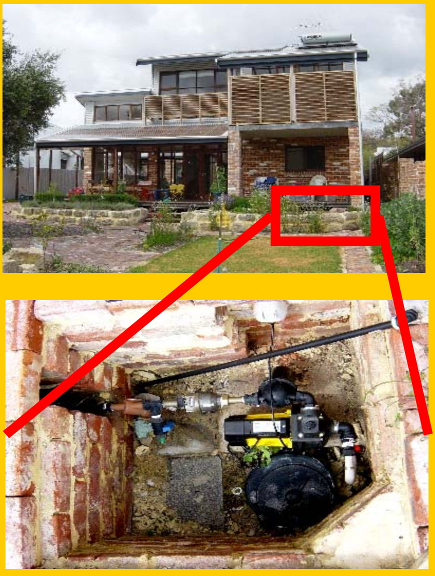
Household Greywater Reuse for Garden Irrigation in Perth



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ABSTRACT

Australians are one of the highest water consumers per capita in the world, and approximately a quarter of Australia's surface water management areas are nearing, or have exceeded, sustainable extraction limits. As the Western Australian population continues to grow, so too does the demand for water and the resulting pressures on current water resources. Individual households can contribute towards reducing water consumption and wastewater volumes by installing small greywater reuse systems and reusing household greywater for non-potable uses such as garden irrigation. The impact of greywater reuse on plants and soils is highly dependent upon site-specific characteristics such as plant species, soil type, and climate. An improved understanding of the effects of greywater reuse on the environment is required. This dissertation focuses on a local system in Perth and uses a combination of experimentation and modelling to determine whether the nutrients supplied by greywater irrigation alone are sufficient to sustain the growth of a family lawn, and whether these nutrients are available for uptake by the turf. A mass balance was carried out to determine the amount of nutrients flowing into and out of the lawn. The results showed that the nutrients supplied by the greywater are beneficial to the irrigated lawn but are not sufficient to sustain its growth. Consequently, the lawn requires the addition of fertiliser to supplement growth. The dissertation examines why greywater reuse for garden irrigation is not a widespread practice in Perth. Six possible barriers were identified, the most influential of these being the cost of installing and maintaining a greywater reuse system.

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1.1. What is Grey Water?

1.1.1. Definition

Domestic sewage or wastewater is the amalgamation of two distinct flows. The first flow is known as *blackwater* and consists of all wastewater that contains gross faecal coliform contamination. The majority of blackwater is sourced from toilets but can also come from bidets and laundry water used to wash soiled diapers.

The other, more dominant flow is known as *greywater* (*graywater* or *sullage*). Greywater is the term given to all untreated household wastewater that has not been contaminated with toilet water and includes water sourced from hand basins, bathtubs and showers.

For the purpose of this study, greywater includes all household wastewater other than toilet and kitchen wastewater.

1.1.2. Typical Characteristics and Composition of Greywater

Siegrist (1977) states that greywater constitutes the following percentages of the total household wastewater load (the balance is sourced from blackwater):

- 63% of the BOD_5
- 39% of the suspended solids
- 18% of the nitrogen
- 70% of the phosphorus
- 65% of the flow

The chemical, physical and biological characteristics of greywater vary from household to household and depend on the number of occupants and their practices. There are typically three streams of greywater, sourced from the kitchen, from the bathroom and from the laundry.

Bathroom

Wastewater originating from the bathroom makes up approximately 55% of the total greywater volume produced by a typical household in Western Australia (Department of Health 2002). Personal cleaning products, hair, lint, body fats, hair dyes, and oils often contaminate bathroom wastewater. Also present are some faecal contamination, bacteria and viruses.

Laundry

Wastewater originating from the laundry makes up approximately 34% of the total greywater volume produced by a typical household in Western Australia (Department of Health 2002). The quality of laundry water depends on the cleanliness of the items washed. The wastewater typically contains cleaning agents, chemicals, nutrients, lint, oils and greases. Some faecal contamination, bacteria and viruses may also be present, especially if the water has been used to clean soiled napkins.

Kitchen

Wastewater originating from the kitchen makes up approximately 11% of the total greywater volume produced in a typical household in Western Australia (Department of Health 2002). Kitchen wastewater is heavily contaminated with food particles, cooking oils, grease, and cleaning products. Food particles, cooking oils and grease place heavier loads on greywater reuse systems, increasing filter maintenance requirements, and the potential for blockages in the system (Jeppesen & Solley 1994). The particles and fats can also block soil pores and decrease the efficiency of irrigation, as the microorganisms living in the soil cannot break them down easily.

The relatively low flow contribution that contains high concentrations of organic particulates, cooking oils and greases, detergents, and other cleaning agents that are difficult to treat and potentially detrimental to irrigated soils are the grounds on which this study, along with a number of others, bases the decision to exclude kitchen wastewater from the greywater stream (Prillwitz & Farwell 1995; Emmerson 1998; Allen & Pezzaniti 2001).

1.2. Why Reuse Greywater For Irrigation?

Approximately 80% of Australia is classified as semi-arid, making it the driest inhabited continent on Earth (ABS 2002). The dry nature of the land results in a low population density, with the majority of the population situated in higher rainfall areas on the southern parts of the continent (Anderson 1996). Australia’s low population density accounts for the apparent high volumes of available water per capita relative to many other countries (World Bank 2002). However, Australians are also one of the highest water consumers per capita in the world (Gleick 2000), and approximately a quarter of Australia's surface water management areas are nearing, or have exceeded, sustainable extraction limits (ABS 2002).

Approximately 241 GL of scheme water is consumed within the Perth region each year (Loh & Peter 2003). Approximately 70% of Perth's total scheme water demand is consumed by private residences, and, on average, over half of this water is used to water lawns and gardens (Loh & Peter 2003). This means that watering lawns and gardens accounts for over 90 GL of potable water use per year.

As the Western Australian population continues to grow, so too does the demand for water and the resulting pressures on current water resources. Consequently, the disposal of increasing volumes of wastewater is also becoming a significant environmental challenge. The concept of wastewater reuse has been present since cities were first constructed downstream of one another along major rivers. The rivers were originally used to supply water to communities and to carry away their wastewater, causing one city's waste to become another's source. For example, it has been said that water in the Rhine River has passed through eight people's kidneys by the time it reaches the North Seas (Denlay & Dowsett 1994). However, the reuse of wastewater has not yet been thoroughly investigated as a public policy in Australia (Emmerson 1998).

Although large-scale municipal wastewater reuse has not been realised to its full potential in Australia, individual households can contribute towards reducing water consumption and wastewater volumes by installing small de-centralised greywater reuse systems (although both household blackwater and greywater have the potential for reuse, greywater is easier, more convenient, safer and faster to reuse (Emmerson 1998)). If every household in Perth began reusing their greywater for the irrigation of lawns and gardens, potentially 35% less scheme water would be used and require treatment and disposal each year. Based on statistics presented by Loh and Peter (2003), these savings could be in the order of around 175 litres per person per day.

An obvious consideration that follows such savings in water use and corresponding decreases in sewage volumes is the effects of these reduced volumes on the sewerage transport and treatment system. The capacity of the sewerage system must necessarily remain unchanged for the following reasons:

- the system is designed to allow for increased wet weather flows as well as decreased dry weather flows (Jeppesen & Solley 1994);
- greywater that is reused for irrigative purposes will be diverted straight to the sewer during wet weather when the vegetation does not require additional watering; and
- realistically, not all residences will employ greywater reuse systems for practical, economic, psychological, or other reasons.

The Brisbane City Council (1988) conducted trials to gauge the effects of low flush toilet volumes on the performance of a sewer system. The study concluded that the low volumes were sufficient to provide a transport medium for the toilet waste, and that the flow reduction had not detrimental effects on the sewer. In addition, informal conversations with a number of employees of the Water Corporation have established that a decrease in flow volume is more likely to benefit the sewage treatment process through savings in energy, and money that would otherwise be spent on dewatering processes. Therefore, lower flows as a result of the implementation of household greywater reuse systems are not an issue of concern.

1.3. Non-Potable, Residential Reuse Schemes Worldwide

Non-potable, residential re-use schemes are comprised of local systems and dual reticulation systems. Local systems are those that operate in a single house or building complex, and are the main focus of this study. Dual reticulation systems are those in which wastewater is centrally treated and distributed as reclaimed water for non-contact uses such as toilet flushing and irrigation. Non-potable reuse is the reuse of wastewater for uses other than human consumption such as irrigation, toilet flushing, and water features.

The following sections outline some examples of non-potable, residential greywater and wastewater reuse that have been employed around the world.

1.4. Local Systems

Globally, the United States of America and Japan provide the most publicised examples of water reuse via local systems.

1.4.1. U.S.A.

There has been a relatively long history of greywater reuse in the United States. In 1977, a survey of Californian County Health Officials confirmed that large numbers of unapproved systems were already operating in the state, with estimates in the tens of thousands for the entire country (Milne 1979). However, greywater reuse did not feature in regulations, and was therefore illegal, until 1989 (Jeppesen & Solley 1994).

After severe water shortages in states such as California, Sourthern Arizona, and Florida, water authorities around country began to look for methods for economising water usage and implementing alternative sources. The water authorities of the western states adopted localised greywater reuse as one such method, and the County of Santa Barbara was the first to introduce greywater regulations in 1989 (Jeppesen & Solley 1994). Ten other counties and cities followed soon after between 1989 and 1992. As of 1998, twenty-two of the western states of America permitted the direct reuse of untreated domestic greywater for sub-surface watering (Emmerson 1998).

A wide variety of local greywater reuse systems are presently operating across the United States. Examples include indoor planter beds, vegetable gardens, landscape features, and greenhouse gardens (Lindstrom 2000).

1.4.2. Japan

A shortage of potable water in Japan has resulted in water reuse (treated wastewater effluent) for toilet flushing, ornamental ponds and fountains, and landscape watering. This water generally comes from onsite wastewater treatment plants and, due to installation and operational costs, is mainly limited to office buildings and multiple occupancy dwellings (Thomas et al. 1997; Jeppesen & Solley 1994; Emmerson 1998). The Japanese government sets only effluent quality guidelines for water reuse, and the responsibility of administration for onsite reuse is left to the building owner.

Greywater reuse in single-family dwellings is generally in the form of a hand-basin toilet or reusing bathing water for washing clothes. The most common greywater reuse system is a toilet with a hand basin set into the top of the cistern (the hand basin toilet), which allows water from hand washing to form part of the refill volume. Hand basin toilets are reportedly installed in most new houses in Japan (Thomas et al. 1997).

1.4.3. New Zealand

The trend in new residential developments in non-sewered areas of New Zealand is towards the reuse of household sewage for garden irrigation after treatment by an onsite biological treatment unit. Many of the local councils now encourage households to install an Aerated Wastewater Treatment System instead of a traditional septic tank so that wastewater can be treated to a reasonably high quality and irrigated throughout the garden. Regulations require that these systems be maintained at least once every three years (Far North District Council 2004).

1.4.4. Australia

Water reuse is a relatively new idea in Australia. Regulations for the reuse of wastewater have only been developed recently in some states, and in others they are currently being developed or are still non-existent (See Section 4.2.6). It follows that reuse is still illegal in many parts of the country and local reuse systems are not a common occurrence. However, authorities have found that 20 percent of Perth householders engage in some form of greywater reuse (Anda et al. 1996).

Small scale, single household sewage treatment plants are common in non-sewered areas of Australia and, although they are designed and used for sewage disposal, the product of these plants is generally suitable for subsurface irrigation (Thomas et al. 1997). However, it is important that the systems be maintained if the water is to be reused because discharging poor quality water to the environment may cause human and environmental health problems.

1.5. Dual Reticulation Systems

1.5.1. U.S.A.

California and Florida are two of the pioneering water recycling states in the U.S., with over 230 reuse projects operating in California alone in 2003 (Po et al. 2003). Two examples of reuse projects are the Irvine Ranch Water Recycling Program (California) and ‘Project Apricot’ in Altamonte Springs (Florida).

The Irvine Ranch Water Recycling Program is a multi-use recycling project that was initiated in 1967 with the introduction of recycled water to the local agricultural sector to reduce the District’s dependency on imported water (D'Angelo 1998). Since then, recycled water has been used for purposes such as the irrigation of crops, golf courses, parks, school grounds, greenbelts, street medians, and freeway landscaping, other industrial uses, and commercial toilet flushing (Po et al. 2003). Homeowners are also supplied with recycled water for non-potable uses through a dual reticulation system (Holliman 1998). As of 1998, recycled water accounted for approximately 15% of the District's annual water requirements (Young et al. 1998).

'Project Apricot' was motivated by the need to protect Altamonte Springs' potable water supplies. The project provides high quality treated wastewater for all non-potable uses to every developed property in the Altamonte Springs service area for 40% of the price of potable water. Retrofitting of required plumbing to established neighbourhoods in the area was included in the project, and no connection fees are charged to any structure wishing to connect to the scheme. (Newnham 1993)

1.5.2. Japan

Dual reticulation systems that pipe treated water from nearby wastewater treatment plants are an alternative source of recycled water to local onsite wastewater recycling systems in Japan (see Section 1.4.2). Similar to localised greywater reuse, the water obtained from the dual reticulation systems is used for toilet flushing, ornamental ponds and fountains, and landscape watering (Jeppesen & Solley 1994).

1.5.3. Singapore

Singapore is a small island nation that has depended heavily on neighbouring Malaysia for approximately forty percent of its water supply for over 40 years (Onn 2003). This dependence has always been a highly sensitive issue and recent disputes between the two countries over the price of water lead Singapore to seek an alternative source to secure its future water supply. The NEWater recycled water project was commissioned in 2002 as a cheaper alternative to options such as desalinisation (Public Utilities Board 2004).

The project started as an indirect water reuse project with recycled water being mixed with reservoir water before being piped to residential and office taps. In 2003, 1% of the country's treated wastewater was pumped to reservoirs, and the government aims to meet 2.5% of the county's water requirements with NEWater by the year 2011 (Public Utilities Board 2004).

1.5.4. Australia

Non-potable residential reuse projects can be found in every state of Australia. Two examples are found in the Rouse Hill development area (Sydney) and in Palmyra (Perth).

The Rouse Hill project is the largest residential dual reticulation wastewater reuse scheme in Australia (Po et al. 2003), and was initiated to reduce the export of sediment and nutrients to the Hawkesbury/Nepean River System (Williams 1997). Since 2001, residents of the area have been supplied with treated wastewater for toilet flushing, garden irrigation and fire fighting purposes (Sydney Water 2001).

In Palmyra, a block of Homeswest aged persons units were selected to test a water reuse scheme. Greywater is collected from the units and treated by a biological treatment unit on site. The treated wastewater is chlorinated and stored in tanks for use in toilet flushing and irrigation. Blackwater continues to be discharged to the main sewer. (Bingley 1994)

1.6. Systems For Garden Greywater Reuse

There are seven brands of greywater reuse system that are currently approved for use in Western Australia (Department of Health 2004) (included in Appendix 1: Approved Greywater Reuse Systems). It is also possible to obtain approval for a self-designed system tailored to a household's needs. The list of approved systems contains configurations that generally focus on subsurface greywater disposal and consist of a simple storage tank connected to slotted piping or trenches approximately 30-40cm below the ground surface. This method of greywater 'reuse' is only useful to larger plants or trees that have roots deep enough to access the water coming from the pipes or trenches, and in sandy soils water may drain too rapidly to provide any benefit to the vegetation.

Greywater 'reuse' for disposal purposes, as described above, is different to greywater reuse for irrigation purposes. Greywater for irrigation is stored in a storage tank and allowed to run through subsurface irrigation drip lines placed in garden beds or below lawns when the plants require water. In the event that the plants do not require watering, such as a period of high rainfall, the greywater simply overflows into the main sewer (in sewered areas). This is different to those systems described previously because the plants are only watered when required, instead of the water running through the trenches each time the tank fills.

This study is focussed on a specially approved greywater reuse system designed for irrigation purposes. The system is installed in a suburban family home and collects greywater from a family of four before distribution via subsurface irrigation under the lawn. The system was commissioned in 2003. The three major components within the system are a split plumbing system; a greywater tank, disk filter, and electric pump; and a network of subsurface drip irrigation lines. These components are described briefly in the following sections.

1.6.1. Split Plumbing System

The plumbing system within the three bedroom two bathroom residence is split to separate greywater from blackwater. The greywater plumbing collects water from the baths, showers, washbasins, and washing machine/laundry trough and directs it to the greywater storage tank. All other wastewater generated within the household is directed to the sewer. Both plumbing systems conform to current regulations. A schematic diagram showing a split plumbing system is shown in Appendix 2: Example of Split Plumbing.

1.6.2. Tank, Pump and Filter

The system treats greywater to a primary level before it is pumped through the subsurface drip lines. Primary treatment is a form of physical treatment aimed at reducing wastewater velocity to allow solids to settle out. In this case, primary treatment is achieved by allowing the greywater to accumulate in a storage tank before it is pumped through the irrigation lines. The low-density polyethylene tank has a capacity of approximately 205 litres and allows for overflow to the main sewer when there is excess greywater or during maintenance.

During irrigation events, the greywater is drawn from the bottom of the tank by an electric pump and passes through a disk filter, flow meter, and slow release chemical root intrusion cartridge before it reaches the irrigation network. The disk filter prevents lint and hair from blocking the irrigation network and the root intrusion chemical prevents grass roots from entering and blocking the irrigation network. The tank, pump and filter set-up is shown in Figure 1.

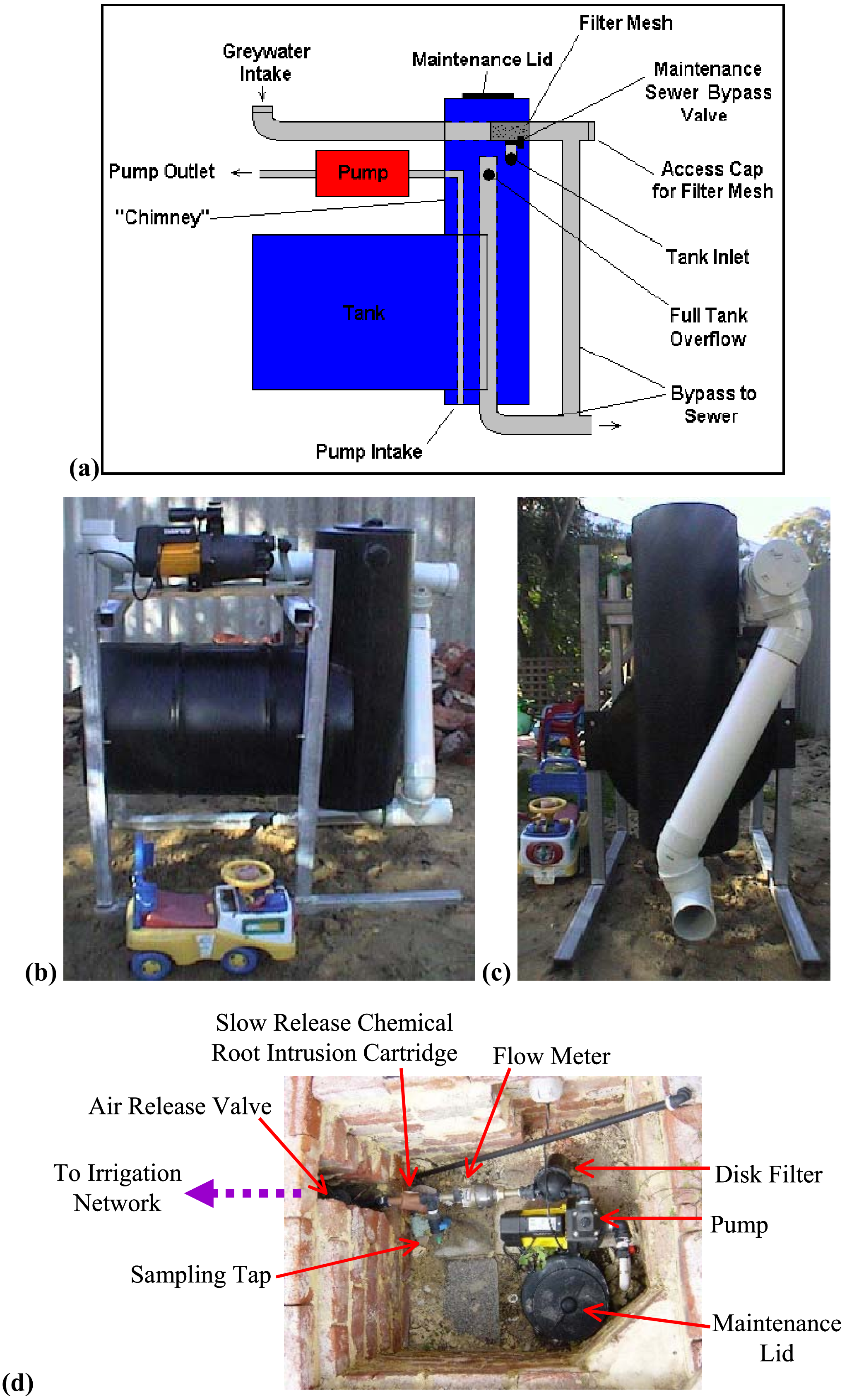

Figure 1: Primary treatment unit set-up (a) schematic diagram of the greywater tank and plumbing (Rowlands 2003), note that the filter mesh has been removed due to frequent blockage (b) front view of the greywater tank and plumbing (Rowlands 2003) (c) side view of the greywater tank and plumbing (Rowlands 2003) (d) above ground layout of installed system

1.6.3. Subsurface Irrigation Network

Subsurface drip irrigation allows greywater to be reused with minimal human contact. The irrigation network consists of ten parallel lines of NETAFIM™ drip irrigation piping at approximately five centimetres below the ground surface. Each row is approximately 30cm apart and each dripper is 40cm apart along the irrigation line. Figure 2 shows the layout of the lawn and irrigation network.

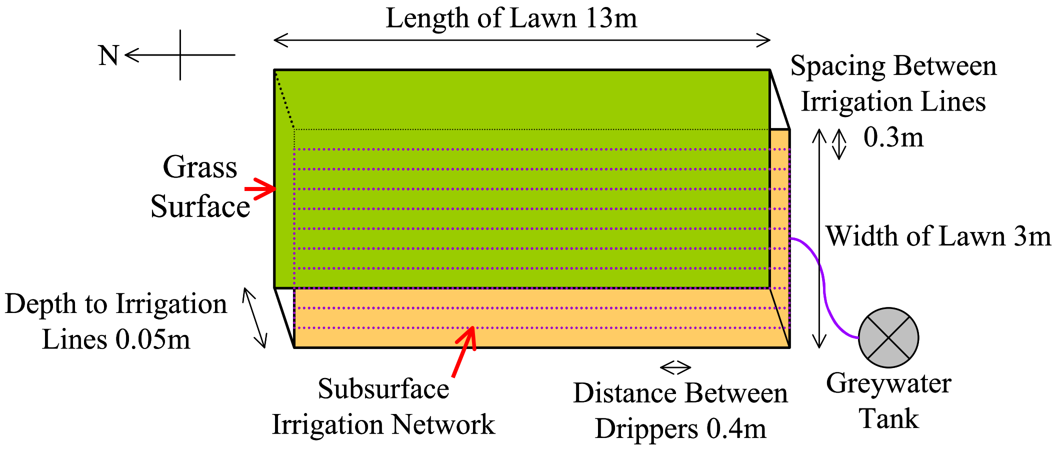

Figure 2: Layout and dimensions of subsurface irrigation network and irrigated lawn

1.7. Existing Literature and Gaps

Water conservation is the most obvious benefit from greywater reuse for garden or lawn irrigation. A number of studies have identified levels of potential water conservation resulting from greywater reuse. Although the identified volumes of water potentially saved differ from study to study, due to differences in the consumption habits of households studied, most studies agree that savings are 30-35% of total water consumption or 40-60% of household wastewater volumes (Christova-Boal et al. 1996; Jeppesen & Solley 1994; Emmerson 1998; Anderson 1996). Irrespective of the exact amounts of potable water saved by greywater reuse systems, all studies agree that potential savings are significant.

The potential savings to be achieved by greywater and wastewater reuse has generated much interest amongst researchers and water authorities. As a result, surveys have been conducted to identify priority regions for water reuse research and the number of studies relating to water reuse have increased in the past fifteen years (Dillon 2000). A review of Australian literature presently available has alluded to the fact that there are significant gaps in greywater reuse research related to public health, environmental impacts, economics and social issues. Studies that have been carried out, however, are generally limited in focus and spread over a wide range of themes. There is a need for studies that compare, contrast, and encompass issues relating to the various available options. Compilations of current knowledge, similar to the bibliographic database reference of (mainly U.S.) greywater research (to 1995) published by the US EPA (Allen & Pezzaniti 2001), is also required. Very little greywater reuse research has been conducted in Western Australia.

There appears to be sufficient interest in greywater reuse amongst researchers, and within some areas of government and selected areas within the community of the Perth region. Surveys of the Australian public, including Western Australians, have indicated that Australians believe that greywater reuse should be employed for conservation purposes (Po et al. 2003; Melbourne Water 1998; Sydney Water 1999; Water Corporation of Western Australia 2003). However, widespread greywater reuse has not been initiated in Western Australia, and specifically in the Perth region. Despite the potential benefits that household greywater may bring to the state, little has been done to identify and address the barriers that may be preventing the widespread reuse of household greywater in Perth.

1.8. Preliminary Studies

Two preliminary studies were carried out at the study site following the commissioning of the system (described in Section 1.6) in 2003. The studies examined the pathological and chemical characteristics (Jogia 2004), and hydrodynamics (Rowlands 2003) of the system.

Jogia (2004) collected data to quantify the fate and transport of pathogens and chemicals through the irrigation system. To determine pathogen transport through the system, Jogia collected and analysed samples of soil, soil water, and greywater for bacterial indicators Total Coliforms, Thermotolerant Coliforms, Escherichia coli, and Enterococci. It must be noted that bacterial indicators can only be used to assess the potential pathogen risk for a given sample, and not the absolute pathogen concentration (Jeppesen & Solley 1994). The soil samples were taken from directly below the turf, and soil water samples were taken from 30cm below the lawn surface. The samples of greywater were taken directly from the greywater storage tank and from the outlet valve between the filter and irrigation network. Assuming that the conditions within the household were constant throughout the sampling period, analysis of Jogia's data showed that the indicator counts at the storage tank and filter were approximately one third that of total coliforms, and one fifth that of thermotolerant coliforms found in wastewater (according to statistics presented by Jeppesen and Solley (1994)). The average greywater counts found in literature are 6×10^{-3} % of total coliforms and 6% of thermotolerant coliforms found in raw wastewater (Jeppesen & Solley 1994; Department of Health 2002), suggesting that the storage tank and filter are sources of pathogens. However, once the greywater was in the root zone, pathogen levels were found to decrease and negligible counts were observed at 30cm below the surface. The raw data is presented in Appendix 3: Pathogen Analysis of Greywater, Soil Water & Soil (Raw Data). Two conclusions were drawn from this analysis. Firstly, householders must be extremely careful during system maintenance and cleaning, and use personal protective equipment to minimise contact with potentially harmful pathogens. This conclusion is supported by the Western Australian Department of Health (2002) and health and safety requirements are specified in the Draft Guidelines for the Reuse of Greywater in Western Australia. Secondly, greywater is safe to use for the subsurface irrigation of residential lawns as pathogens are remediated once the greywater is distributed within the soil.

To determine the transport of chemicals through the irrigation system, Jogia (2004) collected and analysed soil and soil water for a number of plant nutrients and chemicals commonly found in greywater. Figure 3 is derived from the raw data that was collected (see Appendix 4: Chemical Analysis of Greywater and Soil Water (Raw Data)) and shows the ratio of the concentration of the nutrients in the soil water below the lawn compared to the concentration in the greywater used for irrigation. Evident from this graph is that, at the time of study, more nutrients were leaching out of the turf than were contained in the grey water that was irrigating the turf. In most cases the concentration of nutrients in the soil water was between 1 and 10 times greater than in the greywater used to irrigate the lawn, with the exception of Nitrate levels, which reached 600 times greater at one point. These increases in concentration through the lawn are attributed to the age of the roll-on turf. Turf growers provide the grass with excess amounts of fertiliser to ensure a ‘healthy’ looking product and studying a newly laid turf shows that large amounts of nutrients are wasted and leached into the groundwater.

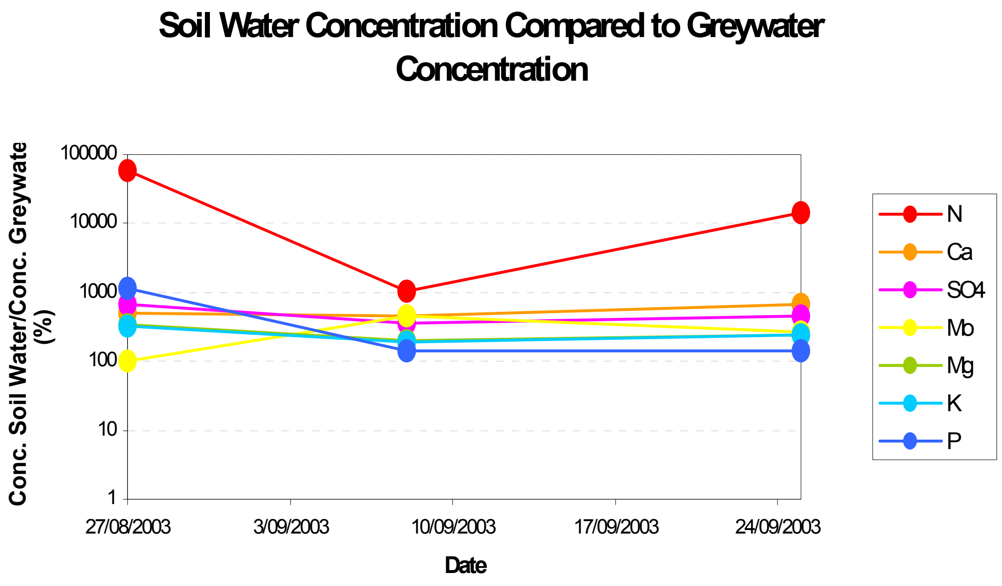

Figure 3: Concentration of selected plant nutrients in soil water compared to that in greywater (data collected by Jogia (2004))

1.9. Objectives

This dissertation attempts to address two information gaps in greywater research relating to the environmental impacts of household greywater reuse for garden irrigation and the factors preventing the widespread reuse of greywater in Perth.

The first objective relates to two questions that were left unanswered by Jogia (2004). The first question asks when the lawn will stop leaching the original fertiliser. The second question asks whether the nutrients in the greywater alone can sustain lawn growth once the excess fertiliser has completely leached out of the system.

The second objective of this study relates to an information gap introduced in Section 1.7 and stems from the fact that although reusing household greywater has the potential to save significant amounts of potable water, there has not been a move towards widespread reuse in Perth. The second objective of this study is to identify the barriers that may be causing this.

2. METHODOLOGY

A combination of fieldwork and modelling was employed to determine the nutrient mass balances within the system to achieve the first objective of the project, and barriers to widespread greywater reuse were identified through a review of literature and experiences. The methodology behind the fieldwork and modelling is described in this section.

2.1. Site Description

The study site is a suburban residence located at 74 Keightly Road in Shenton Park, approximately 10 kilometres west of Perth, Western Australia. The site is situated 19.2-20.2 m above sea level on a mixture of medium to coarse Tamala limestone, leached yellow, and Bassendean sand (Department of Environment 2003). The soil directly beneath the site is sandy, homogeneous, largely unstratified, and contains a very low clay content (approximately 2% clay) according to Water and Rivers Commission bore drilling logs from nearby bores on Rosalie Street (1978) and soil analysis carried out by Jogia (2004). The water table lies 13.9m (± 3m seasonal variation) below the surface (Department of Environment 2003). The climate is Mediterranean with hot dry summers and mild wet winters.

The surface of the site slopes gently from the highest point at the southeast corner to the lowest point at the northwest corner at a gradient of 1:15, resulting in no subsurface lateral flow. The 3m x 13m Velvet Buffalo Grass lawn overlaying the subsurface irrigation network is located in the northwest corner of the property. The soil beneath the lawn is sandy with traces of building rubble. The greywater unit is partially submerged at the southern end of the lawn and the sewer main runs down the property's western boundary at a depth of 2.5m. To the east of the lawn are two fishponds and several large trees. A layout of the property is shown in Appendix 5: Study Site Floor Plans.

The greywater reused at the site is sourced from a residence that consciously uses household products that are as environmentally friendly as possible. In general, this means that the detergents and cleaners employed contain lower phosphorus and sodium contents than regular products. The greywater reuse system and components are described in Section 1.6.

2.2. Mass Balance and Components

Figure 4 shows a diagram of the mass balance used to determine whether the nutrients in the greywater are sufficient to keep the lawn alive. The left hand side of the figure shows a schematic of the mass balance and control volume, which is the turf and 30cm of soil. The control volume was chosen to reach a depth of 30cm to allow data to be comparable to those collected by Jogia in 2003. The flux of nutrients into the control volume is from rainfall and greywater irrigation, and the flux of nutrients out of the control volume is through evapotranspiration and infiltration. The right hand side of Figure 4 is a simplified mass balance diagram with the flux of nutrients into the control volume shown coming through the lawn at the top and the flux of nutrients leaving the control volume through the soil at the bottom.

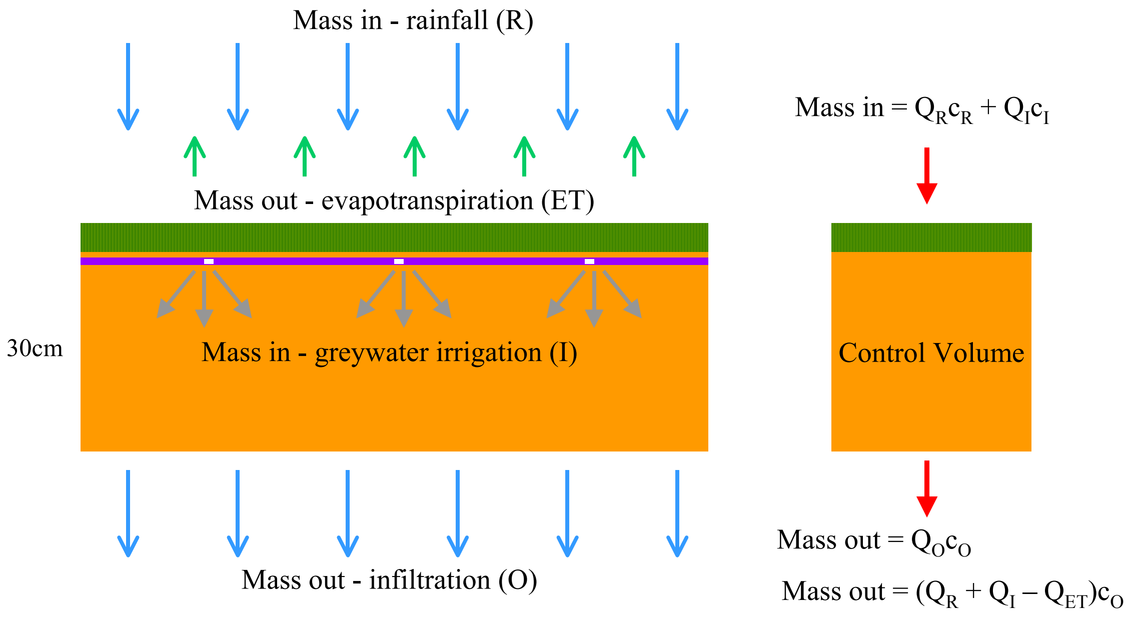

Figure 4: Schematic diagram of nutrient mass balance

The mass balance equations are shown on the right in Figure 4. The nutrient mass flux into the control volume is calculated using rainfall, irrigation, and the concentration of nutrients in the rain and greywater. The mass flux out is calculated using infiltration rates and the concentration of nutrients in soil water. Data has been collected for all terms except the water leaving the control volume. Table 1 identifies the parameters and the method used for obtaining values for each.

Table 1: Nutrient mass balance parameters

Parameter	Description	Method
Q_R	Inflow from rainfall	Measured
c_R	Concentration of nutrients in rain	≈ 0
Q_I	Inflow from irrigation	Measured
c_I	Concentration of nutrients in greywater	Measured
Q_O	Outflow by infiltration	Modelled
c_O	Concentration of nutrients in soil water leaving the control volume	Measured
Q_{ET}	Outflow by evapotranspiration	Modelled

A MATLAB script was written to calculate the mass balance for each day over the study period (June – September 2004). The script uses data supplied for each of the mass balance parameters (Q_R, c_R, Q_I, c_I, Q_O, and c_O – Q_{ET} is accounted for by the model output for Q_O) to calculate the mass balance for each day during the study period using the equations shown in Figure 4. The script assumes a 24hr time step as this is the smallest timescale data has been collected over. Hence, changes in outflow have been averaged over 24hrs and fluctuations over smaller timescales have been ignored. The script also assumes no time lag between inputs and outputs because a small depth is used and the sandy soil drains quickly. The script has been included in Appendix 6: Mass Balance Script.

Sections 2.3 to 2.6 detail the methods used to measure or model each of the mass balance components. Measurements were carried out between 17 June 2004 and 25 September 2004.

2.3. Greywater

The nutrient mass balance components related to the greywater used to irrigate the lawn are the inflow of water from irrigation (Q_I) and the concentration of nutrients added to the system through greywater irrigation (c_I).

2.3.1. Q_I – Inflow From Irrigation

The greywater reuse system's built-in flow meter was used to gauge the volume of water irrigated during each irrigation event. The lawn was irrigated with a total volume of 200L of greywater approximately twice weekly for the duration of the fieldwork. The dates of irrigation are shown in Appendix 8: Sampling Calendar.

2.3.2. c_I = Concentration Of Nutrients In Greywater

Greywater was analysed for selected primary plant nutrients (nitrogen, phosphorus and potassium), secondary plant nutrients (calcium, magnesium, sulphur), and plant micronutrients (molybdenum, vanadium) during the measurement period. 250mL samples of greywater were taken in clean bottles from the sampling tap between the flow meter and root intrusion chemical cartridge (see Section 1.6.2 for set-up) during irrigation events (see Appendix 8: Sampling Calendar for dates). The samples were frozen before being sent to the Marine and Freshwater Research Laboratory (MAFRL) at Murdoch University for analysis using the methods described in Appendix 9: Laboratory Test Methods.

MAFRL also analysed the samples for lead, and total organic carbon (see Appendix 9: Laboratory Test Methods). The nutrients and elements were selected to coincide with those found to be leaching in larger quantities than their inputs in the previous study by Jogia (2004). A list of essential plant nutrients and their functions is included in Appendix 7: Essential Plant Nutrients.

2.4. Soil Water Nutrient Analysis

The nutrient mass balance requires the concentration of nutrients leaving the control volume (c_O) at 30cm depth to be measured. The methods used to obtain c_O are described here.

2.4.1. Sample Collection

Jogia (2004) used subsurface water samplers, shown on the left in Figure 5, to collect soil water 30cm below the root zone. When under vacuum, these samplers collect soil water from the surrounding soil. In an attempt to keep methods uniform to allow data to be comparable with Jogia’s study, the subsurface water samplers were initially employed to collect soil water from 1 June 2004 until 7 August 2004. Five samplers were installed to 30cm depth, with four within the lawn area and one control located in a side garden with no greywater irrigation (shown on the right in Figure 5). However, no water collected in the cups during this time and an alternative method was required.

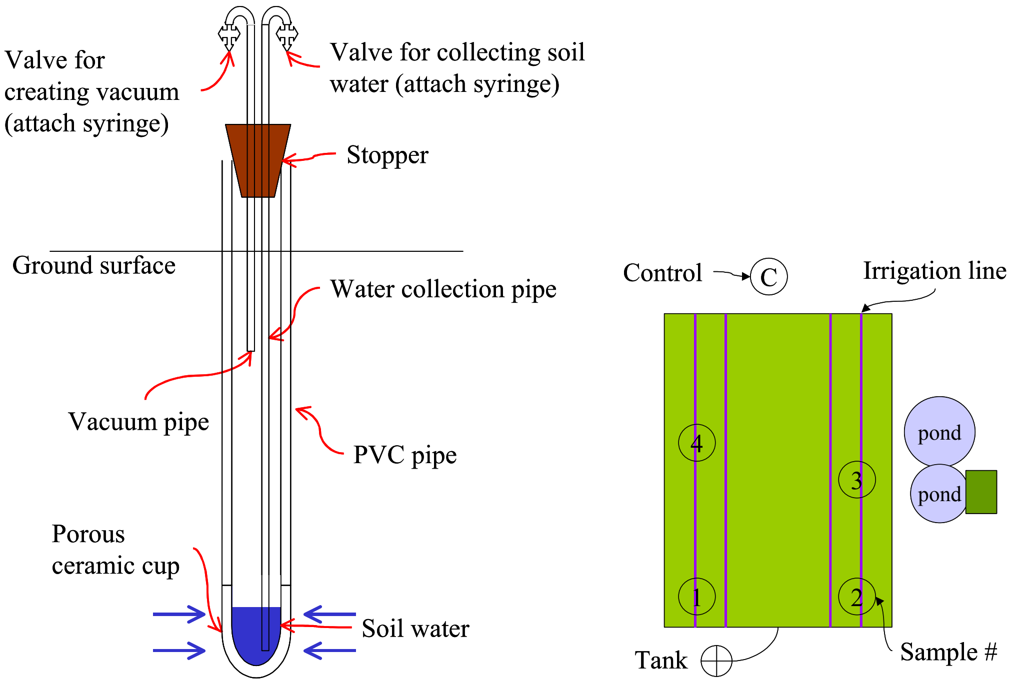

Figure 5: Subsurface water sampler and location of samplers in the lawn

The second, successful method used to obtain soil water nutrient concentrations involved collecting samples of soil, diluting the soil with deionised water, and then filtering and analysing the resulting solutions. 175mL plugs of soil were collected at a mean depth of 30cm using a 5cm diameter metal pipe and mallet. Samples were collected each week for six weeks (see Appendix 8: Sampling Calendar for sample dates) from four locations in the lawn area and a control in a side garden that was not irrigated with greywater. The samples from the lawn area were positioned around subsurface drippers as shown on the left in Figure 6, and the samples were located as shown on the right.

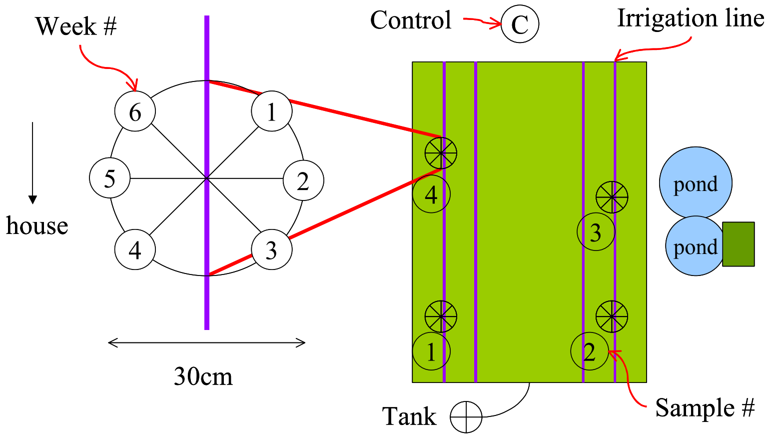

Figure 6: Position of weekly samples around a subsurface dripper and location of five samples in the lawn and garden area

The soil samples were sealed in clean, airtight containers and refrigerated until they were processed.

2.4.2. Soil Moisture Content, Dilution and Water Extraction

To obtain the concentration of nutrients in the soil water from the soil samples that were collected, the initial soil moisture contents were measured and the soil was diluted with deionised water. Diluting the soil samples with water effectively obtained all soluble chemical species, and therefore all species potentially available for plant uptake, in solution for analysis. This method was suitable because the project is only concerned with soluble species that can potentially be taken up by plants or leached through to the groundwater. Measuring the soil moisture content allowed the concentrations from the analysis of the dilutions to be related back to actual soil moisture concentrations.

Soil Moisture Content

A small portion of each soil sample was placed in a small, clean aluminium pie dish and the weight recorded as the 'wet weight'. After drying in an oven at 105°C for 24 hours, the soil was weighed again and recorded as the 'dry weight'. The percentage water content of the soil at the time of sampling was then calculated using Equation 1.

Equation 1: Percent water content by mass of soil sample

$$\%WaterContent = \frac{wetweight - dryweight}{dryweight} \times 100$$

Dilution and Water Extraction

Each soil sample was diluted in a ratio of one part soil to two parts deionised water in a clean container. Each dilution comprised of approximately 80g of soil and 160g of deionised water. The diluted samples were then tumbled for 24 hours to allow the samples to be fully mixed. After tumbling, the fine particles were suspended in the solution and the sand settled out on the bottom of the sample container.

This method for nutrient extraction is a version of the 1:2 soil:water ratio method (Rayment & Higginson 1992). An alternative method, the saturated paste extract method (detailed in Rayment & Higginson (1992)), was not employed because it is extremely time consuming and relies heavily on judgement and subjectivity.

The seven methods for water extraction and filtration were tested to separate the solution from the sand and fine particles. The seventh method was the most successful and was employed for all samples. The methods and outcomes are described briefly in Table 2.

Table 2: Methods tested for separating solution from sand and find soil particles

Method	Description	Outcome
1	Centrifuge the sample through #2 filter paper	No particulates caught by the filter paper
2	Filter sample through two layers of #2 filter paper Filter sample though three layers of #2 filter paper	No particulates caught by the filter paper
3	Filter sample through a #1 filter paper in a funnel	Filtrate is clearer than sample but method is time consuming
4	Vacuum filter sample through two layers of #2 filter paper	Filtrate is clearer than sample but not as clear as in method 3
5	Filter sample through 0.45µm syringe filters	Filtrate is extremely clear but filters block fast and method is expensive/wasteful without macro filtering first
6	Decant the samples into centrifuge tubes and centrifuge for 5 minutes at 4000rpm to separate suspended solid matter from solution	Solids began to separate but the bottom of the tube began to fail – a longer time at lower speed is required
7	Decant the samples into centrifuge tubes and centrifuge for 3 hours (or until solution looks clear) at 2000rpm to separate suspended solid matter from water, then pass the fluid through 0.45µm syringe filters	Successful – final filtered solution can be achieved with minimal number of filters

The samples were then frozen for preservation once the solutions were separated from the sand and fine particles using method seven (above).

2.4.3. c_O = Concentration Of Nutrients In Soil Water Leaving The Control Volume

The diluted soil water samples were analysed for the same suite of nutrients and elements as the greywater samples – selected primary plant nutrients (nitrogen, phosphorus and potassium), secondary plant nutrients (calcium, magnesium, sulphur), and plant micronutrients (molybdenum, vanadium), lead, and total organic carbon. MAFRL analysed the samples using the methods described in Appendix 9: Laboratory Test Methods. Further tests for organic carbon and organic matter content were carried out to determine the organic content in the soils (see Appendix 10: Methods for Determining The Carbon and Organic Matter Content In Soil).

Obtaining the concentration of nutrients in soil water from the analysis of the diluted soil water samples involves multiplying the concentrations obtained from MAFRL by the dilution, then dividing by the soil water content. The steps for calculating the soil water concentration for each nutrient or chemical analysed are as follows.

1. Calculate the dilution used to extract the nutrients from the initial soil sample using the volume of deionised water added and the mass of soil used (Equation 2).

Equation 2: Dilution used to extract nutrients from soil

$$Dilution = \frac{VolumeWaterAdded}{MassSoil}$$

2. Calculate the mass of the given nutrient in the soil from the concentrations obtained by MAFRL's analysis and the dilution calculated above (Equation 3).

Equation 3: Mass of nutrients per unit mass of soil

$$MassNutrientsPerUnitMassSoil = NutrientConcentration \times Dilution$$

3. Calculate the percentage water content in the original soil sample using the wet and dry weights of the soil (see Equation 1 above).

4. Calculate the concentration of the nutrient in the soil water within the original soil sample using mass of nutrients in each unit mass of soil and the soil water content (Equation 4).

Equation 4: Concentration of nutrients in the soil water

$$NutrientConcentrationInSoilWater = \frac{MassNutrientsPerUnitMassSoil}{\%WaterContent} \times 100$$

2.5. Other Measured Parameters

2.5.1. Q_R – Inflow From Rainfall

A rain gauge was used to measure the rainfall at the site over the sampling period. The rainfall data was compared to data collected by the Bureau of Meteorology's Swanbourne station to estimate rainfall on days when the gauge was not read.

2.5.2. Q_E – Outflow Through Evaporation

Potential evaporation data was obtained from the Bureau of Meteorology's Perth Airport station over the sampling period. The evaporation data was used as an input to both models for calculating the water output from the system.

2.6. Soil Water Infiltration and Movement (SWIM) Model

The Soil Water Infiltration and Movement (SWIMv1.1) Model simulates water infiltration and movement in soils and was used to estimate the flow of water out of the control volume (Q_O) over the study period. SWIM allows water to be added to a system through precipitation and removed through runoff, drainage, evaporation, and transpiration. The model obeys the law of conservation of mass and assumes that conditions can be treated as horizontally uniform, that flow is described by the Richards equation and that soil hydraulic properties can be described by simple functions (Ross 1997). This model was chosen as the primary model for estimating Q_O because Rowlands employed it over the study site in 2003.

SWIM solves the Richards equation numerically by using efficient computation techniques (Ross 1990) that ensure that mass is conserved, even when obtaining fast and approximate solutions (Scientific Software Group 1998). Richards' equation does not accurately describe every flow situation, however, it is the accepted basis of soil water flow and is assumed to apply to the study site. SWIM allows the simulation of infiltration, redistribution, deep drainage, simultaneous evapotranspiration by up to four types of vegetation, transient surface-water storage and runoff. The model allows soils to be vertically heterogeneous but assumes horizontal uniformity. A single, shallow (30cm), homogeneous soil layer has been assumed for the purpose of this study.

SWIM allows the input of parameters describing the simulation, vegetation characteristics, soil and surface conductance, surface storage, runoff, soil properties, and precipitation and potential evapotranspiration. Table 3 summarises the inputs used for this study.

Table 3: Input parameters to the Soil Water Infiltration and Movement model

Parameter Group	Parameter	Value
Simulation Control	Starting time	Day 1 (31/05/2004)
	Finishing time	Day 119 (27/09/2004)
	Print interval	24 hrs
Soil	Water suction or wilting point	-15000 cm
	Water content at permanent wilt point	0.016
	Saturation water content (θ_{Sat})	0.366
	Residual water content ($\theta_{Residual}$)	0.01
	Field capacity water content	0.0965
	Air entry potential or bubbling pressure (ψ)	-7.3 cm
	Slope of water retention curve ($m = 1 - 1/n$)	0.35
	Hydraulic conductivity at field saturation (K_{Sat})	137 cm/hr
Vegetation	Root length density	1.0 cm/cm^3
	Depth constant	8 cm
Precipitation	Cumulative rainfall + irrigation data	See below
Potential Evapotranspiration	Cumulative potential evapotranspiration data	$0.8 \times E_{Pan}$

The soil and vegetation parameters were determined by Rowlands (2003) (see Appendix 11: Water Retention Curve for the origins of parameter 'm'). Rainfall data was gauged at the study site and supplemented with data from the Bureau of Meteorology's Swanbourne Station when necessary. Irrigation data was recorded as described in Section 2.3.1. Potential evaporation was estimated from evaporation (pan) data obtained from the Bureau of Meteorology. The precipitation, irrigation, and potential evapotranspiration data is contained in Appendix 12: Cumulative Rainfall + Irrigation Data, and Potential Evaporation Data.

SWIM's outputs include time, computational errors from solving the water balance equation, potential and actual evaporation and transpiration, water variables, and the water balance. The model's total output has been utilised to estimate Q_O for this study by Equation 5. This calculation assumes an average outflow over the study period because the resolution of the data collected for other components of the mass balance does not allow computation at any finer detail. The assumption is valid because the control volume and soils drain quickly and water contents within the soil vary significantly over each 24 hr period.

Equation 5: Estimation of Q_O from SWIM output

$$Q_O(mm/day) = \frac{TotalOutput}{NumberOfDays}$$

2.6.1. Sensitivity Analysis

The vegetation input parameters used by SWIM were estimated by Rowlands (2003). However, vegetation changes with time and a sensitivity analysis was carried out to determine the influence of any difference between the actual values and the 2003 estimates. Varying the root density and depth inputs, whilst gauging the difference in the model's output, revealed that the output is sensitive to vegetation parameters. This was expected because SWIM is a complex model that depends heavily on the vegetation characteristics to calculate evapotranspiration. The actual vegetation characteristics for the study site are unknown and it was necessary to estimate the characteristics for this study because vegetation characteristics are difficult to define without extensive experimentation and disturbance to the study area. Therefore, the output from SWIM required validation against another model and field data.

2.6.2. Validation By Comparison With A Multiple Wetting Front Model

The Gravitational Multiple Wetting Front And Redistribution (GMWFR) model was used to validate the output estimation for Q_O obtained from SWIM. The model tracks the movement of square infiltration waves as they move under gravitation through the soil profile. Each front is square in shape and multiple fronts are super-imposed upon each other to form a soil moisture pattern with depth. The GMWFR obeys the law of conservation of mass and can be reduced to single-layer model.

The multiple wetting front model assumes gravitational drainage only and does not account for suction-based movement. Consequently, the model will inaccurately represent the impacts of evapotranspiration upon the soil moisture profile when suction-based upward movement of water is significant, and cannot deal with ponded infiltration (Struthers 2004). This limitation should not feature in this study as the soils are low in clay content and are not extremely dry. The lawn area should never become ponded under Department of Health guidelines (Department of Health 2002).

The GMWFR allows the input of parameters describing basic soil properties, shape parameters, vegetation, rainfall, potential evaporation, and total soil depth. Table 4 summarises the inputs used for this study.

Table 4: Input parameters to the Gravitational Multiple Wetting Front and Redistribution model

Parameter	Discription	Value
iThick	Layer thicknesses (assume single layer model)	300 mm
BSEL	Lowest layer influenced by bare soil evaporation (1 = single/top layer)	1
Ksat	Saturated conductivity	32880 mm/day
VWCi	Initial VWC	0.0158
VWCr	Residual VWC	0.01
VWCs	Saturation water content (porosity)	0.366
VWCwp	VWC of permanent wilt point (VWC at 15000cm suction)	0.016
VWCfc	Field capacity VWC (Plant transpiration equals demand for VWC>=VWCfc)	0.03
a	Discharge coefficient	0
sdur	Storm duration assumption	1/3 days
mergtol	VWC difference tolerance for separate fronts (will merge fronts with VWC values closer than this to each other)	9e-4
ETL	Lowest layer influenced by transpiration (1 = neglect root zone growth)	1
input1.txt	A text file containing the columns: Date (Excel format), Daily Precipitation, Potential Evaporation, Observed Drainage	

The inputs assume a single layer control volume. The values of all soil related parameters are those that were used as inputs to SWIM and were determined by Rowlands (2003). The inputs for daily precipitation and potential evaporation were also the same as those supplied to SWIM. The observed drainage supplied for comparison purposes were the daily drainage values from the SWIM output.

2.6.3. Validation By Comparison With Field Data

Both model outputs were compared to field data taken during and after the sampling period. For comparison purposes, the gravimetric soil moisture (P_W) values obtained (described in Section 2.4.2) were converted to volumetric soil moisture (P_V) using Equation 6. The bulk density (ρ_b) of the soil was determined to be 1.4526 by Rowlands (2003).

Equation 6: Conversion of gravimetric soil moisture to volumetric soil moisture

$$P_W = \rho_b \times P_V$$

Additional soil moisture readings were taken daily following the last irrigation event during the sampling period to gauge the soil's drying characteristics. ECH_2O soil moisture monitor and dielectric aquameters (Decagon Devices, USA see Figure 7) were buried horizontally at 30cm depth below sample drippers 1, 2, and 4 (see Figure 6 for positions). The readings were then calibrated against those obtained from a reliable and frequently used Trase moisture measurement system (Soil Moisture Equipment Corp., USA). Calibration readings were taken at the study site and under laboratory conditions in moist, saturated, drained and dry 30cm sand columns. The dry moisture range is most important because it corresponds closest to the actual field conditions. In the laboratory, the 20cm ECH_2O meter and 10cm Trase probe were planted vertically in the soil column. The difference between the lengths of the two probes was expected to result in higher moisture content readings from the ECH_2O meter when in the moist, saturated and drained columns due to an increasing water content gradient with depth in the vertical columns.

Figure 7: ECH_2O soil moisture monitor (centre right) and two dielectric aquameters (top and bottom)

3. RESULTS

3.1. Initial Observations

Patches of turf death were observed in early March, indicating that the excess nutrients had stopped leaching from the turf because irrigation and other factors remained constant over the period before and after this occurred. The grass has never required mowing since it was laid approximately two years ago.

3.2. Chemical Properties

Tests for organic carbon and organic matter in the original soil samples and water samples showed that the soil is low in organic carbon and organic matter. The soil underlying the study site is also homogeneous in terms of organic carbon content and organic matter. The results from the soil tests are shown in Table 5.

Table 5: Percentage carbon and organic matter found in the soils

	8/08/2004	**8/08/2004**	**8/08/2004**	**8/08/2004**	**1/09/2004**
	Sample 1	**Sample 2**	**Sample 3**	**Sample 4**	**Control**
%C	0.24	0.16	0.16	0.27	0.16
%OM	0.48	0.31	0.32	0.55	0.32

The concentration of molybdenum was below the detection limit (0.004mg/L) in all greywater and soil samples.

There were no significant differences between the nutrient and elemental content of the greywater when compared to the data obtained by Jogia (2004).

There were significant decreases in the calcium, potassium, magnesium, sulphate and vanadium content of the soil water when compared to the data obtained by Jogia (2004).

3.3. SWIM

Total output estimated by the Soil Water Infiltration and Movement model was 122mm over 119 days for the lawn area. This is equivalent to an average of 1.03mm per day during the sampling period.

Table 6 shows the results from the calibration readings taken by the ECH_2O and Trase monitors. When the differences in penetration depth and moisture gradient with depth are taken into account, the ECH_2O monitor read accurately in the moist, saturated and drained moisture content ranges. The ECH_2O monitor read moisture contents 2% lower than the Trase monitor's readings in the dry range. This value was used as a correction to the field data before comparisons were made with the SWIM output.

Table 6: Percentage moisture content readings from ECH_2O and Trase monitors for calibration

Condition	ECH_2O	Trase
Site	8.6%	17% 17.5% 7% 12%
Moist soil column	30-33%	20-21%
Saturated soil column	39%	37.4%
Drained soil column	34.1%	32.4%
Dry soil column	5.8%	7.3-8.4%

The Gravitational Multiple Wetting Front and Redistribution model estimated total output over the study period to be 365mm. This is equivalent to an average of 3mm per day during the sampling period.

Figure 8 compares the flow outputs from the Soil Water Infiltration and Movement model and the Gravitational Multiple Wetting Front and Redistribution model. The total outflows produced are within the same order of magnitude but the GMWFR produces approximately three times more output than SWIM.

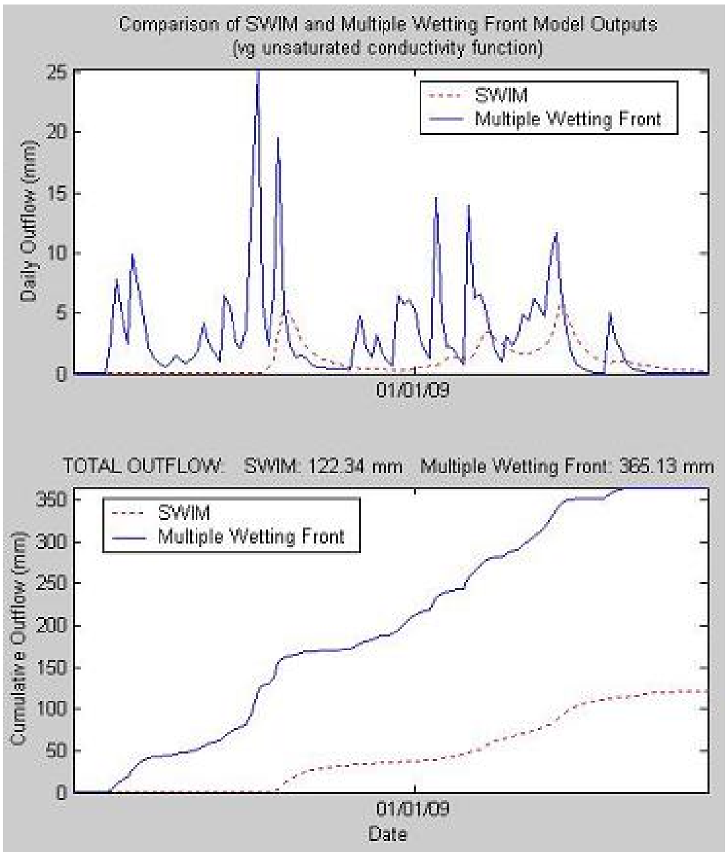

Figure 8: Comparison between infiltration outputs for daily outflow (top) and cumulative outflow (bottom) from the Soil Water Infiltration and Movement and Gravitational Multiple Wetting Front and Redistribution models.

Figure 9 shows a comparison between the soil moisture output at 30cm depth from SWIM and those obtained from field measurements and soil analysis in the laboratory. The SWIM output fit both the readings from the ECH$_2$O monitor and the data from the laboratory analysis well, with the exceptions being when soil moisture was measured or samples were taken after irrigation events when the water content was elevated for a short period of time.

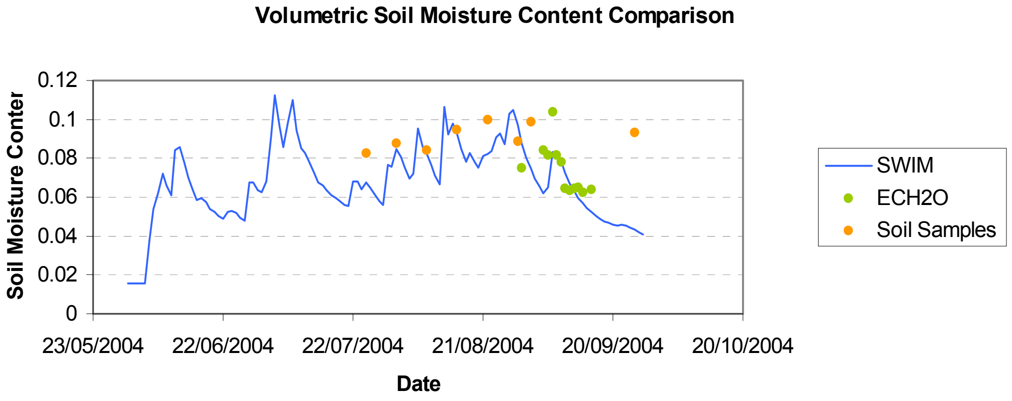

Figure 9: Comparison of the Soil Moisture Infiltration and Movement model soil moisture output with probe and soil sample data

3.4. Mass Balance

Paired t-tests showed no significant differences in the mass of each nutrient or element leaving the control volume between weeks except those shown in Table 7. Of the significant differences found, evidence against the null hypothesis was only strong for the differences between the mass of lead and vanadium leaving the control volume in weeks four and five.

Table 7: Significant differences resulting from paired t-test with null hypothesis: no change in mass leaving the control volume between weeks.

	Comparison	Alternative Hypothesis	t	Critical $t_{0.05}$ with 3df	Conclusion	P Value
Ca	Paired t wk 4-5	Mean of differences > 0 (decrease)	3.915	2.353	Significant decrease	0.0148
Mg	Paired t wk 1-2	Mean of differences > 0 (decrease)	2.281	2.353	Significant decrease	0.0534
Pb	Paired t wk 4-5	Mean of differences > 0 (increase)	6.496	2.353	Significant increase	0.0037
V	Paired t wk 4-5	Mean of differences > 0 (decrease)	9.841	2.353	Significant decrease	0.0011
SO_4	Paired t wk 1-2	Mean of differences > 0 (decrease)	2.395	2.353	Significant decrease	0.0481
	Paired t wk 2-3	Mean of differences > 0 (decrease)	4.431	2.353	Significant decrease	0.0107
TP	Paired t wk 4-5	Mean of differences > 0 (decrease)	2.765	2.353	Significant decrease	0.0349
TN	Paired t wk 4-5	Mean of differences > 0 (decrease)	2.447	2.353	Significant decrease	0.0460

Paired t-tests showed no significant differences in the mass of each nutrient or element leaving the control volume between sample areas (1, 2, 3, and 4 see Figure 6) except those shown in Table 8. Of the significant differences found, evidence against the null hypothesis was only strong for the differences between the mass of potassium leaving between sample areas one and three, and the mass of magnesium leaving between sample areas one and two.

Table 8: Significant differences resulting from paired t-test with null hypothesis (H_0): no change in mass leaving the control volume between sample areas

	Comparison	Alternative Hypothesis	t	Critical $t_{0.05}$ with 5df	Conclusion	P Value
Ca	Paired t s 1-3	Mean of differences > 0 (increase)	2.928	2.015	Significant increase	0.0164
	Paired t s 2-3	Mean of differences > 0 (increase)	2.214	2.015	Significant increase	0.0389
	Paired t s 3-4	Mean of differences > 0 (decrease)	2.562	2.015	Significant decrease	0.0253
K	Paired t s 1-3	Mean of differences > 0 (increase)	4.056	2.015	Significant increase	0.0049
	Paired t s 2-3	Mean of differences > 0 (increase)	2.903	2.015	Significant increase	0.0168
Mg	Paired t s 1-2	Mean of differences > 0 (decrease)	3.790	2.015	Significant decrease	0.0064
	Paired t s 2-3	Mean of differences > 0 (increase)	2.662	2.015	Significant increase	0.0224
	Paired t s 3-4	Mean of differences > 0 (decrease)	2.092	2.015	Significant decrease	0.0453
V	Paired t s 2-4	Mean of differences > 0 (decrease)	2.366	2.015	Significant decrease	0.0322
	Paired t s 3-4	Mean of differences > 0 (decrease)	2.100	2.015	Significant decrease	0.0449
SO_4	Paired t s 3-4	Mean of differences > 0 (decrease)	2.091	2.015	Significant decrease	0.0454
TP	Paired t s 1-3	Mean of differences > 0 (increase)	3.168	2.015	Significant increase	0.0124
TN	Paired t s 1-3	Mean of differences > 0 (increase)	2.955	2.015	Significant increase	0.0159
	Paired t s 2-3	Mean of differences > 0 (increase)	2.458	2.015	Significant increase	0.0287
NPOC	Paired t s 1-2	Mean of differences > 0 (decrease)	3.852	2.353	Significant decrease	0.0155
	Paired t s 2-4	Mean of differences > 0 (increase)	2.419	2.353	Significant increase	0.0471

The calcium mass balance is shown graphically in Figure 10. The mass flux into the system at the time of sampling is denoted by red triangles and coloured points denote the mass flux out for each of the four sample areas. It is interesting to note that the mass of calcium leaving the system through infiltration is greater than the mass entering the system through greywater irrigation. The mass leaving the system does not appear to correspond to the mass entering the system. The mass of calcium leaving the system is significantly higher in sample 3 than the other samples.

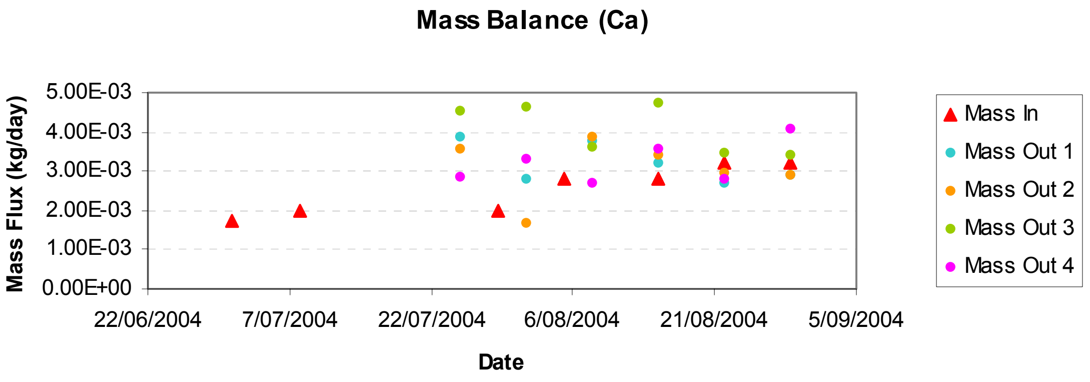

Figure 10: Mass of calcium into and out of the control volume at discrete times between 17/06/04 and 25/09/04

The potassium mass balance is shown graphically in Figure 11. The mass flux into the system at the time of sampling is denoted by red triangles and coloured points denote the mass flux out for each of the four sample areas. It is interesting to note that the mass of potassium leaving the system through infiltration is consistently less than the mass entering the system through greywater irrigation. The mass of potassium leaving the system does not appear to correspond to the mass entering the system. The average difference between mass input and output on the days when both greywater and soil samples were taken is 7.93×10^{-4} kg/day. The mass of potassium leaving the system is significantly higher in sample 3 than the other samples.

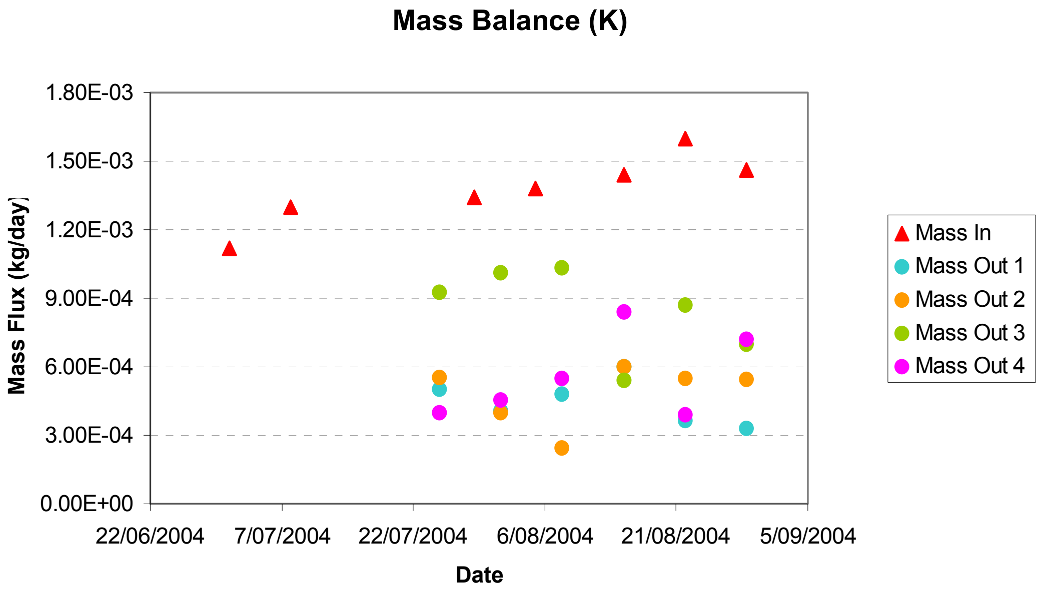

Figure 11: Mass of potassium into and out of the control volume at discrete times between 17/06/04 and 25/09/04

The magnesium mass balance is shown graphically in Figure 12. The mass flux into the system at the time of sampling is denoted by red triangles and coloured points denote the mass flux out for each of the four sample areas. The mass of magnesium leaving the system through infiltration is consistently less than the mass entering the system through greywater irrigation. There is little variation in the mass of magnesium entering and leaving the system over time. The average difference between mass input and output on the days when both greywater and soil samples were taken is 1.21×10^{-3} kg/day.

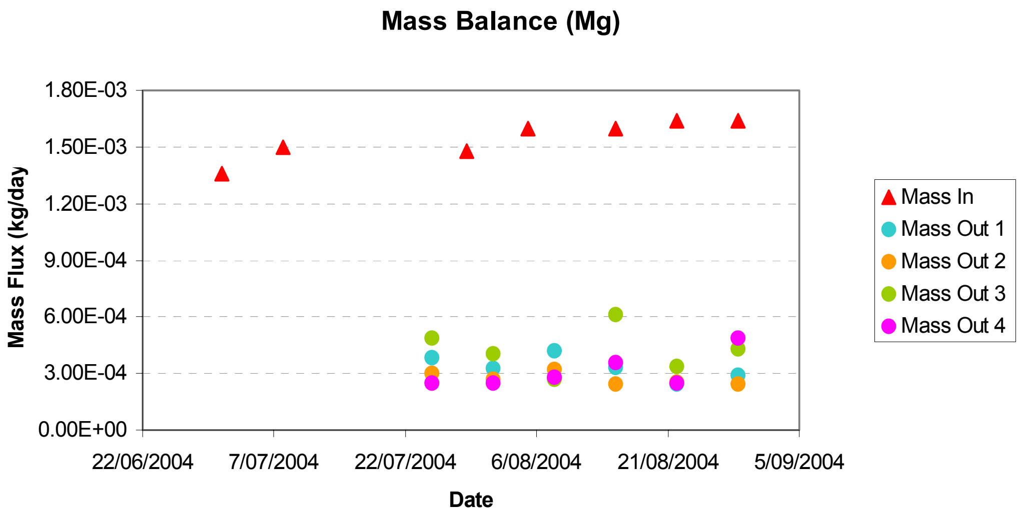

Figure 12: Mass of magnesium into and out of the control volume at discrete times between 17/06/04 and 25/09/04

The lead mass balance is shown graphically in Figure 13. The mass flux into the system at the time of sampling is denoted by red triangles and coloured points denote the mass flux out for each of the four sample areas. The concentration of lead in greywater sampled between 17/6/2004 and 15/8/2004 was below the minimum detection limit and the mass into the system corresponding to this limit has therefore been plotted instead. The mass of lead leaving the system through infiltration is generally greater than the mass entering the system through greywater irrigation. Samples taken on 22/8/2004 and 29/8/2004 contained significantly higher concentrations of lead, and greater mass fluxes through the system on those days.

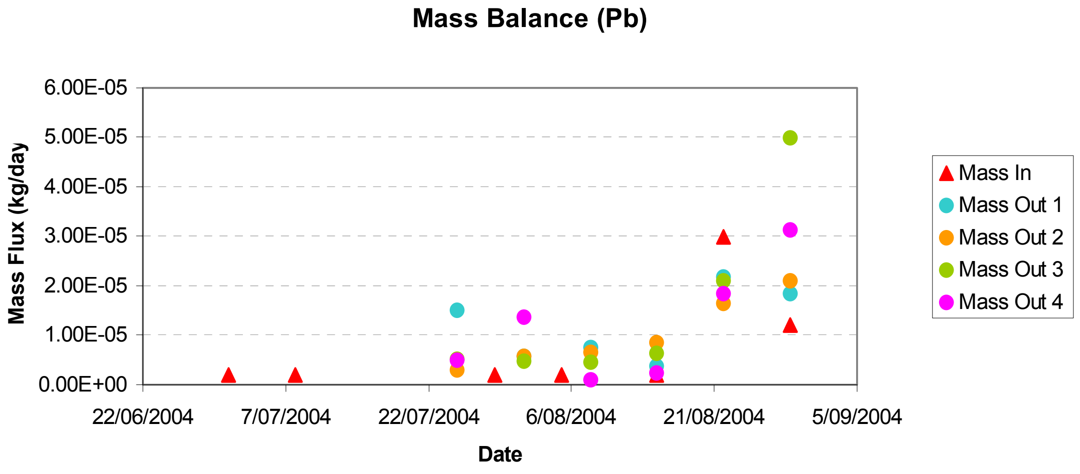

Figure 13: Mass of lead into and out of the control volume at discrete times between 17/06/04 and 25/09/04

The vanadium mass balance is shown graphically in Figure 14. The mass flux into the system at the time of sampling is denoted by red triangles and coloured points denote the mass flux out for each of the four sample areas. The concentration of vanadium in all greywater samples was below the minimum detection limit and the mass into the system corresponding to this limit has therefore been plotted instead. The mass of vanadium leaving the system through infiltration is consistently greater than the mass entering the system through greywater irrigation. The mass of vanadium leaving the system at each sample area did not follow any significant trend.

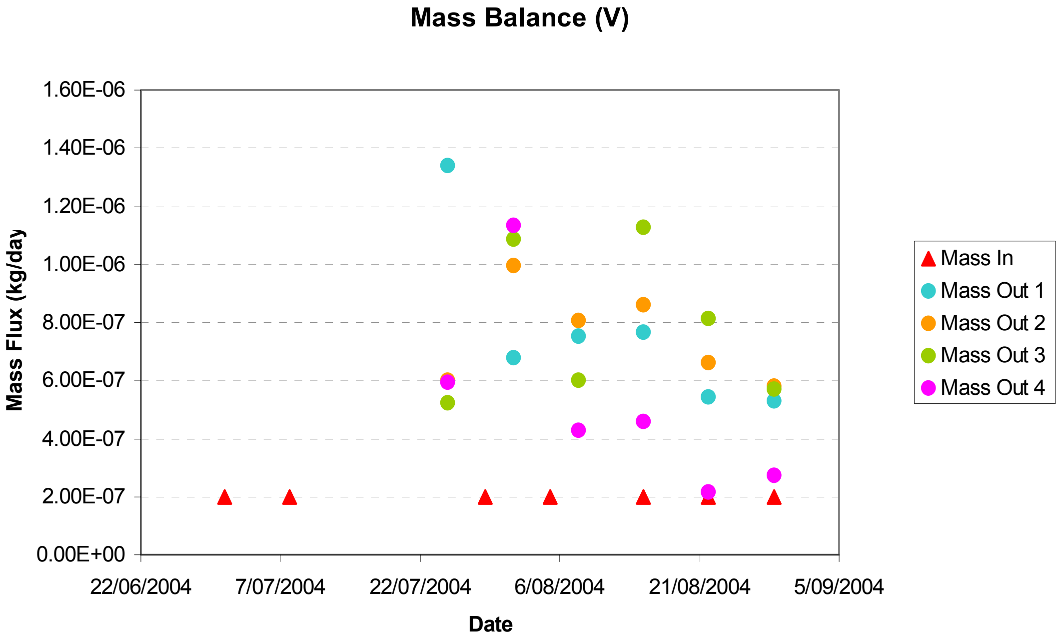

Figure 14: Mass of vanadium into and out of the control volume at discrete times between 17/06/04 and 25/09/04

The sulphate mass balance is shown graphically in Figure 15. The mass flux into the system at the time of sampling is denoted by red triangles and coloured points denote the mass flux out for each of the four sample areas. The mass of sulphates entering the system is variable with time. The mass of sulphate leaving the system through infiltration is consistently less than the mass entering the system through greywater irrigation. The mass of sulphate leaving the system showed a decreasing trend over the first three sample dates for all samples taken, and remained relatively constant for the remaining samples. The average difference between mass input and output on the days when both greywater and soil samples were taken is 2.81×10^{-3} kg/day.

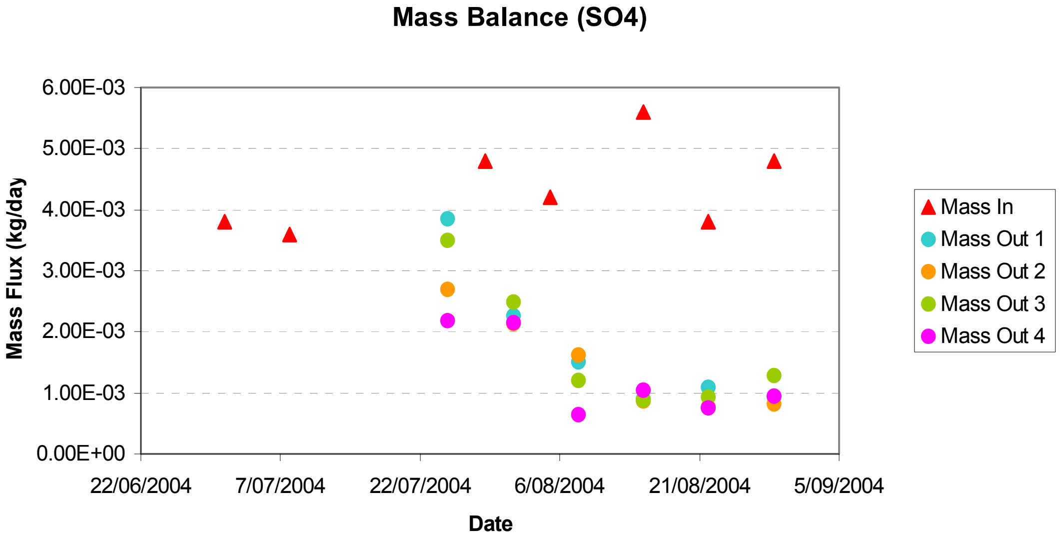

Figure 15: Mass of sulphate into and out of the control volume at discrete times between 17/06/04 and 25/09/04

The total phosphorus mass balance is shown graphically in Figure 16. The mass flux into the system at the time of sampling is denoted by red triangles and coloured points denote the mass flux out for each of the four sample areas. The mass of total phosphorus entering the system is variable with time. The mass of total phosphorus leaving the system through infiltration is generally greater than the mass entering the system through greywater irrigation. The mass of total phosphorus leaving the system showed a decreasing trend over time.

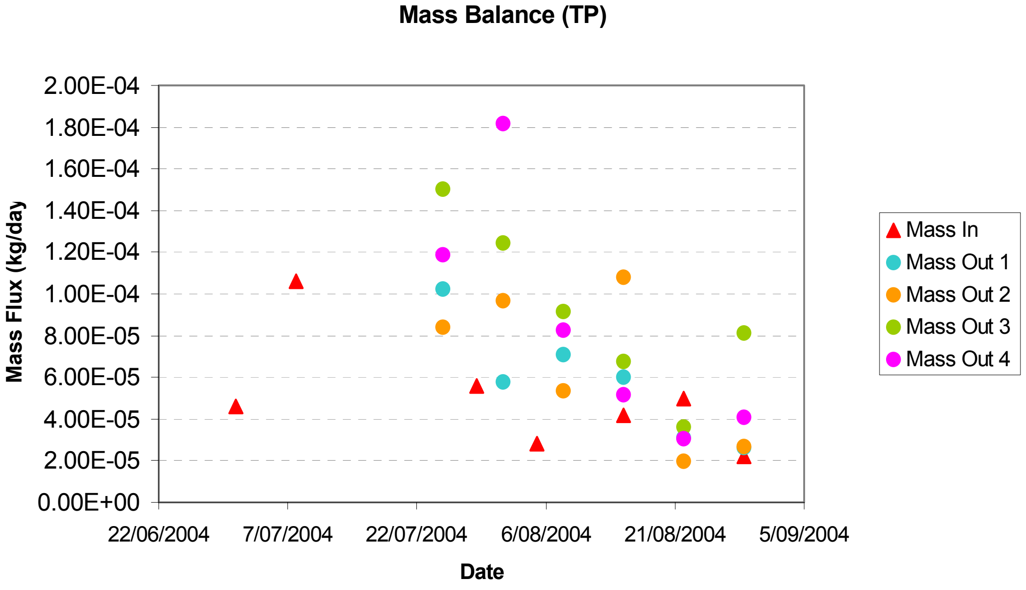

Figure 16: Mass of total phosphorus into and out of the control volume at discrete times between 17/06/04 and 25/09/04

The total nitrogen mass balance is shown graphically in Figure 17. The mass flux into the system at the time of sampling is denoted by red triangles and coloured points denote the mass flux out for each of the four sample areas. The mass of total nitrogen entering the system is highly variable with time. The mass of total nitrogen leaving the system through infiltration is consistently less than the mass entering the system through greywater irrigation. The mass of total nitrogen leaving the system was relatively consistent over time. The average difference between mass input and output on the days when both greywater and soil samples were taken is 3.88×10^{-4} kg/day.

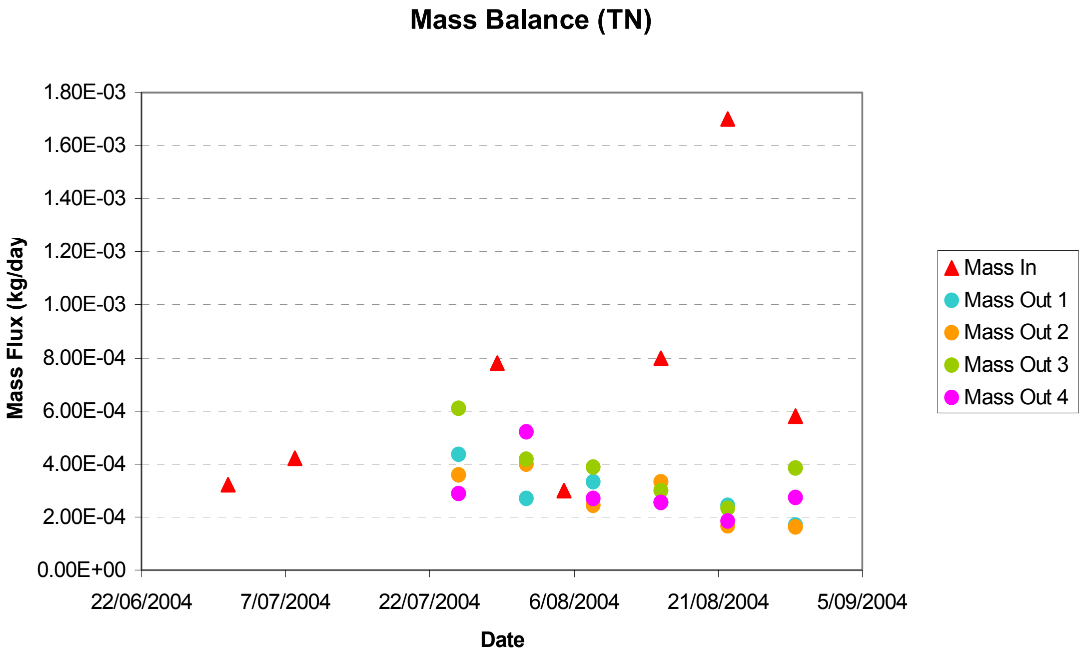

Figure 17: Mass of total nitrogen into and out of the control volume at discrete times between 17/06/04 and 25/09/04

4. DISCUSSION

4.1. Mass Balances

The validation of the SWIM output by comparison with the GMWRF output and soil moisture content data taken from the field indicated that SWIM is accurate. The GMWRF output was approximately three times greater than SWIM's estimate, however, this is could be due to the way in which the GMWRF accounts for vegetative loses. SWIM is a highly complex model that is designed to deal with vegetation, and perhaps the GMWRF model takes a more simplified approach to the effects of vegetation on the system. The detailed determination of the actual cause of the difference in outputs is outside the scope of this project, and is unnecessary as SWIM was accurate when compared to the actual observed soil moisture content. The model's accuracy when compared to the actual observed soil moisture data indicates that the estimated vegetation parameters were reasonable for the study area. Therefore, SWIM produces a reasonable estimate for use in the calculation of the mass balance.

The output from SWIM suggests an average outflow of 1mm per day from the control volume. It follows that evapotranspiration accounts for approximately 77% of all water supplied to the control volume, averaged over the study period. This result indicates that, in addition to rainfall, 200L of greywater irrigation twice a week provides sufficient amounts of water for the lawn to survive. This finding is supported by Rowlands (2003) who determined that the volume of water provided by rainfall alone is sufficient to sustain the warm season turf grass between April and October.

The assumptions made during the mass balance calculation must be noted whilst analysing the results. The mass balance is calculated using average outflow over the period of study; rainfall and evaporation data for 24hr periods; soil moistures and nutrient concentrations specific to the time samples were obtained; and irrigation volumes that are applied over a period of around 15 minutes. The calculation assumes that the soils are homogeneous over the study area, and that all data is applicable to, and averaged over each 24hr time step. However, the application of greywater spans for only 15 minutes and the concentrations of nutrients and elements obtained apply only to the time at which samples were taken. For simplicity, it has been assumed that the mass of nutrients and elements leaving the control volume is representative of the actual outflow over time. The calculation also assumes homogeneity over the lawn area and control volume.

There is some spatial variability in the mass of nutrients leaving the control volume. In particular, sample 3 consistently showed greater concentrations leaving the control volume than the other samples for the majority of elements tested. This variability may be due to the health or degree of disturbance to the overlying turf during the initial experimental set-up when the turf was disturbed to locate the irrigation lines. If this is the case, the less dense vegetation above the area where sample 3 was taken is demanding less nutrients and allowing more to pass through the control volume with infiltration. Alternatively, assuming that the irrigation network equally distributes greywater and nutrients over the entire lawn, this spatial variation may be due to differences in soil structure, such as the existence of macropores, in the area where sample 3 was taken allowing more nutrients through.

There does not appear to be any variability between the means of all samples between weeks. From the sampling regime (one sample a week progressively around a circle for six weeks surrounding one dripper for each of the four sample areas), either a consistent increase or decrease over time was expected if the soil was holding the nutrients. However, there are no trends in the concentrations of any of the nutrients or elements leaving the control volume, suggesting that the soil is not storing any of the nutrients or elements and what is not being taken up by the vegetation is leaching through to the groundwater. This is expected because the soil under the lawn is largely sandy with very little clay content, and thus little storage capacity.

The nutrient mass balance showed that there is a source of lead within the system after the greywater storage tank. The lead is most likely to be sourced from within the soil and may be due to a build up from atmospheric lead over time. The significant increase in the lead content of all samples taken on 22/8/2004 and 29/8/2004 may be due to contamination or error in the laboratory on the day that they were analysed. Reasons for this are that samples from these two days were analysed together (all other samples had been analysed at least a fortnight earlier), the sampling methods on those two days were replications of the methods carried out previously, and it is highly unlikely that the lead contents increased so dramatically in all greywater and soil water samples when there were no significant events within the household that may have increased the lead content in the greywater produced.

The nutrient mass balance also showed that there were increased masses of calcium, vanadium and total phosphorus leaving the control volume in comparison to the masses entering through greywater irrigation. This is possibly due to a remaining excess of these elements from the original turf farm fertiliser. An explanation for the remaining excess may be that these elements are released slower than the other fertiliser components. The excess of total phosphorus and little visible turf growth (a symptom of nitrogen deficiency in plants and turf (Bennett 1993; Turner 1993)) suggests that the turf growth is nitrogen limited.

The initial turf death was assumed to indicate that all nutrients from the original fertilisers had ceased leaching. However, the results from the mass balance show that calcium, vanadium and total phosphorus are still in excess within the control volume, suggesting that the growth of the turf is limited by other nutrients. A list of known essential plant nutrients and their functions is included in Appendix 7: Essential Plant Nutrients, and Table 9 below shows the general sufficiency range for turfgrass nutrients. The figures quoted in the table are the percentage (macronutrients) or parts per million (micronutrients) of grass tissue composed of each nutrient.

Table 9: General sufficiency range for turfgrass (adapted from Turner (1993))

Macronutrients		**Micronutrients**	
Nutrient	**Range**	**Nutrient**	**Range**
N, %	2.8 – 3.5	Fe, ppm	35 – 100
P, %	0.1 – 0.4	Zn, ppm	22 – 30
K, %	1.0 – 2.5	Mn, ppm	25 – 150
Ca, %	0.5 – 1.2	Cu, ppm	5 – 20
Mg, %	0.2 – 2.6	B, ppm	10 - 60
S, %	0.2 – 0.4		

Turf analysis carried out by Jogia (2004) established that the grass in its initial condition was healthy and that most of the nutrients were within the general ranges presented above. The exceptions were zinc and iron, which were present at 44–81ppm and 2.4–0.76ppt respectively, and were not cause for concern as no deleterious effects of high zinc concentrations have been recorded (Turner 1993), and none of the typical symptoms of iron toxicity were observed.

Jogia's data also showed a decrease in within-plant nutrient levels over time (July – October 2003). This observation, along with evidence that turf death occurred in early March 2004 and the fact that the grass has never required mowing since it was laid suggests that there is in fact a nutrient deficiency occurring and that the greywater, although beneficial, is not providing sufficient nutrients to the turf. This may be partially attributed to the inability of the sandy soils to store the nutrients for lengthy periods of time, possibly inhibiting the plants from consuming optimal amounts of nutrients. It is clear from the mass balance data that macronutrients potassium, magnesium, sulphate, and total nitrogen are being stored within the control volume. This is interpreted as consumption by the grass as the sandy soils allow quick drainage and have little capacity to hold the nutrients. The excess of calcium, vanadium and total phosphorus prevents the uptake of these nutrients from being determined. The low (below detection limit) concentrations of molybdenum in samples have also prevented a meaningful mass balance, and thus the determination of plant uptake for this nutrient. Grass samples were not analysed during this study and it is recommended that the grass is analysed to determine its nutrient composition and thus confirm, or otherwise, the nutrient deficiencies suggested here. Once this analysis has been performed, a fertiliser regime can be determined for the lawn to allow optimal turf growth whilst minimising leaching of nutrients to the groundwater.

It must be noted that this study is focussed on a family home that engages in environmentally friendly practices and uses household products that are as gentle to the environment as possible. Environmentally friendly products generally contain a more neutral pH, less sodium and less phosphorus than normal household products (Patterson 2000). Thus if greywater is reused from a residence using normal household products, the discharge of phosphorus and sodium to the irrigated area will be greater and may have an effect on the nutrient balance within the soils. It is recommended that households engaging in greywater reuse also use environmentally friendly products to complement their environmental efforts through greywater reuse.

4.2. Overcoming Possible Barriers to Widespread Greywater Reuse

The results from the mass balances carried out by this study, and the chemical and pathological study by Jogia (2004) have examined the major environmental and water quality issues associated with the reuse of greywater for garden irrigation. Having established that greywater reuse is a benefit to irrigated lawns and does not pose a health threat to humans under appropriate circumstances, this dissertation continues further to identify the major barriers that may be preventing the widespread reuse of greywater in Perth.

Public perceptions and acceptance are now recognised as the key elements of success for any development that has the potential to change a community’s way of living. Consequently, these elements are also considered as major barriers to the widespread reuse of greywater by households in Perth due to the nature of household greywater reuse systems and the commitment they entail.

Recent studies and community consultation sessions have shown that, in general, large-scale water reuse is widely accepted by the Australian community. A focus group held by the Water Corporation of Western Australia (2003) indicated that people rated the idea of using recycled water very positively, with similar findings by studies in Melbourne (Melbourne Water 1998) and Sydney (Sydney Water 1999). However, support for water reuse does not translate directly into willingness to use recycled water, with participants in independent talks and surveys sharing the common view that recycling water was a positive move, but they themselves could not use the recycled water (Po et al. 2003).

Studies in the U.S.A. and Australia have shown that the degree of opposition to a reuse scheme is related to the amount of contact that users will have with the reclaimed water, with the reuse of water for potable purposes receiving the greatest opposition (summarised in Table 10). The reuse of recycled water for home lawn/garden irrigation purposes attracted little opposition from participants of the surveys.

Table 10: The percentage of respondents who were opposed to specific uses of recycled water from different studies, adapted from Po et al. (2003)

	ARCWIS (2002) N=665 %	Sydney Water (1999) N=900 %	Lohman & Milliken (1985)* N=403 %	Milliken & Lohman (1983)* N=399 %	Bruvold (1981)* N=140 %	Olson et al. (1979)* N=244 %	Kasperon et al. (1974)* N=400 %	Stone & Kahle (1974)* N=1000 %	Bruvold (1972)* N=972 %
Drinking	74	69	67	63	58	54	44	46	56
Cooking at home	-	62	55	55	-	52	42	38	55
Bathing at home	52	43	38	40	-	37	-	22	37
Swimming	-	-	-	-	-	25	15	20	24
Washing clothes	30	22	30	24	-	19	15	-	23
Irrigation on dairy pastures	-	-	-	-	-	15	-	-	14
Irrigation of vegetable crops	-	-	9	7	21	15	16	-	14
Vineyard irrigation	-	-	-	-	-	15	-	-	13
Orchard irrigation	-	-	-	-	-	10	-	-	10
Hay or alfalfa irrigation	-	-	-	-	-	8	-	9	8
Home toilet flushing	4	4	4	3	-	7	-	5	23
Home lawn/garden irrigation	4	3	3	1	5	6	-	6	3
Irrigation of recreation parks	-	3	-	-	4	5	-	-	3
Golf course irrigation	2	-	-	-	4	3	2	5	2

*cited in Bruvold (1988) – these studies were conducted in the US.

Similar results have also been obtained by studies specific to greywater reuse in other parts of Australia. These studies, however, looked more in depth into respondents' perceptions and acceptance and found that, although there was a high degree of willingness to reuse greywater for garden/lawn irrigation, other factors could reduce this preparedness. The influencing factors found by these studies included attitudes towards water conservation, cost, space, odour, health issues, security of supply and local government restrictions. Overall, respondents would only consider reusing their greywater if they could be sure that the benefits outweighed the costs of their efforts within a few years (Christova-Boal et al. 1996; White et al. 2003; Emmerson 1998).

Anecdotal evidence suggests that if homeowners perceive a benefit, whether financial, economic or social, from the reuse of greywater, they are prepared to use such systems, even where they are currently illegal (Emmerson 1998). A survey by the Australian Bureau of Statistics (ABS) (1998) found that approximately 19% of Australians and approximately 15% of Western Australians used recycled water to conserve garden water. However, only 0.4% of Australians, and no Western Australians, used recycled or greywater as their main source of garden water (ABS 1998). These numbers are extremely low, indicating that, although the general community supports the use of recycled water for lawn/garden purposes, the factors influencing perceptions and acceptance of greywater reuse are outweighing people's support for its use and therefore, the support is not being translated into practice.

The factors in the literature that may influence the behavioural acceptability of a reuse scheme to the general community are detailed by Po et al. (2003) as:

- Disgust
- Perceptions of risk associated with using recycled water
- The specific uses of recycled water
- The sources of water to be recycled
- The issue of choice
- Trust and knowledge
- Attitudes toward the environment
- Environmental justice issues
- The cost of recycled water
- Socio-demographic factors

These can be categorised into six major issues that may be acting as barriers to the widespread reuse of greywater by households in Perth. These are:

- Public perceptions
- Costs
- Environmental considerations
- Public health
- Authorities' perceptions
- Regulations and regulators

The following sections briefly examine each of the six major issues.

4.2.1. Public Perceptions

As detailed above, there appears to be widespread support for greywater reuse for lawn/garden irrigation, but support has not been translated into actions in Western Australia. This barrier must be addressed by first defining the major issues influencing the community in question, then working within the community to overcome these barriers. Giving the public a sense of ownership by involving them in the development process for a given project has been proven to be more successful than an education and awareness campaign alone (Po et al. 2003). Giving the public the power to make an informed choice about their options encourages them to participate in water reuse solutions to water supply problems.

4.2.2. Costs Associated With Greywater Reuse

Accessibility of Information

The level of awareness about environmental issues, especially water and wastewater related issues, is key to informing a decision about greywater reuse systems. In general, people who are more informed about environmental issues are more likely to consider installing a greywater reuse system in their home. However, once the decision is made to seek further information regarding the greywater systems that are most suitable to the site under consideration and the process by which one can go about installing a greywater system, the location of such documents can prove to be a difficult task. Browsing through the relevant Western Australian Government internet websites illustrates that information is not easily locatable on the Department of Health, Water Corporation, or Local Government websites unless one has prior knowledge about the names of the relevant documentation. Contact details for the persons in charge of greywater related issues are also difficult to locate, but are given in the documentation. However, it is not only government information that is difficult to obtain. Communication with suppliers of greywater systems or components is difficult unless one has some background knowledge about the systems or components in question. When telephoning businesses to obtain quotes and information for various Health Department approved systems, it was found that people did not impart information easily or knew little about their products. One would gain little motivation to install a greywater reuse system from the information given by the businesses. This difficulty in accessing information regarding greywater reuse systems in Western Australia, and the lack of motivation to install such a system are major barriers to the widespread implementation of household greywater reuse systems in the state. Unless the wider community is educated about water issues and greywater reuse, it is highly unlikely that greywater reuse will become a widespread practice.

Accessibility of Greywater

The first step towards reusing greywater is accessing the greywater within a residence. Many existing slab-based houses are plumbed such that greywater and blackwater streams merge in pipes embedded within the concrete slab (Emmerson 1998). In these cases, accessing greywater is extremely costly and troublesome and will not be economically viable. Existing non-slab houses can be re-plumbed to allow access to greywater relatively easily, but the costs incurred are still high enough to deter the average homeowner. The most cost-efficient option is to incorporate a greywater reuse system into the construction of a new house, resulting in little extra cost on top of the standard plumbing (Emmerson 1998; Brennan & Patterson 2004). These three options lead to the conclusion that reusing greywater is realistically limited to new houses and new housing developments.

Installation and Maintenance

Treatment of greywater to a quality safe for human contact is expensive to achieve on an individual household basis. It is also difficult to ensure that treatment systems are maintained because no enforced maintenance regulations exist. Surveys in the U.S.A. and Australia have found that 60-80% of “on-site domestic wastewater treatment plants” are not maintained adequately and consistently do not produce an acceptable quality effluent (Jeppesen 1996).

However, if greywater is to be used for non-contact, subsurface irrigation, only primary treatment (treatment by physical processes such as filtration or settling) is required and systems are relatively cheap to install, run and maintain. As mentioned previously, there are currently seven systems that are approved for use in Western Australia (Department of Health 2004). These systems are generally for non-contact irrigation use only and range in price from around \$1000 fully installed to around \$4000 fully installed. The cheaper systems are basic systems that involve a simple storage tank connected to subsurface slotted piping or trenches. The more expensive units incorporate a pump and filter.

System maintenance will vary depending on configurations and householders. The system studied collects greywater from a household containing two adults and two young girls in a storage tank before it is pumped through subsurface drip irrigation lines under the lawn. Maintenance of this system requires the tank filter to be cleaned approximately once every nine weeks. This simple task involves purging the disc filter for five minutes with a garden hose to remove all the lint and hair accumulated over time.

Costs Over Conventional Scheme Water Use

Water use and sewerage services are not currently a major factor in the cost of living in Australia. Based on the weights used to calculate the 14th Series Consumer Price Index (a reflection of the relative expenditures of Australian households on average), water and sewerage costs account for only 0.87% of household expenditure. Water and sewerage services are cheap in comparison to other household expenditure such as food (17.72%), private motoring (14.40%), alcohol and tobacco (7.41%), clothing (5.19%), health (4.69%), communication (2.88%), electricity (1.66%), and pets (0.76%) (Trewin 2000). Therefore, the present cost of consuming water is very low to Australian household consumers in general.

The cost of installing a greywater reuse system will be site-specific, depending on the system design and the characteristics of the residence. The cost to purchase and install a primary treated greywater reuse system in Perth currently ranges between \$1000 and \$4000. The Western Australian government is offering a \$500 rebate on greywater reuse systems under its Waterwise Rebate Program (Government of Western Australia 2004), reducing the initial costs of a fully installed system to between \$500 and \$3500.

The average residence in Perth consumed 278kL of water during the last financial year (Water Corporation 2004b). If all greywater is reused, then according to the flow contributions described in Section 1.1.2 there is a potential for over 75kL of water to be saved each year.

The cost of water to residents in the Perth metropolitan area is currently 67.4 c/kL (for the 151–350kL/year usage bracket) (Water Corporation 2004b). Using this price and the amount of water potentially saved by greywater reuse, the savings in water would be around 76kL or $51.15 per year. The time it would take to break even on installing the greywater reuse system (not including maintenance costs) would then be in the order of 10 to 69 years (payback periods in the literature for different systems range between 7 and 21 years (Brennan & Patterson 2004; Jeppesen 1996; Emmerson 1998)). The average lifespan of a greywater reuse system is said to be around 10 years (Emmerson 1998).

Results from a social survey conducted in Melbourne, suggest that people are only willing to invest in a greywater reuse system if the payback period is between 2 to 4 years (Christova-Boal et al. 1996). It is therefore unlikely that localised greywater reuse will become widespread in Perth, or even Australia, in the short term unless the price of water dramatically increases and/or the price of the systems dramatically decrease. For example, if the cost of the systems remain the same, the price of water would have to increase to between $1.65/kL and $11.53/kL to decrease the payback period to 4 years, or between $3.29/kL and $23.06/kL to achieve a 2 year payback period. This is comparable to other studies that have found the required cost of water to be between $3/kL and $33/kL to enable different greywater systems to be cost effective (WSAA 1998; Allen & Pezzaniti 2001; Leahy et al. 1998).

Presently, there is no real incentive (monetary or otherwise) for installing a greywater reuse system. The government rebate reduces the initial cost, but the only reward for the installation, maintenance, and long-term use of a greywater reuse system is to please one’s own environmental conscience.

4.2.3. Environmental Considerations

The effects of the application of greywater to soils vary with soil type and climate. The most common environmental concerns related to greywater reuse include the effects of greywater constituents on soils and plants, the possibility of contamination of groundwater and other water bodies though infiltration and runoff, and aesthetics.

Effects of Greywater on Soils and Vegetation

Greywater typically contains chemicals such as boron, sodium, salts, chlorine and alkaline chemicals which may be harmful to vegetation or soils if reused for garden irrigation (Jeppesen & Solley 1994).

Boron is contained in many detergents and powdered cleansers. It is beneficial as a micronutrient for plants in small concentrations but is toxic to plants, and can be toxic to animals, in high concentrations (Prillwitz & Farwell 1995). The maximum concentration of boron for long term use on sensitive plants is recommended as 0.75 g/L by the U.S. Environmental Protection Agency (1992). The use of household products containing minimal boron contents is therefore recommended.

Excessive sodium application to clay soils reduces pore volumes resulting in greasy soils with poor soil structures and decreased drainage capacity (Jeppesen & Solley 1994). High levels of sodium can also be detrimental to the growth of some plants. Laundry detergents are a major contributor of sodium to the greywater stream as sodium salts are used in laundry powder detergents as a ‘filler’ (Patterson 2000; Prillwitz & Farwell 1995). The use of household products containing lower sodium contents, such as liquid detergents instead of powdered cleaners, is therefore recommended.

The use of greywater for garden irrigation may not be appropriate in some cases. The pH of greywater typically ranges between 6.5 and 9.0 and long-term irrigation may cause soils to become progressively more alkaline (Department of Health 2002). Care must therefore be taken when using greywater to irrigate shade loving and acid loving plants such as azaleas, camellias, gardenias, begonias, and ferns (Prillwitz & Farwell 1995). The pH levels of irrigated soils may be managed by mixing soil conditioners into the soil.

The irrigation of native Western Australian plants must also be carried out with caution as greywater is relatively high in nutrient content and these plants often require nutrient depleted conditions or have low phosphorus tolerance (Jeppesen & Solley 1994; Beavers 1995). For example, plants of the Proteaceae family, such as grevillea, hakea, banksia and silky oak, are susceptible to excess phosphates and are therefore not suited to irrigation by greywater. For this reason, the Department of Health (2002) recommends that only products with very low phosphorus content should be used.

The phosphorus content in various detergents can range from 0.05% up to 10%. One must therefore be careful in choosing detergents as a survey of household detergents carried out by Patterson (2000) found that products labelled with easily identifiable symbols **P** (the product complies with agreed industry standards on phosphorus which impose a maximum content of 7.8g per wash) and **NP** (no added phosphorus) can be misleading. Results from the study showed that the actual phosphorus contents in laundry products labelled **P** alone ranged from approximately 1mg/L to approximately 54mg/L in a full wash load. The maximum phosphorus content of 7.8g per wash is equivalent to a concentration of 50mg/L in a full wash load. A two-page article containing the sodium and phosphorus results from the study has been published to assist in identifying the most suitable products (Patterson c. 2000).

Contamination Of The Water Table And Other Water Bodies

Excess irrigation with greywater may lead to groundwater contamination or greywater runoff, depending on irrigation rates and soil conditions. Nutrients and other contaminants contained within the greywater may have adverse effects on the environment and irrigation systems must be carefully designed to prevent situations in which contamination may occur. System flow rates on coarse sandy soil or gravel should be designed to avoid greywater leaching into groundwater or surface water bodies. Greywater systems in sandy soiled areas should also be installed more than 100 metres away from a wetland, streamflow (including stormwater drains) or other water sensitive ecosystems if the Phosphorous Retention Index (PRI) of the soil is less than 5 (Department of Health 2002).

Aesthetics

The storage of greywater for more than 24 hours can result in the generation of offensive odours (Jeppesen 1996; Water Authority of Western Australia 1994) and the growth of microorganisms. Jeppesen (1996) recommends direct reuse without storage to minimise the microorganism growth, and hence reduce offensive odours and the health risk with contact. However, the Department of Health's Draft Guidelines for the Reuse of Greywater in Western Australia (2002) suggests that systems treating bathroom and/or laundry greywater only must be designed for at least 24 hour combined retention for the daily flow of greywater, with 40 litres/person/year of capacity allowed for scum and sludge accumulation. Therefore, a compromise must be made in designing a greywater reuse system to have at least 24 hours retention and to minimise odours by other methods such as sealing the tank and subsurface irrigation.

4.2.4. Public Health

Microbial Quality of Greywater

Greywater is ultimately a form of sewage and must be treated with the appropriate care. The microbial quality of wastewater, and hence greywater, is commonly measured by the presence of faecal coliforms, which indicate the presence of intestinal pathogens such as Salmonella or enteric viruses. One such coliform is *Escherichia coli*, or E. Coli as it is more commonly known. In general, a high faecal coliform count is undesirable as it implies a greater chance for human illness to develop as a result of contact with the greywater during reuse (Allen & Pezzaniti 2001; Rose et al. 1991). It must be noted that faecal coliform counts are only used as pollution indicators, not the absolute risk of developing an illness, because, as noted by Millis (1993), pathogens such as *Giardia, Acanthamoeba, Cryptosporidium, Naegleria* can occur in water where coliforms may not be a very sensitive indicator.

Data for Australian and overseas domestic wastewater quality are provided by Brower and Brueja (1983), and summarised by Geary (1987). Results from a Melbourne study of bathroom and laundry effluent is presented in Christova-Boal, Eden and McFarlane (1994). Few studies have specifically addressed the microbial count of greywater (Emmerson 1998). A literature review by Allen & Pezzaniti (2001) summarised reasonably typical pathogen characteristics of household wastewater as indicated in Table 11.

Table 11: Typical pathogen characteristics of household wastewater (adapted from Allen & Pezzaniti (2001))

Area of Origin	Pathogens
WC	Very High
Kitchen	Low
Laundry	Usually low
Bathroom	Usually low

The literature indicates that, even though laundry and bathroom greywater are usually low in pathogens, the use of greywater can pose a potential public health risk (Allen & Pezzaniti 2001). A study by Allen (1997) revealed sporadic presence of faecal coliforms in combined laundry/bathroom from a "low-risk" household of two adults and a teenage child. Higher concentrations of bacteria indicator organisms are likely in households with young children or people with illnesses.

Public Health

Human health concerns are a critical issue in the evaluation of greywater reuse. The health risks associated with greywater reuse generally relate to acute effects associated with infection from pathogens such as bacteria, protozoa, viruses and parasites (Emmerson 1998). No studies to date have identified long-term or chronic impacts associated with the reuse of greywater (Law 1997) and no illnesses resulting from contact with greywater reuse have been reported, despite widespread practice of greywater reuse (Jeppesen & Solley 1994). This (lack of) information must be treated with care as it does not mean that no illnesses have occurred and does not rule out the possibility of disease transmission from contact with reused greywater. Although there have been no documented disease outbreaks resulting from the reuse of greywater in Australia, the consequences associated with the reuse of raw or improperly treated wastewater in other countries is well documented (Emmerson 1998).

The safest method of greywater reuse is to prevent human contact with the greywater. The 22 western states of the U.S. have firmly adopted this principle in allowing domestic greywater re-use as part of their uniform plumbing code (Jeppesen 1996). Surface spray irrigation of greywater produces aerosols or droplets that cannot be confined to a given area, posing a potential health risk. Therefore, subsurface irrigation is recommended to minimise the environmental and health risks associated with greywater use. In fact, section 2.1 of the Department of Health's Draft Guidelines for the Reuse of Greywater in Western Australia state that:

> Greywater systems (this does not include bucketing) must dispose of greywater below the ground surface unless treated and disinfected to an appropriate standard

Despite the potential public health issues associated with the reuse of greywater, research to date has indicated that any problems that do exist can be controlled or eliminated using current technology and practices (Emmerson 1998).

Mosquitoes and Vermin

Birds, animals, mosquitoes and other vermin such as rats, mice, cockroaches and flies, can transmit pathogens. Inadequately maintained greywater systems and poor irrigation methods or practices could provide further breeding habitats for these creatures (Jeppesen & Solley 1994; Emmerson

1998). Screening vents, use of airtight access covers and proper system planning and maintenance should prevent the possibility of pathogen transmission through these avenues.

Owner Maintained Systems

Proper maintenance is the key to the success of a greywater reuse system and it is in the householder's best interest to commit to maintaining the system. However, according to Jeppesen and Solley (1994), surveys in the U.S.A., Australia and Brisbane have found that 60 to 80 percent of on-site domestic wastewater treatment plants are not maintained adequately and hence consistently do not produce effluent of an acceptable quality. It is imperative that any person who makes the decision to install a greywater reuse system, or inherit such a system, is aware of the commitment required and the health hazards associated with poor maintenance.

4.2.5. Authorities' Perceptions

Studies, in combination with anecdotal evidence, suggest that the public may be more willing to accept greywater reuse than water utilities or health authorities (Thomas et al. 1997). However, the greater caution on behalf of the government agencies may be attributed to two main factors.

The first factor influencing the differing levels of perceived acceptability of greywater reuse between the community and the government agencies is level of concern for public health and safety. For example, many residential households reuse greywater, particularly from washing machines, for garden watering despite the disease risk and illegality of the practice (Thomas et al. 1997). This may be due to the differing levels of awareness about the possible health risks involved with greywater reuse and the duty of care that government agencies must provide when considering changes to water supplies. To illustrate this point, informal conversations with employees of the Department of Health (Environmental Health division) and the Water Corporation indicated that many of the employees are supportive of greywater reuse as long as regular maintenance of systems is carried out to prevent possible health risks. It is also interesting to note that the younger employees showed more willingness to support wastewater recycling whilst the more senior employees were more likely to have reservations about the possible health risks.

The second factor influencing the differences in perceptions is the cost involved in treating and reusing water. Employees of the Water Corporation indicated that the Water Corporation would not increase their reuse more than their 20% target (by 2012) (Water Corporation 2004a) for both economic and health reasons. They also suggested that large-scale wastewater recycling would be considered almost as a last resort when water supply issues became extremely pressing, mainly because of the costs involved in treating the wastewater to an acceptable quality for reuse. The present costs incurred by the Water Corporation in treating wastewater for reuse far outweigh any costs that householders incur when ‘bucketing’ their untreated greywater onto their gardens or installing backyard greywater reuse systems, hence the difference between the public and the water provider in willingness to carry out reuse.

4.2.6. Regulations

Various legislation covering health, building, sewage, clean water, plumbing and draining governs the disposal of domestic wastewater in all Australian States. Legislation in each of the States requires the discharge of all wastewater to a sewer in sewered areas. Exemptions from this requirement are allowed with permission by the regulatory authority, which is usually the water provider or the local government authority.

Direct greywater reuse is illegal in most circumstances in Australia and there are no scientifically based national water recycling guidelines (Brennan & Patterson 2004). However, greywater reuse for lawn or garden irrigation is permitted in most states if it has passed through some form of treatment prior to use. Water reuse is a relatively new idea in Australia and regulations specifically for the reuse of wastewater have only been developed recently in some states, and are currently being developed or are still non-existent in other states. Current regulations are set by the state health departments and are generally conservative to avoid potential environmental and public health risks. In 1996, Jeppesen and Solley produced a research report called “Model Guidelines for Domestic Greywater Reuse for Australia”, which is now commonly referred to in the current regulating documents. The independence of the states in defining greywater guidelines has also resulted in inconsistencies between states and, in some cases, local communities. Table 12 presents the existing state guidelines.

Table 12: Variation of State Regulation of Greywater: Australia 2003 (Brennan & Patterson 2004)

State	Method	Regulation
NSW	Diversion*	Diversion of greywater from the bath, shower or laundry without storage or treatment generally does not need approval; however, Hastings Council (NSW) permits the use of greywater from washing machines only during periods of water restrictions.
	Storage**	Permitted with treatment via a domestic greywater treatment system (DGTS) that provides collection, storage, treatment and disinfection. Approval by local authorities.
Victoria	Diversion	Method does not need council's 'septic tank permit' but approval is needed to alter the sewer connection; may only be used for subsurface irrigation.
	Storage	Permitted with treatment via a domestic greywater treatment system (DGTS) which provides collection, storage, treatment and disinfection. Output may be used for surface or subsurface irrigation. Environment Protection Authority is approving authority.
Queensland	Sewered area	Greywater reuse is prohibited; must discharge to sewer (DNRM, 2003).
	Unsewered areas	Greywater is considered sewage and comes under the Onsite Sewerage Code; only when treated to secondary standard can it be reused.
South Australia	Primary treated	Greywater must be disposed of subsurface, while surface discharge requires treatment and disinfection. Greywater systems are considered alternative on-site wastewater systems and require approval before installation.
Western Australia	Bucketing	Permitted without regulation.
	Primary	Must be distributed in below ground trenches.
	Secondary treated	Application by microdrip or spray irrigation; requires approval from WA Health before installation (20/30/10 for BOD5, TSS and FC)

* greywater diversion devices [GDD] either by gravity flow or through a pump diversion (that is not a storage tank)

** Performance guidelines are set for the DGTS for BOD, TSS and FC.

Greywater is traditionally recognised as a separate form of wastewater in non-sewered areas. Again, specific regulations are determined by the local authorities, but most base their guidelines on the Australian Standards AS 1547 (Disposal Systems For Effluent From Domestic Premises) (Emmerson 1998).

In 1996, the Western Australian Health Department released *Draft Guidelines for Domestic Greywater Reuse in Western Australia*. Since then, the guidelines were updated and released for comment in 2002. The reviewed guidelines are due for release at the end of 2004.

In accordance with the Western Australian guidelines, a greywater system must undergo a formal application and approval process before it can be installed and used (Department of Health 2002). The process comprises of an Application to Construct or Install an Apparatus for the Treatment of Sewage to the Local Government. The Local Government will seek approval from the Sewerage Service Provider responsible (the Water Corporation in Perth), and the Department of Health before approving an application. A licensed plumber, who has approval from the Sewerage System Provider, must carry out all plumbing work if any connections or modifications to the existing sewerage system are required. Approvals for household scale greywater reuse system take at least 3 weeks, on average, to turn over.

5. CONCLUSIONS AND RECOMMENDATIONS

Three of the nutrients that were leaching in greater quantities than were supplied by greywater irrigation during a previous study are still continuing to do so one year after the initial study. The mass balances carried out for these nutrients indicate that the control volume is a source for calcium, vanadium, and total phosphorus, and suggest that these nutrients are still being released from the excess fertiliser initially applied by the turf farm. The control volume is also acting as a source of lead.

The mass balances for the remaining essential plant nutrients tested indicate that the turf is consuming the potassium, magnesium, sulphate, and total nitrogen supplied by the greywater. Thus the nutrients supplied by the greywater are a benefit to the lawn to which it is applied. However, evidence suggests that there is a nutrient deficiency preventing the grass from achieving optimal growth, and that the nutrients in the greywater are not sufficient to sustain the growth of a family lawn.

This dissertation and the previous study by Jogia (2004) examined the environmental and water quality aspects of greywater reuse. The studies have established that fertiliser should be applied to lawns to supplement the nutrients supplied by greywater irrigation to enable optimal lawn growth, and that greywater reuse for irrigation is not a human health hazard when utilised correctly. The only real health hazard within the greywater system studied is possible contact with the greywater in the storage tank. Appropriate precautions must therefore be made during regular maintenance events and whilst carrying out activities that involve possible contact with the stored greywater.

Having established that greywater reuse is a benefit to irrigated lawns and does not pose a health threat to humans under appropriate circumstances, this dissertation went further to identify the major barriers that may be preventing the widespread reuse of greywater in Perth. Six major barriers were identified that may be preventing the widespread reuse of household greywater for garden irrigation in Perth. These are public perceptions, costs, environmental considerations, public health, authorities' perceptions, and regulations. The most influential of these barriers is the cost involved in reusing greywater. Greywater reuse is realistically limited to new houses and new housing developments due to the costs of accessing plumbing in existing structures. Purchasing and installing a system can cost between $500 and $3500 fully installed with a $500 government rebate, depending on the design and system requirements. At these prices, the payback period for the simplest form of reuse system at the current water prices is 10 years. Given that studies have found that people are only willing to invest in systems if the payback period is less than 2 years, the price of water would have to increase to \$3.29/kL for the investment to occur. Therefore, it is highly unlikely that greywater reuse will become widespread in Perth, or even Australia, in the short term unless the price of water dramatically increases and the system technology progresses rapidly.

Specific to the greywater system and study site, it is recommended that further studies be carried out to determine the fertiliser regime required by the irrigated lawn, and the long-term effects of primary treated greywater reuse on the irrigated soils and plants. The three studies carried out thus far on the system and study site have focussed on the soil mechanics, and environmental and human health effects of reusing greywater. A further recommendation is to carry out a study that examines the greywater reuse system to identify areas that may be developed further to optimise the system's performance. Studies that compare, contrast, and encompass issues relating to the various available options for reuse would also be beneficial.

Additionally, it is recommended that the barriers to widespread greywater reuse be addressed to encourage more greywater reuse in Perth. The first steps towards addressing the barriers may include education and awareness programs to promote environmentally friendly thinking and sustainable practices within the community. A compilation of all current knowledge relating to greywater reuse would also aid this process by improving the accessibility of information.

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7. GLOSSARY

Biological Treatment Unit – a wastewater treatment unit that uses bacteria to break down solid wastes.

Blackwater – all wastewater that contains gross faecal coliform contamination. The majority of blackwater is sourced from toilets but can also come from bidets and laundry water used to wash soiled diapers.

Bulk Density – dry mass of soil per unit volume.

Direct Reuse – the use of reclaimed water that has been transported from the wastewater reclamation plant to the water reuse site without intervening discharge to a natural body of water, such as in a domestic water supply reservoir or groundwater.

Domestic Wastewater – spent water from a household, including sewage.

Dual Reticulation System – those reuse systems in which wastewater is centrally treated and redistributed to households as reclaimed water for non-contact uses such as toilet flushing and irrigation.

ECH_2O – an in situ soil moisture monitor.

Gravimetric Soil Moisture Content – soil moisture content calculated by mass.

Gravitational Multiple Wetting Front And Redistribution (GMWFR) Model – a computer model that tracks the movement of square infiltration waves as they move under gravitation through the soil profile.

Greywater (Graywater, Sullage) – all untreated household wastewater that has not been contaminated with toilet water and includes water sourced from hand basins, bathtubs and showers. For the purpose of this study, greywater includes all household wastewater other than toilet and kitchen wastewater.

Greywater Reuse System – any system, including plumbing, storage tanks, electric pumps, and distribution networks, that serve to distribute greywater for a specific reuse.

Indirect Reuse – use of reclaimed water indirectly by passing through a natural body of water or use of groundwater that has been recharged with reclaimed water.

Irrigation Network – the web of plumbing used to feed water to vegetation.

Local System – those reuse systems that operate in a single house or building complex, and are the main focus of this study.

Non-potable Reuse – all reuse applications that do not involve either direct or indirect potable reuse. The reuse of wastewater for uses other than human consumption such as irrigation, toilet flushing, and water features.

Potable Reuse – an augmentation of drinking water supplies directly or indirectly by reclaimed water that is highly treated to protect public health.

Primary Treatment – the use of physical processes such as sedimentation to separate the solid wastes from wastewater.

Reclaimed Water – water that, as a result of wastewater treatment, is suitable for a direct beneficial use or a controlled use that would not otherwise occur.

Sewage – diluted human waste.

Soil Water Infiltration and Movement (SWIM) Model – a computer model that simulates water infiltration and movement in soils.

Subsurface Drip Irrigation – a method for irrigation by which water is passed through pipes and distributed through small holes ('drippers') directly to the roots of vegetation beneath the ground surface. This method of irrigation minimises human contact with the water used for irrigation.

Trase – an in situ soil moisture monitor.

Volumetric Soil Moisture Content – soil moisture content calculated by volume.

Water/Wastewater Reuse – the use of treated wastewater for a beneficial use.

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9. APPENDIX 1: APPROVED GREYWATER REUSE SYSTEMS

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GREYWATER REUSE SYSTEMS APPROVED by the DEPARTMENT OF HEALTH

SYSTEMS APPROVED FOR SEWERED and NON SEWERED AREAS

BRAND	MODEL	APPROVAL NUMBER	DATE APPROVED	Capacity / Greywater Flow Volume (Litres/day)	Able to be installed in sewered areas?	MANUFACTURER
Greywater Saver	Greywater Saver GS50/L Greywater Saver GS50/S Greywater Saver GS80	GW0202	21/1/03	Up to 5 bedrooms (no kitchen greywater allowed)	YES	Greywater Saver Pty Ltd PO Box 7082 Spearwood WA 6163 Ph: 0403 319 410 Fax: (08) 9467 6154 sales@greywatersaver.com www.greywatersaver.com
Galvin Concrete and Sheetmetal	Greywater 6000 Greywater Recycle Tank	GW0201	19/3/03	Commercial Use 6000L capacity	YES	Galvin Concrete and Sheetmetal Pty Ltd 40 Motivation Drive Wangara WA 6065 Ph: (08) 9302 2175 Fax: (08) 9302 2189
	Greywater 1800 Greywater Recycle Tank		10/7/02	5 Bedrooms	YES	
	Greywater 1200 Greywater Recycle Tank			Up to 4 bedrooms or 5 persons	YES	
	Galvin Subsurface Irrigation System			To be used with a Galvin Greywater Recycle Tank	Not applicable	
Western Wastewater Treatments	TRIAL APPROVAL Aquarius Domestic Greywater Unit (DGU)	TRIAL APPROVAL GW0305	TRIAL APPROVAL 31/1/03 for 6 months for 10 units	TRIAL APPROVAL Up to 5 bedrooms (no kitchen greywater allowed)	YES	Western Wastewater Treatment Pty Ltd 11 – 13 Burgay Court Osbourne Park WA 6017 Ph: (08) 9445 2280
Ecomax Waste Management	Greymax	GW0303	30/1/03	Up to 5 bedrooms (no kitchen greywater allowed)	YES	Ecomax Waste Management Systems Pty Ltd 116-118 Bannister Road Canning Vale WA 6155 Ph: (08) 9335 1600

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GREYWATER REUSE SYSTEMS APPROVED by the DEPARTMENT OF HEALTH
SYSTEMS APPROVED FOR SEWERED and NON SEWERED AREAS

BRAND	MODEL	APPROVAL NUMBER	DATE APPROVED	Capacity / Greywater Flow Volume (Litres/day)	Able to be installed in sewered areas?	MANUFACTURER
Greywater Reuse Systems (GRS)	GT Series Innotech Plastic Tanks (GT 500, GT 700, GT 900)	GW0309	31/3/03	500L, 700L or 900L	YES	Greywater Reuse Systems PO Box 1125 Midland Business Centre WA 6936 Ph: (08) 9294 4141 www.greywaterreuse.com.au
	GRS Concrete Tanks (CT 175, CT 225, CT 400, CT 740, CT 1080, CT 1450)	GW0308	31/3/03	175L, 225L, 400L, 740L, 1080L, or 1450L	YES	
	GRS Watersave Filter	GW0307	13/3/03	Up to 5 bedrooms (no kitchen greywater allowed)	YES	
	GRS Watersave Mini Piped Trench	GW0307	13/3/03	To be used with approved tank or GRS Watersave Filter	Not applicable	
	GRS Watersave Standard Piped Trench					

SYSTEMS APPROVED FOR NON-SEWERED AREAS ONLY

Greywater Reuse Systems (GRS)	GRS Standard Piped Trench	GW0304	29/1/03	To be used with a 1800L sedimentation tank	NO	Greywater Reuse Systems PO Box 1125 Midland Business Centre WA 6936 Ph: (08) 9252 0456
Niimi Absorption Trench	Niimi Absorption Trench	GW9601	3/5/96	To be used with a 1800L sedimentation tank	NO	Mr Michael Ward PO Box 2 Glen Forrest WA 6071 Ph: (08) 9295 1039

10.APPENDIX 2: EXAMPLE OF SPLIT PLUMBING

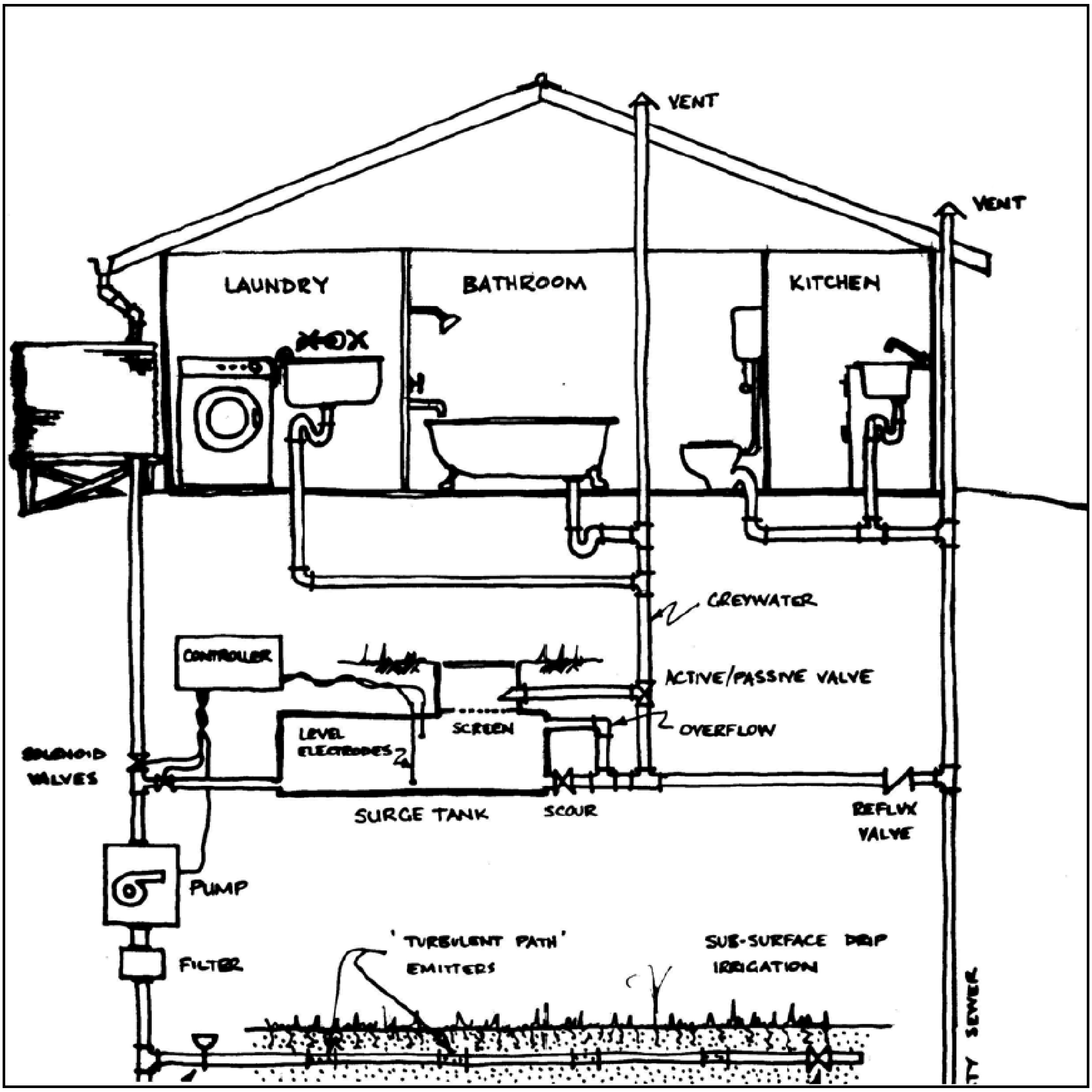


Figure from (Rowlands 2003)

11. APPENDIX 3: PATHOGEN ANALYSIS OF GREYWATER, SOIL WATER & SOIL (RAW DATA)

	Analysis	**Presumptive Total Coliforms**	**Confirmed Total Coliforms**	**Presumptive Thermotolerant Coliforms**	**Confirmed Thermotolerant Coliforms**	**Escherichia coli**	**Confirmed Enterococci**	**Comments**
	Units	**CFU/100mL**	**CFU/100mL**	**CFU/100mL**	**CFU/100mL**	**CFU/100mL**	**MPN/100mL**	
Filtered Greywater	20-Aug-03	est. >1000000	est. >1000000	-	est. <10	est. <10	>24000	*Sample showed visible discolouration*
	27-Aug-03	est. >1000	est. >1000	est. >1000	est. >10	est. >10	61	
	1-Sep-03	est. >1000000	-	est. >10000	est. <100	est. <100	63	
	2-Sep-03	est. >10000000	-	est. 40000	est. 40000	est. <10000	20	
	3-Sep-03	est. >1000000	est. >1000000	est. 60000	est. 60000	est. <10000	<10	
	4-Sep-03	est. >1000000	est. >1000000	est. 60000	est. 60000	est. 60000	10	
	10-Sep-03	3800000	3800000	est. 70000	est. 70000	est. 35000	140	
	17-Sep-03	est. >1000000	-	220000	44000	44000	3700	
	25-Sep-03	est. >10000000	est. >10000000	est. >10000	est. >10000	est. >2000	20	
	8-Oct-03	est. >1000000	-	est. 1300	est. 1300	est. 1300	300	*Due to the high background growth of bacteria, the Thermotolerant Coliform count may be underestimated*
Unfiltered Greywater	20-Aug-03	est. >1000000	est. >1000000	est. 20000	est. 20000	est. <10	97	
	27-Aug-03	est. >1000000	est. >1000000	est. 1500	est. <100	est. <100	10	
	1-Sep-03	est. >1000000	-	est. 10000	est. <10000	est. <10000	<10	
	2-Sep-03	est. >1000000	-	est. 50000	est. 50000	est. <10000	<10	
	3-Sep-03	est. >1000000	est. >1000000	200000	200000	est. <10000	200	
	4-Sep-03	est. >1000000	est. >1000000	est. 150000	est. 150000	est. 120000	31	
	10-Sep-03	est. >10000000	est. >10000000	est. 1800	est. 1400	est. 1400	1600	
	17-Sep-03	est. 1200000	-	est. >1000000	est. <10000	est. <10000	2400	
	25-Sep-03	est. >10000000	est. >10000000	est. >10000	est. >10000	est. <100	<10	
	8-Oct-03	est. >1000000	-	est. >10000	est. >10000	est. <9000	170	

	Analysis	Presumptive Total Coliforms	Confirmed Total Coliforms	Presumptive Thermotolerant Coliforms	Confirmed Thermotolerant Coliforms	Escherichia coli	Confirmed Enterococci	Comments
	Units	**CFU/100mL**	**CFU/100mL**	**CFU/100mL**	**CFU/100mL**	**CFU/100mL**	**MPN/100mL**	
Soil Water 1	27-Aug-03	560	560	est. 110	est. <10	est. <10	<10	
Soil Water 2	27-Aug-03	-	est. <10	-	est. <10	est. <10	<10	*Due to a high background growth of non-coliform organisms, the Coliform count may be underestimated*
	10-Sep-03	est. 50	est. 50	-	est. <10	est. <10	10	
	17-Sep-03	est. <10	-	-	est. <10	est. <10	<10	
	8-Oct-03	est. <10	-	-	est. <10	est. <10	<10	
Soil Water 4	27-Aug-03	est. 10	est. 10	-	est. <10	est. <10	<10	*Due to a high background growth of non-coliform organisms, the Coliform count may be underestimated*

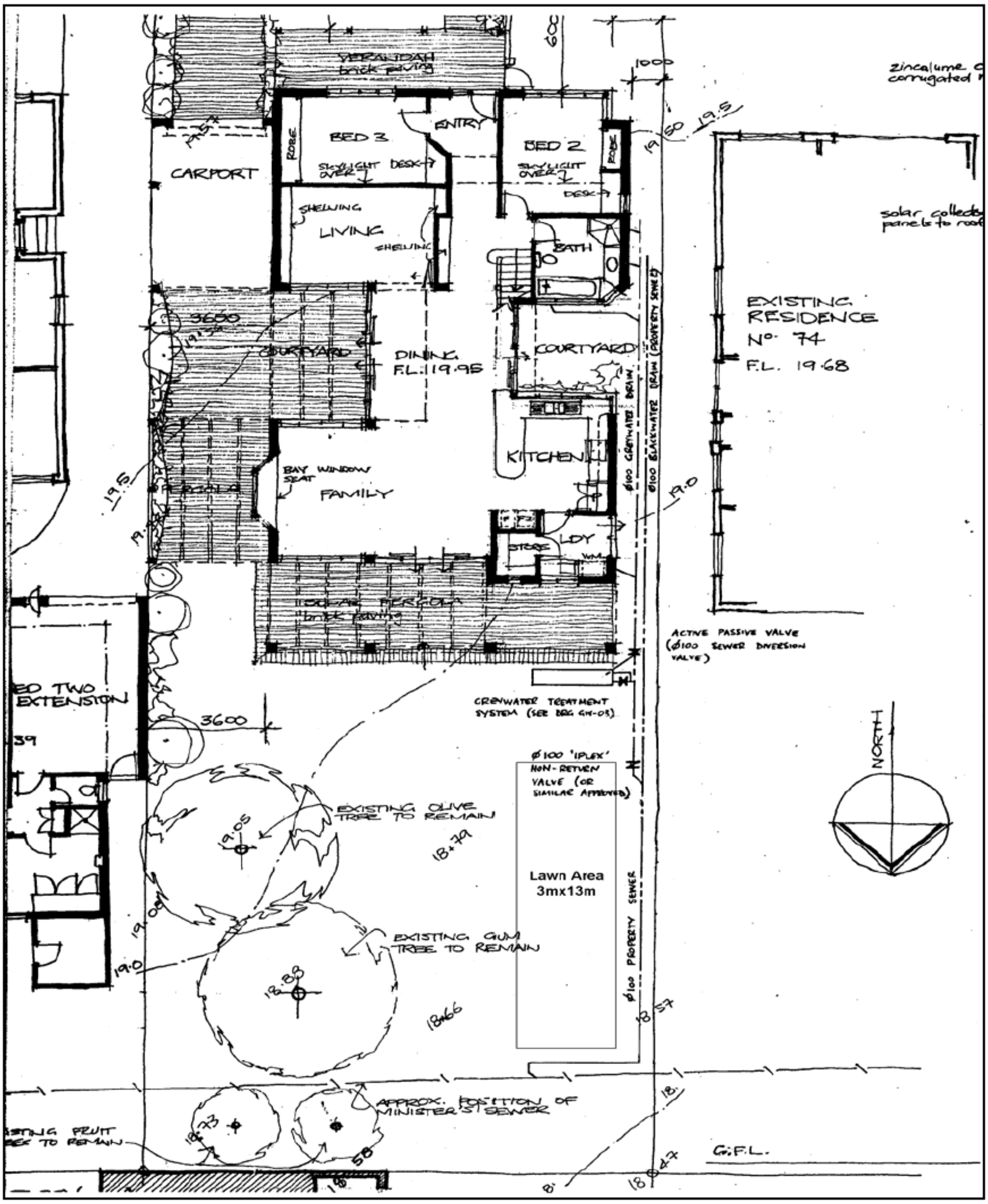
		Confirmed Total Coliforms	Confirmed Thermotolerant Coliforms	Escherichia coli	Confirmed Enterococci
		MPN/g	**MPN/g**	**MPN/g**	**MPN/g**
Soil Sample (Root Zone)	17-Sep-03	<3	<3	<3	20
Soil Sample (30cm Depth)	17-Sep-03	<3	<3	<3	2400

12. APPENDIX 4: CHEMICAL ANALYSIS OF GREYWATER AND SOIL WATER (RAW DATA)

		CCWA ID	**03E0272/001**	**03E0272/002**	**03E0402/002**	**03E0402/001**	**03E0472/002**	**03E0472/001**	**03E0472/003**
		Client ID	**Filtered GW**	**30cm Below RZ**	**Filtered GW**	**30cm Below RZ**	**Filtered GW**	**30cm Below RZ**	**Garden Tap H2O**
		Sampled on	**27/08/2003**	**27/08/2003**	**25/09/2003**	**25/09/2003**	**8/09/2003**	**8/09/2003**	**8/09/2003**
		Received on	**28/08/2003**	**28/08/2003**	**26/09/2003**	**26/09/2003**	**10/10/2003**	**10/10/2003**	**10/10/2003**
iMET1WCICP	**Al**	**mg/L**	0.054	0.008	0.11	0.006	0.041	0.008	0.035
iALK1WATI	**Alkalin**	**mg/L**	95	265	118	198	115	250	85
iMET1WCICP	**B**	**mg/L**	0.07	0.11	1.1	0.1	0.26	0.1	0.09
Iele1wcim	**As**	**mg/L**	-	-	<0.005	0.005	<0.001	0.007	<0.001
iMET1WCICP	**Ca**	**mg/L**	21.6	106	14.5	99.1	20.2	92.9	19
iMET1WCICP	**Cd**	**mg/L**	<0.005	0.005	<0.0005	0.0005	<0.0005	0.0005	<0.0005
iCL1WAAA	**Cl**	**mg/L**	-	-	-	-	-	-	-
iMET1WCICP	**Co**	**mg/L**	<0.005	0.005	<0.005	0.005	<0.005	0.005	<0.005
iMET1WCICP	**Cr**	**mg/L**	<0.002	0.002	<0.002	0.002	<0.002	0.002	<0.002
iMET1WCICP	**Cu**	**mg/L**	0.24	0.043	0.1	0.055	0.096	0.037	0.012
iEC1WZSE	**ECond**	**mS/m**	73.1	102	103	114	99.6	109	89.2
iF1WASE	**F**	**mg/L**	0.8	0.2	0.5	0.1	0.6	0.1	0.7
iMET1WCICP	**Fe**	**mg/L**	0.063	0.018	0.11	0.019	0.036	0.018	0.044
iHTOT2WACA	**Hardness**	**mg/L**	84	370	67	320	80	290	75
iMET1WCICP	**K**	**mg/L**	6.3	20	6.6	15.8	6.8	12.7	5.2
iMET1WCICP	**Mg**	**mg/L**	7.3	25.1	7.6	18.3	7.1	13.9	6.6
iMET1WCICP	**Mn**	**mg/L**	<0.005	0.005	0.009	0.001	0.008	0.001	0.003
iMET1WCICP	**Mo**	**mg/L**	0.01	0.01	0.0021	0.0057	<0.002	0.009	<0.002
iAMMN1WFIA	**N_NH3**	**mg/L**	0.01	0.01	5.1	0.03	2.2	0.13	<0.01
iNTAN1WFIA	**N_NO3**	**mg/L**	0.01	6	0.01	1.4	0.04	0.41	0.03
iNTK1CALC	**N_TK**	**mg/L**	1.6	2.2	8.1	1.4	6	1.6	0.13
iNP1WTFIA	**N_total**	**mg/L**	1.6	8.3	8.1	2.8			
iMET1WCICP	**Na**	**mg/L**	105	61	167	99.3	165	109	151
iMET1WCICP	**Ni**	**mg/L**	<0.01	0.01	0.0052	0.0042	<0.001	0.001	<0.001
iOGP1WTGR	**O&G**	**mg/L**	<10	I.S.	30	30	18		<10
iP1WTFIA	**P_SR**	**mg/L**	0.02	0.23	0.16	0.23	0.3	0.42	0.01

		CCWA ID	**03E0272/001**	**03E0272/002**	**03E0402/002**	**03E0402/001**	**03E0472/002**	**03E0472/001**	**03E0472/003**
		Client ID	**Filtered GW**	**30cm Below RZ**	**Filtered GW**	**30cm Below RZ**	**Filtered GW**	**30cm Below RZ**	**Garden Tap H2O**
		Sampled on	**27/08/2003**	**27/08/2003**	**25/09/2003**	**25/09/2003**	**8/09/2003**	**8/09/2003**	**8/09/2003**
		Received on	**28/08/2003**	**28/08/2003**	**26/09/2003**	**26/09/2003**	**10/10/2003**	**10/10/2003**	**10/10/2003**
iPP1WTFIA	**P_total**	**mg/L**	0.37	0.29	0.39	0.39	1	0.43	0.02
iELE1WCIM	**Pb**	**mg/L**	0.0017	0.015	0.0014	0.0045	0.002	0.012	<0.0006
iMET1WCICP	**SO4_S**	**mg/L**	22.7	152	18.6	85.9	16.3	58.1	17.6
iSOL1WPGR	**Solid_su**	**mg/L**	I.S.	I.S.	28	6	11	3	2
iSOL1WDGR	**TDS_180C**	**mg/L**	390	640	580	700	670	680	550
iTURB1WCZZ	**Turbidit**	**NTU**	19	1	43	0.7	24	0.7	0.5
iMET1WCICP	**V**	**mg/L**	<0.005	0.008	<0.005	0.008	<0.005	0.007	<0.005
iMET1WCICP	**Zn**	**mg/L**	0.034	0.042	0.028	0.028	0.027	0.021	<0.005
iPH1WASE	**pH**		7.1	7.9	6.9	7.7	7.8	7.6	7.3

13. APPENDIX 5: STUDY SITE FLOOR PLANS



Note that two ponds and a reed bed (approximately 9m^2 in total) have been added between the lawn, the olive tree, and the gum tree.

14.APPENDIX 6: MASS BALANCE SCRIPT

```
% This m-file solves the mass balances specific to the dissertation.
% Plots of each of the nutrient mass balances and tables of mass data are given as outputs (optional)
%
% usage:    mb1.m
% input:    the names of two text files:
%           one containing nutrient data related to the lawn
%           one containing nutrient data related to the control garden
%           the columns of the text files are specified below
%
% name:             May-Le Ng
% student number:   0110517
% date:             1 October 2004

clear

% Site characteristics
L = 13;     % length lawn
W = 3;      % width lawn
A = L*W;    % area lawn
Lg = 2;     % length garden
Wg = 1;     % width garden
Ag = Lg*Wg; % area garden

% Input data for lawn samples from text file containing columns:
% Date(excel number) Rainfall(mm) Vol Greywater(L) Conc in Greywater(x8) (mg/L) Outflow (mm) Conc in Soil
Water(x8) (mg/L)
% Concentrations are of: Ca K Mg Pb V SO4 TOTAL-P TOTAL-N
data=input('Enter the lawn datafile name: ','s');

file=importdata(data);
date=file(:,1);
rain=file(:,2);                 % rainfall
vgw=file(:,3);                  % volume greywater irrigated
concg=file(:,4:11);             % matrix with all chemical concentrations
out=file(:,12:15);
conco=file(:,16:47);            % matrix with all chemical concentrations

% Input data for control sample from text file containing columns:
% Date(excel number) Rainfall(mm) Outflow (mm) Conc in Soil Water(x8) (mg/L)
% Concentrations are of: Ca K Mg Pb V SO4 TOTAL-P TOTAL-N
datac=input('Enter the control datafile name: ','s');

filec=importdata(datac);
datec=filec(:,1);
rainc=filec(:,2);               % rainfall
outc=filec(:,3);
concoc=filec(:,4:11);           % matrix with all chemical concentrations

chem={'Ca' 'K' 'Mg' 'Pb' 'V' 'SO4' 'TP' 'TN'};
day=[1:length(date)]';

% Mass balance components (assumes average the volume over the whole day)
qr=rain*A*1e-3;                 % inflow from rainfall [m3/day]
cr=0;                           % concentration in rain [kg/m3]
qi=vgw*1e-3;                    % inflow from irrigation [m3/day]
ci=concg*1e-6*1e3;              % concentration in greywater irrigated [kg/m3]
qo=122/119*A*1e-3;              % outflow through infiltration [m3/day]
```

```
co=conco*1e-6*1e3;              % concentration in outflow [kg/m3]

qrc=rainc*Ag*1e-3;              % inflow from rainfall [m3/day]
crc=0;                          % concentration in rain [kg/m3]
cic=0;                          % concentration in greywater irrigated [kg/m3]
qoc=96.5/119*A*1e-3;            % outflow through infiltration [m3/day]
coc=concoc*1e-6*1e3;            % concentration in outflow [kg/m3]

% Mass balance
[l,w1]=size(concg);
massin=[];
massout=[];
massinc=[];
massoutc=[];
for ii=1:w1
   massin(:,ii)=ci(:,ii).*(qi);          % mass in = ci.Qi    lawn area
   massinc(:,ii)=crc.*qrc;               % mass in = ci.Qr    control garden
   massoutc(:,ii)=coc(:,ii).*qoc;        % mass out = co.Qo   control garden
end
[l,w2]=size(conco);
for ii=1:w2
   massout(:,ii)=co(:,ii).*qo;           % mass out = co.Qo   lawn area
end

% Find where there are non-zero entries in the mass matrices
a=find(massin(:,1));
b=find(massout(:,1));
c=find(massinc(:,1));
d=find(massoutc(:,1));
massin1=massin(a,:);
massout1=massout(b,:);
massinc1=massinc(c,:);
massoutc1=massoutc(d,:);
day1=day(a);
day2=day(b);
dayc1=day(c);
dayc2=day(d);

massinc1=zeros(1,8);            % there are no incoming nutrients to the control garden
dayc1=[32 39 60 67 77 84 91]';  % days to plot incoming nutrients = 0

% Convert day numbers to dates
n=datenum('31-May-2004');       % convert string to date number eg 31-May-2004 -> 732098
dayn1=[];
daycn1=[];
dayn2=[];
daycn2=[];
for ii=1:length(day1)
   dayn1(ii)=day1(ii)+n-1;      % converting excel date numbers to matlab date numbers
   daycn1(ii)=dayc1(ii)+n-1;
end
for ii=1:length(day2)
   dayn2(ii)=day2(ii)+n-1;
end
for ii=1:length(dayc2)
   daycn2(ii)=dayc2(ii)+n-1;
end

% Plot massin and massout vs time (optional)
plt=input('View the mass balance plots: y/n? ','s');
```

```
if plt~='n'
   count=0;
   for ii=1:4:32
      count=count+1;
      figure
      plot(dayn1,massin1(:,count),'ro',dayn2,massout1(:,ii),'g.',dayn2,massout1(:,ii+1),...
         'b.',dayn2,massout1(:,ii+2),'m.',dayn2,massout1(:,ii+3),'c.',daycn2,massoutc1(:,count),...
         'k.',daycn1,massinc1(:,count),'rx')
      datetick('x',20)
      set(gca,'YGrid','on')
      xlabel('Date')
      ylabel('Mass Flux (kg/Day)')
      legend('Mass In','Mass Out 1','Mass Out 2','Mass Out 3','Mass Out 4','Mass Out C','Mass In C',-1)
      title(sprintf('%s Mass Balance',chem{count}))
      axis tight
   end
end

% Output massin and massout vs time tables (optional)
table=input('View the mass balance tables: y/n? ','s');
date1=datestr(dayn1,20);
date2=datestr(dayn2,20);
datec1=datestr(daycn1,20);
datec2=datestr(daycn2,20);
xdayn1=m2xdate(dayn1);
xdaycn1=m2xdate(daycn1);
xdayn2=m2xdate(dayn2);
xdaycn2=m2xdate(daycn2);
if table~='n'
   count=0;
   for ii=1:4:32
      count=count+1;
      fprintf('\n     Mass Balance For %s\n*date in Excel datenumber, mass in kg*\n',chem{count})
      fprintf('  Date        Mass In\n')
      format short e
      disp([xdayn1'  massin1(:,count)])
      fprintf('\n  Date        Mass Out 1   Mass Out 2   Mass Out 3   Mass Out 4\n')
      disp([xdayn2'  massout1(:,ii:ii+3)])
   end
end
format
```

15. APPENDIX 7: ESSENTIAL PLANT NUTRIENTS

Adapted from (Bennett 1993)

ESSENTIAL ELEMENTS

Macronutrients		
Carbon	CO_2	Required for photosynthesis to occur
Hydrogen	H_2O	Required for photosynthesis to occur
Oxygen	H_2O, O_2	Required for photosynthesis to occur
Nitrogen	NH_4^+, NO_3^-	Utilised to form amino acids, proteins, nucleic acids, N bases, nucleotides, amides, and amines. Plays a key role in many metabolic reactions.
Phosphorus	$H_2PO_4^-$, HPO_4^{2-}	Constituent of plant enzymes and proteins and is a structural component of phosphoproteins, phospholipids, and nucleic acids. Plays a vital role in the life cycle of plants and is important in reproductive growth. Also plays a role n nearly all metabolic processes.
Potassium	K^+	Required for turgor buildup in plants and maintains the osmotic potential of cells, which in guard cells governs the opening of stomata. Involved in water uptake from soil, water retention in the plant tissue, and long-distance transport of water and assimilates in the phloem and xylem. Also functions in pH stabilization in cells and is important in cell growth.
Calcium	Ca^{2+}	Is a component of every cell wall and is involved in cell elongation and cell division. Also influences the pH of cells and the structural stability and permeability of cell membranes.
Magnesium	Mg^{2+}	An essential part of the chlorophyll molecule that aids in the formation of sugars, oils, and fats.
Sulfur	SO_4^{2-}	A constituent of two amino acids, which are essential for protein formation. Also involved in the formation of vitamins and synthesis of some hormones.

Micronutrients		
Iron	Fe^{2+}, Fe^{3+}	Essential for the synthesis of chlorophyll. Involved in N fixation, photosynthesis, and electron transfer. Also involved in respiratory enzyme systems.
Zinc	Zn^{2+}, $Zn(OH)_2$	Metal component in a number of enzyme systems that function as part of electron transfer systems and in protein synthesis and degradation.
Manganese	Mn^{2+}	Involved in the evolution of O_2 in photosynthesis.
Copper	Cu^{2+}	Involved in cell wall formation and electron transport and oxidation reactions. Affects the formation and chemical composition of cell walls, and thus affect lignification.
Boron	$B(OH)_3$	Involved in the transport of sugars across cell membranes and in the sysnthesis of cell wall material. Influences transpiration through the control of sugar and starch formation. Also influences cell development and elongation. Plays a role in amino acid formation and synthesis of proteins.
Molybdenum	MoO_4^{2-}	Serves as a metal component of two enzyme systems. Involved in the reduction of nitrate and the fixation of nitrogen.
Chlorine	Cl^-	Participates in the capture and storage of light energy through its involvement in photophosphorylation reactions in photosynthesis. Involved in the regulation of osmotic pressure.
Silicon	$Si(OH)_4$	Involved in the protection and regulation of photosynthesis and other enzyme activity. Plays a role in the structural rigidity of cell walls.
Sodium	Na^+	Involved in osmotic regulation.
Cobalt	Co^{2+}	Involved in the growth of certain lower plant organism involved in symbiotic N fixation.
Vanadium	V^+	Functions in oxidation-reduction reactions, and promotes chlorophyll synthesis.

16. APPENDIX 8: SAMPLING CALENDAR

June

Sun	*Mon*	*Tue*	*Wed*	*Thu*	*Fri*	*Sat*
		1	**2**	**3**	**4**	**5**
6	**7**	**8**	**9**	**10**	**11**	**12**
13	**14**	**15**	**16**	**17** 250mL Greywater	**18**	**19**
20 Irrigated 200L	**21**	**22**	**23** Irrigated 200L	**24**	**25**	**26**
27 Irrigated 200L	**28**	**29**	**30**			

2004

July

Sun	*Mon*	*Tue*	*Wed*	*Thu*	*Fri*	*Sat*
				1 Irrigated 200L 250mL Greywater	**2**	**3**
4 Irrigated 200L	**5**	**6**	**7**	**8** Irrigated 200L 250mL Greywater	**9**	**10**
11 Irrigated 200L	**12**	**13**	**14**	**15** Irrigated 200L	**16**	**17**
18 Irrigated 200L	**19**	**20**	**21**	**22** Irrigated 200L	**23**	**24**
25 Irrigated 200L 4x Soil Samples 100mL Deionised Water	**26**	**27**	**28**	**29** Irrigated 200L 250mL Greywater	**30**	**31**

2004

August

Sun	*Mon*	*Tue*	*Wed*	*Thu*	*Fri*	*Sat*
1 Irrigated 200L 4x Soil Samples	**2**	**3**	**4**	**5** Irrigated 200L 250mL Greywater	**6**	**7**
8 Irrigated 200L 4x Soil Samples	**9** 100mL Deionised Water	**10**	**11**	**12** Irrigated 200L	**13**	**14**
15 Irrigated 200L 250mL Greywater 4x Soil Samples	**16**	**17**	**18**	**19**	**20**	**21**
22 Irrigated 200L 250mL Greywater 4x Soil Samples	**23**	**24**	**25**	**26**	**27**	**28**
29 Irrigated 200L 250mL Greywater 4x Soil Samples	**30**	**31**				

2004

September

Sun	*Mon*	*Tue*	*Wed*	*Thu*	*Fri*	*Sat*
			1 4x Soil Samples	**2**	**3**	**4**
5 Irrigated 200L	**6**	**7**	**8**	**9**	**10**	**11**
12	**13**	**14**	**15**	**16**	**17**	**18**
19 Irrigated 200L	**20**	**21**	**22** Irrigated 200L	**23**	**24**	**25**
26	**27**	**28**	**29**	**30**		

2004

17. APPENDIX 9: LABORATORY TEST METHODS

17.1. Analysis for Ca, K, Mg, Mo, Pb, V, Hardness

Determination of elements in waters and other appropriate solutions by ICP-AES, MAFRL Method: ICP 001
Varian (Vista AX) ICP-AES CCD Simultaneous

17.2. Analysis for SO_4^{2-}

Sulphate in natural waters by FIA, MAFRL Method 5050

(LOQ = 1 mg.SO_4^{2-}.L^{-1}) (Range = 1 – 50 mg.SO_4^{2-}.L^{-1})

Lachat Automated Flow Injection Analyser

Lachat Instruments QuickChem Method 10-116-10-1-C (19th Jun 1995) *Sulphate in waters.* (Lachat Instruments, 6645 West Mill Road, Millwaaukee, WI 53218, USA

17.3. Analysis for Total Phosphorus

TOTAL PHOSPHORUS IN NATURAL WATERS BY AUTOCLAVE DIGESTION

Scope

This method determines the concentration of total phosphorus in natural waters with salinities ranging up to 36ppt.

Principle

Inorganic and organically bound phosphorus in water samples is converted to orthophosphate by digestion at elevated temperature and pressure in an autoclave, using an alkaline solution of potassium persulphate. Total phosphorus is determined by analysing the resulting orthophosphate from the digest. Orthophosphate reacts with ammonium molybdate and antimony potassium tartrate under acidic conditions to form a heteropoly acid (phosphomolybdic acid) which is reduced to the intensely coloured molybdenum blue complex by ascorbic acid. The ascorbic acid and molybdate reagents are merged on the chemistry manifold, and then the reagent stream is merged with the carrier stream. The sample reaches the detector in less than ten seconds after injection. The intensity of the colour produced absorbs light at 880 nm and is proportional to the concentration of orthophosphate.

Total phosphorus in natural waters by autoclave digestion, MAFRL Method 4700

(LOQ = 5 μg.P.L^{-1}) (Range = 5– 500 μg.P.L^{-1})

Lachat Automated Flow Injection Analyser

Lachat Instruments QuickChem Method 31-115-01-3-A (17th Aug 1994). *Phosphate in Brackish or Seawater.* (Lachat Instruments, 6645 West Mill Road, Millwaaukee, WI 53218, USA)

17.4. Analysis for Total Nitrogen

TOTAL NITROGEN IN NATURAL WATERS BY AUTOCLAVE DIGESTION

Scope

This method determines the concentration of total nitrogen in natural waters with salinities ranging up to 36 ppt.

Principle

Inorganic and organically bound nitrogen in water samples are converted to free nitrate by digestion at elevated temperature and pressure in an autoclave, using an alkaline solution of potassium persulphate. Total nitrogen is determined by analysing the nitrate in the digest. Nitrate is reduced to nitrite by means of a heterogeneous reaction in a copper-cadmium reductor column. Under acidic conditions the nitrite ion reacts with sulphanilamide to yield a diazo compound that couples with N-1-naphtylethylene diamine dihydrochloride to form a reddish-purple azo dye. The reaction is specific for nitrite and very sensitive. The azo dye that is formed is detected colourimetrically at 540 nm.

Total nitrogen in natural waters by autoclave digestion, MAFRL Method 2700

(LOQ = 50 μg.N.L^{-1}) (Range = 50 - 1000 μg.N.L^{-1})

Lachat Automated Flow Injection Analyser

Lachat Instruments QuickChem Method 31-107-04-1-A (18th Jul 1996) *Nitrate and/or Nitrite in Brackish Waters or Seawater* (Lachat Instruments, 6645 West Mill Road, Millwaaukee, WI 53218, USA)

17.5. Analysis for NPOC

Total organic carbon in water, MAFRL Method 6000

(LOQ = 0.6 mg.C.L^{-1}) (Range = 0.6 – 1000 mg.C.L^{-1})

Automated Combustion-NDIR Method

Shimadzu Corporation *Total Organic Carbon Analyser Model TOC 5000A Instruction Manual.* (Environmental Analysis Instruments Plant, Environmental Instrumentation Division: Tokyo, Japan).

18. APPENDIX 10: METHODS FOR DETERMINING THE CARBON AND ORGANIC MATTER CONTENT IN SOIL

From (School of Earth and Geographical Sciences 2004)

Determination of the Organic Matter Content of Soil Samples

Aims

To determine the organic Carbon concentration in soil samples using a procedure called the Walkley-Black wet oxidation method.

Experimental Procedure

1. Weigh out accurately two approximately 0.2g sub samples of each of your soil samples. Record the exact weights on your results sheet. Transfer the weighted sub samples into 250ml Erlenmeyer flasks, making sure all particles have been transferred.
2. Add 5ml of 0.2M dichromate to each flask, mixing carefully and thoroughly, but not too vigorously, to make sure you prevent soil particles from sticking ot the sides of the flask.
3. Slowly and carefully add 10ml of conc. H_2SO_4 using the special measurer provided. DO NOT PIPETTE BY MOUTH! The heat of dilution of the acid raises the temperature to about 110°C, which accelerates the oxidation of the carbon.
4. Gently swirl the samples for *1 minute*, taking care to avoid throwing soil onto the sides of the flask. If the solution turns green, add another aliquot of oxidant (dichromate + sulphuric acid) and allow the flasks to stand on a heatproof mat for *30 minutes* before proceeding. Remember to record the volume of dichromate added on your results sheet.
5. Add 100ml of deionised water and 5ml of 85% Phosphoric acid using the special measure provided (DO NOT PIPETTE BY MOUTH!) and 2ml barium diphenylamine sulphonate indicator. The solution will change colour from orange to dirty brown.
6. Titrate by adding ferrous sulphate solution from a burette (remember to note its exact molarity). Shake the flask constantly. The colour of the solution turns to a deep emerald green at the end point. You may see a brown/deep purple/grey colour change just before the end point is reached. To see the end point more clearly, use a Pasteur pipette to suck up some solution that is in the flask. The thin column of liquid in the pipette gives a better indication of colour. If there is a lot of clay in your soil sample, you may have to let the soil particles settle between each addition of $FeSO_4$, since the fine clay particles tend to mask the end point.
7. Record titre at the end point on the Report Sheet.
8. Titrate the remaining flasks carefully, recording your raw data on the Report Sheet. Calculate the % organic carbon.

Results

Calculation of % Organic Carbon

A known excess of oxidising agent (dichromate) has been used to oxidise the carbon, which is acting as a reducing agent.

The oxidising agent that was in excess of the amount required to oxidise the carbon was then measured by titrating against Fe^{2+}. Knowing the amount of dichromate added initially, we may then calculate the amount that was consumed by oxidation of the carbon the amount of oxidising agent consumed gives the amount of carbon oxidised.

The balanced equation for the oxidation of Fe^{2+} by $Cr_2O_7^{2-}$ is given below. This equation tells you how many moles of Fe^{2+} reacted with every mole of $Cr_2O_7^{2-}$.

$Cr_2O_7^{2-} + 14H^+ + 6Fe^{2+} \leftrightarrow 2Cr^{3+} + 6Fe^{3+} + 7H_2O$

Therefore 1 mole of $Cr_2O_7^{2-}$ is required to oxidise 6 moles of Fe^{2+}

1. Calculate from the molarity (i.e. moles/litre) of Fe^{2+} and the titre volume the number of moles of Fe^{2+} that were added, record this on the report sheet.

I.e. (titre volume of $FeSO_4$ (ml) x M of $FeSO_4$) / 1000 ml

2. Knowing that 6 moles of Fe^{2+} reacts with 1 mole of $Cr_2O_7^{2-}$, calculate the moles of $Cr_2O_7^{2-}$ that reacted with the moles of Fe^{2+} estimated in step 1. This gives you the amount of $Cr_2O_7^{2-}$ that was not used in oxidising the carbon.

I.e. Moles of Fe^{2+} oxidised x (1/6)

3. Now calculate the total moles of $Cr_2O_7^{2-}$ added at the beginning of the analysis

E.g. 5ml of 0.2M $K_2Cr_2O_7$ contains 5 x 0.2 / 1000 = 1 x 10^{-3} moles of $Cr_2O_7^{2-}$.

4. Calculate the total moles of $Cr_2O_7^{2-}$ consumed by the oxidation of carbon by subtracting the quantity estimated in step 2 from the quantity estimated in step 3.

When organic compounds are oxidised, the electron change depends upon the amount of oxygen, as well as hydrogen and carbon, present. For example, the oxidation of sugars involves a four-electron change per carbon.

$C_{12}H_{22}O_{11} + 13H_2O \leftrightarrow 12CO_2 + 48H^+ + 48e^-$

The oxidation of soil organic matter has been shown to give approximately 77% of a four-electron change per carbon in the Walkley-Black method, i.e. 3.1 electrons per carbon, as some of the carbon may be considered to be already partially oxidised in organic molecules.

The two half reactions may be represented by the following equations:

1 mole of organic C $\leftrightarrow 3.1e^-$ + oxidation products
$Cr_2O_7^{2-} + 14H^+ + 6e^- \leftrightarrow 2Cr^{3+} + 7H_2O$

Remembering that the number of electrons lost in an oxidation reaction must equal the number gained in the associated reduction, the balanced equation for the oxidation of soil carbon in dichromate is:

6M of org C + $3.1Cr_2O_7^{2-} + 43.4H^+ \leftrightarrow$ 6 oxidation product + $6.2Cr^{3+} + 21.7H_2O$

1 mole of $Cr_2O_7^{2-}$ is required to oxidise 1.9 moles of organic carbon

5. You can now calculate the number of moles of C in your soil sample by multiplying the quantity estimated in step 4 by 1.9. express your results as % organic carbon of the soil. One mole of carbon weighs 12 grams. Multiply the moles of C by 12 to give grams of C. if A grams of carbon are found in B grams of soil, %C = A/B x 100%.

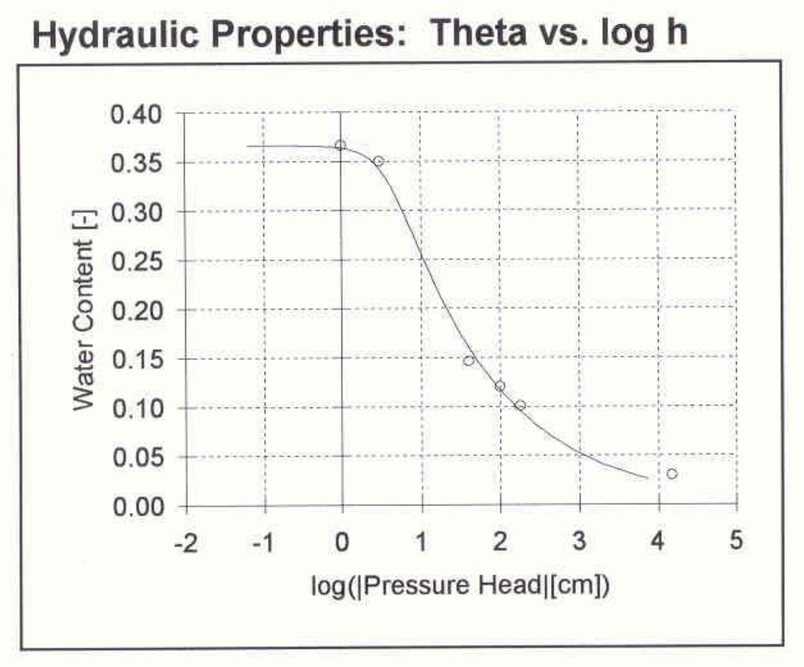
Soil carbon data can easily be converted to organic matter (OM) by assuming that %OM is twice that of % organic carbon. Knowing this, calculate %OM for your samples.

Result Sheet

Sample	Rough	1	2	3	4	5
Weight of soil (g)						
Vol $K_2Cr_2O_7$ (ml)						
Titre after (ml)						
Titre before (ml)						
Vol $FeSO_4$ (ml)						
%C						
%OM						

19. APPENDIX 11: WATER RETENTION CURVE

Derived by Rowlands (2003)



20. APPENDIX 12: CUMULATIVE RAINFALL + IRRIGATION DATA, AND POTENTIAL EVAPORATION DATA

Date	cumulative rainfall + irrigation (mm)	raw cumulative potential evaporation (mm)	Date	cumulative rainfall + irrigation (mm)	raw cumulative potential evaporation (mm)	Date	cumulative rainfall + irrigation (mm)	raw cumulative potential evaporation (mm)
31/05/2004	14	2.6	10/07/2004	235.5	74.4	19/08/2004	409.4	161.2
1/06/2004	14.5	4	11/07/2004	240.5	76.6	20/08/2004	412.4	162.2
2/06/2004	14.5	6.2	12/07/2004	240.5	78.2	21/08/2004	421.9	165
3/06/2004	14.5	9	13/07/2004	240.5	80.4	22/08/2004	426.9	167.4
4/06/2004	14.5	11.4	14/07/2004	240.5	82.4	23/08/2004	432.9	169.4
5/06/2004	33.5	11.6	15/07/2004	245.5	84.6	24/08/2004	443.9	173.4
6/06/2004	38.5	14.2	16/07/2004	245.5	87.4	25/08/2004	451.9	179.2
7/06/2004	46.5	14.6	17/07/2004	245.5	89.4	26/08/2004	454.4	181.4
8/06/2004	56.5	16.2	18/07/2004	250.5	92.6	27/08/2004	473.4	186.2
9/06/2004	56.5	17.8	19/07/2004	250.5	95	28/08/2004	486.4	188.4
10/06/2004	58.5	19.2	20/07/2004	250.5	98	29/08/2004	491.4	191.4
11/06/2004	78.5	21.2	21/07/2004	256.5	99.2	30/08/2004	491.4	192.8
12/06/2004	85.5	26	22/07/2004	268.9	101.4	31/08/2004	491.4	195.6
13/06/2004	86.5	27.6	23/07/2004	269.5	103.2	1/09/2004	491.4	199.2
14/06/2004	86.5	28.6	24/07/2004	269.5	105.6	2/09/2004	491.4	202.8
15/06/2004	86.5	31.2	25/07/2004	278.5	107.4	3/09/2004	491.4	208.2
16/06/2004	86.5	33	26/07/2004	278.5	110	4/09/2004	491.4	216.8
17/06/2004	95	34.8	27/07/2004	278.5	112	5/09/2004	500.4	218.2
18/06/2004	95	36	28/07/2004	278.5	113.8	6/09/2004	514.4	221.8
19/06/2004	95	37.6	29/07/2004	283.5	116.2	7/09/2004	518.4	223.4
20/06/2004	100	39.4	30/07/2004	300.5	117.6	8/09/2004	520.4	226.6
21/06/2004	100	41.2	31/07/2004	302	119.6	9/09/2004	520.9	227.8
22/06/2004	104	43.2	1/08/2004	314	121.4	10/09/2004	520.9	232.6
23/06/2004	112	44.6	2/08/2004	316	123.8	11/09/2004	520.9	236.6
24/06/2004	114	46.6	3/08/2004	317	125	12/09/2004	520.9	239.6
25/06/2004	116	47.6	4/08/2004	317.6	126.6	13/09/2004	520.9	244.8
26/06/2004	116	49.4	5/08/2004	325.6	128	14/09/2004	520.9	247.6
27/06/2004	121	52.2	6/08/2004	344.6	129	15/09/2004	520.9	251.6
28/06/2004	137	54.4	7/08/2004	344.6	131.6	16/09/2004	520.9	254
29/06/2004	137.5	56.4	8/08/2004	349.6	133.8	17/09/2004	520.9	257.8
30/06/2004	139.5	58.2	9/08/2004	349.6	136.6	18/09/2004	521.1	261.4
1/07/2004	144.5	59.4	10/08/2004	349.6	139	19/09/2004	526.1	265.2
2/07/2004	152.5	62	11/08/2004	349.6	142.2	20/09/2004	526.1	269.4
3/07/2004	170.5	63.4	12/08/2004	381.2	144.6	21/09/2004	531.1	273.4
4/07/2004	196.5	63.8	13/08/2004	381.4	147.2	22/09/2004	536.1	276.6
5/07/2004	198.5	66	14/08/2004	394.4	149.6	23/09/2004	536.1	281.8
6/07/2004	198.5	68.8	15/08/2004	399.4	153.4	24/09/2004	536.1	285.8
7/07/2004	215.5	70.8	16/08/2004	399.4	155	25/09/2004	536.1	291
8/07/2004	235.5	72.2	17/08/2004	399.4	157	26/09/2004	536.1	295.4
9/07/2004	235.5	73.2	18/08/2004	409.4	159.8	27/09/2004	536.1	300