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Long-term Effects of Landscape Irrigation Using Household Graywater—Literature Review and Synthesis

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LONG-TERM EFFECTS OF LANDSCAPE IRRIGATION USING HOUSEHOLD GRAYWATER – LITERATURE REVIEW AND SYNTHESIS

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ABSTRACT AND BENEFITS

Abstract:

The use of household graywater for landscape irrigation is gaining in popularity in the United States. This literature review identifies the current state of knowledge regarding the long-term impacts of landscape irrigation with household graywater and identifies the knowledge gaps that need to be addressed in an experimental plan. The review examines overall graywater issues including: 1) quantity, quality, treatment methods, and legality; 2) potential effects of graywater on residential landscape plants; 3) potential effects of graywater on soil microbial function; 4) use of indicator organisms for human health considerations; and 5) soil chemistry changes due to graywater application.

Knowledge gaps were found in the following areas: 1) documentation on whether or not constituents in graywater will accumulate in the soil in sufficient quantities to harm plants or perhaps be transported below the root zone to the groundwater during the rainy season; 2) information on the effects of graywater irrigation on landscape plants, which are typically inferred from experiments with recycled treated wastewater used for irrigation; 3) information on both short-term and long-term effects of graywater irrigation on indigenous soil microorganism communities and their important ecosystem functions; 4) information on whether the indicator organism counts are an accurate predictor of an actual health threat posed to individuals coming into direct contact with graywater; and 5) guidance to help the homeowner design a proper graywater capture, storage and distribution system.

A targeted research program is needed to address these knowledge gaps and it should include all applicable scientific disciplines.

Benefits:

- Contains a detailed literature review and synthesis of the current state of the knowledge on graywater reuse for landscape irrigation at the household level.
- Identifies information gaps for future research on the long-term use of graywater for irrigation of residential landscapes, particularly as it relates to human health, landscape plants and/or the environment.

Keywords: Graywater, water reuse, water conservation, landscape irrigation, detergents

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EXECUTIVE SUMMARY

ES.1 Introduction

The use of household graywater for landscape irrigation is gaining in popularity in the United States. A study conducted by the Soap and Detergent Association (SDA) in 1999 revealed that 7% of U.S. households were reusing graywater (NPD Group, 1999). Another study in the same year (Little, 1999) found that 13% of the households in Arizona used graywater for irrigation with the most utilized source being from clothes washers (66%). Several states, including California, Arizona, New Mexico, Utah, Texas, have regulated the practice. But there are two areas of concern with the practice. One is the potential threat to human health and the other is the potential long term impact of graywater on plants, soil chemistry and microbiology.

The objective of this literature review was to bring together the current state of knowledge on potential long-term impacts of landscape irrigation with household graywater and to identify the data gaps that need to be addressed in future research. The literature review comprises Chapters 1.0 through 4.0 of this report and they focus on: 1) overall graywater issues including quantity, quality, treatment methods, and legality; 2) possible graywater effects on residential landscape plants; 3) effects on soil microbial function; 4) use of indicator organisms for human health considerations; and 5) soil chemistry changes due to graywater application. Chapter 5.0 synthesizes the key findings and knowledge gaps from four subject categories forming the basis for a research program to fill in the knowledge gaps.

ES.2 Graywater Quantity and Graywater Systems

By the strictest definition, graywater is any wastewater not generated from toilet flushing, otherwise referred to as blackwater, and this definition is used rather widely, especially in Europe and Australia. But in the United States, the more common definition of graywater is wastewater that originates from residential clothes washers, bathtubs, showers, and sinks, but does not include wastewater from kitchen sinks, dishwashers and toilets. Kitchen sinks and dishwashers are not usually incorporated into graywater flow due to the high organic content leading to oxygen depletion and increased microbial activity of the graywater. In this report graywater is defined as wastewater that originates from residential clothes washers, bathtubs, showers, and sinks. Toilets, kitchen sinks and dishwashers are not included.

Graywater constitutes about 50% of the total wastewater generated (69 gallons/person/day) within a household. Given an average household population of 2.6 persons in the U.S., there are approximately 90 gallons of graywater per day per household available for outside use. This supply is not sufficient to irrigate an entire yard landscaped in bedding plants and bluegrass, but a homeowner with a 2,500 ft^2 house on a 1/4 acre lot could irrigate about 1/2 of the yard with graywater if xeriscaping is used.

In order install an efficient graywater irrigation system it is necessary to know the water requirements of the plants to be irrigated, and to have a collection and storage system that will deliver graywater at the appropriate time and in the appropriate amount to the landscape. But currently, *guidance on application rates is lacking. While some very sophisticated graywater systems are available for the storage, treatment and delivery of graywater to its end use, guidance is lacking for the homeowner to design a proper system in terms the size of storage tank required, and the required pump capacity where a gravity system is not feasible*.

ES.3 Graywater Chemistry Issues

Graywater contains a complex mixture of chemicals used in a variety of household products. These chemicals can be categorized according to their function in the products such as surfactants, detergents, bleaches, dyes, enzymes, fragrances, flavorings, preservatives, builders, etc. A survey by the National Institute of Medicine and the National Institute of Health reported that household products contain over 2,500 chemicals in 5,000 products (National Institute of Health, 2004). It is assumed that many, if not most, of these chemicals occur in graywater. These chemicals can change the bulk chemical characteristics of the water such as pH, suspended solids, biological oxygen demand, and conductivity.

The literature reveals that a number of constituents in typical graywater are known to be potentially harmful to plants singly or in combination with other chemicals in the graywater. But *it remains to be documented whether or not these constituents will accumulate in the soil in sufficient quantities to harm plants or perhaps be transported below the root zone, possibly to the groundwater, during the rainy season.* Although there are a number of graywater systems that have been in operation for some years with no obvious detriment to vegetation, the scientific documentation is lacking. *No published studies were found that examined the changes in soil chemistry as a result of irrigation with graywater*.

ES.4 Effects of Graywater Irrigation on Landscape Plants

Information on the effects of graywater irrigation on landscape plants is scarce. In Arizona, a two-year study on landscape plants irrigated with graywater in residential areas revealed that, except for a slight increase in boron, no salts had accumulated in either the plants or the surrounding soil (NSFC, 2002). In California, a graywater pilot project was conducted Los Angeles in the early 1990s, consisting of eight residential graywater test systems (City of Los Angeles, 1992). This study found that the Soil Adsorption Ratio (SAR) and Na^+ increased over the course of the study; however, negative effects on plant growth and quality of landscape plants were not observed. The authors pointed out that any harmful effects might take a number of years to manifest themselves. At this time, knowledge is lacking on the long term effects of graywater irrigation on landscape plants

Plant resistance levels have been mainly extrapolated from other salinity experiments or from experiments with recycled wastewater used for irrigation. These studies found that most deciduous trees are more tolerant to salt than evergreens because they lose their leaves each fall thereby preventing a great degree of build up of harmful constituents from season to season. The literature review reveals clearly that we do not know much about how bedding plants, which are one of the most likely candidates for graywater irrigation, will respond to irrigation with either reused wastewater or graywater. Since most bedding plants are annuals and will not accumulate chemicals from year to year, it seems that this group should be high on the priority list for further research.

While treated wastewater reuse research may provide a first estimate of which plants are most likely to do poorly if irrigated with graywater, and which plants can be expected to perform well, there are several important differences that must be considered. For example, the chemical composition of graywater differs from treated wastewater in some aspects, such as the proportions of salts, organic matter, and surfactants. Also, treated wastewater is aerobic and nearly neutral pH, while graywater will have a lower DO and if stored prior to application may be anaerobic with low pH potentially resulting in a different chemistry in the applied water. The application method for household graywater irrigation is typically via subsurface, drip, or surface flooding on small areas whereas the majority of recycled treated wastewater is applied via sprinkler irrigation in large landscapes. Drip and subsurface irrigation concentrates the application area and may result in higher chemical concentrations in the root zone. But a related issue, noted above, is the role of rainfall. The rain may reduce chemical concentrations in the soil by transporting them to low soil horizons, thus mitigating on a seasonal basis the chemical buildup that occurs during the irrigation period. For these reasons, it is necessary that an experimental program be developed in which actual graywater is used for studies similar to those that have been done with treated wastewater. Extrapolation of short term results to long term impacts will be a key consideration in designing an experimental plan.

ES.5 Effects of Graywater Irrigation on Soil Microbiology

Information is lacking on the effects of graywater irrigation on indigenous soil microorganisms, both short term effects and long term effects. Impacts are difficult to predict due to the ever-changing and heterogeneous nature of graywater chemical constituents. Organic matter and nutrients in graywater may stimulate microbial growth and degradation activities in the soil in the short term, but the long-term impacts of graywater irrigation might be detrimental to soil microorganisms and their important ecosystem functions due to the buildup of chemical constituents, including salts and potential toxins. Another possible complication is that graywater storage systems can harbor diverse, microbial biofilm communities that are capable of degrading some constituents of graywater, including surfactants (a positive effect), but may also cause physical clogging of the flow regulators in drip irrigation systems, and possible soil pore spaces.

On the positive side, most studies that have examined the impacts of wastewater effluent have shown a benefit to soil microbial communities due to the inputs of organic matter and nutrients. This is encouraging, considering that wastewater can also contain heavy metals, which could negatively impact soil microorganisms in ways that graywater would not.

ES.6 Public Health Issues

It is well established that the levels of fecal coliform in graywater exceed allowable criteria set by regulatory agencies for discharge of wastewater, and for natural waters subject to body contact. But there is controversy regarding whether the indicator organism counts are an accurate indicator of the actual health threat posed to the homeowner who comes into direct contact with graywater because fecal coliform concentrations have been observed to multiply in graywater, whereas pathogens die off rapidly. Therefore, a high graywater fecal coliform count may not indicate the same level of pathogen exposure risk as the same fecal coliform count found in treated wastewater. Even so, many states that permit graywater use require a subsurface irrigation system to reduce human exposure to pathogens, but this requirement detracts significantly from its attractiveness to the average homeowner. Drip irrigation would be much more attractive, but before it is recommended it is important to determine how well the fecal bacteria survive in the surface layer of the soil.

Additional experiments are needed on raw and stored graywater to determine the survivability (or growth) of different indicator organisms and the correlation of their concentrations to the concentration of pathogens in the same graywater sample leading to the determination of a suitable indicator organism that is a good measure of actual human health risk. If possible, the tests should be run on a (large) sample of fresh graywater, and on the same sample periodically as it is stored at room temperature.

ES.7 Summary and Recommendations

Most of the knowledge gaps identified in this report are interrelated, even though they have been identified in connection with an individual scientific field like graywater chemistry, plant and soil health, human health, or groundwater pollution. To fill the knowledge gaps, a targeted research program is needed that includes all applicable scientific disciplines. This research should seek to answer with some certainty the following three broad questions:

1. Over the long term, will a residential landscape that is irrigated with graywater remain healthy and vibrant? If not, are there steps that can be taken to minimize or mitigate the impact?
2. Over the long term, does irrigation of a residential landscape with graywater pose a threat to the quality of groundwater? If so, can these threats be minimized or eliminated?
3. Over the long term, does irrigation of a residential landscape with graywater pose a health risk to humans? Can these risks be minimized?

Answering these three basic questions will result in solid scientific underpinnings for the practice of residential irrigation with graywater by providing proper guidance to homeowners on the proper type of collection and distribution system to install, the type of plants that can be irrigated with graywater and the proper application rates for the selected landscape. Homeowners will know by examining their landscape when it is time to amend soil, or take other mitigation measures to restore plant health and vigor and what methods to use. In doing so, the regulatory community (plumbing inspectors, public health officials and environmental regulators) can take comfort in knowing that the systems are adequate, safe and pose little or no threat to the quality of the environment. Simultaneously, they will know that household demands for potable water can be reduced by 30-50%.

CHAPTER 1.0

OVERALL GRAYWATER ISSUES

1.1 Introduction

The use of household graywater for landscape irrigation is gaining in popularity as individuals and communities throughout the U.S. become increasingly interested in innovative approaches to water resource sustainability. Several U.S. states, including California, Arizona, New Mexico, Utah, and Texas, have legalized the practice. Though household irrigation is gaining momentum, there are some concerns with the practice, which necessitate further scientific study. One concern is the threat to human health; the other is the impact of graywater on plants and soil chemistry and microbiology

The objective of this literature review is to identify the current state of knowledge on the long-term impacts of landscape irrigation with household graywater and identify the data gaps that should be addressed in the experimental plan. The literature review focuses on: 1) overall graywater issues including quality, quantity, treatment methods, and legality, 2) possible graywater effects on residential landscaping, 3) effects on soil microbiology and indicator organisms for human health considerations, and 4) soil chemistry changes due to graywater application. The last chapter of this document synthesizes the key findings and knowledge gaps from each of the four individual areas and recommends a research approach to address them.

1.2 Graywater Background

There is no doubt that graywater reuse practices, commercial or residential, are increasing in acceptance and implementation throughout the United States and even more so internationally. For example, hotels are using green practices which include graywater reuse as a notable part (March et al., 2004), and University dormitories are seeing the added benefits of recycling graywater to flush toilets (Surendran et al., 1998). Individual homeowners connect hoses to their washing machines to utilize the wash water for landscape features (Prillwitz et al., 1995), and some community developments are being built with parallel plumbing systems to separate, collect, treat and reuse graywater (Otterpohl et al., 2003).

One indication of the increasing acceptance of household graywater reuse is its legalization by several states within the past decade (see Section 1.2.7). A study funded by The Soap and Detergent Association (NPD Group, 1999) found that 7% of U.S. households were reusing graywater. In addition, some local studies on graywater irrigation practices and impacts have been completed. For example, in 1999, the Water Conservation Alliance of Southern Arizona conducted a study of residential graywater that included a survey of graywater reuse in the greater Tuscon, AZ area (Little, 1999). The survey results from 600 responses showed a weighted average of 13% of the households using graywater for irrigation. The results also indicated that the most utilized household graywater source was from the clothes washer (66%). The Gray Water Pilot Project in the City of Los Angeles, CA (1992) conducted research on eight voluntary residential sites retro-fitted with graywater systems for the purpose of residential sub-surface irrigation. The focus of the study was on changes in the soil characteristics due to graywater irrigation. The results showed an increase in sodium levels (NA^+) and in the Soil Adsorption Ratio (SAR), but the plants appeared to be unaffected.

1.3 Graywater Definition and Quantity Characterization

Within a residence several graywater sources contribute to the total indoor water use budget. Research has been performed at various levels to determine the quantity of graywater generated by each of these uses in a household. A study for the AWWA Research Foundation titled the Residential End Uses of Water Study (Mayer et al., 1999) presents usage data collected in 14 North American cities (12 study sites) for approximately 1,200 households. Highly detailed data observations were collected using computer software and data loggers over a total time period of 14 weeks. The combined average indoor water use for all 14 cities was determined to be 69 gallons per capita per day (gpcd). Figure 1-1 graphically displays the average distribution between each individual use.

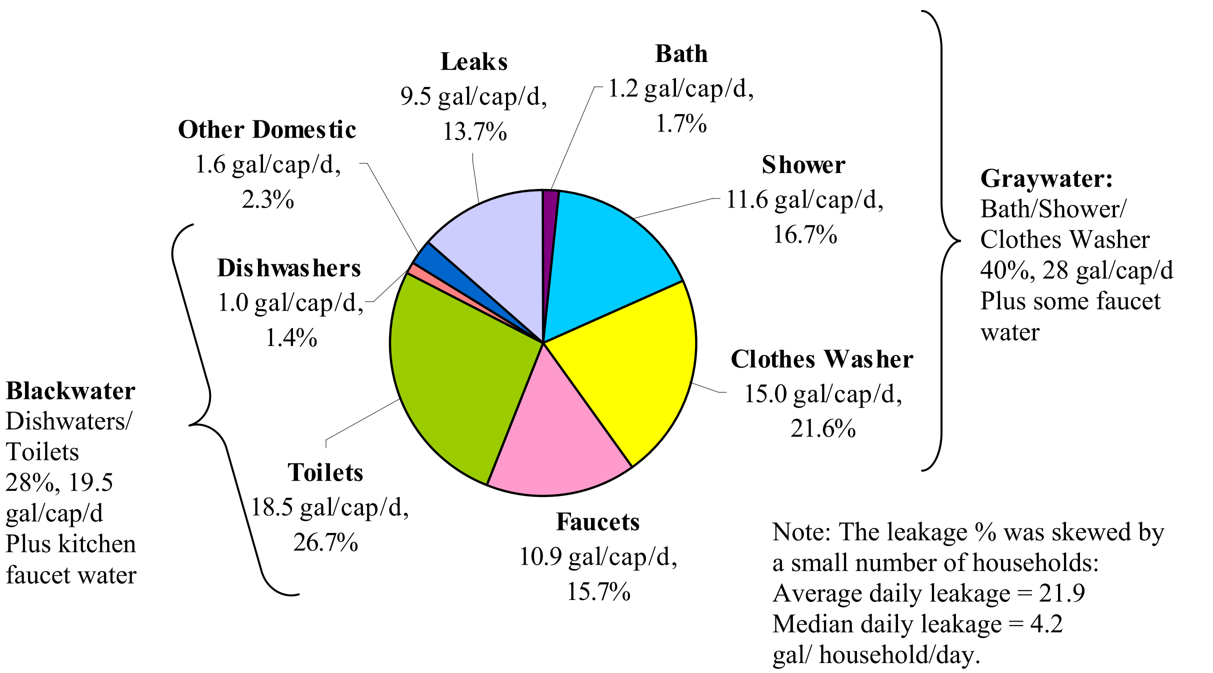


Figure 1-1. Average Indoor Residential Water Usage for 12 North American Cities. Adapted from Residential End Uses of Water, by permission. Copyright ©1999, American Water Works Association and Awwa Research Foundation (AwwaRF).

Of these end uses, the sources contributing to graywater are typically baths (1.7%), clothes washers (21.6%), showers (16.7%) and a portion of the faucets (15.7%). The sources of faucet flow are bathroom basins, hand dishwashing, drinking water and teeth brushing. Excluding faucet contributions the indoor graywater flow is 40% of total indoor water usage. Including faucet flows, graywater comprises more than one-half of the water used indoors.

Outdoor usage of potable water comprises over 50% of the residential water budget and can vary depending upon region. The research by Mayer et al. (1999) calculated an average of 101 gpcd allocated to outdoor uses, representing roughly 59% of the potable residential water budget. Examination of indoor vs. outdoor water use for the individual cities participating in the study reveals that outdoor use is typically greater than indoor use. Figure 1-2 graphically compares the water usage of 12 NA households. If study site #12 (which is uniquely different from the other 11 sites in terms of the ratio of indoor to outdoor water use) is not used, the average ratio of indoor to outdoor residential water usage for the other eleven study sites is 1.0. But for seven of those eleven households (64% of the households) outdoor water usage is greater than inside usage, i.e. the ratio shown on Figure 1-2 is less than 1.0.

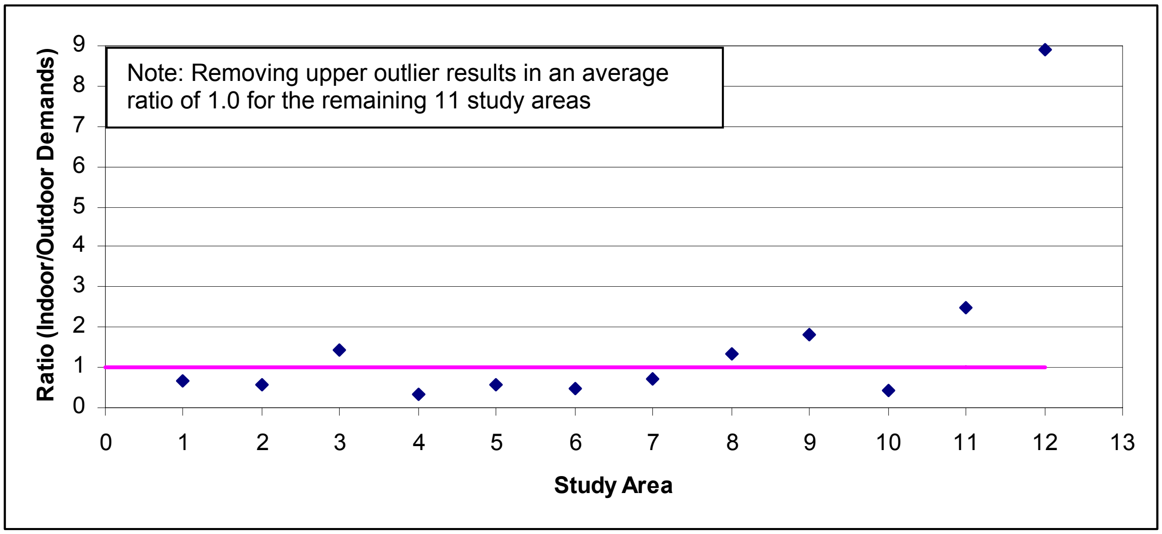


Figure 1-2. Ratio of Indoor to Outdoor Water Usage for 12 North American Study Areas.

An estimate of potential graywater supply for landscape irrigation can be made using results from the AWWA study (Mayer et al., 1999). As noted above, for the 14 North American cities studied, average indoor water usage was reported to be 69 gpcd. With an average household of 2.6 persons (U.S. Census 2000/2003), the average indoor water uses per household is 180 gallons per day. Approximately 50% of this flow is allocated to toilet flushing, the kitchen sink and leaks, leaving the remaining 50% or 90 gallons per day for residential landscape use. Table 1-1 shows how much of a typical yard could be irrigated with graywater for various application rates. The table ignores the fact that that rainfall will reduce the evapotranspiration demands that must be supplied by rainwater, but for arid and semiarid areas, it is fairly accurate.

It is immediately evident from Table 2-1 that a household will not generate enough graywater to irrigate an entire yard landscaped in bedding plants and bluegrass. On the other hand a homeowner with a 2,500 ft^2 house on a 1/4 acre lot could landscape about 1/2 of the yard (3,750 ft^2) using xeriscape irrigated with graywater at a rate of 0.3 to 0.4 inches/week. The remainder of the yard could comprise non-living landscape cover material, as is common in Arizona and New Mexico, or grass and flower beds as is common in Colorado, California, and other semi-arid states. The grass and flower beds would require irrigation with potable water.

Residential water budgets vary for many reasons such as a particularly dry year, installation of water conserving devices and differences in landscape features, especially percent of landscape in lawn. It can be concluded generally that during the irrigation season, the graywater generated by a household can be used entirely for landscape irrigation. But what is not addressed in the literature is guidance regarding whether it is better to irrigate a given area

Table 1-1. Potential Yard Area For Graywater Irrigation For Various Application Rates.

Evapo-transporation Rate (in/mo)	Req'd Graywater Application Rate (in/wk)	Yard Area that can be watered (ft^2)	Typical Plants
0.5	0.1	8,086	Xeriscape
1.0	0.3	4,043	
1.5	0.4	2,695	
2.0	0.5	2,021	Trees
3.0	0.8	1,348	
4.0	1.0	1,011	Bedding Plants
6.0	1.5	674	
8.0	2.0	505	Bluegrass

exclusively with graywater, and the remaining area with potable water, or should the areas irrigated with graywater be rotated to avoid the possibility of chemical buildup in the soil, or possible damage to plants.

1.3.1 Water Conservation Efforts

Low flush toilets, low flow showerheads and faucets, irrigation timers, and voluntary watering restrictions are a few of the options available for conserving water in the home. Some of these options such as low flow showerheads and faucets reduce the amount of graywater produced and thus might limit the ability to meet intended household demands for reusing graywater; others like irrigation timers, and voluntary watering restrictions reduce graywater demand. As conservation efforts improve, both the supply of and the demand for recycled graywater (i.e. toilet flushing) will likely be diminished within a household (Leggett, 2002).

1.4 Graywater Quality

The physical, chemical, and microbial characteristics of graywater varies based upon the sources connected to the collection system, household inhabitants, household chemicals used by the residents for personal hygiene and house cleaning, personal care, plus medications and waste products disposed of in sinks (Eriksson et. al., 2002). The graywater composition typically will vary depending on the source water as depicted in Table 1-2. Christova-Boal et al. (1996) states that graywater will occasionally contain oils, paints, and solvents contributed from household activities. These intermittent chemicals inputs could have detrimental effects on graywater irrigated areas.

Table 1-2. Graywater Characteristics by Source[1].

Water Source	Characteristics
Automatic Clothes Washer	Bleach, Foam, High pH, Hot water, Nitrate, Oil and Grease, Oxygen demand, Phosphate, Salinity, Soaps, Sodium, Suspended solids, and Turbidity
Automatic Dish Washer	Bacteria, Foam, Food particles, High pH, Hot water, Odor, Oil and grease, Organic matter, Oxygen demand, Salinity, Soaps, Suspended solids, and Turbidity
Bath tub and shower	Bacteria, Hair, Hot water, Odor, Oil and grease, Oxygen demand, Soaps, Suspended solids, and Turbidity
Evaporative Cooler	Salinity
Sinks, including kitchen	Bacteria, Food particles, Hot water, Odor, Oil and grease, Organic matter, Oxygen demand, Soaps, Suspended solids, and Turbidity

[1]adapted from the New Mexico State University's Safe Use of Household Graywater guide (1994)

The kitchen sink and dishwasher waters often carry microbial contamination from such practices as rinsing raw meat. Raw foods often contain enteric organisms that may possibly pose a health risk (Casanova, 2001). Due to the potential for increased health risks (via pathogens) and additional solids and organic loading, it is generally recommended that kitchen sink and dishwasher water flows be connected to the sanitary sewer and not be included in the graywater collection system.

Graywater quality data from these studies are presented in Table 1-3. Rose et al. (1991) is one of the most frequently referenced research papers on bacterial differences between sources (shower vs. laundry) and household composition (children under 12 present). The work presented by Casanova et al. (2001) is taken from ongoing research at the Casa Del Agua, an operational graywater demonstration project in Tucson, AZ. Eriksson et al. (2003) present graywater constituent data in the beginning of their research to determine the presence of pharmaceutical and personal care products (PPCP) in graywater.

All of the values in Table 1-3 are for raw graywater, before any treatment has taken place, and therefore represent a variety of influent graywater qualities. The range in constituent values needs to be considered when designing a graywater reuse system because no single graywater system is the same as another.

1.5 Health Risks—General

The fecal coliform counts reported for graywater indicate a potential health risk associated with graywater reuse. Rose et al. (1991) found that graywater from households with young children has higher bacterial concentrations. Rose et al. (1991) also found that shower water is higher in total and fecal coliform than laundry water. However, the degree of risk to human health that exists as the result of bacterial counts is controversial. Dixon et al. (1999a) discussed instituting guidelines for graywater reuse that assess the range of risk associated with exposure to graywater accompanied with the level of microbial contamination and targeted population. The authors pose an interesting question (which they do not answer) "should the seemingly (and practically) harmless activity of taking a bath be regarded as a health risk comparable in magnitude with that associated with flushing the WC (toilet) with graywater?" Ottoson et al. (2003) indicated a potential for over-estimation of the fecal load using Coliform as bacterial indicators for enteric pathogens. The conclusions encourage use of fecal enterococci as a guideline if one must be used.

1.6 Applications and End-Uses for Graywater

The initial applications of residential graywater in the U.S. likely began with homeowners hand-bailing graywater, such as shower water and washer water, to help irrigate flowers, shrubs and other landscape features during times of drought. That practice has evolved into current day practice (mostly in arid and semi-arid states) of routing graywater into yards for landscape irrigation, as discussed previously. Another reason for reusing graywater is remotely located homes may not be connected to municipal sewer systems and therefore must manage wastewater on-site. It is this second option of on-site wastewater treatment systems for which U.S. EPA (2002) addresses the possibility of reusing graywater in an effort to reduce hydraulic and pollutant loading to the waste treatment system.

Gunther (2000) successfully constructed a “wetpark” in Sweden, essentially a treatment wetland, for a clustered community treating graywater to a level that is acceptable for reuse by the residences. The design achieves effective treatment while providing a natural area for passive recreational use.

Toilet flushing is another application for graywater re-use currently being practiced in Germany (Nolde, 1999), England (Hills, 2000) and Australia (New South Wales Health, 2000).

Table 1-3. Graywater Characterizations from Three Studies.

Reference	Eriksson et al. (2003)	Rose et al. (1991)				Casanova et al. (2001)
Source	Composite	Shower	Laundry Wash	Laundry Rinse	Composite	Composite
Concentration (mg/L)	Range	Range				
Temperature (^{o}C)	21.6 – 28.2					
pH	7.6 – 8.6				6.54	7.47
COD	77 – 240					
BOD	26 – 130					64.85
TSS	7 – 207					35.09
Turbidity (NTU)		28 – 96	39 – 296	14 – 29	76.3	43
NH_4-N	0.02 – 0.42	0.11 – 0.37	0.1 – 3.47	0.06 – 0.33	0.74	
NO_3-N	<0.02 – 0.26				0.98	
Total-N	3.6 – 6.4				1.7	
PO_4-P					9.3	
Tot-P	0.28 – 0.779					
Sulfate					22.9	59.59
Chloride					9	20.54
Hardness					144	
Alkalinity					158	
Ca	99 – 100					
K	5.9 – 7.4					
Mg	20.8 - 23					
Na	44.7 – 98.5					
Total bacterial pop. (CFU/100mL)	4.0×10^7 – 1.5×10^8	1.0×10^7 - 1.0×10^8	1.0×10^7 - 1.0×10^8	1.0×10^7 - 1.0×10^8	6.1×10^8	
Total coliform (CFU/100 mL)	6.0×10^3 – 3.2×10^5	1.0×10^5	199	56	2.8×10^7	8.03×10^7
Fecal coliform (CFU/100mL)		6.0×10^3	126	25	1.82×10^4 - 7.94×10^6	5.63×10^5
Fecal Streptococci (CFU/100mL)						2.38×10^2
E. Coli (CFU/100 mL)	<100 - 2800					

1.7 Graywater Storage and Treatment Methods

Different graywater storage and treatment systems exist in the market place. There are systems marketed by some manufacturers in states that allow graywater irrigation. For systems invented by manufacturers, the extent of treatment can vary widely. For state-recommended systems, slight variations were noticed. The manufactured systems surveyed in this study ranged from simple collection of graywater without treatment to more complex systems that mimic conventional wastewater treatment plants, but on a smaller scale. Usually, the more complex systems are utilized for uses other than irrigation (e.g. toilet flushing). Typically, the minimum treatment is to use coarse filtration mesh screen to remove large objects like hair, thread, and lint.

There are many graywater systems being marketed. However, the systems described below were selected on the basis of their diversity. They were chosen to show the big picture and the wide variations in the existing systems along with the different treatment methods that can be adopted. The different systems discussed below are shown in Figure 1-3. Table 1-4 summarizes the main characteristics of each system. All systems except the California Graywater System are patented and sell for $1100 (12-gallon Earthstar system, parts only) to several thousand dollars. The California Graywater System installed by a plumber in a house already dual plumbed is estimated to cost about $750. This does not include the cost of the outdoor irrigation system, which would be the same for any of these systems.

1.7.1 Earthstar Graywater System (location of manufacture not available)

Earthstar Graywater is a graywater system from Gaiam Real Goods. The system's main components are a 12- or 55-gallon tank, sand filter, automatic float switch, and a pump. When the water reaches the desired level in the tank, the automatic float switch triggers the operation of the pump to start evacuating the tank to the yard. The system is intended for irrigation use. The sand filter is used for tank water cleaning; an automatic backwash is applied every two months.

1.7.2 Clivus Multrum (Australia)

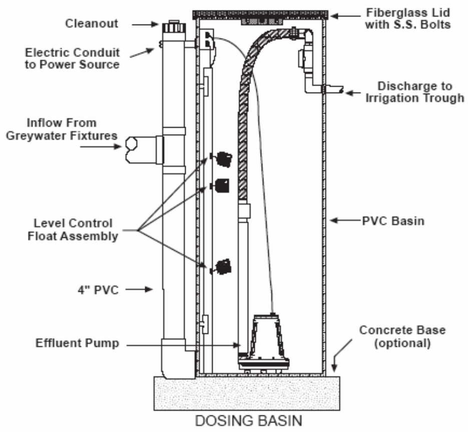
The Clivus Multrum system looks like a wet well in the pumping station. The main components are the dosing basin, a submersible pump, and level control float. No treatment is included. The system is intended for irrigation use. The irrigation system adopted in this system is underground irrigation using either an irrigation chamber (a half-round pipe 8-12" diameter) or wood irrigation trough. The pump starts working when the amount of water in the dosing basin is enough to create 1-1/2 inches of water depth in the irrigation chamber. This minimum of 1-1/2 inches is set to insure a constant depth over the entire irrigation chamber.

1.7.3 Graywater System for Toilet Flushing (Germany)

This graywater treatment system was found in a German Water Sector Report on the web at www.umweltbundesamt.org. It utilizes graywater for toilet flushing. The system looks like a miniature wastewater treatment plant. It includes coarse filter, two chambers, UV disinfection unit, storage tank, and backup potable water feed if the graywater is not enough to feed the toilets. Comparing it to larger-scale wastewater treatment plants, one can see that the coarse filter functions as the bar screen in the WWTP. The two chambers act as primary and secondary treatment tanks. Aeration is also included in the tanks. In addition, the system has a small-scale UV disinfection unit. Finally, there is a third tank that works as a storage reservoir to feed the toilets.

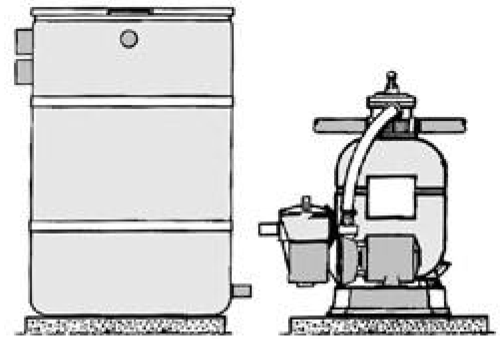
1.7.4 Graywater Saver (Australia)

Graywater Saver is an Australian owned and patented graywater reuse system. The system collects graywater for the use in irrigation (irrigation trenches). The system is one of the simplest in operation and construction. The only treatment used is a mesh basket filter. No

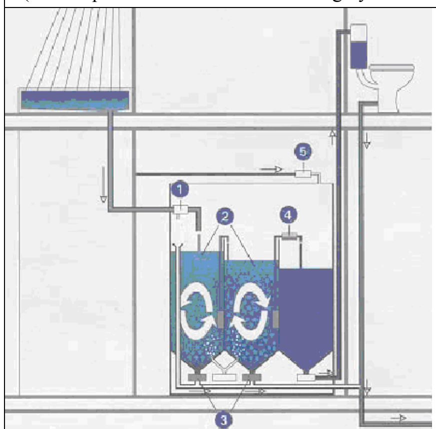


Clivus Multrum System
(Ref: http://www.clivusmultrum.com/greywater.html)

Graywater Saver
(Ref: http://www.greywatersaver.com/)

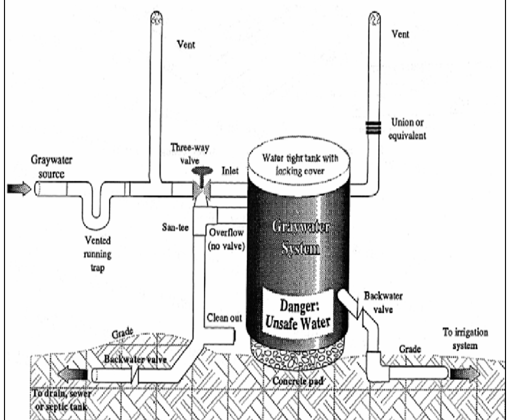


Earthstar Greywater Systems
http://www.realgoods.com/renew/shop/product.cfm/dp/2300/sd/2301/ts/3044831



- Filtration
- Primary & secondary cleansing chambers
- Sludge extraction
- UV disinfection unit
- Tap water backfeed

Graywater System for Toilet Flushing
(Ref: http://www.umweltbundesamt.org/Wsektor/wasserdoku/english/kap41_e.pdf)



California Graywater System
(Ref: http://www.owue.water.ca.gov/docs/Revised_Graywater_Standards.pdf)

Figure 1-3. Different Graywater Collection and Treatment Systems.

storage is provided for the graywater. The system is also flexible in diverting the graywater to the sewer system by the use of push-pull valve.

1.7.5 State Recommended Systems

Most states that regulate graywater irrigation specify a simple graywater system that includes storage and, in some states, coarse filtration such as the California Graywater System shown in Figure 1-3. Most of the specified systems have a tightly covered and locked graywater tank, a trap, screened vents for both trap and tank, a warning sign for non-potable water existence, a three-way valve to divert graywater to the sewer system, and an overflow exit and cleanout pipe connected to the sewer system. These systems also typically have some kind of course filtration at the tank outlet and some variations in the irrigation system used.

Though a wide range of treatment methods exist it should be noted that the NPD Group (1999) survey revealed that the majority of graywater reusers did not store (82%) or treat (93%) their graywater before use.

Depending on holding time, graywater storage can be either beneficial or detrimental to water quality. The effect of storage on graywater quality was studied by Dixon et al. in 1996. They discovered that the quality of graywater, in terms of total suspended solids (TSS) and chemical oxygen demand (COD), improved when stored for 24 hours; however, storage for over 48 hours could be problematic due to a decrease in dissolved oxygen levels. Aeration of the graywater could minimize any deleterious effect of storage, but they noted that graywater tanks would have to be designed for settling solids.

One treatment aspect not included in most graywater systems, both commercial and state-recommended systems, is a disinfection process. Many researchers have looked at microbiological quality aspects of graywater and potential health effects (Rose et al. 1991, Christova-Boal et al. 1996, Casanova et al. 2001). The lack of disinfection could be a potential human health risk for irrigation since, according to a study completed for the Soap and Detergent Association by the NPD Group (1999), the majority of graywater users (93%) did not treat their graywater and many graywater users (46%) irrigated fruits and vegetables plants with their graywater.

1.8 Graywater Regulations in the United States

Graywater regulations vary widely from state to state. Some states have comprehensive graywater regulations and guidelines, others define graywater without any provisions for irrigation, and others have no mention of graywater at all. Several other states allow graywater systems to be installed under research or on a case-by-case basis, but do not specify legal parameters. Typically arid states have been the most notable advocates for graywater irrigation and therefore their graywater guidelines are more comprehensive. For the purposes of this study we have focused on the states with more comprehensive graywater guidelines or regulations. These states include: Arizona, California, Idaho, Nevada, New Mexico, South Dakota, Texas, Utah, and Washington. A more comprehensive look at a wider range of graywater definitions can be found in Weston (1996) and/or Texas Onsite Wastewater Treatment Research Council (2004).

Table 1-4. Equipment Summary for Presented Graywater Systems.

SYSTEM	Main Components	Use	Storage	Aeration	Filtration	Pumping	Disinfection
CSU*	Tank, sand filter, UV.	Irrigation	300 gallon tank	Yes	Sand filter	Yes	UV
Earthstar	Tank, sand filter, automatic float switch, and a pump.	Irrigation	55-gallon tank	No	Sand filter	Yes	No
Clivus Multrum	Dosing basin, level control float, and submersible pump.	Irrigation	Dosing basin Approx. 250 gal	No	No	Yes (submersible pump)	No
Graywater for Toilet Flushing, German	Coarse filter, two sedimentation chambers, UV, pump, and a storage tank	Toilet flushing	Yes	Yes	Coarse filtration	Yes	UV
Graywater Saver	Small collector, strainer, pull-push valve.	Irrigation	No	No	Coarse filtration through mesh basket filter (strainer)	No	No
State-designed systems	Tightly covered tank, trap, vents	Irrigation	Yes	No	Yes/No	Typical No, but can be applied if needed	No

*CSU: A graywater system installed at a private residence that the report authors are studying.

Several state regulations or guidelines have similar requirements or restrictions, which may include topics such as permits, no spray, no runoff, setback distances, no vegetable watering, no hazardous or toxic chemicals, filtration requirements, reduced irrigation system pressure, etc. Tables summarizing the pertinent States' graywater regulations and guidelines and their graywater irrigation treatment and application requirements may be found in Appendix A.

1.9 Key Findings and Knowledge Gaps

Worldwide, graywater reuse is increasing in popularity for both landscape irrigation, and for toilet flushing in multi-units dwellings such as hotels and apartments and dormitories. In the U.S. the most popular use by far is residential landscape irrigation principally with washing machine water. Recognizing the increasing popularity of graywater reuse, the states of Arizona, California, Idaho, Nevada, New Mexico, South Dakota, Texas, Utah, and Washington have developed comprehensive guidelines or regulations for graywater reuse. However, our understanding of the best methods for capture and application of graywater for landscape irrigation and of the health threats posed by such application are lacking in several areas.

1. Quantity Issues: While the quantity of graywater generated in a typical household is not sufficient to supply the total landscape water demands for the majority of households, the volume should be sufficient to meet the irrigation demands of the

non-grassed areas such as flowerbeds and shrubs. However, guidance on application rates is lacking.

2. System Issues: While some very sophisticated systems are available for the storage treatment and delivery of graywater to its end use, most existing graywater systems in the US are very simple, e.g. gravity drains from the washing machine or graywater collection system. In essence, these systems perform more like graywater disposal systems than irrigation systems. Given that there was guidance for application rates (see No. 1 above), guidance is lacking for the homeowner to design a proper system in terms the size of storage tank required, and the required pump capacity where a gravity system is not feasible.

3. Quality Issues: There is a multitude of chemicals in graywater due to the wide array of products that are disposed of in house drains. Furthermore the types of chemicals and their concentrations will vary with the personal habits, and preferences of household individuals. One can also speculate that there will be variations in quality over time, and possibly season, as household activities change, (e.g. changes in brand or type of personal hygiene products and/or cleaning products used), children grow up, guests visit, and maintenance activities occur where waste products are disposed of in the sink or laundry tub. What is not known is how the combination of chemicals affect irrigated areas in terms of plant health, and soil microbiology and soil chemistry.

4. Health Issues: It is well established that the levels of fecal coliform in graywater exceed allowable values set by regulatory agencies for discharge of wastewater, and for natural waters subject to body contact. But there is controversy with respect to the actual health threat posed by direct contact of the homeowner with graywater in terms of exposure to disease causing pathogens and viruses. There is also a question about the extent of this health threat to humans and animals once it has been applied to the soil.

These issues are addressed in more detail in the following three chapters, which deal with Landscape Plants, Microbial Ecology of Graywater, and Graywater Chemistry Issues, respectively. Chapter 5.0, the final chapter, comprises a Synthesis of Findings and Recommendations.

CHAPTER 2.0

LANDSCAPE PLANTS

2.1 Introduction

Household cleaning products often are sources of sodium, chloride, and other salts. When subsurface irrigation is used, sodium and chloride higher than 100 and 140 mg/L, respectively, may cause toxic effects to the saline/salt sensitive plants (Ayers and Westcot, 1985). The reported average sodium content in graywater collected in Los Angeles is 118 mg/L (City of Los Angeles, 1992). It is reported that the boron content in the water can increase by 0.1-0.4 mg/L during domestic usage and reach 0.4-1.5 mg/L in graywater (van der Leeden et al., 1990). Boron content in irrigation water higher than 0.5-1.0 mg/L can be toxic to some sensitive trees and ornamental shrubs. Therefore, before graywater reuse can be recommended, a synthesis of existing information on the relative salinity tolerance of turfgrasses and landscape plants needs to be made. Understanding the responses of urban landscape plants to graywater irrigation and avoiding the use of sensitive plants are critical to the long-term success of this practice.

2.2 Literature Review

Many studies have indicated that some species of landscape plants are quite sensitive to salinity (such as sodium and total salts) while other plants are relatively tolerant to salinity. Dissolved salts in soil solution can be absorbed by roots. These ions are carried through the sap stream to leaves (such as leaf margins and shoot tips) where they may accumulate to toxic levels. Salts that accumulate to a high level can result in characteristics of marginal (or tip) scorch. From a study associated with recycled wastewater it was found that most deciduous trees are more tolerant to salt than evergreens because they lose their leaves each fall thereby preventing a great degree of build up of harmful constituents from season to season (Denver Water, 2005). Qian et al. (2005) reported that ponderosa pines grown on sites irrigated with recycled wastewater exhibited much higher needle burn symptoms than those grown on sites irrigated with surface water. The level of needle burn was largely influenced by leaf tissue sodium concentration. Of the evergreens, conifers appeared to be more sensitive than junipers.

The literature review of plant response to graywater irrigation included estimating the salinity tolerance of landscape plants. Table 2-1 shows a list of plants commonly used in residential landscaping in the states of Colorado, California, Florida, and Arizona. They are grouped by plant categories, i.e. turfgrasses, bedding plants, evergreen woody plants and deciduous woody plants, and their general salinity tolerance is indicated as high (H), medium (M) or low (L).

Table 2-1. Most Commonly Used Landscape Plants And The Reported Salinity Tolerance By State.

H=High Tolerance, M=Moderate Tolerance, L=Low Tolerance[1]

Plant Group	Colorado	California	Florida	Arizona
Turf	1. Poa pratensis - Kentucky bluegrass(L) 2. Festuca arundinacea – Tall fescues (M) 3. Lolium perenne - Perennial ryegrass (M) 4. Buchloe dactyloides – Buffalograss (L)	1. Cynodon dactylon – Bermudagrass (H) 2. Festuca arundinacea - Tall fescue (M) 3. Zoysia – Zoysiagrass(H) 4. Buchloe dactyloides - Buffalograss (L) 5. Lolium perenne - Perennial ryegrass (M)	1. Cynodon dactylon – Bermudagrass (H) 2. Stenotaphrum secundatum - St. Augustinegrass (H) 3. Eremochloa ophiuroides – Centipedegrass (L)	1. Cynodon dactylon – Bermudagrass (H) 2. Zoysia – Zoysiagrass (H) 3. Buchloe dactyloides - Buffalograss (L) 4. Festuca arundinacea - Tall fescue (M)
Bedding Plants	1. Begonia semperfropens – Greenleaf Begonia 2. Genus Petunia – Petunia (L) 3. Impatiens wallweana – Impatiens 4. Paragonum x hortoram – Geranium (H)	1. Begonia semperfropens – Greenleaf Begonia 2. Genus Petunia – Petunia (L) 3. Impatiens wallweana – Impatiens 4. Paragonum x hortoram – Geranium (H)	1. Begonia semperfropens – Greenleaf Begonia 2. Genus Petunia – Petunia (L) 3. Impatiens wallweana – Impatiens 4. Paragonum x hortoram – Geranium (H)	1. Begonia semperfropens – Greenleaf Begonia 2. Genus Petunia – Petunia (L) 3. Impatiens wallweana – Impatiens 4. Paragonum x hortoram – Geranium (H)
Evergreen Woody Plants	1. Picea pungens – Colorado Spruce (L) 2. Pinus nigra – Austrian Pine (H) 3. Pinus sylvestris – Scotch Pine (L) (M) 4. Juniperus chinensis – Chinese Juniper (M) 5. Juniperus horizontalis – Creeping Juniper (M) 6. Thuja occidentalis – Arborvitae (M) 7. Pinus ponderosa – Ponderosa Pine (H)	1. Araucaria heterophylla-Norfolk Island Pine (H) 2. Sequoia sempervirens – Coast Redwood (No Data) 3. Juniperus chinensis – Chinese Juniper (M) 4. Cupressus sempervirens – Italian Cypress (No Data) 5. Schinus molle – California Pepper Tree (No Data) 6. Nerium oleander – Oleander (H) (M-H) 7. Plumbago auriculata – Plumbago (H) 8. Genus eucalyptus – Eucalyptus Tree(s) (No data) 9. Arecastrum romanzoffianum – Queen Palm (H) 10. Pinus nigra – Austrian Pine (H) 11. Juniperus horizontalis – Creeping Juniper (M) 12. Thuja occidentalis – Arborvitae (M)	1. Phoenix dactylifera – Date Palm (H) 2. Arecastrum romanzoffianum – Queen Palm (H) 3. Eneste ventricosum – Abyssinian banana (no data) 4. Strelitza reginne – Bird of Paradise (L) 5. Cycas revoluta – Sago Palm (H) 6. Pinus nigra – Austrian Pine (H) 7. Juniperus chinensis – Chinese Juniper (M) 8. Juniperus horizontalis – Creeping Juniper (M) 9. Thuja occidentalis – Arborvitae (M5)	1. Nerium oleander – Oleander (H) (M-H) 2. Juniperus Sabina – Sabin Juniper (M-H) 3. Carnegiea gigantean – Saguaro (no data) 3. Genus Yucca – Yucca (no data) 4. Pinus nigra – Austrian Pine (H) 5. Juniperus chinensis – Chinese Juniper (M) 6. Juniperus horizontalis – Creeping Juniper (M) 7. Thuja occidentalis – Arborvitae (M)

[1] This table comprises the combined information from: Tanji and Kielen, 2002 ; City of Los Angeles, 1992; Clatterbuck, 2003; Curtis et al., 1977; Francois, 1980; Harivandi, 1999; Johnson and Sucoff, 1999; Maas, 1986; Wu et al., 1997.

Plant Group	Colorado	California	Florida	Arizona
Deciduous Woody Plants	1. Populus tremuloides – Quaking Aspen (H) 2. Populus deltoides – Cottonwood (H) 3. Acer platanoides – Norway Maple (H) 4. Genus Malus – Crabapple (M) (L) 5. Ulmus americana – American Elm (M) (H); Ulmus pumila – Siberian Elm (M-H) 6. Fraxinus pennsylvanica – Green Ash (M) 7. Gleditsia triacanthos – Common Honeylocust (H) 8. Syringa chinensis Chinese Lilac (M) 9. Forsythia x intermedia – Forsythia (M4) (H) 10. Tilia cordata - Littleleaf Linden (L) 11. Pyrus Calleryana – callery Pear (H) 12. Celtis occidentalis – Hackberry (L) 13. Acer rubrum – Red Maple (L); Acer Saccharinum – Silver Maple (L); Acer ginnalla – Amur Maple (L1) 14. Cercis Canadensis - Redbud (No data) 15. Prunus 'Newport' – Newport Plum (M-H2) 16. Prunus virginiana – Chokecherry (M-H2) 17. Quercus robur – English Oak (M-H2)	1. Plantus racemosa – California Sycamore (no data) 2. Quercus lobata – Valley Oak (H) 3. Lagerstroemia indica – Crape Myrtle (L) 4. Ulmus americana – American Elm (M) (H) 5. Liquidambar stryaciflua – Sweetgum (H) (L) (M-H) 6. Genus Malus – Crabapple (M) (L) 7. Pyrus Calleryana – Callery Pear (H) 8. Celtis occidentalis – Hackberry (L) 9. Acer rubrum – Red Maple (L) 10. Cercis Canadensis – Redbud (no data)	*1. Quercus laurifolia* — Laurel Oak (H) *2. Lagerstroemia indica* — Crape Myrtle (L) 3. *Quercus virginiana* — Live Oak (H) 4. Genus Malus – Crabapple (M) (L) 5. Pyrus Calleryana – Callery Pear (H) 6. Celtis occidentalis – Hackberry (L) 7. Acer rubrum – Red Maple (L) 8. Cercis Canadensis - Redbud (no data)	1. Cercidium flordum – Palo Verde (no data) 2. Prospois chilensis _ Chilean Mesquite (no data) 3. Genus Malus – Crabapple (M) (L) 4. Pyrus Calleryana – Callery Pear (H) 5. Celtis occidentalis – Hackberry (L) 6. Acer rubrum – Red Maple (L) 7. Cercis Canadensis - Redbud (no data)

Note that there are no data available on salinity tolerance for several plants commonly used in residential landscaping.

The salt tolerance of the plants listed in Table 2-1 is based almost exclusively on studies where the applied water was some type other than graywater. There is very limited information on graywater irrigation on landscape plants. Most evaluations were short term. Wu et al. (1995) studied the effects of simulated graywater (high concentrations of Cl^-, Mg^{2+}, Ca^{2+}, and K^+) on the growth and ion uptake of nine plant species for 12 weeks. Five species were not affected by irrigation with simulated graywater (Azalea, Japanese boxwood, Hydrangea, Raphiolepsis, and

Jasmine) as evidenced by shoot growth and tolerance ratio (which was defined as the percentage of growth in graywater irrigated plants compared to the percentage of growth for the control plants). The growth of Lace fern, on the other hand, was severely affected by irrigation with graywater. Generally, there was a greater reduction of growth in those species that accumulated more Cl. Tissue Ca levels appeared to play a role in tolerance to Cl. Higher tissue Ca levels enabled the plants to have a greater tolerance to Cl.

In Arizona, a two-year study, completed in 2000, evaluated the effect on landscape plants irrigated with graywater in residential areas (NSFC, 2002). A drip system, buried a few inches underground was used. The study revealed that, except for a slight increase in boron, no salts had accumulated in either the plants or the surrounding soil. The boron detected was still within acceptable levels.

In California, a graywater pilot project was conducted in the early 1990s, which consisted of eight graywater test systems installed at residences in LA (City of Los Angeles, 1992). This study found that the Soil Adsorption Ratio (SAR) and Na^+ increased over the course of the study. However, negative effects on plant growth and quality of landscape plants were not observed. The authors pointed out that any harmful effects might take a number of years to manifest themselves.

Surfactants are widely used in household cleaning products. Rinallo et al. (1988) studied the effects of an anionic synthetic surfactant (ABS) and a non-ionic surfactant (Citowett) on wheat plantlets. Both beneficial and detrimental effects of surfactants on plants were observed. Growth stimulation effects occurred at low surfactant concentrations and short periods (< 8 days) exposure, whereas phytotoxic effects occurred with high concentration and/or long duration exposure. As part of NASA's controlled ecological life support system program, Bubenheim et al., (1997) tested the effect of an anion surfactant 'Igepon' on the growth of lettuce. They found Igepon concentration of 250 mg/L in nutrient solutions resulted in lettuce phytotoxic effects (browning of roots) within 4 hrs of exposure and suppression of root dry mass within 24 hrs. Plants showed recovery within three days following initial exposure, due to rapid degradation of surfactants by roots-associated microbes.

2.3 Key Findings and Knowledge Gaps

Information on the effects of graywater on landscape plants is scarce. Plant resistance levels listed in Table 2-1 were extrapolated mainly from other salinity experiments or from experiments using recycled wastewater for irrigation. But this information can be used to form a first estimate of which plants are most likely to do poorly if irrigated with graywater, and which plants can be expected to perform well. Table 2-2 lists the plants in these two categories. In the absence of additional information, the salt sensitive species, determined from previous studies and observations, probably should not be used when graywater is the irrigation water. However, these plants may serve as indicator plants to provide a pre-warning to landscape managers of associated problems.

The plants listed in Table 2-2 provide a good list of plants from which to choose for initial experiments on their response to graywater irrigation. If the plants respond in a fashion similar to that indicated in Table 2-1, we can have some confidence that the other plants listed in the table will respond similarly to graywater irrigation.

Table 2-2. Estimate Of How Certain Plants Will Likely React To Graywater Irrigation.

Sensitive Plants	Tolerant Plants
Turf Kentucky Bluegrass Buffalograss Centipedegrass	**Turf** Burmudagrass St. Augustinegrass Zoyiagrass
Bedding Plants Petunia	**Bedding Plants** Geranium
Evergreen Woody Plants Colorado Spruce Bird of Paradise	**Evergreen – Woody Plants** Austrian Pine Norfolk Island Pine Sabin Juniper Plumbago Oleander Queen Palm Date Palm Sago Palm
Deciduous Woody Plants Crabapple Littleleaf Linden Hackberry Red Maple Amur Maple Crepe Myrtle	**Deciduous Woody Plants** Quaking Aspen Cottonwood Norway Maple Honeylocust Callery Pear Valley Oak Live Oak Laurel Oak

Table 2-2 indicates clearly that we do not know much about bedding plants, which are one of the most likely candidates for graywater irrigation. Since most bedding plants are annuals and will not accumulate chemicals from year to year, it seems that this group should be high on the priority list for further research.

There are a number of other issues involved with graywater irrigation for which the current literature gives us little insight. These include:

1. The application method for household graywater irrigation differs from recycled wastewater. Usually graywater is applied via subsurface, drip, or surface flooding irrigation systems in residential landscapes, whereas the majority of recycled wastewater is applied via sprinkler irrigation in large landscapes. Drip and subsurface irrigation concentrates the application area and may result in higher chemical concentrations in the root zone.

2. Graywater is more likely to be applied sparingly, meeting only the evapotranspiration needs of the plants, especially in a well designed system vs. a graywater disposal system, as discussed in Chapter 2.0, whereas, reuse applications usually overwater. But a related issue rain. The rain may reduce chemical concentrations in the soil by flushing, mitigating on a seasonal basis the buildup that occurs during the irrigation period.

3. The chemical composition of graywater differs from treated wastewater in some aspects, such as the proportions of salts, organic matter, and surfactants. Also, treated

wastewater is aerobic and nearly neutral pH, while graywater will have a lower DO and if stored prior to application may be anaerobic with low pH resulting in a different chemistry in the applied water than if it were aerobic

4. Finally, the graywater irrigation experiments that have been conducted are short term. The question remains as to what effect long term irrigation with graywater will have on the plant health, especially for evergreen plants

CHAPTER 3.0

MICROBIAL ECOLOGY OF GRAYWATER

Because exposure of humans to pathogens is the major health-associated risk of recycling graywater for household use, most microbial studies of graywater have focused on presence and survival of pathogens and pathogen indicators in graywater. Less work has been done on the fate of these microorganisms following graywater release into the environment, and only a few studies have examined the potential impacts of graywater application on indigenous soil microorganisms.

3.1 Pathogens and Pathogen Indicators in Graywater

Pathogens can enter graywater by several mechanisms. For example, pathogens associated with fecal material can enter graywater during showering, bathing, and laundering of fecally contaminated laundry (e.g., diapers). Pathogens can also be introduced to graywater by food-handling in the kitchen, if kitchen wastewater is included in the graywater (Ottoson et al., 2003). Pathogens of concern in wastewaters in general include: bacteria such as enterotoxigenic *Escherichia coli, Salmonella, Shigella, Vibrio cholerae, Campylobacter*, and *Legionella*; protozoan such as *Giardia* and *Cryptosporidium*; and viruses such as enteroviruses, hepatitis A, rotavirus, and Norwalk virus.

Rarely are pathogens directly enumerated in graywater reuse studies, presumably due to the expense involved and the risk of exposure to investigators. Instead, most studies test for various pathogen indicators (organisms that are relatively benign, easy to enumerate, and whose presence may infer that a pathogen is present). Examples of commonly used indicators are total coliform, fecal coliform, fecal streptococci, and *E. coli*. Total coliform are a broad bacterial category based on certain biochemical properties; they are aerobic or facultative anaerobe, gram-negative, non-endospore forming, rod-shaped bacteria which ferment lactose to gas at 35ºC (Tortora et al., 1989). Although many studies have used total coliform as indicator organisms (Table 3-1), coliform are not solely enteric bacteria; they can be found naturally in water, plant and soil samples. Because of their ubiquitous presence in nature, total coliform is not an accurate indicator of fecal contamination. Fecal coliform, on the other hand, are a thermotolerant subgroup of total coliform that are found in gastrointestinal (GI) tracts of warm-blooded animals. The presence of fecal coliform in water indicates that the water has become contaminated with fecal matter, and that enteric pathogens may be present. Because fecal coliform are not indigenous to water and soil, their presence is a better indicator of fecal contamination than total coliform. More specific indicators include *E. coli*, fecal streptococci, and the enterococci. *Escherichia coli* are present mostly in human and animal GI tracts, and most strains are nonpathogenic. This organism is commonly used as an indicator of fecal contamination in environmental samples, and also as an index of enteric pathogens, including Salmonella (Gerba and Rose, 2003). However, because *E. coli* is capable of growing in warm environments, its numbers in sub-tropical soils may not be a suitable indicator of fecal contamination load or presence of pathogens (Desmarais et al., 2002). More recently, the enterococci have been used as indicators of enteric pathogens. Enterococci are a subgroup of fecal streptococci which are capable of growing in 6.5% NaCl. Because of the higher salt-tolerance, enterococci have been useful indicators of fecal contamination in marine and recreational waters. With regard to graywater, enterococci proved useful as indicator organisms as they did not overestimate the fecal contamination load as much as coliform bacteria, and they correlated well with rotovirus risk (Ottoson et al., 2003).

Numerous studies have inferred fecal contamination of graywater via the presence of indicator organisms (e.g., Novotny, 1990; Rose et al., 1991; Christova-Boal et al., 1996; Casanova et al., 2001; and Ottoson et al., 2003); averages or ranges of several findings are reported in Table 3-1. It should be noted that the presence of indicators does not always indicate the presence of pathogens. For example, in a study of graywater produced by four households in Australia, Christova-Boal et al. (1996) reported non-detectable levels of *Salmonella, Campylobacter, Giardia,* and *Cryptosporidium*, despite the presence of several indicator organisms. Nevertheless, the occurrence and concentration of pathogen indicators, and presumably enteric pathogens, in graywater is dependent on a number of factors, including the source of graywater, whether children are present in the household, and whether graywater is stored. For example, counts of indicator organisms were typically higher in graywater derived from bathroom showers and sinks than graywater originating from laundry water (Siegrist, 1977; Rose et al., 1991; Christova-Boal et al., 1996). Also, families with children generally produce graywater with higher counts of indicators than families with no children (Rose et al., 1991; Casanova et al., 2001). Although Novotny (1990) found no difference in total and fecal coliform numbers with and without garbage disposal waste, counts of some food-born pathogens, such as Salmonella and Campylobacter, can be higher in graywater if kitchen waste is included, due to washing of meat, poultry, and raw produce.

Several studies have demonstrated that indicator organisms can persist and even multiply in stored graywater due to available nutrients and/or biofilm formation which enhances pathogen survival (Rose et al., 1991; Ford et al., 1992). Moreover, pathogens seeded into graywater are capable of reproducing during graywater storage. *Salmonella typhimurium* and *Shigella dysenteriae*, for example, survived several days when seeded in graywater at pH 6.5 and 25ºC (Rose et al., 1991). On the other hand, a viral pathogen (Poliovirus type 1) decreased 90% or more after 6 days in graywater at pH 6.5 (Rose et al., 1991). This raises the question of whether the typical concentrations of indicator organisms used assess the human health risk with respect to fecal contamination in wastewater are a meaningful measure of the actual human health risk posed by graywater. Many researchers think not (see Section 1.5 in Chapter 1.0).

3.2 Other Microorganisms in Graywater

Graywater treatment systems harbor diverse, ever-changing microbial biofilm communities that are capable of degrading some constituents of graywater, including surfactants. Because the community composition changes rapidly in response to different input rates and input quality, it is very difficult to predict what types of non-pathogenic microbial species are associated with graywater (Stamper et al., 2003). While the degradative activity of the graywater microbial community can be beneficial, potential problems that can arise due to community activity

Table 3-1. Microbial Characteristics of Graywater (CFU/100 ml).

	Siegrist 1977 bath graywater	Siegrist 1977 laundry graywater	Novotny 1990 includes garbage disposal waste	Novotny 1990 excludes garbage disposal waste	Rose et al. 1991	Christova-Boal et al. 1996 bath graywater	Christova-Boal et al. 1996 laundry graywater	Casanova et al. 2001 graywater from 2 adults	Casanova et al. 2001 graywater from two adults and one child	Ottoson et al. 2003
Total coliform	10^3	10^2	10^7-10^8	10^7-10^8	2.5×10^7	2.7×10^1 – 2.4×10^7	2.3×10^3 – 3.3×10^5	8.0×10^7	1.9×10^8	1.3×10^8
Fecal coliform	10^3	10^2	10^6-10^7	10^6-10^7	2.0×10^4 – 7.9×10^6	2.2×10^1 – 3.3×10^3	2.0×10^1– 1.1×10^3	5.6×10^5	1.1×10^7	--
Fecal streptococci	--	--	--	--	--	1.9×10^1 – 2.4×10^3	1.4×10^1– $< 2.4 \times 10^3$	2.4×10^2	--	--
Fecal enterococci	--	--	--	--	--	--	--	--	--	2.5×10^4
Escherichia coli	--	--	--	--	--	--	--	--	--	1.0×10^6
Staphylococcus aureus	--	--	--	--	--	--	--	0	--	--
Pseudomonas aeruginosa	--	--	--	--	--	--	--	2.0×10^4	--	--
Clostridium perfringens spores	--	--	--	--	--	--	--	--	--	2.0×10^3
Coliphages	--	--	--	--	--	--	--	< 1	--	2.0×10^3

include: a) fouling of the graywater with their own waste products; b) nuisance odor production; and, c) biofilm formation which can lead to blockage of irrigation distribution lines and enhanced pathogen survival (Ford et al., 1992).

3.3 Fate of Pathogens in Soil

Humans can potentially be exposed to pathogens by eating plants or accidentally ingesting soils irrigated with graywater, or by coming into contact with ponded graywater or surface waters contaminated with graywater runoff. The risk of exposure in such cases is dependent on pathogen survival on plant surfaces, and in soils and waterbodies receiving irrigated graywater. Another potential route for human exposure is subsurface contamination of groundwater; this is dependent not only on survival of pathogens in soil, but on the ability of pathogens to be transported through soil into groundwater and survival thereafter. Survival in soil, while dependent on many factors including soil type and climate, has been demonstrated for indicator organisms and pathogens such as *Salmonella* and *Vibrio cholera*, but little information is available with regard to the fate and survival of graywater microorganisms in soils and groundwater following irrigation.

Survival of pathogens originating from animal wastes and sewage has been reviewed by Van Donsel et al. (1967), Sorber and Moore (1987), Smith (1996), and Nicholson et al. (2000). For most enteric pathogens and indicators, the soil represents a relatively harsh and nutrient-poor environment, and Nicholson et al. (2000) concluded that the majority of pathogens in manures applied to soil will decline to below detection limits after three months. Pathogen survival in soil is dependent on several factors, including temperature and moisture regime (climate), soil type, organic matter content, and the type of pathogen itself (Bitton and Harvey, 1992), with temperature likely as the most significant factor (Tyrrel and Quinton, 2003). With regards to pathogen type, survival times vary, from less than 20 days for *Vibrio cholera* and *Entamoeba histolytica* cysts to less then 100 days for *Salmonella* and enteroviruses (Crook et al., 1994). Under warm, moist environmental conditions, however, certain organisms such as *E. coli* have been known to persist and even reproduce, particularly in soils and riverbanks in the subtropics, including Florida.

Application of wastewater, including graywater, to soil generally increases the number of indicator microorganisms and presumably pathogens in soil. In a study of eleven households recycling graywater in Arizona, researchers found higher counts of fecal coliform in soil irrigated with graywater compared to soils irrigated with potable water, especially if the households had children or included kitchen waste in the graywater (Casanova et al., 2001). Land application of graywater can increase the levels of fecal coliform in soil, indicating that pathogens may be able to survive and possibly multiply in soil. In one field study, forage crops were irrigated for two years with either secondary treated wastewater or with potable water (Malkawi and Mohammad, 2003). Within 24 hours of an irrigation event, counts of total coliform and fecal coliform were approximately 10-fold higher in soil irrigated with wastewater than soil irrigated with potable water. However, the number of coliform declined rapidly in the field soils, reaching their lowest levels 48 hours after application. Garland et al. (2000) advise that pathogen exposure risks can be reduced by stopping graywater irrigation to edible plants one week prior to harvest.

In the above studies, numbers of total and fecal coliform increased in gray- and wastewater irrigated soils presumably due to retention of microorganism by the soil. Soils have long been regarded as natural filtration systems for the removal of microorganisms from wastewater effluent as it percolates through soil. As contaminated water percolates through soil, pathogens can be removed by a variety of mechanisms, including filtration, adhesion to soil particles due to sorption and biofilm formation, and mortality (Sélas et al., 2002). Malkawi and Mohammad (2003) attributed the reduction of coliform numbers 48 hours after irrigation to either sorption onto soil particles or cell death. Experimental data from a laboratory study found that the removal efficiency of total coliform, which varied from 56 to 79%, increased with decreasing grain size in artificially constructed sand columns (Tanik and Comakoglu, 1997). Rapid infiltration of wastewater, and smallest reductions of total coliform, occurred in columns constructed with crushed stone, which had a large grain size diameter of 10 mm, compared to columns constructed of sand. In a more realistic test, columns constructed with native soils were treated with aerated lagoon effluent to mimic soil infiltration of treated sewage for reuse in northern Chili (Castillo et al., 2001). A comparison of influent and effluent microbiological indicator levels revealed that soils were highly effective in removing enteric bacteria, achieving a 10^5-to-10^7-fold reduction in fecal coliform, *E. coli*, and *Salmonella*.

If pathogens are not effectively removed from wastewater via sorption or filtration, then there is the potential for groundwater contamination due to leaching of contaminated water through the soil profile into groundwater. For example, counts of total coliform and fecal coliform were only slightly higher in the 0-5 cm depth when compared to the 5-15 cm depth; thus the first few cm of soil was not an effective means of removing significant numbers of pathogen indicators from irrigation water (Malkawi and Mohammad, 2003). Movement of pathogens into groundwater can be a significant problem. According to Bitton and Harvey (1992), one-third of waterborne disease outbreaks in the U.S. are due to contaminated groundwater.

Currently, the major sources of pathogens in groundwater are wastewater effluents, sewage sludge from wastewater treatment, and septic tank effluent. It is not well known if microorganisms from graywater irrigation applications might become a source for groundwater pathogen contamination; however, given the wide-spread distances between current graywater applications and the small quantity of water applied at any given location, it would seem that threat of groundwater pollution of public water supplies is small.

3.4 Graywater Impacts on Indigenous Soil Microorganisms

Information is lacking on the effects of graywater application to indigenous soil microorganisms, and impacts are difficult to predict due to the ever-changing and heterogeneous nature of graywater chemical constituents. On one hand, organic constituents such as surfactants may be a source of easily degradable carbon substrates for many microbial populations in soil, thus stimulating their growth and overall activity. Similarly, inputs of N (nitrogen) and P (phosphorus) via graywater application may stimulate soil microorganisms if these nutrients are normally present in limiting concentrations. On the other hand, salts and chloride from bleaching agents may have detrimental effects on soil microbes by creating osmotic stress or increasing the pH of the soil environment. Such detrimental impacts may affect certain microorganisms that conduct important biological functions in the soil ecosystem. For example, in a laboratory study conducted by Friedel et al. (1999), soils were "irrigated" with nontreated wastewater containing branched alkylbenzene sulfonate surfactants (ABS). Researchers found that increasing concentrations of ABS led to a decrease in soil microbial biomass and an increase in respiratory activity, which indicated a less-efficient metabolism by the soil community. Also, the addition of ABS to the soil stimulated denitrification activity, suggesting that high rates of denitrification, as well as production of the greenhouse gas N_2O, could occur in fields irrigated with wastewater containing ABS.

Most studies that have examined the impacts of wastewater effluent on soil microbial communities found that application to the soil benefits soil microbial communities due to the inputs of organic matter and nutrients. This is encouraging, considering that wastewater can also contain heavy metals, which would negatively impact soil microorganisms in ways that graywater would not. Several long-term studies indicate that the benefits of organic matter and nutrients in wastewater outweigh detrimental effects of heavy metals, thus leading to an overall increase in microbial counts, total biomass, and microbial activity in wastewater-irrigated soil. For example, long-term irrigation of soils (over 100 years) with wastewater resulted in significantly higher counts of actinomycetes and fungi, increased active microbial biomass, and greater activities of microbial enzymes compared to soil that was never irrigated (Filip et al., 1999 and 2000). Although these researchers did not have control soils that were irrigated with potable water, their studies demonstrate that wastewater irrigation does not have a long-term detrimental impact to soil microorganisms, including their ability to catalyze major substrate transformations in soil. Tam (1998) also found that organic matter and nutrients in wastewater caused a large increase in bacterial growth in mangrove soils receiving artificial wastewater compared to control soils. Similar to the above findings of Filip et al. (1999, 2000), the activities of several microbial enzymes were not impacted by wastewater irrigation (Tam, 1998). In another field study, which did include irrigated control soil, Meli et al. (2002) measured significantly greater amounts of microbial biomass carbon, soluble carbon, and microbial respiration and enzymatic activities in citrus orchard soils irrigated with treated (lagooned) urban wastewater compared to soil irrigated with potable water. Also, the ratio of CO_2 respired per microbial biomass carbon was lower, indicating that treated wastewater, compared to potable water, resulted in an improvement of the metabolic efficiency of the soil microbial community. Thus, despite the negative findings of Friedel et al. (1999) in a laboratory study, field studies based on wastewater experiments indicate that graywater has the potential to benefit soil microbial communities by providing organic substrates and nutrients, which are often limiting in soil. Stimulation of microbial populations and subsequent degradation of organic substrates have been demonstrated for a variety of graywater constituents, including ABS and other surfactants (e.g., alcohol ethoxylate, alcohol ether sulfate, and sodium N-coconut acid-N-methyl taurate), the soap ingredient sodium stearate, as well as trace constituents such as dichlorobenzene, an ingredient found in deodorant and toilet bowl cleaners, and alkylphenol, a biodegradation intermediate of polyethoxylated alkylphenol surfactants (Robertson, 1994; Knaebel et al., 1994 and 1996; Shimp et al., 1994; Konopka et al., 1996, 1997, 1998, and 1999; Garland et al., 2000; Staples et al., 2001; Doi et al., 2002; Nielsen et al., 2002).

3.5 Key Findings and Knowledge Gaps

A primary issue with regard to use of graywater for landscape irrigation is the potential for human exposure to pathogenic microorganisms. The presence of enteric bacteria in graywater indicates that graywater is contaminated with fecal matter and presumably pathogens, although the degree of contamination varies with source of graywater, whether children are present in the household, and graywater storage time. Risks to humans can be minimized by using properly designed graywater distribution systems. But the actual risk to human health associated with graywater reuse is not known because studies have shown that indicator bacteria can actually multiply while the graywater is in storage, while studies of actual pathogenic organisms have found that the pathogen counts decrease rapidly over time.

With regard to pathogen movement and survival in the soil column, there are several data gaps in the literature. Studies based on wastewater effluent, animal wastes, and sewage sludge indicate that pathogens are capable of persisting for some time in soil and can move into the groundwater under certain environmental conditions. Risks may be lower with graywater due to lower graywater irrigation rates and the smaller area of land expected to receive graywater irrigation in comparison to agricultural soils receiving large quantities of sewage sludge or animal wastes, or streams receiving wastewater effluent.

Lastly, few studies have addressed the potential for graywater to impact indigenous soil microbial communities. Organic matter and nutrients in graywater may stimulate microbial growth and degradation activities in the field, the long-term impacts of graywater constituents, including salts and potential toxins, on soil microorganisms and their important ecosystem functions is unknown.

The following studies are needed to fill these knowledge gaps:

1. Additional experiments are needed on raw and stored graywater to determine the survivability (or growth) of different indicator organisms and the correlation of their concentrations to the concentration of true pathogens in the same graywater sample leading to the determination of a suitable indicator organism that is a good measure of actual human health risk. If possible, the tests should be run on a (large) sample of fresh graywater, and on the same sample periodically as it is stored at room temperature. We consider this a high research priority because this is the most probable path of exposure of the homeowner to pathogens, occurring as the system is serviced periodically.

2. A measurement of indicator bacteria and pathogen survival and growth in the soil are needed to determine if a health threat might exist for an individual or animal coming into contact with the irrigated soil.

3. Laboratory soil column and field experiments would useful to assess the risk of groundwater contamination by graywater application in comparison to other sources of contamination. However, the cost to do this type of testing is substantial; so given the small application rates to any given landscaped area and the currently low total volume of graywater applications, we would not consider this a high research priority.

4. Experiments are needed on graywater distribution systems to determine whether graywater will cause blockage, especially in the flow regulators for drip irrigation systems.

5. Finally and most importantly from the standpoint of determining the long term effects of graywater irrigation of residential landscapes, controlled experiments are needed to assess the long-term impacts of graywater constituents, including salts and potential toxins, on indigenous soil microorganism communities and their important ecosystem functions.

CHAPTER 4.0

GRAYWATER CHEMISTRY ISSUES

This review of graywater chemistry focuses on those aspects most relevant to its potential use in irrigating residential landscapes. It surveys the chemistry of graywater, its effects on soil chemistry, and the mobility of chemicals toward groundwater. A survey of the literature encompassing these aspects yielded very few articles specifically about graywater, so related systems (e.g., septic tank effluent, secondary treated wastewater) were considered.

4.1 Graywater Chemistry

In addition to the chemical composition of the source water, graywater contains a complex mixture of chemicals used in a variety of household products. These chemicals can be categorized according to their function in the products such as surfactants, detergents, bleaches, dyes, enzymes, fragrances, flavorings, preservatives, builders, etc. A survey by the National Institute of Medicine and the National Institute of Health of chemicals used in household products yielded over 2,500 chemical names in 5,000 products (National Institute of Health, 2004). This number could be larger or smaller because although there was redundancy in the chemicals listed due to inconsistent nomenclature, there were also whole series of homologs included with a single chemical term. It is assumed here that many, if not most, of these chemicals occur in graywater.

Eriksson et al. (2003) gives a semi-quantitative summary of analyses for 191 of the most common surfactants, fragrances and other classes of xenobiotic chemicals in graywater that originate from household chemicals. The addition of these chemicals can also change the bulk chemical characteristics of the water such as pH, suspended solids, biological oxygen demand, and conductivity (see for example Eriksson et al., 2002). Classes of chemicals found include surfactants, emulsifiers, fragrances, flavors, preservatives, and plasticizers. They reported that half of the compounds were long-chain fatty acids. However, the analytical method only measures thermally stable chemicals and it did not include several classes of surfactants.

Examples of other sources of chemicals include salts from water softeners, UV blockers, and pharmaceuticals. In a study of rivers downstream of urban areas, (Kolpin et al., 2002) numerous chemicals from household products, as well as pharmaceuticals, were detected suggesting a residential source. This study suggests that they may occur in some graywater.

4.1.1 Laundry Detergents and Graywater Chemistry

Laundry detergents use a variety of ingredients that have different functions, including surfactants, builders, bleaches, enzymes, and fabric whiteners. Table 4-1 lists the major ingredients, their function, and their weight percent in liquid and powdered detergents.

The primary surfactants used in laundry detergents are anionic (linear alkyl benzene sulfonates (LAS), alcohol sulfates or alkyl sulfates (AS), and alcohol ether sulfates or alkyl ethoxy sulfates (AES)) and nonionic (alcohol ethoxylates (AE)). Each class of surfactant includes a range of isomers and homologs that typically differ in the length of their alkyl or ethoxy chains. LAS generally contain between 10 and 13 carbon atoms in the alkyl chain, and isomers also differ in where the benzene sulfonate is attached to the chain.

Table 4-1. Components and Their Concentration In Laundry Detergents.

Component	Liquid Detergent* (Weight Percent)	Powered Detergent** (Weight Percent)
Surfactants		
Anionic - LAS, AS, AES	15 – 30	15 – 25
Nonionic – AE	0 – 15	0 – 5
Builders		
Zeolite (H)	-	20 – 30
Citrate (H, S, P)	0 – 10	0 – 5
Polycarboxylate polymers (S)	-	0 – 3
Carbonate (H, P)	-	8 – 25
Sodium silicate (H)	-	1 – 3
Sodium sulfate	-	10 – 25
Enzymes	0 – 1.5	0 – 3
Fabric Whiteners	0 – 0.5	0.1 – 0.5
Dye binders	-	-
Bleach		
Perborate	-	0 – 5
Activator	-	0 – 5

H – hardness control, S – soil dispersant, P – pH control
*From Lai (1996)
**Adapted from Showell (1998)

In contrast to branched alkyl benzene sulfonates used prior to 1965, linear alkyl benzene sulfonates used in detergents today are much more biodegradable. Degradation under aerobic conditions gives half-lives on the order of weeks (Schoberl et al., 1988), and there is no indication of metabolite accumulation (Steber and Berger, 1995). The AS surfactants usually contain 12 to 18 carbon atoms and biodegradation is initiated by cleavage of the sulfate ester bond. Biodegradation is nearly complete within days, but is slowed by branching of the alkyl group (Swisher, 1987; Steber and Berger, 1995). AES surfactants are similar to AS surfactants but have an ethoxy chain between the sulfate and alkyl groups. AES typically have 10 to 14 carbons in the alkyl group, and 1 to 4 ethoxy units. Degradation starts with cleavage of one of the ether bonds (Steber and Berger, 1995), and degradation is essentially complete under aerobic conditions within several days (Painter, 1992). The nonionic AE surfactants are widely used in both liquid and powder laundry detergents. AE surfactants have alkyl chains that may be branched with 9 to 15 carbons and ethoxy chains with 7 to 13 units. Biodegradation is affected primarily by branching of the alkyl chain, but biodegradation of the linear alkyl chain length is nearly complete within a month (Kravetz et al., 1991).

Builders include a variety of inorganic and organic substances added to adjust the water chemistry to a higher pH and bind hardness cations that would otherwise bind and interfere with the surfactants. In the U.S., phosphates have been largely replaced by inorganic substances such as zeolites (an aluminosilicate that readily hydrolyzes/breaks-down in the presence of water), carbonate salts, and silicate salts. Generally, these substances are added as sodium salts that exchange sodium for calcium in the water.

Enzymes are proteins added in small amounts to breakdown large molecules into smaller, more soluble molecules, and include proteases, amylases, lipases, and cellulases. Protease enzymes aid in removing proteinaceous stains (e.g., blood and grass), amylase enzymes are added to remove starch-based stains (e.g., gravies and sauces), and lipase enzymes break down lipids in oily and greasy stains. Cellulase enzymes are intended for cotton fabric care and remove damaged cellulose microfibers in fabrics by hydrolyzing a glycosidic bond. Enzymes are expected to be completely degraded in soils and release nitrogen to the soil.

Chemicals are also added to whiten fabrics and maintain color. The most common fluorescent fabric whiteners are derivatives of diaminostilbene disulfonic acid. Because these chemicals sorb to fabrics, their concentrations in graywater may be low. Polymers such as nonionic polyvinyl pyrrolidone are added to keep dyes in solution that are released from fabrics and prevent them from redepositing on clothes. Similarly, carboxymethylcellulose and polyacrylates are added to prevent released soil from redepositing on cleaned fabrics.

Chlorine-based bleaches have been largely replaced with oxygen-based bleaches, most notably perborates and percarbonate. To make perborate more effective at lower temperatures, an activator such as tetraacetyl ethylenediamine (TAED), or nonanoyloxybenzene sulfonate (NOBS) is added. Percarbonate leaves no residual chemical in the water, whereas borate remains after perborate activation. During activation, NOBS is transformed into phenol sulfonate and a fatty acid (Grime, 1994).

Fabric softeners and anti-static agents may be added at the end of the wash cycle, and the excess will be carried into the graywater. The most common softeners are cationic surfactants, primarily quaternary ammonium compounds, and include dialkyldimethylammonium chlorides (DADMAC) and diethyl ester dimethylammonium chloride ((DEEDMAC). In soils, DADMACs will sorb to soil surfaces which limits mobility. The biodegradation rate decreases with increasing length of the alkyl chain and with sorption to solids (Ginkel et al., 2000). DEEDMAC has been found to be readily biodegradable with 80% degradation in 28 days (Giolando et al., 1995).

Triclosan (TCS) is used in aqueous liquid detergents to prevent microbial activity in the product and to act as an anti-bacterial during product use. In the past, TCS was thought to be resistant to biodegradation. But more recent testing has revealed that there was a problem with the testing method (MITI, 1992) and that TCS is actually readily biodegradable under aerobic conditions (McAvoy, et. al. 2002).

Graywater from large-scale commercial laundering services is expected to differ from residential graywater due to different detergent formulation, laundry source, and water softening. The formulation of surfactants used will likely be tailored to the source of the laundry, and the concentration of surfactants may be lower due to the use of water softening. The replacement of divalent cations with sodium in water softeners will also result in concentrations of sodium in the graywater that are elevated compared to residential graywater. For commercial laundry, the chemicals removed from the clothing will depend on the source of the laundry.

Published analyses of laundry graywater are generally focused on conventional analytes that are relevant to sewage treatment plant operations. Table 4-2 summarizes the range of concentrations of chemical constituents of laundry graywater (Siegrist et al., 1976; Rose et al., 1991; Christova-Boal et al., 1996; Surendran et al., 1998 (in Eriksson et al., 2002)). Not all studies measured all of the chemicals listed. The most notable differences with household graywater are the higher pH, alkalinity, and sodium.

Table 4-2 Range of Laundry Graywater Chemistry.

Chemical or parameter	Laundry Concentration Range (mg/L)
General	
pH	9.3 – 10
Alkalinity as $CaCO_3$	83 – 200
Conductivity μS/cm	190 – 1,400
TSS	88 – 250
TDS	590
TOC	72 – 280
BOD_5	48 – 290
Major ions	
Calcium	3.9 – 12
Magnesium	1.1 – 2.9
Potassium	1.1 – 17
Sodium	49 – 480
Chloride	9 – 88
Sulfate	30 – 120
Nutrients	
NO_3 and NO_2 as N	0.1 – 0.6
NH_4 as N	<0.1 – 3.47
TKN as N	1 – 40
P	0.062 – 57
Metals	
Boron	<0.1 – 0.5
Cadmium	<0.01
Copper	<0.05 – 0.32
Iron	0.29 – 1.0
Lead	0.033
Zinc	0.09 – 0.32
Organic Chemicals	
Azure A actives (anionic surfs)	30 – 150

In the absence of data for laundry detergent components, an estimate of the concentrations in laundry graywater can be made based on recommended detergent doses, component concentrations in detergents, and volume of water used per wash cycle. A typical washer uses about 40 gallons (150 liters) per cycle, and an average of 64 grams of powdered detergent per load (the average of five powered laundry detergents at the grocery store (36, 52, 55, 80, and 95 g/load)), giving a total concentration of detergent components of about 0.43 g/L. Using the middle of the range of weight percent values for powdered detergents in Table 4-1, the approximate concentrations of detergent components is summarized in Table 4-3. These estimates are only intended to indicate the order of magnitude of the concentrations and do not take into account loss by sorption to fabrics or reaction with other chemicals.

4.2 Effects on Soil Chemistry

The application of any irrigation water will introduce chemicals to the soil and potentially have short- and long-term effects. This potential depends on application rate, chemical concentrations in the water, degradation rate of the chemical, sorption, leaching, and plant uptake. In evaluating the potential effects of graywater on soil chemistry, it should be recognized that conditions in soils evolve through a complex interplay of physical, chemical, and biological

Table 4-3. Estimated Concentrations of Detergent Components in Laundry Graywater.

Component	Middle Weight (Percent)	Concentration (mg/L)
Surfactants		
LAS, AS, AES	20	90
AE	2.5	10
Builders		
Zeolite	25	100
Citrate	2.5	10
Polycarboxylate polymers	1.5	6
Carbonate	17	70
Sodium silicate	2	9
Sodium sulfate	18	80
Enzymes	1.5	6
Fabric Whiteners	0.3	1
Dye binders	-	-
Bleach		
Perborate	2.5	10
Activator	2.5	10

processes. The result is that what may start as a change in physical conditions may lead to a larger effect on microbial communities and ultimately chemical conditions. Therefore, graywater will have both direct and indirect effects on soil chemistry.

The direct effects of graywater on soil chemistry potentially include changes in pH, salinity, and concentrations of chemicals introduced by the graywater. No published studies were found that evaluated these changes in the soil. However, the effects of salinity from graywater will be largely the same as from other sources of irrigation water that have the same salinity, and can be used as guidance (Rowe and Abdel-Magid, 1995). Salinity not only affects plants, but also can have detrimental effects on the physical properties of soils (Halliwell et al., 2001), such as swelling. Considerable guidance exists on managing salinity in irrigated soils based on the chemistry of the water, application rates, evaporation, leaching, types of crop, soil type, and other environmental factors (Hillel, 2000; Tanji, 1990). Salinity may be a larger issue in those areas of the country where water softeners are used to replace the divalent cations, Ca^{+2} and Mg^{+2}, with Na^{+}.

Graywater functions as a source of both nitrogen and phosphorus to soils. Phosphate is used as a detergent builder in some household products, (it has largely been eliminated from laundry detergents), while nitrogen is commonly present in quaternary ammonium salts, enzymes, and ammonium, as ammonium is commonly a counter ion in anionic surfactants detergents as well as Na. Menzies et al. (1999) found that after 20 years of applying 3 m/yr of secondary treated sewage effluent, a sandy soil accumulated approximately 700 kg P/ha. They also found that at this high rate of application (3 m/yr) the surface horizon underwent podzolization, and extractable Fe and Al decreased, which decreased the soils capacity to retain more P.

The pH of graywater is generally circumneutral (Christova-Boal et al. 1996; Surendran and Wheatley, 1998; Shin et al. 1998; Gerba et al. 1995), but tends to be slightly higher than the source water due to the addition of detergents. Laundry water has elevated pH and alkalinity because of detergents and can have pH values as high as 10 and alkalinity as high as 200 mg/L as $CaCO_3$ (Christova-Boal et al., 1996). The effect on soil pH depends on the pHs and buffering capacities of both the graywater and soil, as well as, microbial activity, with anoxic conditions leading to alkalinity generation and increased pH, and oxic conditions leading to acidity.

4.2.1 Accumulation of Organic Chemicals

Graywater can directly affect the chemistry of soil via the accumulation of organic chemicals. The extent to which an organic chemical accumulates in the soil depends on a combination of the rate of degradation, how strongly it is associated with soil particles, the infiltration rate and plant uptake. It should be noted that in the process of degradation, new chemicals might be generated (Branner et al., 1999) that have greater or lesser mobility and degradability than the parent chemical.

The rate at which organic chemicals are degraded depends on the chemical and the environmental conditions. Conditions such as concentration of oxygen (e.g., Jensen, 1999) or other terminal electron acceptors, complexation of the chemical with organic matter (Knaebel et al., 1994), temperature, soil moisture and acclimation of microbes (Doi et al., 2002) can all play a role in degradation. Under aerobic conditions, the half-life of linear alkylbenzene sulfonate (LAS) in soil and sediment has been reported in the range of one to four weeks by a number of investigators (Jensen, 1999; Litz et al., 1987; Holt and Bernstein, 1992; Shimp et al., 1994; Branner et al., 1999). Although non-first order degradation rate constants have been fit to the data (Dorfler et al., 1996), overall rates of degradation were similar.

Nonylphenol ethoxylates (NPE) are in the class of non-ionic surfactants. NPE have varying numbers of ethoxylate groups that are attached to the nonylphenol, and are easily removed during degradation, which produces the nonylphenol (NP). Degradation to NP occurs at a slightly faster rate than for LAS, with half-lives between 0.5 and three weeks (Holt et al., 1989; Staples et al., 1999; Topp and Starrett, 2000).

Soaps are readily degraded by microbes (Steber and Berger, 1995), with nearly complete degradation in aerobic and anaerobic digestors in about four weeks. However the degradation rate of C12 – C18 soaps has been found to decrease when their original counter ion, generally Na^+, is replaced with a divalent cation, such as Ca^{+2} (deWolf et al., 1998). Therefore, regional differences in soil types can be expected to influence the degradation rate of some chemicals.

The mobility of neutral organic chemicals depends largely on the concentration of particulate organic carbon in the soil, while for chemicals with a charge its mobility depends on the availability of oppositely charged surfaces. In the soil environment where most surfaces carry a negative charge, anionic surfactants such as LAS tend to sorb less to the soil than cationic surfactants. Soil distribution coefficients (K_d) for LAS range from about 1 to 3,000 L/kg depending on soil characteristics (Ou et al., 1996; Doi et al., 2002), but the most common values are in the range of 1-10 L/kg according to McAvoy et al. (1994). K_d values for NP range from about 8 to 300 L/kg (During et al., 2002). These ranges of K_d indicate that in a soil environment where there is generally much less water than solids, the vast majority of these chemicals are associated with solids and are not very mobile.

4.2.2 Accumulation of Metals

Unlike organic chemicals, metals are not degradable and have a greater tendency to accumulate in soils. Metals tend to sorb strongly to particles, whether organic or inorganic. How strongly these metals associate with solids and their tendency to accumulate in the soil, depends on a number of factors including, soil pH, mineralogy, concentrations of complexing ligands and ions, and redox conditions (Adriano, 1986). The metals most commonly found at elevated concentrations in residential sewage and graywater are copper, zinc, and lead (Eriksson et al., 2002). The concentrations of these metals generally increase after residential use due to release from plumbing and fixtures. The concentrations of copper, lead, and zinc may be more of a regional issue due to corrosiveness of the source water. Once discharged to soil, copper will tend to associate most strongly with organic matter, while lead will associate with iron oxides and clays (Adriano, 1986). Iron is not significant because soils generally contain about 0.05-5% (Brady, 1974) and significant accumulation is unlikely. Effects of septic tank effluent on metals in soil and groundwater would not represent effects of graywater because anoxic conditions in septic tanks remove metals as sulfides.

4.2.3 Indirect Effects

The indirect effects of graywater on soil chemistry relate primarily to soil chemistry changes resulting from modified microbial activity in the presence of graywater. This influence on microbial activity is through the supply of organic carbon contained in graywater. Total organic carbon concentration in graywater, excluding kitchen sinks, range from about 30 to 280 mg/L (Siegrist et al., 1976; Surendran and Wheatley, 1998; Burrows et al., 1991). Magesan et al. (1999) found that application of wastewater with high C:N ratios and BOD clogged soils and decreased hydraulic conductivity.

Depending on soil texture, application rate of graywater may have a profound effect on soil chemistry. In fine-grained, poorly drained soils, high application rates may cause extended periods of saturation that prevents penetration of oxygen into the soil, resulting in a shift from aerobic to anaerobic conditions. Anaerobic conditions lead to dissolution of iron oxides (e.g., Veneman et al., 1998), and production of sulfide by sulfate-reducing bacteria. Contributing to the potential oxygen deficit is the relatively high concentration of DOC in the graywater that stimulates microbial activity.

4.3 Effects on Ground Water Chemistry

Whether chemicals reach the groundwater and are transported in the aquifer depends on water infiltration rates, plant uptake, how strongly the chemicals sorb to solids, distance to the water table, and the chemical degradation rates. Most of the removal occurs in the upper soil horizons where there are typically higher concentrations of organic matter, which increase sorption and higher organic carbon concentrations and temperatures, which increase microbial activity.

Even before graywater is applied, residential landscaping soils are likely to have a variety of chemicals that originate from multiple sources such as the nurseries where plants were bought, chemicals associated with the prior use of the soil (e.g., as a lawn), and consumer-applied pesticides. It has been observed in many environments that dissolved organic carbon tends to decrease the amount of chemicals sorbed to solids and to increase mobility (e.g., Williams et al., 2000; Graber et al., 1995; Cox et al., 2001). Also, numerous studies have reported the enhanced mobility of chemicals caused by application of sewage sludge and treated sewage effluent (e.g., Williams et al., 2002; Said-Pullicino et al., 2004), although it is not known what components in sewage are enhancing the mobility. Given the organic content of graywater and its similarities to treated sewage effluent it might be expected that dissolved organic matter in graywater will mobilize the chemicals already existing in the soil. Of particular interest are the surfactants.

Surfactants are designed to solubilize and keep in solution chemicals that normally have low solubility. As such, surfactants are used not only in household cleaning products, but also in soil remediation as an adjuvant to leach chemicals from contaminated soils (Krogh et al., 2003). But the ability of surfactants to solubilize chemicals depends largely on maintaining the concentration of the surfactant above the critical micelle concentration (CMC), and it is not clear that surfactant concentrations in soils are above the CMC. As adjuvants, surfactants have been used on chemicals with solubilities ranging from that of benzene to PCBs. For remediating contaminated soils, specific surfactants are selected according to the type of chemical to be removed and the soil. For example, anionic surfactants have been used to leach metals from soils (Burchfield et al., 1994). In tests using anionic, cationic and neutral surfactants, Lee et al. (2004) found that anionic and neutral surfactants were better at desorbing chemicals. This is consistent with the observations of Klumpp et al. (1991), who found that cationic surfactants formed hemimicelles on solids (apparently by sorption of the positively charged end of the surfactant to the negatively charged particles) and increased the sorption of chemicals.

With the exception of dissolved, oxidized molecules such as nitrate, which will be transported, unchanged in concentration, with the applied graywater unless it is removed by plant, the transport, fate, and effects of graywater chemicals applied to the soil environment depend on a combination of the properties of the chemical and the soil environment, both of which can range widely. Considerable data exist for the behavior of chemicals found in graywater when applied to soil, but essentially none of the data were developed using graywater as the application medium. Still, the behavior when applied as graywater is expected to fall within observations for other systems.

4.4 Key Findings and Knowledge Gaps

The chemistry of graywater is a very complex, and will vary from household to household depending on the brand of household and personal care product used. Furthermore, the chemistry of the graywater changes with duration of storage. Based on current knowledge, the following classes of parameters are considered the most important with respect to plant heath, soil chemistry and threat to groundwater pollution:

- Ions affecting the salinity indices used for plants
- Toxic metals that might affect plant growth and/or groundwater quality
- Alkalinity
- Organic compounds
- Surfactants and antibacterial chemicals
- Nutrients
- Miscellaneous water quality parameters e.g. pH, temperature, DO, EC

The primary chemical issues related to graywater use in landscape irrigation are soil salinity, accumulation of organic chemical residues, and leaching of chemicals to the ground water. While salinity changes and the behavior of organic chemicals in soil as a result of graywater irrigation have not been documented, information does exists for predicting and preventing salinity buildup from irrigation, and this guidance is likely applicable to graywater. The results from similar systems (e.g., septic systems) suggest that there is no significant accumulation over time, but the application rates (gal/ft^2/month) would generally be much greater than those used for landscape irrigation, and thus would be expected to flush more chemicals through the soil column.

The chemicals in the graywater applied to soils during landscape irrigation can alter biological, chemical, and physical properties of the soil. These chemicals can produce both beneficial and detrimental effects. The effects of graywater chemicals in the soils during irrigation, and their degradation products, are not clear. Chemicals that are poorly sorbed and poorly degraded have the potential to be leached and enter the ground water. The mobility of certain other graywater chemicals may be enhanced by dissolved organic carbon and surfactants present in the graywater. Whether these issues limit the feasibility of irrigation with graywater is expected to be a function of the chemical, soil characteristics, and application rates.

To fill the knowledge gaps related to graywater chemistry the following studies are required on the chemicals in graywater that have a harmful effect on plants and groundwater:

1. Experiments to determine whether storage of graywater prior to use affects the chemical form of the constituents of concern in the graywater,

2. Experiments that examine the buildup of chemicals in the soil that are harmful to plants and toxic to indigenous microbial organisms,

3. Effectiveness of rainwater and or periodic irrigation with potable water in washing the undesirable chemicals from the root zone, and the determination of how far and at what rate the flushed chemicals might migrate downward toward the groundwater table.

4. Potential for overwatering to cause chemical migration downward through the root zone toward the groundwater.

5. Studies of methods to rejuvenate soil once undesirable chemicals accumulate to a point that they affect plant growth or pose a threat to groundwater quality. This is not considered a high research priority however, because there is much information in the agricultural literature on soil rejuvenation to mitigate chemical buildup in soils.

CHAPTER 5.0

SYNTHESIS OF FINDINGS AND RECOMMENDATIONS

In the U.S. graywater reuse for landscape irrigation is increasing in popularity. Recognizing this, the states of Arizona, California, Idaho, Nevada, New Mexico, South Dakota, Texas, Utah, and Washington have developed comprehensive guidelines or regulations for graywater reuse. The previous four chapters, organized by scientific discipline, presented a review of the literature pertinent to the long term effects of the use of residential graywater for landscape irrigation. Knowledge gaps were identified. In this chapter, the key findings and information gaps from each of the individual chapters are consolidated and grouped under four subject categories: 1) Graywater Supply Potential for Landscape Irrigation; 2) Graywater Quality and Implications for Landscape Irrigation; 3) Graywater Effects on Plants and Soils; and 4) Graywater Reuse Health Risks. The key knowledge gaps in these subject areas are italicized for easy identification. Section 5.5 summarizes the research needs in three basic questions.

5.1 Graywater Supply Potential for Residential Landscape Irrigation

The quantity of graywater generated in a typical household is not sufficient to supply the total landscape water demands for the majority of households nor is the timing of the graywater production in sync with the need of the plants for watering. But if a graywater capture and storage system is installed in the residence, the graywater volume generated by a typical household should be sufficient to meet the irrigation demands of the non-grassed areas such as flowerbeds and shrubs. However, guidance is lacking on the required frequency of irrigation and application rates. There is a definite need for this guidance to help homeowners make appropriate landscaping decisions when designing for graywater irrigation. All the information and data necessary to develop guidelines are available; however, what is required is to organize and collate it into a Graywater Landscape Irrigation Manual. No additional research is required.

Most existing graywater systems in the U.S. are very simple, e.g. gravity drains from the washing machine or graywater collection system. In essence, these systems perform more like graywater disposal systems than irrigation systems. But there is a growing desire to install graywater irrigation systems that maximize the amount of landscape that can be irrigated with the available graywater supply. There are a number of graywater collection and storage systems available on the commercial market for this purpose. Some of them are fairly simple while others are very elaborate and sophisticated. Several websites and some of the state graywater guidelines contain simple schematic drawings that show proper design for venting and bypassing, but guidance is lacking to help the homeowner design a proper system in terms the size of storage tank required, necessary treatment (if any) and required pump capacity when a gravity irrigation system is not possible or when a pressure distribution system (such as drip irrigation) is desired. Except as graywater quality may be affected by the length of time in storage, or the treatment process selected (if any), this guidance can be developed using existing information; no additional research is required.

5.2 Graywater Quality and Implications for Landscape Irrigation

Graywater contains a multitude of chemicals due to the wide array of products that are disposed of in the house drains. Furthermore the types of chemicals and their concentrations will vary with the personal habits, and individual preferences of product brands. One can also speculate that there will be variations in quality over time, and possibly season, as household activities change, (e.g. changes in brand or type of personal hygiene products and/or cleaning products used), children grow up, guests visit, and homeowner maintenance activities take place resulting in waste products (e.g. oils, paints, solvents, etc.) that are disposed of in the sink, floor drain or laundry tub. What is not known is how the combination of chemicals affects irrigated areas in terms of plant health, soil microbiology and soil chemistry.

The literature reveals that typical graywater contains a number of constituents that either singly or in combination with other chemicals in the graywater are known to be potentially harmful to plants. But it remains to be documented whether or not these constituents will accumulate in the soil in sufficient quantities to harm plants or perhaps be transported below the root zone to the groundwater during the rainy season. Although there are a number of graywater systems that have been in operation for some years with no obvious detriment to vegetation, the scientific documentation is lacking.

The application of any irrigation water will introduce chemicals to the soil resulting in both short- and long-term effects on the soil, plants and groundwater. The severity of this effect depends on the type of soil, application rate, chemical concentrations in the water, degradation rate of the chemicals, sorption, leaching, and plant uptake. When evaluating the potential effects of graywater on soil chemistry, it should be recognized that conditions in soils evolve through a complex interplay of physical, chemical, and biological processes. The direct effects of graywater on soil chemistry potentially include changes in pH, salinity, and concentrations of chemicals introduced by the graywater. No published studies were found that examined the changes in the soil chemistry as a result of irrigation with graywater. The rate at which organic mobility of neutral organic chemicals depends largely on the concentration of particulate organic carbon in the soil, while the mobility of chemicals with charge will depend on the availability of oppositely charged surfaces. In the soil environment where most surfaces carry a negative charge, anionic surfactants such as LAS tend to sorb less to the soil than cationic surfactants.

Other knowledge gaps regarding graywater chemistry and its impact on plants, soils and groundwater include:

♦ The storage of graywater prior to application and how it affects the chemical form of the constituents of concern,

♦ The potential for chemicals that are harmful to plants and toxic to indigenous microbial organisms, to build up in the soil as a result of graywater irrigation,

The potential for overwatering to cause chemicals to migrate through the root zone and down toward the groundwater, and

♦ The effectiveness of rainwater and/or periodic irrigation with potable water in transporting the chemicals from the root zone, chemical transformations that may occur as constituents are transported from the root zone and the possibility that these chemicals will migrate downward into the groundwater.

5.3 Graywater Effects on Plants and Soil Microorganisms

Information on the effects of graywater irrigation on landscape plants is scarce. Plant resistance levels have been mainly extrapolated from other salinity experiments or from experiments with recycled wastewater used for irrigation. When using treated wastewater reuse information to infer plant response to graywater irrigation, several differences need to be considered. For example, the chemical composition of graywater differs from treated wastewater in some aspects, such as the proportions of salts, organic matter, and surfactants. Also, treated wastewater is aerobic and nearly neutral pH, while graywater will have a lower DO and if stored prior to application may be anaerobic with low pH potentially resulting in a different chemistry in the applied water.

Even so, Table 2-2 in Chapter 2.0 clearly reveals that we do not know much about how bedding plants, which are one of the most likely candidates for graywater irrigation, will respond to irrigation with either reused treated wastewater or graywater. Since most bedding plants are annuals and will not accumulate chemicals from year to year, it seems that this group should be high on the priority list for further research.

There are other issues regarding irrigation of plants with graywater for which the current literature gives us little insight. These include:

1. The application method for household graywater irrigation differs from recycled treated wastewater. Usually graywater is applied via subsurface, drip, or surface flooding irrigation systems in residential landscapes, whereas the majority of recycled treated wastewater is applied via sprinkler irrigation in large landscapes. Drip and subsurface irrigation concentrates the application area and may result in higher chemical concentrations in the root zone.

2. Graywater is more likely to be applied sparingly, meeting only the evapotranspiration needs of the plants, especially in a well designed system vs. a graywater disposal system as discussed in Chapter 2.0. Treated wastewater reuse applications usually over-water the soil. A related issue is the role of rainfall. The rain may reduce chemical concentrations in the soil by transporting the constituents to lower soil horizons, thus mitigating on a seasonal basis the chemical buildup that occurs during the irrigation period.

3. Finally, the graywater irrigation experiments reported in the literature have been conducted over a short term time period. The question remains as to what effect long term irrigation with graywater will have on the plant health, especially for evergreen plants.

Information is also lacking on the effects of graywater irrigation on indigenous soil microorganisms, both short term effects and long term effects. Impacts are difficult to predict due to the ever-changing and heterogeneous nature of graywater chemical constituents; however, most studies that have examined the impacts of wastewater effluent have shown a benefit to soil microbial communities due to the inputs of organic matter and nutrients. This is encouraging, considering that wastewater can also contain heavy metals, which could negatively impact soil microorganisms in ways that graywater would not.

Because the indigenous microbial community composition changes rapidly in response to different input rates and input quality, it is very difficult to predict what types of microbial species in the soil are associated with graywater irrigation. Organic matter and nutrients in graywater may stimulate microbial growth and degradation activities in the soil in the short term, but the long-term impacts of graywater irrigation might be detrimental to soil microorganisms and their important ecosystem functions due to the buildup of chemical constituents, including salts and potential toxins. Another possible complication is that graywater storage systems can harbor diverse, microbial biofilm communities that are capable of degrading some constituents of graywater, including surfactants (a positive effect), but may also cause physical clogging of the flow regulators in drip irrigation systems, and possible soil pores.

Thus, experiments are required in two areas:

1. Experiments to determine whether microbial biofilms will grow in graywater storage tanks and cause blockage in: a) the graywater distribution system, especially in the flow regulators for drip irrigation systems and/or b) the soil pores in the irrigated soil.

2. Controlled experiments are also needed to assess the long-term impacts of graywater constituents, including salts and potential toxins, on indigenous soil microorganism communities and their important ecosystem functions and whether these changes are detrimental in terms of ability of plants to grow and prosper, and the possibility of mobilizing chemicals to move toward the groundwater.

5.4 Graywater Reuse Health Risks

It is well established that the levels of fecal coliform in graywater exceed allowable criteria set by regulatory agencies for discharge of wastewater, and for natural waters subject to body contact. But there is controversy regarding whether the indicator organism counts are an accurate indicator of the actual health threat posed to the homeowner who comes into direct contact with graywater because fecal coliform concentrations have been observed to multiply in graywater, whereas pathogens have never been observed to grow in graywater and die off rapidly. Therefore, a high graywater fecal coliform count may not indicate the same level of pathogen exposure risk as the same fecal coliform count found in treated wastewater. Even so, many states that permit graywater use require a subsurface irrigation system to reduce human exposure to pathogens, but this requirement detracts significantly from its attractiveness to the average homeowner. Drip irrigation would be much more attractive, but before it is recommended, it is important to determine how well the fecal bacteria survive in the surface layer of the soil.

Additional experiments are needed on raw and stored graywater to determine the survivability (or growth) of different indicator organisms and the correlation of their concentrations to the concentration of pathogens in the same graywater sample leading to the determination of a suitable indicator organism that is a good measure of an actual human health risk. If possible, the tests should be run on a (large) sample of fresh graywater, and on the same sample periodically as it is stored at room temperature. This is an important research topic because the servicing of the system is the most probable path of exposure of the homeowner to pathogens.

It is possible that a simple form of treatment of the graywater prior to application (e.g. aeration or UV) may reduce the human health risk. There are a number of commercial systems available (see Chapter 1.0), some of which claim to produce water of better quality than treated municipal wastewater, but those installations are quite expensive, and are not attractive to the average graywater irrigator.

5.5 Key Research Questions for Assessing the Long-Term Impacts of Graywater Irrigation

Most of the knowledge gaps identified in this report are interrelated, even though they have been identified in connection with an individual scientific field, i.e. graywater chemistry, plant and soil health, human health, or groundwater pollution. To fill the knowledge gaps, a targeted research program is needed that includes all of the applicable scientific disciplines. This program is needed to answer with some certainty the following three broad questions:

1. Over the long term, will a residential landscape that is irrigated with graywater remain healthy and vibrant? If not, are there steps that can be taken to minimize or mitigate the impact?

2. Over the long term does irrigation of a residential landscape with graywater pose a threat to the quality of groundwater? If so, can these threats be minimized or eliminated?

3. Over the long term does graywater irrigation of a residential landscape with graywater pose a health risk to humans? Can the risk be minimized?

A research program is needed to answer these three basic question, which should result in a solid scientific underpinnings for the practice of residential irrigation with graywater by providing proper guidance to homeowners on the proper type of collection and distribution system to install, the type of plants that can be irrigated with graywater and the proper application rates for the selected landscape. Homeowners will know by examining their landscape when it is time to amend soil, or take other mitigation measures to restore plant health and vigor and what methods to use. In doing so, the regulatory community (plumbing inspectors, public health officials and environmental regulators) can take comfort in knowing that the systems are adequate, safe and pose little or no threat to the quality of the environment. Simultaneously, they will know that household demands for potable water can be reduced by 30-50%

APPENDIX A

STATE GRAYWATER INFORMATION

State	Regulations, Definitions, and Rules										
	Regulations				Definitions	Administrative Rules					
	Regulating Body	***Regulations or Guidelines***	***Legal Document Source***	***Effective Date***	***Graywater Definition***	***Allowed Users***	***Permit required?***	***Allowed flow (gpd)***	***State Design Manual***	***No Septic Tank Size Reductions***	**Local or State Control**
Arizona	Arizona Department of Environmental Quality: www.adeq.state.az.us	Reclaimed Water General Permit for Gray Water, 18-9-711 Type 1 Reclaimed Water Permit	Title 18: http://www.azsos.gov/public_services/title_18/18-09.pdf	Jan. 16, 2001	Graywater means wastewater collected separately from a sewage flow that originates from a clothes washer, bathtub, shower, and sink, but does not include wastewater from a kitchen sink, dishwasher, or toilet.	Single Family	No	Less than 400	Info. brochure	X, Installation of graywater systems does not reduce septic tank requirements.	Towns, cities, or counties may further limit the use of gray water described in this Section by rule or ordinance.
		18-9-719 Type 3 Reclaimed Water Permit					Yes. Submittal to department.	Between 400 and 3000			
California	California Department of Water Resources, Water Conservation Office	Revised Graywater Standards, Title 24, Part 5, California Administrative Code	Title 24, Part 5: http://www.owue.water.ca.gov/docs/Revised_Graywater_Standards.pdf	March 18, 1997	Graywater is untreated waste water which has not come into contact with toilet waste. Graywater includes waste water from bathtubs, showers, bathroom wash basins, clothes washing machines, and laundry tubs, or an equivalent discharge as approved by the Administrative Authority. It does not include waste water from kitchen sinks, photo lab sinks, dishwashers, or laundry water from soiled diapers.	Single Family, Multi-family, Com-merical, & Industrial	X		X, Design criteria and a sample design.	The capacity of the private sewage disposal system...shall not be decreased by the existence or proposed installation of a graywater system servicing the premises.	

State	Regulations, Definitions, and Rules										
	Regulations				Definitions	Administrative Rules					
	Regulating Body	***Regulations or Guidelines***	***Legal Document Source***	***Effective Date***	***Graywater Definition***	***Allowed Users***	***Permit required?***	***Allowed flow (gpd)***	***State Design Manual***	***No Septic Tank Size Reductions***	**Local or State Control**
Idaho	Idaho Department of Environmental Quality	Gray Water Systems, VIII.D.1	http://www.deq.state.id.us/waste/tgm_sewage.htm	September 16, 2004	Graywater is untreated household wastewater that has not come into contact with toilet waste. Graywater includes used water from bathtubs, showers, bathroom wash basins and water from clothes washing machines and laundry tubs. It shall not include wastewater from kitchen sinks, water softeners, dishwashers or laundry water from soiled diapers.		X		X	X, Installation of graywater systems does not reduce septic tank requirements.	
Nevada	Nevada Department of Conservation and Natural Resources	System Utilizing Graywater for Underground Irrigation, General requirements & Design criteria: Chapter 444 Section 837	http://www.leg.state.nv.us/nac/NAC-444.html#NAC444Sec837#NAC444Sec837	March 25, 1999	“Graywater” means untreated household wastewater that has not come into contact with toilet waste. The term includes, without limitation, used water from bathtubs, showers and bathroom washbasins, and water from machines for washing clothes and laundry tubs, but does not include wastewater from kitchen sinks or dishwashers.	Single Family	X	Not specified - but from a single family dwelling	X, Design criteria and a sample diagram.	X	
New Mexico	New Mexico Environmental Department	House Bill 114 - PERMIT USE OF GRAY WATER, March 11th 2003	House Bill 114 - http://legis.state.nm.us/Sessions/03%20Regular/FinalVersions/house/HB0114.pdf	December 16, 2003	"Graywater" means untreated household wastewater that has not come in contact with toilet waste and includes wastewater from bathtubs, showers, washbasins, clothes washing machines and laundry tubs, but does not include wastewater from kitchen sinks or dishwashers or laundry water from the washing of material soiled with human excreta, such as diapers;		No permit required when daily flow is less than 250 gallons	250			Gray water use shall comply with all applicable municipal or county ordinances and local building codes.

State	Regulations, Definitions, and Rules										
	Regulations				Definitions	Administrative Rules					
	Regulating Body	***Regulations or Guidelines***	***Legal Document Source***	***Effective Date***	***Graywater Definition***	***Allowed Users***	***Permit required?***	***Allowed flow (gpd)***	***State Design Manual***	***No Septic Tank Size Reductions***	**Local or State Control**
South Dakota	South Dakota Department of Environment and Natural Resources	Works of Sanitary Significance 74:53:01:38 Requirements for a graywater system.	Works of Sanitary Significance 74:53:01:38: http://legis.state.sd.us/rules/rules/7453.htm#74:53:01:38	July 1, 1996	"Graywater," the wastewater generated by water-using fixtures and appliances which do not discharge garbage or urinary or fecal wastes.					"Graywater tanks are septic tanks" Graywater tank effluent can be used for irrigation.	
Texas	Texas Natural Resource Conservation Commission	NRCC Chapter 210 - Use of Reclaimed Water Rule Project No. 2003-056-317-WT, House Bill 2661, Standards for Control of Graywater	http://www.tnrcc.state.tx.us/oprd/rule_lib/adoptions/03056210_ado.pdf	Effective September 1, 2003 (HB 2661)	Graywater is defined as wastewater from: (1) showers; (2) bathtubs; (3) handwashing lavatories; (4) sinks that are not used for disposal of hazardous or toxic ingredients; (5) sinks not used for food preparation or disposal; and (6) clothes-washing machines. Graywater does not include wastewater from the washing of material, including diapers, soiled with human excreta or wastewater that has come into contact with toilet waste.	Domestic, commercial, and industrial purposes. (HB 2661)	The commission may not require a permit for the domestic use of less than 400 gallons of graywater.	400 gpd without a permit			Must comply with regulation and any requirements of the local permitting authority
Utah	Department of Environmental Quality	Graywater Systems Rule, R317-401 Rule R317-401.	Utah Administrative Code, Rule R317-401: http://www.rules.utah.gov/publicat/code/r317/r317-401.htm	August 1, 2004	"Graywater" is untreated wastewater, which has not come into contact with toilet waste. Graywater includes wastewater from bathtubs, showers, bathroom washbasins, clothes washing machines, laundry tubs, etc., and does not include wastewater from kitchen sinks, photo lab sinks, dishwashers, garage floor drains, or other hazardous chemicals.	Single Family	Yes. Submittal to health department.	Not specified - but from a single family dwelling			Local heath department has authority - can limit, prohibit, and or charge fees.

WERF SDA

State	Regulations, Definitions, and Rules										
	Regulations				Definitions	Administrative Rules					
	Regulating Body	***Regulations or Guidelines***	***Legal Document Source***	***Effective Date***	***Graywater Definition***	***Allowed Users***	***Permit required?***	***Allowed flow (gpd)***	***State Design Manual***	***No Septic Tank Size Reductions***	**Local or State Control**
Washington	Washington State Department of Health: Office of Environmental Health and Safety	Water Conserving On-Site Wastewater Treatment Systems	Legal Document: http://www.leg.wa.gov/RCW/index.cfm?fuseaction=chapterdigest&chapter=90.46	May 15, 2000	Greywater is wastewater from bathtubs, showers, bathroom sinks, washing machines, dishwashers and kitchen sinks: any source in your home other than toilets.		X			Graywater systems include septic tanks but the effluent can be used for irrigation. Laundry only systems are allowed.	Local heath department has authority.

State	Graywater System Requirements																
	Storage and Treatment						Usage Requirements										
	Over-flow to sewer or septic tank	***Tank Size***	***Tank cover***	***Identify as Non-potable***	***Filter-ation***	***Irrigation System Pressure***	***No runoff from lot***	***No dis-charge to surface water***	***No ponding***	***Located Outside Flood-plain***	***Avoid human contact***	***No public nuis-ance***	***No spraying/ Sub-surface irrigation***	***No veggie watering***	***Set-back distan ces***	***Distance to ground-water***	***No hazardous chemicals/ materials***
Arizona	X		X	X			X Use within property boundary	X	X	X, Cannot be located in a wash or drainage way	X		X	Graywater not allowed for food plant irrigation, except citrus and nut trees		Operated to maintain a min. vertical separation distance of at least 5 ft to the top of the season-ally high groundwater table.	X
California	X		X	X	Minimum 140 mesh filter with a min. capacity of 25 gal/min.	Irrigation systems pressure cannot be greater than 20 psi.	X	X	X		X			X	X		
Idaho	X	Minimum of 50 gallons	Tank must be water-tight	X		Minimum filter capacity of 25 gal/min.	X	X					X, Not applied on the land surface or be allowed to reach the land surface.	X, May not be used to irrigate vegetable gardens.	X		

State	Graywater System Requirements																	
	Storage and Treatment						Usage Requirements											
	Over-flow to sewer or septic tank	*Tank Size*	*Tank cover*	*Identify as Non-potable*	*Filter-ation*	*Irrigation System Pressure*	*No runoff from lot*	*No dis-charge to surface water*	*No ponding*	*Located Outside Flood-plain*	*Avoid human contact*	*No public nuisance*	*No spraying/ Sub-surface irrigation*	*No veggie watering*	*Set-back distances*	*Distance to ground-water*	*No hazardous chemicals/ materials*
Nevada	X	Minimum of 50 gals	X	X			X	X No surfacing of graywater.	X No surfacing of graywater.				X No surfacing of graywater.				
New Mexico	X		X	X			X	X	X	X	X Also avoid contact with pets.	X	X	X	X	X Vertical separation of at least five feet between the point of discharge and the ground water table.	X
South Dakota							X Cannot enter waters of the State (74:53:01:12)	X Cannot enter waters of the State (74:53:01:12)				X (74:53:01:12)		X No areas intended for food production	X (74:53:01:19)	X (74:53:01:19)	

State	Graywater System Requirements																
	Storage and Treatment						Usage Requirements										
	Over-flow to sewer or septic tank	***Tank Size***	***Tank cover***	***Identify as Non-potable***	***Filter-ation***	***Irrigation System Pressure***	***No runoff from lot***	***No dis-charge to surface water***	***No ponding***	***Located Outside Flood-plain***	***Avoid human contact***	***No public nuisance***	***No spraying/ Sub-surface irrigation***	***No veggie watering***	***Set-back distances***	***Distance to ground-water***	***No hazardous chemicals/ materials***
Texas	X		X	X	Lint trap is laundry water is used.		X		X		The disposal area shall have limited access and use by residents and pets. (285.20)	X	X	X Edible parts of crops intended for human consumption cannot come in direct contact with the graywater			X
Utah	X	250 gallons	Tank must be water-tight	X	Minimum 140 mesh filter with a min. capacity of 25 gal/min.	Irrigation systems pressure cannot be greater than 20 psi.	X	X	X				X	X No direct contact with edible part of fruit/vegetables.	X	No irrigation point shall be within two vertical feet of the maximum groundwater table.	X
Washington		40 gals for laundry only system		X	Minimum filter or screen with 1/16 inch opening (laundry only)								X	X			

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