteristics (DOH, 2005).

Generally, the physical and chemical characteristics of greywater from laundry and bathroom without kitchen sources are similar to those of diluted wastewater (Christova-Boal, 1996), which makes it a more attractive option for reuse among householders. This is mainly due to its COD to BOD_5 ratio which is usually around 4:1 (Jefferson *et al.*, 1999). The levels of pathogens and nitrogen were found to be lower in greywater as compared to wastewater due to the exclusion of toilet waste. According to Winward *et al.* (2008), the organic composition and suspended solids, or particles, in a low-load greywater are expected to originate from the human body during bathing.

Table 2.2:Typical composition of greywater compared with raw sewage (DOH, 2005)

Parameter	Unit	Greywater[a]		Raw Sewage
		Range	Mean	
Suspended Solids	mg/L	45-330	115	100-500
Turbidity	NTU	22- >200	100	NA
BOD_5	mg/L	90-290	160	100-500
Nitrite	mg/L	<0.1-0.8	0.3	1-10
Ammonia	mg/L	<1.0-25.4	5.3	10-30
Total Kjedahl Nitrogen	mg/L	2.1-31.5	12	20-80
Total Phosphorus	mg/L	0.6-27.3	8	5-30
Sulphate	mg/L	7.9-110	35	25-100
pH		6.6-8.7	7.5	6.5-8.5
Conductivity	mS/cm	325-1140	600	300-800
Hardness (Ca & Mg)	mg/L	15-55	45	200-700
Sodium	mg/L	29-230	70	70-300

[a] Based on Jeppersen and Solley (1994)
NA- Not Applicable

Although greywater is thought to be poor in nutrients, some detergents contain high amounts of phosphate and boron. The concentration of Na ranges from 200 to 700 mg/L in many laundry powder detergents (Handreck, 2008). In Germany, *phosphate*-free detergent was introduced in 1986 (Jacob and Wirtschaftsforschung, 2005) to protect surface waters from eutrophication. Greywater from laundries that use detergents containing boron in the range of 0.5 - 3.0 mg/L (Handreck, 2008) is harmful to plants. In Israel, an agreement was reached with Israel's detergent manufacturers to restrict boron content in household detergents (ha-sevivah, 1998). Other constituents include chloride, which is derived from salts used in dishwashers and for refreshing ion-exchange columns.

Another substance that needs to be considered is surfactant, which is commonly found in greywater, and is the most abundant organic chemical source in municipal greywater (Abu-Zreig *et al.*, 2003). Surfactants are organic molecules consisting of hydrophilic and hydrophobic groups. Anionic surfactant is the largest-volume synthetic surfactant, used in the manufacture of household detergents and cleaners industry (Jacobsen *et al.*, 2004). Surfactants reduce the surface tension of the water so that it can wet fibres and surfaces. They loosen and encapsulate the dirt, and in that way ensure that the soiling will not re-deposit on the surfaces. Although surfactants are used as a less toxic substitute for soap in laundry detergents (Smulders *et al.*, 2002), they are found in numerous household cleaning and personal care products and therefore are dominant source of the xenobiotic organic compounds (XOCs) found in greywater.

2.7 GREYWATER REUSE SYSTEMS

Greywater reuse systems range from simple direct diversion systems (either gravity-fed or pumped) that redirect untreated greywater from wastewater pipes to the garden, to filtration and disinfection treatment systems and more sophisticated technologies such as reverse osmosis. In Australia, the costs of these units typically range from $400 for simple direct diversion systems through to $15,000 for higher-end systems with storage capacities. To a certain degree, the variation in the cost of these systems correlates with their effectiveness and reliability at providing irrigation.

In Western Australia, greywater use can be used without treatment, such as bucketing. However, direct disposal of untreated greywater may be an unnecessary health risk. It is therefore and greywater treatment systems (GTS) are recommended that greywater is treated before reuse for irrigation (DOH, 2010).

Greywater treatment can be classified into four different categories as described in **Table 2.3**. Implementation of greywater systems in Western Australia are discussed briefly including local and state government approval, installation at each home, rebate acquisition, and ongoing maintenance as depicted in **Figure 2.2**.

Table 2.3. Typology of greywater treatment

Type of treatment	**Description**	**System category**	**Typical reuse application**
Raw greywater	No treatment	Bucketing	Pouring on to back garden beds, lawn
Primary filters/ diversion units	Greywater is treated using coarse screening filters. This can often be achieved using inline systems where irrigate directly as it is received and require no storage is provided.	GDD	Subsurface (dripline) irrigation or absorption trench
Secondary units (mechanical)	A secondary level of treatment is achieved using a simple and generally compact packaged treatment plant. Storage of the greywater is required.	GTS	Subsurface irrigation; or spray irrigation with additional disinfection treatment.
Secondary units (land based)	A secondary level of treatment is achieved using amended soil filter, sand filter, constructed wetland or reedbed spread over an area of land.	GTS	Subsurface irrigation; or spray irrigation with additional disinfection treatment.
Advanced units	An advanced or tertiary level of treatment is achieved using biological, physical and chemical processes e.g. media or membrane filtration as well as chemical dosing, precipitation and sludge removal, and disinfection.	GTS	Subsurface irrigation, spray irrigation, toilet flushing, washing machines.

Abbreviation: GDD- Greywater diversion device, GTS-Greywater treatment system

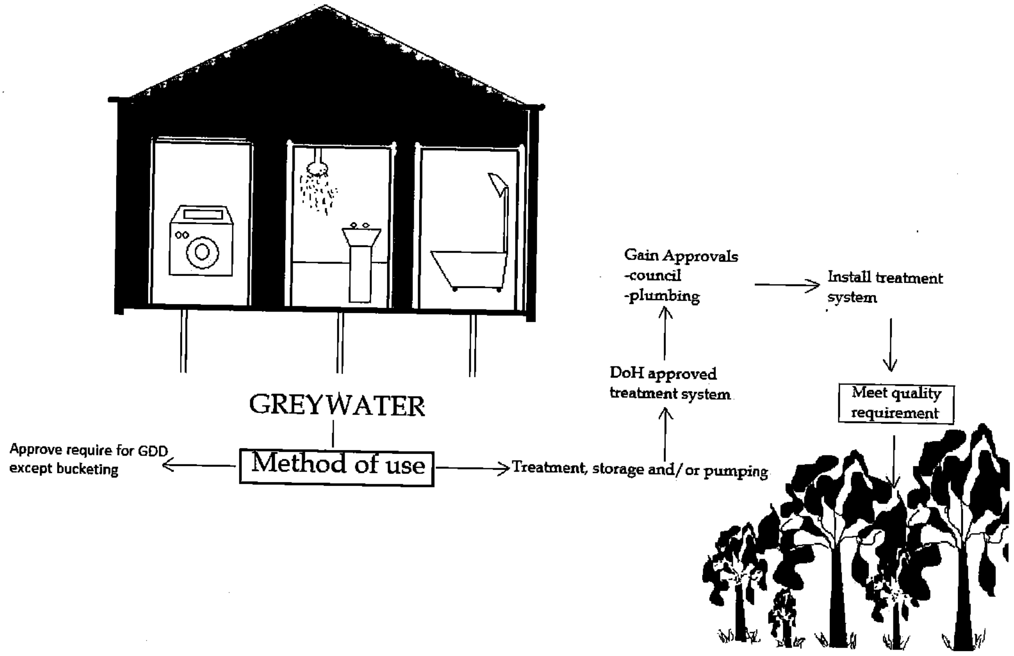

Figure 2.2. The sequence of the household greywater reuse system in WA

2.8 EFFECTS OF GREYWATER IRRIGATION

2.8.1 Soil

Physical properties

The saline greywater from laundry detergents can affect soil salinity. As salts are not degraded in the soil, overloading the garden with salts causes degradation of the soil structure and permeability. Several studies have investigated the movement of applied greywater through soil profile. This is mostly described as the infiltration rate or as hydraulic conductivity (K_s), which describes the ease of which water can move through pores. Amoozegar *et al.* (2004) reported that the application of saline greywater from laundry and dishwashing machine in sandy soils resulted in initial increase in K_s before declining over time. Abu-Zreig *et al.* (2003), through experimental works, observed that the application of anionic surfactant at a concentration in the range of 3000 mg/L resulted in a decrease in hydraulic conductivity in both loamy and sandy loam agricultural soils. Patterson,

(1996) demonstrated in this study that increasing SAR will cause a decrease in a soil's K_s of the soil in column studies.

Capillary rise (P_c) indicates the attraction of water molecules to soil particles through the soil pores. Thomas (1971) concludes that capillary conductivity or the transmission rate of water was higher in a drying soil. Intensive studies on capillary rise have been conducted in Israel by Wiel-Shafran *et al.* (2005) and Gross *et al.* (2005). Reduction of capillary rise due to elevated laundry detergent solutions concentrations (anionic surfactant concentrations ranging from 0 to 1000 mg/L) in sand columns was found by Weil-Shafran *et al.* (2006). They also found a significant presence of anionic surfactants, up to 60 mg/kg in soils that were irrigated with greywater. Results from Gross *et al.* (2005) also suggest that soil irrigated with greywater might become more hydrophobic as a result of the effects of surfactants on the capillary rise in loess sands. Thus the decline of leaching rates over time is expected when regular irrigation with water containing surfactant and salts is performed, because of the accumulation of surfactants and salts in the soil profile.

Soil salinity

The direct effects of greywater on soil chemistry can include changes in salinity. Irrigation water containing high levels of sodium (Na) causes degradation of the soil structure and permeability. Salinity management is often critical for successful greywater irrigation and can be quantified by using a SAR index (Lazarova and Asano, 2004). The SAR is an index of the ratio of Na to Ca and Mg as follows:

$$SAR = [Na^+] / \sqrt{[Ca^{2+}] + [Mg^{2+}] / 2}$$ **Equation 2.1**

SAR of greywater from use sites generally exceeds 4 with an average of 5.9 (Gross *et al.*, 2008). SAR in laundry greywater alone can reach up to 12.32 (Misra and Sivongxay, 2009) which is higher than the recommended value of 4 (ANZECC and ARMCANZ, 2000). Irrigation water salinity ratings based on EC and plant suitability can be referred to **Table 2.4**.

Table 2.4. Irrigation water salinity ratings based on electrical conductivity (ANZECC and ARMCANZ, 2000)

EC (dS/m)	Water salinity rating	Plant suitability
<0.65	Very low	Sensitive crops
0.65-1.3	Low	Moderately sensitive crops
1.3-2.9	Medium	Moderately tolerant crops
2.9-5.2	High	Tolerant crops
5.2-8.1	Very high	Very tolerant crops
>8.1	Extreme	Generally too saline

Long-term and continued use of water with a high-adjusted SAR will lead to a reduction of soil infiltration ability and permeability (Weil-Shafran *et al.*, 2006; Stevens, 2006). Qian and Mecham (2005) suggested that management such as Ca product topdressing or amendments and frequent aeration are needed to mitigate these effects. In Jordan, the increase of SAR in soil over time was found in sites that used treated greywater for olive trees and irrigation of some vegetable crops. In order to reduce this effect, soils should be flushed with fresh water (Al-Hamaiedeh and Bino, 2010).

The effects of salt found in greywater, especially Na, on soils can be measured by the ratio of salinity as EC to sodicity as SAR. The change is affected by the bulk solution salinity containing Na, which tends to be adsorbed in the soil exchange. This reaction may affect the soil's physical and chemical properties. Warrence *et al.* (2002) illustrated that reduced infiltration and hydraulic conductivity, and surface crusting caused by Na, can be mitigated by the flocculating effects of increased salt levels, or an increase in EC. Conversely, even relatively low sodium levels may cause dispersion if EC levels are sufficiently low.

Surfactants and water repellent soils

The ability of surfactants to dissolve relatively insoluble xenobiotics is well known and has been exploited extensively in many industries (Haigh, 1996). By design, surfactants are able to dissolve and keep in solution chemicals that normally have low solubility. As such, surfactants are not only used in household cleaning products, but also used in turf areas to improve wettability of water-repellant soil (Feng *et al.*, 2002). This agrees with Cisar *et al.* (2000) and Kostka (2000) who reported that surfactants decreased the incidence of localized dry spots and generally improved tuft quality.

Water repellent behaviour in soil is caused by dry coatings of hydrophobic material on soil particles or aggregates, as well as hydrophobic organic matter, such as fungal strands and particles of decomposing plant material. Depending on the severity of water repellency, water drops will penetrate the surface after a few seconds, or for extreme water repellency, infiltration may be delayed for hours or even days (DeBano, 1981; Doerr *et al.*, 2000). Since water infiltration into water repellent soil-profiles is partial, it makes the water unavailable for the plant roots. If some water penetrates the profile, it is characterized by preferential flow path causing the soil to wet in some places, and remain dry in other places. In Western Australia, up to five million hectares are affected or have the potential to be affected by water repellency or non-wetting (Blackwell, 1996). These are mainly sandy soils with less than 5 per cent clay content in the West Midlands, Swan Coastal Plain and the South Coast sand plains.

In soil remediation, the surfactant may assist in the adsorption, mobility and degradation of other organic substances in soil. Liu and Roy (1995) revealed that *sodium dodecylsulfate* (SDS), an anionic surfactant, successfully removed the hydrophobic organics from soil during in situ flushing. However, according to Abu-Zreig (2003), although surfactants used for soil conditioning and those used in detergents belong to a similar group, they differ in chemical structure, chemical characteristics and physical properties.

2.8.2 Plants

Irrigation with greywater can, in some plants, supply all the nutrients required for crop growth. Important nutrients to consider for the crop growth of greywater irrigation are P, N and K. Levels of N and other plant nutrients are always low (Jefferson et al., 2004), but in some greywater high concentration of P can be found, owing to detergent use.

There is currently very limited information on the effects of greywater irrigation on landscape plants, with short-term studies constituting most of the information available (Roesner et al., 2006). However, many studies have been done to evaluate the impacts of greywater irrigation on crop plants, most probably because of the possible health risk from human consumption.

In South Africa, a small-scale greywater pilot study was used to determine the microbiological impact on food crops such as spinach, green peppers, madumbis, potatoes, onions, beetroot and carrots (Jackson *et al.*, 2006). The study highlighted that raw crop vegetables irrigated with greywater posed a higher risk than vegetables with skin. It is highly recommended to install a greywater treatment to reduce pollutants. In Israel, Gross *et al.* (2008) noticed brown patches (*chlorosis*) on lettuce plants caused by the elevated salinity and B levels in the leaves. Nevertheless, irrigation of crop plants is possible but should only be done following primary treatment.

Lazarova and Asano (2004) claimed that the most common phytotoxic ions in municipal effluents are B, Cl and Na. Large quantities of B can be toxic to plants and typically come from water softeners, cleaners and detergents, largely in the form of sodium perborate, which is commonly used for whitening purposes. B can be toxic at levels only slightly greater than those required by plants for good growth. According to ANZECC (1992), B concentration lower than 1 mg/L is essential for plant development but higher levels can cause problems in sensitive plants. Lazarova and Asano (2004) later indicated that B can be found in urban wastewater at concentration levels as high as 5 mg/L with an average of 1 mg/L. Gross (2006)'s study found greywater's B concentrations to average at 1.3 mg/L – levels which may limit the growth of plants.

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