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Los Angeles

Feasibility of Onsite Residential Graywater Recycling Using a Semi-Batch Vertical Flow Wetland for Non-Potable Water Reuse

A dissertation submitted in partial satisfaction of the

requirements for the degree Doctor of Philosophy

in Chemical Engineering

By

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ABSTRACT OF THE DISSERTATION

Feasibility of Onsite Residential Graywater Recycling Using a Semi-Batch Vertical Flow Wetland for Nonpotable Water Uses

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Water sustainability has become a critical issue in various regions around the world given rapid population rise and the impact of climate change on water resources. In this regard, onsite treatment and reuse of graywater (defined as wastewater is not originated from toilets or urinals), for non-potable applications, can be an important element of the approach to water sustainability. Treatment of graywater prior to reuse is essential in order to enable effective product water reuse and storage without creating nuisance, as well as comply with local regulatory requirements. In order to encourage adoption of graywater treatment, low-cost graywater treatment systems suitable for onsite residential deployment must be made available. The goal of the present research was to develop a low-cost, compact graywater treatment system using a semi-batch vertical flow wetland (SB-VFW) approach for residential graywater reuse for recycling.

In order to assess the treatment performance and to elucidate the treatment mechanism and the removal kinetics, a SB-VFW system was developed and evaluated in a 13-month field study in a single-family home in Los Angeles. The SB-VFW consisted of a coconut coir dust layer (soil) and a cross flow media layer (CFM) was demonstrated to be effective for treatment of bathroom and laundry graywater. The treatment system was able to attain California Title 22 water reclamation requirements in ~3 hours for a 300-liter batch. The soil was found to be important for the removal of organics, turbidity, and suspended solids; while the use of CFM media enhanced aeration in the SB-VFW system. Organics removal in the SB-VFW was evaluated using a first-order kinetic model and found that graywater with lower organic removal rate constants stimulated more biomass growth and could lead to excess biomass accumulation when treatment time was short.

Economic feasibility of onsite graywater treatment and reuse using SB-VFW systems were evaluated and found that a less-than-two-year return-on-investment could be achievable. Besides water-savings, energy required for graywater treatment using the SB-VFW approach was lower than the energy needed for potable water importation and centralized wastewater treatment. The present research demonstrated that onsite residential graywater treatment and reuse is both technically and economically feasible.

The dissertation of Zita Lai Ting Yu is approved.

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2015

This dissertation is dedicated to my mother and my sister.

對您們的愛與感激全都盡在不言中

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Publications

- **Zita L.T. Yu,** Anditya Rahardianto, J.R. DeShazo, Michael K. Stenstrom and Yoram Cohen, 2013. *Critical review: regulatory incentives and impediments for onsite graywater reuse in the United States*. Water Environment Research, Vol. 85, 7, 2013, 650-662.
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Invited Talks

- **Zita L.T. Yu**. *Onsite Residential Graywater Reuse: A Strategy toward Water Sustainability*. Advisory Committee on Water Resources and Quality of Water Supplies, Hong Kong SAR Water Supplies Department. November 26, 2013. Hong Kong.
- **Zita L.T. Yu**. *Onsite Residential Graywater Reuse: Evaluation of Regulatory, Technology and Economic Drivers*. AIChE & A&WMA Joint Workshop on Municipal Water Reuse. American Institute of Chemical Engineers, Air and Waste Management Association and International Society for Water Solutions. September 23-24, 2013. Long Beach, CA, USA.
- **Zita L.T. Yu**. *Onsite Residential Graywater Reuse and Recycling: Regulatory Incentives and Impediments*. Water Science and Policy Center, University of California, Riverside: WSPC Seminar Series. January 28, 2013. Riverside, CA, USA.

1 INTRODUCTION

1.1 Onsite graywater reuse and the need for low cost treatment system

In recent years, there has been a growing interest in the development of water sustainability through conservation, water use efficiency, generation of new supplies, as well as water reuse [1]. Implementation of water sustainability strategies present a challenge especially in regions of fast population growth and water scarcity [2]. For example, centralized water utilities in a number of States (e.g., California, Florida and Texas) have been developing alternative water sources (e.g., seawater and brackish water), reclaiming wastewater for groundwater recharge, engaging in large-scale evaporation retardation practices in water conveyance and storage, as well as implementing various water conservation measures [3]. Such centralized water management options, which often involve high capital and operational costs [4], are often financed at the municipal level with limited Federal Government support [5]. Development of an expanded water portfolio is even more challenging given the high cost of maintenance and upgrade of existing aging and overloaded centralized wastewater conveyance and treatment infrastructures currently serving large metropolitan areas in the United States [6]. It is estimated that water infrastructure maintenance/upgrade for the wastewater treatment sector alone would cost the United States >$200 billion over approximately the next 20 years [7]. Given the current massive Federal budget deficit (estimated at about $18 trillion in October, 2014 [8]), it may be difficult if not unrealistic for municipal governments to expect significant Federal assistance for major centralized water infrastructure projects.

Given the rising burden on centralized water conveyance and treatment systems, water reuse has emerged as a viable approach toward water sustainability. Treatment of wastewater for direct aquifer recharge and industrial reuse, as well as certain irrigation applications are now widely practiced in various states [9]. There has also been a major movement to augment local water portfolios through increasing aquifer recharge via better management of storm water [10, 11] as well as rainwater harvesting at the individual household level [12]. The practice of rainwater harvesting for reducing individual household is growing in the United States [13]. Rain water harvesting is seen as an approach (for individual households) to reduce dependence on potable water for non-potable water applications such as landscape irrigation [14]. Rain water harvesting, however, is less likely to have a significant impact in much of the Southwestern United States, which has relatively low rainfall with sparse and often unpredictable rainfall patterns [15]. For example, the City of Los Angeles, with the lowest rainfall in the last 43 years of less than five inches recorded in 2013, typically rains between November and April with an average rainfall of less than three days per month (**Figure 1.1**). The amount of rainwater can be captured by rain barrel onsite is limited. On the other hand, it has been argued that, at the household level, graywater reuse (given appropriate point-of-use treatment) can reduce overall potable water demand for non-potable applications [16-18].

Graywater is generally defined as domestic wastewater not originated from toilets or urinals [18-20]. Graywater constitutes up to ~70% (by volume) of the total indoor wastewater generation, but with only about 23% of the total mass of generated suspended solids [20, 21]. Therefore, one would expect that widespread practice of distributed (onsite) graywater treatment and reuse could potentially lead to significant reduction in both potable water demand (for non-potable uses) and volume of household wastewater delivered to centralized wastewater treatment plants [18]. Indeed, it is not surprising that water-stressed countries, such as Israel [22] and Australia [23], are promoting graywater treatment and reuse for non-potable applications (e.g., landscape irrigation), such as for cold water feed for washing machines and for toilet flushing [23].

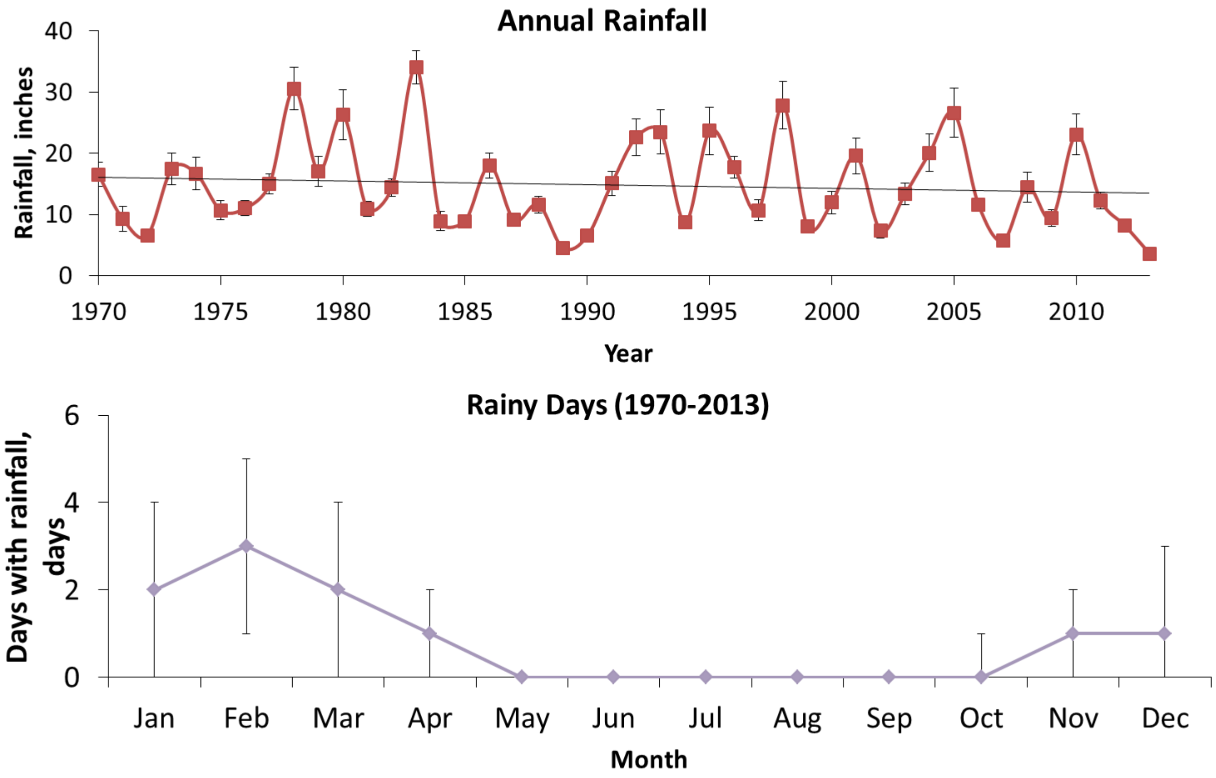


Figure 1.1 Annual rainfall and days with rainfall between 1970 and 2013 in the City of Los Angeles (data from [15])

In the United States, the benefits of graywater reuse are becoming increasingly recognized by water agencies [24] and among green enthusiasts [25, 26]. Graywater policies and regulations at the State level, however, are key to widespread adoption of onsite domestic graywater treatment and reuse. Graywater policies and regulations vary widely among individual States with respect to allowable graywater reuse applications, acceptable reuse practices, and treatment requirements. Also, the often cumbersome permitting process for graywater reuse and the lack of public education resources have adversely affected the overall acceptance and adoption of onsite graywater treatment and reuse, as well as development of standardized technological approaches in the United States [16, 26].

The availability of proven and affordable treatment systems is also crucial for the technology adoption for graywater treatment prior to reuse. Treatment of graywater not only minimizes human exposure to pathogens but also prevents environmental pollution. Although graywater reuse without treatment is generally encouraged for subsurface irrigation [27], aboveground nonpotable water reuse, providing the greatest flexibility to homeowners, is often only allowed when treatment is provided. The cost of treatment encompasses the system cost, operations and maintenance (O&M) costs and building retrofitting cost. Graywater treatment systems (provide organic, total suspended solids and turbidity removal) marketed for single-family homes can vary between \$6,000 and ~\$13,000 for treatment capacity of 1.2 – 1.6 m^3 /day [28, 29]. Additionally, maintenance is usually required and can range between \$200 to \$900 per year [30]. It has been suggested that high treatment cost favors onsite graywater treatment in high density multifamily homes, but impedes the adoption of onsite graywater treatment in low-density residential housing such as single-family homes [31]. Clearly, robust but low cost graywater reclamation and treatment systems are needed for at the point-of-generation and point-of-reuse deployment if graywater reuse is to develop into a significant water resource. Furthermore, detailed data regarding the achievable water quality for treated graywater by means of distributed graywater treatment/reuse systems and field experience with onsite graywater recycling are lacking. Such information is essential for forming the basis for setting guidelines to promote the development of affordable and proven graywater treatment technologies [32].

1.2 Constructed wetlands as a low-cost option for onsite residential graywater treatment

Graywater contained various contaminants, such as organics, suspended solids and pathogens (**Table 1.1**). Treatment of grayater treatment beyond secondary treatment has been argued to be beneficial from an environmental protection point of view by removing degradable organics prior to discharge into the environment [33]. Residents can also be benefited from graywater treatment from avoiding occurance of odor nuisance due to degradation of organics in untreated graywater due to prolonged raw graywater storage [34]. Removal of total suspended solids (TSS), colloidal materials and degradable organics are key to ensure effective disinfection [35] for safe non-potable graywater reuse. Deployment of onsite graywater treatment systems that provide secondary or tertiary treatment level in residential settings is technical and financially challenging. Unlike centralized facilities, onsite treatment systems for graywater reuse are expected to be operated in the absence of technical staff assisted with only regular technician visits. Unmanned unapproach can be achieved with high level of system automation. Complex treatment system designs coupled with sophisticated automation systems are expected to increase the overall system capital, operation and maintenance costs, and hence their affordability by homeowners. However, high capital, operations, and maintenance (O&M) costs [28, 36] have hindered homeowners' adoption of such commercial treatment systems [37, 38]. Thus, there have been efforts to develop low-cost constructed wetlands that require low maintenance as treatment technology for graywater treatment [39].

Previous studies evaluated subsurface horizontal flow (HF, **Figure 1.2**) [40-42], vertical flow (VF, **Figure 1.3**) [43-45] and hybrid constructed wetlands that consist of a VF followed by a HF wetlands for graywater treatment [46, 47]. Results from the above studies indicate that in order to produce treated graywater effluent with <10 mg/L of BOD (**Table 1.2**) to comply with the required tertiary treatment level for aboveground graywater reuse in the U.S. (Wisconsin, California, NSF/ANSI 350R) and in Australia (**Table 1.2**), continous flow wetlands would require long hydraulic retention time (HRT) (4 to 8 days). Merely reducing the treatment system area and hydraulic retention time in once through flow sysems produced effluent of poor quality [45]. It is also noted that the above previously proposed wetland systems were of low hydraulic loading rate (~0.04 to 0.08 m^3/m^2-day as shown in **Table 1.2**). Such performance level, for example, would require a wetland area of 4.3 – 8.5 m^2 to treat ~340 liters/day of bathroom and clothes washing graywater generated in a single family home in California [48]. Such space requirement and associated construction costs [49] would make conventional wetlands impractical for graywater treatment in residential homes in most urban areas. Furthermore, long HRTs of 4 to 8 days would require provision of significant onsite storage capacity for collected raw graywater which could create odor nuisance [34]. Morevoer, it is noted that in various regions, storage of graywater is limited in terms of both storage time and capacity [27]. Clearly, short HRTs would be desirable to reduce raw graywater storage needs and thus the preference for alternative compact and low cost wetland design suitable for residential use.

Operation of wetlands in semi-batch mode with graywater recirculation (**Figure 1.4**) is an approach to reduce the required HRT and thus is an attractive alternative to the single pass conventional constructed wetlands. Previous work has reported on a semi-batch vertical flow wetland (SB-VFW) for treatment of graywater which achieved BOD_5 and fecal coliform removal at essentially 100% and 99%, respectively [44]. This performance level was achived with relatively small footprint system (~1 m^2) and treatment time of 8 – 12 hours [44] and was shown to be comparable to the performance of much larger horizontal flow wetland treatment (**Tables 1.3 and 1.4**). The above VF wetland design utilized stratified heterogenous layers of silica-based soil, small randomly packed bed of spherical plastic media and rocks (**Figure 1.4**) [50]. The treatment operation involved recirculation of water that permeates and drips from the wetland into a reservoir directly underneath. The silica-based soil layer served as a filtration zone, and the plastic media provided surface area for biofilm growth. The "raindrop" effect created by water flow from the wetland to the receiving resservoir below promoted aerobic conditions. It was reported that treatment capacity was 0.45 m^3/ m^2-day for untreated graywater containing 158 ± 30 mg/L total suspended solids (TSS) and 839 ± 47 mg/L COD. The above system produced, for a treatment time of 12 hours, effluent that had low TSS range of 0 – 6 mg/L and low BOD_5 range of 0 – 1.5 mg/L [44]. It is noted that despite such low BOD_5, the effluent COD range of 60–220 mg/L was relatively high for the BOD_5 concentrations achieved as compared to the BOD and COD data reported for other wetlands that achieved similar BOD removals (**Tables 1.3 and 1.4)**. In the above system, particles that leached from the silica-based soil resulted in an average effluent turbidity of 6 NTU with a range of 2 - 12 NTU [51]. Such turbidity range exceeds the most stringent standards for aboveground non-potable water uses (**Table 1.2**), and may also decrease disinfection effectiveness [35]. Preventing fine soil leaching and increasing hydraulic loading rate are necessary to address the current limitations of recirculating vertical-flow wetland designs. A possible solution would be to replace the high density silica-based soil used with lower density non-silty soil substitute. For example, recent studies have proposed that organic materials as low density soil substitutes (e.g. palm tree mulch [52] and tree bark [53]) may be suitable for use in VF wetlands. It was reported, however, that palm tree mulch was not as effective for organic and TSS removal, compared to sand filtes, achieving only an average of 53% BOD, 38% COD and 70% TSS removals as compared to 85% BOD, 62% COD and 95% TSS removals achieved using silica based soil [52].

The design of a VF wetland (whether operated in a single or multipass modes) requires a specific system performance model to tailor the system to the target treatment level for the expected range of raw graywater quality. A first-order plug-flow reactor developed for conventional wetlands [54] but modified for recirculation was used to calculate needed wetland area. The above apporach provided a correlation between the required recirculation flow rate and needed wetland area but without evaluating the effective of organic loading on the treatment time. Another first-order kinetics model for a VF wetland was proposed [55], based on the assumption of a completely mixed batch reactor, for determining the needed wetland volume to achieve TSS removal for a given treatment time. It was concluded that the treatment efficiency (with wetland area of 0.9 m^2 and treatment capacity of 450 L/day) was independent of recirculation flow rate above a recirculation flow rate of 3 m^3/hr [55]. It was suggested that performance improvement could be attained by increasing wetland bed volumes and decreasing the treatment volume. Although the above studies have provided useful insight regarding the operation of VF wetlands, there remains a critical need for a systematic evaluation and optimization of the residential VF wetland approach to graywater treatment with respect to key operational and design parameters and their interplay such as treatment time, hydraulic retention time, and wetland area and depth.

In order to demonstrate the suitability of the SB-VFW approach for low-cost graywater treatment in urban environment in the present work, a 12-month field evaluation of bathroom and laundry graywater treatment using a suitably designed semi-batch vertical flow wetland (SB-VFW) in a single-family home in the City of Los Angeles was conducted. The overall goals were to demonstrate that a suitably designed SB-VFW can: (a) produce treated effluent that meets stringent water quality requirements for aboveground graywater reuse, (b) have high hydraulic loading rate of >1 m^3/m^2-day, (c) be economically feasible in different parts of the world even in the absense of financial subsidies, (f) develop an operation strategy to minimize clogging and ensure long-term performance of the SB-VFW.

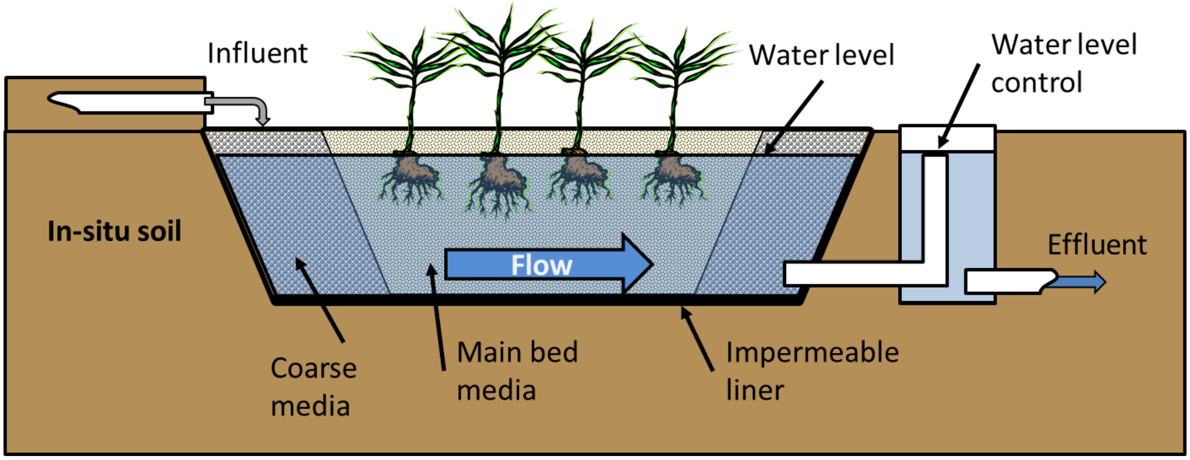


Figure 1.2 The design of a typical single-pass subsurface horizontal flow wetland that is built into the ground. Wetland beds typically consist of course media such as large gravels or rocks at the influent dosing point and the effluent collection point. The treatment bed (main bed) is usually not graded and consists of siliceous materials, such as mixed of soil, sand and small gravels

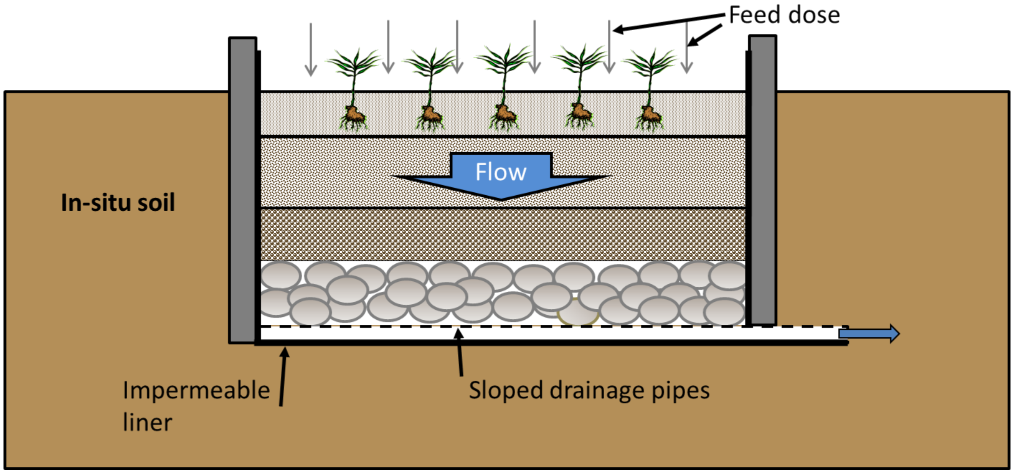


Figure 1.3 Conventional design of single-pass vertical flow constructed wetland that is built into the ground. The wetland bed typically consists of stratified beds of graded siliceous materials varying from soil, sand to large gravels and rocks. Influent is typically dosed intermittently by perforated pipes or by flooding the entire wetland bed. Effluent is collected by a network of sloped drainage pipes

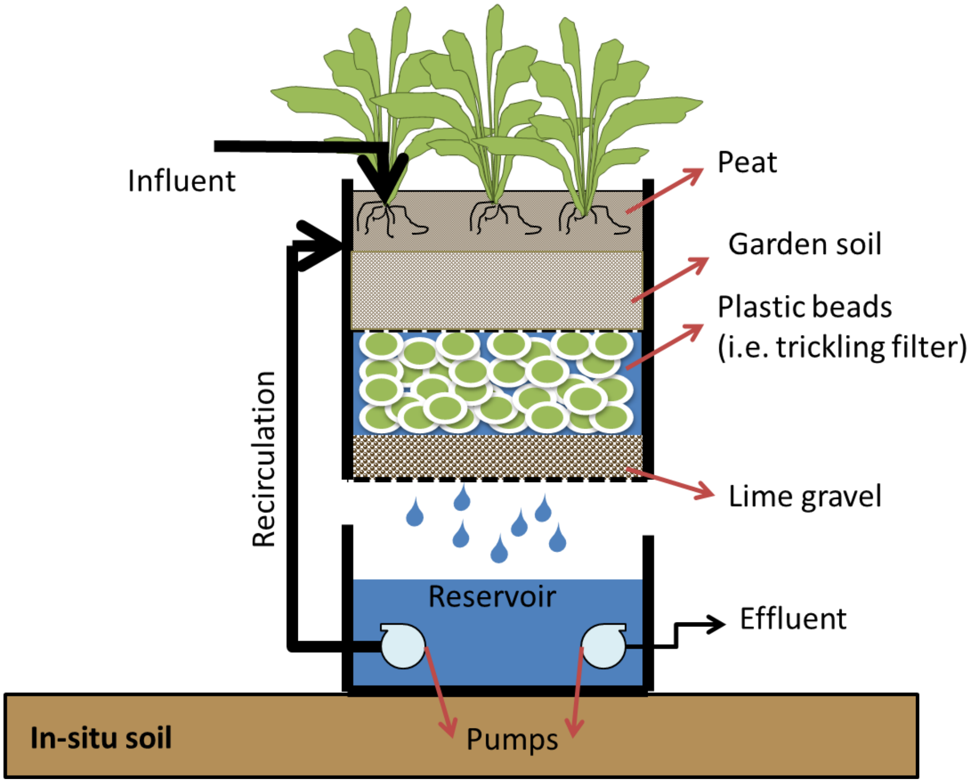


Figure 1.4 The design of a typical aboveground containerized, semi-batch vertical flow wetland with recirculation. Influent is distributed at root zone using perforated pipes

Table 1.1 Average reported water quality for mixed graywater containing laundry and bathroom sources and graywater containing only from bathroom sources

Parameters	Graywater (laundry + bathroom)	
	laundry + bathroom	Bathroom
Turbidity, NTU	24±8	58±26.2
TDS, mg/L	410*	388*
TSS, mg/L	68±88	47±16
pH	8±2	7.4±0.5
BOD, mg/L	185±73	99±73
COD, mg/L	366±173	221±160
TOC, mg/L	-	38±12.7
NH4-N, mg/L	1*	3.8±4.3
NO3-N, mg/L	24±33	2.1±2.6
TN, mg/L	31±27	7.5±2.5
PO4-P, mg/L	15±23	0.5
TP, mg/L	11*	--
E. Coli, CFU/100mL	--	4×10^{6}*
Fecal, CFU/100mL	4×10^{4}*	$8\times10^{5}\pm2\times10^{5}$

Total Coliform, CFU/100mL	4x10^{7}±5x10^{7}	1x 10^{4}±1x10^{5}
References	[20, 56-60]	[31, 56, 59-66]

Note: * indicates only one cited literature reported the data

Table 1.2 Water quality criteria for aboveground non-potable graywater reuse in different countries

Standards	Type of reuse	Treatment level equivalent	Water quality criteria
United Kingdom [67]	Sprinkler; Car washing; Toilet flushing; Garden watering; Pressure washing; Washing machine use		<10 NTU of turbidity; pH 5-9.5; < 2 mg/L of residual chlorine; < 0.5 mg/L of residual chlorine for non-spray garden watering; 0.0 mg/L of residual bromine for all spray application and non-spray garden watering
California, USA [68]	Aboveground non-potable reuse	Disinfected tertiary	Turbidity: 2 NTU (avg.); 5 NTU (max) Total coliform: 2.2 MPN/100 mL (avg.), 23MPN/100 mL (max in 30 days)
Wisconsin, USA [69]	Surface irrigation except food crops; clothes and vehicle washing; air conditioning; soil compaction; dust control; washing aggregate; making concrete	Disinfected tertiary	pH 6–9; ≤ 10 mg/L of BOD_5; ≤ 5 mg/L of TSS; 1.0–10 mg/L of free chlorine residue
	Toilet and urinal flushing	Disinfected primary with filtration	pH 6–9; ≤200 mg/L of BOD_5; ≤ 5 mg/L TSS; 0.1–4.0 mg/L of free chlorine residue
NSF/ANSI 350R	Restricted indoor and unrestricted outdoor water reuse	Residential capacity ≤ 1,500 GPD	pH 6-9; $CBOD_5$: ≤ 10 mg/L of (avg.), 25 mg/L (max.); TSS: ≤ 10 mg/L (avg.); 30 mg/L (max.) Turbidity: 5 NTU (avg.); 10 NTU (max.) E. coli: 14 MPN/100mL (mean); 240 MPN/100 mL (max.) 0.5≤ Storage vessel disinfection ≤ 2.5mg/L
New South Wales, Australia [23]	Toilet flushing; Cold water supply to washing machines; Garden irrigation with local approval	Disinfected Secondary	< 20 mg/L BOD_5; < 20 mg/L TSS; <10 cfu/100ml fecal coliforms
Western Australia, Australia [70]	Toilet flushing Cold water supply to washing machines; Irrigation	Disinfected Tertiary	<10mg/L of BOD; <10mg/L of TSS; <1 MPN/100mL of *E. coli* <1 pfu/100mL of coliphages; <1 cfu/100mL of clostridia;
Victoria, Australia [71]	Toilet flushing; Cold water supply to washing machines; Surface irrigation, Sub-surface irrigation	Disinfected Tertiary	<10 mg/L of BOD; <10 mg/L of TSS; <10 cfu/100ml of fecal coliforms;

Table 1.3 Various wetland designs for treatment of graywater

Country	Graywater sources	Wetland type	Media	Recirculation	Mode of operation	Treatment capacity, m^3/day	Wetland area, m^2	Treatment capacity per area, m^3/m^2-day
Sweden (Fittschen and Niemczyn, 1997)	sinks, kitchen, shower, washing machine	HSSF	Soil, not specified	No	Continuous flow	40	600	0.07
Sweden (Schonborn et al., 1997)	sinks, kitchen, shower, washing machine, urinal	VF-HSSF	Fine grained sand, iron armament pieces, sandy and stony loam	No	Continuous flow	40	38	0.04
Nepal (Shreshtha et. al, 2001)	Bathroom sinks, shower, washing machines and kitchen sinks	VF	Coarse sand	No	Continuous flow	0.5	6	0.08
Costa Rica (Dallas and Ho, 2005)	Mixed, not specified	HSSF	PET	No	Lab, batch	0.01	0.38	0.03
	Mixed, not specified	HSSF	Crushed rocks	No	Lab, batch	0.01	0.38	0.03
Costa Rica (Dallas et al., 2004)	Mixed, not specified	HSSF	Crushed rocks	No	Continuous flow	2.5	30	0.08
Israel (Gross et al., 2007; *Sklarz et al., 2009)	Mixed, not specified	VF	Peat, soil and randomly packed plastic media or tuff	Yes	Semi-batch	0.45	0.9	0.5
Uganda (Katukiza et al., 2014)	Bathroom sinks, shower, laundry and kitchen sinks	VF	Crushed lava rock	No	Batch, single pass	0.22	0.2	1.1
Norway [72]	Bathroom sinks, shower, laundry and kitchen sinks	VF-HSSF	Filtralite®	Yes – VF only	Continuous flow with recirculation	0.08	NR	NA
Brazil (Paulo et al., 2009)	Laundry, bathroom	HSSF-VF	Coarse and fine gravel	No	Continuous flow	0.7	7.8	0.09

Note: HSSF represents a horizontal subsurface flow wetland, VF represents a vertical flow wetland, NR represents “not reported”

Table 1.4 Reported treatment performance of wetlands presented in Table 1.3 used for treatment of graywater

Country	Graywater sources	Wetland type	Recirculation	HRT, days	Turbidity, % removal (NTU)	Organics, % removal (mg/L)	TSS, % removal (mg/L)	Total coliform, % removed (/100mL)
Sweden (Fittschen and Niemczyn, 1997)	sinks, kitchen, shower, washing machine	HSSF	No	4	NR	BOD_7: 95.8% (<5); COD: 87% (46)	NR	NR
Sweden (Schonborn et al., 1997)	sinks, kitchen, shower, washing machine, urinal	VF-HSSF	No	NR	NR	BOD_5: 96% (5 mg/L); COD: 91% (27)	NR	NR
Nepal (Shrestha et. al, 2001)	Bathroom, shower, washing machines and kitchen sinks	VF	No	NR	NR	BOD_5: 97% (5.2)	97% (2.6)	NR
Costa Rica (Dallas and Ho, 2005)	Mixed, not specified	HSSF	No	4.2	NR	BOD_5: 92% (13)	NR	Fecal coliform 99.99% (2.1 x 10^3 CFU)
	Mixed, not specified	HSSF	No	2.5	NR	BOD_5: 88% (18)	NR	Fecal coliform 99% (2.6 x 10^5 CFU)
Costa Rica (Dallas et al., 2004)	Mixed, not specified	HSSF	No	7.90	98% (2)	BOD_5: 99% (3)	NR	Fecal coliform: 99.999% (16 CFU)
Israel (Gross et al., 2007; *Sklarz et al., 2009)	Mixed, not specified	VF	Yes	0.3-0.5	87%* (6*)	BOD_5: 100% (0.7); or COD : 81% (157)	98% (3)	Fecal coliform: 99% (2 x 10^5 CFU)
Uganda (Katukiza et al., 2014)	Bathroom, shower, laundry and kitchen sinks	VF	No	0.06/10 L-batch	NR	BOD_5: 72% (390); COD: 90% (198); TOC: 69% (277)	93% (80)	99.9% (3.38 x 10^4 CFU)
Norway [72]	Bathroom sinks, shower, laundry and kitchen sinks	VF-HSSF	Yes – VF only	0.3-0.7	NR	BOD_7: 87-98% (20-43); COD 83-88% (58-88)	66-90% (13-54)	NR
Brazil (Paulo et al., 2009)	Laundry, bathroom	HSSF-VF	No	0.8	95% (13)	BOD_5: 95% (22)	92% (9.6)	NR

Note: Values in brackets are reported average effluent concentration values. HSSF represents a horizontal subsurface flow wetland, VF represents a vertical flow wetlands. HRT represents hydraulic retention time. NR represents data not reported.

1.3 The cost-benefits of onsite residential graywater recycling using vertical flow wetlands in the City of Los Angeles: a Case Study

Onsite graywater recycling can offer metropolitan cities that have limited capability for reusing reclaimed wastewater an alternative non-potable water source. The City of Los Angeles, a large metropolitan city located in an arid region in Southern California is one of those Cities facing the above constraints. The City has population of ~4.1 million and has limited local water resources, relying mainly on imported water. The City purchases 48% of its water supply from the California's state water wholesale agency, the Metropolitan Water District (MWD), which obtains its water from the Colorado River and from the California Bay Delta region [73]. The City also imports another 38% of its water via the Los Angeles (L.A.) Aqueduct. Local groundwater accounts for only 14% of LA's water supply. A small fraction of the City's water supply (~1%) is from centralized water recycling and from water conservation, respectively. The low utilization of recycled water is mainly due to the lack of distribution infrastructure throughout the City. As a result, ~76% of the City's effluent is disposed in the Pacific Ocean while the reclaimed water is used mainly for irrigation in recreational areas [73]. Given that the residential water use accounts for 65% of the City's water demand, the City has encouraged rainwater capture projects in residential homes as an alternative onsite water source for irrigation. However, the City's low annual precipitation of 37 cm/year 33-year-average usually occurs over a short period of 10 days (33-year average) (**Figure 1.1**). Therefore, captured rainwater is unlikely to meet the non-potable water demand in the residential sector [73]. In contrast, onsite graywater recycling in residential homes could serve as an important water source for the City but such the feasibility of such an approach has not been fully evaluated. Furthermore, the broader economic and environmental implications and the economic drivers to help the growth of this sector have not been fully assessed.

1.4 Dissertation Hypothesis, Objectives and Structure

The thesis research focused on the the feasibility of onsite graywater treatment using a low cost treatment for aboveground nonpotable graywater reuse single family homes. The **central hypothesis** of the thesis research is that low cost and robust graywater treatment technology that can produce effluent meeting aboveground nonpotable water use requirements coupled with sound graywater reuse policy would maximize the environmental, public health, and economic benefits of onsite residential graywater recycling (treatment + reuse). The objectives of the thesis research are to:

- Further our understanding the policy incentives and impediments of graywater reuse in the United States, and the regulatory water quality requirements for aboveground nonpotable graywater reuse;
- Further our understanding the viability of deploying current state-of-the-art graywater treatment technology in single residential homes;
- Evaluate the feasibility of designing and constructing a low-cost and compact smemi-batch vertical flow wetland (SB-VFW) using off the shelf components for onsite residential graywater treatment in a single family home;
- Further our understanding on the viability of applying coconut coir and structure trickling filter media as non-conventional wetland bed materials for treatment of graywater using a SB-VFW system design;
- Further our understanding on the impact of graywater quality on the treatment performance of a coconut coir based SB-VFW; and
- Further our understanding on the importance of the treatment system costs on the economics of onsite graywater recycling for homeowners;

- Further our understanding on the economic and environmental significance of onsite graywater recycling adoption in a metropolitan city using a low-cost treatment system such as the one developed and demonstrated in this thesis research, using the City of Los Angeles as a case study.

This thesis covers the above objectives over five chapters followed by the conclusions. The first part of this thesis, Chapter 2, focuses on the review of graywater policies and relevant regulations/guidelines within the fifty States that may affect graywater reuse. This chapter addresses a number of major issues regarding graywater reuse that include the acceptability of graywater as a separate domestic wastewater source that can be harvested for reuse post onsite treatment, types of allowable graywater uses, and treatment requirements prior to use and storage. The roles of these policies, which influence the economic viability of graywater, are highlighted throughout the review. In addition, the incentives and impediments for onsite graywater reuse and recycling in the United States are also discussed with the goal of identifying means of fostering growth of this emerging water reuse sector. The text and figures from Chapter 2 was published under the title of "*Critical review: regulatory incentives and impediments for onsite graywater reuse in the United States*" in the Journal of Water and Environment Research 85, 650-662.

Chapter 3 focuses on the evaluation of graywater treatment technology based not only on their performance but also on their suitability for deployment in residential settings. The study will discuss the advantages and limitations of biological, physical and chemical treatment processes with respect to their performance, operability, space requirement, maintenance and cost requirements. The outcome of the study provided important insights for technology selection for residential deployment as well as for shaping future research for the development of residential graywater treatment technology.

Chapter 4 evaluates the application of the proposed SB-VFW system for treatment of mixed bathroom and laundry graywater in order to characterize the SB-VFW system design, assess the potential for simultaneous nitrification and denitrification in the treatment process avoid clogging due to excessive biofilm growth, and evaluate the potential benefit to treatment effectiveness when using a bio-based laundry detergent. The above objectives were accomplished in a five months field study in a residential home using a uniquely designed VFW with circulation. The text and figures from Chapter 4 has been submitted under the title of *"Performance and Economic Evaluation of a Modular Vertical-Flow Wetland for Onsite Residential Bathroom Graywater Treatment"* to the Journal of Environmental Management 85, 650-662 for publication at the filing of this dissertation.

Chapter 5 focuses on demonstrating the technical and economic feasibility of a vertical flow (VF) wetland system for residential graywater treatment that overcomes the stated shortcomings of previous vertical wetland approaches by using coconut coir soil substitute with high water permeability for the wetland, replacing the conventional large gravels with cross flow plastic media consisting of large flow channels and high surface area that allow for both biofilm growth film and aeration, and ensuring adequate distribution of graywater onto the wetland. The SB-VFW was evaluated over a period of eigh months in a single family home for treatment of graywater from bathroom sinks, showers and baths. A first-order kinetics model along with collected field data was then used to evaluate the relationships between operational parameters and treatment performance, thereby providing the basis for scale-up. Furthermore, the economic feasibility of onsite residential graywater treatment were evaluated based on capital and O&M

costs derived from the field study. The overall goals were to demonstrate that a suitably designed semi-batch vertical flow wetland (SB-VFW) can: produce treated effluent that meets stringent water quality requirements for aboveground graywater reuse, have high hydraulic loading rate of >1 m^3/ m^2-day, and be economically feasible in different parts of the world even in the absense of financial subsidies. The text and figures from Chapter 5 will be accepted under the title of *"Feasibility of a Semi-Batch Vertical-Flow Wetland for Onsite Residential Graywater Treatment"* by the Journal Ecological Engineering for publication at the filing of this dissertation.

Chapter 6 focuses on evaluation of the economic drivers for fostering onsite graywater recycling in metropolitan cities in arid regions using the City of Los Angeles as a case study. The objectives of the case study were to evaluate the relationship between housing types and reuse opportunities, conduct cost-benefit analysis of onsite graywater recycling for property owners, assess the cost-benefit of graywater recycling for water and wastewater agencies, and identify the key economic drivers needed for encouraging graywater recycling. The text and figures from Chapter 6 has been submitted under the title of *"Cost-Benefit Analysis of Onsite Residential Graywater Recycling – A Case Study: the City of Los Angeles"* to the Journal of American Water Work Association for publication at the filing of this dissertation.

Chapter 7 summarizes the main conclusions of this dissertation. Several appendices are also included as supplemental materials for various chapters. These appendices are listed as follows:

- Appendix 1: Summary table of graywater regulations in the US
- Appendix 2: Graywater definitions in the United States
- Appendix 3: System design drawing and components
- Appendix 4: System operation and maintenance

- Appendix 5: Water quality data
- Appendix 6: Supplemental data for plots/figures and tables
- Appendix 7: Biofilm images

2 CRITICAL REVIEW: REGULATORY INCENTIVES AND IMPEDIMENTS FOR ONSITE GRAYWATER REUSE IN THE UNITED STATES

2.1 Overview

In recent years, there has been a growing interest in the development of water sustainability through conservation, water use efficiency, generation of new supplies, as well as water reuse [1]. Implementation of water sustainability strategies present a challenge especially in regions of fast population growth and water scarcity [2]. For example, centralized water utilities in a number of States (e.g., California, Florida and Texas) have been developing alternative water sources (e.g., seawater and brackish water), reclaiming wastewater for groundwater recharge, engaging in large-scale evaporation retardation practices in water conveyance and storage, as well as implementing various water conservation measures [3]. Such centralized water management options, which often involve high capital and operational costs [4], are often financed at the municipal level with limited Federal Government support [5]. Development of expanded water portfolio is even more challenging given the high cost of maintenance and upgrade of existing aging and overloaded centralized wastewater conveyance and treatment infrastructures currently serving large metropolitan areas in the United States [6]. It is estimated that water infrastructure maintenance/upgrade for the wastewater treatment sector alone would cost the United States >$200 billion over approximately the next 20 years [7]. Given the current massive Federal budget deficit (estimated at about $15 trillion [8]), it may be difficult if not unrealistic for municipal governments to expect significant Federal assistance for major centralized water infrastructure projects.

Given the rising burden on centralized water conveyance and treatment systems, water reuse has emerged as a viable approach toward water sustainability. Treatment of wastewater for direct aquifer recharge and industrial reuse, as well as certain irrigation applications are now widely practiced in various states [9]. There has also been a major movement to augment local water portfolios through increasing aquifer recharge via better management of storm water [10, 11] as well as rainwater harvesting at the individual household level [12]. The practice of rainwater harvesting for reducing individual household is growing in the United States [13]. Rain water harvesting is seen as an approach (for individual households) to reduce dependence on potable water for non-potable water applications such as landscape irrigation [14]. Rain water harvesting, however, is less likely to have a significant impact in much of the Southwestern United States, which has relatively low rainfall with sparse and often unpredictable rainfall patterns [15]. On the other hand, it has been argued that, at the household level, graywater reuse (given appropriate point-of-use treatment) can reduce overall water consumption for non-potable applications [17, 18, 74].

Graywater is generally defined as domestic wastewater not originated from toilets or urinals [18-20]. Graywater constitutes up to ~70% (by volume) of the total indoor wastewater generation, but with only about 23% of the total mass of generated suspended solids [20, 21]. Therefore, one would expect that widespread practice of distributed (on-site) graywater treatment and reuse could potentially lead to significant reduction in both potable water demand (for non-potable uses) and volume of household wastewater delivered to centralized wastewater treatment plants [18]. Indeed, it is not surprising that water-stressed countries, such as Israel [22] and

Australia [23], are promoting graywater treatment and reuse for non-potable applications (e.g., landscape irrigation), such as for cold water feed for washing machines and for toilet flushing [23].

In the United States, the benefits of graywater reuse are becoming increasingly recognized by water agencies [24] and among green enthusiasts [25, 26]. Graywater policies and regulations at the State level, however, are key to widespread adoption of onsite domestic graywater treatment and reuse. Graywater policies and regulations vary widely among individual States with respect to allowable graywater reuse applications, acceptable reuse practices, and treatment requirements. Also, the often cumbersome permitting process for graywater reuse and the lack of public education resources have adversely affected the overall acceptance and adoption of onsite graywater treatment and reuse, as well as development of standardized technological approaches in the United States [26, 74].

Graywater policies are essential to propelling the acceptance, economic viability and adoption of graywater reuse as a key element of water sustainability and moving toward a paradigm shift in water reuse. Accordingly, this review focuses on graywater policies and relevant regulations/guidelines within the fifty States that may affect graywater reuse. The review addresses a number of major issues regarding graywater reuse that include the acceptability of graywater as a separate domestic wastewater source that can be harvested for reuse post onsite treatment, types of allowable graywater uses, and treatment requirements prior to use and storage. The roles of these policies, which influence the economic viability of graywater, are highlighted throughout the review. In addition, the incentives and impediments for onsite graywater reuse and recycling in the United States are also discussed with the goal of identifying means of fostering growth of this emerging water reuse sector.

2.2 Graywater Quality and Quantity

Graywater is typically defined as wastewater not originating from toilet or urinals such as from bathtubs, showers, bathroom washbasins, clothes washing machines, laundry tubs, kitchen sinks and dishwashers [19, 20]. In the United States, about 127 to 151 liters/day/person of graywater [75] is generated on average, with laundry, baths and shower graywater constituting the bulk of the graywater volume (**Table 2.1**). The daily generated volume of household graywater depends on personal habits and use of water-saving devices [76].

Graywater is less contaminated than domestic wastewater with lower contents of total suspended solids (TSS), organic matter (e.g. BOD and COD), nutrients (e.g. nitrogen and phosphorous) and microorganisms, but with heavy metal concentrations similar to those in domestic wastewater [19]. The quality of graywater can be affected by various factors including family structure (e.g., number of children and adults) [77] and the types of household cleaning and personal products used [19]. It has been reported that graywater generated by families with young children contain higher concentration of indicator microorganisms (i.e. total and fecal coliforms) [77]. Also, household and personal care products affect inorganic constituents and nutrients levels in graywater [19]. For example, detergents can increase graywater salinity, chlorine can lead to zinc leaching from plumbing fixtures, and sunscreen and deodorant can elevate the concentration of zinc in graywater [19]. It is noted that the content of phosphates in conventional dish detergents has been limited by sixteen states [78] to a maximum of 0.5% (by weight), with such limit for laundry detergents mandated by 27 States [79].

Table 2.1 Characteristics of individual graywater streams in the United States

Contaminant	Mixed Gray-water	Graywater Streams							
		Garbage disposal	Kitchen sink	Dish-washer	Laundry machine		Bath / Shower	Hand washing basin	Shower and laundry
					Wash	Rinse			
Volume, L/capita-day	127 – 151	-	18–20	4	40 – 57		38 – 49	20	-
pH	6.7 – 7.5	-	-	-	-	-	-	-	6.5
Temperature, ˚C		21.7	26.7	38.3	32.2	28.3	29.4	-	
Turbidity, NTU	64	-	-	-	39 – 296	14 – 29	28 – 96	-	76
TSS, mg/L	40 – 43	1490	720	440	280	120	120	-	-
TVSS, mg/L	-	1270	670	370	170	69	85	-	-
COD, mg/L	65	-	-	-	-	-	-	-	-
BOD_5, mg/L	35 – 120	1,030	1,460	1,040	380	150	170	-	-
TOC, mg/L	-	690	880	600	280	100	100	-	-
TN, mg/L	-	60	74	40	21	6	17	-	1.7
NH_4-N, mg/L	-	0.9	6	4.5	0.7	0.4	2	-	0.7
NO_3-N, mg/L	1.8	0	0.3	0.3	0.6	0.4	0.4	-	1
TP, mg/L	-	12	74	68	57	21	2	-	9
PO_4-P, mg/L	-	8	31	32	15	4	1	-	-
Sulfate, mg/L	60	-	-	-	-	-	-	-	23
Chloride, mg/L	21	-	-	-	-	-	-	-	9
Fecal coliform, CFU/100-mL	$5.6\text{x}10^5$ –$1\text{x}10^8$	-	-	-	1,400 – 6,300	25 – 320	220	-	-
Total coliform, CFU/100-mL	$6.3\text{x}10^6$ – $2.5\text{x}10^8$	-	-	-	18,000	56 – 5,300	1,100 – $1.0\text{x}10^5$	-	$2.8\text{x}10^7$
Fecal Streptococci, CFU/100-mL	240	-	-	-	210	75	44	-	$1.8\text{x}10^4$ – $7.9\text{x}10^6$
Total bacterial, CFU/100-mL	$8.0\text{x}10^7$	-	-	-	$1\text{x}10^7$ –$1\text{x}10^8$	$1\text{x}10^7$ –$1\text{x}10^8$	$1\text{x}10^7$ – $1\text{x}10^8$	-	$6.1\text{x}10^8$

Note: Data was compiled from [75, 77, 80-82]

Water quality of individual graywater streams vary depending on their origins. Kitchen graywater is the portion of graywater from dishwasher and kitchen sinks. These graywater streams are more contaminated (**Table 2.1**) compared to other non-kitchen graywater streams, containing more solids, oil and grease, organics, microorganisms and surfactant [20]. Kitchen graywater contributes ~22-24 liters/capita-day to the total household generated wastewater volume and is a major source of solids, volatile organics, BOD, COD, nutrients (see **Table 2.1**), and micro-organisms found in graywater [81]. Other sources of graywater, originate from hand washing basins, bath tubs, showers and laundry, contain less soil and grease, solids, and microorganisms than kitchen graywater [20, 81]. Non-kitchen graywater forms a major portion of domestic graywater with reported volumetric flow rate ranging from about 98 to 126 liters/capita-day [75]. It has been reported that laundry graywater generated during wash cycles is the most contaminated of the various non-kitchen graywater sources [20], while graywater from hand washing basins is the least contaminated [20]. Microorganisms are also found in non-kitchen graywater with majority of fecal coliforms, however, originating from the wash cycles of laundry machines and showers [20].

2.3 Graywater Regulations and Policies

Accepting and Defining "Graywater"

The acceptance of "*graywater*" as a separate wastewater source is a first step toward allowing its segregation, collection, treatment and reuse. At present, 41 States provide regulatory definitions of graywater, while nine States are yet to include graywater in their State regulations (**Fig. 2.1**). Of the 41 States that provide graywater definitions, five States define graywater only in their state plumbing code, 14 States define graywater only in other State regulations (e.g., onsite sewage disposal regulations, water pollution control regulations, health and safety code, graywater reuse guidelines, environmental codes, House Bills, water and wastewater regulations), and the remaining 22 States define graywater in both plumbing codes and other State regulations (**Fig. 2.1**).

Differences in regulatory definitions of graywater adopted by various States typically center on whether or not kitchen graywater should be included in the definition of graywater (**Fig. 2.1**). In the plumbing codes of 26 States, only certain non-kitchen graywater sources are considered as graywater. The California plumbing code, for example, excludes laundry water that has been soiled by diapers from being considered as graywater [68]. The Illinois and Wisconsin State plumbing codes, on the other hand, include both kitchen and non-kitchen graywater as graywater [83, 84]. Graywater definitions in non-plumbing code regulations of 36 States appear to emphasize either the inclusion or exclusion of kitchen graywater sources from the definition of graywater. At present, fourteen of these 36 States consider only non-kitchen graywater to be graywater, 15 States include both kitchen and non-kitchen graywater in their graywater definition, while four States include kitchen graywater from dishwashers but exclude water either from kitchen sinks or from kitchen sinks with garbage disposals. It is interesting to note that, North Dakota provides guidelines for segregation of different household wastewater streams including water from kitchen sinks for the purpose of treatment and disposal (e.g., septic tanks), although it does not have an explicit regulatory definition for "*graywater*" [85].

Among the States that have included graywater regulations in non-plumbing code regulations, three States (Hawaii, Minnesota, and Oregon) have included two different definitions of graywater in two separate regulations (**Fig. 2.2)**. All three States include, in the definition of graywater, both light and kitchen graywater streams in one regulation. However, in a second definition of graywater in other regulations, Minnesota and Oregon exclude water from kitchen sinks with garbage disposal, while Hawaii excludes all water from kitchen sinks. More discrepancies regarding graywater definitions are found for States that have included graywater guidelines in both plumbing codes and other State regulations. For example, it is interesting to note 11 of the 20 States that exclude all kitchen graywater streams from graywater definitions in their plumbing codes, include kitchen graywater streams in their other State regulations.

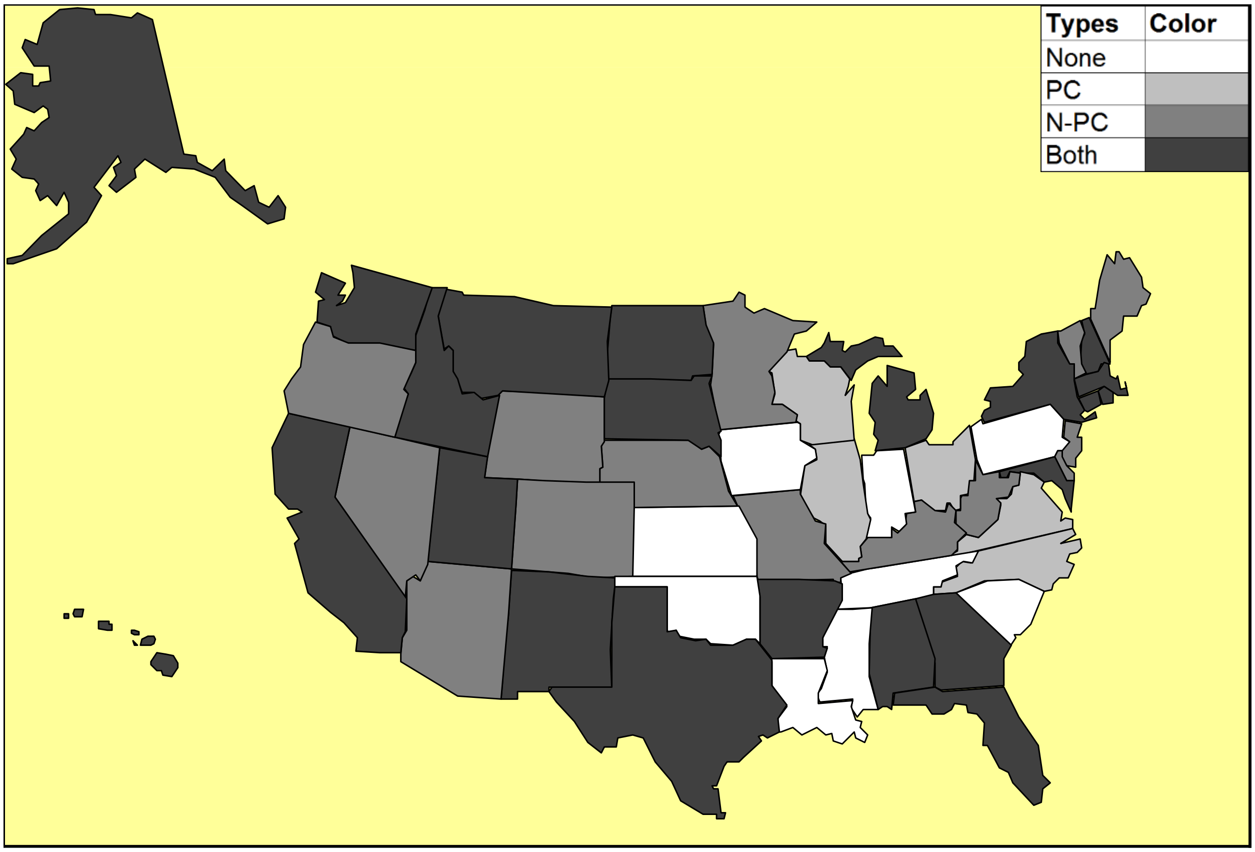


Figure 2.1 Provision of graywater definitions in State regulations and plumbing codes by States. (Note: None – no regulations; PC – graywater regulations found in State plumbing codes only; N-PC – graywater regulations found in non-plumbing code regulations only; Both – graywater regulations found in both State plumbing codes and other regulations)

The lack of consistent graywater definitions among the States (**Fig. 2.2**) is problematic as it may complicate compliance and enforcement. Additionally, inconsistent or conflicting definitions can be perception of "*legal barriers*" which can reduce the level of productive cooperation (e.g., with respect to permitting) between the existing and potential future graywater reuse communities. Consistent regulatory graywater definitions are essential since these can have major impacts on the: (1) acceptance of graywater reuse; (2) the volume of graywater that can be collected and reused and/or recycled; (3) required graywater treatment technology and the cost of such treatment. For residential onsite graywater reuse, consistent, simple and clear graywater definition is needed to enable practitioners to easily assess graywater treatment options, and accordingly the most suitable practical treatment technology and permitted reuse applications. Inconsistent graywater definitions, within the regulations of certain States and even minor differences in graywater definitions among States, can be a hurdle that retards the widespread development of graywater treatment technology and its standardization.

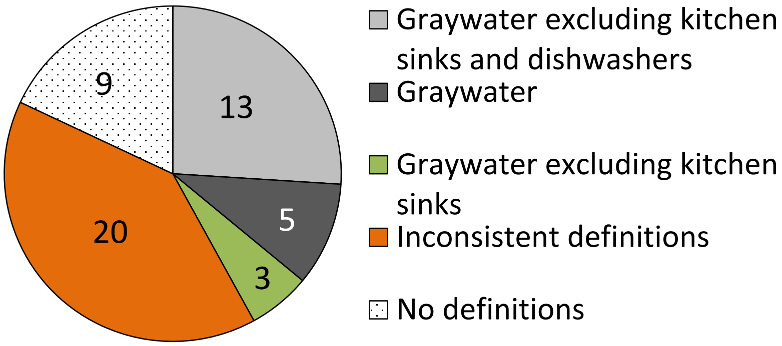


Figure 2.2 States with graywater definitions

The definition of graywater and allowable reuse policies may determine the economic viability of graywater systems in several ways. Most obviously, it can influence the cost of the technology needed for treatment. It may also determine the quantity of graywater available onsite, thereby influencing the minimum scale of production for an onsite system, which will determine the unit cost of treatment. At the industry level, fragmented state policies may prevent graywater technologies from reaching scales of production that would allow reduction in system costs to fall over time as has occurred for similar technologies. More inclusive graywater definitions and more consistent state policies could lead to declining graywater unit costs.

The definition of graywater and allowable reuse applications are key factors that determine the required level of graywater treatment and the technology that can be effectively implemented at the residential level. For example, homeowners may find it difficult to consistently control the reuse of laundry graywater when such water may intermittently include wastewater from washing of soiled diapers (currently excluded by graywater definitions in 12 States). Another example is the exclusion of kitchen sink graywater (with or without garbage disposals) from graywater definition. Graywater generated from kitchen sinks and dishwashers generally outflows into the same plumbing drain, which is then conveyed to the main house drain. The exclusion of kitchen sink graywater from the definition of graywater (e.g. Texas, Minnesota and Oregon) means that residential graywater reuse would require additional costly plumbing connections for segregating this graywater source from dishwasher wastewater. Given the similarity in TOC, BOD and TN levels between graywater from kitchen sinks or dishwashers (**Table 2.1)**, one could argue that both water sources could be treated and reused, provided that suspended solids are effectively removed from kitchen sinks, especially those with garbage disposal systems.

Who Can Collect Graywater at home?

Establishing an unambiguous graywater definition is an essential element of promoting onsite graywater reuse and recycling. However, having a graywater definition does not necessarily translate into the granting of permission for graywater collection, which is a necessary element of graywater reuse. For example, of the 41 States that define graywater only 38 allow onsite graywater collection while three do not permit graywater collection. Among the 38 States that allow graywater collection, six ban graywater collection for households that have accessible sewer connections (**Fig. 2.3**). The implication is that in the above States, households that are served by centralized treatment facilities cannot benefit from onsite graywater reuse. On the other hand, it is noted that 17 States allow graywater reuse irrespective of the availability of public sewer connections (**Fig. 2.3**), while 15 States do not appear to have explicitly stated restrictions regarding graywater collection in areas served by centralized public sewer systems (**Fig. 2.3**). It is reasonable to conclude that even in urban areas, onsite graywater reuse would relieve the treatment and water conveyance burden on already overloaded and aging centralized facilities. However, restriction on graywater collection, based on whether public sewers are available, would impede the growth of onsite graywater reuse since the majority of the US population resides in urban areas or those served by public utilities.

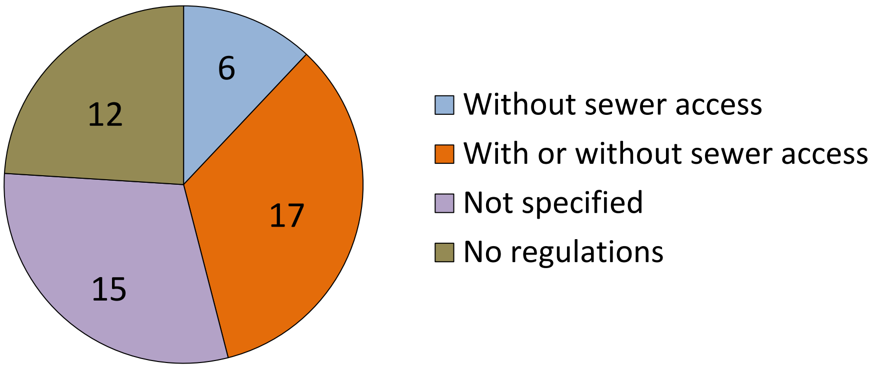


Figure 2.3 **Allowance of graywater collection**

Permits

The requirement of permits for onsite graywater reuse serves multiple purposes including, but not limited to, compilations of information regarding graywater reuse locations, treatment types and capacities, oversight to ensure that installed systems meeting treatment requirements for the intended/permitted water use applications. Unfortunately, the permitting process is often perceived as being tedious, time-consuming, and costly legal barrier for homeowners to cross [26]. Burdensome permitting procedures can increase the cost of deploying of graywater systems. In addition, it has been reported that lack of readily available "user-friendly" information concerning permit requirements and assistance, during the planning and permitting phases, can create "*mental barriers*" for homeowners who attempt to engage in graywater reuse [26]. However, permitting for onsite graywater collection and/or reuse is required in 30 States (**Fig. 2.4**), two States (Maryland and North Carolina) do not specify if permit are required, while six States (Arizona, California, New Mexico, Montana, Texas and Wyoming) allow onsite graywater collection and reuse without permits subject to reuse volume thresholds (up to 7,571 liters in Wyoming) and reuse application (**Table 2.2),** with Montana only specifying that graywater reuse is restricted to toilet flushing without a reuse threshold volume. In California, only graywater from a single laundry machine serving up to two families can be used without permit for subsurface irrigation; the above is perplexing since laundry graywater has been reported to be more contaminated than other non-kitchen graywater streams [19, 20, 82] (**Table 2.1**). Clearly, there appears to be lack of uniformity with respect the restrictions on allowable use or volume of graywater even among States that do not require permits for reuse.

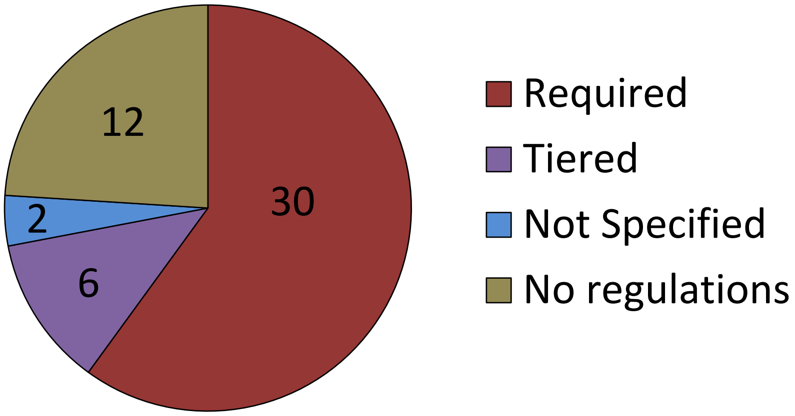


Figure 2.4 **Permit requirements for onsite graywater reuse and / disposal**

Table 2.2 Allowable daily quantity for graywater recycling systems to be operated without permits

State	Allowable Daily Quantity without Permits	Allowable Applications without Permits
Arizona	Less than 1,514 liters	Surface irrigation for non-edible crops without human contact
California	Volume generated by a single laundry machine serving up to two family	Subsurface irrigation of non-edible crops and subsurface irrigation
New Mexico	Less than 946 liters	Discharge disposal; or non-food crop and composting irrigation.
Montana	Not specified	Toilet flushing
Texas	Less than 1,514 liters originating from a single family dwelling	Non-sprayed garden or landscape irrigation, foundation stabilization, composting, disposal for a single family dwelling
Wyoming	Less than 7,571 liters	Non-potable water applications with minimal human contact.

There is a concern that permitting requirements are too restrictive and costly and permitting processes are too cumbersome and time-consuming. These may stifle the growth of graywater reuse and/or drive homeowners away seeking legitimate permitting of their graywater collection and treatment systems and reuse applications [25, 26]. Graywater reuse permits, if established by regulators, can be an effective instrument that encourages compliance and promotes effective graywater reuse with the goal of fostering environmental protection. However, in order for the permitting process to be beneficial to homeowners, there should be sufficient public education resources and assistance, during the permitting process regarding graywater reuse systems planning and installation phases.

Reuse Water Quality

Public and regulatory concerns regarding potential of human exposure to pathogens [77, 81, 86] as a consequence of onsite graywater reuse has prompted the call for establishing protective guidelines/regulations. At present, 35 of the 38 States that allow graywater reuse do not have established graywater quality criteria for reuse, while three have specific water quality requirements as listed in **Table 2.3**. The above 35 States have adopted one or more of the following guidelines for reducing human exposure to graywater: (1) allow only subsurface irrigation or disposal (16 States), (2) also allow above surface irrigation but disallow spray irrigation (4 States), and (3) allow use of graywater for toilet flushing (7 States).

Table 2.3 Water quality criteria for onsite graywater reuse[(a)]

Standards	Type of reuse	Treatment Level Equivalent	Water Quality Criteria
Alabama	Drip irrigation	Secondary	Secondary with filtration
California	Subsurface irrigation	Primary	Not Specified
	Above ground non-potable reuse	Disinfected tertiary (Title 22 Recycled Water quality)	Turbidity: 2NTU (avg); 5 NTU (Max) Total Coliform: 2.2 MPN / 100 mL (avg), 23/100 mL (Max in 30 days)
Wisconsin	Subsurface irrigation	Secondary	$\leq$ 15 mg/L oil and grease; $\leq$ 30 mg/L BOD_5 $\leq$35 mg/L TSS; < 200 fecal coliform cfu/100mL
	Surface irrigation except food crops, vehicle washing, clothes washing, air conditioning, soil compaction, dust control, washing aggregate and making concrete	Disinfected tertiary	pH 6-9; $\leq$ 10 mg/L BOD_5; $\leq$ 5 mg/L TSS Free chlorine residual 1.0-10 mg/L
	Toilet and urinal flushing	Disinfected primary with filtration	pH 6-9; 200 mg/L BOD_5; $\leq$ 5 mg/L TSS Free chlorine residual 0.1 mg/L – 4.0 mg/L

(a) States that provide specific water quality requirements for treated graywater

Graywater treatment standards (with respect to achievable treated water quality) have been established by the States of Alabama, California and Wisconsin (**Table 2.3**). Alabama, only reports graywater treatment requirements for drip irrigation to secondary wastewater effluent standard with post filtration prior to use in drip irrigation. However, treatment is not required of graywater bound for underground disposal in Alabama. Also, water quality criteria are not provided for graywater reuse for toilet flushing. California, requires that graywater reused for non-potable aboveground and indoor (e.g., toilet flushing) applications must be treated to achieve water quality equivalent (at the minimum) to that of disinfected tertiary wastewater effluent (see **Table 2.3**). It is noted that Wisconsin adopted separate water quality standard for subsurface irrigation, toilet flushing and other above ground non-potable reuse applications (**Table 2.3**). Graywater reused for toilet and urinal flushing requires treatment to at least disinfected filtered primary wastewater effluent, subsurface irrigation requires graywater treatment to secondary wastewater effluent quality, while aboveground non-potable reuse of graywater requires treatment to the quality level of disinfected tertiary wastewater effluent.

Although the above approaches are sincere attempts to reduce potential exposures to contaminants that may be present in graywater, certain requirements may be seen as either too restrictive or too lax, or there is lack of clarity regarding allowable reuse applications. For example, although allowance of direct reuse of graywater (i.e., without treatment) for subsurface in California and direct disposal in Alabama may be consistent with reduction of human exposure (to graywater), there remains the potential for soil subsurface and groundwater contamination. Allowed graywater reuse by 35 States without specification of treatment levels or water quality is also troubling from the viewpoint of public health and environmental protection. For example, it has been reported that use of untreated graywater for irrigation, i.e. primary effluent quality, can lead to reduced water infiltration, increase soil salinity and levels of various organic and inorganic contaminant in the vadose zone [87-89].

Graywater Reuse Applications

Graywater reuse can provide an alternative non-potable water source to augment potable water use, while reducing the overall discharge of wastewater into centralized water treatment facilities. Therefore, there are economic benefits of graywater with respect to quantity and value of portable water that it replaces as well as the wastewater treatment costs that it avoids. The size of both of these benefits could be determined by the range of acceptable graywater reuses that are permitted by policy. In the United States 18 States allow outdoor non-potable graywater reuse (whether treated or non-treated), 7 States allow indoor reuse (e.g., toilet flushing) with various levels of treatment, while 9 States only allow graywater disposal also at various required treatment levels. The allowable water applications, as specified in various graywater regulations in the United States, include the following main categories **(Fig. 2.5)**: irrigation (landscape, compost, above ground, and subsurface), toilet flushing, and other above ground non-potable uses (e.g., laundry machines water feed, dust control and vehicle washing). Subsurface irrigation is allowed by the largest number of States (18), followed by surface irrigation by means other than spray irrigation (9).

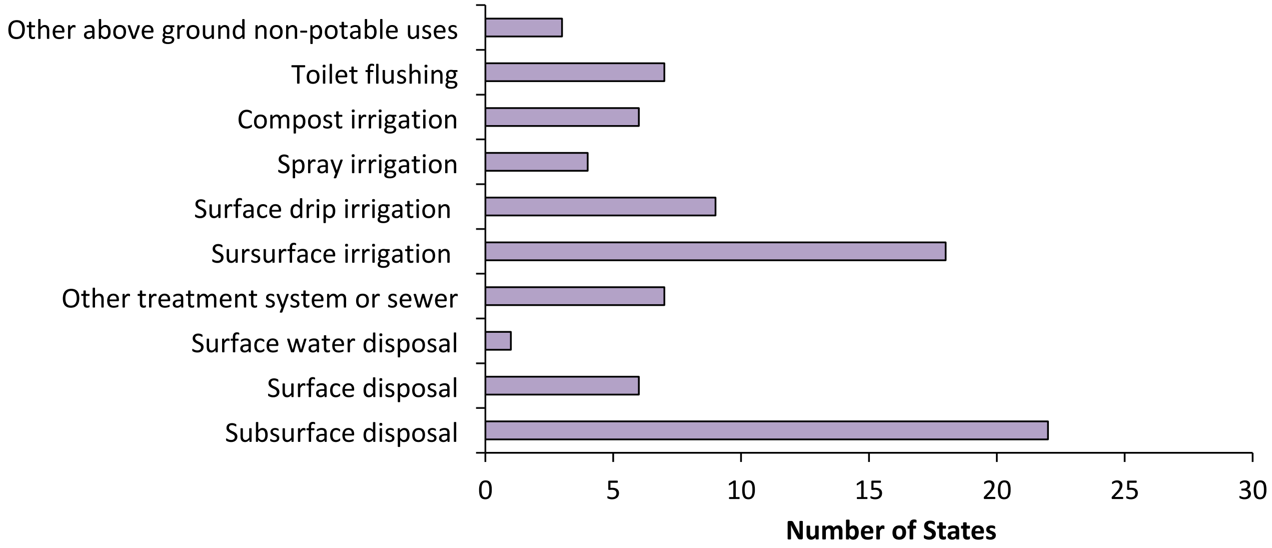


Figure 2.5 Beneficial graywater uses and disposal methods in the 38 States that allow graywater collection. Evaluation excluded 11 States under the *Toilet Flushing* category, 10 under *Subsurface Irrigation*, and one under *Subsurface Disposal* due to apparent inconsistencies in the above categories between their State plumbing codes and other State regulations

Graywater that undergoes appropriate treatment, is clearly identified by 7 States as being allowed for indoor use (e.g., toilet flushing). Also, treatment of graywater for outdoor reuse (e.g., irrigation) may require different levels of treatment. Although irrigation is favored by a large number of States, water saving benefits can be limited in regions with abundant rainfall, winter temperature that drops below freezing [90] and poor soil drainage [91, 92]. Furthermore, if the ground water table is too shallow, discharging untreated graywater or partially treated graywater into the ground for irrigation is prohibited, e.g. California [68] and Arkansas [93]. Also, restrictions of subsurface as oppose to above surface irrigation increases the cost of graywater reuse for irrigation. In the United States, it appears that regulations advocate subsurface outdoor irrigation and subsurface disposal of graywater, while graywater for toilet flushing is the major permitted indoor reuse application (**Fig. 2.5**). It is noted that, 11 of the 18 States that allow graywater reuse for toilet flushing appear to have inconsistent regulations regarding whether it is acceptable to reuse graywater for toilet flushing (**Fig. 2.5**). California and Wisconsin specify the allowed use of treated graywater as feed water for washing machines and for car washing (see **Table 2.3**). The above range of graywater reuse applications is limited. In this regard, broadening the type of permitted indoor and outdoor uses of graywater would clearly expand the beneficial use of graywater and thus also more likely to improve the economics of graywater reuse.

Regulations and/or codes regarding beneficial graywater reuse, which have been indicated in 38 States, can serve to encourage and guide the development of the practice of graywater reuse. There are, however, conflicting regulations whereby a given State regulation or code may permit specific graywater management or reuse options while the same options may be disallowed by another regulation in the same State (**Fig. 2.6**). For example, non-plumbing regulations for 11 States state that graywater can only be disposed underground, these same States' plumbing codes permit toilet flushing with disinfected primary treated graywater. If State regulations regarding graywater, by different agencies within the same state (e.g., building departments, public health and environmental protection agencies), are confusing in the planning and permitting stage of graywater management they may become a deterrent to the growth of this sector of water reuse.

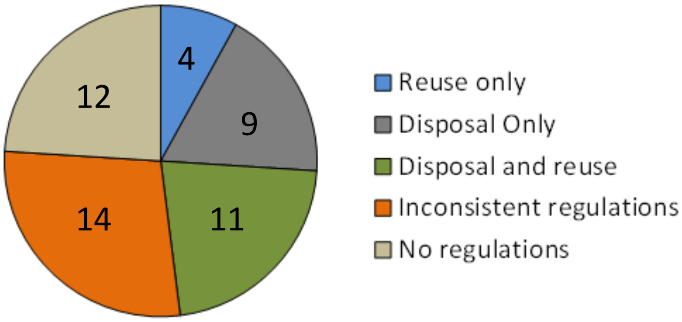


Figure 2.6 **States allowing graywater reuse and / or disposal**

Graywater Treatment Requirements

Specification of the level of graywater treatment that is appropriate for the intended water reuse application is key to safeguarding public health and the environment. However, differences in treated graywater water quality requirements, for a given reuse application, storage or disposal, can differ from State to State (**Fig. 2.7**). Gravitational settling of solids in storage tanks is the most common primary treatment method for subsurface irrigation and toilet flushing. Primary treatment is required for treating graywater reused for subsurface irrigation (20 states), above ground irrigation that excludes spray irrigation (3 states) and toilet flushing (13 States). Septic tanks are specified by New York and South Dakota as the required or acceptable graywater treatment method for subsurface and/or above ground irrigation (except spray irrigation); while in South Dakota, septic tanks are specified as suitable for toilet flushing reuse of graywater [94]. It has been suggested that graywater that is used for irrigation post only primary treatment may have an adverse impact on some plants as well as altering soil drainage and adsorption properties [89, 95]; these studies suggest that the suitability of only primary treatment for irrigation requires further evaluation. It is noted that, secondary treatment (i.e., BOD removal) is required by three States (Alabama, Alaska and Wisconsin) for subsurface and surface irrigation that excludes spray irrigation. The use of tertiary treatment with disinfection using chlorine or other proven disinfection technology is only required in the States of California (for all above ground non-potable graywater uses) and Wisconsin (for all above ground except toilet flushing) (**Table 2.3**). It is noted that the provision regarding residual chlorine in treated effluent is only specified by Wisconsin. California specifies that the quality of treated graywater for above ground non-potable reuse must meet Title 22 Recycled Water quality [68].

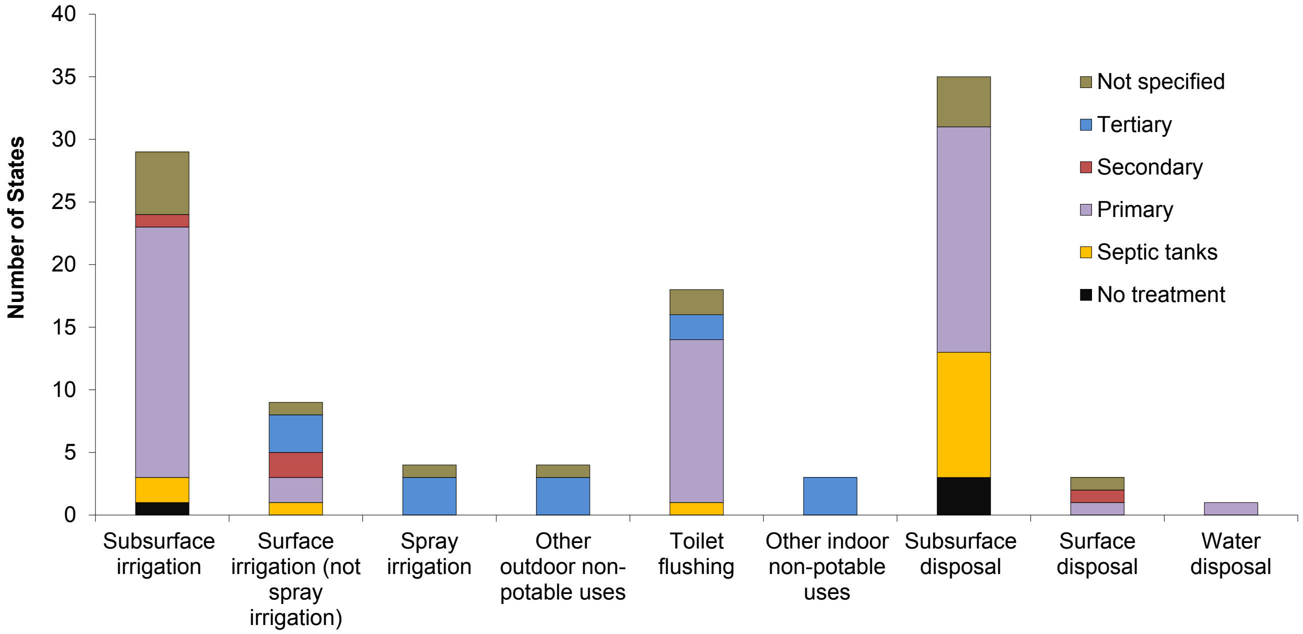


Figure 2.7 Treatment requirement for allowable graywater reuse applications and disposal in the United States. Evaluation includes acceptable alternatives stated in plumbing codes and other state regulations

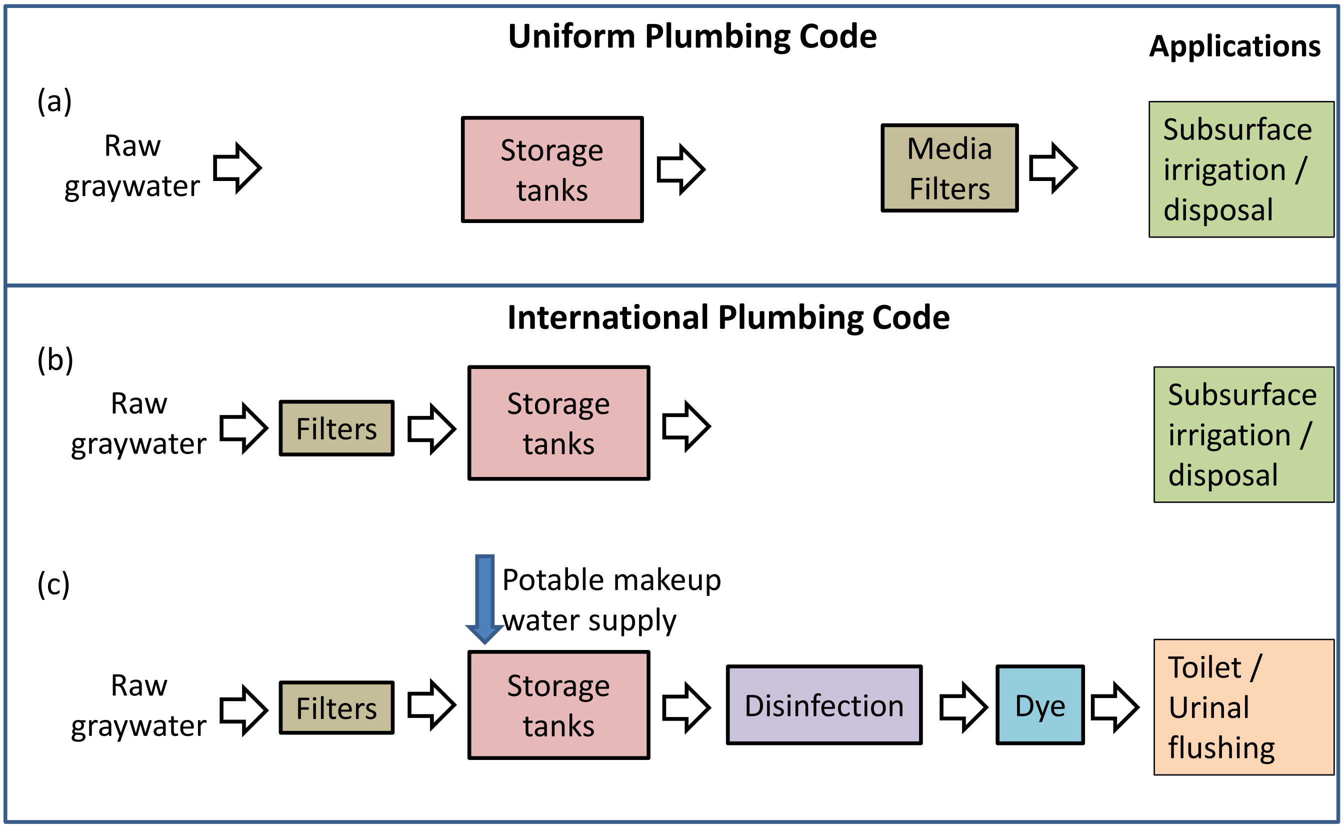


Figure 2.8 Graywater treatment processes specified in the Uniform Plumbing Code (UPC) for subsurface irrigation and the International Plumbing Code (IPC) for subsurface irrigation / disposal and toilet flushing

Detailed graywater treatment process specifications are available in two widely adopted standard plumbing codes: the International Plumbing Code (IPC) (10 States) and the Uniform Plumbing Code (UPC) (8 States). Treatment process specifications for primary treatment for subsurface irrigation or disposal are presented in both IPC and UPC (**Fig. 2.8**). The main difference between the above specifications is that the IPC specifies filtration of graywater prior to entering the storage tanks (**Fig. 2.8b**), while the UPC requires filtration when graywater is drawn from a storage tank prior to entering the subsurface irrigation or disposal systems (**Fig. 2.8a**). Another primary treatment design specification is presented in IPC for graywater use for toilet/urinal flushing. Such a system is similar to the primary treatment system used for subsurface irrigation, except that it requires potable makeup water supply to the storage tank, and it also requires disinfection and coloring of graywater just prior to reuse for toilet flushing (**Fig. 2.8c**).

Graywater Disposal

Land disposal of primary treated graywater is practiced in 18 States, while septic tank effluent disposal / treatment is practiced in 10 States (**Fig. 2.7).** California and Maine, however, permit subsurface disposal (or irrigation) of untreated laundry graywater, while disposal into a mini-dry well is allowed in New Hampshire. Ground surface and water discharge of secondary treated graywater is acceptable in Alaska. Onsite disposal (i.e., to subsurface, above surface or natural water body) of graywater treated to various levels is allowed by 34 states (**Figure 6**) with 9 of those States disallowing any reuses including subsurface irrigation. Allowing only onsite disposal but not subsurface irrigation is perplexing. Such a restriction on graywater management: (a) removes the local economic benefits of water reuse and (b) eliminates the benefit of reducing the burden on centralized wastewater treatment facilities. It is not unreasonable to assert that onsite disposal would provide little incentive to homeowners unless such a practice would also reduce their sewer charges.

Storage

Graywater storage is an essential component of onsite graywater management since graywater generation is intermittent. Additionally, raw graywater storage tanks enable primary treatment through gravitational settling. Storage can be in either a holding tank (which can be either above or below ground) or via septic tanks which by their nature are installed below surface. It has been reported that total suspended solid (TSS) and chemical oxygen demand

(COD) are reduced when graywater is stored in holding tanks for ~ 24 hours; however, odor problem can arise if graywater is stored for more than ~48 hours [34]. On the other hand, when septic tanks are utilized, overall effluent quality improves with longer retention times [25].

The required storage volume depends on both the household level of graywater generation, demand for graywater reuse capacity, and specific regulatory specifications. It is estimated that an average household of 2 to 3 people generates ~379 liters of non-kitchen graywater per day [96]; thus, one would expect the need for storage of about the same volume or greater. Presently, 26 States specify the minimum onsite storage requirements in State regulations, with 189 liters specified by 15 States, 946 liters or above by 8 States and 3,785 liters by 4 States (**Fig. 2.9, Table 2.4**). A few States (New York, Kentucky, New Mexico and Wisconsin) specify graywater storage volume requirements based on household size and daily volume of generated graywater. Also, six States do not provide requirements with respect to graywater storage. Inconsistencies between regulations in a given State regarding storage size and sizing requirements are found in six States (**Table 2.4**).

Storing untreated graywater (i.e. primary effluent) in holding tanks that are too large (larger than required household capacity) or storage times that are too long can create nuisance in residential homes [25, 34]. It has been suggested that untreated graywater that is stored in holding tanks for up to a day should be drained daily to avoid septic conditions from developing by aged untreated graywater [25]. Long storage times may be problematic, for example, when toilet flushing is the intended use, as it could create environmental nuisance for homeowners. In order to properly handle excess capacity of graywater via storage it has been suggested that: (1) graywater to be stored should receive at least secondary treatment; (2) untreated graywater could be stored in septic tanks although this approach would make graywater unavailable for other reuse applications except for subsurface irrigation and disposal; and (3) storage tanks for raw graywater could be undersized so as to allow overflow to the sewer and thus minimize the risk of storing untreated graywater for prolonged periods.

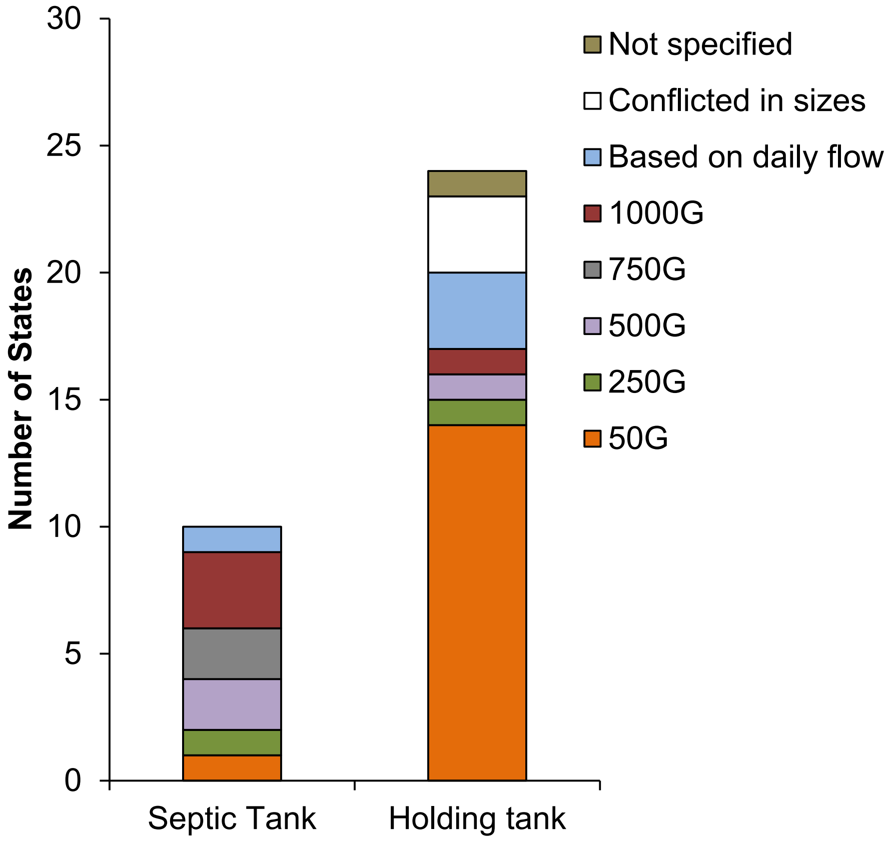


Figure 2.9 **Minimum storage volume requirements**

Table 2.4 Graywater storage requirements specified by 38 States that allow graywater segregation and collection

States	Other State regulations			Plumbing code		
	Tank type	Mini. Volume, liter	Holding time, hour	Tank type	Mini. Volume, liter	Holding time, hours
Alabama	HT	3785	48	HT	189	SI: 24; TF: 72
Alaska	HT	189	NS	HT	189	NS
Arizona	HT	NS	NS	NA		
Arkansas	HT	189	NS	HT	189	NS
California	NA			HT	NS	NS
Colorado	ST	1893	30	NA		
Connecticut	ST	1893	24	HT	189 L	TF: 72
Florida	ST	946	NS	HT	189 L	SI: 24; TF: 72
Georgia	HT	1893	NS	HT	TF: daily use	TF: 24
Hawaii	HT	189	24	HT	NS	NS
	HT	2271	NS			
Idaho	HT	189	NS	HT	189 L	NS
Kentucky	HT	x2 design flow	NS	NA		
Maine[(a)]	ST	2839	NS	NA		
Maryland	NA			NS	NS	NS
Massachusetts	ST	3785	NS	NS	NS	NS
Michigan	HT	189	NS	HT	TF: 189 L; SI: daily use	SI: 24; TF: 72
Minnesota[(a)]	ST	2839	NS			
Missouri[(a)]	HT	3785	NS	NA		
Montana	HT	189	NS	HT	189 L	NS
Nevada	HT	189	NS	NA		
New Hampshire	HT	189	NS	HT	TF: 189 L; SI: NS	SI: 24; TF: 72;
New Jersey[(a)]	ST	946	NS	NA		
New Mexico	HT	Daily use	24	NA		
New York	ST	284/bedroom-day	NS	HT	TF: 189 L	TF: 72
North Carolina	HT	189	NS	HT	TF: 189 L; SI: NS	TF: 72; SI: 24
North Dakota	ST	189	NS	HT	189 L	NS
Ohio	NS	NS	NS	NS	NS	NS
Oregon[(a)]	NS	NS	NS	NA		
Rhode Island	HT	NS	NS	HT	NS	NS
South Dakota	HT	189	72	HT	TF: 189 L	TF: 72
Texas	HT	189	NS	HT	TF: 189 L; SI: daily use	TF: 72 SI: 24
Utah	HT	946	NS	HT	TF: 189 L	TF: 72
Vermont[(a)]	ST	3785	NS	NA		
Virginia	NA			NS	NS	NS
Washington	HT	NS	24	NA		
West Virginia[(a)]	ST	1893	NS	NA		
Wisconsin	NA			HT	246/bedroom-day	NS
Wyoming	HT	189	24	NA		

Note: HT – holding tanks; ST – septic tanks; TF – toilet flushing; SI – subsurface irrigation; NS – not specified; NA – not applicable. [(a)] State allows onsite disposal but not reuse.

2.4 Regulations Incentives and Impediments

Incentives

Although the graywater sector in the U.S. is still in its early development, there are encouraging signs that regulators are working to lower regulatory barriers, thereby encouraging onsite graywater reuse and recycling. General regulatory actions that represent positive movement toward expansion of the graywater sector include: (1) provision of regulatory definitions of graywater; (2) allowance of graywater collection in areas with sewer connections; (3) simplifying the process of permitting or registering residential graywater collection, treatment and reuse systems; and (4) allowance of diversified graywater use applications.

The provision and inclusion of graywater definitions in the plumbing codes and other State regulations for 41 States (**Fig. 2.1**) suggests that, most States accept graywater as a separable stream of domestic wastewater that has water quality characteristics different from domestic wastewater and black water. Although the provision of regulatory definitions does not always translate into granting homeowners permission for collecting and reusing graywater, it represents an important first step toward allowing graywater reuse. Additionally, allowance of graywater reuse by 29 States (**Fig. 2.6**) demonstrates acceptance of graywater as an alternative water source for non-potable applications. About seventy five percent of homes in the United States are served by public sewers [97], hence allowing these homes to collect graywater is an important step toward point-of-use graywater recycling. Such a move would help relieve the burden on centralized wastewater treatment facilities. The fact that 17 States already allow graywater collection in areas with public sewer access (**Fig. 2.3**), suggests that there is already national movement forward for graywater reuse in residential areas.

It has been suggested that when the graywater reuse permitting processes is time consuming and costly, homeowners can be led to either abandon the idea of graywater reuse, or may opt for unpermitted reuse activities [25, 26]. It is interesting to note that six States do not require permits for reuse of untreated graywater, but place restrictions on the maximum reuse quantity and specific reuse applications (**Table 2.3**). Given various concerns regarding potential health impacts associated with graywater reuse [77, 81, 86], it is imperative that the permitting process addresses the need for identifying homes and other residential/commercial facilities where graywater reuse is practiced. Moreover, the permitting process should not be imposing but rather be useful in promoting responsible graywater reuse.

Although graywater reuse applications for outdoor irrigation and toilet flushing are permitted in 18 and 7 States, respectively (**Fig. 2.5**), available graywater capacity may be higher than the volume demand in most urban centers [96]. Therefore, broadening the permitted graywater non-potable reuse applications beyond outdoor irrigation and including toilet flushing would provide homeowners greater flexibility over graywater reuse particularly in areas where irrigation needs can vary considerably over the course of the year. Broadening the range of permitted outdoor (e.g. car washing and dust control) and indoor (e.g. irrigation and laundry) non-potable reuse would increase the available capacity for reuse, with minimal plumbing retrofit, and thus increase the economic value of graywater reuse.

Impediments

Inconsistent graywater definitions and reuse regulations between State plumbing codes and other State regulations (**Figs. 2.2** and **2.6, Table 2.4**), for the same State, can lead to confusion regarding agency jurisdiction for enforcement, graywater storage and treatment requirements and allowable graywater reuse applications. It is also noted that while 9 States only allow graywater disposal but not reuse, 12 States do not provide graywater reuse regulations. The term "*Graywater Systems*" often does not clearly differentiate between graywater collection, storage and treatment systems. Moreover, State graywater regulations do not specify the required effluent water quality produced by such a system. In contrast, the *International Plumbing Code* (*IPC*) and *Uniform Plumbing Code* (*UPC*) provide specific details regarding graywater system components, plumbing connections, treatment processes and reuse applications (**Figure 9**). However, the entirety of the IPC and UPC are not followed by most States, which typically include various amendments/additional restrictive regulations to their own plumbing codes and/or other State regulations. The full benefit of graywater reuse is limited in most States, primarily due to restriction on graywater storage volume and limitations of outdoor reuse to mostly irrigation (18 States, **Fig. 2.5**). Requirements for installation of large raw graywater storage tanks (**Fig. 2.9** and **Table 2.4**) may be infeasible in most urban areas, while nuisance (e.g. odor) created by prolong storage of raw graywater could discourage the practice residential graywater reuse. Clearly, lower storage capacity would be appropriate by increasing the allowed range of graywater reuse applications beyond simply outdoor irrigation (**Fig. 2.5**). Irrigation opportunities are particularly limited in densely populated areas (due to small outdoor areas), and requirements of subsurface irrigation adds to the cost of graywater reuse, especially when the graywater volume demand for irrigation is below the generated graywater capacity. The restriction of outdoor non-potable graywater reuse to irrigation is suggestive of a conservative regulatory approach to public health protection. Although reuse of untreated or primary treated graywater for subsurface irrigation is likely to minimize direct human contact, contaminants in graywater, which are introduced to the soil subsurface, may be of environmental concern. Therefore, in order to broaden the range of non-potable graywater reuse applications (e.g., laundry feed water, vehicle washing and dust control), while alleviating public health concerns, use of adequate treatment could be suggested in graywater regulations. Moreover, certification of graywater systems that meet regulatory standards could be more beneficial to homeowners than specific requirements of water quality standards. For example, the Australian New South Wales Department of Health provides certificates for accreditation of graywater treatment systems for irrigation, toilet flushing and cold water supply to washing machines [23]. Also, the National Sanitation Foundation (NSF) published a NSF/ANSI Standard 350: On-Site Residential and Commercial Water Reuse Treatment Systems for certification of graywater treatment systems that produce treated effluent suitable for non-potable applications [98]. Certification of graywater systems and/or technologies could encourage the development of low cost graywater systems, which will then expand this water reuse sector.

Residential homeowners should not be expected to have the capability of conducting detailed monitoring of treated graywater quality and treatment system performance as would be expected in centralized wastewater treatment facilities. For example, meeting strict requirements of water quality as set forth by California and Wisconsin (**Table 2.2**), for non-potable reuse application in residential homes would be extremely demanding for homeowners. Moreover, enforcement and monitoring of graywater reuse based on water quality criteria stipulated by California and Wisconsin will be a challenge. In this regard, homeowners would benefit from graywater reuse regulations or guidelines that provide guidance with respect to use of best treatment practices, as well as acceptable low cost water quality testing methods that could be carried out by homeowners.

Finally, no state policies require wastewater utilities to credit graywater producers/consumers for reducing the quantity of wastewater that must be treated by the sewerage system. Such a credit system may appear at first glance difficult to accomplish administratively. Most wastewater charges are calculated as multipliers on the quantity of water sold to a homeowner or business. However, the graywater permitting process represents an opportunity to calculate the quantity or percentage of wastewater diverted into the graywater system. The utility would then need only adjusts the household's wastewater multiplier in order to credit them on their bill for the cost-savings that the household provides the wastewater utility.

2.5 Closure

Review of graywater reuse regulations with respect to restrictions, definitions, reuse water quality criteria, types of reuse applications, treatment and storage requirements concerning onsite graywater collection, treatment and reuse in the United States suggests the existence of a number of impediments to overcome and possible key incentives for growth of this important water sector. Although regulations for promoting safe graywater reuse are provided by 29 States, inconsistencies between State plumbing codes and other State regulations (22 States) make implementation of graywater reuse a challenge and unnecessarily costly. While graywater is accepted as a separate wastewater stream by 41 States (three explicitly do not allow graywater segregation or collection), some disallow collection for areas serviced by centralized sewer systems, disallow segregation and/or collection, exclude kitchen graywater (5-10% of total indoor water use) or disallow a host of non-potable reuse applications (even with treatment). Graywater reuse is generally permitted for irrigation but is mostly restricted to outdoor subsurface irrigation (18 States) and/or indoor toilet flushing (7 States) with primary treatment. Graywater reuse applications for above ground irrigation and other non-potable outdoor or indoor reuse applications are generally disallowed. Restrictions on graywater reuse applications reduce the usable graywater reuse capacity and thus the size of the derived economic benefits.

Graywater reuse has been practiced over the centuries and will continue to be practiced (in many areas both in the US and around the world) whether regulated or not. In these times of increasing water scarcity and need to establish sustainable water use practices, it is imperative that the development of well-designed graywater reuse regulations and technologies are encouraged in order to ensure safe and responsible graywater reuse.

3 CRITICAL REVIEW OF GRAYWATER TREATMENT TECHNOLOGY FOR ONSITE RESIDENTIAL DEPLOYMENT IN THE UNITED STATES

3.1 Overview

World population growth has sparked interest in exploring alternative water sources that will foster water sustainability. Reduction of potable water demand through the use of water conservation devices is nearing plateau in the urban environments, therefore alternative measures are needed to further reduce potable water demand [99]. One such measure is to increase recycling of graywater at point-of-use (i.e. onsite), which is currently underutilized. Graywater is generally defined as domestic wastewater not containing toilet wastewater. Graywater accounts for up to ~75% of residential indoor water use depending on the level of water efficiency in individual homes [75, 100]. It has been argued that recycling graywater would reducepotable water demand by providing an alternative water stream for non-potable water uses, such as toilet flushing and irrigation[29, 101, 102]. Onsite graywater recyclingcan also promote water reuse in areas that do not have infracstructure to centrally produce and distribute reclaimed wastewater effluent[99, 103]. Given the above, onsite residential graywater recycling has the potential to become an important water reuse segment in both urban and rural areas[102, 104].

The requirements for onsite graywater treatment prior to reuse vary between jurisdictions, and depend on the purpose of non-potable reuse[27, 105]. For example, in California, graywater reuse for subsurface irrigation only requires screening to remove large filterable solids, while in Wisconsin treatment is required to remove suspended solids and degradable organics prior to such reuse [27]. Despite differences in regulations, it has been argued that grayater treatment for removal of organics would be beneficial from an environmental protection standpoint [33].

Additionally, provision for treatment and disinfection would remove pathegens [106, 107], which is crucial to safeguard public health.

Reuse of treated graywater (to secondary effluent quality, **Table 2**) for irrigation has been shown to have a negligible effect on irrigated soil pathogen diversity and quantity compared to using freshwater for irrigation [108]. Furthermore, irrigating plants with treated graywater has been shown to have no adverse impact on soil properties [95]. Residents who engage in graywater reuse can also benefit from graywater treatment that targets organic removal and thus reduces odor nuisance due to prolonged raw graywater storage [34]. Removal of total suspended solids (TSS), colloidal materials and degradable organics are also crucial for disinfection effectiveness[35] and thus safe for non-potable graywater reuse. It is noted, however, that deployment of advanced treatment systems in single-family homes without onsite operators in residential homes can be technically and financially challenging. Complex treatment systems have higher capital costs [28], which provide long or no return-on-investment making them economically unfavorable [109]. Chemical storage for certain types of treatment processes also posts additional safety concerns in residential homes.

Literature reviews of graywater treatment technologies have been focused primarily on the removal of organics and suspended solids [105, 110, 111]. Assessment of the impact of various technologies / systems on onsite residenital deployment has not been presented in previous reviews. For example, previous studies concluded that anaerobic biological processes are low-cost tretament opotions suitable graywater treatment [21, 105, 110]. However, these studies did not consider the health and safety risks associated with potential emissions of corrosive, toxic and odorous gases, such as hydrogen sulfide, methane, and volatile acids [35]. Given the above, there is a need to systematically review reported graywater treatment technologies with the goal of assessing their suitability and practicality for single residential deployment.

The present review focuses graywater treatment processes based on both performance and feasibility of deployment in single-family residential settings or small communities. The review also discusses the advantages and limitations of biological, physical and chemical treatment processes with respect to space, labor, and cost (capital and operational and maintenance (O&M)) requirements. The review aims to provide a framework for technology selection for residential deployment, as well as an assessment of research needs to advance the development of effective and affordable residential graywater treatment technologies.

3.2 Water quality, water reuse requirements for nonpotable water applications

Graywater is commonly defined as domestic wastewater not originating from toilets or urinals [19, 20, 112]. Indoor water use activities that generate graywater are handwashing, showers, bathing, laundry, dishwashing and other kitchen water use. The above activities account for up to 75% of the indoor wastewater flow [19, 20, 113]. The quantity of available graywater can also be affected by indoor water use habits and the use of water saving devices and appliances, such as water-efficient clothes washers. For example, water-efficient single-family homes produce ~30 L/day-capital less graywater than those less water-efficient older homes [113]. It is noted that kitchen wastewater is often excluded from the definition of graywater[27]. For example, in the United States, 36States exclude wastewater from kitchen sources in their graywater definitions [27].While kitchen graywater accounts for ~12 % of the total indoor water consumption in the US [16], in other parts of the world (e.g. the UK and India), kitchen water use (including drinking) can account for as much as 20-40% of the total indoor water use [105]. Exclusion of such a stream would reduce the reusable graywater quantity.

Contaminants in graywater can be broadly divided into three categories: (i)solids (e.g. food debris, hair and lint [19]), (ii) chemical (e.g. organics, total dissolved solids (TDS) [20]), and (iii) biological (e.g. pathogens [114]). Contaminant loading in graywater varies depending on the sources and the household products used. For example, kitchen graywater, in jurisdictions that consider this stream as part of graywater, is the major source for degradable organics, oil and grease, suspended solids (~43% of total graywater suspended solids [115]) and pathogens[20, 106] in graywater (**Table 3.1**). Graywater that does not contain kitchen sources has lower levels of suspended solids, organic, oil and grease, and pathogens [20, 106]. Additionally, ingredients in personal care and household products play an important role in graywater quality. For example, the use of potassium-based detergents could avoid salinization of soil when graywater is reused for irrigation; while bleach-free products should be used when biological treatment is used or when raw graywater is reused directly for irrigation [116]. Thus, it has been suggested that careful selection on household products and personal care products is important for graywater reuse with or without treatment [116].

Graywater reuse requirements vary depending on local, regional and national regulations [27, 117]. In the United States, the treatment requirement for nonpotable graywater reuse can range from primary treatment for large solid removal to disinfected tertiary treatment level (**Table 3.2**,[27]). Graywater reuse for non-spray irrigation usually requires the removal of suspended solids through primary treatment or secondary treatment to remove organics. Other aboveground nonpotable water applications, including spray irrigation, typically require treatment of graywater to disinfected tertiary levels, except for toilet flushing. Graywater reuse for toilet flushing requires treatment and disinfection to primary effluent quality; while

California is the only State that requires graywater to be treated to disinfected tertiary level for such a nonpotable reuse application [27].

Table 3.1 Average water quality parameters for graywater extracted from 29 literature publications

	Shower/ Bath[1]	Wash-basins	Laundry	Bathroom + laundry with baby diapers	Kitchen	Bathroom	Graywater, mixed
pH	7.4±0.3 (6.9-7.8)	7.4±0.4 (7-8.1)	8.9±1.1 (7.5-10.2)	--	7.2	7.4	7.3
Turbidity, NTU	46.5±27.2 (18.1-105)	102 (102)	108	--	99	58	427
TDS, mg/L	579±20 (559-599)	520 (520)	590	--	310	388	291
TSS, mg/L	109	109.3±87.8 (40-135)	97	--	323	81.1	316.6
BOD, mg/L	182.6±106 (59-424)	144.8±85.4 (57-252)	443.5	--	569.7	101.1	189.0
COD, mg/L	346.8 ± 186 (109-645)	298.5±113.3 (166-433)	1011	(150-250)	1,359.8	235.9	375.9
TOC, mg/L	105±11.9 (91-120)	87.5±47.5 (40-135)	235.5	(250-430)	408.0	38.0	145.9
NH4-N, mg/L	4±4.1 (0.9-11.8)	0.7±0.2 (0.4-0.9)	4.55	--	2.4	3.8	4.6
NO3-N, mg/L	2.3±3.4 (ND-7.5)	0.3±0 (0.3)	1.6	--	0.5	2.1	2
TN, mg/L	16.4±0 (16.4)	--	1.8	--	(40-74)	7.5	24.3
PO4-P, mg/L	3.1±3.4 (<1-10)	30.3±15.3 (15-45.5)	92.9	--	191.5	0.5	21.3
TP, mg/L	1.5±0.2 (1.3-1.6)	0.7±0.1 (0.6-0.8)	22	--	2.6	--	5.2
Cal^-, mg/L	225±59 (166-284)	237±0 (237)	262.3	--	469.5	--	281
Oil & grease, mg/L	120.5±43.5 (77-164)	135±0 (135)	146.9	--	325.5	--	193
E. Coli, CFU/100 mL	--	--	--	--	--	$4x10^6$	$4.6x10^3$
Fecal, CFU/100 mL	$2x10^6$±$2x10^6$ ($600-4x10^6$)	$1.8x10^3$±$1.7x10^3$ ($32-3.5x10^3$)	$2x10^6$	(10^4-10^6)	$6.3x10^5$	$8.2x10^4$	$3.1x10^7$
Total coliform, CFU/100 mL	$62x10^6$±0 ($6x10^6$)	$5x10^6$±0 ($5x10^4$)	$7x10^5$	(10^4-10^6)	--	$9.3x10^4$	$1.3x10^7$

Note: Values in parentheses are the range of values reported in the literature. Values were calculated from data extracted from the published literature: [1][20, 56, 65, 118-120], [2][20, 56, 120], [3][61], [4][19, 20, 56, 121, 122], [5][31, 56, 59-66], [6][20, 40, 44, 62, 64, 66, 123-131]

Table 3.2 The typical relationship between treatment levels, typical effluent quality and allowable reuse applications in the US

Treatment Levels	**Target Contaminants**	**Typical effluent quality** [35]	**Allowable graywater reuse applications** [27]
Primary	Suspended solids	TSS ≥ 30 mg/L BOD_5≥30 mg/L	Subsurface disposal, irrigation (not spray), toilet flushing[1]
Secondary	Organics, nutrients and colloids	TSS ≤ 30 mg/L BOD_5 ≤ 30 mg/L	Surface disposal and irrigation (not spray)
Tertiary	Fine suspended solids and colloids	Turbidity ≤ 2 NTU BOD_5 ≤ 10 mg/L	Above ground outdoor (including irrigation) and indoor non-potable water uses
Disinfected tertiary	Microorganisms	Total coliform ≤ 2.2 MPN/100 mL; *E. coli* = none	

Note: [1]with chlorine disinfection prior to reuse

3.3 Characteristics of onsite treatment systems for residential homes

The success and utilization of treatment systems for onsite residential graywater recycling must overcome constraints that are unique to this class of users. These constraints include cost, space, water quality (hence allowable water applications), and the level of difficulty operating and maintaining the treatment systems. Graywater treatment costs encompass infrastructure, capital, O&M, and building retrofits. In new construction, retrofitting cost can be reduced if local building codes are amended to that ensure appropriate plumbing is installed in new constructions or major renovation projects. Capital, O&M and infrastructure costs are obstacles that hinder wide adoption of onsite graywater treatment [132]. Thus, treatment systems that have low capital and O&M costs and can produce effluent of high quality are expected to have higher utilization even in developing regions [132, 133].Onsite treatment systems should be robust with long service life time and ease of maintenance so as not to be overly burdensome to homeowners [134]. Accordingly, desirable attributes for evaluating the suitability of onsite graywater treatment systems for onsite deployment are proposed (**Table 3.3**) consistent with the criteria residential emergency water treatment systems [135].

Table 3.3 Assessment criteria for graywater treatment systems for onsite residential deployment

Attributes	Rating and definitions
Capital cost	**Low**: < \$2,000 per household[1] **Medium**: >\$2,000, <\$6,000 per household[1] **High**: >\$6,000 per household[1]
Footprint	**Small**: smaller than a double door refrigerator **Medium**: between a double door refrigerator and a four-door sedan car. **Large**: Greater than a four-door sedan car
Water quality prior to disinfection	**Primary** level[2] **Secondary** level[2] **Tertiary** level[2] **Microbial-free tertiary** level[2]
Ease of deployment[3]	**Difficult**: large and >50lbs, require construction and assembly of the whole system onsite or require relatively extensive assembly of parts of the systems **Moderate:** Moderately large and >50 lbs.[4]; require some simple set-up setup **Easy**: <50lbs and small sized; require some simple materials for set-up
Ease of use[3]	**Difficult:** Complex process design; can only be operated by skilled operators **Fairly difficult**: Difficult to operate by unskilled personnel; require proper chemical dosage. **Moderate**: Require some simple onsite training to user **Easy**: No special training is necessary
Treatment time[3]	**Long**: > 8 hours **Moderate**: >1 to <8 hours **Short**: < 1 hour
Ease of Maintenance[3]	**Difficult**: Complex maintenance by trained technicians; done regularly; time consuming **Moderate**: Slightly complicated maintenance activities; done regularly **Simple**: Maintenance done occasionally; can be carried out by homeowners; not time consuming **None**: No maintenance required
Energy requirement[3]	**High**: Use>2.8 kWh/m^3(5) **Moderate:** Use < 2.8 kWh/m^3(5), but >1.3 kWh/m^3(6) **Low**: Use <1.3 kWh/m^3 (6); can be powered by onsite renewable energy or standard voltage rating used in residential homes **None**: No energy required
Flexibility to handle no flow	**Inflexible**: Flow must be maintained to avoid treatment performance loss **Moderately inflexible:** Maybe able to accommodate a day or two without flow, system must be maintained in operational mode or special arrangement must be made for system turn off to avoid key component damage **Flexible**: System can handle extended period of no flow without causing treatment performance loss or system component damage
Length of startup period	**Long:** >1 weeks **Moderate** : > 1 day but <1 week **Short**: < 1 day **None:** no startup period

Note: [1]Household with three residents; [2]Water quality is presented in **Table 2**; [3]Adapted from [134], [4]Recommended maximum lifting weight for men [136].[5]Energy required for municipal drinking water and wastewater conveyance (including import and distribution) and treatment [109], [6]Energy required for conveyance and treatment of municipal wastewater [109]

3.4 Onsite Graywater Treatment

3.4.1 Physical Processes

Physical processes involve separation of solid contaminants from graywater by physical means without the addition of chemicals. Screening, sedimentation, flotation, granular and membrane filtration have all been used for treatment of graywater (**Fig. 1**).Physical treatment processes, except for flotation, are effective for capturing suspended solids, and even down to colloidal particulate and bacteria size using membrane filtration. Screening, sedimentation and sand filters are effective in capturing large particles, but they are less effective for removal of turbidity associated with colloidal particles (e.g. colloids of ~<0.18 µm accounts for 90% of the total number of particles [44, 126, 137]), and removal of dissolved organics and oil and grease in graywater. Oil and grease, commonly found in kitchen graywater, can be removed using oil traps, which use flotation to separate oil from the water to prevent clogging screens, and damaging sand filters [116] and membranes [138]. A summary of technology assessment of physical treatment processes discussed above (screening, sedimentation, media filtration and membrane filtration) is presented in **Table 3.4**.

Kitchen sinks, showers and bathroom sinks, and laundry account for ~44%, ~23% and ~17% of total suspended solids (TSS) in graywater, respectively [115, 139]. Large suspended solids can be effectively removed by screening, sedimentation and media filtration, yielding primary effluent water quality [53, 102, 140]. The use of a grease trap and sedimentation tank with baffles allow removal of oil and grease by flotation from graywater in addition to large solids removal [116]. Primary effluent may contain significant amount of organics, which can cause odor during storage[34] and thus odor control / elimination is critical for public acceptance of graywater reuse [141]. During storage, odor can be prevented by aeration [34, 121] and chlorination [140]. However, organics in primary treated graywater increase chlorine demand [142], and as much as 75 mg/L of chlorine dosing has been used for chlorination of primary treated graywater for toilet reuse in Spain [140]).

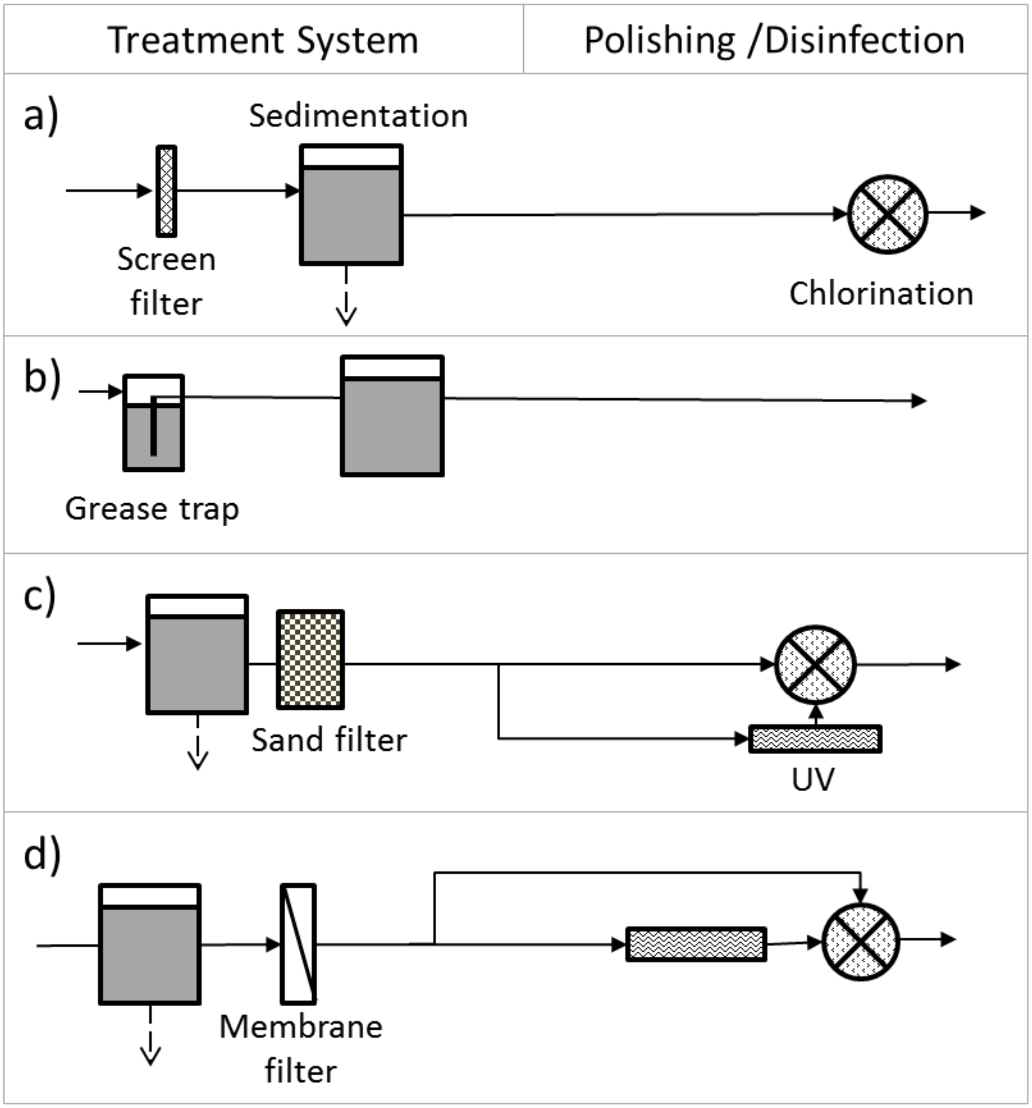


Figure 3.1 Typical physical treatment processes for graywater treatment. a) screening followed by sedimentation and chlorination [140], b) grease trap followed by sedimentation[116], c) sedimentation followed by sand filtration [102, 143], d) sedimentation followed by membrane filtration and disinfection [125, 144]

Maintenance of simple graywater systems requires regular cleaning of solids accumulated on screens, media filters, and in sedimentation tanks, as well as oil and grease in grease traps to avoid fouled solid accumulation. It has been reported that the time required for servicing a screen and sedimentation tanks is about 2.5 mins/m^3 water treated [140]. Although these cleaning activities are simple, residents might find them unpleasant [116]. Relative to cleaning of screens, media filtration often requires more frequent maintenance in order to prevent clogging. It has been estimated that a sand filter clogs after 5 to 8 hours of run time with hydraulic load of 3–4m^3/m^2–h and TSS load of 4,500 g/m^2–d [143]. Cleaning of sand filters can be achieved by automated backwash [145], or manual scraping of the cake layer and washing off fouled materials on sand [146]. Given sand filters' tendency to clog, screening and sedimentation are preferred for pretreatment of graywater prior to sand filtration or other subsequent treatment [61]. The maintenance requirement for sand filtration is expected to lower when used as post-treatment for chemical and biological processes[35]. Automation of filter media backwash is expected to be more convenient and less burdensome than manual filter cleaning for residential home owners despite its high cost ($5,000 /single-family home unit [145].

Direct membrane filtration using microfiltration (MF), ultrafiltration (UF) and nanofiltration (NF)) is the only physical treatment process that can achieve higher water quality (secondary or tertiary levels) for graywater reuse. A typical treatment arrangement for membrane filtration is presented in **Fig. 3.1**. Direct membrane filtration provides excellent turbidity and microorganism removal for graywater treatment. Permeate turbidity from membrane filtration using MF, UF and NF can usually be<2 NTU level for treatment of showers, bathroom, laundry, kitchen, and mixed graywater[63, 100, 121, 125, 137] meeting the turbidity requirement for tertiary treatment. Furthermore, complete removal of pathogens such as fecal coliforms and enterococcus before disinfection is another added advantage of direct membrane filtration [63].

Organics removal by membrane filtrations vary depending on the membrane pore size. Nanofiltration (NF) membranes provide high COD rejection of >90% [63, 137]; while microfiltration (MF) and ultrafiltration (UF) membranes typically achieved lower organic removal (40-75%)[58, 121, 125, 144, 147]. NF achieves high organics removal but requires high transmembrane pressure (TMP) in the range of 600 - 4,000kPa [63, 137, 148]. Operation at high TMPs was reported to cause rapid irreversible membrane fouling and high-energy consumption [63, 137]. It has been estimated that the energy required for operation and liquid waste generated from membrane cleaning of 4.5 m^2 NF tubular membrane module with 3 m^3/day treatment capacity would be 11.7 kWh/m^3 and 0.8 m^3/chemical clean, respectively [63].

MF requires lower TMPs (98 – 120 kPa [121, 125]) than UF membranes (100-500 kPa [58, 125, 137, 149]). Pore size of and TMP difference for MF and UF membranes have little impact on organic removal [125, 137]. Formation of cake layers on MF facilitates higher filtration stability with higher flux than UF membranes [125]. In contrast, permeate flux decline in UF treatment of graywater with up to 80% over three days of operation even with membrane backwash every 30 minutes was reported [147]. The need for frequent backwash and chemical cleaning increases operational costs, accelerates polymeric membrane degradation and hence leads to higher membrane replacement cost. Moreover, the use of automation control system also increases maintenance complexity and capital cost.

A summary of technology assessment of physical treatment processes discussed above (screening, sedimentation, media filtration and membrane filtration) is presented in **Table 3.4**. The main advantages of physical treatment processes are that they require little or no startup time and thus can be reliably used for intermittent treatment of graywater in residential settling. Screening and sedimentation are the most cost-effective treatment options if graywater reuse only requires solid removal or as pretreatment method for other treatment processes. Standalone sand filtration is the least favorable treatment method for treating raw graywater due to its high maintenance requirement [143](**Table 3.4**). Direct membrane filtration can achieve significant organics (e.g. NF) and turbidity (e.g. MF, UF and NF) removal, but high capital and O&M costs make this approach economically unfavorable for residential graywater treatment. However, treatment performance of MF and UF membrane filtration can be enhanced by reducing their fouling propensity through coupling the membrane process with biological and chemical processes as discussed in **Sections 3.4 and 3.5**.

Table 3.4 An assessment summary of graywater physical treatment technology

	Screening	Sedimentation	Flotation	Media filtration	Membrane filtration
Capital cost	Low	Low	Low	Medium	Moderate to High
Footprint	Small	Large	Small to medium	Medium	Medium
Water quality	Primary	Primary	Pretreatment	Primary	Microbial-free secondary to tertiary
Ease of deployment	Easy	Moderate	Moderate	Difficult	Moderate
Ease of use	Easy	Easy	Easy	Moderate	Moderate to fairly difficult
Treatment time	Short	Moderate to long	Short	Short	Short
Ease of Maintenance	Simple	Moderate	Moderate	High	Moderate to difficult
Energy requirement	None-low	None	None	None to low[1]	Moderate to high
Flexibility to handle without a base flow	Flexible	Flexible	Flexible	Flexible	Flexible[1] to moderately inflexible[2]
Startup period	None	None	None	None	None

Note: [1] ceramic membranes, [2] polymeric membranes

3.4.2 Chemical Processes

Chemical processes that have been evaluated for graywater treatment include chemical coagulation/flocculation[147], dissolved air flotation[150], ion exchange[65],chemical oxidation using chlorination[147], electrocoagulation[126] and advanced oxidation processes (AOPs) [151]. The target contaminants and removal mechanisms are different among these processes. For example, coagulation processes mainly facilitate physical aggregation of particulates to enhance turbidity removal (**Fig. 3.2**); while ion-exchange, chemical oxidation and AOPs facilitate the removal of dissolved contaminants (**Fig. 3.3**). A summary of the treatment assessment for chemical treatment processes is presented in **Table 3.5**.

Coagulation/flocculation is a treatment process involving direct coagulant addition and mixing in graywater to facilitate particulate aggregation and precipitation to form flocs. The aggregated flocs can then be removed by sedimentation[58, 65], media filtration [58, 143], membrane filtration[147], or dissolved air flotation [150]. Typical coagulants used for graywater treatment are aluminum sulfate, ferric sulfate [65], ferric chloride [147] in acidic to mildly acid conditions (pH 4.5 – 6.5). It has been reported that the mixing and settling time varies in the range of 30 - 95 minutes for graywater treatment in commercial buildings [65, 147]. Coagulation / flocculation with sedimentation followed by sand filtration was reported to provide good turbidity removal for treatment of commercial building graywater (e.g. up to 92% for mixed graywater source with influent turbidity of 50 NTU [143]) but was less effective for organics with removal of 57% BOD_5 (effluent BOD_5 of 44 mg/L) and 65% COD (effluent COD of 63 mg/L) [143]. It has been shown that the use of granular activated carbon (GAC) filtration is effective for further reduction of laundry graywater BOD_5 and COD by 95%and 93%, respectively, and anion surfactant removal of >95% (as compared to <1% without the use of GAC) [58]. Coagulation / flocculation has also been demonstrated to enhance the effectiveness of UF membrane filtration for treatment of bathroom graywater with permeate quality achieving tertiary effluent water quality (~8.4 mg/L of TOC and ~1 NTU of turbidity, [147]). Coagulation also reduced membrane fouling by increasing graywater aggregate particle size [147].

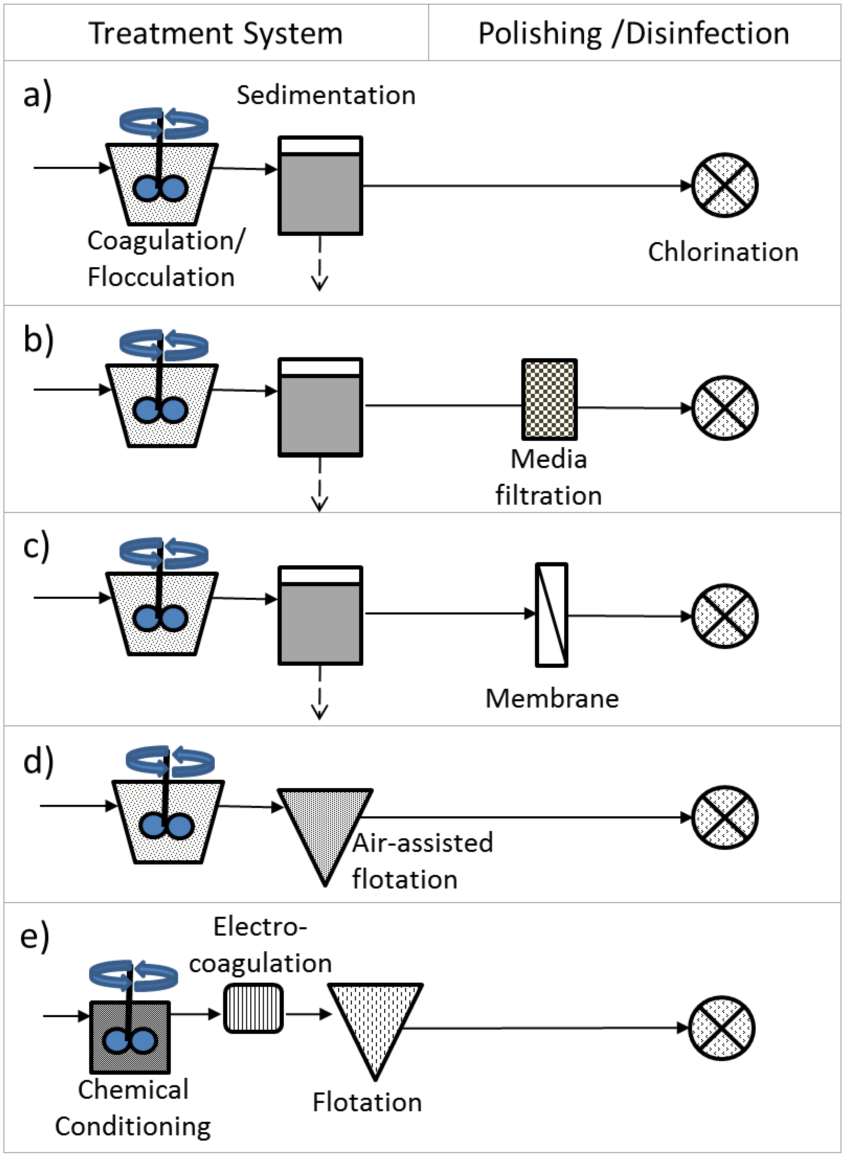


Figure 3.2 Chemical processes that target removal of particulates have been used for graywater treatment. a) coagulation/flocculation followed by sedimentation[143], b) coagulation/flocculation followed by sedimentation and media filtration [58], c) coagulation/flocculation followed by sedimentation and membrane filtration [147], d) dissolved air flotation[152], e) electrocoagulation[126]

Electrocoagulation is an electrolysis process where coagulant is released into the water through sacrificing an aluminum anode in chamber; while gas-assisted aeration takes place at the cathode as hydrogen gas releases in another chamber (**Fig. 3.2e**). It has been used for treatment of office building graywater [126], and was reported that the system achieved effluent turbidity of 3.6 NTU (92% removal), TSS of 9 mg/L (69% removal), BOD_5 of 9 mg/L (60% removal) and COD of 22 mg/L (60% removal). The treatment process was also reported to be effective in removing pathogens, achieving 100% E. coli removal [126]. However, it is unclear whether the observed germicidal effect was a result of the electrolysis process or a result of 1 M sulfuric acid used for pre-conditioning the graywater to increase conductivity. The challenge of utilizing electrocoagulation is the lack of fundamental understanding of the treatment kinetics, which makes system scale-up and optimization difficult [153]. Additionally, the need for hazardous chemical storage and potential fire hazards associated with hydrogen gas emission poses further limitations to widespread use.

Chemical oxidation using chlorination processes followed by membrane filtration, ion-exchange processes, and AOPs has also been evaluated for graywater treatment (**Fig. 3.3**). Chemical oxidation using a strong oxidant (e.g., hypochlorite) prior to membrane filtration was shown to cause more membrane fouling and adversely affect treatment performance (**Fig. 3.3a**, [147]). Chemical oxidation breaks down large organic molecules to form smaller molecules, which intensifies membrane fouling and increases passage of small and more readily degradable organics through the membranes [147]. As a result, higher permeate TOC of 14 mg/L was detected with chlorination as pre-membrane filtration treatment as compared to 8 mg/L TOC without the use of chlorination or 7mg/L TOC with the use of coagulation [147].

Ion exchange involves removal of charged ions from a solute onto an insoluble exchange material by displacing ions from the exchanger [35]. The use of magnetic ion-exchange (MEIX) resins has also been evaluated but shown to be unfeasible for graywater treatment even with the aid of coagulant (aluminum sulfate) at low pH (4.5) [65]. Another process that has not been demonstrated with success is the use of advanced oxidation processes (AOP, **Fig. 3.3c**) to generate hydroxyl free radicals for removal of organics in graywater [65, 139, 151]. These AOPs used either TiO_2 [65, 151][94, 95, 101] or hydrogen peroxide [139] as photocatalysts to generate free radicals by exposing to UV light for graywater treatment. The UV/TiO_2 process could not remove sufficient organics and turbidity to meet tertiary effluent water quality even at high TiO_2 dosage (5 g/L) and long UV exposure time (>2 hours) [65, 151]. Also, UV transmittance in water was sensitive to the solid photocatalyst concentration with TiO_2 above 0.1g/L was reported to hinder the generation of free radicals in regions away from the UV lamp surface [65]. The UV/H_2O_2 system avoided the UV transmittance issues associated with the UV/TIO_2 system. However, the UV exposure time required for the UV/H_2O_2 system was still long (5 hours) in order to produce effluent BOD_5 of 15mg/L (~80% removal) at pH 10 [139]. High energy consumption required for UV irradiation (e.g. UV dose at 54,000 mJ/cm^2 required for typical AOP processes [154]) and the need for hazardous chemical storage make AOP processes impractical and economically unfeasible for residential graywater treatment.

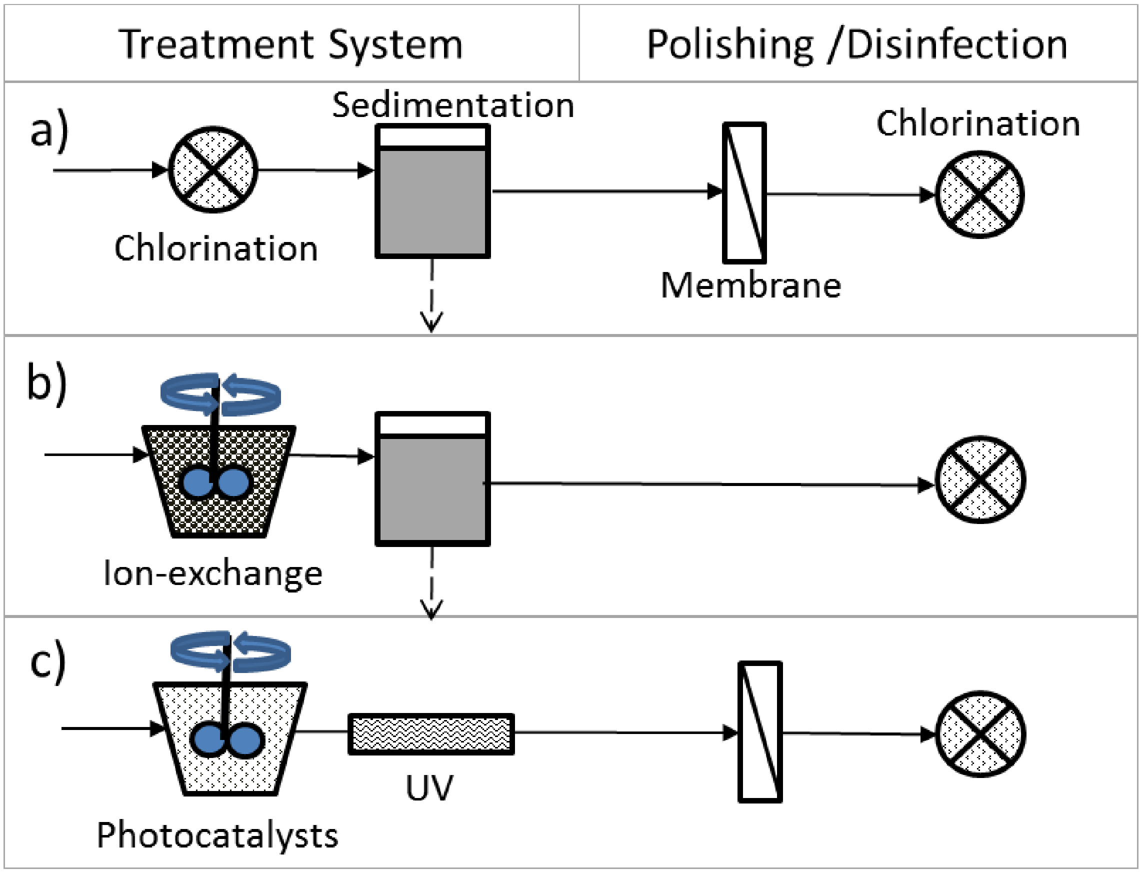


Figure 3.3 Graywater chemical treatment processes that target removal and destruction/degradation of dissolved contaminant. a) chemical oxidation using chlorine followed by sedimentation and membrane filtration[147], b) ion exchange processes followed by sedimentation[65], c) photocatalysis followed by membrane filtration[151, 155]. Note: In all the indicated approaches the feed is first treated by screening and sedimentation

Table 3.5 Assessment of chemical processes used for onsite residential graywater treatment

	Coagulation / flocculation with media filter	Coagulation/ flocculation with membrane filtration	Dissolved air floatation	Electro-coagulation	Chemical oxidation with membrane	Ion exchange with settling	AOPs with membrane
Capital cost	High	High	High	High	High	High	High
Footprint	Medium to large	Medium	Small to medium	Medium to large	Medium	Large	Large
Water quality	Primary	Tertiary	Primary	Secondary	Primary	Primary	Primary
Ease of deployment	Difficult	Moderate to difficult	Moderate to difficult	Difficult	Moderate to difficult	Moderate to difficult	Medium to difficult
Ease of use	Fairly difficult to difficult	Fairly difficult to difficult	Fairly difficult to difficult	Fairly difficult to difficult	Fairly difficult to difficult	Fairly difficult to difficult	Fairly difficult to difficult
Treatment time	Short	Short	Short	Short	Short	Moderate	Moderate
Ease of Maintenance	Difficult	Difficult	Difficult	Difficult	Difficult	Difficult	Difficult
Energy requirement	Moderate	Moderate to high	Moderate to high	High	Moderate to high	Moderate	High
Flexibility to handle no flow	Flexible	Flexible[1] to moderately inflexible[2]	Flexible	Flexible	Flexible[1] to moderately inflexible[2]	Flexible	Flexible[1] to moderately inflexible[2]
Startup period	None						

3.4.3 Biological treatment processes

Biological treatment processes have been used for graywater treatment to remove organics, suspended solids, and turbidity. These include suspended and attached growth processes that were operated in aerobic, anoxic and anaerobic conditions in batch or continuous flow modes. Aerobic biological processes have been demonstrated to be effective for organics removals in graywater, achieving BOD and COD removal of greater than 90% [38, 42, 156]. The inclusion of anoxic and anaerobic conditions into aerobic biological processes has been shown to improve sludge settling characteristics and nutrient removal (e.g. NO_3^{2-} and PO^{4-}) [124, 130]. The main disadvantage of biological processes are the need for aeration where it can account for up to 84% of the energy consumption in small scale onsite biological treatment systems [157].

Biological treatment processes that do not required aeration through diffusers have also been evaluated, including rotating biological contactors and anaerobic treatment processes.

Aerobic Suspended Growth Biological Processes

Activated sludge (AS, **Fig. 3.4a**), sequential batch reactors (SBRs, **Fig. 3.4b**), and membrane bioreactors (MBRs) are aerobic suspended growth processes that have been evaluated for graywater treatment. AS and SBR processes that rely on biomass settling to achieve solid-liquid separation are particularly challenging to operate [35]. AS processes require onsite operators because they are more complicated to operate compared to other suspended growth treatment processes. Although their use in graywater treatment has been demonstrated to be successful, their deployment are limited to large-scale system, such as in a large remote village [158]. The use of SBRs and MBRs are far more common for deployment in urban areas for onsite graywater treatment, such as in commercial buildings [124, 156] or in a single-family homes [159].

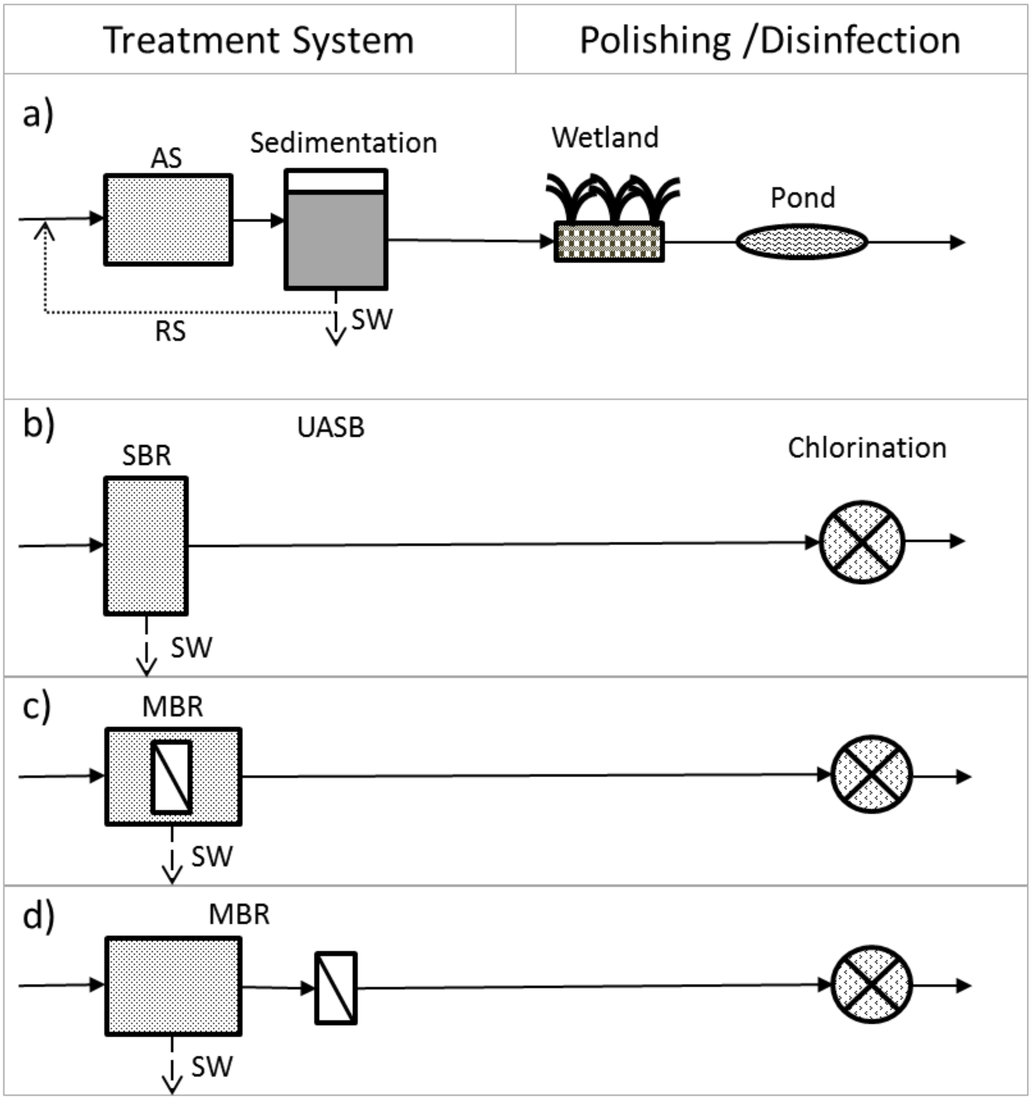


Figure 3.4 **Aerobic suspended growth biological processes reported for graywater treatment. a) Activated sludge processes followed by a wetland and a pond[158], b) Sequential batch reactors (SBRs) followed by chlorination[159], c) Submerged MBRs, d) side-stream MBRs[57].**

A SBR consists of one reactor for aeration and sludge settling to take place. The absence of inflow and outflow during treatment in SBRs allows for simpler reactor design and the use of relatively simple timer-based process control systems, and thus are less expensive compared to continuous flow processes (e.g. AS). SBR effluent quality can be affected by poor settling sludge and over withdrawal of supernatant from the reactor. SBR performance for graywater treatment has been laboratory evaluated in a number of studies [122, 160]. Effluent produced by laboratory SBR systems for treating mixed graywater exceeded the secondary effluent quality standard (**Table 3.2**) with effluent BOD_5 of 37 mg/L and TSS of 9-45 mg/L [122, 160]. High effluent turbidity (<19 NTU [122]) is also another shortcoming of SBRs. Although it is not validated in the peer-reviewed literature, commercial SBR systems for graywater treatment in single-family homes are claimed to achieve greater BOD (<20 mg/L) and TSS (<20 mg/L) [159] levels compared to the above laboratory SBR systems [122, 160]. The cost of a commercial single-reactor SBR system (with built-in chlorinator) that has a treatment capacity of 1 m^3/day is relatively high ($9,000/system [159] with an average daily energy consumption of ~1.6 kWh/day [159].

A membrane bioreactor (MBR) consists of an aeration tank and a membrane module for liquid-solid separation. The use of membranes in MBRs eliminates poor effluent quality issue resulted from poor sludge settling and the need for clarifiers, hence enable compact system size [161]. Membrane modules in a typical MBR system can either be submerged in the aeration tank (submerged MBR, **Fig. 3.4c**) or be installed as an external unit (side-stream MBRs, **Fig. 3.4d**). Submerged membrane systems generally have higher capital cost and larger system footprint, but have low operational and maintenance costs compared to side-stream systems [162]. The most distinctive advantage of using membrane filtration in biological graywater treatment systems is their ability to retain pathogens in the reactor from treated effluent [35], which in turn provides another barrier in addition to disinfection. Given this advantage, MBRs are the most studies suspended growth biological treatment processes for graywater treatment.

MBRs can be operated in continuous-flow and batch modes for graywater treatment. The use of batch operation in graywater treatment enables for creation of anoxic, oxic, and anaerobic

(AOA) conditions in the same reactor by simply control the air supply in the aeration tank to enhance nitrogen removal (e.g. complete nitrification and denitrification) [124, 156, 163]. MBRs operated in either continuous-flow and batch modes have been shown to be highly effective for graywater treatment with effluent quality of tertiary quality [62, 118, 123, 124, 156, 164-167] and pathogen count of below detection limits in permeate prior to disinfection [62, 123, 163].

The use of membrane helps to maintain high effluent water quality, but proper operation of the biological reactors have been shown to be important for graywater treatment. For example, high organic loading rate (9.2 to 12.7 kg COD/m^3-day), insufficient treatment time (HRT <2 hr) and short biomass retention time (SRT <1 d) can lead to poor effluent quality in MBRs used for graywater treatment [128]. Also, long SRT (48 days [164] to greater than 360 days [166]) is desirable as compared to shorter SRT (15-20day) [59] when MBRs are aerated continuously for graywater treatment. It has also been reported that shorter SRT (10-20d) does not seem to affect treatment performance in MBRs that are aerated intermittently for graywater treatment [130]. High biomass concentration in MBRs that used for graywater treatment (mixed liquor suspended solids (MLSS) of >10,000 mg/L) does not appear to shorten hydraulic retention time (14-24 hr) ([57, 168]). Lower MLSS between 1500-3000 mg/L in batch operation [156] and 3000-4500 mg/L in continuous flow operation [130] have been shown to achieve lower effluent organic levels (COD of <15 mg/L) for graywater treatment. The daily energy consumed by small-scale MBR systems for onsite graywater treatment is quite high with reported range of between 2.8 and 3.4 kWh per day [30]. These observations suggest that further optimization of the aeration to lower energy demand would be important for future development of graywater MBR systems.

Transmembrane pressure (TMP) used to drive water through the membranes is another energy intensive processes in graywater MBRs. Graywater MBRs operated at high TMPs (e.g.

100-300 kPa) produce higher permeate flux (38-70 L/m^2-hr) to increase treated water productivity [57, 59, 121]. However, high TMPs can result in higher permeate COD (up to 110 mg/L COD) and TSS concentrations (up to 15 mg/L TSS) [57, 59, 121], as well as exacerbate irreversible membrane fouling [162]. Even though lower TMPs produces lower permeate flux (e.g. only 3 to 22 kPa to produce 6-25 L/m^2-hr [118, 164, 165, 168] and result in the use of higher membrane areas to produce the same flux. However, using lower TMPs also lowers membrane fouling. Lower TMP approach is especially favorable in places where electricity cost is high.

Membrane fouling is controlled by membrane cleaning, thus more severe fouling typically results in higher cleaning costs. Side-stream MBR systems used for graywater treatment systems have been reported to require more frequent and aggressive cleaning strategy than submerged MBR systems. The side-stream graywater MBR system required air backwash every 20 minutes for 10 seconds and periodic chemical cleaning with 1N NaOH solutions in order to maintain desirable permeate flux [124]. Submerged graywater MBR systems have been reported to have lower cleaning requirements. For example, air scouring has been reported to be sufficient to maintain steady flux in plate-and-frame membranes [156]; while occasional backwash and chemical cleaning is required for submerged MBR systems with hollow fiber, tubular and spiral wound membranes used for graywater treatment [59, 118, 164, 165]. Based on the observation reported, submerged plate-and-frame MBRs are expected to have lower membrane cleaning requirement compared to side-stream MBR systems as well as submerged MBR systems using other membrane configuration for onsite graywater treatment.

Aerobic Attached Growth Biological Processes

Aerobic attached-growth biological processes have evaluated for onsite graywater treatment in large residential buildings [60, 61, 66, 127, 169, 170] and university dormitory [56]. These processes differ from suspended-growth processes because organics-degrading microorganisms grow on fixed surfaces of solid media [35]. The transport of substrate, nutrients and dissolved oxygen (DO) or other electron acceptors (e.g. NO_x and SO_4^{2-}) is governed by diffusion through the biofilm. These processes still require sufficient aeration but are less susceptible to shock loads compared to suspended growth processes. Biofilm thickness is controlled by changing hydraulic and organic loading rates through effluent recycling to induce more biofilm washed off from media and induce endogenous biomass decay, respectively [35]. Sludge washed off from the biofilms have better settling characteristics [35]. Thus, clarifiers [60, 61] or granular media filtration [56, 59] have been used as a post-treatment to polish graywater effluent. A more compact aerobic attached growth design can be achieved using membrane filtration. Such an approach has been commercialized, although detailed field performance data is yet to emerge [138].

Rotating biological contactors (RBC) and trickling filters are two key non-submerged attached growth processes. RBCs (**Fig. 3.5a**) is the primary non-submerged attached-growth processes that have been evaluated extensively for graywater treatment [60, 61, 127, 149, 169]; while a batch trickling filter system has been commercialized for onsite graywater treatment [138]. The main difference between RBCs and trickling filters is that the media in the former remain rotating while the latter are stationary [35]. In trickling filter treatment, graywater is delivered to the top of a filter tower and is distributed over the filter media. Aeration takes place through air entrainment into the trickling water films. The treatment performance is governed by the hydraulic loading rate, portion of effluent recycle to the top of the tower, and total media surface area. Treatment capacity can be expanded by increasing the depth of the filter bed without increasing the system footprint. The performance of trickling filters for residential graywater treatment has not been reported in literature. However, It has been claimed that trickling filter treatment followed by hollow fiber membrane filtration and UV disinfection could meet tertiary effluent quality requirements [171].

RBCs typically consist of plastic disks or rotating wheels with packing that are supported by shafts over a basin (**Fig. 3.5a**) [35]. The shafts are rotated to provide alternating exposure of the surfaces covered with biofilms to water and air. Aeration occurs when the plastic media on the wheels leave the water and are exposed to air. Oxygen transfer coefficient increases with rotational speed [172]. The treatment process requires tapering of the surface area from high area per volume of flow at the inflow of the process to lower area per unit volume at the outflow to the process. The hydraulic retention time decreases as water flows downstream through the treatment process. RBCs were evaluated for treatment of graywater in buildings ranging from an apartment building with seven units to a hotel that had 400 guests [31, 60, 170]. These systems used two to four RBC units staged in series [31, 60, 170]. A single RBC system with 0.4 m^3/day that used clarifiers as post-treatment was shown to achieve >90% BOD removal [127]. Sand filtration has been used as the final polishing step before UV or chlorination disinfection, which was shown to be sufficient to achieve tertiary effluent water quality[59, 170]. RBCs can achieve consistent treatment performance even with graywater influent water quality fluctuation [59, 61]. Based on the experience learned from municipal wastewater treatment, RBCs are also less energy intensive than other biological treatment processes consuming about 25% and 70-80% of the energy required for activated sludge and biological aerated filters, respectively [172].

Submerged Attached Growth Biological Processes

The use of biological aerated filters (BAFs) for graywater treatment (**Fig. 3.5c-e**) has been evaluated in the laboratory and commercialized as onsite residential graywater treatment systems. A single-stage downflow fixed bed biofilters [173, 174] and a two-stage fluidized-bed SBR in-series (**Fig. 3.5d**) [175] have been developed as commercial graywater treatment systems. Post-treatments used for these systems include clarifiers followed by chlorination [173] or UV disinfection [175], and sand filtration with UV disinfection [174] with the effluent claimed to meet tertiary effluent water quality standard. Energy demand of these commercial treatment systems was reported to be about 3 kWh/m^3 by manufacturer [175].

BAF systems with structure media have also been evaluated for graywater treatment [56, 176]. Two pilot systems utilized a combination of up-flow anaerobic fixed bed filters followed by down-flow aerobic filters. In one system, reticulated foam was used as growth media. The system achieved good organic removal with effluent turbidity of 1.1 NTU and BOD of 0.5 mg/L [56]. Reticulated foam provided large surfaces for biofilm growth, however, it could not be backwashed, thus periodical replacement of clogged foam was necessary [56]. Anaerobic and aerobic biofilters made of spherical reticulate plastic filter media and plastic sheet media, respectively, were also evaluated for treatment of mixed graywater [176]. Sedimentation for removal of large suspended solids was the first graywater treatment step followed by sequential anaerobic-aerobic biofilters. Sludge was removed in a clarifier, and then returned to the biofilters. The system achieved effluent BOD of 7.8 mg/L and TSS of 5.9 mg/L [176]. The effluent was then disinfected using solid chlorine tablets prior to reuse.

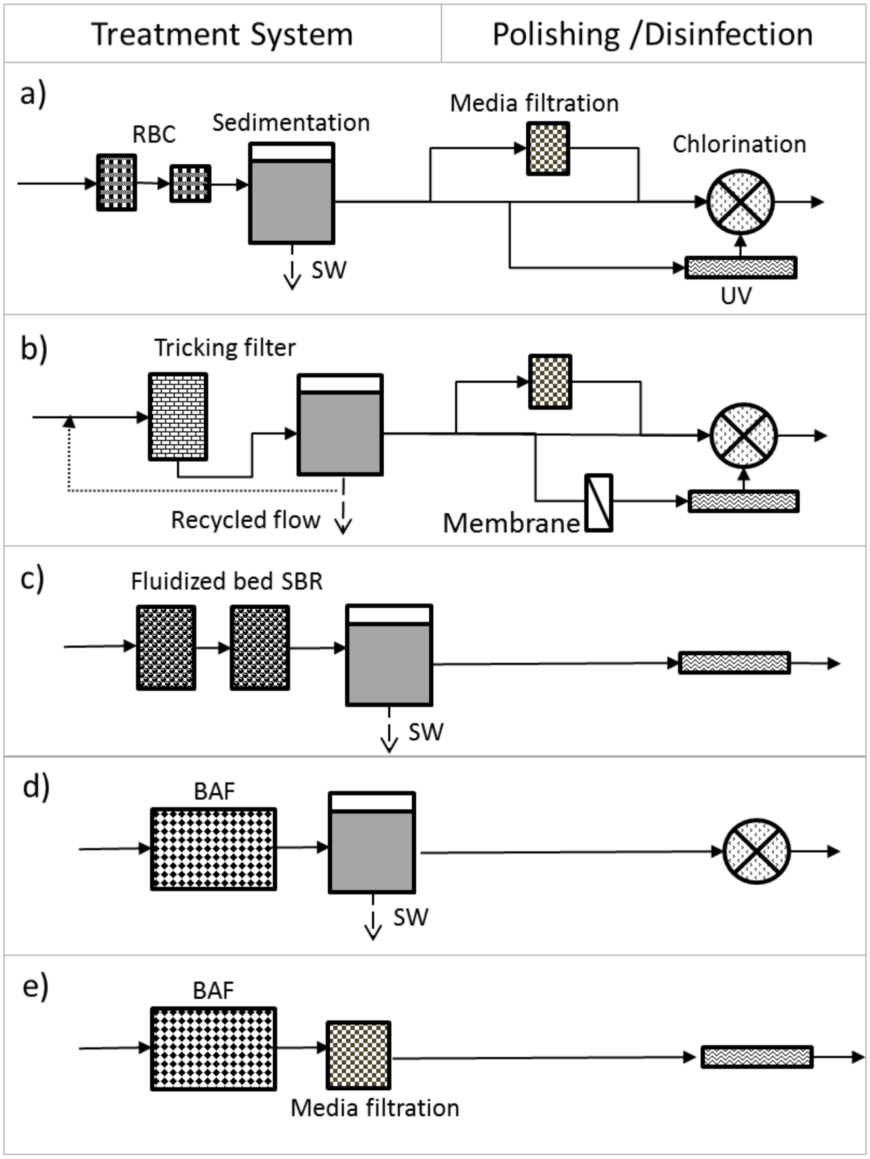


Figure 3.5 **Aerobic attached growth biological treatment processes that have been used for graywater treatment. a) Rotating biological contactors (RBC) with different post treatment methods, b) trickling filters with different post treatment, c) Fluidized bed, d) biological aerated filter (BAF) followed by a clarifier and chlorine disinfection, e) BAF followed by a media filtration and UV disinfection**

Anaerobic Suspended Growth Biological Processes

Anaerobic processes are low cost and can be low maintenance treatment processes because they do not require aeration and control of biomass concentration through sludge wasting [177]. Furthermore, anaerobic processes are able to degrade certain organic compounds, such as xenobiotics, that are otherwise difficult to degrade in aerobic processes even after acclimation [35]. However, anaerobic processes require long startup period, long treatment time and are not effective as a standalone process for graywater treatment [178-180]. For example, upflow anaerobic sludge blankets (UASBs) have reported COD removal efficiency between 0 to 64% after 16 hours of treatment [180, 181]. Septic tank treating bathroom and kitchen graywater produced poor effluent (effluent COD of 366 mg/L and TSS of 162 mg/L [112]). Given the poor water quality, the use of septic tanks for gray water treatment is not recommended except in cases where there is no interest in reclaiming the gray water, and effluent disposal in leach fields is feasible. Anaerobic treatment processes can potentially be used as pretreatment for aerobic treatment [105], but the release of corrosive and odorous gases such as methane and hydrogen sulfide must be avoided.

Biological Treatment Assessment

Based on the above discussions, a summary of the assessment of the biological processes used for graywater treatment is presented in **Table 3.6**. Aerobic biological processes are highly effective for graywater treatment producing high effluent quality. MBRs are expected to have high energy demand for aeration as well as to provide transmembrane pressure needed to produce permeate flux. Another energy intensive process is BAFs where higher rating blowers may be needed in order to generate sufficient pressure to ensure air bubbles can reach the tightly packed plastic media. RBCs and trickling filters are two less energy intensive aerobic processes that are viable for graywater treatment, which make them more economical and viable for onsite residential deployment. Extended period of idling of aerobic biological treatment systems is not feasible as biomass will die off and restarting the system will require several days to a week or more. In all cases, systems using biological treatment should be enclosed or isolated to avoid human contact and protect from vector infestation and extremes in temperature.

Table 3.6 Assessment of biological treatment processes reported for graywater treatment

	Activated sludge	SBR	MBR	Trickling filters	RBC	Submerged aerated filters	Anaerobic process
Capital cost	High	High	High	Medium to high	Medium to high	High	Low to medium
Footprint	Large	Medium to Large	Medium - Large	Small to medium	Medium	Small	Large
Water quality	Up to secondary	Up to secondary	Tertiary	Secondary	Secondary	Secondary to tertiary	Primary
Ease of deployment	Difficult	Moderate	Moderate to difficult	Moderate to difficult	Moderate to difficult	Difficult	Moderate
Ease of use	Difficult	Fairly difficult to difficult	Fairly difficult to difficult	Moderate	Moderate	Difficult	Moderate to difficult
Treatment time	Moderate to long	Moderate to long	Moderate	Moderate	Moderate	Moderate	Long
Ease of Maintenance	Difficult	Difficult	Difficult	Simple to moderate	Simple to Moderate	Difficult	Difficult
Energy requirement	High	High	High	Moderate	Moderate	High	None
Flexibility to handle no flow	Inflexible to moderately inflexible	Inflexible	Inflexible	Inflexible	Inflexible	Inflexible	Flexible
Startup period	Long	Long	Long	Medium to long	Medium to long	Long	Long

3.5 Natural Treatment Processes

3.5.1 Natural Treatment Processes

Constructed wetland is the most widely used for graywater treatment among all natural treatment process. They are engineered processes that mimic processes in nature to degrade organics, remove solids and reduce indicator pathogens. Constructed wetlands are particularly attractive for onsite graywater treatment because they are less energy intensive, more environmentally friendly, have lower construction, O&M costs compared to other treatment processes, and require minimal onsite supervision [182, 183]. Furthermore, they can handle flow fluctuation (including no flow), are resilient, and can recover upon exposure to extreme conditions such as high and low water pH, interruption of water recirculation, and high concentrations of different pollutants without treatment performance being impaired [184, 185].

These positive attributes make treatment wetlands particularly suitable for graywater treatment in residential homes. Previous studies evaluated subsurface horizontal flow (HSSF, **Fig. 3.6**) [40-42], vertical flow (VF, **Fig. 3.7**) [43-45] and hybrid constructed wetlands [46, 47, 186] for graywater treatment with success. A study evaluated hydroponic processes for treatment of graywater and showed that the treatment system achieved 97% BOD_5 (effluent BOD_5 of 3.7 mg/L), 96% turbidity (effluent turbidity of 3.9 mg/L), 58% of suspended solids (effluent TSS of 16.8 mg/L) removal after 6 days of treatment [80]. A summary of the natural systems assessed for graywater treatment is presented in **Table 3.7**.

Table 3.7 Assessment of natural processes that have been used for graywater treatment

	Single-pass HSSF, VF, and hybrid systems	Semi batch vertical flow wetland	Hydroponic system
Capital cost	High	Low to medium	High
Footprint	Large	Small	Large
Water quality	Tertiary	Secondary to tertiary	Secondary
Ease of deployment	Difficult	Moderate	Difficult
Ease of use	Easy to moderate	Easy to moderate	Moderate to fairly difficult
Treatment time	Long	Moderate to long	Long
Ease of Maintenance	Simple	Simple	Simple to moderate
Energy requirement	None-low	Moderate	Low to moderate
Flexibility to handle no flow	Flexible	Flexible	Moderately inflexible
Startup period	None	None	Moderate to long

3.5.2 Horizontal Subsurface Flow Constructed Wetland

Properly designed horizontal subsurfcae flow constructed wetlands (**Fig. 1.2**) are effective for graywater treatment producing high effluent quality (<10 mg/L of BOD[40, 42]and 2 NTU [40]) that meets tertiary treatment level. However, single-pass continous flow wetlands for graywater treatment tend to have long hydraulic retention time (HRT) (4 to 8 days) [40, 42].

Merely reducing the treatment system area and hydraulic retention time in single-pass systems produced effluent of poor quality [45, 187]. It is also noted that the above previously proposed wetland systems were of low hydraulic loading rate (~0.04 to 0.08 m^3/m^2-daycalculated from [42, 43]). Such performance level, for example, would require a wetland area of 4.3 – 8.5 m^2 to treat ~340 liters/day of bathroom and clothes washing graywater generated in a single-family home [48]. Furthermore, long HRTs of 4 to 8 days would require provision of significant onsite storage capacity for collected raw graywater which could create odor nuisance [34]. Morevoer, it is noted that in various regions, storage of graywater is limited in terms of both storage time and capacity [27]. Clearly, shorter HRTs would be desirable to reduce raw graywater storage needs and thus the preference is for alternative compact and low cost wetland design suitable for residential use.

3.5.3 Vertical Flow Constructed Wetlands

Single-pass vertical flow (VF) constructed wetlands (**Fig. 1.3**) have also been used for graywater treatment with success. The VF constructed wetland achieved effluent BOD of 5 mg/L and TSS of 3 mg/L [43] meeting the tertiary effluent water quality standard (**Table 3.2**). However, the treatment capacity per area is still low at 0.08 m^3/m^2-day and still requires large area (~ 6 m^2) [43] (**Section 3.4.4.2**). Single-pass VF wetlands with smaller footprint have also been evaluated for graywater treatment, which have been shown to be less effective with high effluent BOD and TSS (e.g. >30 mg/L BOD and >30 mg/L TSS [45, 53, 188]). Such space requirement and associated construction costs [49] would make singles wetlands impractical for graywater treatment in residential homes in most urban areas.

Semi-batch VFWs (SB-VFWs, **Fig. 1.4**) have been used as a compact wetland method for graywater treatment. SB-VFWs enhance aerobic biodegradation in the wetland bed, increase contact time between water and the biofilm in the wetland, and thus enhance removal of organics

[189]. SB-VFWs also has shorter HRT (5– 12 hours [44, 186] and thus is an attractive alternative to the single pass conventional constructed wetlands for graywater treatment. Additionally, the evaluation of a SB-VFW for treatment of domestic wastewater demonstrated that SB-VFWs are robust to withstand disturbance due to influent water quality fluctuation, such as high bleach, organics, and detergent loadings, as well as extreme pH levels [185]. Moreover, SB-VFWs have been shown to be effective to reduce pathogens in graywater compared to untreated graywater [106]. Treated graywater effluent by SB-VFWs has also been demonstrated to cause neither adverse impacts on soil or plant growth [95] nor increase in diversity and abundance of pathogens in irrigated soils compared to fresh water [108].These characteristics coupled with the relatively simple operation make SB-VFWs a desirable treatment process for onsite deployment in single-family residential homes [44, 185, 189].

Previous work has reported on a SB-VFW for treatment of graywater which achieved BOD_5 and fecal coliform removal at essentially 100% and 99%, respectively [44]. This performance level was achived with relatively small footprint system (~1 m^2) and treatment time of 8 – 12 hours [44] and was shown to be comparable to the performance of much larger horizontal flow wetland treatment (**Tables 1.3 and 1.4**). The above SB-VFW wetland design utilized stratified heterogenous layers of silica-based soil, small randomly packed bed of spherical plastic media and rocks [50]. Its operational mode involved recirculating water dripped from the wetland into a holding tank below the wetland. The silica-based soil layer served as a filtration zone, and the plastic media provided surface area for biofilm growth. The "raindrop" effect created by water flow from the wetland to the receiving resservoir below promoted aerobic conditions. It was reported that treatment capacity was 0.45 m^3/ m^2-day for untreated graywater containing 158 ± 30 mg/L total suspended solids (TSS) and 839 ± 47 mg/L COD . The above system produced, for a treatment time of 12 hours, effluent that had low TSS range of 0 – 6 mg/L and low BOD_5 range of 0 – 1.5 mg/L [44].

In addition to effectiveness in treatment of graywater[44, 186], SB-VFWs have higher the treatment volume to area ratio (0.5 m^3/m^2 [44]). Thus, they are attractive alternatives to the single pass VF or HSSF constructed wetlands. Furthermore, the reported price range for these systems ranged from $600 [44, 186] to $2,500 for a fully automated treatment system [190], which are within the affordable price range for most homeowners. It has been shown that a return-on-investment of less than two years is feasible for residential homes in most developed countries [190].

3.5.4 Hybrid Constructed Wetland Treatment Systems

Hybrid constructed wetland treatment systems that use HSSF and VF wetlands have also been used for graywater treatment with success (HSSF + VF, [47], VF + HSSF [46], and SB-VFW + horizontal flow wetland [72]). The hybrid systems achieved high organic and suspended solid removal with treated effluent attained secondary to tertiary water quality (5 – 22 mg/L BOD, 10 mg/L TSS and 13 NTU turbidity [46, 47]. The treatment capacity per area achieved were 0.04 – 0.09 m^3/m^2, which are much lower than SB-VFW systems (**Section 3.4.4.3**).

3.6 Treatment technology for aboveground graywater reuse in residential homes

Physical, chemical and biological treatment technologies used for graywater treatment have been evaluated. Graywater treatment technology selection needs to be based the local water requirements for different water reuse applications. Graywater treatment technology must be selected according to whether treatment goals can be met before other criteria are assessed. Accordingly, treatment process assessment based on the criteria established in **Section 3.3** was conducted and a summary of the results is presented in **Table 3.8**.

Treatment technology that is best suited for primary treatment is screening, followed by sedimentation and then media filtration. Screens are usually low cost, small, easy to install, easy to use with short treatment time, and require no startup time and energy, and perform well even with long periods of no flow. However, the amount of solids captured by screens is determined by the screen openings, which in turns affect the level of maintenance. Screen filters with large openings require less frequent cleaning or replacement but they also allow more rapid accumulation of solids in the storage tank. In contrast, small screen openings can be clogged rapidly and hence require frequent cleaning or replacement. Sedimentation is less favorable as compared to screening, however, the intermittent generation of graywater means that onsite storage is necessary. Thus, the occurrence of sedimentation is almost inevitable during storage. Thus, combining screening and sedimentation to achieve primary treatment is considered as the most cost-effective compared to other treatment processes.

When graywater reuse requires effluent quality meeting secondary effluent quality, semi-batch vertical flow wetlands (SB-VFW) are considered to be the most cost effective. Both single-pass subsurface flow wetlands and SB-VFW are easy to maintain, have low energy requirements, and are flexible to handle no flow, and require little startup time. SB-VFW systems have lower capital cost, much smaller than single-pass wetlands, and are relatively easy to deploy. Additionally, some of the SB-VFW designs can achieve tertiary effluent quality [190], which make it a good low cost option in areas where more stringent graywater reuse requirements are in place. Coagulation with membranes can also achieve tertiary effluent quality levels and requires no startup time, however, costs and other operational aspects are expected to limit their adoption in residential graywater reuse.

Table 3.8 Summary table of technology scored the best based on the findings presented in Tables 4-6

Onsite residential graywater reuse criteria	**Graywater Reuse Treatment Goals**		
	Primary effluent	**Secondary effluent**	**Tertiary effluent**
Lowest Capital cost	Screening, sedimentation	Batch vertical flow wetland	Batch vertical flow wetland
Smallest	Screening	Batch vertical flow wetland, BAFs, trickling filters	Batch vertical flow wetland, BAFs,
Easiest to deploy	Screening	Batch vertical flow wetland,	batch vertical flow wetland, Coagulation with membrane,
Easiest to use	Screening, sedimentation	Wetland	batch vertical flow wetland, trickling filters, RBCs
Shortest hydraulic retention time	Screening	Electrocoagulation	Coagulation with membrane
Easiest to maintain	Screening	All wetland	Wetland
Lowest energy requirement	Screening, sedimentation, media filtration, Anaerobic treatment,	All wetland	Wetland
Most flexible to handle no flow	Screening, sedimentation, media filtration	All wetland	Wetland
Shortest startup period	Screening, sedimentation, media filtration AOPs, ion exchange, Coagulation / flocculation with media filter, Dissolved air floatation, anaerobic treatment,	All wetland Electrocoagulation	Wetland, Coagulation with membrane

3.7 Conclusions

Review of graywater treatment technology with respect to treatment performance and their suitability for onsite residential deployment has been conducted. Screening and sedimentation have been identified to be most suited for primary treatment. Semi-batch vertical flow wetlands (SB-VFWs) have been found to be affordable and are suitable for onsite residential deployment. SB-VFWs are expected to be most suitable for single-family homes or other low-density residential housing communities due to ability to handle no flow, their relatively compactness, and low energy requirements. For larger housing type, such as multifamily homes that has a base-flow, rotating bioreactors (RBCs) and trickling filters are also considered as economical options. High cost treatment processes membrane bioreactors (MBRs) would be more suitable for treating high volumes from high-rise apartment building. Biological aerated filters (BAFs) also have a potential for deployment in high-density residential buildings for treatment of graywater, but more studies will be needed to evaluate the technical feasibility, as well as to formulate operational strategy that can provide optimal treatment performance.

Activated sludge and sequential batch reactors are considered to be unsuitable for onsite deployment without the presence of onsite operators due to the highly sensitive treatment process. Anaerobic treatment processes are unsuitable for graywater treatment due to poor effluent quality and emission of corrosive gases during treatment. Physical and chemical processes have been also reviewed but their applications are expected to be limited if water quality for graywater reuse is at secondary or tertiary treatment levels. Direct membrane filtration produces effluent of tertiary water quality but rapid membrane fouling, the need to operate the system at high pressure to produce high flux, and the need for frequent backwash and chemical cleaning make this approach unfavorable. The use of coagulation prior to membrane filtration was shown to be viable fouling control measures although pilot studies are needed for demonstration of achievable water quality and formulation of operation strategy. Specialized treatment processes, such as ion-exchange and advanced oxidation processes (AOPs), have not been demonstrated to be effective for graywater treatment. Emerging technologies, such as electrocoagulation, requires more studies for scale-up and overcome challenges such as electrode passivation and energy requirements.

The review conclude that in order to meet secondary or tertiary effluent water standards, extremely low-cost technology, such as screening, along will not be sufficient. SB-VFWs have been shown to be a viable technology for low-cost and compact graywater treatment technology that is considered to be suitable for onsite deployment in residential homes. Further evaluations on treatment performance, operation and maintenance requirements and economic feasibility are needed in order to validate their potential for onsite deployment.

4 PERFORMANCE EVALUATION OF A SEMI-BATCH VERTICAL-FLOW WETLAND FOR ONSITE RESIDENTIAL GRAYWATER TREATMENT

4.1 Introduction

Graywater, commonly defined as wastewater not containing toilet or urinal waste [19, 110, 191], is a potential resource to alleviate water shortage, increase water security, and foster long-term water sustainability in various regions around the world. It is a stable alternative water supply for non-potable water use (e.g. irrigation and toilet flushing) in urban and rural environments [61, 192]. A recent review of residential graywater reuse regulations in the United States noted that reuse of untreated graywater is restricted to subsurface irrigation or ground disposal [27]. Residential graywater reuse regulations vary throughout the world [110] and even regionally within a given country [27], in terms of the permitted graywater storage, reuse applications and required treatment levels. In order to expand graywater reuse to the residential sector and allow water use for aboveground applications [27], treatment is necessary to safeguard public health and meet regulatory requirements. Moreover, low cost and simple treatment approaches will be critical for widespread adoption of distributed graywater recycling.

In order to meet aboveground graywater reuse requirements (**Table 4.1)**, biological treatment, filtration and disinfection are necessary for removal of organics, suspended solids, and pathogens, respectively [110]. Complex biological treatment processes such as membrane bioreactors, along with a filtration process train [193], have been developed for onsite residential homes aboveground non-potable graywater reuse. However, high capital and operations and maintenance (O&M) costs [28, 36] have hindered homeowners' adoption of such commercial treatment systems [37, 38]. In contrast, constructed wetlands have long been considered as a suitable low-cost alternative treatment technology for graywater treatment [194].

Table 4.1 Water quality criteria for aboveground non-potable graywater reuse in selected countries

Standards	Type of reuse	Treatment leve equivalent	Water quality criteria
United Kingdom [67	Sprinkler; Car washing; Toilet flushing; Garden watering; Pressure washing; Washing machine us		<10 NTU of turbidity; pH 5-9.5; < 2 mg/L of residual chlorine; < 0.5 mg/L of residual chlorine for non-spray garden watering; 0.0 mg/L of residual bromine for all spray application and non-spray garden watering
California, USA [68	Aboveground non-potable reuse	Disinfected tertiary	Turbidity: 2 NTU (avg.); 5 NTU (max) Total coliform: 2.2 MPN/100 mL (avg.), 23MPN/100 mL (max in 30 days)
Wisconsin, USA [69	Surface irrigation except food crops; clothes and vehicle washing; air conditioning; soil compaction; dust control; washing aggregate; making concrete	Disinfected tertiary	pH 6–9; ≤ 10 mg/L of BOD$_5$; ≤ 5 mg/L of TSS; 1.0–10 mg/L of free residual chlorine
	Toilet and urinal flushing	Disinfected primary with filtration	pH 6–9; ≤200 mg/L of BOD$_5$; ≤ 5 mg/L TSS; 0.1–4.0 mg/L of free residual chlorine
NSF/ANSI 350R	Restricted indoor and unrestricted outdoor water reuse	Residential capacity ≤ 1,50 GPD	pH 6-9; CBOD$_5$: ≤ 10 mg/L of (avg.), 25 mg/L (max.); TSS: ≤ 10 mg/L (avg.); 30 mg/L (max.) Turbidity: 5 NTU (avg.); 10 NTU (max.) E. coli: 14 MPN/100mL (mean); 240 MPN/100mL (max.) Storage vessel disinfection: ≥0.5 - ≤2.5mg/L
New South Wales, Australia [23]	Toilet flushing; Cold water supply to washing machines; Garden irrigation wi local approval	Disinfected Secondary	< 20 mg/L BOD$_5$; < 20 mg/L TSS; <10 cfu/100ml fecal coliforms
Western Australia, Australia [70]	Toilet flushing Cold water supply to washing machines; Irrigation	Disinfected Tertiary	<10mg/L of BOD; <10mg/L of TSS; <1 MPN/100mL of *E. coli* <1 pfu/100mL of coliphages; <1 cfu/100mL of clostridia;
Victoria, Australia [71]	Toilet flushing; Cold water supply to washing machines; Surface irrigation, Sub-surface irrigatio	Disinfected Tertiary	<10 mg/L of BOD; <10 mg/L of TSS; <10 cfu/100ml of fecal coliforms;

Previous studies evaluated subsurface horizontal flow (HF) [40-42], vertical flow (VF) [43-45] and hybrid constructed wetlands [46, 47] treatment of mixed graywater from laundry, kitchen and bathroom (baths, showers, and handwashing basins) sources (**Tables 1.3 and 1.4**). Results from these studies indicate that in order to produce treated graywater effluent with <10 mg/L of BOD (**Tables 1.3 and 1.4**) to comply with the required tertiary treatment level for aboveground graywater reuse in the U.S. (Wisconsin, California, NSF/ANSI 350R) and in Australia (**Tables 1.3 and 1.4**), single-pass wetlands would require long hydraulic retention time (HRT) (4 to 8 days). Merely reducing the treatment system area and hydraulic retention time in single-pass wetlands was reported to produce effluent of poor quality [45]. It is also noted that the above previously proposed wetland systems were of low hydraulic loading rate (~0.04 to 0.08 m^3/m^2-day as shown in **Tables 1.3 and 1.4**). Such performance level, for example, would require a wetland area of 4.3 – 8.5 m^2 to treat ~340 liters/day of bathroom and clothes washing graywater generated in a single-family home in California [48]. Such space requirement and associated construction costs [49] would make conventional wetlands impractical for graywater treatment in residential homes in most urban areas. Furthermore, long HRTs of 4 to 8 days would require provision of significant onsite storage capacity for collected raw graywater which could create odor nuisance [34]. Morevoer, it is noted that in various regions, storage of graywater is limited in terms of both storage time and capacity [27]. Clearly, short HRTs would be desirable to reduce raw graywater storage needs and thus the preference for an alternative low-cost and compact wetland design suitable for residential use.

Vertical flow wetlands (VFWs) with graywater recirculation operated in a semi-batch mode (SB-VFWs) were first proposed for treatment of agriculture wastewater [195]. The SB-VFWs have since been used to treat other types of wastewater [189], including domestic wasetwater

[51, 185] and graywater [44, 186]. The SB-VFWs have also been used for pretreatment of graywater for a horizontal flow wetland in a hybrid system (**Tables 1.3** and **1.4**) [72]. SB-VFWs enhance aerobic biodegradation in the wetland bed, increase contact time between water and the biofilm in the wetland, and thus enhance removal of organics [189]. The presence of vegetation in constructed wetlands does not result in direct organic removal but improves nutrient removal (such as nitrate and phosphate) by uptake into plant tissue [196]. The root structure also provides surfaces for microbial attachment, improving the environment for microorganisms to degrade contaminants [197]. Additionally, oxygen leakage through plant roots enhances aerobic biodegradation which is the main degradable organic removal mechanism [198]. Recirculation and the vertical flow regime in SB-VFWs also allows water to pass through soil multiple times to enhance filtration, which is the primary physical removal mechanism in vertical flow wetland treatment systems [199].

SB-VFWs also have been reported as having shorter HRT than single-pass conventional constructed wetlands for graywater treatment (**Table 1.4**). Additionally, the evaluation of a SB-VFW for treatment of domestic wastewater which has distinctively different water quality characteristics compared to graywater demonstrated that SB-VFWs are robust to disturbances due to influent water quality fluctuation, such as high bleach, organics, and detergent loadings, as well as extreme pH levels [185]. Wetlands can also provide pathogen removal through filtration. It has also been reported that wetland is a hostile environment for pathogens, promoting natural die-off [199-201]. The treatment of mixed graywater using SB-VFWs reduces pathogens in graywater compared to untreated graywater [106]. Treated graywater effluent using SB-VFWs has not observed to cause adverse impacts on soil or plant growth [95] or to promote pathogen diversity or population growth in irrigated soils. These effects are similar to those seen in irrigation with fresh water [108]. Given the above characteristics of SB-VFWs coupled with their relatively simple operation make this graywater treatment approach attractive for onsite deployment in single-family residential homes [44, 185, 189].

Previous work has reported the use of SB-VFWs for treating mixed graywater (i.e. mixed bathroom, kitchen, and laundry graywater) [44]. The system achieved BOD_5 and fecal coliform removal at essentially 100% and 99%, respectively. This performance level was attained with a relatively small footprint system (~2 m^2/m^3) and treatment time of 8 – 12 hours [44] with comparable performance to much larger horizontal flow wetland treatment (**Tables 1.3 and 1.4**). The above SB-VFW wetland design utilized stratified heterogenous layers of silica-based soil, a small randomly packed bed of spherical plastic media and rocks [50]. Its operational mode involved recirculating water that dripped from the wetland into a holding tank below the wetland. The silica-based soil layer served as a filtration zone and along with the plastic media provided the necessary surface for biofilm growth to enable biodegradation [35, 202]. The "raindrop" effect created by water flow from the wetland to the receiving resservoir below promoted aeration [203]. The reported hydraulic loading rate was 0.45 m^3/ m^2-day for untreated graywater containing 158 ± 30 mg/L total suspended solids (TSS) and 839 ± 47 mg/L COD . The above system produced, for a treatment time of 12 hours, low TSS effluent (< 6 mg/L) and BOD_5 range of nondetect levels to 1.5 mg/L [44]. It is noted that despite such low BOD_5, the effluent COD range of 60–220 mg/L was relatively high for the BOD_5 levels achieved as compared to the BOD and COD data reported for other wetlands that attained similar levels of BOD removal (**Tables 1.4)**.

The above study did not report the system's turbidity removal, and important water quality parameter required for compliance with California Title 22 reclamation requriements (**Table**

4.1). A separate study [51] using the same type of SB-VFW for domestic wastewater treatment reported an average effluent turbidity of 6 NTU with a turbdity range of 2 - 12 NTU. The wastewater effluent TSS was 10 mg/L [51], which was similar to the graywater effluent TSS (0-6mg/L) reported for the same type of graywater treatment reported in a previous study [44]. Such turbidity range exceeds the most stringent standards for aboveground non-ptoable water reuses (**Table 4.1**), and may also decrease disinfection effectiveness [35]. It is possible that the high effluent turbidity could have een the result of fine soil leaching from the soil bed [204].

Preventing fine soil leaching and increasing hydraulic loading rate are necessary to address the current limitations of recirculating vertical-flow wetland designs [205]. A possible solution would be to replace the silty soil with non-silty soil substitute. For example, lime pebbles (up to 4cm in diameter) and zeolite (0 to 6 mm in diameter) have been used to treat mixed graywater from kitchen, laundry, and bathroom sources [186]. Although turbidity data was not reported in the above study, the reported graywater treatment system achieved only 20% to 80% TSS removal (effluent TSS of 43 mg/L to 122 mg/L), and 78-97% BOD removal (effluent BOD of 39 to 156 mg/L) [186]. Another alternative solution would be to replace the high density silica-based wetland bed material with a lower density non-silty plant based soil substitute. Recent studies have proposed that plate-based materials with low density (e.g. palm tree mulch [52] and tree bark [53]) may be suitable for use in single pass VFWs for mixed graywater treatment. It was reported, however, that palm tree mulch was less effective for organic and TSS removal as compared to sand filters, achieving only an average of 53% BOD, 38% COD and 70% TSS removals as compared to 85% BOD, 62% COD and 95% TSS removal achieved by sand filters for treating graywater [52]. In the above study, a lower filtration remvoal may have been the result of the large particle size in plant-based media used in the wetland [52].

Various studies have shown that coconut-based biosorbents can be effective for removal of various aquatic contaminants, including organics and metals [206]. The use coconut coir dust was also been reported in wetland systems for treatment of domestic wastewater [207]. Other studies have reported that coconut coir promotes the growth of denitrifying bacteria, enhancing denitrifcation in horizontal subsurface flow (HSSF) wetlands for treatment of domestic wastewater [208]. The high biosorptivity of coconut coir, its high hydraulic permeability (0.2 cm/s [209]) similar to well-sorted sand permeability of 10^{-3} to 10^{-1}cm/s [210], low bulk density (0.04 – 0.08 g/cm^3) and high porosity (up to 90%) [211], make coconut coir an attractive SB-VFW soiil substitute for graywater treatment. Moreover, coconut coir is a common plant-based soil and peat substitute for gardening purposes [212, 213] and thus readiliy available for residential use. However, the performance improviements of SB-VFW graywater treatment with the above soil substitute has not yet been reported.

The design of VFWs (whether operated in a single- or multipass mode) requires a specific system performance model to tailor the system to the target treatment level for the expected range of raw graywater quality. A first-order plug-flow reactor developed for conventional wetlands [54], developed for conventional wetlands [54], was modified and shown to be suitable for analysis of the performance of SB-VFWs that utilized silica-based soil [44]. The above apporach demonstrated a reasonable correlation between the required recirculation flow rate and wetland area, but did not provide the required treatment time as a function of organic loading rate. Another first-order kinetic model for a SB-VFW [55] was proposed relying on the assumption of a completely mixed batch reactor. The model predicted the needed wetland volume to achieve TSS removal for a given treatment time. Specifically, it was concluded that the treatment efficiency (with wetland area of 0.9 m^2 and treatment capacity of 0.45 m^3/day) was independent of recirculation flow rate above a recirculation flow rate of 3 m^3/hr. As expected, model results confirmed that treatment performance improvement could be achieved by increasing wetland bed volumes and decreasing the graywater volume. Although the above previous studies have provided useful insight regarding the operation of SB-VFWs, there remains a critical need for a systematic evaluation of the SB-VFW approach to residential graywater treatment with respect to key operational and design parameters.

This chapter focuses on demonstrating the technical and economic feasibility of a SB-VFW for residential bathroom graywater treatment that overcomes the shortcomings of previous approaches by: (a) using coconut coir based organic soil substitute of high water permeability for the wetland, (b) replacing the conventional large gravels with cross flow plastic media consisting of large flow channels and high surface area that allows for both biofilm growth and aeration, and (c) ensuring adequate distribution of graywater onto the wetland along with sufficient recirculation. The SB-VFW was evaluated over a period of eigh months in a single family home for treatment of graywater from bathroom sinks, showers and baths. A first-order kinetic model along with collected field data was then used to evaluate the relationships between operational parameters and treatment performance, thereby providing the basis for scale-up. Furthermore, the economic feasibility of onsite residential graywater treatment was evaluated based on capital and O&M costs derived from the field study. The overall goals were to demonstrate that a suitably designed SB-VFW can: (a) produce treated effluent that meets stringent water quality requirements for aboveground graywater reuse, (b) have high hydraulic loading rate of >1 m^3/ m^2-day, and (c) be economically feasible in different parts of the world even in the absense of financial subsidies.

4.2 Materials and Methods

4.2.1 Graywater source, instrumentation and analytical methods

Onsite treatment of bathroom graywater graywater), generated from bathroom sinks, showers and baths, using a SB-VFW was investigated over a period of eight months in a single family home. In the present arrangement **(Fig. 4.1)**, graywater was diverted to a belowground collection tank by gravity. Subsequently, graywater was pumped from the collection tank into the treatment system using a sump pump (Little Giant 5-ASP, Fort Wayne, IN). Ten 300-mL grab samples were collected directly from the mid-water column of the collection tank (influent) and the reservoir (effluent) of the pilot system using two auto-samplers (Hach Sigma MAX900, Loveland, CO) during each batch of the experiment. These ten samples include one influent sample collected just prior to pumping the graywater into the treatment system; and a total of nine grab effluent samples from the treatment unit were collected for evaluation over a 24-hr period at times of 0, 0.15, 0.5, 0.75, 1, 2, 3, 8 and 24 hours. Collected samples were kept in a cooler (< 4°C) before transporting back to the laboratory for water quality analysis.

Total organic carbon (TOC) and dissolved organic carbon (DOC) were determined via Standard Methods 5310C (Aurora 1030D TOC Analyzer, OI Analytical, College Station, TX). Samples for TOC and DOC analysis were processed for analysis immediately after the samples were arrived in the laboratory (<24 hours). Samples for DOC analysis were prepared by filtering the water samples through 0.8 µm filters (MCE with modified acrylic housing, Millipore Millex Sterile Syringe Filters, EMD Millipore, Billerica, MA). TOC as well as DOC were monitored during the entire study period. During the startup period (the first three months), TOC was measured less frequently. Graywater was treated every other day due to the lower than expected bathroom graywater production. There were 21 treatment batch runs evaluated after the startup period with 8 samples per treatment batch, making a total of 168 samples tested from the field study. In addition to the above, collected influent and effluent samples were analyzed for chemical oxygen demand (COD) (Hach Method 8000, Loveland, CO) and biochemical oxygen demand (BOD) (Standard Methods 5210B) in order to establish the ratios between TOC, DOC, COD and BOD. BOD tests were conducted by a CA State certified laboratory (Weck Laboratories, City of Industry, CA). The TOC to BOD and COD ratio remained relatively constant throughout the study, and this was expected because the wastewater conditions and house occupancy did not change. The house tenants were part of the study and agreed not to change conditions without notifying the authors. Average BOD_5 and COD values were calculated based on the correlation established between the BOD_5/TOC and COD/TOC ratios.

Turbidity (USEPA Method 180.1; 2020 Portable Turbidity Meter, LaMotte, Chestertown, ML) was the primary monitoring parameter to assess reduction in suspended particles/colloidal matter. Turbidity measurements were taken immediately after the samples arrived in the laboratory. Other monitored inorganic water quality parameters included pH, conductivity (Oakton CON 11 Economy Meter, Vernon Hills, IL), temperature, total inorganic carbon (Standard Methods 5310C; Aurora 1030D TOC Analyzer, OI Analytical, College Station, TX), total suspended solids and volatile suspended solids (VSS) (Standard Methods 2540D; Whatman Grade GA/F filter paper, Pittsburgh, PA), and dissolved oxygen (Dissolve Oxygen Tracer PocketTester, LaMotte, Chestertown, ML). Finally, total and fecal coliforms were measured (Standard Methods 9223B; IDEXX Colilert and Colilert-18, Westbrook, ME) in the influent and effluent samples, as well as after chlorine disinfection. Samples for total and fecal coliforms were processed immediately after the samples arrived at the laboratory. The effectiveness of chlorination was evaluated by adding HOCl to 200 ml effluent samples to attain HOCl concentration of 4 mg/L in the sample, which after a period of 10 minutes, was quenched with sodium metabisulfite. It is noted that the above HOCl concentration was sufficient to meet the disinfection goal.

4.2.2 Graywater treatment system

Residential graywater treatment in a single family home was accomplished with a modular SB-VFW (**Fig. 4.1**). The upper section of the system (1.1 m (L) x 0.7 m (W) x 0.7 m (H)) consisted of a wetland (top) and a reservoir (bottom). The upper unit was comprised of a layer of coconut coir dust (the "soil" layer) sitting on top of a layer of cross flow media (CFM). The soil layer was 15 cm thick and was compartmentalized using fabric bags (33 cm (W) x 33 cm (L) x 20 cm (D)) (SmartPots, Oklahoma City, OK) and a variety of ordinary garden plants along with wetland plant species (*Carex spissa* and *Phyla nodiflora*) where planted in the wetland. Household garden plant species planted in the wetland were *Aeonium purpureum* and *Crassula ovate, Equisetum hyemale, Nasturtium, Narcissus*, *impatiens*, *Anigozanthos*, and *Colocasia.* The viability of the plants was visually assessed based on their overall appearance, e.g. leaf greenness and ability to produce flowers for flowering plants. The CFM, which provided for additional surface for biofilm growth and structural support for the upper soil bed, had a specific surface area of 226 m^2/m^3 (AccuPac Cross Flow Media, Brentwood Industries, Reading, PA). The CFM layer was 30 cm deep. The open channel configuration of the CFM enabled significant aeration while avoiding channel clogging [214]. The raindrop effect created by water droplets (from the wetland) impinging onto the graywater-holding reservoir below the CFM also provided additional aeration [203].

The SB-VFW was operated in a semi-batch mode to accommodate the intermittent generation of graywater. A collection tank with a 300-L storage capacity was used for collection and storage of untreated graywater between treatment cycles. Raw graywater flowed into the collection tank (from the residential home) by gravity. A 200-µm nylon fabric screen filter was installed at the inlet of the collection tank for removal of hair and other stringy matter. Once the collection tank was filled, graywater was pumped, via a sump pump (Little Giant 5-ASP, Fort Wayne, IN), from the collection tank to the wetland through a distribution system. The treatment cycle began by pumping the contents of the collection tank into the distribution system above the wetland. The treatment system effluent was then collected in the reservoir and recirculated to the wetland until the treatment cycle was completed (when the collection tank refilled, approximately 24-48 hours). A second sump pump (Little Giant 5-ASP, Fort Wayne, IN) in the reservoir emptied the treated graywater reservoir to storage or directly to irrigation. Automated operation of the graywater treatment with the three pumps (**Fig. 1**) was facilitated using an irrigation controller.

Application of graywater onto the wetland surface, during both delivery of the initial charge and recirculation, was accomplished using a flow distribution system of enclosed conduits (installed just above the soil) with bottom discharge holes. Uniformity of flow distribution was verified by determining the local permeation flow rate (through the wetland soil and CFM) at different locations beneath the CFM. The recirculation flow rate was measured by an inline paddlewheel flow meter (GF Signet P51530-P0, El Monte, CA) connected to a powered transmitter/totalizer (GF Signet 3-8550-2, El Monte CA).. The volume of water collected from the samplers was quantified using a graduated cylinder. The average flow rate at each location was taken as an average of three measurements. The flow measurements were taken across the entire wetland and the average flow across the wetland bed is presented in **Fig. 4.2b**. The fluctuation along each sampling location could have been resulted from sampling errors. Additionally, plastic ribs that were part of the plastic tank and kept to provide mechanical strength to hold up the soil and the CFM in the wetland unit might have caused interference in volumetric flow collected across the bottom of the wetland in the water samplers.

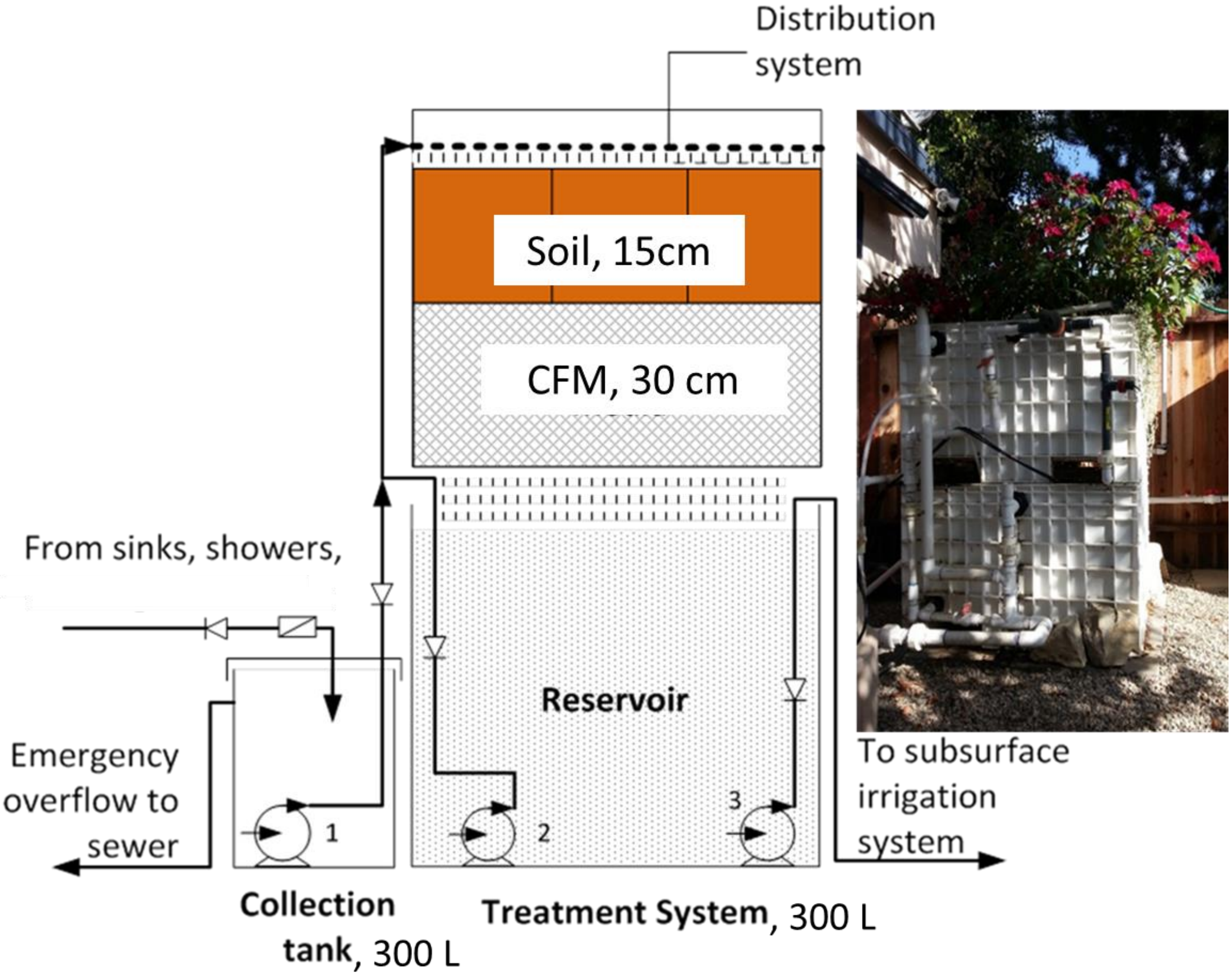


Figure 4.1 Schematic diagram of the graywater treatment system . The upper wetland unit consists of a soil layer and a cross-flow media (CFM). Graywater intake (pump 1), recirculation (pump 2) and discharge (pump 3) are controlled by three different submerged pumps

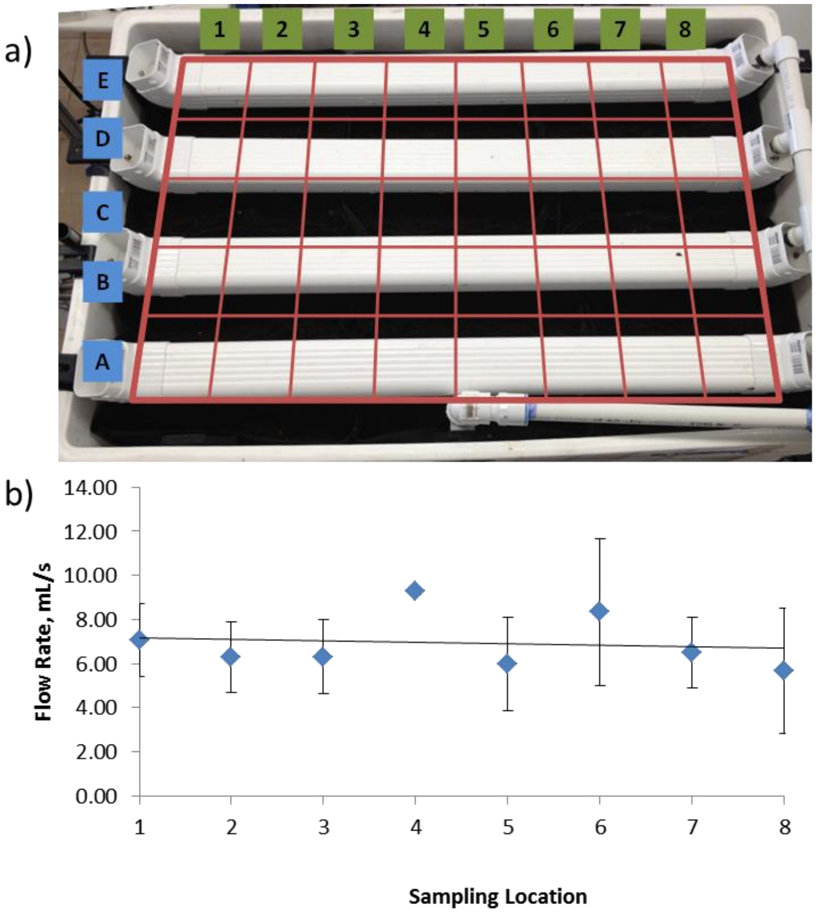


Figure 4.2 a) Top view of the wetland and the sampling grid; b) average volumetric flow rates across the wetland at different sampling locations. Error bar represents one standard deviation

4.3 Results and discussions

4.3.1 Influent and effluent water quality

Untreated bathroom graywater contained organics, TSS and turbidity at levels that did not meet the water quality requirements for aboveground non-potable graywater reuse (**Table 4.1**). The SB-VFW, however, was effective in reducing the concentration of physical and chemical contaminants to levels that complied with aboveground graywater reuse standards (**Table 4.3).** Significant removal of turbidity, which averaged 0.3 NTU for the treated effluent (relative to ~21 NTU for the raw graywater), was achieved well below the stringent turbidity requirement of <2

NTU for aboveground graywater reuse in California (**Table 4.1**). The effluent also had low BOD_5 of 3.1 mg/L and TSS of 0.5 mg/L (representing reduction of ~ 94% and ~99% relative to the influent graywater), also meeting the organic and physical contaminant requirements for aboveground graywater reuse (**Table 4.1**). It is also noted that the detergents used in the household were phosphate free and the raw graywater PO_4-P was only 2.3 mg/L. Untreated graywater pH was 7.2 (relative to ~6.4 for tap water) and decreased to 6.9 after treatment. Raw graywater TDS was 260 mg/L (~18% higher than tap water) and did not change upon treatment. It is noted that the treatment system was able to produce effluent of the above water quality in only about three hours with water quality showing marginal improvement thereafter as noted in **Fig. 4.3.** Moreover, treatment performance was maintained over the course of the study period.

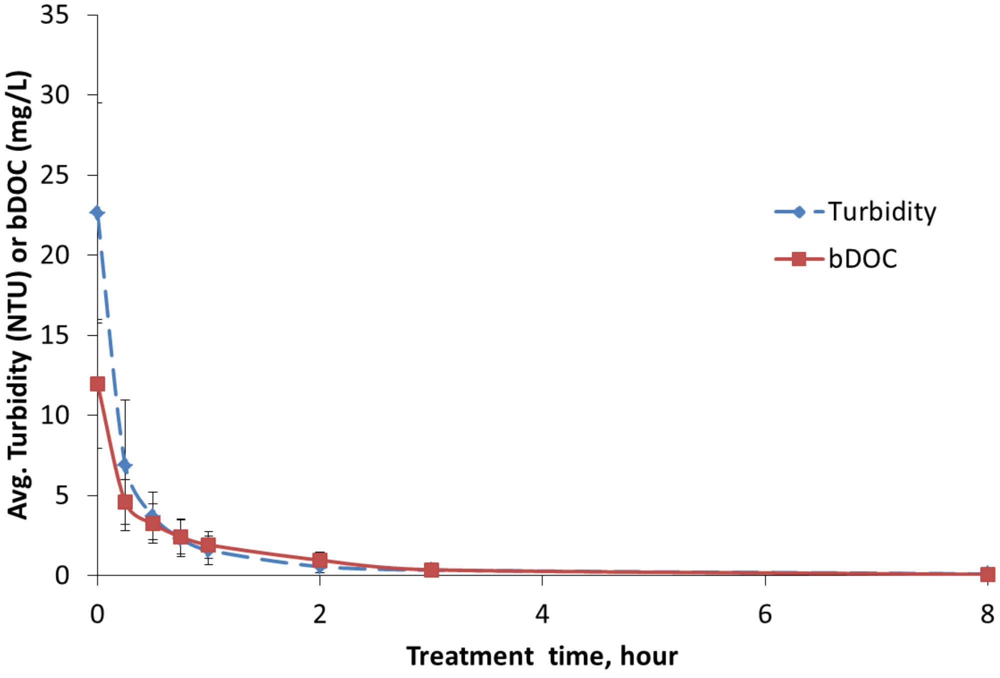


Figure 4.3 Graywater treatment performance with respect to turbidity and bDOC removal. Effluent turbidity and bDOC after 2 hours of recirculation were consistently low despite fluctuations in influent concentrations., declined further after 3 hours and remained at negligibly low level even after 8 hours of recirculation for all treatment batches throughout the study period. Error bars represents one standard deviation for the range of results of multiple runs (n = 16).

The wetland section of the treatment system performed as a packed-bed media filter that captured suspended solids and reduced turbidity. Water recirculation increased the residence time in the soil layer and thus enhanced turbidity removal. Greater than 60% turbidity removal was achieved within the first 15 minutes of treatment and >90% removal within the first hour (**Fig. 4.3**). Moreover, effluent turbidity treated for about two hours was well below 2 NTU. System performance over the eight-month field study demonstrated performance robustness with respect to turbidity removal without the problem of leaching of fine silts or clay associated as encountered with the use of silica type soils [51].

Table 4.2 Average influent and effluent water quality over the eight-month study period

	Influent	**Effluent**
pH (6)[a]	7.35 ± 0.07	6.90 ± 0.09
TDS (6)[a], mg/L	261.00 ± 8.98	257.76 ± 14.11
DO (5)[a], mg/L	1.33 ± 0.45	7.20 ± 1.54
Temp (6)[a], C	18.48 ± 1.58	16.14 ± 2.55
Turbidity (20)[a], NTU	20.59 ± 6.71	0.30 ± 0.27
Suspended solids (5) [a], mg/L	40.02 ± 20.60	0.5 ± 0.12
Volatile suspended solids, mg/L	40.02 ± 20.60	0.5 ± 0.12
TOC (21) [a], mg/L	33.62 ± 4.63	7.34 ± 1.14
bDOC (21) [a], mg/L	12.89 ± 3.89	0.41 ± 0.37
TOC minus DOC (21) [a], mg/L	19.48 ± 8.53	1.44 ± 2.14
Chemical oxygen demand (3) [a], mg/L	148.03 ± 20.25	16.37 ± 2.92
BOD_5 (3) [a], mg/L	49 ± 6.56	3.1 ± 1.18
Total coliforms (before Cl_2 disinfection (4) [a], MPN/100mL	$1.35x10^8$ ($9.65x10^7 – 1.84x10^8$)	$6.49x10^5$ ($4.25x10^5 – 9.42x10^5$)
Total coliforms (after Cl_2 disinfection) (1) [a], MPN/100mL	-	<1 (below detection limit)
Fecal coliform (2) [a], MPN/100mL	<1 (below detection limit)	<1 (below detection limit)
Septic odor[b] (40) [a]	Noticeable	None

Note: [a] Number in parenthesis after constituent is the number of observations.

[b] Septic odor was noted after raw graywater has been stored in the storage tank for ~24 hours

The SB-VFW was effective in removing TOC (with an average organic loading rate of 0.10 kg-TOC/m^3-day) and especially the degradable TOC fraction. Over the course of the eight-month study, TOC was typically reduced by ~80% (from 33.6 ± 4.6 mg/L to 7.3 ± 1.1 mg/L) within just 3 hours of treatment. It is noted that plant uptake of organic materials was not expected [205] over the typical short batch treatment period. More frequent grab sampling, during the first treatment hour, revealed that ~62% of the biodegradable dissolved organic carbon (bDOC) was removed within the first 15 minutes of treatment, and 97% bDOC removal was achieved within 3 hours (**Fig. 4.3**). The apparent rapid removal of organics and turbidity by SB-VFW within the first 30 minutes of treatment is consistent with observations reported by other studies [44, 55]. Also, the level of bDOC removal was consistent with the low effluent BOD$_5$, which was reduced by 93% ± 3% after three hours of treatment (**Fig. 4.3**).

VFWs typically provide higher DO levels in the soil matrix that promotes efficient organic removal as well as nitrification [197, 215]. High DO levels were attributed to the use of the CFM that enhanced aeration (**Fig. 4.1**). Operation of the treatment system operation without the CFM attained lower effluent DO level of ~3.8 mg/L ± 0.7 mg/L. This result indicated that the CFM media provided improved aeration that resulted in high effluent DO (~7.2 mg/L ± 1.5 mg/L, **Table 4.3**) without the need for mechanical mixing or direct aeration. The above effluent DO results are comparable to those reported in a previous study (effluent DO of 5.2 to 8.7 mg/L) [186]. The CFM did not show visible biofilm but a thin slimy biofilm was present and observable to the touch, however, microbial community in the wetland soil is expected to be diverse [216-218]. The influent ammonia and nitrate averaged 1.8 mg-N/L and 0.2 mg-N/L, respectively with effluent ammonia averaging 0.2 mg-N/L respectively, with effluent while nitrate increased to 5.6 mg-N/L. The wetland effluent was always high in DO and thus denitrification was not expected [197] as confirmed by the above results.

The high hydraulic permeability of the soil layer (0.09 cm/s ± 0.04 cm/s) made it possible to operate the system at high recirculation flow rates, with the highest recirculation rate of 36 L/min (or hydraulic dosinig rate of 0.09cm/s) permitted by the recirculation pump, and provided a short complete-volume-turnover every ~7 minutes (**Fig. 4.1, Section 4.2).** However, introduction of vegetation into the wetland reduced the soil water permeability limited the maximum achievable recirculation flow rate (15-26 L/min or hydraulic dosing rate of 0.03-0.04 cm/s); the above recirculation flow is still significantly higher than reported in previous SB-VFW work (i.e. hydraulic dosing rate of 0.01 cm/s) using silica type soil [44]).

The effect of recirculation flow rate on dissolved organics removal is illustrated in **Fig. 4.4** for the flow rate range of 15-26 L/min, the upper and lower limits being those of the pump's feasible operation. There was no measurable difference in bDOC removal over the above range of recirculation flow rates; hence, for the present system, the lower recirculation flow rate of 15 L/min was adopted as suitable for graywater treatment. However, DOC removal did decrease by about 10% with increasing recirculation rates from the above low to high limits (**Fig. 4.4**). This performance result may have been due to scouring or sloughing of organics from the soil [219]. One should expect that a higher recirculation flow rate would increase the water shear velocity through the wetland unit – a technique that is commonly used in controlling biofilm thickness in trickling filters [35]. The above behavior suggests that lower recirculation flow rates are preferable with the added benefit that ultra-low power pumps, e.g. solar fountain pumps.

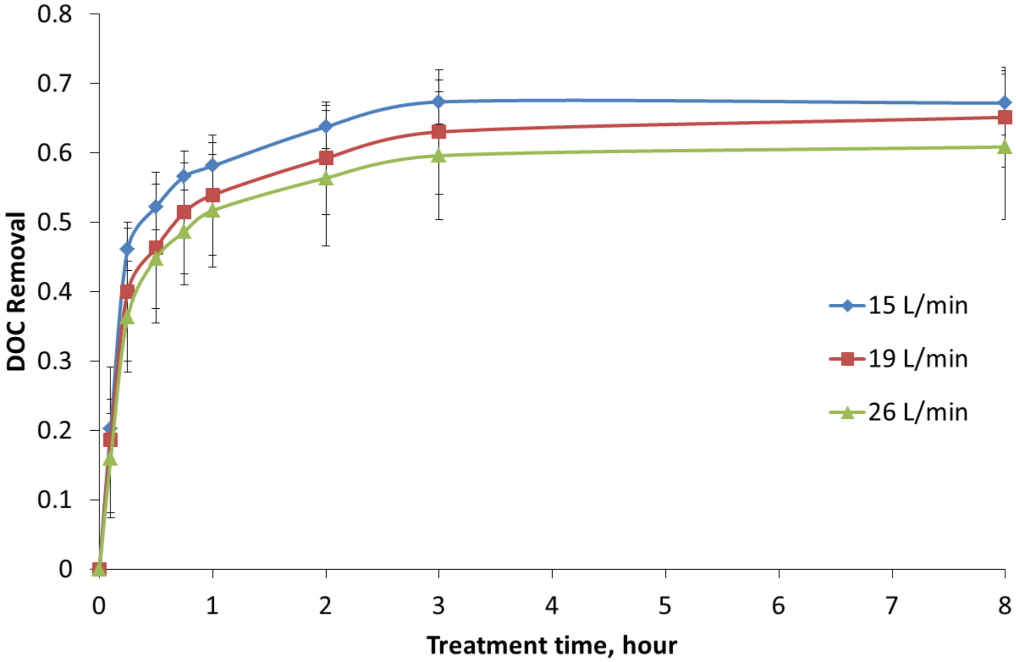


Figure 4.4 Dependence of DOC on treatment time for different recirculation flow rates. The results indicate that three hours of treatment was sufficient with marginal gain for longer treatment period. Lower recirculation flow rate resulted in higher DOC removal. Error bars represent one standard deviation of a range of results of multiple runs.

The origin of turbidity was investigated by comparing the particulate fraction of the organic carbon obtained from subtracting measured DOC from TOC with the overall measured turbidity. The linear correlation between turbidity and particulate organic carbon (**Fig. 4.5**) suggests that turbidity was primarily of organic origin. It is also noted that the various personal care products used by the residents contained 128 ingredients (reported by the manufacturers) of which 95% were organic compounds that could adsorb onto particulate /colloidal matter in the raw graywater. Given the above, it is not surprising that efficient turbidity removal also resulted in TOC removal which was enhanced by the recirculation through the wetland [197] in addition to possible adsorption onto the coconut coir matrix.

The graywater treatment system achieved ~2.3-log reduction of total coliform (i.e., from average influent coliform count of 1.35×10^8 MPN/100 mL to 6.49×10^5 MPN/100mL in the treated effluent). Fecal coliforms were not detected in the influent or effluent samples. Moreover, upon chlorine disinfection to achieve residual chlorine concentration of 4 mg/L, total coliforms were reduced to below the detection limit of 1 MPN/100 mL. This indicates that simple chlorination of the treated effluent should be sufficient for meeting the stringent California total coliform count limit of 2.2 MPN/100 mL for aboveground non-potable water reuse (**Table 4.1**).

Finally, it is interesting to note that over the course of the eight-month study period, the ordinary household plants *Aeonium purpureum* and *Crassula ovate, Equisetum hyemale, Nasturtium, Narcissus*, *impatiens*, *Anigozanthos*, and *Colocasia* thrived and appeared to be most adaptable in the wetland environment. Earthworms were also found in the wetland during the study period, which are known to reducing sludge accumulation in wetlands [202].

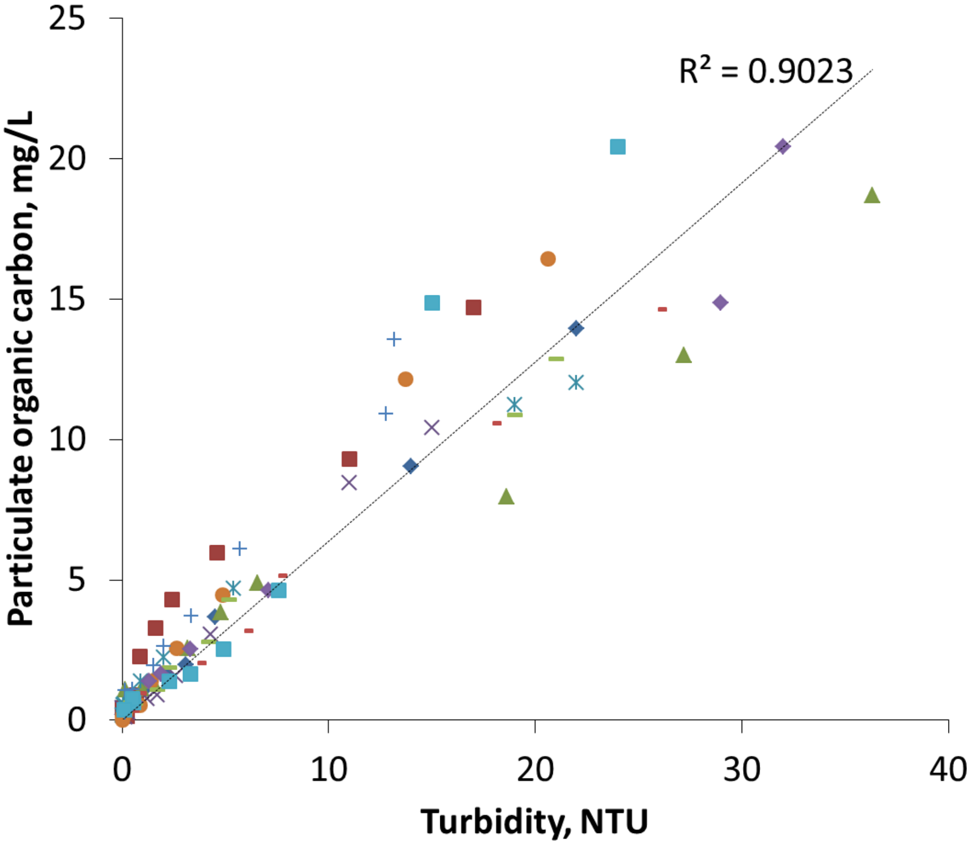


Figure 4.5 Particulate organic carbon and turbidity exhibit a linear relationship indicating that graywater turbidity was primarily organic in origin

4.3.2 Evaluation of operational and design parameters

The system had a volumetric treatment capacity of 0.3 m^3 per treatment cycle (~3-hour treatment time per batch and short system charge and emptying times of ~15-20 minutes), thereby enabling total daily graywater treatment of ~2.1 m^3 in seven treatment cycles. This translates to a hydraulic loading rate of 3.1 m^3/m^2-day for the system area of 0.68 m^2. In practical terms, the present system design is sufficient for treating graywater from one up to about six single family homes. Scale-up to multifamily dwellings should be feasible given the capacity and modularity of the SB-VFW design.

In order to further evaluate the potential scale-up of the SB-VFW approach to graywater treatment, a simple mathematical model was developed for the idealized process as depicted in **Fig. 4.5.** In the model formulation, the wetland was approximated as a plug-flow reactor without dispersion, whereby the reservoir below the wetland was approximated as a completely mixed reactor. For the above system, bDOC level was modeled subject to the following approximations: (a) bDOC removal can be described by a first-order kinetics model, (b) no loss of biomass over the treatment period, (c) negligible water evaporation over the course of a single batch treatment cycle, (d) water distribution over the wetland was reasonably uniform (this was verified via a series of hydraulic studies (**Section 4.2**)), and (e) negligible biofilm sloughing at the low recirculation flow rate employed. Accordingly, the bDOC C_x (mg/L) change, along the depth L of the wetland, can be expressed by the following differential mass balance:

$$\frac{dC_x}{dx} = -k\frac{A\varepsilon}{Q}C_x \qquad (4.1)$$

where Q is the graywater recirculation flow rate (m^3/hr), A is the wetland surface area (m^2), ε is the wetland porosity, k is the removal rate constant (hr^{-1}), and x is the distance from the wetland surface downward and t is time (hr). The above approach is similar to that used in trickling filter models [220-222]. The solution of Eq. (1), subject to the upper boundary conditions of $C=C_0$ at $x=0$ and a lower boundary condition of $C=C_L$ at $x=L$, is:

$$C_L = C_0 \exp\left(-k\frac{A\varepsilon L}{Q}\right) \tag{4.2}$$

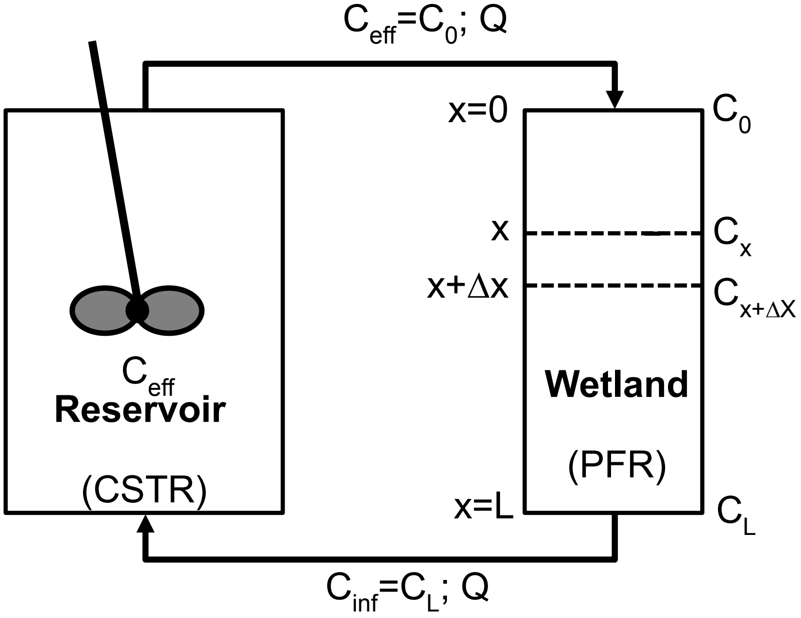


Figure 4.6 A schematic of the batch graywater treatment process. C_{inf} and C_{eff} are the concentrations in the inflow graywater to the wetland system and in the water outflow (after a single pass through the wetland), respectively. Moreover, as shown by the analysis, the design flexibility (e.g. system area, soil depth) and operability (e.g. hydraulic retention time) of the SB-VFW could be advantageous when space in residential homes is limited; and Q is the recirculation flow rate

It is noted that the effluent from (C_L) and inflow to (C_o) the wetland are equal to the influent bDOC (C_{inf}) from and effluent bDOC (C_{eff}) to the reservoir below the wetland (i.e., $C_L=C_{inf}$ and $C_{eff}=C_o$), respectively. Assuming negligible bDOC removal in the well-mixed reservoir of volume V_R compared to that in the wetland, the rate of change of bDOC in the reservoir is given as:

$$\frac{dC_{eff}}{dt} = \frac{Q}{V_R}\left(C_{inf} - C_{eff}\right) \qquad (4.3)$$

which can be solved setting $C_{eff} = C_o$ noting that $C_{inf} = C_L$ and then combining Eqs. (4.2) and (4.3) to yield

$$\frac{dC_{eff}}{dt} = -\frac{Q}{V_R}\left[1 - exp\left(-k\frac{A\varepsilon L}{Q}\right)\right]C_{eff} \qquad (4.4)$$

Upon integration of Eq. 4.4, with the initial value $C_{eff} = C_{i,gr}$ (i.e., bDOC concentration in the initial raw graywater batch) at t=0, the time dependent treated graywater bDOC in the reservoir (C_{eff}) is then given by:

$$C_{eff} = C_{i,gr} \cdot exp\left[-\frac{t}{\theta}\left[1 - exp\left(-k\frac{A\varepsilon L}{Q}\right)\right]\right] \qquad (4.5)$$

in which θ is the hydraulic retention time in the wetland layer (i.e., the ratio V_R/Q). The average bDOC removal rate constant (*k*) in Eq. (4.5) can be extracted from the time-evolution data of the graywater effluent bDOC. In this approach, *k* is considered an overall bDOC removal rate constant, which can be a function of the graywater properties as well as the wetland's biomass content. Using operational data over periods of 2-3 weeks each for three different wetland hydraulic retention times (0.19 hr, 0.27 hr and 0.33 hr; equivalent to hydraulic dosing rate of 3.18 m^3/m^2-hr, 2.29 m^3/m^2-hr and 1.32 m^3/m^2-hr, respectively), the average *k* value was determined to be 5.8 ± 0.9 hr^{-1}. The model fit to the data (with an average $R^2 = \sim 0.99$ for the comparison of predicted versus measured values and average absolute relative error of 2%) for the different cases is shown in **Fig. 4.6** for a different values of the hydraulic retention time (θ) in the wetland, area (A), and soil depth (L). The above removal rate constant was adopted as a reasonable value for assessing the expected treatment performance and economic feasibility of the present SB-VFW system.

Performance sensitivity evaluation of the graywater treatment system with respect to bDOC was conducted with the model as per **Eq. 4.5** using the average bDOC removal rate constant of 5.8 hr^{-1}, as a function of: a) hydraulic retention time (θ) in the wetland; b) wetland bed thickness (L); c) wetland area (A), and d) removal rate constant (k). In all cases, graywater treatment effectiveness was evaluated based on a 3-hour treatment time or 7 cycles per day. As shown in **Fig. 4.7(a)** reducing the wetland hydraulic retention time in the wetland by nearly a factor of five (from 0.3 hr to 0.06 hr) will have little impact on the treatment time necessary to achieve 98% bDOC removal. Increasing hydraulic retention time beyond one hour would significantly increase the required treatment time (e.g., treatment time of 6-8 hrs for a corresponding θ range of 1-1.5 hr). The above behavior can be rationalized by noting that for the short 3-hr treatment time, the number of turnovers (i.e. of the reservoir water volume) decreases with increasing hydraulic retention time, therefore, resulting in reduced level of treatment. For the present system design, it appears that hydraulic retention time of ~0.3 hr is already near optimal for treatment of graywater at 0.3 m^3/batch. A deeper bed would shorten the treatment time necessary to achieve 98% bDOC removal (relative to the influent bDOC) (**Fig. 4.7b**) as an alternative to using a wetland of higher superficial area (**Fig. 4.7c**). However, it is noted that bDOC reduction (down to 1 mg/L) achieved with the present system (0.15 m soil depth and area of 0.68 m^2) was already well below the typical effluent concentrations from secondary wastewater treatment plants practicing biological nutrient removal [223].

The above analysis demonstrates that the current system design is adequate for treatment of bathroom graywater for aboveground non-potable reuse purposes as per the highest levels of treated graywater quality required in the USA (California and Wisconsin), the UK and Australia (**Table 4.3**). As shown by the analysis, the design flexibility (e.g., system area, soil depth) and operability (e.g., hydraulic retention time) of the SB-VFW could be advantageous when space in residential homes is limited. The present study was conducted in a Mediterranean-like climate, and thus deployment of SB-VFW in other climates may require design adaptation and operational optimization to account for temperature dependence and variability [224].

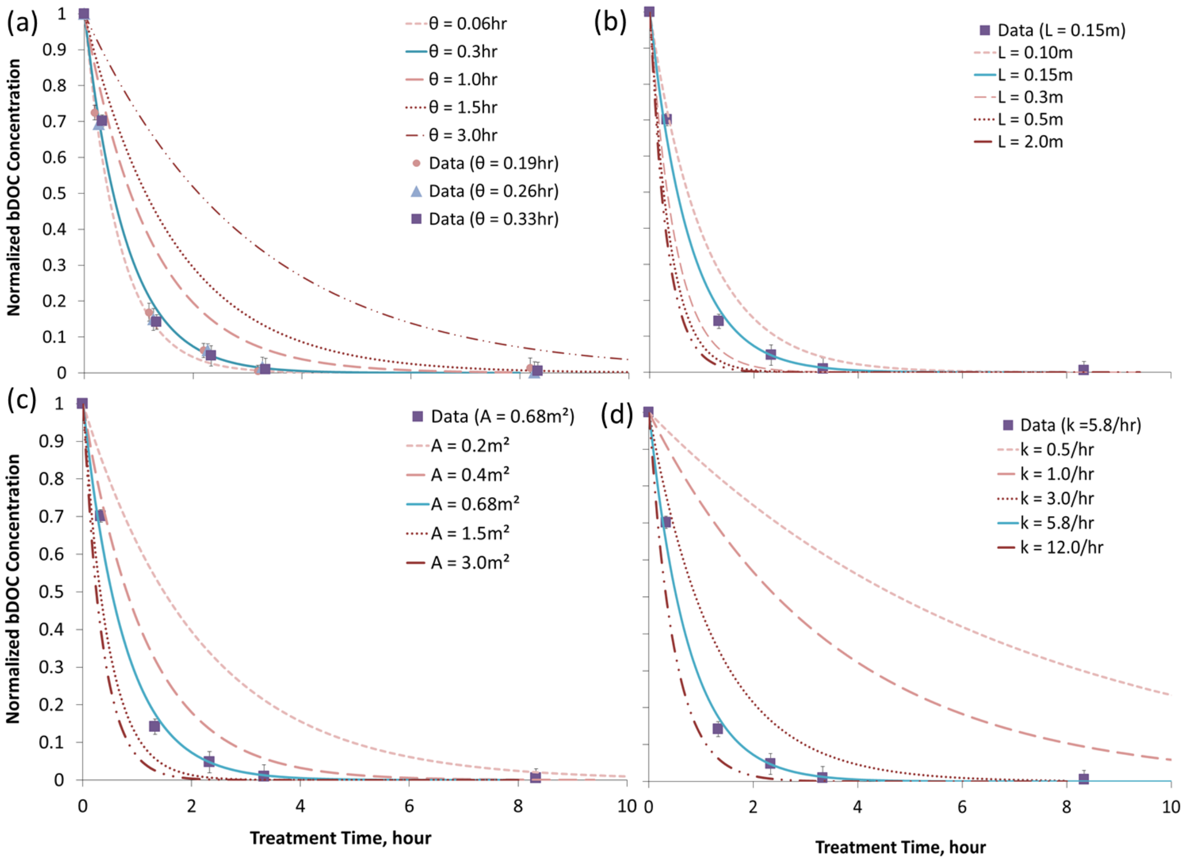


Figure 4.7 Graywater treatment performance sensitivity evaluation for the vertical flow wetland with respect to (a) hydraulic retention time (*θ*), (b) wetland bed thickness (*h*), (c) wetland area (*A*), and (d) bDOC removal rate constants (*k*). A hydraulic retention time of θ= 0.33hr was used in generating (b), (c) and (d). The bDOC removal rate constant $k = 5.8$ hr^{-1} was used in (a), (b) and (c). Error bars represent one standard deviation of the sample data.

4.3.3 Economic assessment of residential deployment of the treatment system

Economic analyses of breakeven periods and return-on-investment (ROI) were carried out with respect to daily graywater treatment volume for deployment of a SB-VFW system in a single family home. The capital and O&M costs used in the analyses were based on system construction costs and O&M cost data generated from the field study. It is estimated that the capital cost of a prefabricated system (including system delivery and installation) could range from \$1000 to \$2500 depending on the level of system automation. Specifically, capital cost for a manual system is estimated to be in the range of \$1,000 - \$1,500; while the capital cost for an automated system would be in the range of \$2,000 - \$2,500. The upper bounds on the capital costs for manual and automated systems were used in a conservative calculation of the ROIs for deployment in different countries. These costs were adjusted according to the consumer price indices (CPI 2005 = 100, [225]). The cost-savings and operational costs (i.e. electricity cost) were calculated considering local utility rates. The labor costs associated with annual maintenance were adjusted according to the gross national incomes (GNI, [225]) relative to the United States. **Table 4.4** lists the utility rates, CPIs and GNIs of selected countries used in the ROI analysis.

The breakeven period, Y, was defined as the time required for the accumulative total net cost-savings from water conserved and avoided sewer charges to be equal to system capital costs, i.e.,

$$Y = \frac{P}{\alpha W \cdot V_d - \alpha E \cdot R \cdot V_d - M} \tag{4.6}$$

in which P is the system capital costs (\$), Y is the breakeven period (year), W is the water rate (\$/m^3), V_d is the daily volume to be treated and reused (m^3/day), E is the daily power consumption (kWh/m^3), R is the electricity rate (\$/kWh), α is the conversion factor (356 days / year), and M is the annual maintenance cost (\$/year). The breakeven period depends on system capital cost (including installation), O&M costs, the daily volume of graywater generated, system treatment capacity, and the amount of conserved potable water. Given the relatively low cost of the treatment systems, financing cost was assumed negligible. Also, since the cost estimate focused on the treatment system itself, costs of house plumbing retrofit were not considered as part of the system capital or O&M costs. Retrofitting costs can be highly variable depending on the type of house construction and possibly lowest for new construction. Following the above approach, return-on-investment (*ROI*), determined as the ratio between net cost-saving from avoided water consumption cost (including the cost of water and sewer charges, if present) and system capital cost, as an indicator of economic viability of the treatment system was determined from,

$$ROI = \frac{(\alpha W \cdot V_d - \alpha E \cdot R \cdot V_d - M)}{P} \times 100\% \tag{4.7}$$

Table 4.3 Average combined water and sanitation tariffs and electricity rates used to calculate cost-savings from water conservation and the operational costs for the graywater treatment system

Countries / City	Australia	Denmark	Germany	Greece	Mexico	USA	Los Angeles
Average water cost $^+$, US\$/m^3 ^{a}	3.40	8.61	5.56	1.58	0.37	2.10	2.96 ^{d}
Electricity rate, US\$/kWh ^{b}	0.40	0.40	0.35	0.17	0.19	0.13	0.21
Consumer price indices (2005 = 100) ^{c}	108.51	114.87	87.14	83.79	46.96	77.39	--
Gross national income per capita ^{C}, \$	59,360	59,850	44,260	23,260	9,640	52,340	--

Note: $^+$ includes water cost and sewer cost if present; ^{a} [226]; ^{b}[227]; ^{c} [225]; ^{d} [228]

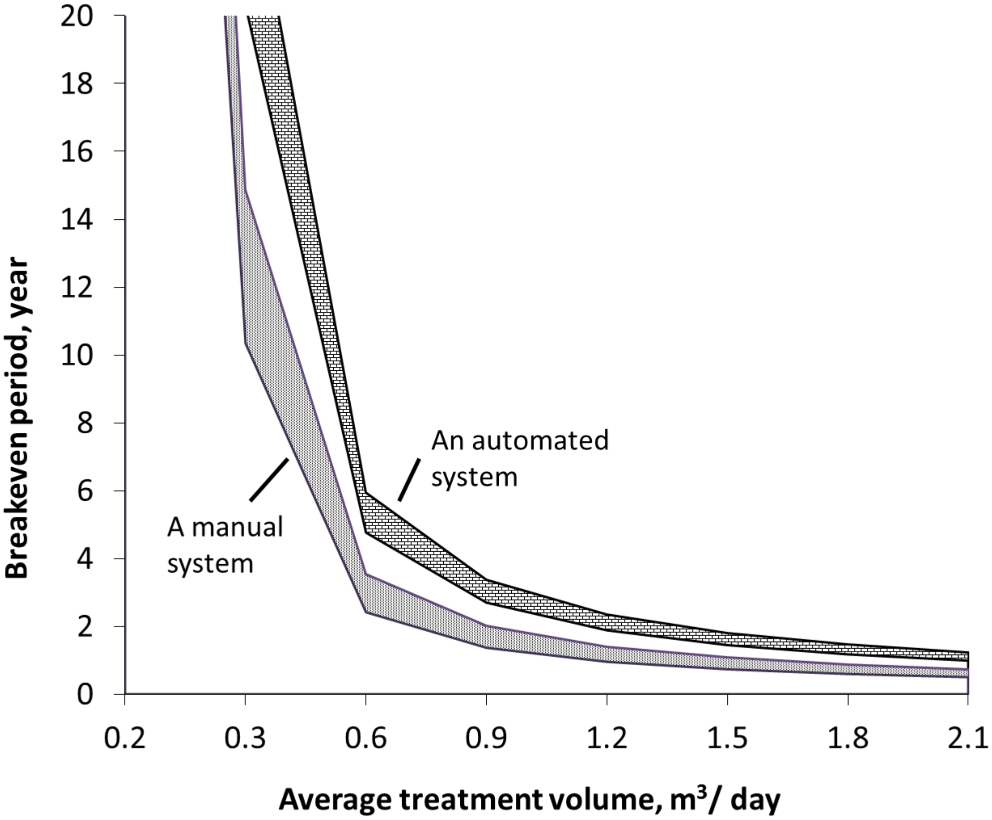


Figure 4.8 Variation of the breakeven period with daily treatment volume for an automated and manual treatment systems with estimated retail price ranges of $2,000-$2,500 and $1,000-$1,500, respectively, for the City of Los Angeles

Following the above, the breakeven periods and ROIs for deployment of a SB-VFW in a single family home in Los Angeles and in selected countries were determined as a function of the treatment volume (**Figs. 4.8** to **4.10)**, respectively. The breakeven period shows that there is a significant economy of scale. The higher priced automated system has longer breakeven period but, as expected, the difference diminishes as the daily treatment volume increases. It is noted that, the breakeven curves in **Fig. 4.8** are not smooth because the system must operate with an integer number of treatment cycles. At daily treatment volumes greater than 0.6 m^3/day, the breakeven period for the manual system is less than 2.5 – 3.5 years; while a breakeven period of

4 – 6 years would be required for the automated system. A breakeven period shorter than 2 years is expected for daily treatment volume above 0.9 m^3/day (3 batches/day) for a manual system and >1.2 m^3/day (4 batches/day) for an automated system. Given that bathroom graywater production is ~ 64 L/day-capita in California [48], property owners of large households or multifamily homes could breakeven within a relatively short period even in the absence of financial subsidies.

In the absence of financial subsidies, water cost will govern the financial benefits of onsite graywater reuse for end users. High water costs in countries, such as Denmark and Germany, would provide high ROIs even for a system that would treat only a small daily volume of graywater (**Fig. 4.9** and **Fig. 4.10)**. In countries or areas with high cost of electricity relative to that of water, such as in Mexico, the ROI will be lower. In extreme cases of high electricity cost, treating graywater may not be economically beneficial as is indicated by negative ROIs (**Fig. 4.9** and **Fig. 4.10**). Clearly, higher water costs, relative to electricity costs will make onsite graywater recycling more economical in single-family homes. In countries or regions with low water cost relative to electricity cost, graywater treatment will be less favorable, and may be economically feasible only for larger-scale deployment. In some special cases, such as in areas with limited access to centralized sewers and wastewater treatment systems, graywater treatment and reuse may be justified given the benefits of reducing sewage flows. Graywater treatment may also be advantageous in developed areas with collection and treatment systems that are at capacity or overloaded. Therefore, the addition of graywater treatment may extend the life of existing treatment systems and avoid capital expansion while providing an alternative avenue for increasing water reuse.

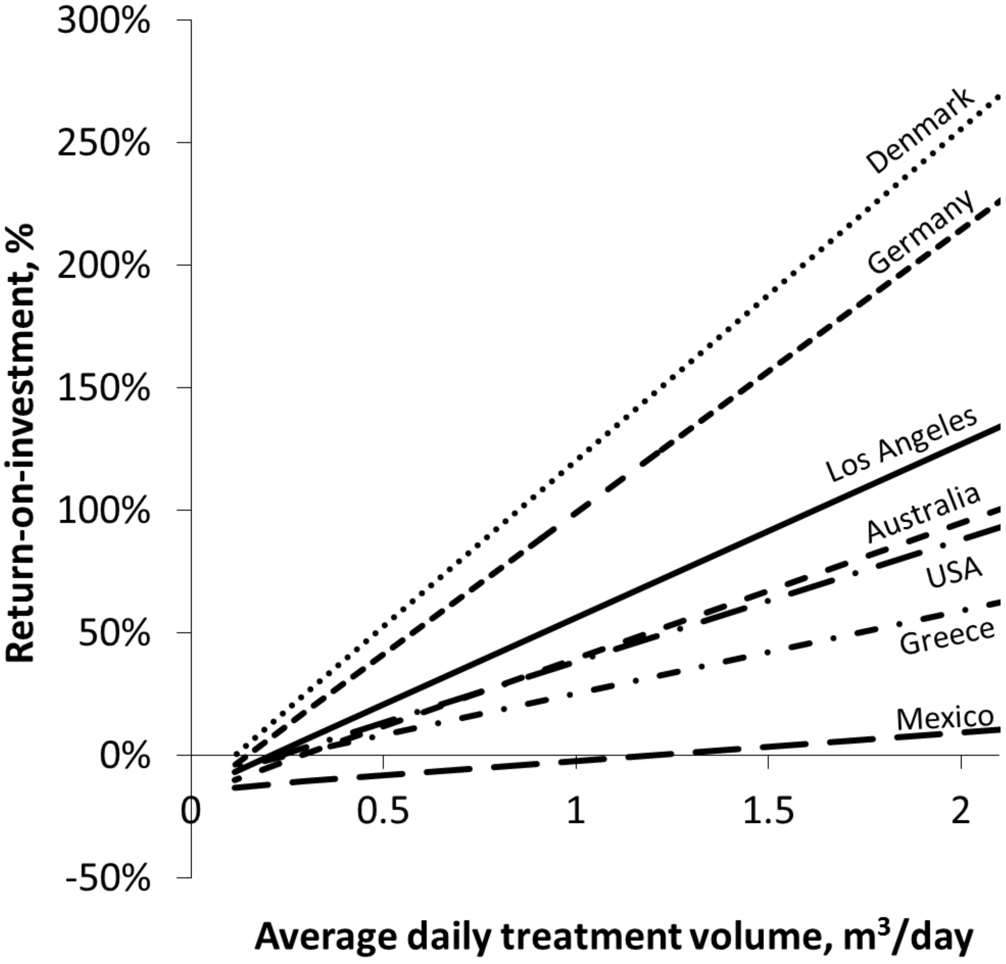


Figure 4.9 ROI of a manual treatment system with the estimated upper retail price range of \$1,500. The ROIs for an automated treatment system (upper capital cost range = \$2,500) follows the same trend, but with ~ 40% lower ROI compared to a manual system

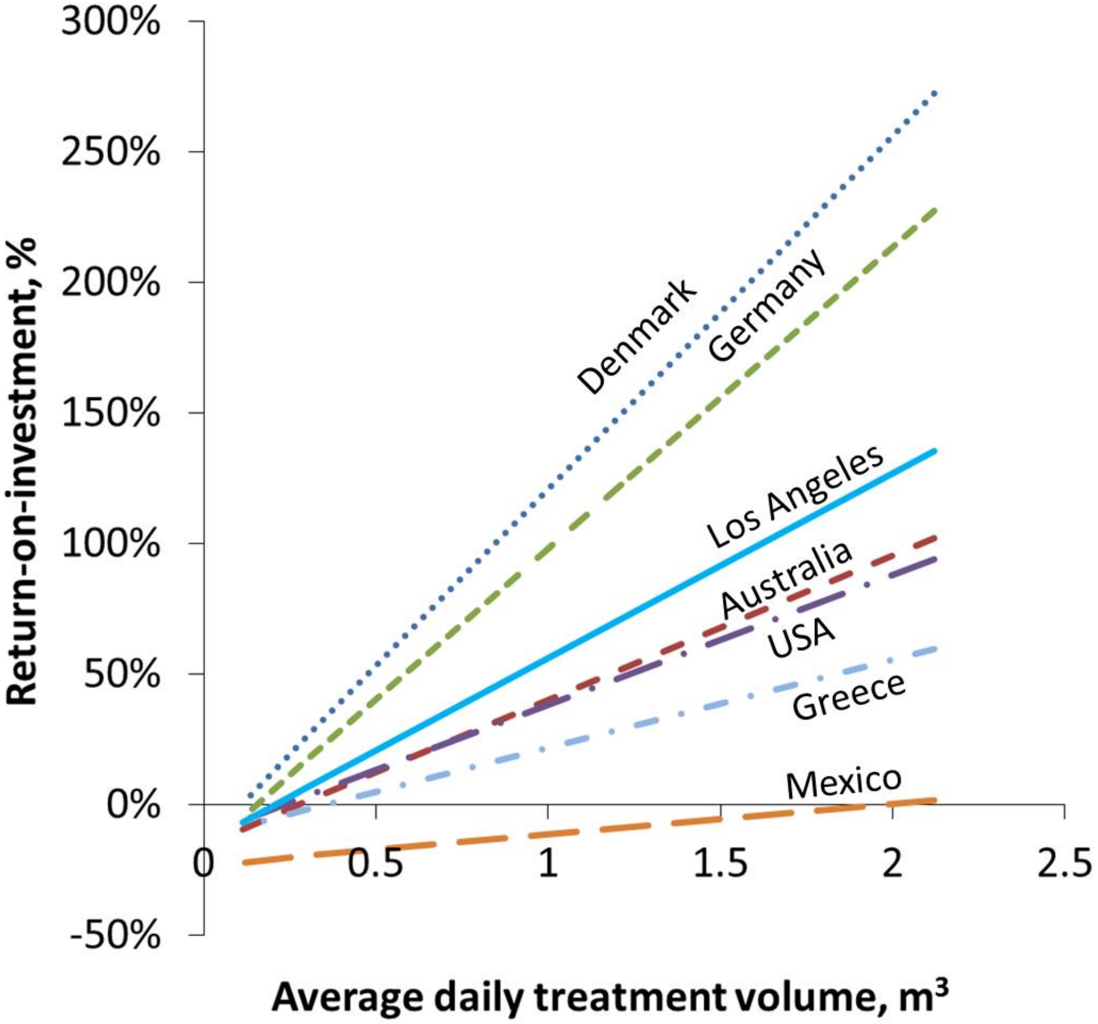


Figure 4.10 The ROI of an automated treatment system with the estimated upper retail price range of $2,500

4.4 Conclusions

Graywater treatment performance and economics of a low-cost and compact semi-batch vertical flow wetland (SB-VFW)for residential deployment were investigated in an eight-month pilot field study. Treatment of bathroom graywater (from showers, baths and bathroom sinks) produced effluent of high quality within treatment time of three hours. The treatment process followed first-order kinetics and treated effluent turbidity (~0.3 NTU), and BOD_5 (~3.1 mg/L) meeting graywater reuse guidelines for non-potable applications. After disinfection, total coliform counts were below the required 2.2 MPN/100mL for aboveground water reuse. Economic analysis showed that, for the present type of treatment systems (costing $1000 to $2500 for a treatment capacity of 0.21 m^3/day), the breakeven period was in the range of 2 to 6 years depending on the daily treatment volume. Higher water costs (water cost plus sewer charges, if present) favor graywater treatment, especially when electricity costs are modest or low. However, if electricity costs are high relative to water cost, graywater treatment is less favorable or may even result in negative ROI. With appropriate financial conditions or subsidies, onsite graywater recycling can have positive environmental and societal impacts in areas of limited or no sewer or wastewater treatment access. A decentralized graywater treatment approach may also provide financial benefits from reduced need for capital expansion or retrofitting existing centralized systems while increasing water reuse opportunities. The results of this study suggest that there is merit in exploring distributed deployment of residential graywater systems and further evaluating the efficiency of the approach for treatment that also includes laundry water.

5 TREATMENT OF BATHROOM AND LAUNDRY GRAYWATER USING THE SB-VFW AND THE EFFECT OF DETERGENT TYPES ON ITS TREATMENT PERFORMANCE

5.1 Introduction

In Chapter 4, a low-cost semi-batch vertical flow wetland (SB-VFW) that used coconut-coir soil substitute deployed in a single-family home for treatment of bathroom graywater showed that it produced effluent quality meeting stringent aboveground graywater reuse requirements (**Table 4.1**). However, the treatment performance for treating graywater containing laundry wastewater has not been evaluated. In this Chapter, the graywater SB-VFW treatment system was used to further optimize the treatment approach in a five-month field study with the following specific objectives: (a) demonstrate the feasibility of achieving water quality (e.g., BOD5, TOC and turbidity) for permitted aboveground non-potable reuse even with the inclusion of laundry graywater (**Table 4.1**), (b) assess the potential for simultaneous nitrification and denitrification, and (c) evaluate treatment effectiveness when using a bio-based laundry detergent with the goal of reducing graywater organic content and avoiding excessive biofilm growth.

5.2 Materials and methods

5.2.1 Materials and graywater sources

The performance of the graywater treatment system (described in **Section 4.2.2**) was evaluated for treatment of bathroom, showers, handwashing sinks and laundry waters. Two types of detergents were used for clothes washing: (a) a United States Department of Agriculture certified bio-based laundry (BBL) detergent, (b) a conventional non-bio-based laundry (non-BBL) detergent. The BBL detergent was reported to be less toxic to graywater effluent microbial community compared to the non-BBL detergent [229]. The non-BBL detergent contained 22 organic compounds; while the BBL detergent contained 16 ingredients, seven of which were organic compounds and nine were inorganic compounds. The total organic carbon (TOC) content for the BBL and non-BBL detergents were determined (**Section 4.2.3**) to be ~72 mg-TOC/g-detergent and ~150 mg-TOC/g-detergent, respectively.

5.2.2 Graywater treatment system

Onsite residential graywater treatment and reuse was evaluated over a five-month study with an automated SB-VFW system (**Fig. 4.1**) deployed in a single-family home. The wetland (top) and reservoir (bottom) units had dimensions of 1.1 m (L) x 0.7 m (W) x 0.7 m (H). The wetland unit consisted of a bottom plastic container, with large holes bored through the bottom, for housing a coconut coir soil substitute layer (the "soil" layer) placed above a layer of cross-flow media (CFM). The soil layer, which was compartmentalized using fabric containers (SmartPots, Oklahoma City, OK), served as the medium for soil microbial community and for plant growth. A number of ordinary garden plants, along with wetland plant species (*Carex spissa* and *Phyla nodiflora*), were planted in the wetland. Household garden plant species included *Aeonium purpureum* and *Crassula ovate, Equisetum hyemale, Nasturtium, Narcissus impatiens*, *Anigozanthos*, and *Colocasia.* The viability of the plants was assessed based on their overall appearance, e.g. leaf greenness and ability to produce flowers for flowering plants. CFM installed below the soil layer had a specific surface area of 226 m^2/m^3 (AccuPac Cross Flow Media, Brentwood Industries, Reading, PA). The CFM provided structural support for the soil layer with its open channel configuration enabling significant aeration while avoiding channel clogging. Dripping water from the wetland unit was captured by the reservoir below (the bottom reservoir), from which water was recirculated to the wetland during the treatment period.

Graywater, which was recirculated from the bottom reservoir, was distributed over the wetland using a gravity-driven flow distribution system. The distribution system consisted of partially filled enclosed conduits with holes at the bottom (installed just above the soil layer), which were arranged to facilitate even flow distribution over the wetland. Uniformity of the flow distribution was verified by determining the local flow rate at the different locations beneath the wetland unit. The enclosed conduits also served to avoid direct human contact with graywater and reduce water loss due to evaporation. The recirculation flow rate was measured by an inline paddlewheel flow meter (GF Signet P51530-P0, El Monte, CA) connected to a powered transmitter/totalizer (GF Signet 3-8550-2, El Monte CA).

Automated system operation was enabled by a low-cost irrigation controller for operation of the system pumps for water inflow to the SB-VFW, recirculation within the SB-VFW system and water outflow for reuse (**Fig. 4.1**). Graywater was pumped from the collection tank to the SB-VFW system using a submerged sump pump having a maximum pumping flow delivery of up to 3,400 L/hr (Little Giant 5-ASP, Fort Wayne, IN) that was installed inside the collection tank. A small fountain pump (100 W) (Laguna Maxflow 2400, Mansfield, MA) submerged in the bottom SB-VFW reservoir was used for graywater recirculation. A third sump pump (Little Giant 5-ASP, Fort Wayne, IN) in the bottom reservoir served for pumping the treated effluent for irrigation. In principle, a single pump could be used for both recirculation and for outflow (e.g. irrigation); however, for the purpose of the present study, two pumps were used to simplify the operational control.

The SB-VFW system was designed to operate in a semi-batch mode given the intermittent generation of graywater. A collection tank of 300 L storage capacity was used for collecting and storing raw graywater between treatment cycles. Raw graywater entered the collection tank by gravity feed and was first filtered through a nylon filter fitted over the inlet pipe in order to protect the sump pump from being damaged by hair and other stringy substances. Once filled, raw graywater was pumped from the collection tank to the wetland feed distribution system with graywater recirculating (through the wetland unit) until the treated graywater effluent discharge.

5.2.3 Analytical methods

The SB-VFW system treatment effectiveness was evaluated based on water quality analysis of the influent and treated effluent. Grab samples were collected directly from the mid-water column of the collection tank (influent) and the reservoir of the SB-VFW system (effluent) using two auto-samplers (Hach Sigma MAX900, Loveland, CO). For each experiment, influent samples were collected just prior to pumping the graywater into the SB-VFW system, Grab effluent samples from the SB-VFW system were collected for evaluation over a 24-hour period at times of 0, 0.5, 1, 2, 3, 8 and 24 hours. Collected samples were kept in a cooler (< 4°C) before transporting back to the laboratory for water quality analysis. It is noted that all the reported water quality data are provided as average values over the different operational periods unless specified otherwise.

Water quality of the treated graywater was evaluated with respect to the SB-VFW system's ability to remove organics (TOC, five-day biochemical oxygen demand (BOD_5), and chemical oxygen demand (COD)), TSS and turbidity to levels that would meet the aboveground nonpotable water reuse requirements (**Table 1**). System performance was also assessed with respect to removal of ammonium-nitrogen (NH_4-N) and Nitrate-Nitrogen (NO_3-N). The study consisted of two phases. Phase I focused on evaluating the long-term treatment performance of the SB-VFW system for graywater that contained BBL detergent from clothes washing daily. Additionally, detergent shockload tests were performed in two consecutive days to evaluate the impact of sudden increase in organics and turbidity on treatment performance. On the first day of the detergent shockload test, 160 g of BBL detergent was added into the 300 L graywater collection tank containing the raw graywater, followed by manual mechanical mixing prior to taking a grab sample for analysis. The raw graywater was then pumped into the treatment system and the recirculation commenced. On the next day, 80 g of BBL detergent was added into 300 L of raw graywater and a grab sample was collected for analysis. Effluent samples were collected at 0, 0.5, 1, 2, 3, 8 and 24 hours and analyzed for turbidity and organics for each day of the detergent shockload tests. During Phase II, non-BBL detergent was used by the residents. Water sampling and laboratory analysis protocols in Phase II were identical to those used in Phase I. Detergent shockload was not conducted during Phase II because of rapid deterioration of treatment performance during the first month after commencing with the treatment of non-BBL graywater.

Total organic carbon (TOC) and dissolved organic carbon (DOC) were determined using Standard Methods 5310C (Aurora 1030D TOC Analyzer, OI Analytical, College Station, TX). Samples for DOC analysis were prepared by water samples filtration through 0.8 μm filters (MCE with modified acrylic housing, Millipore Millex Sterile Syringe Filters, EMD Millipore, Billerica, MA). In order to determine the biodegradable portion of the TOC in the influent and effluent streams, five-day seeded TOC tests [230] were conducted. For both cases, 300-mL volume samples were placed in amber bottles and kept in the dark at room temperature (22°C). In the five-day test, the influent was seeded with 1mL of the effluent. It is noted that the effluent was not added to the influent sample in the non-seeded biodegradable TOC test, and the effluent samples were not seeded. All samples were aerated daily (during the test period). The difference in TOC before and after the above tests represented the level of non-biodegradable organics.

Turbidity (USEPA Method 180.1; 2020 Portable Turbidity Meter, LaMotte, Chestertown, ML) was used as the primary monitoring parameter to assess reduction in suspended particles/colloidal matter. Other monitored inorganic water quality parameters included pH, conductivity (Oakton CON 11 Economy Meter, Vernon Hills, IL), temperature, total inorganic carbon (Standard Methods 5310C; Aurora 1030D TOC Analyzer, OI Analytical, College Station, TX), particle size (AccuSizer 780, Santa Barbara, CA), ammonium (Hach Method 10205, Loveland, CO), nitrate (Hach Method 10206, Loveland, CO), phosphate (Hach Methods 10209 and 10210, Loveland, CO), and dissolved oxygen (Dissolve Oxygen Tracer PocketTester, LaMotte, Chestertown, ML). While TOC and DOC were the primary parameters for monitoring organic concentrations, BOD_5 and COD were calculated by establishing the relationships between TOC and COD (COD:TOC ratio) and BOD_5 and COD (BOD:COD ratio) using three batches of samples. COD was calculated from the TOC using an influent COD:TOC ratio of 4.40, an effluent (after 3 hours treatment) COD:TOC ratio of 2.22 based on previous observations (Yu et al., 2014). The estimated COD was then used for calculating BOD_5. Influent and effluent (after 3 hours treatment) BOD_5:COD ratios were 0.31 and 0.16, respectively.

Biofilm growth on the CFM surfaces was evaluated using clear polyvinyl film sampling coupons that were attached to the bottom of the wetland unit. These coupons were sampled after three months of treating BBL graywater, and after a month of treating non-BBL graywater. The biofilm sample coupons were stained using gram stain (Gram Stain Advanced, Hardy Diagnostics, Santa Maria, CA), air dried, and cover-slipped in Prolong Gold (Life Technologies, Carlsbad, CA) before imaging on an Zeiss Imager D1 microscope with Axiocam ICc 1 color camera, and processed using the Axiovision Software (Zeiss Microscopy GmbH, Oberkochen, Germany).

5.3 Results and Discussions

5.3.1 Influent and effluent water quality

Raw graywater that contained laundry water generated from clothes washing using the BBL ("BBL graywater") or non-BBL ("non-BBL graywater") detergents had organics, total suspended solids (TSS) and turbidity concentrations exceeding the water quality requirements for aboveground water reuse (**Table 4.1**). Continuous field operation of the SB-VFW system for the BBL and non-BBL graywater over 3.5 and 1.5 months, respectively, demonstrated that average treated water quality (**Table 5.1**) complied with the aboveground graywater reuse standards (**Table 4.1**). Significant turbidity removal was achieved with average effluent turbidity of 0.3 NTU for BBL graywater (relative to ~22 NTU for the raw BBL graywater) after three hours of treatment, and 0.1 NTU for non-BBL graywater (relative to ~30 NTU for the raw non-BBL graywater) after 24 hours of treatment. Such effluent levels were well below even the most stringent turbidity requirement of <2 NTU for aboveground graywater reuse in California (**Table 4.1**).

Table 5.1 Water quality of influent (raw) and treated (effluent) BBL and non-BBL graywater

	BBL Graywater		**Non-BBL graywater**	
	Raw graywater (a)	Effluent after 3-hr (a) treatment	Raw graywater (b)	Effluent after 24-hr treatment (b)
pH	6.8	6.6	6.8	6.6 ± 0.1
TDS, mg/L	337 ± 28	347 ± 26	295 ± 7	313 ± 12
DO, mg/L	1.6 ± 0.4	4.9 ± 1.3	2.5 ± 1.8	7.0±1.3
Temp, C	21.4 ± 1.2	22.0 ± 1.0	20.1 ± 2.6	17.4 ± 2.6
Turbidity, NTU	21.6 ± 12.7	0.3 ± 0.3	29.8 ± 13.1	0.5 ± 0.1
TSS, mg/L	23.5 ± 9.3	<1	35.3 ± 1.3	< 1
TOC, mg/L	31.5 ± 8.9	6.2 ± 1.0	101.2 ± 22.0	8.0 ± 1.1
Total inorganic carbon (TIC), mg/L	29.4 ± 5.4	30.5 ± 6.3	21.1 ± 6.6	20.0 ± 8.0
DOC, mg/L	24.6 ± 7.7	5.6 ± 0.9	87.8 ± 17.5	7.7 ± 1.3
bDOC, mg/L	20.4 ± 7.7	1.4 ± 0.8	80.1 ± 15.5	2.5 ± 1.1
DIC, mg/L	28.6 ± 4.6	27.4 ± 5.7	19.0 ± 6.3	18.2 ± 7.8
Particulate TOC, mg/L	7.7 ± 2.7	0.5 ± 0.3	13.4 ± 4.6	0.4 ± 0.3
COD[a], mg/L	128 ± 46	6.0 ± 4.7	490 ± 112	17.4 ± 5.7
BOD[b], mg/L	40 ± 14	< 1	152 ± 36	2.8 ± 2.2
NH_4-N, mg/L	5.30 ± 1.95	1.70 ± 0.82	2.24 ± 0.39	0.10 ± 0.02
NO_3-N, mg/L	0.12 ± 0.05	2.47 ± 1.52	0.21 ± 0.03	0.13 ± 0.03
PO_4-P, mg/L	3.89 ± 0.73	2.44 ± 0.24	4.00 ± 0.80	2.13 ± 0.47

[a] COD was calculated from the TOC using an influent COD:TOC ratio of 4.40, an effluent COD:TOC ratio of.2.22 based on three selected observations from three separate treatment cycles (or days) collected in the same week (**Section 2.3**). Influent and effluent BOD:COD ratios were 0.31 and 0.16, respectively. N - number treatment cycles

(i.e., days); [(b)] average for 25 batches; [(c)] average for five batches. Note: Samples from two separate treatment cycles (i.e., days) were collected twice weekly and once per week when treating BBL and non-BBL graywater, respectively.

The BBL and non-BBL graywater effluent had low BOD_5 of 0.5 mg/L and 2.8 mg/L (representing reduction of >97% relative to both types of influent), respectively, and TSS of < 1 mg/L for both effluent (representing reduction of >97% and >95% relative to the influent graywater); the above treatment performance was also well within the BOD_5 and TSS requirements for aboveground graywater reuse in Australia and Wisconsin (**Table 4.1**). Raw BBL and non-BBL graywater pH was 6.8 (relative to tap water pH of 6.4) and decreased to 6.6 after 24 hours of treatment. The slightly higher raw graywater pH was likely due to the use of detergents containing alkalis (e.g., sodium bicarbonate and sodium citrate in BBL detergent, and monoetholamine citrate in non-BBL detergent), which increases surface charge of fabric and soil particles to enhance cleaning performance [231]. The slight reduction of graywater effluent pH after treatment could be due to alkalis reduction due to biodegradation of organic alkalis, such as citrate, or other physio-biochemical reactions that neutralized inorganic alkalis such as sodium bicarbonate and carbonate. The raw BBL and non-BBL graywater TDS levels were 337 mg/L (53% higher than tap water) and 295 mg/L (34% above tap water) and increased slightly (by 3% and 6%, respectively) after treatment. Such slight increase in TDS post treatment, although within experimental variability, could also be the result of dissolution of divalent salt precipitate (e.g., calcium carbonate present in the raw graywater) during recirculation in which the pH decreased relative to the raw graywater. It is also noted that the non-BBL graywater part of the study was commenced after 3.5 months operation with the BBL graywater. Therefore, it is possible that the non-BBL treated graywater effluent TDS was skewed to higher level than the influent due to slow release of sodium and/or calcium salts that may have accumulated in the soil matrix. Irrespective of the above, it is stressed that the treated effluent TDS for both types of graywater was well below the maximum recommended level (i.e. 1,000 mg/L for irrigation [232]).

The treatment time required for reaching the target effluent quality for aboveground nonpotable water reuse (**Table 4.1**) for BBL and non-BBL graywater were 3 and 24 hours, respectively. The above performance difference was attributed to the lower TOC level in the raw BBL graywater (~32 mg/L) with 22% of the TOC in particulate. The biodegradable dissolved organic carbon (bDOC) in the raw BBL graywater was at ~20.4 mg/L bDOC, which was about 64% of the total TOC level, and was reduced by 93% after 3 hours of treatment. On the other hand, the raw non-BBL graywater TOC was 101 mg/L with 14% of the TOC in particulate form, while the remaining being in dissolved form. Raw non-BBL graywater bDOC was 80 mg/L (accounted for 80% of the TOC), and was reduced by 99% after 24 hours of treatment (**Fig. 5.1a**). High TOC in the raw non-BBL graywater was attributed to both its high TOC content (150 mg TOC/g-detergent relative to 71 mg TOC/g-detergent for the BBL detergent) and its higher (recommended) detergent dosage. The recommended laundry dosages by the manufacturers for the non-BBL detergent were ~44 g-detergent/normal-load and ~64 g/heavy-load as compared to ~19 g-detergent/normal-load and ~38 g-detergent/heavy-load for BBL detergent, which led to higher TOC in the raw non-BBL graywater.

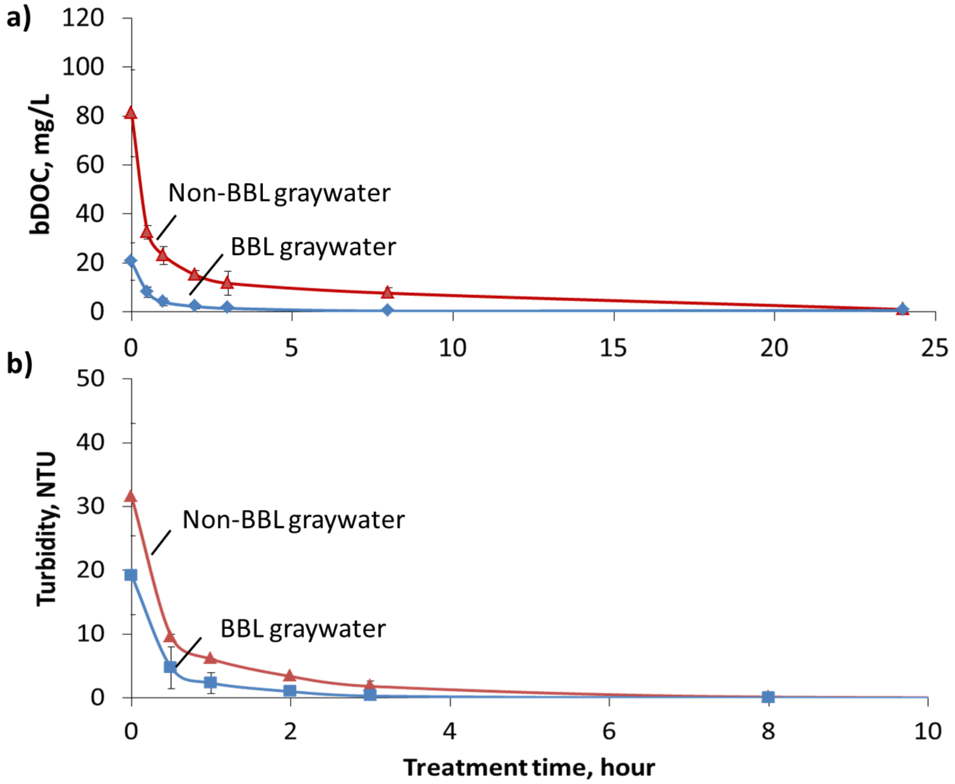


Figure 5.1 Average bDOC (a) and turbidity (b) removal of BBL (25 treatment cycles) and non-BBL (four treatment cycles) graywater indicates that the SB-VFW system was effective in removing both turbidity and bDOC. Error bars represents one standard deviation of the data set.

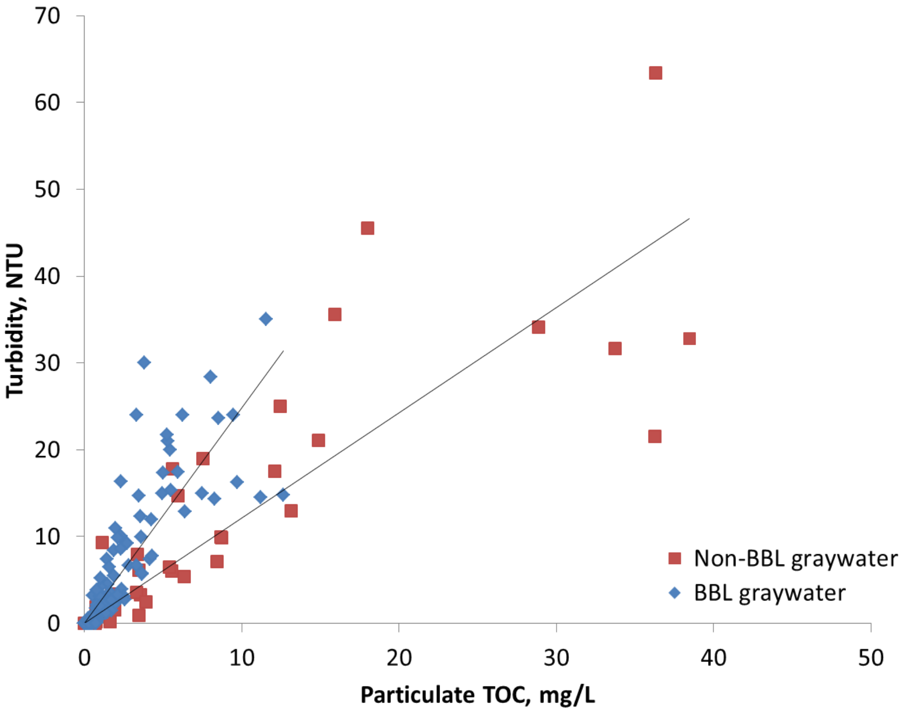


Figure 5.2 Correlation of particulate TOC (i.e. total TOC - DOC) with turbidity for the five-month study demonstrating a linear relationship suggesting graywater turbidity was possibly largely of organic origin. The data set comprised of 25 and 4 of 24-hour treatment cycles (i.e. days) of BBL and non-BBL graywater samples, respectively, collected over the five-month study period. The R^2 values for the BBL and non-BBL graywater linear correlations were 0.72 and 0.67, respectively

The raw graywater turbidity correlated linearly with the total organic carbon associated with particulate organics (i.e. TOC minus DOC, represented as particulate TOC) as shown in **Fig. 5.2**. The SB-VFW was effective for turbidity removal of up to 99% (from 30 NTU to 0.3 NTU) within three hours of treatment. Coincidentally, the time required for 93% bDOC removal was achieved in after three hour of treatment. A similar level of turbidity removal (~98%) was achieved for the non-BBL graywater within ~8 hours (to 0.5 NTU, **Fig. 5.1b**), along with 90% bDOC (to 8 mg/L bDOC) over the same period with further removal to 97% bDOC (to ~2.5 mg/L) at 24 hours. The slower bDOC degradation kinetics for the non-BBL relative to the BBL graywater for the SB-VFW system can be analyzed using a simple model that considers the hydraulic retention time in the wetland, wetland bed thickness, wetland area and removal rate constant [190]. Accordingly, the bDOC level can be expressed as

$$C_{eff} = C_{i,gr} \cdot exp\left[-\frac{t}{\theta}\left[1 - exp\left(-k\frac{A\varepsilon L}{Q}\right)\right]\right] \tag{5}$$

where C_{eff} is the effluent bDOC (mg/L), $C_{i,gr}$ is the influent bDOC, θ is hydraulic retention time in the wetland (i.e., the ratio V_R/Q, $\theta = 0.53$ hr); V_R is the reservoir volume ($V_R = 0.3$ m^3; L wetland bed thickness (L, L = 0.12 m); A is the wetland area (A = 0.68 m^2), Q is the graywater recirculation flow rate (Q = 0.58 m^3/hr), ε is the wetland porosity (ε = 0.9), *k* is the removal rate constant (hr^{-1}) and *t* is time (hr). The bDOC removal rate constants for BBL and non-BBL graywater being 4.0 hr^{-1} and 1.5 hr^{-1}, respectively, were determined from fitting Eq. 5 to the bDOC data (**Fig. 5.1**). It is noted that the faster bDOC removal kinetics for BBL graywater could be, in part, due to the greater biomass availability in the SB-VFW in comparison to that which is achieved with the BBL graywater of low content of degradable organics. The above results and improved treatment effluent quality for BBL graywater relative to non-BBL graywater suggests that use of BBL detergent would be preferable when considering residential graywater treatment and reuse.

5.3.2 SB-VFW system characterization and long-term treatment of BBL graywater

The SB-VFW wetland unit acted as a packed-bed filter that captured particulates and provided surface area for biofilm growth. Thin slimy ("biofilm") layers were observed on the CFM surface and plastic coupon samples just underneath the soil layer. Microscope biofilm images revealed a rich collection of diverse organisms (**Fig. 5.3**). The role of the CFM layer on bDOC and turbidity removal was evaluated by removing it from the SB-VFW system for 14 days. The effluent bDOC levels after three hours of treatment of BBL graywater with and without the CFM, were both ~1.3 mg/L (**Table 5.2**). Similarly, the effluent turbidity after three hours of treatment were ~0.3 NTU and 0.2 NTU with and without the CFM, respectively (**Table 5.2**). Turbidity and bDOC removal in the above tests indicated that the CFM did not affect removal of organics and turbidity. The CFM, however, enabled aeration enhancement during the treatment process (**Fig. 5.4**) as evident by the higher DO level (~6 mg/L) relative to the case without the CFM (~4 mg/L). High DO (e.g. > 6 mg/L) has been reported to enhance biodegradation of organics [233] as well as nitrification (> 5 mg/L DO) [234]. Furthermore, higher DO concentration allowed for greater oxygen diffusion into the biofilm, thereby enhancing organic degradation by the biofilm [235].

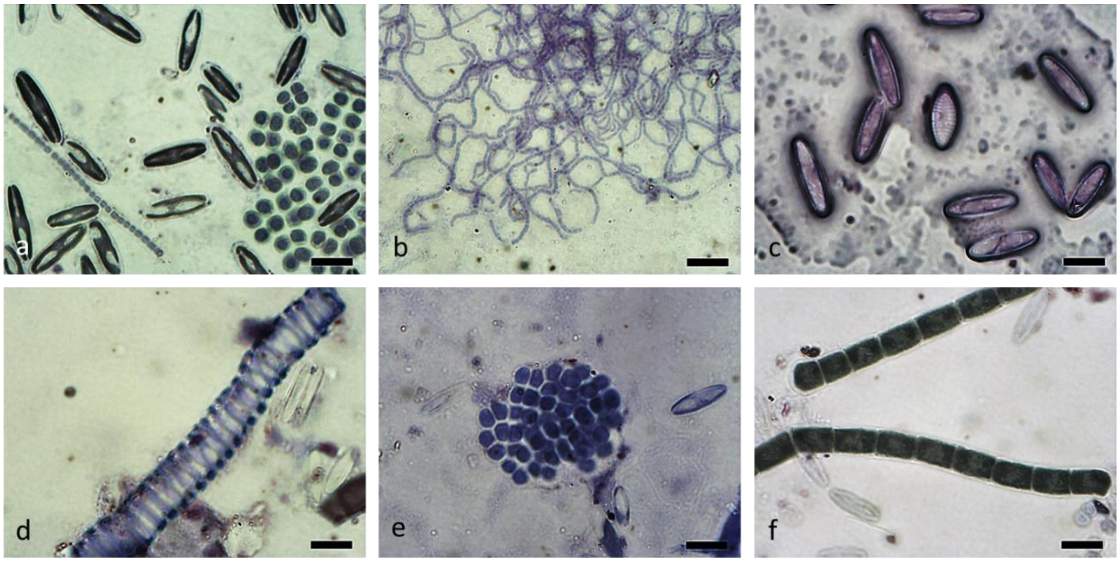


Figure 5.3 Microscopic images of biofilm collected from the plastic media when treating BBL graywater. a) protozoa and algae, b) fungi, c) protozoa and bacteria, d) protozoa, e) a cluster of algae, f) algae. The presence of protozoa suggests aerobic environment on the plastic media. Scale bars represent 10 µm

Table 5.2 Effluent bDOC and turbidity achieved by the wetland with and without the use of cross flow media

Parameters	Treatment time, hours	With CFM[a]	Without CFM[b]
bDOC, mg/L	3	1.3 ± 0.8	1.3 ± 1.2
	8	0.3 ± 0.2	0.2 ± 0.2
Turbidity, NTU	3	0.3 ± 0.1	0.2 ± 0.1
	8	0.0 ± 0.0	0.0 ± 0.0

Note: [a]10 graywater batches treated over five weeks; [b] 3 graywater batches treated during the same one week period

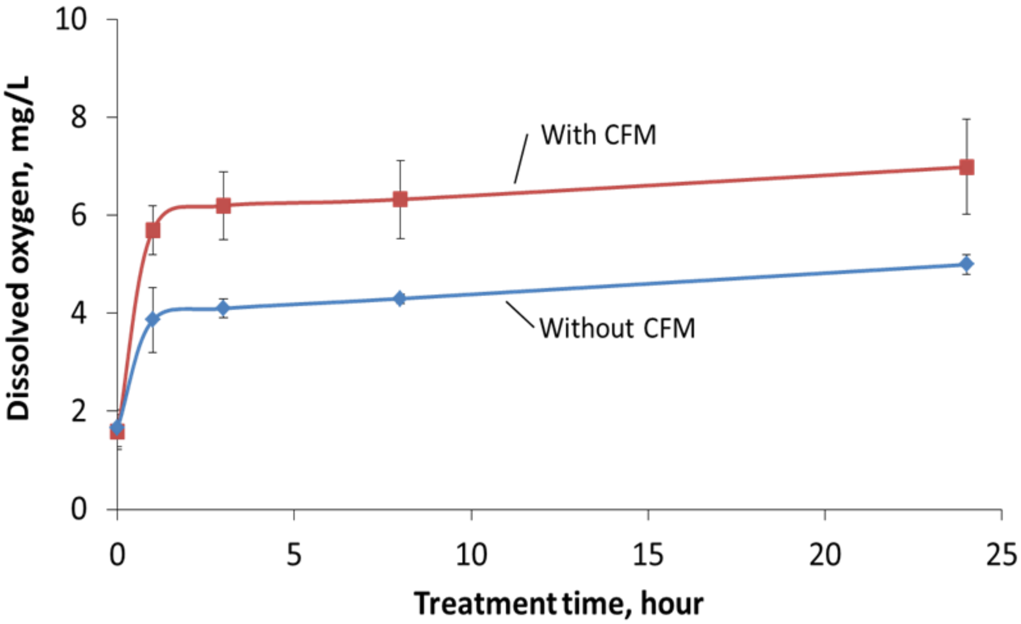


Figure 5.4 Dissolved oxygen level achieved for graywater treatment with and without the CFM over a period of 4 and 2 weeks of treatment, respectively

Particle size analysis revealed that the soil layer provided effective removal of particles from non-BBL graywater. The SB-VFW system was effective in removing large particles and achieved ~88% size reduction (i.e. from 56 µm to 6 µm) within the first hour of treatment (**Fig. 5.5**). Further reduction of particle size to 3.8 µm and 67% reduction of effluent particle concentration (down to ~5,800 particles/mL) was achieved after three hours of treatment (**Fig. 5.5**). Over the same treatment period, the effluent bDOC of ~1 mg/L was attained indicating that a limited source of organics was available for the microorganisms in the SB-VFW system. It has been shown that low organic content stimulates extracellular polymer substance (EPS) excretion by microorganisms, which would promote bioflocculation to form larger suspended particles in the water phase [236]. The presence of larger aggregates, as a result of bioflocculation, is indeed suggested by the suspended matter size increase (e.g. from 3.8 µm to 44 µm) and particle concentration decrease (e.g. from ~5,800 particles/mL to 2,000/ml after 24 hours of treatment), which are consistent with other biological treatment systems [237].

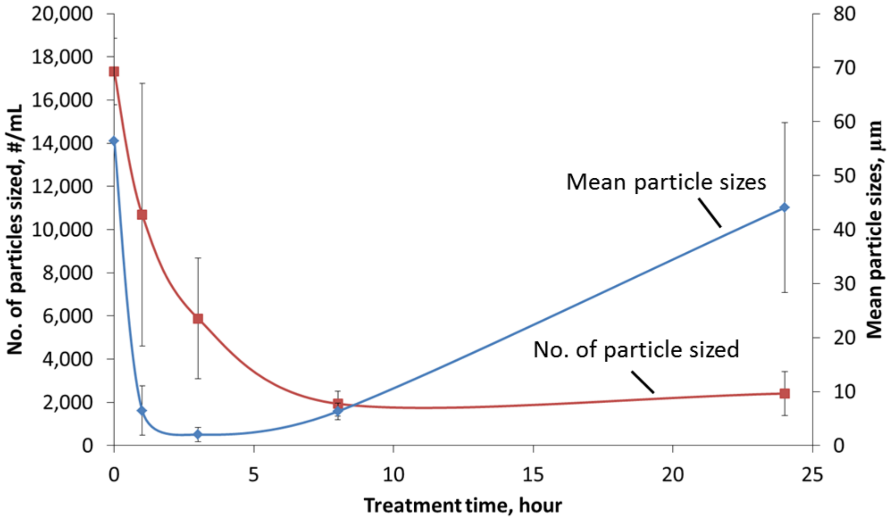


Figure 5.5 Effluent mean particle size and particle number concentrations during treatment of BBL graywater (one-week operation of three separate batches, three replicates per samples)

The aerobic environment in the SB-VFW allowed for nitrification to take place, which was indicated by ammonium-nitrogen (NH_4-N) removal and nitrate-nitrogen (NO_3-N) production during the 24-hour treatment cycle (**Fig. 5.6**). For example, the raw BBL graywater contained 5.2 ± 2.0 mg/L NH_4-N, which was reduced to 0.1 ± 0.1 mg/L after eight hours of treatment. Simultaneously, NO_3-N was undetected in the influent, but increased to ~2.5 ± 1.5 mg/L and ~5.9 ± 1.4 mg/L after three- and 24- hour of treatment, respectively. The continual increase of NO_3-N indicates that denitrification did not take place. However, denitrification was observed only at higher organic loading during two BBL detergent shockloading events where TOC was increased from the normal average of 32 ± 8.9 mg/L to 84 ± 1.5 mg/L and 45 ± 0.9 mg/L, with NO_3-N remaining < 0.1 mg/L during those two 24-hour treatment cycles. Nitrification also took place during the detergent shockloading events with NH_4-N being reduced from 2.6 mg/L to <0.1 mg/L within the first three hours and maintaining at the same above level over the 24 hour treatment period. Nitrification-denitrification during the detergent shockloading tests suggests that aerobic and anoxic environments co-existed in the soil layer of the SB-VFW system while sufficient carbon source and an anoxic environment enabled denitrification.

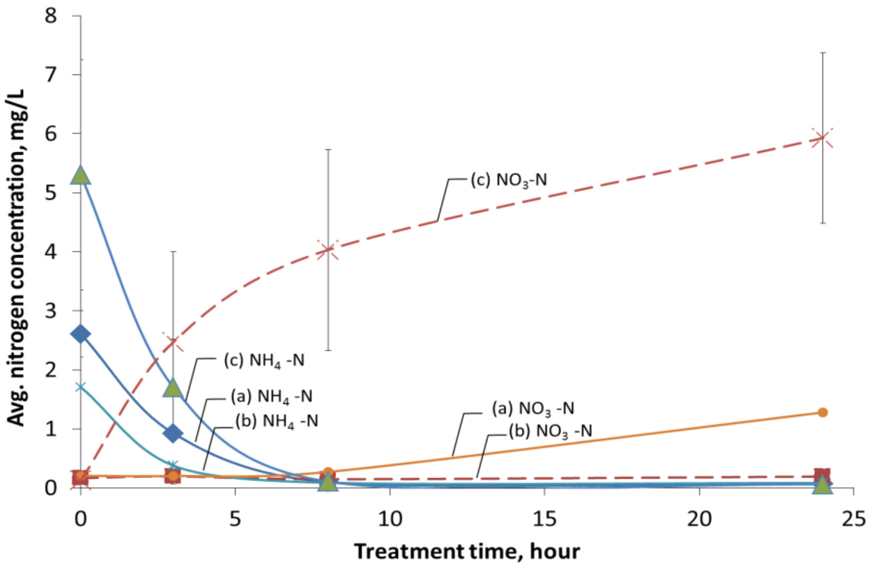


Figure 5.6 Change in NH_4-N and NO_3-N levels for: (a) treatment of BBL graywater batch spiked with BBL detergent (i.e., average over two shockload events), (b) treatment of a new BBL graywater batch after discharge of detergents spiked graywater treated in (a), and (c) normal BBL graywater treatment operation (three weeks average) prior to laundry detergent shockload events

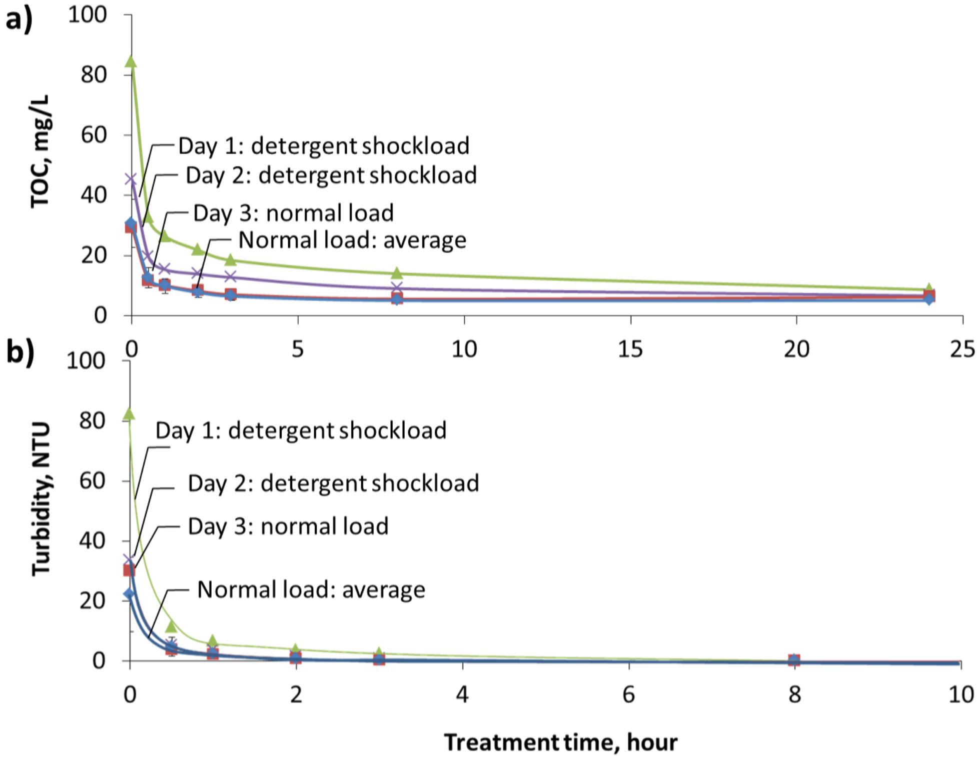


Figure 5.7 The impact of (a) TOC and (b) turbidity removal by the treatment system during BBL detergent shockload tests (Day 1: detergent shockload (160g BBL detergent added into 300 L raw BBL graywater) and Day 2: detergent shockload (80g BBL detergent added into 300 L raw BBL graywater), immediately after detergent shockload tests (Day 3: normal load) and the average normal load water quality

The SB-VFW system remained effective with respect to turbidity removal but TOC removal required longer treatment time than usual during two sequential detergent shockloading tests. On the first day of the detergent shockload test, the SB-VFW system achieved ~61% TOC removal from raw BBL graywater (84 mg/L TOC) within the first half-hour (**Fig. 5.7a**). Turbidity removal of 86% was achieved (from 82 to 11 NTU) for the same treatment period (**Fig. 5.7b**); and reached removal of 99.6% and was below detection after 8 and 24 hours of treatment, respectively (**Fig. 5.7b**). On the second day of the detergent shockload test, the SB-VFW system produced effluent with turbidity of < 1 NTU (0.8 NTU) after three hours of treatment, and TOC of 6.8 mg/L after 24-hour of treatment (**Fig. 5.7**). SB-VFW treatment of a new BBL graywater batch immediately after the two-day detergent shockload tests was again at a high treatment efficiency (**Fig. 5.7**, e.g. ~ 0.3 mg/L bDOC and 0.2 NTU turbidity) with 3-hour of treatment. The above observations suggest that the SB-VFW is resilience to detergent shockloads and thus indicates that the system can handles fluctuation in TOC and turbidity levels.

5.3.3 Organic loading and clogging of the SB-VFW system

The SB-VFW system operated in a stable manner, without clogging during the three month of daily BBL graywater treatment at a recirculation flow rate of 9.5 L/min (or 46 turnovers / 24-hour). During the operation of the system, the soil hydraulic conductivity was invariant (~1.5 cm/min). High organic content is known to enhance biomass growth and may also affect the hydraulic conductivity of the soil layer [238]. Accordingly, in order to further evaluate the importance of controlling organic loadings in the raw graywater when using the SB-VFW system, the residents were asked to switch from using the non-BBL detergent to the BBL detergent, which contained a lower level of organics (by a factor of ~2.5 times). After the switch from treating BBL graywater to non-BBL graywater, the hydraulic conductivity of the SB-VFW system remained (for nearly 22 days; **Fig. 9a**) at about 1.5 cm/min as during the previous 3.5 months of treating BBL graywater. The treatment system achieved 66% bDOC removal (e.g. from 90 mg/L to 32 mg/L bDOC) within the first 30 minutes of treatment (**Fig. 5.8a**) and further removed of up to 84% after three hours of treatment. The effluent bDOC was at 2 mg/L, achieving 98% removal after 24 hours (**Fig. 5.8a**). Progressive wetland soil clogging eventually resulted in significant loss of hydraulic conductivity, and by day 34, water overflow from the wetland into the bottom reservoir resulted in marked increase in effluent turbidity and bDOC. The above system behavior is consistent with other reported studies in which it was reported that soil clogging can be a concern at high organic loading rate, as well as with detergents of organic content [238, 239].

Reduction of the soil hydraulic conductivity after treating non-BBL graywater for over a month was likely due to excess biomass growth stimulated by the organic rich non-BBL graywater. Increase biomass was evident as a biofilm growth (~2 mm) on the CFM surfaces (**Section 5.3.2**) was observed when treating non-BBL graywater. In contrast, a thinner biofilm layer of <1 mm (**Fig. 5.5**) was observed when treating BBL graywater. The thick biofilm encountered when treating the organic-rich non-BBL graywater suggests that this type of graywater was capable of supporting greater biomass growth (**Fig. 5.9**). Excessive biomass growth can lead to reduction in soil porosity and thus its hydraulic conductivity, and eventually clogging in the SP-VFWs soil [238].

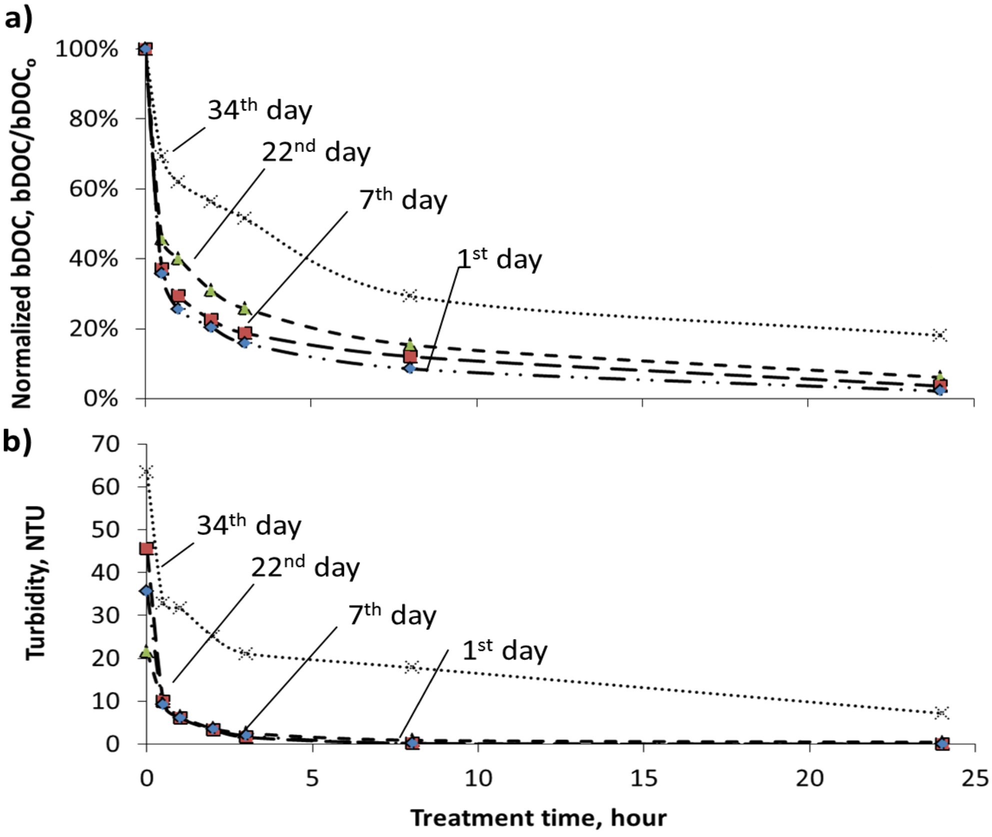


Figure 5.8 (a) bDOC, and b) turbidity treatment performance change during the one month of treating non-BBL containing graywater

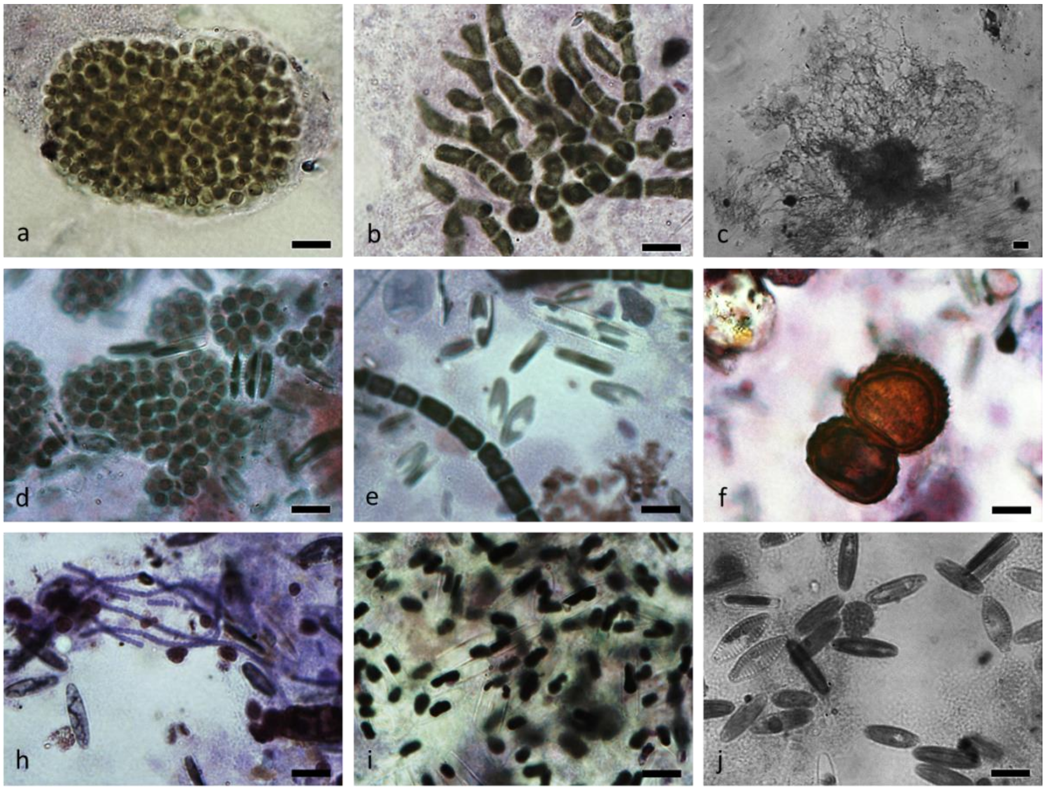


Figure 5.9 Microscopic images of biofilm collected from the plastic media when the treatment system was treating non-BBL graywater. a) a cluster of algae, b) algae, c) fungi, d) clusters of algae and protozoa, e) algae and protozoa, d) eukaryotic microorganisms, h) algae and protozoa, i) protozoa, j) protozoa. Protozoa were found in large number in the biofilm indicating that there was plentiful of bacteria for protozoa to forage on. Scale bars are 10 µm

The SB-VFW system is a batch treatment process, and thus the relationship between biomass growth and organic concentration in the SB-VFW system can be conceptualized by a typical biological batch reactor biomass growth behavior as depicted in **Fig. 5.10**. In a typical biological batch reactor, biomass growth occurs in the presence of organics while biomass reduction takes place when undergoing endogenous decay under low organic conditions (**Fig. 5.10**) [35]. In the present system, when BBL graywater was treated, the bDOC of the recirculating water was already at ~ 1 mg/L after 3 hours of treatment, which means that water of low organic content was recirculated in the SB-VFW system for approximately 21 hours during the 24-hour treatment cycle (**Fig. 2.2a**). Recirculation of water of low organic concentration beyond 3-hours after complete removal of organics allowed for endogenous biomass decay (**Fig. 5.10**). When non-BBL graywater was treated, however, the bDOC concentration remained relatively high (reduced to ~2 mg/L bDOC after 24 hours of treatment) even for a 24-hour of treatment cycle (**Fig. 2a**). Therefore, it is reasonable to expect that the biomass growth was only at the stationary phase when a fresh batch of raw graywater recharged into the SB-VFW system.

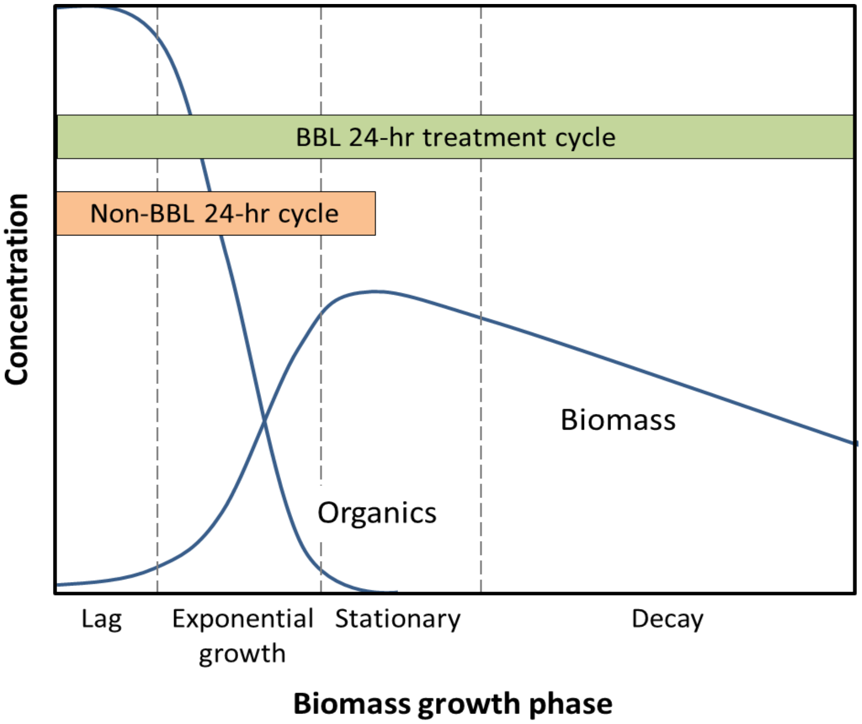


Figure 5.10 The biomass growth phase diagram for the SB-VFW system adapted from a typical biological batch reactor [35]. The cycle of non-BBL graywater is shown to only overlap with the lag, exponential growth and stationary phases; while the non-BBL graywater treatment cycle is shown to overlap with the above three phases in addition to the decay phase

In order to illustrate the importance of endogenous decay, a hypothetical treatment cycle of the SB-VFW system, for the BBL and non-BBL, is presented in **Fig. 5.10**. Results of the present study suggest that in the non-BBL treatment cycle, there was relatively abundance of organics at the end of the 24-hour treatment cycle, which permitted the biomass to undergo the lag, exponential growth and the stationary phases before the next treatment cycle began. An absence of an endogenous decay phase in the non-BBL graywater treatment cycle would mean that the biomass would continue growing and accumulating after each treatment cycle. It is hypothesized that the above would explain the gradual clogging of the wetland (soil layer). The resulting hydraulic conductivity reduction would then necessitate lowering of the recirculation flow rate to avoid excessive ponding and possible overflowing of water from the top wetland section (**Fig. 5.1**). In contrast, in the treatment of BBL graywater, the organics were significantly depleted for a given batch within 3 hours of treatment with bDOC reduced to achieve ~1 mg/L (**Fig. 5.2**). As a result, the biomass is likely to have undergone an extended endogenous decay phase during the remaining 24-hour treatment cycle. It is argued here that the endogenous biomass decay phase is crucial for maintaining a stable biomass (i.e. prevent excessive growth) in the soil layer. The above arguments and higher performance of the SB-VFW for treatment of BBL relative to non-BBL graywater suggest that the use of detergents that are lean in organics would be more suitable if one's goal is to effectively treat graywater for aboveground onsite reuse. For graywater that is high in organics, a thicker soil layer or longer treatment time would be necessary in order to promote sufficient endogenous biomass decay to avoid overgrowth of biomass that would then clog the soil layer. However, the above options would result in higher system footprint and possibly increased odor and other nuisance due to longer raw graywater storage time, as well as larger storage volume. On the other hand, for treatment of graywater with low organic concentrations, a smaller treatment system could also be devised to provide sufficient treatment.

5.4 Conclusions

The feasibility of residential graywater treatment via a semi-batch vertical flow wetland (SB-VFW) with recirculation was evaluated in a 5-month field study. The study demonstrated the following:

1) Treatment of graywater, from showers, sinks and laundry, in the SB-VFW which contained a coconut coir soil substitute, was achieved to a level that meets the strict water quality requirements (with respect to BOD5, TOC and turbidity) for above ground non-potable reuse.
2) Treatment time of about three hours was typically sufficient for batches of up to ~ 300 liters in a small footprint SB-VFW system.
3) System performance was stable when a bio-based laundry detergent was utilized owing to its lower organic content relative to typical non-bio-based detergents. Clogging of the wetland soil medium due to biofilm overgrowth was avoided when treating graywater of low organic loading (e.g. when utilizing a bio-based detergent) owing to the formation of a stable biofilm exists in the wetland. However, higher organic loading rates or with detergents of higher organic content, clogging may be a concern.

Results of the present study suggest that there is merit in exploring the use of compact SB-VFW systems for increasing graywater reuse in urban environments as well as possibly for deployment as a polishing process for certain industrial water treatment applications.

6 A COST-BENEFIT ANALYSIS OF ONSITE RESIDENTIAL GRAYWATER RECYCLING – A CASE STUDY: THE CITY OF LOS ANGELES

6.1 Overview

Onsite graywater reuse has emerged as an important sector in water reuse, especially in arid regions and where water reuse capability is limited. In order to minimize human exposure to pathogens, graywater reuse without treatment is generally encouraged for subsurface irrigation [27]. Aboveground water reuse is often only allowed when treatment is provided. The cost of treatment encompasses the system cost, operations and maintenance (O&M) costs and building retrofitting cost. Graywater treatment systems (provide organic, total suspended solids and turbidity removal) marketed for single-family homes can vary between $6,000 and ~$13,000 for treatment capacity of 1.2 – 1.6 m^3/day [28]. Additionally, maintenance is usually required and can ranges between $200 to $900 per year [30]. It has been suggested that high treatment cost favors onsite graywater treatment in high density multifamily homes [31], but impedes the adoption of onsite graywater treatment in low-density residential housing such as single-family homes. As shown in **Section 4.3.3**, relatively short breakeven periods are achievable using a wetland treatment system in a single-family home. Even shorter payback periods and broader economic implications of onsite graywater reuse may be possible in cities in arid regions that are facing water scarcity and have limited capability for reusing centralized recycled water due to the lack of distribution system.

The City of Los Angeles, located in an arid region in Southern California is one of those Cities facing the above constrains. The City has population of ~4.1 million and has limited local water resources, relying mainly on imported water. The City purchases 48% of its water supply from the California's state water wholesale agency, the Metropolitan Water District (MWD), which obtains its water from the Colorado River and from the California Bay Delta region [73]. The City also imports another 38% of its water via the Los Angeles (L.A.) Aqueduct. Local groundwater accounts for only 14% of LA's water supply. A small fraction of the City's water supply (~1%) is from centralized water recycling and from water conservation, respectively. Low utilization of recycled water is mainly due to the lack of distribution infrastructure throughout the City [240]. As a result, ~76% of the City's effluent is disposed in the Pacific Ocean while the reclaimed water is used mainly for irrigation in recreational areas [73]. Given that the residential water use accounts for 65% of the City's water demand, the City has encouraged rainwater capture projects in residential homes as an alternative onsite water source for irrigation. However, the City's low annual precipitation of 37 cm/year 33-year-average usually occurs over a short period of 10 days (33-year average) [15]. Therefore, the captured rainwater is unlikely to meet the non-potable water demand in the residential sector [73]. In contrast, onsite graywater recycling in residential homes could serve as an important water source for the City but has not been fully evaluated. Furthermore, the broader economic and environmental implications and the economic drivers to help the growth of this sector have not been fully assessed.

This Chapter focuses on evaluation of the economic drivers for fostering onsite graywater recycling in metropolitan cities in arid regions using the City of Los Angeles as a case study. The objectives of the study are to: 1) evaluate the relationship between housing types and reuse opportunities; 2) conduct cost-benefit analysis of onsite graywater recycling for property owners,

3) assess the cost-benefit of graywater recycling for water and wastewater agencies, and 4) identify the key economic drivers for encouraging graywater recycling.

6.2 Water Uses in Los Angeles Households

The City of Los Angeles consumes 685 million m^3 /year of potable water with ~68% used for residential purposes. In order to evaluate onsite production and utilization of graywater in single and multifamily residential homes, water consumption for indoor and outdoor water use was estimated using published indoor water use surveys [48, 96] and land and water consumption data from Los Angeles Department of Power and Water (LADWP) [73]. Indoor water use was assumed to be for toilet flushing, kitchen uses (dishwashing, food preparation and drinking), clothes washing, showers, baths and hand washing and other personal hygiene activities. Outdoor water use was assumed primarily for landscape irrigation and was estimated as:

$$Ir_{total} = \frac{f \times LA \times ET_o \times PF}{Ir_{ef}} \tag{6.1}$$

where Ir_{total} is outdoor irrigation water use, L/year, ET_o is Reference evapotranspiration rate of plants for the City of Los Angeles, inch/year, Ir_{eff} = Irrigation efficiency, LA is the landscaped area, ft^2, f is a unit conversion factor equal to 2.35, and PF is the plant factor (0-1) which represents the irrigation demand of vegetation planted with lower number require less water [241]. The values of the parameters for calculating the indoor and outdoor water use are presented in **Table 6.1**.

Of the ~4.1 million population in the City of Los Angeles, based on the assumption of 3 people per household in the City of L.A. [242], there are ~1.85 million residents living in 627,400 single-family units while the remaining 2.25 million residents are living in 764,400 multifamily units [73]. Single-family home residents consume ~301million m^3/year as compared to ~227 million m^3/year by multifamily home residents [73]. **Fig. 6.1** shows that on average a single-family home (with three residents) water use is about 1,320 L/day; while a single multifamily residence uses ~810 L/day. The most striking water use pattern difference between these two residential classes is irrigation. A single-family home uses ~52% of its water for irrigation, which is significantly more than the 18% used in a multifamily home. Such estimates are consistent with the data reported by LADWP [73]. **Fig. 6.1** also shows that about half of the water consumed indoor becomes graywater, which in principle can be collected, treated and reused for non-potable water applications onsite.

There are three main non-potable water applications in residential homes that can benefit from graywater recycling, namely irrigation, toilet flushing and laundry [27]. **Fig. 6.2** shows the extent of potable water reduction that can result from onsite graywater recycling. Onsite graywater recycling could displace ~50% of the irrigation water and reduce daily potable water use by 27% to 970 L/day in a single-family home. On the other hand, onsite graywater recycling would satisfy the water demand for both irrigation and toilet flushing and reduce potable water consumption by 38% to 500 L/day in a household living in a multifamily dwelling. The estimated available graywater in the City of Los Angeles is equivalent to be ~25% of its 2013 water supply.

Table 6.1 **Parameters used to calculate indoor and outdoor water consumption resulting from activities in single and multifamily homes**

Parameters	Value	Reference
Toilet flushing, L/day-capita	59	[48, 96]
Kitchen sinks, L/day-capita	17	
Laundry machine, L/day-capita	52	
Showers, L/day-capita	41	
Bathtubs, L/day-capita	4	
Handwashing basins, L/day-capita	17	
Average household size, person/household	3	[242]
Total number of households residing in single family houses	627,395	[73]
Total number of household residing in multifamily buildings	764,402	[73]
Single family home land area, km^2	499	[73]
Multifamily home land area, km^2	128	[73]
Percent of irrigated land, %	30	[243]
Evapotranspiration rate, inch/year	50.1	[241]
Irrigation efficiency, %	70	[241]
Plant factor for single family home (assuming 20%, 40% and 40% of low, medium and high water use plants, respectively, were used)	0.58	[241]
Plant factor for single family home (assuming 15%, 15% and 70% of low, medium and high water use plants, respectively, were used)	0.67	[241]

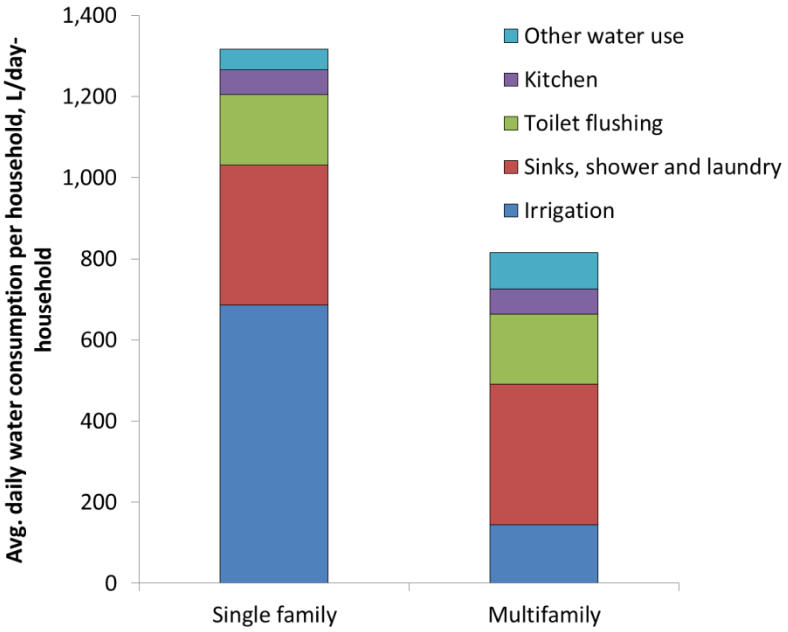


Figure 6.1 **Drinking water demand in a typical 3-person single-family household and in a multifamily dwelling**

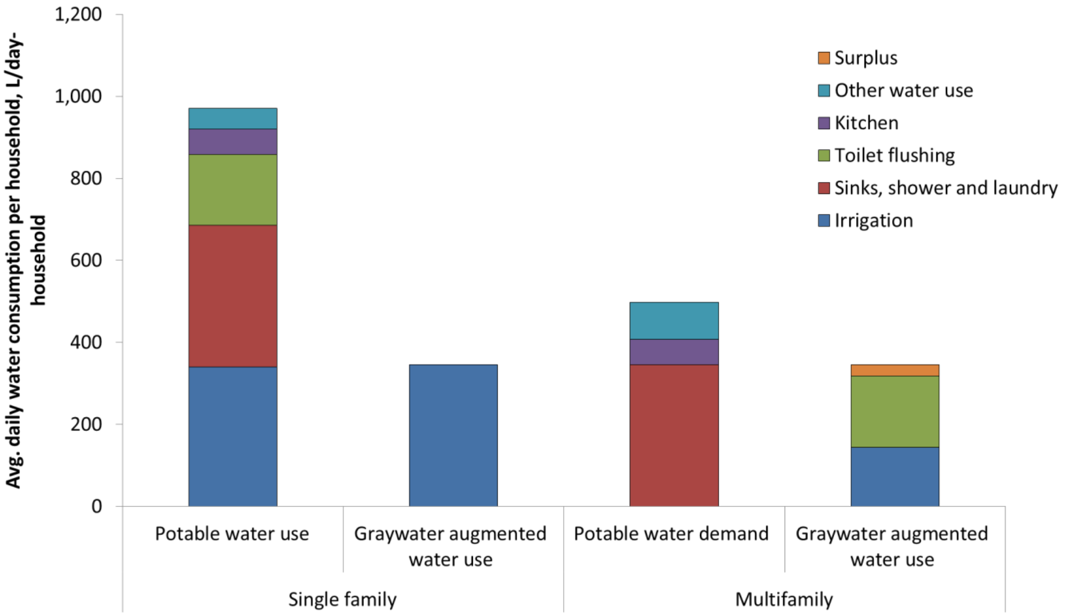


Figure 6.2 **Potential reduction in potable water demand achievable with onsite graywater recycling in single and multifamily homes in LA**

6.3 Cost-benefit analysis of onsite recycling for residential homes

Graywater treatment cost is a combination of system capital and recurring O&M costs, as well as the cost of financing if required. Low-cost treatment systems would be preferred for residential deployment. Small treatment systems that are commercially available for single-family can vary in cost between $6,000 and >$13,000 for treatment capacity range of 1.2 – 1.6 m^3/day [28]. Operational cost includes mainly electricity, and possibly chemicals depending on the treatment technology. In addition, periodic maintenance visits may be required and can be in the range of $200-$900 per year [30]. It is expected that the SB-VFW system presented in **Chapters 4 and 5** developed for graywater recycling would be lower cost in the range of $1,500-$2,500 for treatment capacity of up to 2.1 m^3/day [244]. It is estimated that such wetlands would require only low-cost biannual maintenance visits (cost \$100/year, details are presented in **Appendix 7**).

In order to evaluate the achievable cost-saving provided by residential graywater treatment systems, the low-cost vertical wetland treatment [244] and a typical commercial treatment system of \$7,000 are used for comparison [245]. The commercial system is a submerged attached growth biological treatment system with sand filtration as post-treatment [174]. The annual maintenance cost is ~\$430/year [245]. The annualized cost-saving from graywater recycling using these two treatment systems with an average service lifetime of 15 years without financing was assumed and is calculated using **Eq. 6.2**.

$$Cost - saving = \alpha W \cdot V_d - \frac{P}{Y} - \alpha E \cdot R \cdot V_d - M \tag{6.2}$$

in which P is the system capital costs (\$), Y is the service lifetime (year), W is the water rate (\$/m^3), V_d is the daily volume to be treated and reused (m^3/day), E is the daily power consumption (kWh/m^3), R is the electricity rate (\$/kWh), α is the conversion factor (356 days / year), and M is the annual maintenance cost (\$/year).

The wetland treatment system provides greater cost-saving than the higher cost commercial treatment system (**Fig. 6.3**). The annual cost of the wetland system with maximum treatment capacity of 2.1 m^3/day is ~\$420 with \$170 attributed to depreciation of the treatment system over a service lifetime of 15 years. In contrast, the annual cost for a commercial system with maximum treatment capacity of 1.2 m^3/day, without financing, is ~\$1,000 with \$470 attributed to depreciation of the treatment system over a service lifetime of 15 years. The annual cost of treatment would be less than paying water and sewer charges if recycling is >60 m^3/year or 165 L/day when using the lower cost wetland treatment system. Clearly, the economy of scale is important (**Fig. 6.3**). Given that a typical 3-resident home generates ~130 m^3/year, the cost from water savings would be sufficient to offset the cost of treatment and would be lower than not having graywater recycling. Net savings can be achieved in low-density multifamily homes because their treatment volumes likely exceed 130 m^3/year. In contrast, graywater treatment cost using the more expensive commercial system for a 3-person residential home (treating ~130 m^3/year) is expected to be higher than paying the current City water and sewer charges. For the commercial system, recycling 310 m^3/year of gray water is required to recover the operating and capital cost. The analysis suggests that treatment systems that have higher capital and annual maintenance costs may only be economically feasible for dwellings large than single family.

Local building codes are likely to affect home plumbing retrofitting costs associated with diversion of graywater to the treatment systems. Costs for graywater plumbing retrofit will increase when one needs to intercept graywater before it mixes with black water and divert it to a single location for connecting to a treatment system. When treated graywater is reused indoors, (e.g. toilet flushing or laundry machines), a separate plumbing system for non-potable water distribution must be installed, thereby to the cost of retrofitting. Another retrofitting cost may involve distribution system for irrigation with treated graywater.

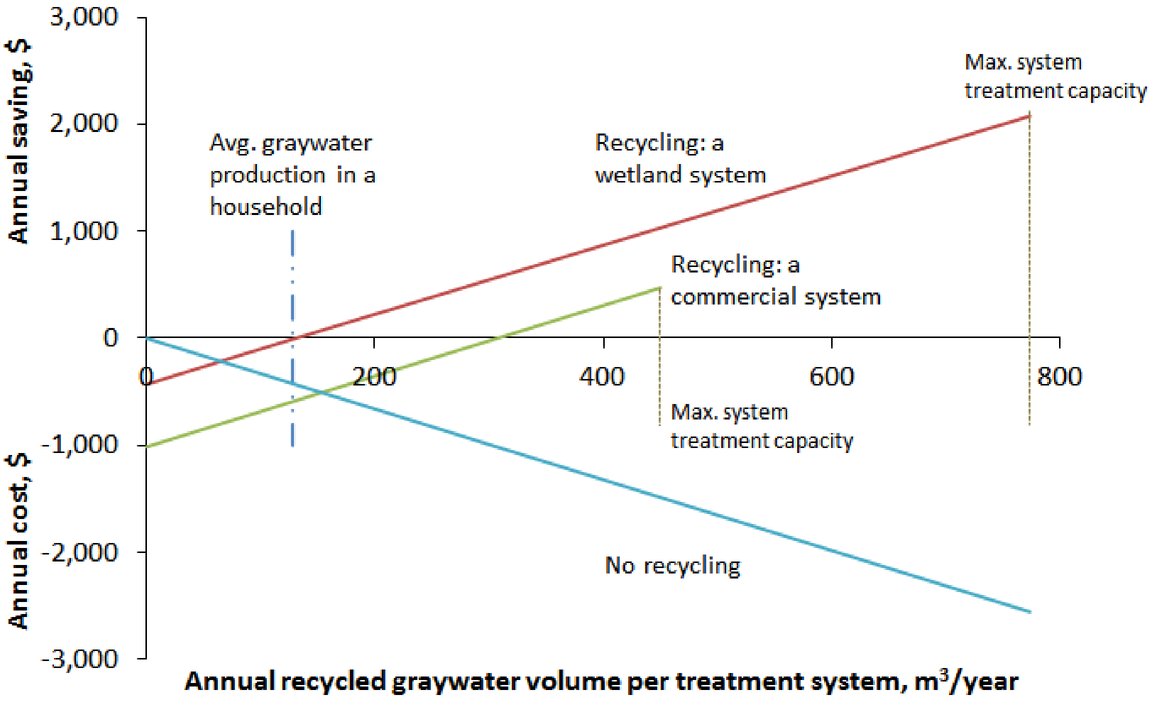


Figure 6.3 **The relationship between annual cost-saving of total graywater recycled annually using of two treatment systems acquired without financing. The wetland system cost is $2,500 with an annual O&M cost of $250. A commercial system with a system cost of $7,000 and annual O&M cost of $530. The cost of water for a home without recycle is also presented for comparison. The y-intercepts presents the fixed cost of each option**

The cost for residential retrofitting will depend on various factors. Analysis of retrofitting costs was based on the cost factors presented in **Table 6.2**; these cost factors are expected to have some degree of site-specific variability. **Fig. 6.4** shows that the costs of different types of retrofitting of existing buildings. Six building types are evaluated: 1) a one-story single-family houses with two bathrooms built on raised foundations, 2) the same house but built on a concrete slab, 3) the same house but is under construction, 4) a two-story multifamily building with 9 bathrooms and 6 units built on raised foundations, 5) the same building but built on a concrete slab, 6) the same building but is under construction. The cost of installing graywater collection and distribution systems in new construction is assumed to be negligible, thus only material cost is considered.

Table 6.2 Parameters used for estimating the cost of installing collection and distribution systems for graywater recycling

Collection system				**Ref.**
Material cost per bathroom and a laundry machine				
ABS pipes, fittings, valves, \$/ bathroom	120			Appendix 7
Labor costs	**Plumber**	**site worker**		
hourly rate, \$/hour	65	25		[242]
Retrofitting labor hours	**1st 2 bathroom**	**Each additional bathroom**	**Laundry**	
With crawl space, hr	4	1.5	2	Estimated
On concrete slab, hr	16	8	8	Estimated
Outdoor distribution system for Irrigation (yard size: 19 m^2)				
Labor hours	**Plumber**	**Site workers**		
Subsurface irrigation, hr	16	25		Estimated
Connecting to existing irrigation system, hr	8	0		Estimated
Indoor distribution system for toilet flushing				
Materials	**1st 2 toilets**	**Each additional toilet**		
PVC pipes, fittings and pump, \$	920	80		Appendix 7
Total labor hours	**1st 2 toilets**	**Each additional toilet**		
With crawl space	8	4		Estimated
On concrete slab	16	8		Estimated

Note: The labor hours required to install or retrofit plumbing or irrigation systems presented above were developed on the best reasonable estimate basis for the purpose of study presented in Chapter 6. The actual labor needed in a real situation may vary significantly depending on the site situation

It should be recognized that including indoor recycling increases the overall cost of graywater recycling as compared to reuse graywater for irrigation alone. Furthermore, the inclusion of plumbing needed for graywater collection and reuse in new construction is less costly than retrofitting existing homes for graywater reuse. Therefore, the most favorable conditions for graywater recycling will be for new construction with recycling only for irrigation (**Fig. 6.4**). The above findings demonstrate the importance of anticipating plumbing requirements for new buildings in order to reduce retrofitting costs. For example, the City of Tucson Arizona requires residential construction to provide plumbing for facilitating onsite graywater reuse [246]. At present, California only requires multifamily dwellings and commercial buildings to install dual plumbing for the supply of portable and recycled water [68]. However, California does not require plumbing installation for graywater diversion for onsite recycling in all buildings. The absence of such building requirement means that retrofitting cost for graywater recycling will remain high as illustrate in **Fig. 6.4**.

In addition to the need for including graywater recycling plumbing in new construction, selecting plumbing materials to facilitate retrofitting will also reduce cost. The results presented in **Fig. 6.4** are based on the use of plastic pipes and fittings. Retrofitting costs are expected to increase if metal pipes and fittings are required for the collection and distribution of graywater. California only allows plastic pipes and fittings to be used in single-family or residential buildings that are two-stories or less for fire safety reasons [68]. The cost for retrofitting larger residential buildings will be even more expensive due to higher labor and material costs.

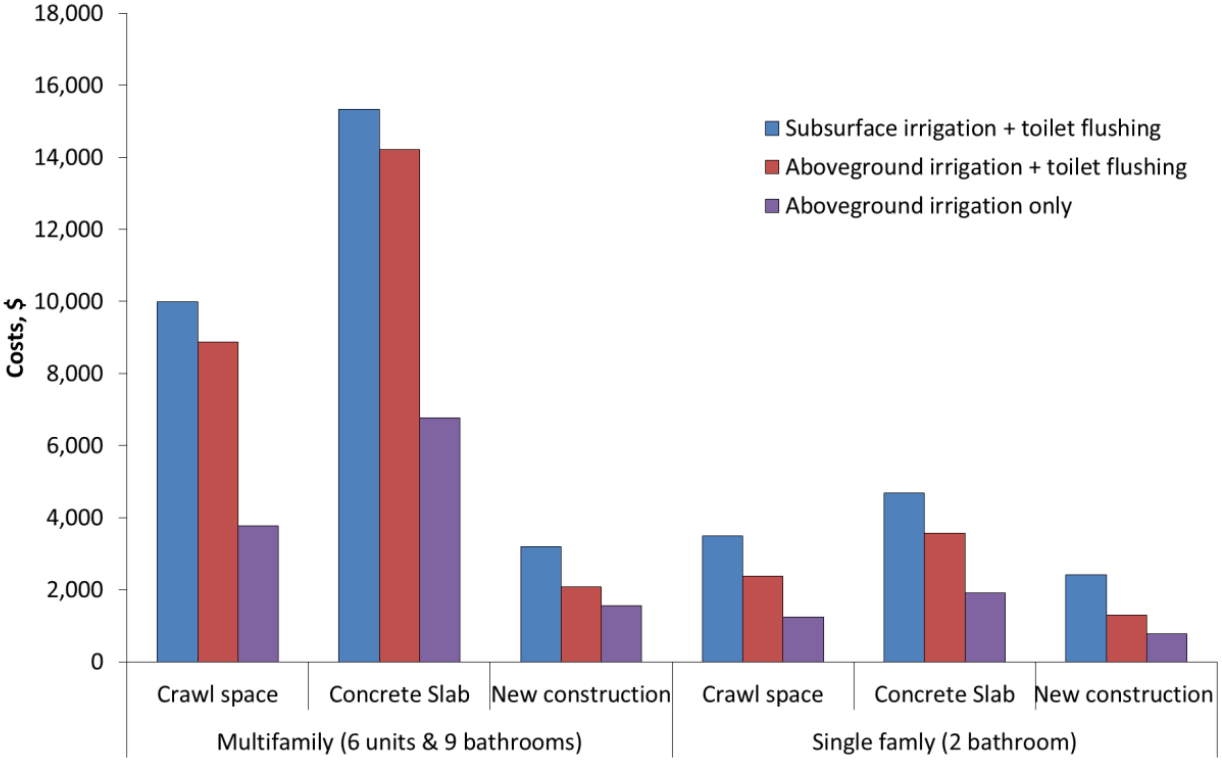


Figure 6.4 **Construction related costs for providing plumbing for raw graywater collection and treated graywater reuse for indoor and outdoor reuse or outdoor only water reuse. A multifamily home with 6 units and 9 bathrooms and a single family home with 2 bathrooms that have crawl space, built on concrete lab, and new construction are evaluated**

6.4 Cost benefits of graywater recycling for water and wastewater agencies

Graywater recycling can provide the City with greater water supply reliability and reduce the energy demand for water supply and wastewater treatment (WWT). As shown in **Fig. 6.5** water supply from MWD has the highest energy density of 2.3 kWh/m^3 [73]as compared to other existing water sources. The energy density for water imported via the LA Aqueduct is unusually low because the water source is located at high elevation and flows to the City by gravity [73]. Onsite graywater treatment using a SB-VFW is estimated at 1.2 kWh/m^3 [190]. The energy required for graywater recycling using the SB-VFW is about 1.1 kWh/m^3 lower than energy of water purchased from MWD and relative to centralized wastewater treatment. Onsite graywater recycling offers an opportunity to lower the energy footprint related to water supply and treatment.

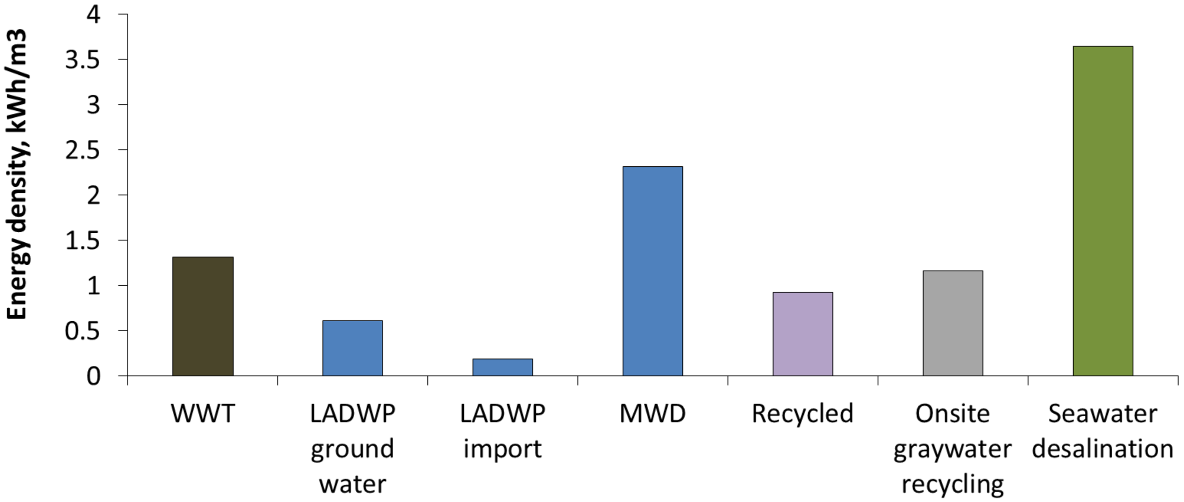


Figure 6.5 Energy density of wastewater treatment (WWT) and other potable and non-potable water sources. Energy density data for WWT including conveyance are from [247]; for LADWP groundwater, LADWP import, MWD and recycled water after secondary treatment were from [73]; for onsite graywater recycling using vertical flow wetland were from [190]; for seawater desalination were from [248]

Given the energy density data presented in Fig. 6.5, opportunity for energy conservation through onsite graywater recycling exists. It is estimated that even at a low population participation rate of 1% (i.e. equivalent to 2% of the 3-resident single-family home units), the City could reduce water supply and treatment related energy use by 4,300 MWh/year, while reducing potable drinking demand by 0.2% and wastewater loading to centralized WWT plants by 0.3% (**Fig. 6.6**). Higher participation rate, e.g. 10%, would translate to ~43,000 MWh/year of energy saving. Such graywater recycling volume could reduce drinking water demand by 2.3%

and wastewater treatment load by 3.5%. Although there are concerns that reduction of wastewater flow to centralized treatment plant could impair sewer conveyance system and wastewater treatment performance, there is very little evidence that supports or validates such concern. Given the projected annual population growth rate of 0.4% for the City for the next 20 years [73], the City's centralized treatment plants may benefit from graywater diversion by reducing its daily peak loads, maintaining a relatively stable wastewater treatment loading and hence avoiding the cost of expansion.

It is instructive to compare the cost of potable and non-potable water supply [73] relatively to the cost of onsite graywater treatment using a low-cost vertical flow wetland system [244]. The costs of potable water sources are lower than non-potable water sources. Rainwater and storm water can be an important source to supplement non-potable water supply during the short rainy period, but it is an expensive and not a sustainable water source throughout the year. In this regard, the cost of graywater recycling of \$0.5/m^3 (**Fig. 6.7**) using a low cost treatment system would make graywater recycling competitive against other non-potable options, including centralized water recycling. The current cost of water from MWD (with a median cost of ~\$0.6/m^3) is higher than all other potable water sources including onsite graywater recycling, and its cost is expected to rise further in the future.

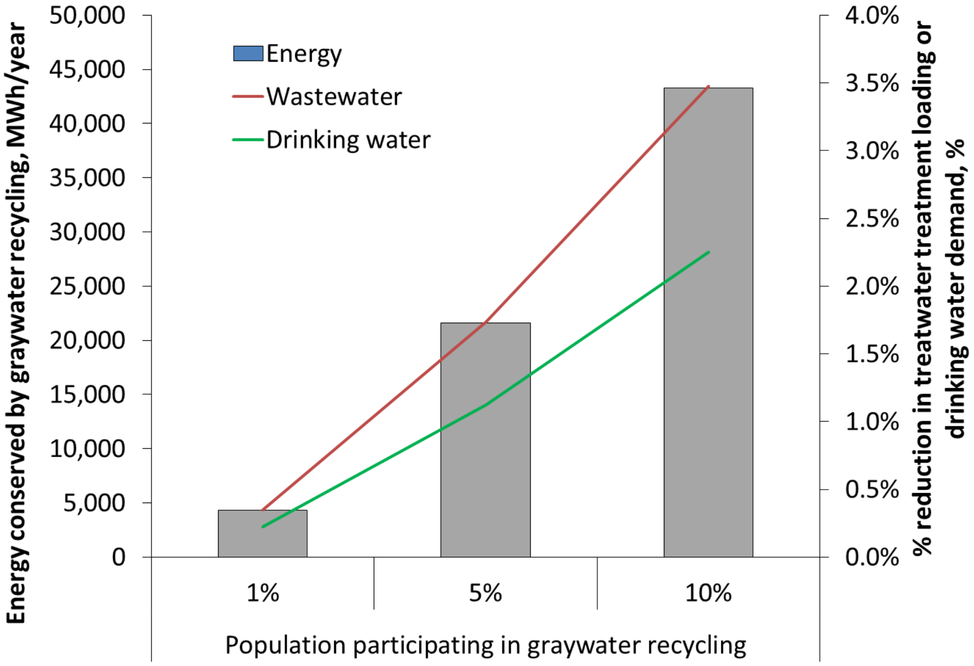


Figure 6.6 **Energy saving, and potable water demand from MWD and wastewater loading to wastewater treatment plant reduction resulting from onsite graywater recycling**

In order to estimate the potential water cost increase for MWD water supply in the future, and a cost project analysis was conducted. MWD sells two tiers of water, Tier 1 and Tier 2, which can be purchased as treated or untreated. Between 1995 and 2014, the prices for these four types of water have increased at an average annual rate of 3-5% [249] (**Fig. 6.8**). Based on such annual rate increase, the projected treated water supply cost could exceed \$2/m^3 by 2035. Between 2003 and 2010, LADWP annual purchased water averaged ~29% from Tier 1 untreated water, 61% from Tier 1 treated water, 8% from Tier 2 untreated water and 2% from Tier 2 treated water [250]. Assuming that LADWP will continue purchasing the same percentage for each water type from MWD, the average water cost for LADWP could be as much as \$1.2/m^3. Such high price makes graywater a more competitive alternative water source for non-potable use. As technology improves and building regulations change, the cost of graywater recycling could even be lower, and reliance on MWD purchases could be reduced. Reduced dependence on MWD may be important because diminishing water resources in the Bay Delta region and Colorado River, as well as environmental concerns may all impact MWD's ability to provide a reliable water supply to its member agencies.

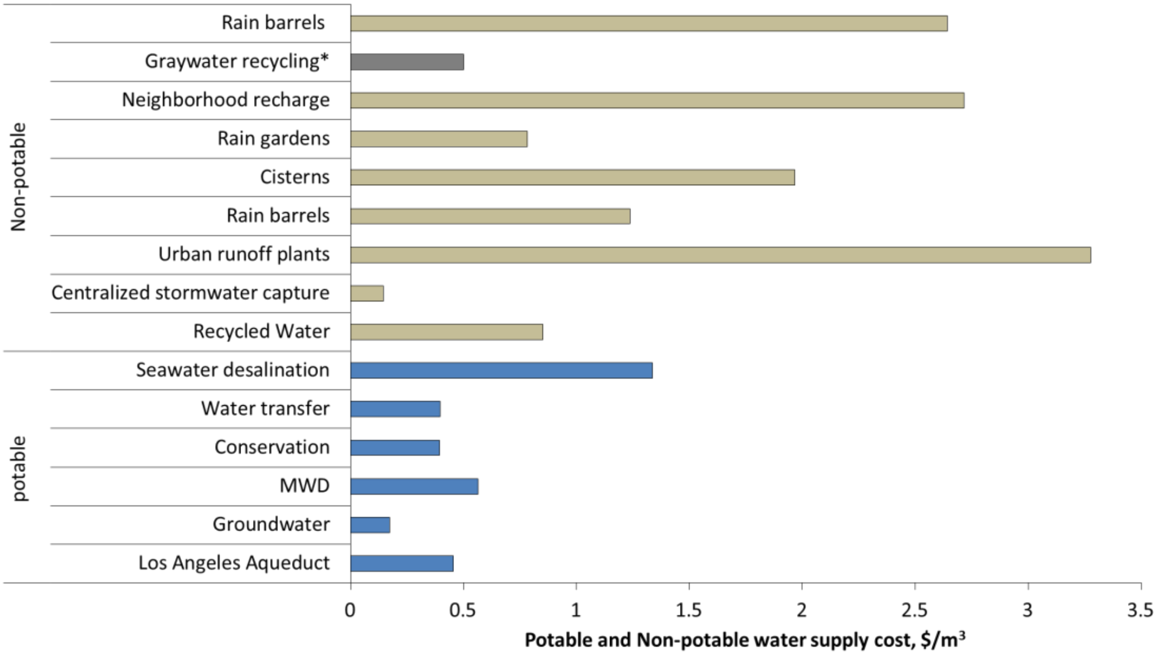


Figure 6.7 **Median potable and non-potable water supply option cost to LADWP [73] with the exception for graywater recycling. The cost of graywater recycling was calculated based on the actual cost of treatment before savings and cost of retrofitting using a wetland treatment system with a system capital cost of $2500 treating 2.1m^3/day [190] without considering financial subsidies from LADWP**

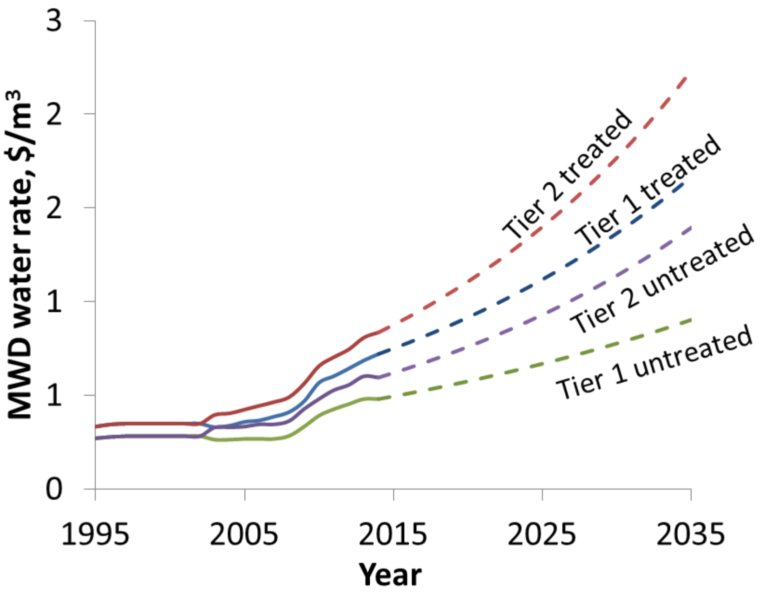


Figure 6.8 **Historical MWD water rates for Tier 1 and Tier 2 treated and untreated water supply between 1995 and 2014. The projected water rates between 2015-2035 are estimated based on the 20-year average annual rate increase of 4.1% for Tier 1 treated, 4.8% for Tier 2 treated, 3.1% for Tier 1 untreated and 4.1% for Tier 2 untreated [249]**

6.5 Economic drivers for fostering onsite graywater recycling

The information presented above (**Section 6.4**) suggests that onsite graywater recycling can provide both economic and environmental benefits to the City. However, in order to encourage adoption of onsite graywater recycling, financial barriers of graywater recycling that include system capital cost, and maintenance and retrofitting costs must be lowered. High upfront costs of retrofitting and system capital costs are the greatest barrier for property owners. Rebates for onsite graywater recycling are not available for residential homes [24]. If rebates for residential homes existed, the size of the rebates must be significantly large to make an impact on the overall cost. In this regard, it is noted that in Australia, rebates were provided rebates of up to $500 or half the project cost for graywater recycling [251] when the least cost treatment option was ~$6,000 [28]. Unless rebates are relatively large, alternative financing may be needed.

An alternative way to overcome the upfront costs for purchase and installation of graywater treatment system is to use the third-party ownership model that is widely used for financing the onsite solar power generation in the residential sector [252]. This model could allow commercial project developers to finance the capital and retrofitting costs of the treatment system and assume maintenance responsibilities. Homeowners will assume no upfront cost or responsibility of maintaining the treatment system but will agree either to pay a monthly leasing fee or to use the resulting water cost savings from graywater recycling as the lease payment. A second reason for adopting the third-party ownership model is that, as in the solar sector, large developers may be in better position to leverage financial subsidy programs offered by the Federal, State and local governments, which otherwise would be unavailable to individual property owners.

In addition to lowering the upfront system capital and installation costs, a third-party ownership program could provide a solution for the management of onsite treatment systems, which is a major implementation barrier for onsite graywater recycling. If a project developer assumes the responsibility of operational and maintenance cost for the treatment system (during the service agreement period), government agencies will be in position to require maintenance records and water quality data to ensure treatment performance that meets required standards for aboveground non-potable reuse. It is interesting to note that the Australian government requires homeowners to retain approved contractors for the services and maintenance of their onsite graywater recycling systems [28]. Such a program can also be implemented for those homeowners who choose to own their treatment systems instead of leasing from a developer.

6.6 Conclusions

The cost and environment benefits of onsite graywater recycling in single-family and low-density residential dwellings have been evaluated using the City of Los Angeles as an example. Graywater recycling can increases the City's ability to reduce potable water consumption, in addition to lowering water supply and treatment-related energy demand. Graywater recycling can reduce the City's potable water consumption by 27% for single-family homes, and by 38% for a multifamily dwelling. At even 1% population participation, the City will be able to reduce water supply and treatment related energy by 4,300 MWh/year. Graywater recycling will reduce potable water demand by 0.2% and wastewater treatment load by 0.3% at such a participation rate.

Amending local building codes to require new constructions to include plumbing to divert graywater for reuse will be important for adoption of residential graywater recycling by homeowners. There are multiple ways that the City can lower financial barriers to adoption of graywater recycling to its residents including: 1) providing rebates to lower the upfront system and retrofit costs, 2) providing low or zero interest financing for system purchase and installation to property owners and allow them to repay through their utility bills, and 3) providing financing incentives to attract investors or developers to provide onsite graywater recycling services through a third-party ownership model. The added benefits for a third-party ownership model are that developers will assume responsibility for regular service and maintenance of the treatment systems to ensure treatment performance and regulatory compliance. In cases where homeowners own their treatment systems, a regulatory requirement for certified service contractors can be implemented.

7 CONCLUSIONS

The overarching goal of this dissertation was to demonstrate that sound graywater policy coupled with the availability of proven low-cost treatment technology that can produce effluent meeting aboveground nonpotable water use requirements would maximize environmental, health and economic benefits of onsite residential graywater reuse. The review of residential graywater reuse regulations in the United States showed that that reuse of untreated graywater is restricted to subsurface irrigation or ground disposal. Residential graywater reuse regulations vary throughout the United States in terms of the permitted graywater storage, reuse applications and required treatment levels. Clearly, in order to expand graywater reuse to the residential sector and allow water use for aboveground applications, treatment is necessary in order to safeguard public health and meet regulatory requirements. Moreover, low cost and simple treatment approaches will be critical for widespread adoption of distributed graywater recycling.

As such, graywater treatment performance and economics of a low-cost and compact vertical flow wetland system for residential deployment were investigated in an eight-month pilot field study. Treatment of bathroom graywater (from showers, baths and bathroom sinks) produced effluent of high quality within treatment time of three hours. The treatment process followed first-order kinetics and treated effluent turbidity (~0.3 NTU), and BOD_5 (~3.1 mg/L) meeting graywater reuse guidelines for non-potable applications. After disinfection, total coliform counts were below the required 2.2 MPN/100mL for aboveground water reuse. Economic analysis showed that, for the present type of treatment systems (costing \$1000 to \$2500 for a treatment capacity of 0.21 m^3/day), the breakeven period was in the range of 2 to 6 years depending on the daily treatment volume. Higher water costs (water cost plus sewer charges, if present) favor graywater treatment, especially when electricity costs are modest or low. However, if electricity costs are high relative to water cost, graywater treatment is less favorable or may even result in negative ROI. With appropriate financial conditions or subsidies, onsite graywater recycling can have positive environmental and societal impacts in areas of limited or no sewer or wastewater treatment access. A decentralized graywater treatment approach may also provide financial benefits from reduced need for capital expansion or retrofitting existing centralized systems while increasing water reuse opportunities. The results of the study suggest that there is merit in exploring distributed deployment of residential graywater systems and further evaluating the efficiency of the approach for treatment that also includes laundry water.

Following upon the success of treating bathroom graywater, treatment performance of a batch vertical-flow wetland with recirculation (SB-VFW) system was investigated for mixed bathroom and laundry graywater in a five-month field study. The study specifically evaluated the impact of organic loading in graywater on the treatment performance using organic-poor bio-based laundry (BBL) and organic-rich non-bio-based laundry (non-BBL) detergents. The BBL detergent contained 72 mg TOC /g-detergent, which had lower TOC than the non-BBL detergent (150 mg TOC/g-detergent). As a result, BBL graywater had lower influent biodegradable DOC (bDOC) of 20.4 mg/L, while non-BBL graywater had higher influent bDOC of 80.1 mg/L. The SB-VFW system produced effluent that met water quality requirements for aboveground graywater reuse (**Table 4.1**). The SB-VFW produced effluent bDOC of 1 mg/L in three hours; while 24-hour treatment was required to produce effluent of 2 mg/L bDOC when non-BBL graywater was treated. The SB-VFW produced effluent turbidity to < 1 NTU in 3 hours for BBL graywater and 8 hours for non-BBL graywater.

Treatment performance of the SB-VFW system remained stable and recirculation flow rate maintained at 9.5 L/min over a three-month evaluation period of treating BBL graywater. The use of cross flow media (CFM) in the SB-VFW system enhanced aeration by maintaining a DO concentration of 6 mg/L as compared to when CFM was removed (4 mg/L); while the soil layer provided organic and turbidity removal. Aerobic environment supported diverse biota growth in the SB-VFW system for aerobic biodegradation as well as nitrification. Simultaneous nitrification and denitrification was observed in higher organic conditions created by adding extra BBL to raw graywater during the shockloading events. Such an observation suggests that aerobic and anoxic environment co-existed in the SB-VFW system and addition of organic source during the treatment cycle could potentially promote denitrification. The shockloading events also demonstrated the robustness of the SB-VFW design.

Treatment of organic-rich non-BBL graywater was shown to be unsuitable for the SB-VFW system because it caused clogging of the soil layer. Clogging was result of excessive biomass growth. Non-BBL graywater required 24 hours to remove bDOC to 2 mg/L, which disallowed biomass to undergo endogenous biomass decay before a new treatment cycle began. The presence of endogenous biomass decay in a batch SB-VFW system is important to prevent clogging because it allows reduction of biomass concentration that has been increased during the exponential growth phase in order to maintain a stable concentration. The stable treatment performance was achieved when BBL graywater was treated because the long hours (21 hrs) of recirculating water with low organic concentrations allowed the reduction of biomass in the SB-VFW system. The study demonstrated that lower organic content in laundry detergents, similar to the BBL, would facilitate the use of low-cost SB-VFW systems and ensure the SB-VFW systems' effectiveness to produce high effluent quality suitable for aboveground graywater nonpotable reuse in residential homes.

The success of the field study demonstrated that onsite graywater treatment for aboveground nonpotable water reuse can be accomplished using the VFW system developed in this thesis research. In order to illustrate the importance of low-cost treatment options in the development of onsite residential graywater treatment, the cost and environment benefits of onsite graywater recycling in single-family and low-density residential dwellings were conducted using the City of Los Angeles as an example. Graywater recycling can increase the City's ability to reduce potable water consumption, in addition to lowering water supply and treatment-related energy demand. Graywater recycling can reduce the City's potable water consumption by 27% for single-family homes, and by 38% for a multifamily dwelling. At even 1% population participation, the City will be able to reduce water supply and treatment related energy by 4,300 MWh/year. Graywater recycling will reduce potable water demand by 0.2% and wastewater treatment load by 0.3% at such a participation rate.

Amending local building codes to require new constructions to include plumbing to divert graywater for reuse will be important for adoption of residential graywater recycling by homeowners. There are multiple ways that the City can lower financial barriers to adoption of graywater recycling to its residents including: 1) providing rebates to lower the upfront system and retrofit costs, 2) providing low or zero interest financing for system purchase and installation to property owners and allow them to repay through their utility bills, and 3) providing financing incentives to attract investors or developers to provide onsite graywater recycling services through a third-party ownership model. The added benefits for a third-party ownership model are that developers will assume responsibility for regular service and maintenance of the treatment systems to ensure treatment performance and regulatory compliance. In cases where homeowners own their treatment systems, a regulatory requirement for certified service contractors can be implemented.

APPENDICES

Appendix 1 Summary table of graywater regulations in the US

This appendix presents clauses extracted from state regulations and plumbing pertaining onsite graywater reuse and the analysis presented in **Chapter 2**. The purpose of this appendix is to provide readers or researchers a summary the regulations that govern graywater reuse in the US.

Table 3 Graywater definitions and states stipulated in non-plumbing code regulations in the 50 States

	Regulation	**Definition**	**GW sources**
Alabama	Department of Public Health and Bureau of Environmental Services Chapter 420-3-1: Onsite Sewage Disposal and Subdivision-Onsite Sewage Systems, Water Supplies and Solid Waste Management (June 30, 2010)	Graywater is defined as that portion of domestic sewage generated by a water-using fixture or appliance, excluding toilet and food preparation waste	washer or residential spa
Alabama	Department of Public Health and Bureau of Environmental Services Chapter 420-3-1: Onsite Sewage Disposal and Subdivision-Onsite Sewage Systems, Water Supplies and Solid Waste Management (June 30, 2010)	Graywater is defined as that portion of domestic sewage generated by a water-using fixture or appliance, excluding toilet and food preparation waste	GW
Alabama	Department of Public Health and Bureau of Environmental Services Chapter 420-3-1: Onsite Sewage Disposal and Subdivision-Onsite Sewage Systems, Water Supplies and Solid Waste Management (June 30, 2010)	Graywater is defined as that portion of domestic sewage generated by a water-using fixture or appliance, excluding toilet and food preparation waste	GW
Alaska	18 AAC 72.Waste Disposal (January, 2010)	Graywater means wastewater a) from a laundry, kitchen, sink, shower, bath, or other domestic sources; and wastewater b) that does not contain excrement, urine, or combined stormwater. "domestic wastewater" means waterborne human wastes or graywater derived from dwellings,	GW
Arizona	Arizona Administrative Code Title 18 Chapter 9 Article 7 on Water Pollution Control (18 A.A.C. 9, Article 7)	"Gray water" 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.	GW
Arizona	Arizona Administrative Code Title 18 Chapter 9 Article 7 on Water Pollution Control (18 A.A.C. 9, Article 7)	"Gray water" 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.	GW does not contain water used to wash diapers unless disinfected.
Arkansas	Rules and Regulations Pertaining to Onsite Wastewater Systems, Designated Representatives and Installers (December 16, 2007)	Graywater, exclusive of urine and feces	produced by the structure served by a composting/incinerating toilet

California	California Health and Safety Code Section 17922.12	For the purposes of this section, "graywater" means untreated wastewater that has not been contaminated by any toilet discharge, has not been affected by infectious, contaminated, or unhealthy bodily wastes, and does not present a threat from contamination by unhealthful processing, manufacturing, or operating wastes. "Graywater" includes wastewater from bathtubs, showers, bathroom washbasins, clothes washing machines, and laundry tubs, but does not include wastewater from kitchen sinks or dishwashers.	*GW*
Colorado	Connecticut Public Health Code: Regulations and Technical Standards for Subsurface Sewage Disposal Systems (last updated January 1, 2011)	Graywater systems – a system designed to collect, treat, and dispose of liquid wastes from sinks, sinks, tubs, showers, and laundry or other approved plumbing fixtures, excluding toilet fixtures.	GW
Connecticut	Connecticut Public Health Code: Regulations and Technical Standards for Subsurface Sewage Disposal Systems (last updated January 1, 2011)	Gray water means domestic sewage containing no fecal material or toilet wastes.	GW
Delaware	Regulations Governing the Design, Installation and Operation of On-Site Wastewater Treatment and Disposal Systems (adopted January 1985, last updated November 2005)	Graywater: The untreated wastewater that has not come into contact with toilet waste. Graywater includes wastewater from bathtubs, showers, bathroom wash basins, clothes washing machines, laundry tubs and other wastewater which does not present a threat from contamination by unhealthy processing, manufacturing or operating wastes. It does not include wastewater from kitchen sinks or dishwashers.	GW
Florida	Chapter 381 Public Health General Provisions;	"Graywater" means that part of domestic sewage that is not blackwater, including waste from the bath, lavatory, laundry, and sink, except kitchen sink waster. "Blackwater" means that part of domestic sewage carried off by toilets, urinals, and kitchen drains.	GW
Florida	Chapter 64E-6, Florida Administrative Code,		Laundry waste
Florida	Standards for Onsite Sewage Treatment and Disposal Systems (April 28, 2010)		GW, BW and laundry wastewater shall be consolidated
Georgia	Rules of Department of Human Resources, Public Health, Chapter 290-5-26: Onsite Sewage Disposal Management Systems (April 1, 2007);	Graywater means wastewater generated by water-using fixtures and appliances, excluding water closets, urinals, bidets, kitchen sinks, and garbage disposals.	GW.
Georgia	The Manual for On-Site Sewage management Systems		
Hawaii	Guidelines for the Reuse of Graywater (June 22, 2009), Hawaii State Department of Health Wastewater Branch	graywater as wastewater discharged from: Showers and bathtubs; Hand-washing lavatories; Wastewater that has not contacted toilet waste; Sinks (not used for disposal of hazardous, toxic materials, food preparation, or food disposal) and Clothes-washing machines (excluding wash water with human excreta e.g., diapers).	GW

	Hawaii Administrative Rules, Chapter 11-62 “Wastewater Systems” (January 14, 2004)	"Graywater" means wastewater from a dwelling or other establishment produced by bathing, washdown, minor laundry and minor culinary operations, and specifically excluding toilet waste.	GW
Idaho	IDAPA 58, Title 01, Chapter 03, Technical Guideance Manual (TGM) Individual/Subsurface Sewage Disposal Rules (2011)	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.	GW
Illinois	Title 77: Public Health, Chapter I: Department of Public Health, Subchapter r:Water and Sewage, Part 905: Private Sewage Disposal Code, Section 905.30, Approved Private Sewage Disposal Systems (15 March 1996)	No definition	NA
Indiana	Regulations, if they existed, would most likely be found under 401 Indiana Administrative Code 6-8.1.	No definition	NA
Iowa	Chapter 69: On-Site Wastewater Treatment and Disposal Systems 567-69.11(455B) (December 11, 2003).	No definition	NA
Kansas	Kansas Administrative Regulations (KAR) Chapter 25, Article 5, Sewage and Excreta Disposal	No definition	NA
Kentucky	902 Kentucky Administrative Regulations 10:085 Kentucky Onsite Sewage Disposal Systems (September 1989).	"Graywater" means wastewater generated by hygiene activities in a residential, commercial, institutional, or recreational facility, excluding blackwater. (5) "Blackwater" means wastewater containing liquid and solid waste generated through use of a urinal, water closet, garbage disposal, or a similar sanitary fixture used in a residential, commercial, institutional, or recreational facility.	Laundry waste
Louisiana	No guidelines	No definition	NA
Maine	Maine Subsurface Wastewater Disposal Rules 144A CMR 241(August 1, 2009).	Gray wastewater: That portion of the wastewater generated within a residential, commercial, or institutional facility that does not include discharges from water closets and urinals.	GW
		Laundry wastes: Laundry wastes from a single-family dwelling may be discharged into a separate laundry disposal field. See Section 1008.0.	Laundry waste
		Hot tubs: Hot tubs must not discharge into any disposal system utilized for any other wastewater, but may be discharged into a gray water disposal system.	Hot tub
Maryland	House Bill 224 Plumbing – Graywater Recycling prohibits counties from adopting or enforcing provisions of a local plumbing code that prohibit a system that recycles graywater as allowed under the State Plumbing Code	Graywater is defined as used, untreated water generated by a clothes washing machine, a shower, or a bath tub. The definition EXCLUDES untreated water generated by a kitchen sink, a toilet, and a dishwasher.	Refer to plumbing code
Massachusetts	310 CMR 15.000: The State Environmental Code, Title 5: Standard Requirements for the Siting Construction, Inspection, Upgrade and Expansion of On-Site Sewage Treatment and Disposal Systems and for the Transport and Disposal of Septage	Graywater - Any putrescible wastewater discharged from domestic activities including but not limited to washing machines, sinks, showers, bath tubs, dishwashers, or other source except toilets, urinals and any drains equipped with garbage grinders.	GW

Michigan	Michigan Public Health Code Act 368 of 1978: Water Supply and Sewer Systems	Wastewater which normally does not receive human body wastes or industrial waste and is approved for use by a local health department.	GW
Minnesota	Minnesota Administrative Rules. Chapter 7080, Individual Subsurface Sewage Treatment Systems: DESIGN STANDARDS FOR INDIVIDUAL SUBSURFACE SEWAGE TREATMENT SYSTEMS (March 11, 2011).	"Gray water" means sewage that does not contain toilet wastes.	GW
	2010 Minnesota Statutes Chapter 115. Water Pollution Control; Sanitary Districts.115.59 Advanced Treatment Systems	"Graywater" means sewage that does not contain toilet wastes or waste from garbage grinders.	GW
Mississippi	Mississippi Individual On-Site Wastewater Disposal System Law, Chapter 41-67 (1996).	No definition	NA
Missouri	Missouri Laws Accompanied by Department of Health and Senior Services Rules Governing On-Site Sewage Systems (updated in 2007)	"Graywater", all domestic waste not covered in paragraph (a) (toilets, urinals and kitchen drains) of this subdivision, including bath, lavatory, laundry and sink waste; 19. Gray water–Liquid waste, specifically excluding toilet, hazardous, culinary and oily wastes, from a dwelling or other establishment which is produced by bathing, laundry, or discharges from floor drains.	GW
Montana	Rule: 17.36.319 Chapter: On-site Sursurface Waste Water Treatment (2009)	Gray water that is collected separately from sewage flow and that does not contain industrial chemicals, hazardous wastes, or wastewater from toilets	GW
Nebraska	Title 124, Rules and Regulations for Design, Operation and Maintenance of Onsite Wastewater Treatment Systems (revised December 26, 2007)	"Graywater" means all domestic waste excluding blackwater and including bath, lavatory, laundry, and sink waste except kitchen sink waste.	NA
Nevada	R129-98. Sewage disposal is regulated under Nevada Administrative Code 444	"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.	GW
New Hampshire	Chapter Env-Ws 1000 Subdivision and Individual Sewage Disposal System Design Rules	"Gray water" means residential wastewater other than from a urinal or a toilet	GW
New Jersey	New .Jersey Administrative Code 7: 9A Standards for Individual Subsurface Sewage Disposal Systems (January 5, 2009).	"Graywater" means that portion of the sanitary sewage generated within a residential, commercial or institutional facility which does not include discharges from water closets or urinals.	GW from a building.
New Jersey			Laundry waste from a building
New Mexico	20 NMAC 7.3, Liquid Waste Disposal Regulations (September 1, 2005)	"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, dishwashers or laundry water from the washing of material soiled with human excreta, such as diapers.	GW

New York	Appendix 75-A, Wastewater Treatment Standards - Individual Household Systems, Statutory Authority: Public Health Law 201(1)(1) (February 3, 2010)	Graywater is defined as Household wastewater without toilet wastes is known as graywater.	GW
North Carolina	TITLE 15A - DEPARTMENT OF ENVIRONMENT, HEALTH, AND NATURAL RESOURCES CHAPTER 18 - ENVIRONMENTAL HEALTH SUBCHAPTER 18A - SANITATION Section .1900 Sewage Treatment and Disposal Systems (April 4, 1990)	No definition	NA
North Dakota	CHAPTER 62-03.1-03 PRIVATE SEWAGE DISPOSAL SYSTEMS (2000) 62-03.1-03-01. General provisions	No definition	Water-carried sewage from bathrooms, kitchens, laundry fixtures, and other household plumbing
Ohio	O.A.C. Chapter 3701-29 Household Sewage Disposal Rules (July 2, 2007)	No definition	NA
Oklahoma	TITLE 252. DEPARTMENT OF ENVIRONMENTAL QUALITY CHAPTER 641. INDIVIDUAL AND SMALL PUBLIC ON-SITE SEWAGE TREATMENT SYSTEMs (July 1, 2011).	No definition	NA
Oregon	Oregon Administrative Rules, Division 71 Onsite Wastewater Treatment Systems (July 1, 2011).	"Gray Water" means household sewage other than "black wastes," such as bath water, kitchen waste water, and laundry wastes. "Black Waste" means human body wastes including feces, urine, other substances of body origin, and toilet paper.	GW
Oregon	House Bill 2080 (2009) Relating to gray water;	"Gray water" means shower and bath waste water, bathroom sink waste water, kitchen sink waste water and laundry waste water. (b) "Gray water" does not mean toilet or garbage wastes or waste water contaminated by soiled diapers.	GW
Pennsylvania	Title 25. Environmental Protection, Chapter 73. Standards for Sewage Disposal Facilities, Current through 28 Pa.B. 348 (17 January 1998)	No definition	NA
Rhode Island	Chapter 12-120-002, Individual Sewage Disposal Systems (September 1998)	"graywater," shall be held to mean any wastewater discharge from a structure excluding the waste discharges from water closets and waste discharges containing human or animal excrement.	NA
South Carolina	Title 44 - Health Chapter 55 Water, Sewage, Waste Disposal and the Like. Article 9. APPROVAL OF SEWAGE DISPOSAL METHODS AT HOMESITES (2010).	Graywater is included within the Department's definition of sewage and must be managed appropriately	NA
South Dakota	Chapter 74:53:01 Individual and Small On-Site Wastewater System (1 July 1996).	"Graywater," the wastewater generated by water-using fixtures and appliances which do not discharge garbage or urinary or fecal wastes.	GW
Tennessee	Rules of Department of Environment and Conservation, Division of Ground Water Protection, Chapter 1200-1-6: Regulations to Govern Subsurface Sewage Disposal Systems (December, 2009)	No definition	NA

Texas	Chapter 285: On-Site Sewage Facilities Subchapter H: Treatment and Disposal of Graywater (August 3, 2006).	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 that are not used for food preparation or disposal; and (6) clothes-washing machines. (b) Graywater does not include wastewater from the washing of material, including diapers, soiled with human excreta or wastewater that has come in contact with toilet waste.	GW
Texas	Texas Health and Safety Code 341.039. GRAYWATER STANDARDS	graywater" means wastewater from clothes-washing machines, showers, bathtubs, hand-washing lavatories, and sinks that are not used for disposal of hazardous or toxic ingredients. The term does not include wastewater: (1) that has come in contact with toilet waste; (2) from the washing of material, including diapers, soiled with human excreta; or (3) from sinks used for food preparation or disposal.	GW
Utah	Rule R317-401 Graywater Systems (Aug 2011)	"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.	
Vermont	Environmental Protection Rules, Chapter 1, Wastewater System and Potable Water Supply Rules (Sep, 2007)	Graywater – means the wastewater from normal domestic activities such as bathing, clothes washing, food preparation, and cleaning but excluding wastewater from toilets.	GW
	Environmental Protection Rules, Chapter 1, Wastewater System and Potable Water Supply Rules (Sep, 2007)	Graywater – means the wastewater from normal domestic activities such as bathing, clothes washing, food preparation, and cleaning but excluding wastewater from toilets.	GW system
Virginia	Title 12. Health. 12 VAC 5-610-10 et seq. Sewage Handling and Disposal Regulations. Virginia State Board of Health (July 1, 2000)	No definition	NA
Virginia	Chapter 613 Emergency Regulations for Alternative Onsite Sewage Systems (April 6, 2011).	No definition	NA
Washington	Chapter 246-274 WAC: Greywater reuse for subsurface irrigation (July 31, 2011)	(4) "Greywater" means domestic type flows from bathtubs, showers, bathroom sinks, washing machines, dishwashers, and kitchen or utility sinks. Greywater does not include flow from a toilet or urinal. (a) "Light greywater" means flows from bathtubs, showers, bathroom sinks, washing machines, and laundry-utility sinks. (b) "Dark greywater" means flows from dishwashers, kitchen and nonlaundry utility sinks alone or in combination with light greywater.	Light GW

Washington	Chapter 246-274 WAC: Greywater reuse for subsurface irrigation (July 31, 2011)	(4) "Greywater" means domestic type flows from bathtubs, showers, bathroom sinks, washing machines, dishwashers, and kitchen or utility sinks. Greywater does not include flow from a toilet or urinal. (a) "Light greywater" means flows from bathtubs, showers, bathroom sinks, washing machines, and laundry-utility sinks. (b) "Dark greywater" means flows from dishwashers, kitchen and nonlaundry utility sinks alone or in combination with light greywater.	Light GW
Washington	Chapter 246-274 WAC: Greywater reuse for subsurface irrigation (July 31, 2011)	(4) "Greywater" means domestic type flows from bathtubs, showers, bathroom sinks, washing machines, dishwashers, and kitchen or utility sinks. Greywater does not include flow from a toilet or urinal. (a) "Light greywater" means flows from bathtubs, showers, bathroom sinks, washing machines, and laundry-utility sinks. (b) "Dark greywater" means flows from dishwashers, kitchen and nonlaundry utility sinks alone or in combination with light greywater.	light or dark GW
West Virginia	Title 64, Interpretive Rules Board of Health, Series 47, Sewage Treatment and Collection System Design Standards (July 1, 2003).	No definition.	Houses served by graywater disposal systems shall not have garbage disposal units connected to the graywater disposal system
Wisconsin	REGULATION(S): Department of Commerce Chapters (81-87). Comm 81; **Comm 82.10** Design, Construction, Installation, Supervision, Maintenance and Inspection of Plumbing; Chapter Comm 83 Private Onsite Wastewater Treatment Systems (December 2010)	"Graywater" means wastewater contaminated by waste materials, exclusive of urine, feces or industrial waste, deposited into plumbing drain systems.	GW
Wyoming	Memorandum: Chapter 3, Section 8 - Permit by Rule Greywater Added (March 2010)	Greywater is household wastewater that has not been contaminated with toilet discharge (blackwater). Greywater includes wastewater from baths, showers, bathroom wash basins, clothes washing machines, sinks (including kitchen sinks) and laundry tubs.	GW
Wyoming	State of Wyoming Water and Wastewater Rules	Greywater is household wastewater that has not been contaminated with toilet discharge (blackwater). Greywater includes wastewater from baths, showers, bathroom wash basins, clothes washing machines, sinks (including kitchen sinks) and laundry tubs.	GW
Wyoming	State of Wyoming Water and Wastewater Rules	Greywater is household wastewater that has not been contaminated with toilet discharge (blackwater). Greywater includes wastewater from baths, showers, bathroom wash basins, clothes washing machines, sinks (including kitchen sinks) and laundry tubs.	Kitchen sink, garbage disposal, and dishwasher

Table 4 Graywater reuse, disposal permit, storage and treatment requirements stipulated in non-plumbing code regulations in the 50 States

States	Reuse	Disposal	Permit	Holding tank	Treatment	Storage
Alabama		sewer; can circumvent a septic tank and discharge in effluent discharge field	Required.	No permanent holding tanks are allowed. No less than 1000 gallons	Not specified	2 days (48 hours).
Alabama		absence of pressure, discharge in effluent discharge field	Required.	No permanent holding tanks are allowed	Not specified	2 days (48 hours).
Alabama	Drip irrigation			Dosing chamber required, at least the peak daily sewage flow for systems <2500 gpd	secondary treatment with filtration	dosing frequency at least 6 times per day
Alaska	Not specified	Not allowed in pit privy	Not speficifed	Not specified	Primary treatment	Not specified
Alaska	Not specified	surface or water disposal	Required.		Secondary treatment w/ disinfection. Unless a report is submitted and justify the primary treatment is suffice.	
Alaska	Not specified	subsurface disposal			Primary treatment	
Arizona	landscape irrigation; composting ; lawn watering; gardening;	disposal to sewer, or onsite treatment system if blockage or backup of the system occurs	Required when daily flow rate is > 400 gallons per day	Not specified	Not specified	Not specified
Arizona	Surface irrigation by flood or drip, no food trees except citrus & nut trees	disposal to sewer, or onsite treatment system if blockage or backup of the system occurs	Required when daily flow rate is > 400 gallons per day	Not specified	Not specified	Not specified
Arkansas	Not allowed	disposed in a ditch or a trench in the fashion that is the same as a septic tank.	Required.	Not specified.	Disinfection required for surface disposal.	Not specified.
Arkansas	Surface discharge.	Not specified.	Not specified.	Not specified.	Not specified.	Not specified.
California	allowed. indoor and outdoor; subsurface irrigation and other safe uses	not specified	Plumbing code	Not specified.	Plumbing code	Not specified

States	Reuse	Disposal	Permit	Holding tank	Treatment	Storage
Colorado	An incineration toilet, which may be used in connection with a graywater system by permit from the local board of health, shall be designed and installed in accordance with all applicable federal, state, and local air-pollution requirement		Not allowed when served by public sewer	Septic Tank; 750 gallons for 2 bedrooms and 250 gallons for every additional bedroom	Graywater systems shall meet at least all minimum design and construction standards for septic tank systems based on the amount and character of wastes for the fixtures and the number of persons served.	retention time >30 hours.
Connecticut	Not allowed	Leachfield	Permit required.	septic tank, > 500 gallon (1-3 persons), or 50% of the capacity specified for the required residential sewage disposal system	Septic tank	24 hour design flow
Delaware	Not specified	Not specified	A written document issued by the Department which states that an on-site wastewater treatment and disposal system appears adequate to serve the purpose for which a particular application is made.	In no case shall the tank have a capacity less than seven days average flow from the wastewater generating facility or 1,000 gallons, whichever is larger	Not specified.	Not specified.
Florida	Not specified	Drain field system	Allow for both sewered or unsewered sites.	250 G receiving < 75 GPD. If >75GPD, tank size should be based on average daily sewage flow plus 200 gallons for sludge storage. Storage tank with multiple compartments	Not Specified.	Not specified
Florida	Not specified	drainfield absorption	Allow for both sewered or unsewered sites.	storage tank with multiple compartments	Not Specified.	Not specified
Florida		drainfield	Not allowed when served by public sewer		aerobic treatment	
Georgia	Not specified	Field absorption with emphasis on field area requirement	Required. Not specified if it is allowed when property to public	>500 G for four bedrooms. /each bedroom over four requires additional	sedimentation	Not specified

States	Reuse	Disposal	Permit	Holding tank	Treatment	Storage
			sewer is made available.	130G capacity for the tank. Or 65% of a conventional septic tank		
Hawaii	Subsurface irrigation, e.g. lawn & plants. No irrigation to root crops, vegetables eaten raw, crops rest on ground, seedling or barren area (create runoff / ponding).	overflow diverted to onsite wastewater treatment system,	Required. Can be used with or without sewer connection	>50G or enough for holding daily graywater produced	Sedimentation	<24 hours
	subsurface irrigation or	effluent from graywater tank conveyed to a sand filter, absorption trenches and beds, mounds or seepage pits	required	>600 gallon tank, minium 150GPD per bedroom.	sedimentation	>600 gallon tank minium 150GPD per bedroom.
	subsurface irrigation	allowed	Required	Not specified	Not specified	Not specified
Idaho	subsurface irrigation. But not vegetable gardens. Mini-leachfield or subsurface drip irrigation	Not specified	Required	Surge tank >50 gallons	Screen filter, sedimentation	Not specified.
Illinois	NA	NA	NA	NA	NA	NA
Indiana	NA	NA	NA	NA	NA	NA
Iowa	NA	NA	NA	NA	NA	NA
Kansas	NA	NA	NA	NA	NA	NA
Kentucky	Not specified	subsurface disposal	Required. Sewer or non sewer	Dosing tank, x2 size of total design daily flow. Soil assessment is emphasized. Holding tank must sized to hold a minimum of 7 days wasteflow	Not specified	holding tanks sized to hold at least 7 days wasteflow. Storage period not specified.
Louisiana	NA	NA	NA	NA	NA	NA
Maine	NA	subsurface graywater disposal system. Field size based on at a minimum of 70% of the base flow or 126 GPD	Required	A septic tank with minimum liquid capacity of an individual septic tank must be 750 gallon for any use.	sedimentation	Npt specified.
	NA	Subsurface Laundry disposal system. field size based on a minimum of 20% of the base flow or 55GPD	Required	No septic tank required	Not required	NA

States	Reuse	Disposal	Permit	Holding tank	Treatment	Storage
	NA	subsurface graywater disposal system. Field size based on at a minimum of 70% of the base flow or 126 GPD	Required	A septic tank with minimum liquid capacity of an individual septic tank must be 750 gallon for any use.	sedimentation	Npt specified.
Maryland	Refer to plumbing code	Refer to plumbing code	Refer to plumbing code	Refer to plumbing code	Refer to plumbing code	Refer to plumbing code
Massachusetts	Allowed but not specified.	Soil Absorption System for subsurface disposal	Required. Not specified if homes with or without public sewer can use this systems.	Graywater systems may include either a septic tank or a filter. Septic tank has to be >1000G.	filtration or sedimentation	Not specified
Michigan	Not specified.	Not specified.	Required. Sewer or non sewer	Not specified	Not specified. Health Department approve after consulting plumbing board	Not specified
Minnesota	Not allowed	Subsurface disposal	Required.	Septic tank: >750G for a 3-bedroom dwelling	sedimentation	Septic tank
	Allowed. within facility (?)	Discharge above ground	Required. Not specified if it is allowed when property to public sewer is made available.	Not specified	MN Rules, Chapter 7050	Not specified
Mississippi	NA	NA	NA	NA	NA	NA
Missouri	Not specified.	subsurface land disposal	Required. Not specified if it is allowed when property to public sewer is made available.	Holding tank >1,000G or 400 gallons x no, of bedrooms	Primary treatment	Not specified.
Montana	Toilet flushing	Allowed. by means of wastewater treatment systems	Not required. Sewered or non sewered	Not specified	Not specified.	Not specified.
Montana	irrigation where a waste segregation system is used.	allowed. by means of wastewater treatment systems	Not specified	Kitchen graywater can be used for irrigation if a waste segregation system is used.	Not specified.	Not specified.
Montana	Subsurface irrigation	allowed. by means of wastewater treatment systems	Required. Not specified if it is allowed when property to public sewer is made available.	Not specified.	Not specified.	Not specified.
Nebraska	No guidelines provided.	No guidelines provided.	NA	NA	NA	NA
Nevada	Underground irrigation with soil percolation rate >120 min per inch. Must not result in the surfacing.	sewer.	Required. For both sewer or non sewer	required. >50G	sedimentation	Not specified

States	Reuse	Disposal	Permit	Holding tank	Treatment	Storage
New Hampshire	Not specified.	Disposal via a mini-drywell	Required. Not specified if it is allowed when property to public sewer is made available.	Not specified.	Primary/Secondary Treatment.	NS
New Jersey	Can be used for blackwater (i.e. toilet flushing?);	seepage pit	Required.	Septic tanks at least 250 g for 1 bedroom; and design based on 75% of the sanitary sewage	sedimentation	Not specified
New Jersey	Not specified	Disposal in seepage pits or disposal field.	Required. As a means of reducing hydraulic loading on an existing disposal field which has been malfunction	Not specified	Not specified	Not specified
New Mexico	household flower gardening, composting or landscaping irrigation via subsurface irrigation system or mulched surface area (no spray, no ponding, no discharge into water course; no food plants except for fruit and nut trees),	Not specified	Required if >250GPD, for both sewered or non-sewered	One day of flow (20% of total flow for laundry waste; 33% of total flow for bathroom waste)	Sedimentation	<24 hours
New York	Not allowed	Subsurface disposal System	Required, sewer and non-sewer	septic tank. Designed flow at 75gpd/bedroom.	Treatment of household wastewater. Septic tank,	Not specified.
North Carolina	NA	NA	NA	NA	NA	NA
North Dakota	Not allowed	Subsurface disposal System	Required	Septic tank or approved sedimentation tank	Pass through a septic or approved sedimentation tank	Not specified.
Ohio	NA	NA	NA	NA	NA	NA
Oklahoma	NA	NA	NA	NA	NA	NA
Oregon	Soil disposal; irrigation and toilet flushing	existing onsite system, new onsite system with a soil absorption facility, public sewerage	Required. Sewer or non sewer	Not specified/	Onsite system; Filtration	Not specified/
Oregon	Allowed, not specified	Allowed, subsurface sewage disposal systems	Required, sewer and non-sewer	Not specified/	onsite wastewater treatment system	Not specified.
Pennsyl-vania	NA	NA	NA	NA	NA	NA

States	Reuse	Disposal	Permit	Holding tank	Treatment	Storage
Rhode Island	No separate guideline for graywater	NA	NA	NA	NA	NA
South Carolina	No separate guideline for graywater	NA	NA	NA	NA	NA
South Dakota	Allowed, toilet flushing, irrigation of lawns and areas not intended for food production	absorption fields, mounds, or seepage pits	Required, only non-sewered	septic tanks	septic tank	3 days
Tennessee	NA	NA	NA	NA	NA	NA
Texas	around the foundation of new housing to minimize foundation movement or cracking; (2) gardening; (3) composting ; or (4) landscaping ; (no ponding, no runoff across property line, no spray irrigation,	allowed, ground. Not specified surface or subsurface	Required if >400 GPD	Required, not specified	Sedimentation, Simple filter,	Not specified
Texas	Not specified	Allowed, support plant growth, sodded with vegetative cover, limited access and use by residents and pets (avoid discharging into wet soil; should avoid detergents with significant amount of phosphorus	Not required for existing homeowners who have been practicing laundry graywater discharge	Not specified/	lint trap	Not specified

States	Reuse	Disposal	Permit	Holding tank	Treatment	Storage
Texas	irrigation and other agricultural purposes; domestic purposes (gardening, composting, landscaping at the residence); commercial purposes; industrial purposes. Subsurface discharge system around foundation of new houses to minimize foundation movement or cracking; (no ponding, no spray, no crossing property line;	Not specified	not specified. Allow for both sewer and non sewer homes	Required, not specified	Not specified	Not specified
Utah	Graywater shall not be: (i) applied above the land surface; (ii) applied to vegetable gardens except where graywater is not likely to have direct contact with the edible part, whether the fruit will be processed or not; (iii) allowed to surface; or (iv) discharged directly into or reach any storm sewer system or any waters of the State.	Not specified	Required, sewer or non sewer	>250 G for 2-bedroom	Filter (115 micro), sedimentation	Not specified

States	Reuse	Disposal	Permit	Holding tank	Treatment	Storage
Vermont	Not specified	soil-based disposal	Required, not specified sewer or non-sewer; given soil condition met the 18" thickness with percolation rate of 120 min/inch	septic tank, with minimum size of 1000 gallons based on a daily flow rate of 667 GPD	Septic tank	Not specified
Vermont		Graywater disposal system is required for residence using composting or incinerating toilets	required	septic tank. Design comply with all of the design facgtors for wastewater disposal system with 25% reduction in size will be approved.	Septic tank	same as wastewater
Virginia	NA	NA	NA	NA	NA	NA
Washington	subsurface irrigation	Not specified	Tier 1: Required, sewer or non sewer. 1 system max @ 60GPD; each household allowed max 2 systems totalling @120GPD	Not allowed	Not specified	Tier1: no storage
Washington	subsurface irrigation	Not specified	Tier 2: Required, sewer or non sewer. total GW <3500GPD GW. If total flow is <3500GPD, GW <300	Allowed. Not specified	not specified. Designed by qualified professional; health officers allow homeowner design their own systems if not located next to marine shore and <300 GPD GW; local health officer design system if they performs soil / site evaluation.	Tier2: <24 hours
Washington	subsurface irrigation	Not specified	Tier 3: Required, sewer or non sewer. total GW <3500GPD GW. If total flow is <3500GPD, GW <300	Allowed. Not specified	bear NSF seal. Light GW: Systems meet NSF/ANSI Standard 350-1, 2011; Dark GW: systems meet NSF/ANSI Standard 40, 2009.	Tier 3: >24 hours,
West Virginia	Not specified	Disposal	Required	septic tank >1000 G for 4-bedroom, and additional of 250G capacity is required for every additional bedroom	Septic tank	Not specified
Wisconsin	Allowed. Depending on treatment levels. Cooling water, subsurface irrigation, surface	Not specified	Required.	yes, not specified	depending on reuse purposes	Not specified/

States	Reuse	Disposal	Permit	Holding tank	Treatment	Storage
	irrigation (except food crops), vehicle washign, clothes washing, air conditioning, soil compaction, dust control, washing aggregate and making concrete, toilet flushing,					
Wyoming	subsurface irrigation; sprayed irrigation not recommended for residents live in urban area and do not own multi-acre property.	allowed, leachfield or mulch basin	Not required, both sewer and non sewer; < 2000 GPD. Must have a backup system for disposal including balckwater disposal system, sewer, or secondary graywater systems that won't fail in freezing temp.	Not recommended;	Not specified	Not specified.
Wyoming	subsurface irrigation; sprayed irrigation not recommended for residents live in urban area and do not own multi-acre property.	underground disposal through leachfield or mulch basins	Not required, both sewer and non sewer; < 2000 GPD. Must have a backup system for disposal including balckwater disposal system, sewer, or secondary graywater systems that won't fail in freezing temp.	Not recommend;	filtration and chlorination is recommended if storage is used.	<24 hrs
Wyoming	recommended: composting ;	allowed, blackwater treatment system or sewer	Not required, both sewer and non sewer; < 2000 GPD. Must have a backup system for disposal including balckwater disposal system, sewer, or secondary graywater systems that won't fail in freezing temp.	Not recommend;	filtration and chlorination is recommended if storage is used.	<24 hrs

Table 5 Graywater definitions and source requirements stipulated in the plumbing codes in the 50 States

State	Plumbing Code	Definition	GW sources
Alabama	Appendix C 2006 ICP	Waste discharged from lavatories, bathtubs, showers, clothes washers and laundry trays	GW
Alaska	Appendix G of 2003 UPC	Graywater is untreated household waste water which has not come into contact with toilet waste. Graywater includes used water from bathtubs, showers, bathroom wash basins, and water from clothes-washer and laundry tubs. It shall not include wastewater from kitchen sinks or dishwashers.	GW
Arizona	No State wide plumbing code (removed in 2007)	NA	NA
Arkansas	2006 Arkansas State Plumbing Code Appendix C 101-102	GRAY WATER. Waste discharged from lavatories, bathtubs, showers, clothes washers and laundry trays	GW
California	Chapter 16A (2009 UPC)	Pursuant to Health adn Safety Code Section 17922.12, " graywater" means untreated wastewater that has not been contaminated by any toilet discharge, has not been affected by infectious, contaminated, or unhealthy bodily wastes, and does not present a threat from contamination by unhealthful processing, manufacturing, or operating wastes. "Graywater" includes but is not limited to wastewater originated from bathtubs, showers, bathroom washbasins, washing machines, and laundry tubs as graywater, but exclude those from kitchen sinks and dishwashers."	
	Appendix G, 2010 California Plumbing Code: California Code of Regulations Title 24, Part 5	Graywater is untreated waste water which has not come into contact with toilet waste. Graywater includes used 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..	
Colorado	2009 IPC Appendix C - Graywater System is not adopted	NA	NA
Connecticut	Appendix C 101 General of 2003 IPC. State Building Code, 2005 Connecticut Supplement.	Graywater system has been defined to get water from everything with Exceptions: Bathtubs, showers, lavatories, clothes washers and laundry sinks shall not be required to discharge to the sanitary drainage system where such fixtures discharge to an approved graywater recycling system.	GW
Delaware	2009 ICP Appendix C is not adopted.	NA	NA
Florida	Appendix C101-103. 2006 IPC. 2007 Florida Building Code	Waste discharged from lavatories, bathtubs, showers, clothes washers and laundry trays.	GW
Georgia	Georgina International Plumbing Code (2006) Appendix C; Amendment 2009-2011	Waste discharged from lavatories, bathtubs, showers, clothes washers and laundry trays.	lavatories, bathtubs, showers, clothes washers and laundry trays; and condensate
Hawaii	Chapter 183 of Tital 3, Hawaii Administrative Rules, State Plumbing Code (2009) based on 2006 UPC. Chapter 16		GW
Idaho	IDAPA 07.02.06: Rules concerning Uniform Plumbing Code. Division of Builidng Safety Appendix G, 2003 UPC by Idaho Plumbing Board	Gray water is untreated household waste water which has not come into contact with toilet waste. Gray water includes used water from bathtubs, showers, bathroom wash basins, and water from clothes-washer and laundry tubs. It shall not include wastewater from kitchen sinks or dishwashers.	NA
Illinois	Illinois Administrative Code Title 77 Chapter I Subchapter r Part 890: Illinois Plumbing Code	"Gray Water": Waste water, such as dishwater, or other waste water not containing fecal matter or urine. "Toxic Transfer Fluids": Sanitary waste, grey water or mixtures containing harmful substances, including but not limited to ethylene glycol, hydrocarbons, oils, ammonia refrigerants, and hydrazine. "Sub-soil Drainage": Liquid waste, such as run off water, seepage water or clear water waste, free of fecal matter and grey water.	NA

State	Plumbing Code	Definition	GW sources
Indiana	Indiana Plumbing Code, 1997 UPC, Appendix G - Deleted	NA	NA
Iowa	Iowa State Plumbing Code 2010, 2009 UPC, Chapter 16 Part I deleted and insert in lieu thereof the follow: Wastewater intended for use in underground irrigation systems shall be treated in accordance with 567—Chapter 69, Private Sewage Disposal Systems. The irrigation system shall comply with 567—69.12(455B)	NA	NA
Kansas	No State Wide Plumbing Code	NA	NA
Kentucky	Kentucky State Plumbing Codes	No definition	NA
Louisiana	Louisinana State Plumbing Code, 2000. 1994 Standard Plumbing Code	No definition	NA
Maine	State of Maine, Plumbing Installations. 2009 UPC does not adopt Chapter 16 Part I Gray Water Systems.	NA	NA
Maryland	Maryland State Plumbing Code. 2006 National Standard Plumbing Code. Appendix G	Graywater: Used untreated water generated by clothes washing machines, showers, bathtubs and lavatories. It shall not include water from kitchen sinks or dishwashers.	GW
Massachusetts	Uniform State Plumbing Code, 248 CMR: Board of State Examiners of Plumbers and Gas Fitters.	Gray-water. Used water out-flowing from a clothes-washer, shower, bathtub or bathroom sink and reused on the same site for below ground irrigation only. Gray-water is typically not treated	GW
Michigan	Michigan State Plumbing Code, 2006 IPC Appendix C 101-103	Waste discharged from lavatories, bathtubs, showers, clothes washers and laundry trays.	GW
Minnesota	2009 Minnesota Plumbing Code	No definition	NA
Mississippi	No State Wide Plumbing Code	NA	NA
Missouri	No State Wide Plumbing Code	NA	NA
Montana	Montana Building Codes, Plumbing Rquirements, 2009 UPC.	Gray water is untreated waste water that has not come into contact with toilet waste, kitchen sink waste, dishwasher waste or similarly contaminated sources. Gray water include waste water from bath tubs, showers, bathroom wash basins, clothes-washers and laundry tubs	
Nebraska	2009 UPC or 2009 IPC. Chapter 16 Part I of 2009 UPC adopted.;		
Nevada	UPC: individual cities or counties can adopt and amend the code accordingly.	NA	NA
New Hampshire	Appendix C of 2009 IPC	Waste discharged from lavatories, bathtubs, showers, clothes washers and laundry trays..	GW
New Jersey	National Standard Plumbing Code 2009. guidelines concerning	NA	NA

State	Plumbing Code	Definition	GW sources
	graywater reuse is not adopted		
New Mexico	2009 New Mexico Plumbing Code: 2009 UPC, Chapter 16 I deleted except for 1602 Definition and 1610. Graywater systems.	Waste water discharged from lavatories, bathtubs, showers, clothes washers and laundry sinks	GW
New York	2007 Plumbing Code of New York State. 2003 IPC Appendix C 101	Waste discharged from lavatories, bathtubs, showers, clothes washers, and laundry trays.	GW
North Carolina	2012 NC Plumbing Code, 2009 IPC, Appendix C Graywater	Waste discharged from lavatories, bathtubs, showers, clothes washers and laundry trays	GW
North Dakota	Plumbing Installation Standards. UPC 2009. Chapter 16	Graywater is untreated waste water that has not come into contact with toilet waste, kitchen sink waste, dishwasher waste or similarly contaminated sources. Gray water includes waste water from bath tubs, showers, bathroom wash basins, clothes washers and laundry tubs	GW
Ohio	Ohio State Plumbing Code. 2009 IPC. Bathtubs, showers, lavatories, clothes washers and laundry sinks shall not be required to discharge to the sanitary drainage system where such fixtures discharge to a gray water recycling system approved by the "Ohio Environmental Protection Agency" in accordance with Chapter 3745-42 of the Administrative Code. (no mention of GW System)	Waste discharged from lavatories, bathtubs, showers, clothes washers and laundry trays	Not defined in Chapter 3745-42 of the Administrative Code
Oklahoma	2009 IPC. Appendiced not adopted.	NA	NA
Oregon	2011 Oregon Plumbing Specialty Code. 2009 UPC. No mention of graywater	No definition	Not segregation
Pennsylvania	Uniform Construction Code, 2009 IPC, no appendices are adopted.	NA	NA
Rhode Island	Rhode Island State Plumbing Code. IPC 2009. Appendix C,	Waste discharged from lavatories, bathtubs, showers, clothes washers and laundry trays.	GW
South Dakota	South Dakota State Plumbing Code. 2009 UPC, Chapter 16 and Appendix G	Waste discharge only of bathtubs, showers, lavatories, clothes washers and laundry sinks.	
Tennessee	No Statewide plumbing code	NA	NA
Texas	Appendix C, 2006 IPC	Waste discharged fromk lavatories, bathtubs, showers, clothes washers and laundry trays.	GW
Utah	Appendix C 101 of 2009 IPC	Waste discharged from lavatories, bathtubs, showers, clothes washers and	
		laundry trays.	
Vermont	2009 IPC. Guidelines concerning graywater reuse and recycling are	NA	

State	Plumbing Code	Definition	GW sources
	not adopted (unclear)		
Virginia	2009 IPC. Appendix O and C graywater and rain water recycling systems.	Bathtubs, showers, lavatories, clothes washers and laundry trays are not required to discharge to the sanitary drainage system where those fixtures discharge to an approved gray water or rain water recycling system.	GW
Washington	Chapter 51-56 WAC State Building code adoption and amendment of the 2009 edition of the uniform plumbing code. Chapter 16 I graywater is not adopted.	Greywater or Gray Water - Domestic type flows from bathtubs, showers, bathroom sinks, washing machines, dishwashers, and kitchen or utility sinks. Gray water does not include flow from a toilet or urinal	NA
West Virginia	Title 87 Legislative Rule State Fire Commission Series 4 State Building Code. 2009 IPC adopted but appendices are not enforceable.	NA	NA
Wisconsin	Plumbing Code: Department of Commerce, Plumbing (Chs. Comm 81-87)		
Wyoming	No Statewide plumbing code	Waste discharged from lavatories, bathtubs, showers, clothes washers, and laundry trays.	

Table 6 Graywater reuse, disposal, permit, storage and treatment requirements stipulated in the plumbing codes in the 50 States

State	Reuses	Disposal	Permit	Holding tank	Treatment	Storage time
Alabama	Toilet flushing; Subsurface irrigation	not specified.	Required	Toilet flushing: X2 daily volume required for flushing but no less than 50G. Subsurface irrigation: not specified	Toilet flushing: Filtration, holding tank, disinfection, coloring; makeup water. Irrigation: Filtration, holding tank; Percolation tests	Toilet flushing: 72 hrs; Subsurface irrigation: 24 hours
Alaska	Subsurface irrigation	subsurface disposal field	Required, both sewer and no sewer	holding tank, At least 50 gallons	Vented running trap, sedimentation	Not specified
Arizona	NA	NA	NA	NA	NA	NA
Arkansas	Toilet flushing; subsurface irrigation	not specified.	Required. Both.	Toilet Flushing: X2 daily volume required for flushing but no less than 50G; Subsurface irrigation: not specified	Toilet flushing: Filtration (media, sand or diatomaceous earth), holding tank, disinfection, coloring; makeup water. Subsurface irrigation: not specified.	Toilet flushing: 72 hours; subsurface irrigation: not specified
California	Subsurface irrigation; or other indoor and outdoor nonpotable use. No ponding, no spray, no runoff	subsurface disposal: disposal field, mulch basins	Required if it's larger than a single laundry machine for a single to two family. Sewer or	Washing machine: direct disposal; simple system and complex system: not specified; Treated graywater: shall have a separate tank .	Washing machine, simple and complex systems: not specified. reated graywater: Meet Title 22 disinfected tertiary recycled water	Not specified.

State	Reuses	Disposal	Permit	Holding tank	Treatment	Storage time
	of GW, no irrigation of root crops or edible parts of food crops that touch the soil.		non-sewer			
	subsurface irrigation, no vegetable garden,	subsurface disposal through disposal field or mulch basins	required. Both	surge tank required, sizes not specified.	sedimentation	Not specified.
Colorado	NA	NA	NA	NA	NA	NA
Connecticut	Toilet and urinal flushing. GW systems shall be permitted to be used for irrigation when specific approval is given by the authority having jurisdiction.	Not specified.	Required, both sewer or non-sewer	Reservoir should be a minimum of x2 the colume of water required to meet the daily flushing requriements but no less than 50G	Toilet flushing: Filtration (media, sand or diatomaceous earth), holding tank, disinfection, coloring; makeup water.	72 Hours
Delaware	NA	NA	NA	NA	NA	NA
Florida	Subsurface irrigation, toilet and urinal flushing,	subsurface disposal through disposal field or mulch basins	required. Both	Toilet flushing: Reservoir should be a minimum of x2 the colume of water required to meet the daily flushing requriements but no less than 50G. Irrigation: sized to limit the retention time of GW to max of 24 hrs	Toilet flushing: Filtration (media, sand or diatomaceous earth), holding tank, disinfection, coloring; makeup water. Irrigation: filtration (media, sand or diatomaceous earth)	Toilet flushing: 72hrs; subsurface irrigation: 24 hours
Georgia	Toilet flushing; Subsurface irrigation	not specified.	Required. For both	sized to daily volume required for flushing; subsurface irrigation shall be designed according Onsite Sewage Disposal Management Systems	Toilet flushing: approved, filtration, holding tank, disinfection, coloring; makeup water; subsurface irrigation shall be designed according Onsite Sewage Disposal Management Systems	Toilet flushing: 24 hrs
Hawaii	Subsurface irrigation	not specified.	Require, Not specified	Not specified.	Vented running trap, holding tank	Not specified
Idaho	NA	NA	NA	A minimum capacity of 50G is required	vented running trap, sedimentation	Not specified.
Illinois	Not allowed	Not allowed	NA	NA	NA	NA
Indiana	NA	NA	NA	NA	NA	NA

State	Reuses	Disposal	Permit	Holding tank	Treatment	Storage time
Iowa	NA	NA	NA	NA	NA	NA
Kansas	NA	NA	NA	NA	NA	NA
Kentucky	NA	NA	NA	NA	NA	NA
Louisiana	NA	NA	NA	NA	NA	NA
Maine	NA	NA	NA	NA	NA	NA
Maryland	toilet and urinal flushing, landscape irrigation, supply water for ornametnal ponds, make-up water for cooling towers.	Not specified	Not Specified.	Not specified.	Acceptable methods: nylon/cloth filters, sand filters, diatomaceous earth filter, rack or grate filters, collection or settling, biological treatment units, RO, physical/ Chemical treatment	Not specified
Massachusetts	Subsurface irrigation	Not specified	A Special-permission must be seeked for installation of a dedicated graywater recycling system	Not specified.	Not specified.	Not specified.
Michigan	Subsurface irrigation, toilet and urinal flushing,	subsurface disposal through disposal field or mulch basins	required. Both	Toilet flushing: Reservoir should be a minimum of x2 the colume of water required to meet the daily flushing requriements but no less than 50G. Irrigation: sized to limit the retention time of GW to max of 24 hrs	Toilet flushing: Filtration (media, sand or diatomaceous earth), holding tank, disinfection, coloring; makeup water. Irrigation: filtration (media, sand or diatomaceous earth)	Toilet flushing: 72hrs; subsurface irrigation: 24 hours
Minnesota	NA	NA	NA	NA	NA	NA
Mississippi	NA	NA	NA	NA	NA	NA
Missouri	NA	NA	NA	NA	NA	NA
Montana			Not required. For personal use.	50G	holding tanks	Not specified
Nebraska						
Nevada	NA	NA	NA	NA	NA	NA
New Hampshire	Toilet flushing; Subsurface irrigation	not specified.	Required. For both	Toilet flushing: X2 daily volume required for flushing but no less than 50G. Subsurface irrigation: not specified	Toilet flushing: Filtration, holding tank, disinfection, coloring; makeup water. Irrigation: Filtration, holding tank; Percolation tests	Toilet flushing: 72 hrs; Subsurface irrigation: 24 hours

State	Reuses	Disposal	Permit	Holding tank	Treatment	Storage time
New Jersey	NA	NA	NA	NA	NA	NA
New Mexico	NA	NA	NA	NA	NA	NA
New York	Recycled gray water shall be utilized only for flushing water closets and urinals that are located in the same building as the gray water recycling system.	Not specified	Not specified	> 50 gallons.	Toilet flushing: Filtration, holding tank, disinfection, coloring; makeup water.	< 72 hours.
North Carolina	Toilet flushing; Subsurface irrigation	not specified.	Required. For both	Toilet flushing: X2 daily volume required for flushing but no less than 50G. Subsurface irrigation: not specified	Toilet flushing: Filtration, holding tank, disinfection, coloring; makeup water. Irrigation: Filtration, holding tank; Percolation tests	Toilet flushing: 72 hrs; Subsurface irrigation: 24 hours
North Dakota	Subsurface irrigation	allowed	required	50G	holding tanks	Not specified
Ohio	Bathtubs, showers, lavatories, clothes washers and laundry sinks shall not be required to discharge to the sanitary drainage system where such fixtures discharge to a gray water recycling system approved by the "Ohio Environmental Protection Agency" in accordance with Chapter	Not specified	Not specified	Not specified	Not specified	Not specified

State	Reuses	Disposal	Permit	Holding tank	Treatment	Storage time
	3745-42 of the Administrative Code. (no mention of GW System)					
Oklahoma	NA	NA	NA	NA	NA	NA
Oregon	NA	NA	NA	NA	NA	NA
Pennsylvania	NA	NA	NA	NA	NA	NA
Rhode Island			Required. Appendix C may only be utilized when specifically permitted by a local or regional sewer authority having jurisdiction, or the Rhode Island Department of Environmental Management for individual sewage disposal system.	The holding capacity of the reservoir shall supplement the daily flushing requirements of the fixtures supplied with rain water.	Disinfection	Not specified.
South Dakota	Irrigation purposes.		Required.	Not less than 50 gallons.	**Filtration.:**	Maximum of 72 hours.
Tennessee	NA	NA	NA	NA	NA	NA
Texas	Toilet flushing and subsurface irrigation.	Not specified.	Not specified.	Toilet flushing: X2 daily volume required for flushing but no less than 50G. Subsurface irrigation: sized to limit the retention time of GW to a max of 24 hrs	Toilet flushing: Filtration, holding tank, disinfection, coloring; makeup water. Irrigation: Filtration, holding tank; Percolation tests	Toilet flushing: 72 hrs; Subsurface irrigation: 24 hours
Utah	Subsurface irrigation of landscape.		Required.	The holding capacity of the reservoir shall supplement the daily	Disinfection	Not specified.
Utah				flushing requirements of the fixtures supplied with rain water.		
Vermont	NA		NA	NA	NA	NA
Virginia			requirement	Not specified.		

State	Reuses	Disposal	Permit	Holding tank	Treatment	Storage time
Washington	Gray water shall not be used for irrigation except as permitted by the department of health rules.	NA	NA	NA	NA	NA
West Virginia	NA	NA	NA	NA	NA	NA
Wisconsin						
Wyoming	Toilet flushing, subsurface irrigation		Required.	Minimum 50 gallon capacity.	Tertiary treatment shall result in water that is adequately oxidized, clarified, coagulated, filtered, and disinfected so that at some location in the treatment process, the seven day median number of total coliform bacteria in daily samples does not exceed two and two-tenths per one hundred milliliters.	Less than 72 hours.

Appendix 2 Graywater definitions in the United States

This appendix presents a summary of graywater definitions in the US. This appendix serves as a reference to readers or researchers who are interested in reading or further evaluating graywater sources in different States.

Table 7 Graywater definition of graywater in the 50 States in the US (Part 1)

States	Washing Machines	Toilet / Urinals	Water soiled with diapers	Swimming pool / hot tub	Combined Stormwater	Water Softener
Alabama	Y	N	NS	Y		Y
Alaska	Y	N	N	Y	N	Y
Arizona	Y	N	NS			Y
Arkansas	Y	N	NS			NS
California	Y	N	N			Y
Colorado	Y	N	NS			Y
Connecticut	Y	N	N			Y
Delaware	Y	N	N			Y
Florida	Y	N	NS			Y
Georgia	Y	N	Y			Y
Hawaii (Gray)	Y	N	N			Y
Hawaii (WWS)	Y	N	NS			
Idaho	Y	N	N			N
Illinois	Y	N	NS			N
Indiana						
Iowa						
Kansas						Y
Kentucky	Y	N	NS			
Louisiana						
Maine	Y	N	NS	Y		Y
Maryland	Y	N	NS			
Massachusetts	Y	N	NS			Y
Michigan	Y	N	Y			?
Minnesota (7080)	Y	N	Y			Y
Minnesota (115)	Y	N	NS			
Mississippi						
Missouri	Y	N	NS			Y
Montana	Y	N	NS			Y
Nebraska	Y	N	NS			N
Nevada	Y	N	NS			Y

States	**Washing Machines**	**Toilet / Urinals**	**Water soiled with diapers**	**Swimming pool / hot tub**	**Combined Stormwater**	**Water Softener**
New Hampshire	Y	N	NS			Y
New Jersey	Y	N	NS			Y
New Mexico	Y	N	N			Y
New York	Y	N	NS			Y
North Carolina	Y	N	NS			Y
North Dakota	Y	N	NS			
Ohio	Y	N	NS			
Oklahoma						
Oregon (Onsite)	Y	N	N			Y
Oregon (House Bill 2080)	Y	N	N			
Pennsylvania						N
Rhode Island	Y	N	N			Y
South Carolina						
South Dakota	Y	N	N			Y
Tennessee						
Texas	Y	N	N			Y
Utah	Y	N	NS			Y
Vermont	Y	N	NS			
Virgina	Y	N	NS			N
Washington	Y	N	NS			Y
West Verginia	Y	N	NS			N
Wisconsin	Y	N	N			Y
Wyoming	Y	N	NS			Y

Note: Y – Yes, N – No, NS – Not specified, ND – No definitions

Table 8 Graywater definition of graywater in the 50 States in the US (Part 2)

States	Bathtubs	Showers	Washbasins	Kitchen Sinks	Kitchen Sinks with Grinder	Dishwasher
Alabama	Y	Y	Y	N	N	N
Alaska	Y	Y	Y	Y	Y	Y
Arizona	Y	Y	Y	N	N	N
Arkansas	Y	Y	Y	Y	Y	Y
California	Y	Y	Y	N	N	N

States	Bathtubs	Showers	Washbasins	Kitchen Sinks	Kitchen Sinks with Grinder	Dishwasher
Colorado	Y	Y	Y	Y	Y	Y
Connecticut	Y	Y	Y	Y	Y	Y
Delaware	Y	Y	Y	N	N	N
Florida	Y	Y	Y	N	N	N
Georgia	Y	Y	Y	N	N	N
Hawaii (Gray)	Y	Y	Y	N	N	Y
Hawaii (WWS)	Y	Y	Y	Y	Y	Y
Idaho	Y	Y	Y	N	N	N
Illinois	Y	Y	Y	Y	Y	Y
Indiana	ND					
Iowa	ND					
Kansas	ND					
Kentucky	Y	Y	Y	N	N	N
Louisiana	ND					
Maine	Y	Y	Y	Y	Y	Y
Maryland	Y	Y	Y	N	N	N
Massachusetts	Y	Y	Y	Y	N	Y
Michigan	Y	Y	Y	Y	Y	Y
Minnesota (7080)	Y	Y	Y	Y	Y	Y
Minnesota (115)	Y	Y	Y	Y	N	Y
Mississippi	ND					
Missouri	Y	Y	Y	N	N	Y
Montana	Y	Y	Y	Y	Y	Y
Nebraska	Y	Y	Y	N	N	N
Nevada	Y	Y	Y	N	N	N
New Hampshire	Y	Y	Y	Y	Y	Y
New Jersey	Y	Y	Y	Y	Y	Y
New Mexico	Y	Y	Y	N	N	N
New York	Y	Y	Y	Y	Y	Y
North Carolina	Y	Y	Y	N	N	N
North Dakota	Y	Y	Y	Y	Y	Y
Ohio	Y	Y	Y	N	N	N
Oklahoma	ND					
Oregon (Onsite)	Y	Y	Y	Y	Y	Y

States	Bathtubs	Showers	Washbasins	Kitchen Sinks	Kitchen Sinks with Grinder	Dishwasher
Oregon (House Bill 2080)	Y	Y	Y	Y	N	Y
Pennsylvania	ND					
Rhode Island	Y	Y	Y	Y	Y	Y
South Carolina	ND					
South Dakota	Y	Y	Y	Y	N	Y
Tennessee	ND					
Texas	Y	Y	Y	N	N	Y
Utah	Y	Y	Y	N	N	N
Vermont	Y	Y	Y	Y	Y	Y
Virgina	Y	Y	Y	N	N	N
Washington	Y	Y	Y	Y	Y	Y
West Verginia	Y	Y	Y	N	N	N
Wisconsin	Y	Y	Y	Y	Y	Y
Wyoming	Y	Y	Y	Y	Y	Y

Note: Y – Yes, N – No, NS – Not specified, ND – No definitions

Appendix 3 System design drawing and components, electrical wiring

This appendix presents detailed system design drawings and wiring for the semi-batch vertical flow wetland (SB-VFW) presented in this dissertation. The purpose of this appendix is to provide sufficient information necessary for readers or researchers to reproduce, modify, or fabricate their own SB-VFWs for their own purposes.

1. System design, plumbing arrangement and components

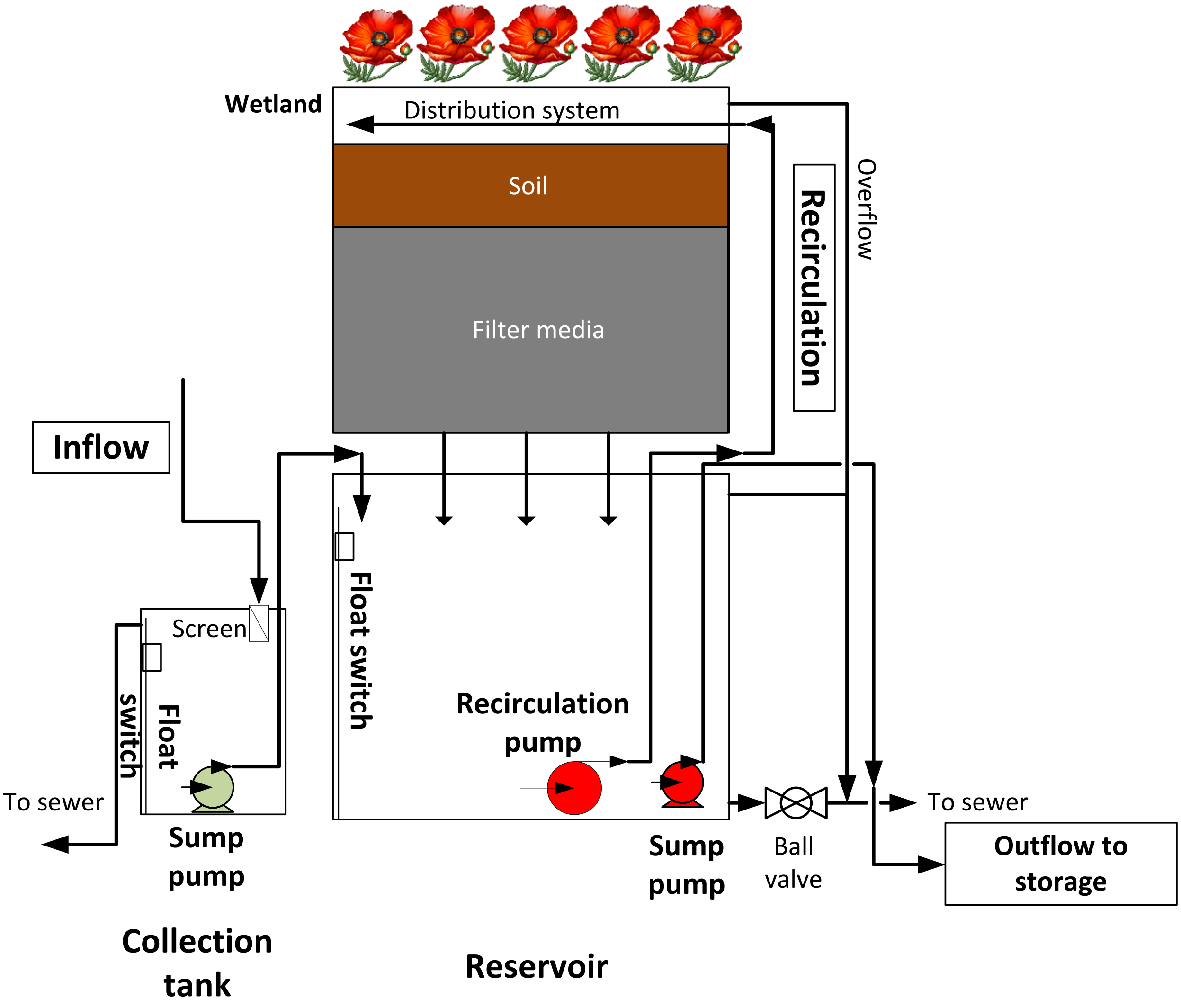


Figure 9 The process flow diagram of the System illustrates the entire treatment process of the System which involves charging of the System using the sump pump in the collection tank; recirculation of graywater between the reservoir and the wetland via a recirculation pump; and discharging the reservoir using a sump pump.

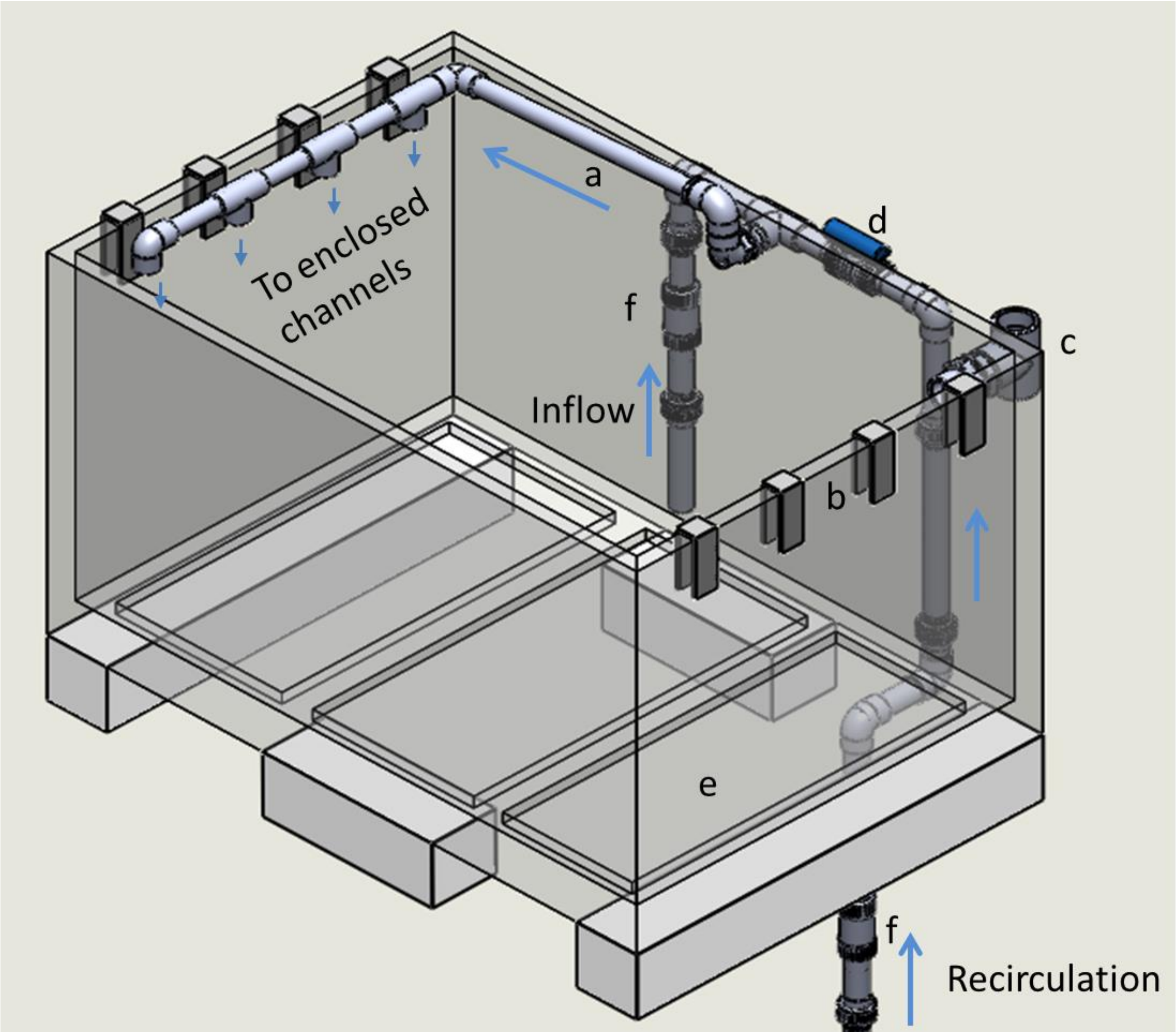


Figure 10 The tank design of the wetland unit before filling with packing materials. The bottom of the tank is cut open to allow water trickles down from the wetland bed to flow freely down into the reservoir. Note: a. distribution pipe; b. enclosed channel hangers; c. overflow to sewer; d. ball valve; f. check valve; e. tank bottom of the wetland treatment unit.

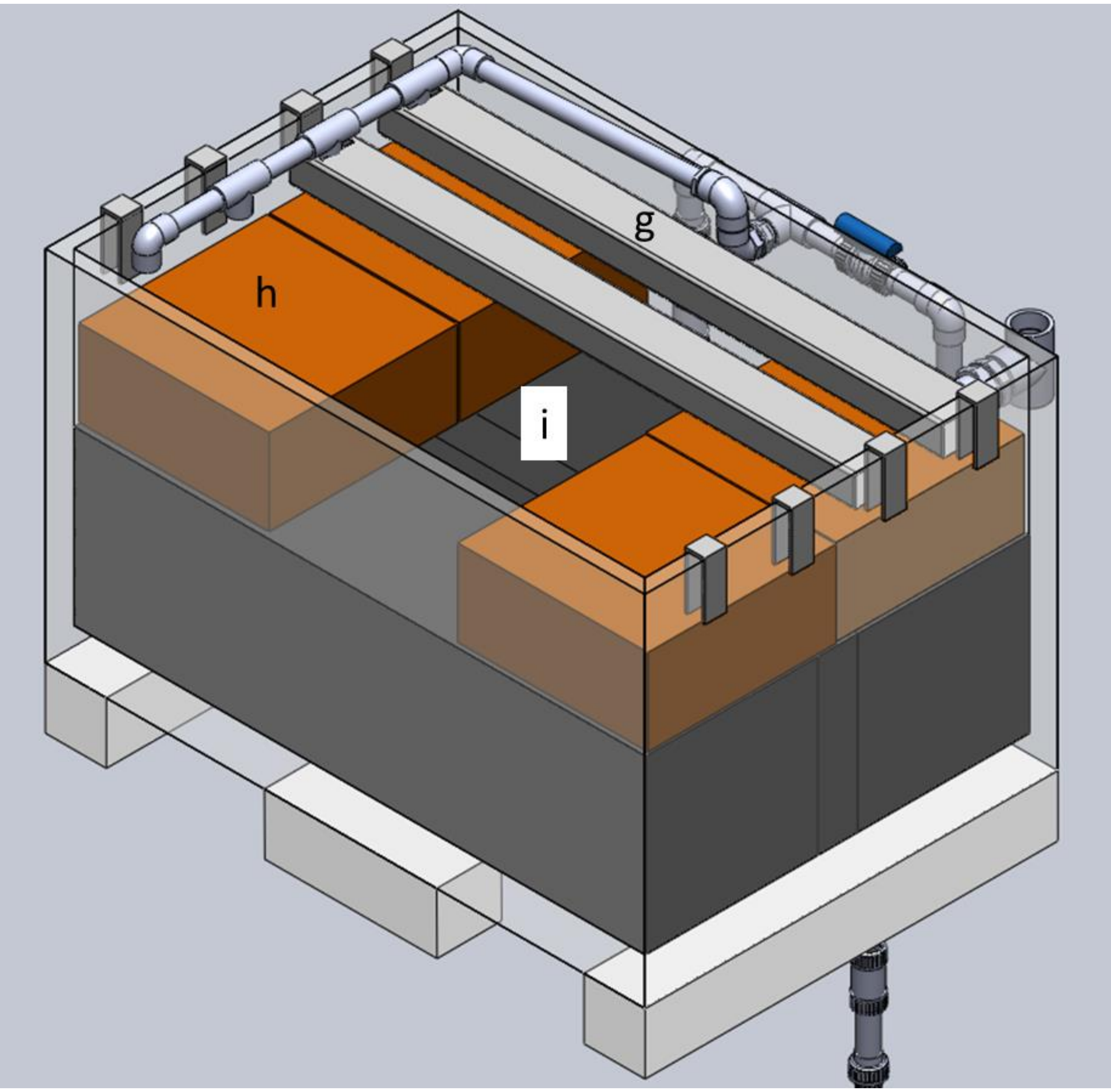


Figure 11 The layout of the wetland unit which consists of a bed of corrugated structure plastic media at the bottom (i.); a compartmentalized soil layer (h.); enclosed channels (g.). Note: Two of the soil compartments and two of the enclosed channels were removed from the diagram to illustrate interior design of the wetland unit.

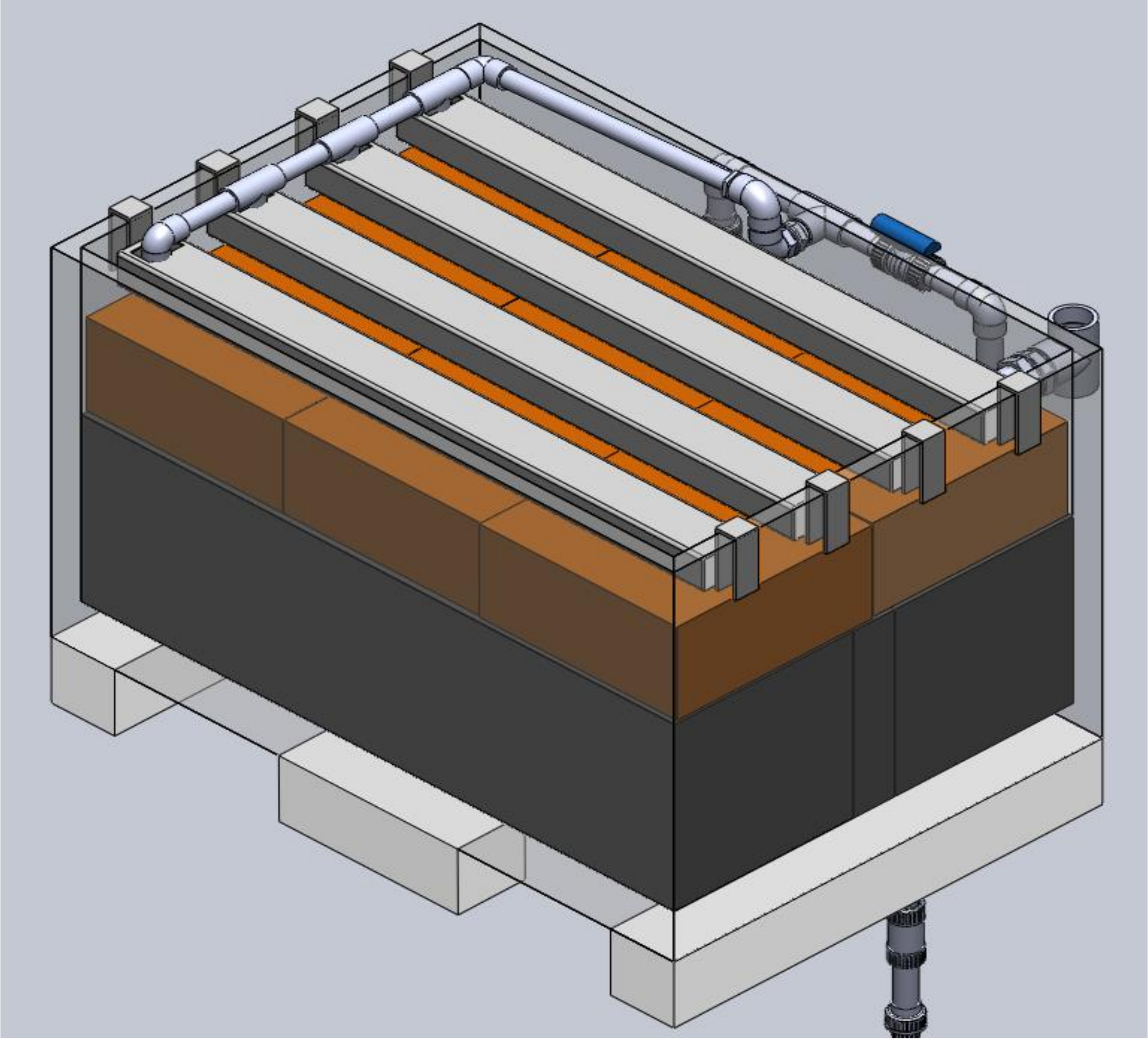


Figure 12 The layout of the wetland unit without vegetation.

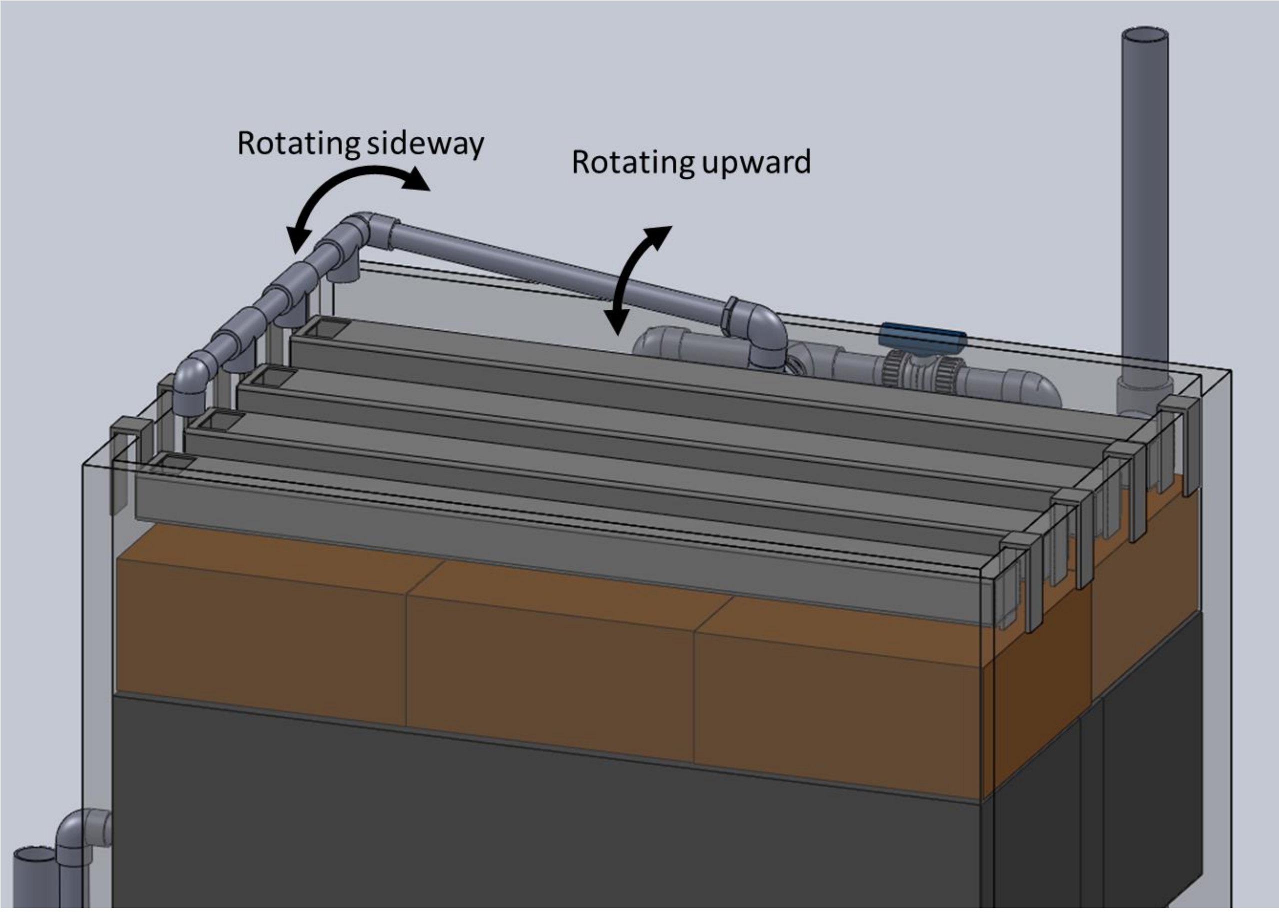


Figure 13 The distribution pipe can be rotated upward to allow the distributors to be taken out for maintenance purposes. It can also be rotated side way to fit the openings of the enclosed channels.

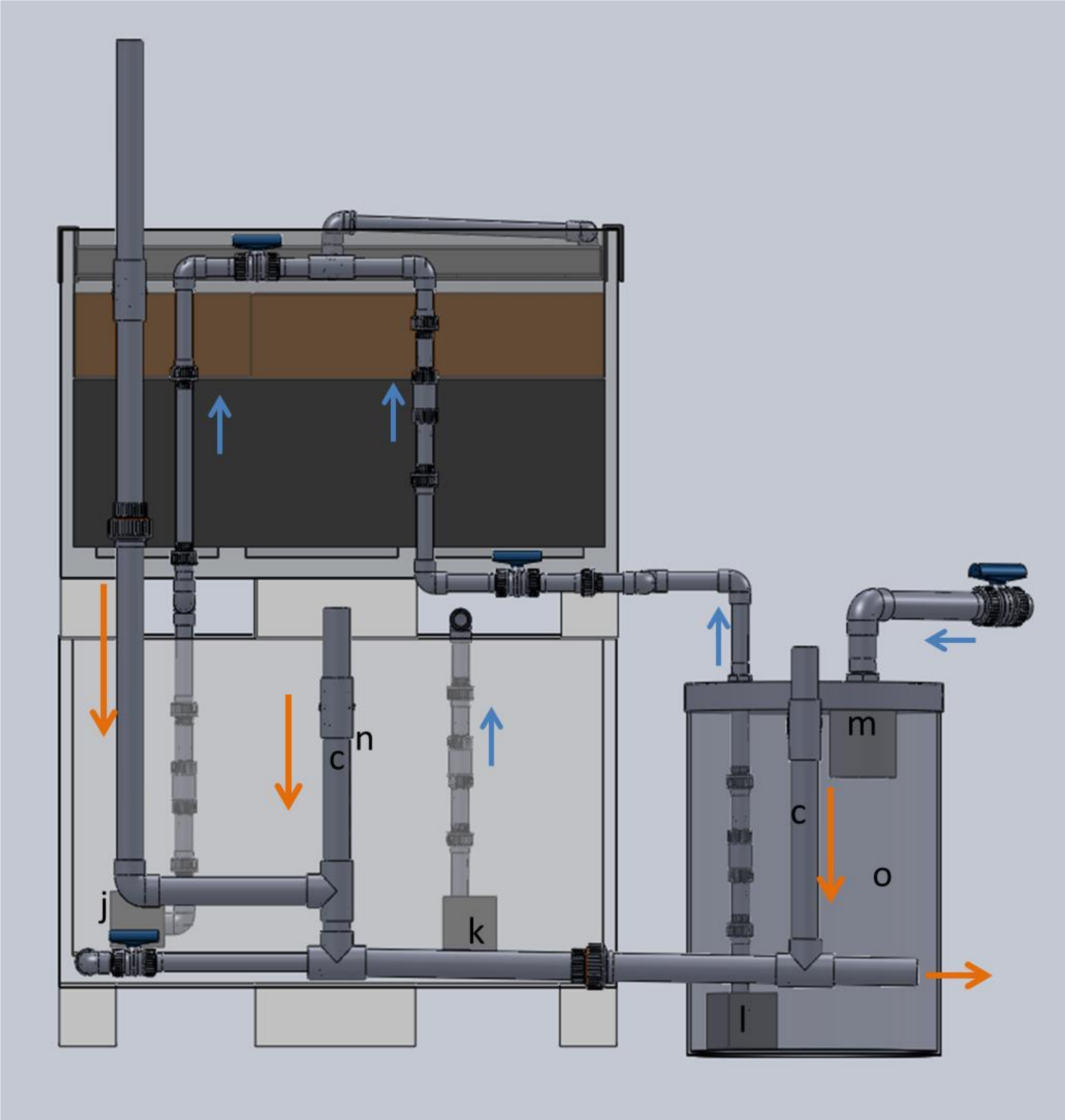


Figure 14 The System viewing from the back. Note: c. overflow to sewer; j. is the recirculation sump; k. effluent sump pump which can be connected a subsurface irrigation system and / or a storage with a disinfection unit (e.g. UV or chlorine tablets); l. sump pump in the collection tank for pumping water into the wetland via the distribution system; m. filter installed in the inlet of the collection tank to capture large debris, such as hair; n. reservoir; o. collection tank. Orange arrows indicate the overflow flow direction; the blue arrows indicate the flow direction of graywater in the System.

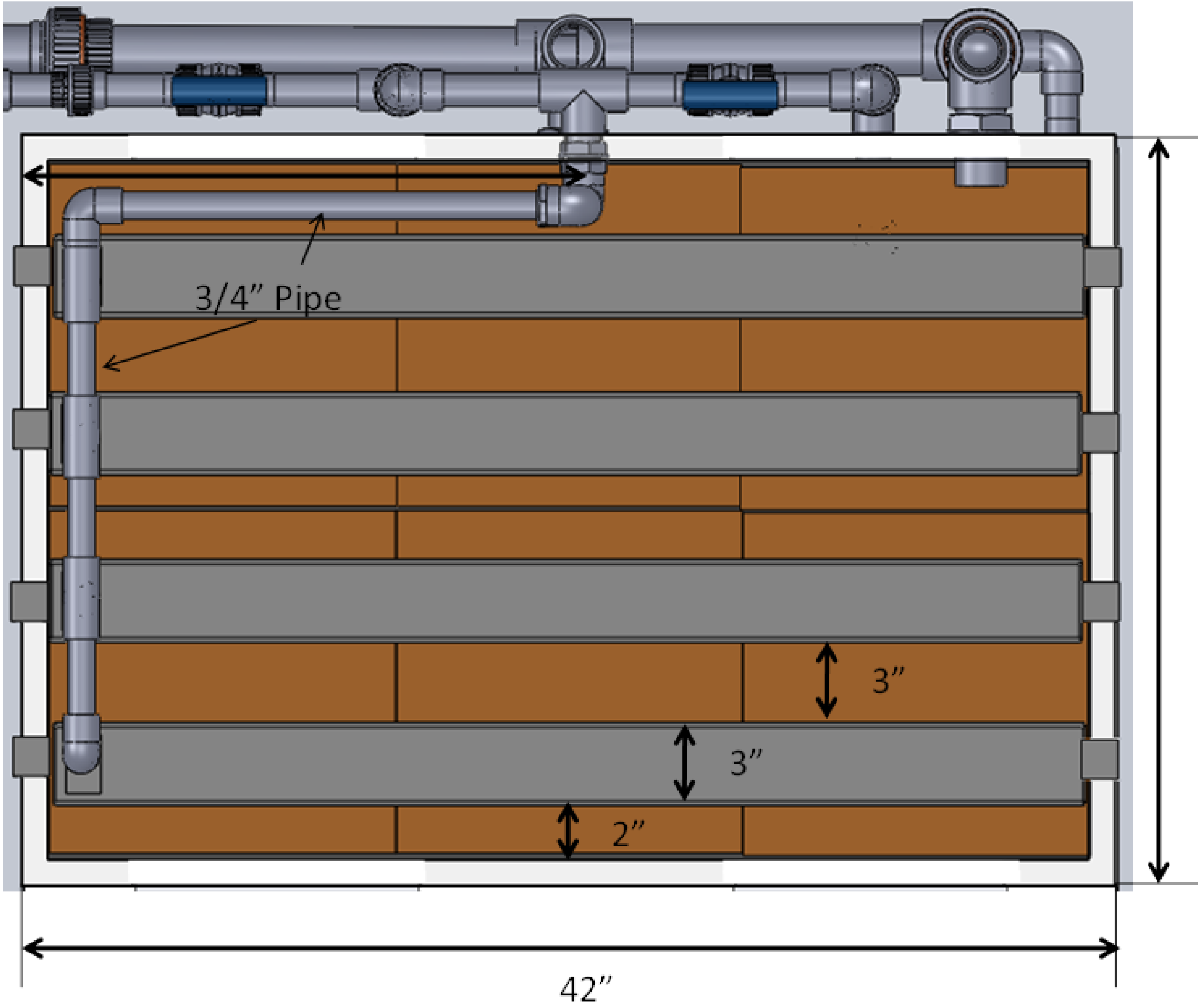


Figure 15 Dimensions of wetland unit and the spacing of the distribution systems (top view).

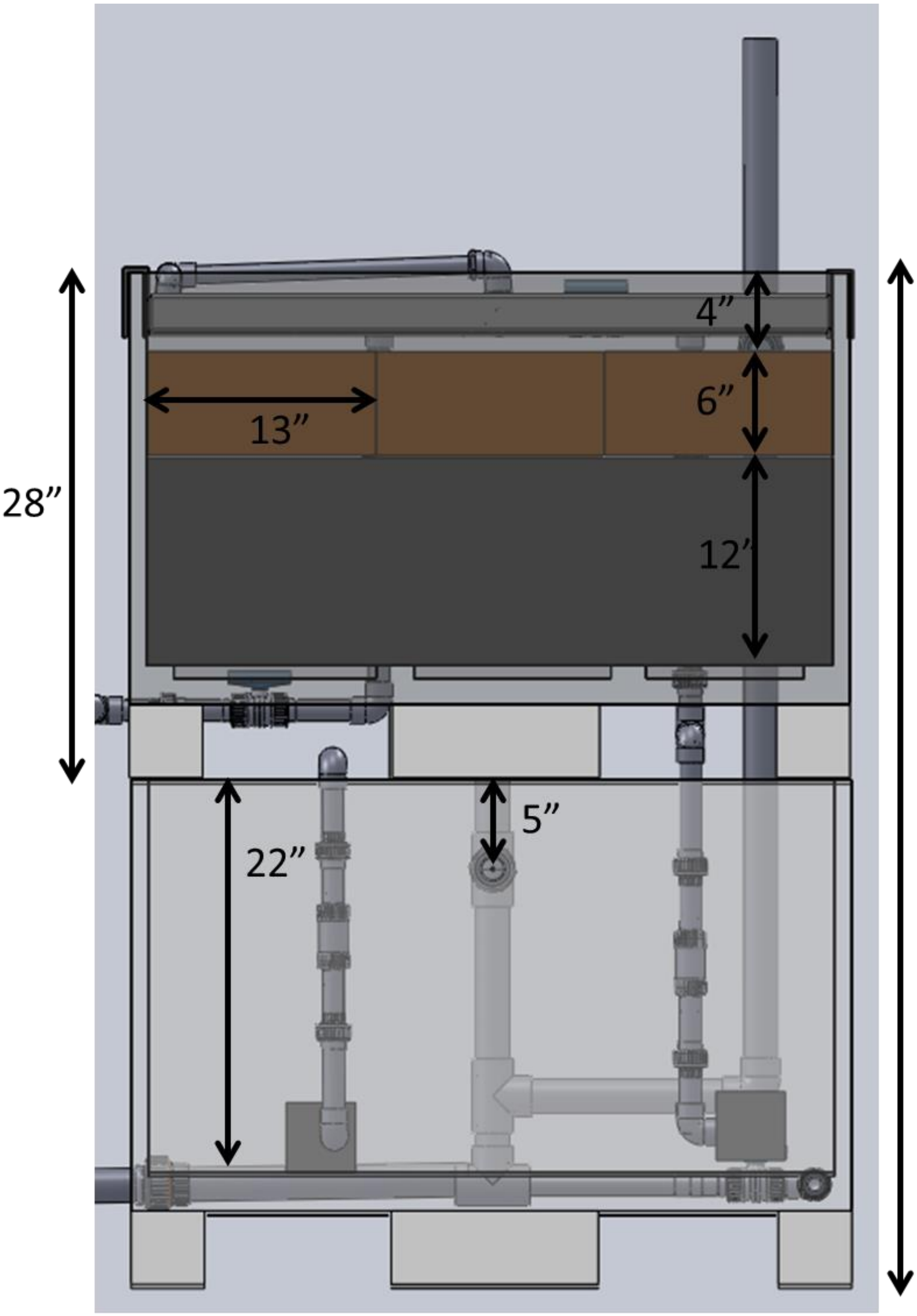


Figure 16 Treatment system dimensions and piping sizes (viewing from the front)

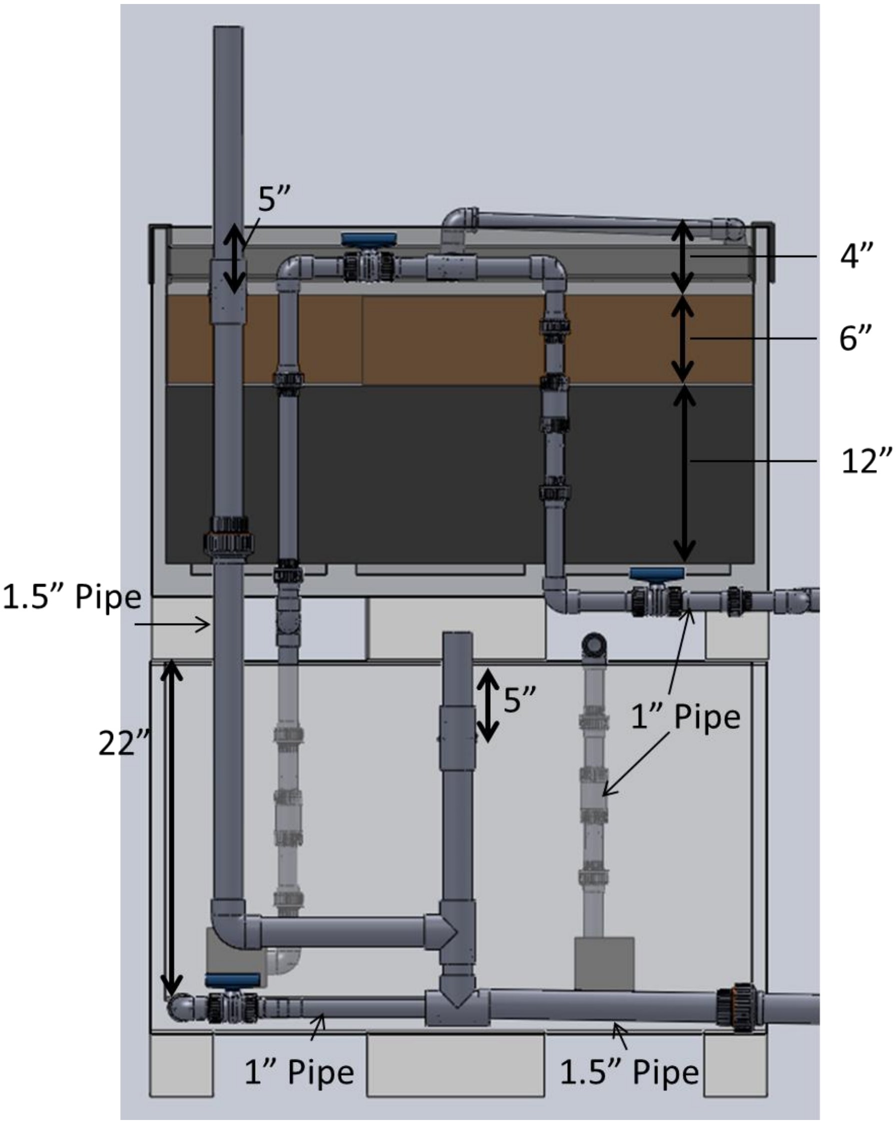


Figure 17 Treatment system dimensions and piping sizes (viewing from the rear)

Table 1 System Component Lists

Component	Manufacturer	Quantity	Description
Containers	Buckhorn	2	white plastic containers: 41.6" x 28.8" x 27.8"
Filter media	Brentwood Industries	1	26.6" x 22.4" x 12"
Recirculation pump	Laguna	1	Submersible fountain pump 2400GPH
Sump pump	Little giant	2	utility sump pump with vertical flow switch
Diaphragm valve	GF Signet	1	1" PVC schedule 80
Ball valve		1	1" PVC schedule 40
Check valves		3	1" PVC swing check valves
Soil mix			soil mix
Timer	K-rain	1	4 Stations outdoor irrigation controller
Pump start relay	Hunter	3	Pump Start Relay
Soil basket	Smart Pot	6	Fabric pots
Vertical level switch	Whitman Controls	1	Vertical level
Y-strainer	Ron-Vik	1	Tee Strainer, 1.5 In, 80 Mesh, FNPT Poly
Plumbing fittings			Unions, elbows, tees, bushing
Pipes			PVC pipes 1", 1.5" and 2"
Float switches		3	Float switches for pump control
Flow meter	GF Signet	1	1" paddle wheel inline flow meter

Note: All components can be purchased through Gringers, homedepot.com, and amazon.com with the exception of the large containers which were purchased directly from the manufacturers.

2. Electrical Wiring

The pumps are connected to the irrigation controller (KRain RPS469, Riviera Beach, FL) through the power relay boxes. The influent sump pump, the recirculation pump, and the effluent sump pump are connected to Station 1, Station 2 and Station 3 terminals in the irrigation controller as illustrated in **Fig. 11**. In order to ensure that pumps will only operate when there is sufficient water in the collection tank and the reservoir, float switches are installed in both the collection tank and the reservoirs.

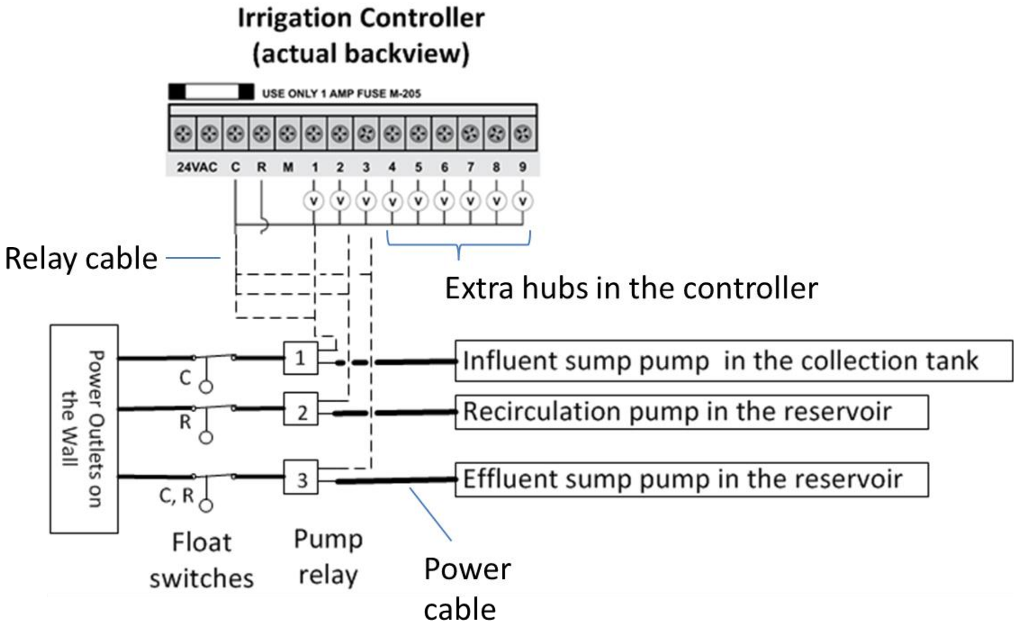


Figure 18 Wire connection between pumps and the irrigation controller. Note: R and C next to the float switches indicates the locations of the float switches to which the pumps are connected. R is the reservoir and C is the collection tank.

Appendix 4 System operation and maintenance

1. System Operation Overview

The treatment process that the System is operated on is a batch treatment. This means that no water inflow into and outflow from the System during the treatment period. The operation of the System is controlled by an irrigation timer that controls three submerged pumps sequentially for three key steps: (1) Step I – recharge of Gray2Blue, (2) Step II - treatment, and (3) Step III – pumping of treated graywater from reservoir to storage or subsurface irrigation. During Step I, raw graywater generated (from the graywater sources) is diverted to the graywater collection tank. The water is then pumped into the System's flow distribution system by a sump pump with a float switch in the collection tank (sump pump I) for distributing the flow over the wetland surface. If the reservoir is full during Step I, excessive graywater is drained into the system main drain to sewer or other disposal systems via a built-in overflow. During Step II, graywater in the reservoir is pumped to the top of the wetland via a recirculation pump to distribute graywater throughout the wetland upper surface. Graywater in the reservoir is recirculated for three hour. While the water in the System is being treated, the collection tank continues to collect graywater that flows into it. During Step III, the treated graywater in the reservoir is pumped from the reservoir directly using a sump pump with a float switch (sump pump II) into either a subsurface irrigation system or a storage system where disinfection is provided for other types of non-potable water reuse purposes. Once water in the reservoir has been discharged, sump pump I is then turned on to recharge the System with raw graywater. In order to ensure that the biofilm on the corrugated plastic media remains wet and not drying up, a second float switch is installed in the collection tank that is connected to the power supply for Sump Pump II in the reservoir. This will ensure the water in the reservoir to be discharged only when there is sufficient water in the collection tank. The three treatment steps, based on the status of the key control components, are presented in **Table 1**.

Table 1. System Operation and Key Controlling Components

Steps	**Description**	**Controllor**		
		Collection Tank	**Reservoir**	
		Sump pump I	**Recirculation pump**	**Sump Pump II**
I	Transfer graywater to Gray2Blue	ON	OFF	OFF
II	Treatment	OFF	ON	OFF
III	Treatment Completed. Transfer of treated graywater from reservoir to subsurface irrigation system	OFF	OFF	ON

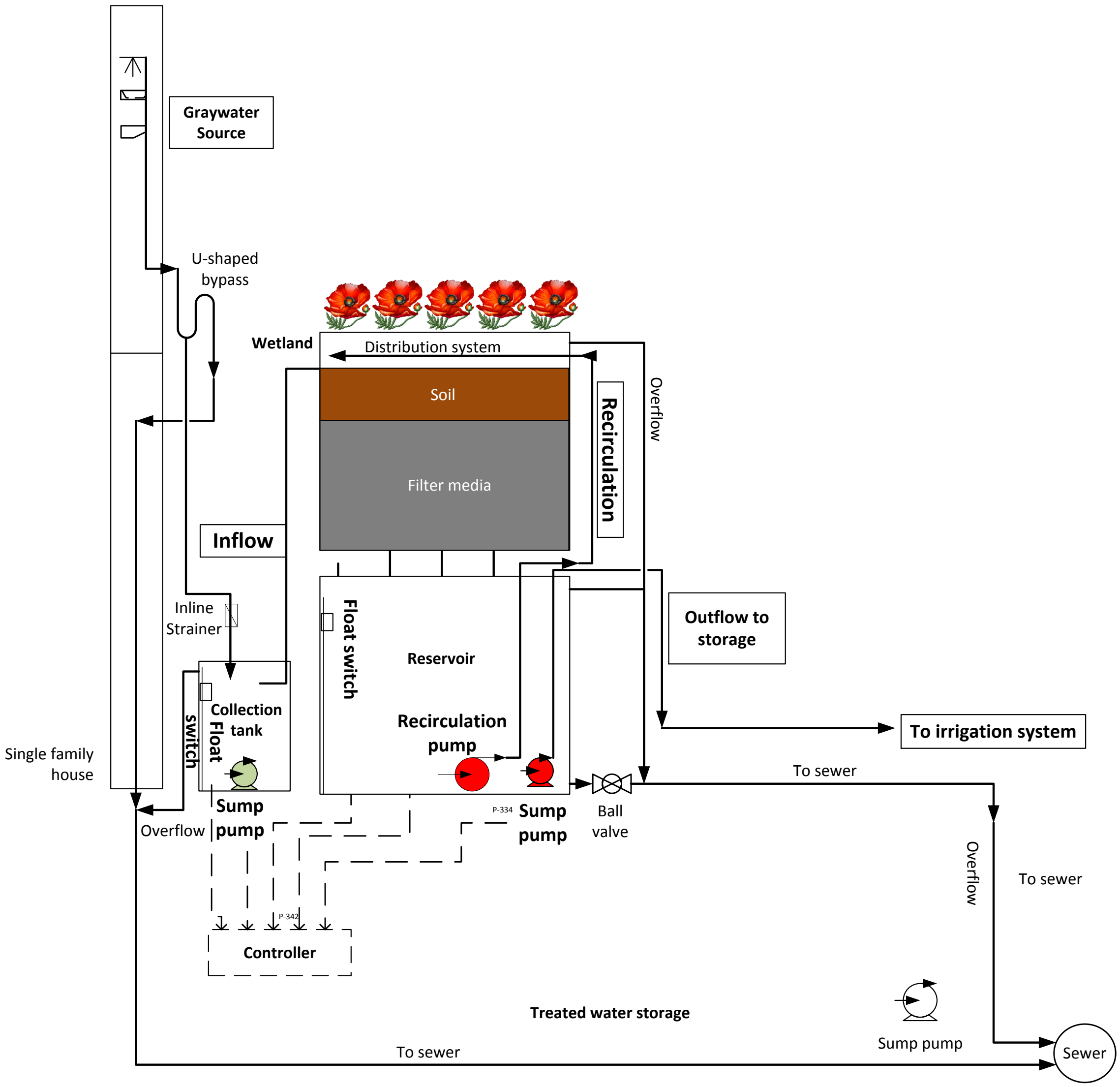


Figure 19 System design and field arrangement

2. Controller Operation

The operation of the SB-VFW is controlled by an irrigation controller (KRain RPS469, Riviera Beach, FL). The information below was extracted directly from the Instruction Manual provided by the manufacturer, which is included in this thesis for reader's convenience. The original manual can be downloaded from the manufacturer's website. Wiring of the pumps to the irrigation controller is presented in **Appendix 3 – Section 2**.

Below are few useful highlights about the irrigation controller buttons (**Fig. 2**) extracted from the KRain manual:

1. When setting, one push of the button will increment one unit.
2. Holding one button down will fast scroll through units.
3. During the programming, only flashing units are able to be set.
4. Adjust flashing units using the ✚ or ▬ buttons.
5. Pressing ➡ will scroll forward through the settings in an orderly sequence.
6. Pressing ⬅ will scroll back to previous settings and setting can be changed.
7. The **P** is used to select different programs. Each push on this button will increment one program number.
8. Once you have selected the primary function (using the turnable knob in the middle, Fig. 2) and program you wish to alter, you can then use the ✚ or ▬ buttons to change that function's value.
9. Only display elements that are flashing can be altered with the ✚ (or) ▬ buttons.
10. Use the ⬅ or ➡ buttons to scroll through other values within the function that can be altered.

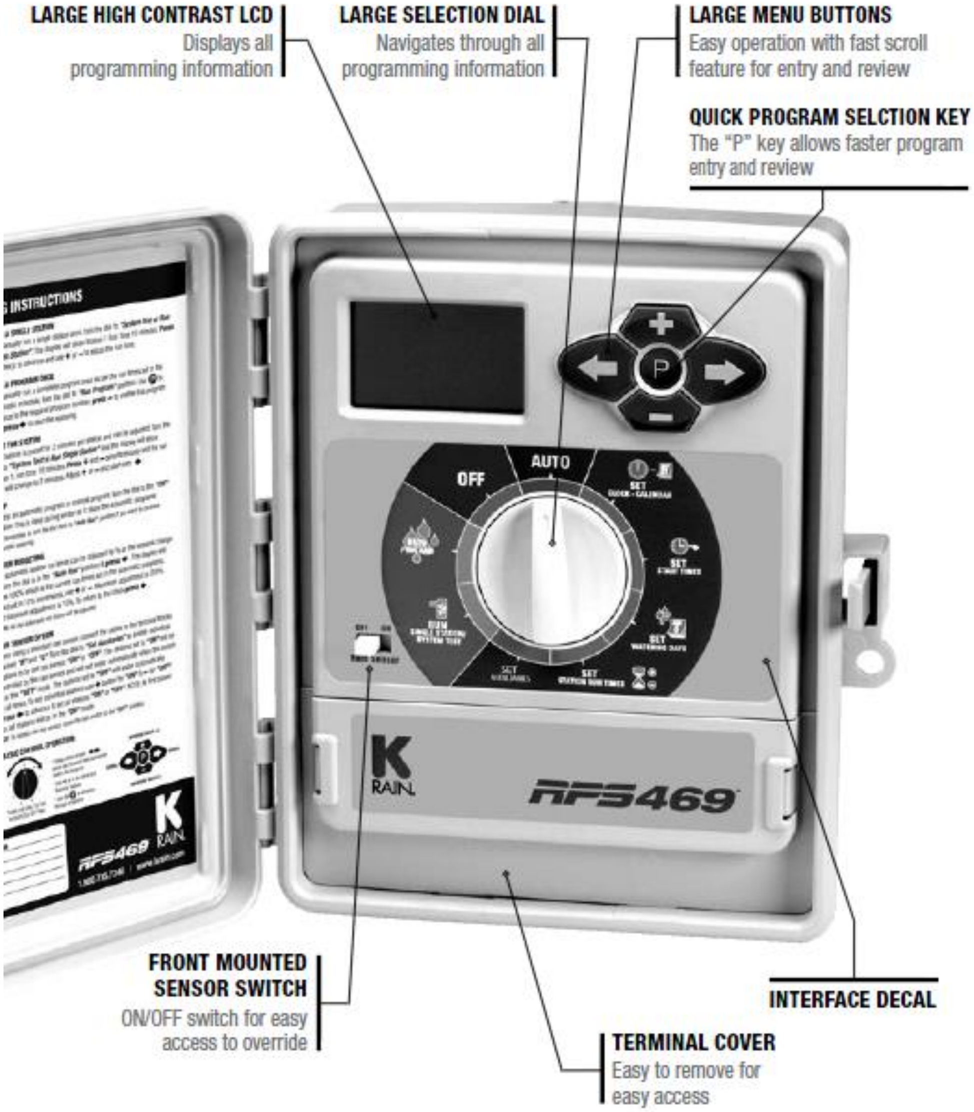


Figure 20 Irrigation controller interface (extracted from the KRain user manual)

2.1 Setup controller time and day (from KRain User Manual)

a) Turn the turnable knob to “Set Clock/Calendar” position.

b) The hour will be flashing. Use the the ✚ (or) ▬ buttons to adjust

c) Press the ➡ button and the “minutes” will flash. Use the ✚ (or) ▬ buttons to adjust the minutes.

d) Press the ➡ button and the “day of the week” will flash. Use the ✚ (or) ▬ buttons to adjust the correct day.

2.2 Program irrigation controller (from KRain User Manual)

I. Set start time

- Turn the turnable knob to “Set Start Times” and ensure that “Prog No 1” is showing. If not, then use the **P** button to select “Prog No 1”. The “Start No” will be flashing on the display.
- Use the ✚ (or) ▬ buttons to change the “Start No” if required, otherwise press the ➡ button and the “hour” will flash. Use the ✚ (or) ▬ buttons to adjust if required.
- Press the ➡ button and the “minutes” will flash. Use the ✚ (or) ▬ buttons to adjust if required.
- Each program has up to 6 start times. Should you require a second start time,
- and the “minutes” will flash. Use the ✚ (or) ▬ buttons to adjust if required

- Press the ➡ button and "Start1" will flash.
- Advance to "Start2" by pressing the ✚ button
- Press the ➡ button and proceed as per setting Start 1.

II. Station run times

Station run time is the length of time that each station (i.e. pumps) is scheduled to operate on a particular program. The maximum run time allowed by the KRain irrigation controller is 12 hours 59 minutes for each station. Please note that the turnable knob must be in to the "Set Station Run Times" position in order to set up the run times. Below are the run time for the influent sump pump, recirculation pump, and effluent sump pump. In the present system, influent sump pump, recirculation pump, and effluent sump pump are connected to Station 1, Station 2, and Station 3 of the irrigation controller (**Appendix 3 – Section 2**). Below are the program and run time for each of the Stations used in the field study.

Table 9 Treatment system operation programmed run time for each treatment cycle used in the field study

Programs	Stations	Start time	Runtime
1	1	10:40 am	23 minutes
	2	11:05 am	12 hours52 minutes
2	2	12:00am	10 hours 22 minutes
3	3	10:30 am	8 minutes

3 Operation

Below are the steps for performing system operation and shutdown.

- **Operation**: Once the Irrigation has been programmed, users will only need to turn the knob on the irrigation controller to AUTO. The system will start pumping and treating graywater automatically.
- **Shutdown**: The system can be shutdown anytime by users by simply turning the knob on the irrigation controller to OFF.
- **Restart**: To restart the treatment system, users can simply turn the knob back to AUTO, the system will restart itself once it reaches the pre-set time.

4 Maintenance

A. Collection tank

- Replace the fabric filter in the collection inlet to capture hairs and large debris. A pair of full-length panty hose with one put inside the other is recommended. These panty hose filters should be replaced monthly.
- Settle solids at the collection tank can be cleanout by a wet vacuum once every six month.
- The lids of the collection tank should always remained closed

B. Treatment system

- The coconut soil should be maintained at about 4 inch below the top edge of the fabric containers. More coconut soil should be added when soil levels are much lower than this level.
- Taller plants with leaves that are height above the irrigation distributors are recommended to prevent leaves from being damaged by water flowing down from the distributor holes.

Appendix 5 Water quality data

This appendix presents water quality data collected during the field study. The purpose of this appendix is to provide detailed data necessary for readers or researchers who are interested in further evaluating graywater quality presented in this dissertation for their own purposes. It is noted that for the field data, all Sample IDs represent the location where samples were collected, the date when samples were collected and hours of treatment undergone. All IDs were arranged in the following way:

- Location. IN represents samples collected in the collection tank, EF represents samples collected in the reservoir of the treatment system.
- Month (one or two digits, depending on the month. For example, January has one digit; while October has two digits),
- Date (two digits), and
- Year (two digits).
- Treatment time. This can only be found in samples collected from the effluent tank.

For example, a sample ID is "EF_50813_3hr" means that the sample was collected from the reservoir on May 8, 2013 after graywater had undergone three hours of treatment in the SB-VFW system.

	IN_032313	EF_032313_3hr	EF_032313_9hr	EF_032313_24hr	IN_032413	EF_032413_7hrs	EF_032413_21hr	EF_032413_32hr	EF_032413_44hr
pH	7.3	6.8	6.8	6.8	7.4	7	6.9	7	6.9
TDS, mg/L	260	269	262	253	243	250	240	249	246
TDS, uS	518	533	525	504	486	504	486	498	489
DO, mg/L			7.6	7.6	1.2	7.3	8.46	8.55	8.42
Temp, C				16.1	20.6		12.4	13.8	12.2
Turbidity, NTU	18	0.08	0	0	16.8	0	0	0	0
TOC, mg/L	30.74	5.73	6.21	8.17	33.5	5.26	6.73	8.94	10.71
DOC, mg/L	24	19.23	14.97	13.74	23.2	17.23	16.02	14.63	13.72
SOC, mg/L	30.74	5.73	6.21	8.17	33.5	5.26	6.73	8.94	10.71
COD, mg/L	130.79	3.25	5.70	15.69	144.86	0.85	8.35	19.62	28.65
BOD, mg/L	39.43	0.5	1	2.57	43.94	0.1	0.22	3.83	6.72

	IN_032613	EF_032613_0hr	EF_032613_7.5hr	EF_0326_22hr
pH				
TDS, mg/L	249	246	245	237
TDS, uS	497	492	489	474
DO, mg/L	1.64	6.1	7.4	7.8
Temp, C	17	15	14.2	11.7
Turbidity, NTU	8.44	8.2	0	0
TOC, mg/L	35.19	24.76	4.84	7.59
DOC, mg/L	21.78	17.13	19.19	15.72
SOC, mg/L	35.19	24.76	4.84	7.59
COD, mg/L	153.48	100.29	1.00	12.74
BOD, mg/L	46.70	29.66	0.50	1.63

	IN_033 113	EF_033 113_1hr	EF_033 113_2hr	EF_033 113_3hr	EF_033 113_4hr	EF_033 113_5hr	EF_033 113_6hr	EF_033 113_7hr	EF_033 113_8hr
pH									
TDS, mg/L	263	280	280	276	276	270	255	249	251
TDS, uS	531	555	559	552	550	542	510	499	503
DO, mg/L	1.56	7.48	7.5	7.47	7.27	7.2	7	7.23	6.62
Temp, C	18.7	17.1	17.5	18.2	18.1	18.7	18.1	18.1	17.2
Turbidity, NTU	19.1	0.25	0.02	0	0	0	0	0	0
TOC, mg/L	34.83	6.5	5.66	5.38	5.53	5.77	5.93	6.13	6.42
DOC, mg/L	27.66	27.52	25.6	22.6	20.51	20.78	20.41	19.8	18.19
SOC, mg/L	34.83	6.5	5.66	5.38	5.53	5.77	5.93	6.13	6.42
COD, mg/L	151.64	7.18256	2.89	1.47	2.23	3.45	4.27	5.29	6.77
BOD, mg/L	46.11	1	0.5	0.1	0.4	0.6	0.7	0.8	0.8

	IN_040 213	EF_040 213_0hr	EF_040 213_10 min	EF_040 213_20 min	EF_040 213_30 min	EF_040 213_40 min	EF_040 213_50 min	EF_040 213_1hr	EF_040 2
pH									
TDS, mg/L	265	291							
TDS, uS	529	577							
DO, mg/L	1.01	5.74							
Temp, C	17.6	16.5							
Turbidity, NTU	16.9	5.83	2.28	1.04	0.45	0.24	0.22	0.1	
TOC, mg/L	36.76	15.02	11.52	9.24	7.98	7.78	7.44	7.25	7.65
DOC, mg/L	24.41	36.45	33.47	33.02	31.82	31.07	29.56	30.16	11.46
SOC, mg/L	36.76	15.02	11.52	9.24	7.98	7.78	7.44	7.25	7.65
COD, mg/L	161.49	50.62	32.78	21.15	14.72	13.70	11.97	11.00	13.04
BOD, mg/L	49.26	13.76	8.04	4.32	2.26	1.94	1.38	1.07	1.73

	IN_0409	EF_0409 _0hr	EF_0409 _10min	EF_0409 _20min	EF_0409 _30min	EF_0409 _40min	EF_0409 _50min	EF_0409 _1hr
TDS, mg/L								
Temp, C								
Turbidity, NTU								
TOC, mg/L	23.05	22.92	20.45	16.38	14.22	12.23	10.41	9.58
TIC, mg/L	21.02	18.97	21.55	21.28	21.65	21.22	21.57	21.55
SOC, mg/L	23.05	22.92	20.45	16.38	14.22	12.23	10.41	9.58
COD, mg/L	91.57	90.91	78.31	57.56	46.55	36.40	27.12	22.88
BOD, mg/L	26.87	26.66	22.63	15.98	12.45	9.20	6.23	4.88

	IN_0416	EF_0416_0 hr	EF_0416_1 5min	EF_0416_3 0min	EF_0416_1 hr	EF_0416_3 hr	EF_0416_7 hr
TDS, mg/L	270	269	274	273	263	254	
Temp, C	14.6	15.2	15.3	15.3			
Turbidity, NTU	16.4	9.59	3.84	1.91	0.54	0.08	0
TOC, mg/L	25.24	17.09	12.72	10.42	8.77	6.91	
TIC, mg/L	20.824	16.4	17.87	17.22	17.34	14.48	18.68
SOC, mg/L	25.24	17.09	12.72	10.42	8.77	6.91	
COD, mg/L	102.74	61.18	38.90	27.17	18.75	9.27	
BOD, mg/L	30.45	17.14	10.00	6.25	3.55	0.52	

	IN_0420	EF_0420 _0hr	EF_0420 _15min	EF_0420 _30min	EF_0420 _45min	EF_0420 _1hr	EF_0420 _2hr	EF_0420 _3hr
Turbidity, NTU	36.3	27.2	18.6	6.54	4.77	3.19	1.49	0.94
SS, mg/L								
TOC, mg/L	36.73	30.05	19.64	15.17	12.87	10.74	7.84	6.19
TIC, mg/L	19.03	15.62	15.68	16.05	15.66	15.65	15.43	14.7
DOC, mg/L	18.03	17.04	11.69	10.28	9.03	8.19	6.45	5.08
DIC, mg/L	12.76	11.51	9.31	11.78	8.56	8.26	9.06	9.42
SOC, mg/L	18.7	13.01	7.95	4.89	3.84	2.55	1.39	1.11
COD, mg/L	161.33	127.27	74.18	51.39	39.66	28.80	14.01	5.60
BOD, mg/L	49.21	38.30	21.30	14.01	10.25	6.77	2.04	0.40

	IN_0424	EF_0424_0hr	EF_0424_15mi	EF_0424_30mi	EF_0424_45mi	EF_0424_1hr	EF_0424_2hr	EF_0424_3hr	EF_0424_8hr
Turbidity, NTU	26	18	7.61	5.96	3.69	3.01	0.82	0.48	0.1
SS, mg/L	54.5	19.5	9.0	5.6	4.1	2.8	1.1	0.5	0.5
TOC, mg/L	35.58	26.72	18.25	15.15	13.11	12.13	10.13	8.99	7.99
TIC, mg/L	10.46	9.81	15.45	14.02	13.18	14.47	14.27	15.15	7.31
DOC, mg/L	20.95	16.15	13.1	11.96	11.07	10.33	9.18	8.66	7.68
DIC, mg/L	6.68	4.3	5.81	6.11	6.3	7.6	5.81	6.92	4.95
SOC, mg/L	14.63	10.57	5.15	3.19	2.04	1.8	0.95	0.33	0.31
COD, mg/L	155.4	110.2	67.10	51.29	40.88	35.89	25.69	19.88	14.78
BOD, mg/L	47.33	32.87	19.03	13.97	10.64	9.04	5.78	3.91	2.28

	IN_0426	EF_0426_0hr	EF_0426_15mi	EF_0426_30mi	EF_0426_45mi	EF_0426_1hr	EF_0426_2hr	EF_0426_3hr	EF_0426_8hr
Turbidity, NTU	21	19	5.2	4.2	2.3	1.7	0.65	0.4	0.15
SS, mg/L									
TOC, mg/L	33.10	27.11	15.77	12.59	10.94	9.23	7.21	6.40	5.53
DOC, mg/L	20.23	16.23	11.45	9.80	9.07	8.15	6.60	5.78	5.20
SOC, mg/L	12.87	10.87	4.31	2.78	1.86	1.07	0.60	0.62	0.33
COD, mg/L	142.85	112.29	54.46	38.23	29.83	21.11	10.80	6.703	2.25
BOD, mg/L	43.29	33.51	14.99	9.79	7.10	4.31	1.012	0.1	0.05

	IN_0501	EF_0501_0hr	EF_0501_15mi	EF_0501_30m	EF_0501_45mi	EF_0501_1hr	EF_0501_2hr	EF_0501_3hr	EF_0501_8hr
Turbidity, NTU	32	29	7.1	3.3	1.9	1.3	0.65	0.55	0.25
SS, mg/L	25.45	24	7	3.67	3	1	0.5	0.5	0
TOC, mg/L	36.39	28.00	14.26	10.60	9.00	8.49	7.28	7.22	7.38
DOC, mg/L	15.97	13.15	9.64	8.08	7.34	7.10	6.65	6.45	7.02
SOC, mg/L	20.41525	14.85	4.62	2.51	1.65	1.38	0.63	0.76	0.36
COD, mg/L	159.60	116.83	46.75	28.11	19.93	17.33	11.20	10.87	11.71
BOD, mg/L	48.66	34.96	12.52	6.55	3.93	3.10	1.13	1.03	1.30

	IN_0503	EF_0503_0hr	EF_0501_15min	EF_0503_30min	EF_0503_45min	EF_0503_1hr	EF_0503_2hr	EF_0503_3hr
Turbidity, NTU	24	15	7.6	4.9	3.3	2.3	0.55	0.5
TOC, mg	28.27	21.70	15.13	12.25	10.45	9.468	7.63	6.99
DOC, mg/L	11.76	11.34	8.83	7.59	7.25	6.96	6.62	6.02
SOC, mg/L	16.50	10.36	6.297	4.65	3.20	2.50	1.00	0.96
COD, mg/L	118.21	84.71	51.20	36.51	27.37	22.32	12.97	9.69
BOD, mg/L	35.40	24.67	13.94	9.24	6.31	4.70	1.70	0.65

	IN_0508	EF_0508_0hr	EF_0508_15min	EF_0508_30min	EF_0508_45min	EF_0508_1hr	EF_0508_2hr	EF_0508_3hr	EF_0508_8hr
Turbidity, NTU	22	14	4.5	3.1	2	1.2	0.4	0.4	0.15
TOC, mg	29.93	21.52	11.93	9.97	8.82	8.24	6.87	6.24	6.12
DOC, mg/L	15.97	12.49	8.26	8.00	7.14	7.06	6.14	5.57	5.76
SOC, mg/L	13.95	9.03	3.66	1.97	1.68	1.17	0.73	0.67	0.35
COD, mg/L	126.70	83.80	34.88	24.91	19.05	16.07	9.10	5.88	5.25
BOD, mg/L	38.12	24.38	8.72	5.53	3.65	2.69	0.46	0.1	0.05

	IN_0510	EF_0510_0hr	EF_0510_15min	EF_0510_30min	EF_0510_45min	EF_0510_1hr	EF_0510_2hr	EF_0510_3hr
Turbidity, NTU	17	11	4.6	2.4	1.6	0.85	0.7	0.25
TOC, mg	38.17	28.36	19.11	14.96	13.14	11.53	8.87	7.25
DOC, mg/L	23.46	19.05	13.13	10.66	9.85	9.26	7.97	7.128616
SOC, mg/L	14.71	9.31	5.97	4.29	3.28	2.26	0.90	0.12
COD, mg/L	168.68	118.68	71.51	50.33	41.03	32.83	19.31	11.04
BOD, mg/L	51.56	35.55	20.45	13.66	10.69	8.06	3.73	1.08

	IN_0513	EF_0513_0hr	EF_0513_15min	EF_0513_30min	EF_0513_45min	EF_0513_1hr	EF_0513_2hr	EF_0513_3hr	EF_0513_8hr
Turbidity, NTU	15	11	4.3	2.6	1.7	1.2	0.3	0.15	0
TOC, mg	28.53	23.39	14.68	12.04	10.76	10.10	8.72	8.05	7.94
DOC, mg/L	18.12	14.95	11.64	10.47	9.86	9.33	8.44	7.96	7.51
SOC, mg/L	10.41	8.44	3.03	1.57	0.90	0.76	0.28	0.09	0.42
COD, mg/L	119.54	93.32	48.92	35.46	28.93	25.55	18.53	15.12	14.55
BOD, mg/L	35.83	27.43	13.21	8.91	6.81	5.73	3.48	2.39	2.21

	IN_0515	EF_0515_0hr	EF_0515_15min	EF_0515_30min	EF_0515_45min	EF_0515_1hr	EF_0515_2hr	EF_0515_3hr	EF_0515_8hr
Turbidity, NTU	22	19	5.4	2	0.9	0.45	0.1	0.05	0
TOC, mg	41.50	31.22	18.21	13.18	11.70	10.49	9.53	8.55	8.13
DOC, mg/L	29.47	19.99	13.50	10.94	10.32	9.862	8.97	8.00	7.95
SOC, mg/L	12.03	11.22	4.70	2.23	1.38	0.62	0.56	0.54	0.17
COD, mg/L	185.701	133.24	66.91	41.27	33.74	27.54	22.65	17.66	15.51
BOD, mg/L	57.01	40.21	18.97	10.76	8.35	6.37	4.80	3.20	2.52

	IN_0517	EF_0517_0hr	EF_0517_15min	EF_0517_30min	EF_0517_45min	EF_0517_1hr	EF_0517_2hr	EF_0517_3hr
Turbidity, NTU	20.6	13.7	4.88	2.66	1.4	0.85	0.15	0
TOC, mg	38.32	28.46	16.27	13.47	11.34	10.04	9.04	8.59
DOC, mg/L	21.87	16.32	11.81	10.93	9.97	9.52	8.79	8.44
SOC, mg/L	16.45	12.14	4.46	2.54	1.37	0.52	0.24	0.14
COD, mg/L	169.49	119.21	57.04	42.77	31.90	25.26	20.13	17.84
BOD, mg/L	51.82	35.72	15.81	11.24	7.77	5.64	4.00	3.26

	IN_0520	EF_0520_0hr	EF_0520_15min	EF_0520_30min	EF_0520_45min	EF_0520_1hr	EF_0520_2hr	EF_0520_3hr	EF_0520_8hr
Turbidity, NTU	13.2	12.8	5.73	3.37	2.04	1.51	0.49	0.15	0.15
TOC, mg	29.79	25.06	17.62	14.46	12.00	11.09	9.32	8.66	6.93
DOC, mg/L	16.25	14.17	11.52	10.75	9.37	9.15	8.24	7.62	6.68
SOC, mg/L	13.54	10.89	6.09	3.70	2.63	1.93	1.08	1.04	0.25
COD, mg/L	125.97	101.87	63.92	47.79	35.27	30.59	21.59	18.23	9.42
BOD, mg/L	37.89	30.17	18.02	12.85	8.84	7.35	4.46	3.39	0.57

	IN_0710	EF_0710hr_0hr	EF_0710_3hr	EF_0710_40hr	IN_0712	EF_0712_0hr	EF_0712_3hr	EF_0712_24hr
TDS, mg/L	278.00	297.00	279.00	273.00	274.00	271.00	273.00	254.00
DO, mg/L	1.87	5.32	6.30	7.44	1.87	5.12	6.44	6.12
Temp, C	20.50	20.00	21.80	20.30	23.10	22.50	23.50	20.60
Turbidity, NTU	11.20	29.90	0.23	0.00	15.10	22.80	0.00	0.00
TOC, mg/L	24.36	34.33	6.31	9.01	22.93	27.88	5.49	6.94
TOC Stnd Dev	0.69	1.05	0.08	0.08	0.15	0.58	0.08	0.04
TIC, mg/L	15.60	15.33	10.46	3.10	17.60	14.98	11.31	4.84
DOC, mg/L	14.90	12.57	6.08	8.57	12.83	10.33	5.33	6.66
DOC Stnd Dev	0.05	0.03	0.04	0.07	0.16	0.02	0.02	0.10
DIC, mg/L	16.41	14.38	9.06	2.34	16.59	15.55	9.34	4.04
SOC, mg/L	9.46	21.76	0.23	0.45	10.10	17.55	0.16	0.28
COD, mg/L	98.24	149.08	6.20	20.01	90.96	116.22	2.05	9.42
BOD, mg/L	29.01	45.29	0.10	3.96	26.68	34.77	0.20	0.57

	IN_0713	IN_0714	EF_0714_0hr	EF_0714_3hr	EF_0714_24h	IN_0715	EF_0715_0hr	EF_0715_3hr	EF_0715_8hr	EF_0715_24hr
TDS, mg/L	278.00	304.00	308.00	318.00	317.00	298.00	309.00	313.00	316.00	302.00
DO, mg/L	1.30	1.98	4.67	6.18	5.38	5.13	5.92	5.02		6.12
Temp, C	21.50	22.00	21.30	22.00	20.60	22.00	22.00	23.50	20.00	18.20
Turbidity, NTU	9.20	18.90	26.10	2.82	0.19	19.00	7.94	0.99	0.11	0.00
TOC, mg/L	14.91	101.00	72.63	21.23	9.60	71.01	29.66	13.10	8.06	7.66
TOC Stnd Dev	0.06	0.96	0.14	0.19	0.15	0.24	0.22	0.10	0.05	0.08
TIC, mg/L	16.05	16.44	15.66	14.51	11.31	14.42	15.34	17.32	15.59	13.05
DOC, mg/L	8.88	88.85	60.83	20.43	9.18	63.46	26.31	11.67	7.85	7.59
DOC Stnd Dev	0.06	0.58	0.59	0.15	0.13	0.97	0.25	0.03	0.08	0.02
DIC, mg/L	15.51	13.13	17.15	14.28	10.14	13.95	15.04	13.84	16.08	11.08
SOC, mg/L	6.03	12.15	11.80	0.80	0.42	7.55	3.35	1.43	0.21	0.07
COD, mg/L	50.05	489.06	344.42	82.30	23.01	336.15	125.29	40.84	15.15	13.10
BOD, mg/L	13.58	154.16	107.84	23.91	4.92	105.19	37.67	10.63	2.40	1.75

	IN_0716	EF_0716_0h	EF_0716_3h	IN_0725	EF_0725_0hr	EF_0725_30m	EF_0725_1hr	EF_0725_2hr	EF_0725_3hr	EF_0725_8hr	EF_0725_24hr
TDS, mg/L	334.00	327.00	338.00								
DO, mg/L	1.22	4.86	4.33								
Temp, C	22.20	21.60	22.50								
Turbidity, NTU	13.00	5.42	2.61	15.00	9.50	5.20	2.10	0.55	0.40	0.00	0.00
TOC, mg/L	95.90	54.84	26.94	23.41	12.92	10.07	7.79	5.92	5.32	5.32	5.92
TOC Stnd Dev	1.57	0.41	0.15	0.24	0.09	0.07	0.32	0.01	0.02	0.03	0.04
TIC, mg/L	19.99	19.03	18.98	25.60	20.18	21.53	19.44	19.72	19.71	16.74	13.83
DOC, mg/L	82.75	48.52	25.64	15.92	10.41	7.92	6.54	5.60	4.84	5.18	5.68
DOC Stnd Dev	1.23	0.19	0.18	0.11	0.03	0.04	0.04	0.04	0.05	0.04	0.02
DIC, mg/L	19.62	15.08	18.89	24.18	19.69	19.44	20.53	17.76	16.00	14.36	11.20
SOC, mg/L	13.16	6.31	1.30	7.49	2.52	2.15	1.25	0.32	0.48	0.14	0.23
COD, mg/L	463.09	253.68	111.40	93.41	39.94	25.37	13.79	4.23	1.16	1.14	4.21
BOD, mg/L	145.84	78.78	33.22	27.46	10.34	5.68	1.97	-1.09	0.23	0.20	0.30

	IN_0726	EF_0726_0hr	EF_0726_3hr	IN_0729	EF_0729_0hr	EF_0729_30mi	EF_0729_1hr	EF_0729_2hr	EF_0729_3hr	EF_0729_24hr
Turbidity, NTU	24.00	12.00	0.15	35.00	10.00	4.50	2.40	0.80	0.50	0.00
TOC, mg/L	26.21	14.69	4.46	51.51	17.89	14.63	11.96	8.74	7.84	5.39
TOC Stnd Dev	0.28	0.03	0.06	0.68	0.17	0.13	0.10	0.02	0.02	0.71
TIC, mg/L	27.92	24.84	22.62	30.69	29.89	30.57	31.40	30.46	32.86	29.91
DOC, mg/L	19.95	10.46	4.21	39.94	15.57	13.17	10.58	8.27	6.96	5.13
DOC Stnd Dev	0.01	0.10	0.03	0.26	0.11	0.15	0.08	0.04	0.05	0.21
DIC, mg/L	27.94	23.62	21.30	29.39	27.25	29.44	28.37	28.73	26.77	27.61
SOC, mg/L	6.26	4.24	0.25	11.57	2.32	1.46	1.38	0.48	0.88	0.26
COD, mg/L	107.67	48.97	1.00	236.69	65.24	48.66	35.03	18.63	14.03	1.54
BOD, mg/L	32.03	13.23	0.20	73.34	18.44	13.13	8.77	3.52	2.05	0.20

	IN_0730	EF_0730_0hr	EF_0730_30mins	EF_0730_1hr	EF_0730_2hr	EF_0730_3hr	EF_0730_8hr	EF_0730_24hr
Turbidity, NTU	24.00	8.40	5.50	2.50	0.70	0.30	0.00	0.00
TOC, mg/L	41.78	15.30	12.58	9.60	7.46	6.46	5.17	5.22
TOC Stnd Dev	0.36	0.09	0.04	0.09	0.10	0.07	0.08	0.03
TIC, mg/L	35.32	34.55	36.30	37.62	35.57	38.39	34.68	29.27
DOC, mg/L	32.32	13.44	10.73	8.29	6.88	5.79	4.50	5.18
DOC Stnd Dev	0.29	0.04	0.08	0.08	0.09	0.05	0.04	0.03
DIC, mg/L	33.51	33.46	34.60	34.02	34.22	33.26	27.50	28.31
SOC, mg/L	9.46	1.87	1.86	1.31	0.58	0.67	0.66	0.04
COD, mg/L	187.11	52.07	38.20	22.99	12.09	6.99	0.39	0.65
BOD, mg/L	57.47	14.23	9.79	4.91	1.42	0.50	0.21	0.13

	IN_0731	EF_0731_0hr	EF_0731_30min	EF_0731_1hr	EF_0731_2hr	EF_0731_3hr	EF_0731_8hr	EF_0731_24hr
Turbidity, NTU	20.00	7.40	3.60	1.60	0.40	0.15	0.00	0.00
TOC, mg/L	25.83	11.84	10.95	8.46	6.61	5.79	4.85	4.76
TOC Stnd Dev	0.51	0.06	0.10	0.11	0.05	0.09	0.03	0.03
TIC, mg/L	26.13	29.72	29.32	30.76	30.97	31.16	31.38	26.93
DOC, mg/L	20.38	10.42	9.33	7.21	6.11	5.20	4.34	4.75
DOC Stnd Dev	0.19	0.10	0.11	0.06	0.07	0.10	0.13	0.08
DIC, mg/L	26.48	24.59	28.22	26.98	28.10	29.33	28.36	25.32
SOC, mg/L	5.45	1.41	1.62	1.25	0.50	0.59	0.50	0.01
COD, mg/L	105.78	34.39	29.89	17.18	7.74	3.58	0.80	0.50
BOD, mg/L	31.42	8.57	7.13	3.05	0.03	0.40	0.20	0.10

	IN_0801	EF_0801 _0hr	EF_0801 _30min	EF_0801 _1hr	EF_0801 _2hr	EF_0801 _3hr	EF_0801 _8hr	EF_0801 _24hr
TDS, mg/L								
Turbidity, NTU	21.00	9.90	3.20	1.60	0.65	0.20	0.00	0.00
TOC, mg/L	30.53	14.15	8.93	7.60	6.13	5.43	4.25	4.78
TOC Stnd Dev	0.25	0.16	0.11	0.08	0.07	0.07	0.06	0.04
TIC, mg/L	37.41	36.41	37.15	39.00	38.81	41.65	38.17	36.62
DOC, mg/L	25.26	12.02	7.50	6.72	5.81	5.03	4.15	4.44
DOC Stnd Dev	0.20	0.12	0.05	0.05	0.07	0.04	0.07	0.06
DIC, mg/L	40.39	30.02	34.42	34.67	36.03	37.22	36.68	32.17
SOC, mg/L	5.27	2.13	1.43	0.88	0.31	0.40	0.10	0.33
COD, mg/L	129.74	46.19	19.58	12.79	5.28	1.71	0.80	1.00
BOD, mg/L	39.10	12.34	3.82	1.65	0.20	0.40	0.00	0.10

	IN_0802	EF_0802 _0hr	EF_0802 _30min	EF_0802 _1hr	EF_0802 _2hr	EF_0802 _3hr	EF_0802 _8hr	EF_0802 _24hr
TDS, mg/L								434.00
Turbidity, NTU	15.30	6.50	3.20	1.80	0.50	0.15	0.00	0.00
TOC, mg/L	31.80	13.33	12.20	9.96	7.73	6.18	4.31	4.54
TOC Stnd Dev	0.33	0.06	0.05	0.12	0.08	0.07	0.05	0.07
TIC, mg/L	24.59	31.80	31.41	31.21	34.60	34.62	33.46	25.18
DOC, mg/L	26.30	11.77	11.06	9.13	6.91	5.92	4.09	4.34
DOC Stnd Dev	0.05	0.10	0.11	0.04	0.07	0.10	0.09	0.02
DIC, mg/L	27.49	30.57	26.40	32.34	31.15	32.66	30.77	25.11
SOC, mg/L	5.50	1.56	1.14	0.83	0.82	0.27	0.22	0.21
COD, mg/L	136.22	42.02	36.25	24.84	13.47	5.56	0.10	0.20
BOD, mg/L	41.17	11.01	9.16	5.51	1.87	0.30	0.00	0.00

	IN_0803	EF_0803 _0hr	EF_0803 _30min	EF_0803 _1hr	EF_0803 _2hr	EF_0803 _3hr	EF_0803 _8hr	EF_0803 _24hr
TDS, mg/L	371.00					402.00		389.00
Turbidity, NTU	16.20	8.77	3.32	1.64	0.41	0.13	0.00	0.00
TOC, mg/L	35.61	14.32	11.89	9.67	7.28	6.50	4.69	4.83
TOC Stnd Dev	0.47	0.13	0.16	0.06	0.08	0.09	0.04	0.05
TIC, mg/L	27.28	28.29	30.42	29.32	32.15	32.62	28.52	23.92
DOC, mg/L	25.91	11.88	10.86	8.71	6.80	5.73	4.34	4.42
DOC Stnd Dev	0.25	0.06	0.09	0.08	0.01	0.05	0.11	0.02
DIC, mg/L	28.88	26.39	28.97	25.53	28.66	27.59	28.54	20.18
SOC, mg/L	9.70	2.43	1.03	0.96	0.48	0.77	0.35	0.40
COD, mg/L	155.62	47.05	34.67	23.37	11.14	7.20	0.20	0.30
BOD, mg/L	47.38	12.62	8.66	5.04	1.12	0.20	0.00	0.00

	IN_0807	EF_0807 _0hr	EF_0807 _30min	EF_0807 _1hr	EF_0807 _2hr	EF_0807 _3hr	EF_0807 _8hr	EF_0807 _24hr
TDS, mg/L	322.00					349.00	372.00	366.00
Turbidity, NTU	14.50	5.70	2.48	1.57	0.58	0.38	0.00	0.00
TOC, mg/L	35.62	15.87	12.85	10.55	8.79	7.08	4.77	4.72
TOC Stnd Dev	0.10	0.19	0.10	0.07	0.05	0.06	0.08	0.02
TIC, mg/L	27.07	27.21	28.37	27.81	27.69	30.81	28.35	22.16
DOC, mg/L	24.44	12.19	10.76	9.49	8.55	6.35	4.66	4.61
DOC Stnd Dev	0.18	0.11	0.08	0.02	0.06	0.10	0.07	0.05
DIC, mg/L	25.42	23.68	25.76	25.99	29.92	28.69	24.27	18.44
SOC, mg/L	11.18	3.68	2.09	1.06	0.24	0.73	0.11	0.11
COD, mg/L	155.67	54.96	39.57	27.86	18.86	10.15	0.50	0.30
BOD, mg/L	47.40	15.15	10.22	6.47	3.59	0.80	0.00	0.00

	IN_0812	EF_0812 _0hr	EF_0812 _30min	EF_0812 _1hr	EF_0812 _2hr	EF_0812 _3hr	EF_0812 _8hr	EF_0812 _24hr
TDS, mg/L	324.00	341.00	345.00	351.00	354.00	356.00	358.00	362.00
DO, mg/L	2.03	4.01	3.62	3.76	3.56	3.60	4.40	5.22
Temp, C	21.50	20.80	20.60	20.80	21.10	21.70	18.30	16.70
Turbidity, NTU	23.60	10.97	4.22	2.18	0.82	0.26	0.00	0.00
TOC, mg/L	24.02	10.54	8.13	7.20	5.87	5.35	4.90	4.92
TOC Stnd Dev	0.51	0.04	0.06	0.07	0.09	0.05	0.01	0.07
TIC, mg/L	25.53	28.09	28.38	29.31	30.25	30.09	29.35	26.75
DOC, mg/L	15.51	8.58	7.09	6.02	4.97	4.67	4.20	4.74
DOC Stnd Dev	0.04	0.04	0.06	0.01	0.02	0.08	0.01	0.05
DIC, mg/L	25.19	25.86	22.19	25.54	25.71	27.79	22.39	22.01
SOC, mg/L	8.51	1.96	1.04	1.18	0.90	0.68	0.71	0.19
COD, mg/L	96.51	27.77	15.49	10.77	3.99	1.32	0.44	0.30
BOD, mg/L	28.46	6.45	2.51	1.00	0.30	0.20	0.10	0.00

	IN_0815	EF_0815 _0hr	EF_0815 _30min	EF_0815 _1hr	EF_0815 _2hr	EF_0815 _3hr	EF_0815 _8hr	EF_0815 _24hr
TDS, mg/L	298.00	323.00	311.00	326.00	330.00	330.00		
DO, mg/L	1.29	3.12	3.99	3.26	3.87	3.90	4.30	4.90
Temp, C	22.50	21.00	21.20	21.30	21.80	21.80		
Turbidity, NTU	14.30	7.40	3.95	2.24	0.77	0.35	0.00	0.00
TOC, mg/L	27.86	17.07	12.82	11.33	8.39	7.40	4.71	4.94
TOC Stnd Dev	0.09	0.08	0.09	0.10	0.01	0.04	0.05	0.03
TIC, mg/L	17.55	24.23	23.80	24.34	25.33	25.57	12.57	12.02
DOC, mg/L	19.60	12.94	10.47	9.40	7.78	6.70	4.39	4.60
DOC Stnd Dev	0.03	0.06	0.07	0.08	0.08	0.14	0.03	0.08
DIC, mg/L	21.68	20.67	22.48	20.52	23.78	24.02	9.88	12.29
SOC, mg/L	8.26	4.13	2.36	1.93	0.61	0.69	0.32	0.34
COD, mg/L	116.12	61.07	39.42	31.79	16.82	11.75	0.30	0.70
BOD, mg/L	34.73	17.11	10.18	7.73	2.94	1.31	0.00	0.00

	IN_0817	EF_0817 _0hr	EF_0817 _30min	EF_0817 1hr	EF_0817 _2hr	EF_0817 _3hr	EF_0817 _8hr	EF_0817 _24hr
TDS, mg/L	386.00	360.00	345.00	346.00	347.00	351.00		
DO, mg/L	1.65	3.89	4.09	4.57	4.44	3.54	4.21	4.87
Temp, C	23.20	20.60	20.80	20.80	22.20	21.50		
Turbidity, NTU	9.95	5.22	3.17	1.70	0.41	0.08	0.00	0.00
TOC, mg/L	21.02	11.04	8.38	6.86	5.76	4.72	4.12	4.96
TOC Stnd Dev	0.10	0.05	0.08	0.12	0.11	0.05	0.07	0.07
TIC, mg/L	29.31	27.34	29.24	30.18	30.64	29.26	29.73	26.09
DOC, mg/L	17.42	10.02	7.83	6.14	5.04	4.45	4.03	4.42
DOC Stnd Dev	0.16	0.04	0.01	0.07	0.05	0.03	0.06	0.01
DIC, mg/L	31.38	25.49	24.47	23.18	26.96	29.22	26.80	23.49
SOC, mg/L	3.60	1.02	0.55	0.73	0.72	0.27	0.09	0.54
COD, mg/L	81.23	30.33	16.77	9.04	3.40	0.80	0.10	0.30
BOD, mg/L	23.56	7.27	2.92	0.45	0.20	0.00	0.00	0.00

	IN_0825	EF_0825 _0hr	EF_0825 _30min	EF_0825 1hr	EF_0825 _2hr	EF_0825 _3hr	EF_0825 _8hr	EF_0825 _24hr
TDS, mg/L	349.00	348.00	346.00	349.00	352.00	353.00	352.00	342.00
DO, mg/L	1.60	5.26	5.16	4.83	4.77	4.97	5.67	5.70
Temp, C	19.70	19.70	19.80	21.10	20.50	20.90	18.50	18.20
Turbidity, NTU	17.40	12.30	5.76	3.13	1.21	0.49	0.00	0.00
TOC, mg/L	30.57	23.73	20.09	16.04	12.42	10.88	7.45	5.27
TOC Stnd Dev	0.26	0.15	0.24	0.09	0.08	0.05	0.04	0.20
TIC, mg/L	30.85	34.01	35.76	35.78	34.15	33.60	32.53	30.24
DOC, mg/L	24.65	20.19	16.43	13.53	11.41	10.04	6.92	5.05
DOC Stnd Dev	0.19	0.17	0.14	0.09	0.09	0.07	0.09	0.07
DIC, mg/L	33.74	33.27	32.85	31.82	32.19	31.02	31.28	26.43
SOC, mg/L	5.93	3.54	3.67	2.51	1.01	0.85	0.53	0.21
COD, mg/L	129.94	95.07	76.50	55.86	37.37	29.54	12.01	0.89
BOD, mg/L	39.16	27.99	22.05	15.44	9.52	7.01	1.40	0.00

	IN_0826	EF_0826 _0hr	EF_0826 _30min	EF_0826 1hr	EF_0826 _2hr	EF_0826 _3hr	EF_0826 _8hr	EF_0826 _24hr
TDS, mg/L	323.00	328.00	331.00	333.00	333.00	336.00	340.00	330.00
DO, mg/L	2.40	4.49	5.77	5.80	6.00		4.66	5.84
Temp, C	21.60	21.50	21.30	21.80	23.10	22.80	21.20	18.60
Turbidity, NTU	12.90	6.70	2.63	1.27	0.38	0.12	0.00	0.00
TOC, mg/L	27.90	14.26	10.47	8.80	6.16	5.37	4.20	4.76
TOC Stnd Dev	0.15	0.10	0.11	0.18	0.04	0.05	0.01	0.05
TIC, mg/L	26.25	29.43	31.03	30.75	31.44	31.36	28.85	26.70
DOC, mg/L	21.53	11.47	8.73	7.30	5.78	5.33	4.20	4.58
DOC Stnd Dev	0.11	0.02	0.16	0.10	0.04	0.07	0.03	0.03
DIC, mg/L	26.36	29.31	26.88	27.12	26.88	29.47	28.11	25.04
SOC, mg/L	6.37	2.79	1.73	1.50	0.38	0.04	0.00	0.18
COD, mg/L	116.33	46.76	27.41	18.89	5.46	1.40	0.50	0.30
BOD, mg/L	34.80	12.53	6.33	3.60	0.70	0.50	0.20	0.00

	IN_0827	EF_0827 _0hr	EF_0827 _30min	EF_0827 1hr	EF_0827 _2hr	EF_0827 _3hr	EF_0827 _8hr	EF_0827 _24hr
TDS, mg/L	318.00	315.00	317.00			329.00	333.00	332.00
DO, mg/L	1.64						6.65	6.55
Temp, C	21.60	20.70	21.30			22.50	20.80	19.20
Turbidity, NTU	14.80	7.80	2.74	1.44	0.47	0.19	0.00	0.00
TOC, mg/L	36.36	19.52	13.86	10.96	7.76	6.97	4.84	4.74
TOC Stnd Dev	0.18	0.22	0.18	0.06	0.04	0.02	0.02	0.05
TIC, mg/L	24.31	26.05	27.36	25.01	27.19	28.58	26.18	23.93
DOC, mg/L	23.75	15.23	11.29	9.23	7.08	6.18	4.48	4.46
DOC Stnd Dev	0.03	0.03	0.06	0.04	0.08	0.03	0.06	0.02
DIC, mg/L	23.55	21.63	26.15	22.33	25.27	24.10	24.34	21.78
SOC, mg/L	12.62	4.29	2.57	1.73	0.68	0.79	0.36	0.28
COD, mg/L	159.46	73.58	44.70	29.90	13.61	9.59	0.30	0.20
BOD, mg/L	48.61	21.11	11.87	7.13	1.91	0.62	0.00	0.00

	IN_0828	EF_0828 _0hr	EF_0828 _30min	EF_0828 _1hr	EF_0828 _2hr	EF_0828 _3hr	EF_0828 _8hr	EF_0828 _24hr
TDS, mg/L	342.00	324.00	324.00	328.00	323.00	332.00	313.00	326.00
DO, mg/L	1.12	4.94	5.30	5.20	5.23	4.90	6.28	6.59
Temp, C	21.60	21.40	21.60	22.30	24.10	23.50	20.80	20.40
Turbidity, NTU	28.40	15.00	6.66	3.27	0.95	0.30	0.00	0.00
TOC, mg/L	40.07	27.60	18.14	12.88	8.86	7.25	5.16	4.81
TOC Stnd Dev	0.05	0.25	0.12	0.06	0.10	0.05	0.03	0.07
TIC, mg/L	29.82	26.86	26.66	27.81	28.79	28.82	25.82	21.11
DOC, mg/L	32.07	22.64	14.81	10.74	8.33	6.72	4.77	4.61
DOC Stnd Dev	0.37	0.11	0.10	0.02	0.05	0.04	0.03	0.07
DIC, mg/L	30.64	28.72	26.15	27.31	27.69	25.01	21.45	20.28
SOC, mg/L	8.01	4.96	3.33	2.14	0.53	0.53	0.40	0.21
COD, mg/L	178.39	114.77	66.55	39.71	19.24	10.99	0.37	0.50
BOD, mg/L	54.68	34.30	18.86	10.27	3.71	1.07	0.00	0.00

	IN_0903	EF_0903 _0hr	EF_0903 _30min	EF_0903 _1hr	EF_0903 _2hr	EF_0903 _3hr	EF_0903 _8hr	EF_0903 _24hr
TDS, mg/L	368.00	340.00	330.00	326.00				
DO, mg/L	1.25	4.90	6.08					
Temp, C	23.00	23.00	23.50	23.80				
Turbidity, NTU	24.00	21.70	16.30	8.56	3.11	1.18	0.08	0.00
TOC, mg/L	31.70	23.47	17.84	13.03	8.58	7.73	6.00	6.12
TOC Stnd Dev	0.21	0.27	0.15	0.13	0.06	0.06	0.04	0.15
TIC, mg/L	39.15	30.78	27.05	28.42	26.56	28.24	21.39	21.33
DOC, mg/L	28.40	18.25	15.53	10.74	7.60	6.37	5.47	5.99
DOC Stnd Dev	0.06	0.10	0.09	0.08	0.12	0.12	0.04	0.01
DIC, mg/L	30.45	23.91	24.62	26.66	24.00	23.80	22.12	18.14
SOC, mg/L	3.30	5.23	2.30	2.30	0.98	1.36	0.53	0.13
COD, mg/L	135.70	93.74	64.99	40.50	17.80	13.48	4.63	5.24
BOD, mg/L	41.01	27.57	18.36	10.52	3.25	1.87	0.20	0.50

	IN_0915	EF_0915_1hr	EF_0915_3hr	EF_0915_8hr	EF_0915_24hr
TDS, mg/L					
DO, mg/L					
Temp, C					
Turbidity, NTU	17.30	2.13	0.29	0.00	0.00
TOC, mg/L	28.40	9.30	6.84		
TOC Stnd Dev	0.24	0.05	0.05		
TIC, mg/L	36.60	32.02	31.63		
DOC, mg/L	23.39	8.54	6.30		
DOC Stnd Dev	0.03	0.09	0.07		
DIC, mg/L	30.81	29.33	29.49		
SOC, mg/L	5.01	0.76	0.54		
COD, mg/L	118.86	21.45	8.93		
BOD, mg/L	35.62	4.42	0.41		

	IN_0916	EF_0916_0hr	EF_0916_1hr	EF_0916_3hr	EF_0916_8hr	EF_0916_24hr	IN_0917	EF_0917_0hr	EF_0917_1hr	EF_0917_3hr	EF_0917_8hr	EF_0917_24hr
TDS, mg/L	324.00	324.00	325.00	333.00	340.00	338.00	295.00	300.00	306.00	306.00		300.00
DO, mg/L	1.58	5.67	6.06	6.40	6.99	7.53	1.67	5.37	6.39	6.36		8.83
Temp, C	20.50	20.70	21.70	23.30	19.60	16.20	20.20	18.80	19.60	21.30		17.30
Turbidity, NTU	25.20		2.71	0.46	0.00	0.00	14.70		0.67	0.00		0.00
TOC, mg/L					5.80	5.06	13.78		6.12	4.87	4.46	4.54
TOC Stnd Dev					0.05	0.04	0.07		0.13	0.02	0.06	0.02
TIC, mg/L					28.43	22.32	30.24		23.55	26.22	25.59	22.95
DOC, mg/L					5.32	4.77	10.31		5.79	4.36	4.20	4.55
DOC Stnd Dev					0.07	0.01	0.09		0.06	0.04	0.05	0.02
DIC, mg/L					32.00	24.71	24.94		22.20	24.97	21.67	20.29
SOC, mg/L					0.49	0.29	3.47		0.33	0.51	0.25	-0.01
COD, mg/L					3.63	0.50	44.30		5.24	1.00	0.70	0.40
BOD, mg/L					0.30	0.10	11.74		0.50	0.70	0.20	0.10

	IN_0926	EF_0926 _0hr	EF_0926 _30min	EF_0926 _1hr	EF_0926 _2hr	EF_0926 _3hr	EF_0926 _8hr	EF_0926 _24hr
TDS, mg/L	590.00	498.00	470.00	474.00	472.00	472.00	488.00	490.00
DO, mg/L	1.91	5.94	5.96	6.00	5.90	6.06	6.67	8.53
Temp, C	21.00	19.60	19.70	20.20	21.00	20.80	18.10	15.30
Turbidity, NTU	82.20	27.40	11.20	6.54	3.50	2.33	0.35	0.00
TOC, mg/L	84.31	53.25	32.55	26.25	21.74	18.36	13.95	8.59
TOC Stnd Dev	1.54	0.55	0.30	0.17	0.23	0.24	0.02	0.11
TIC, mg/L	77.73	65.34	59.88	61.32	65.08	65.05	52.42	64.72
DOC, mg/L	78.48	43.17	28.75	23.59	19.72	15.37	13.19	8.12
DOC Stnd Dev	0.81	0.17	0.17	0.16	0.15	0.15	0.01	0.04
DIC, mg/L	70.27	60.52	57.93	60.48	59.55	57.22	51.66	53.53
SOC, mg/L	5.83	10.08	3.79	2.66	2.02	3.00	0.76	0.48
COD, mg/L	403.99	245.60	140.02	107.90	84.90	67.68	45.19	17.86
BOD, mg/L	126.92	76.20	42.39	32.10	24.74	19.23	12.02	3.27

	IN_0927	EF_0927 _0hr	EF_0927 _30min	EF_0927 _1hr	EF_0927 _2hr	EF_0927 _3hr	EF_0927 _8hr	EF_0927 _24hr
TDS, mg/L	410.00	425.00	432.00	429.00	429.00	433.00	449.00	437.00
DO, mg/L	1.98	6.13	6.45	6.43	6.13	6.25	7.19	8.66
Temp, C	22.20	20.00	20.50	21.00	22.50	21.90	18.10	16.30
Turbidity, NTU	33.50	12.80	5.10	3.43	1.41	0.82	0.10	0.00
TOC, mg/L	45.23	24.51	19.44	15.27	14.03	12.70	9.00	6.58
TOC Stnd Dev	0.09	0.23	0.24	0.14	0.12	0.07	0.10	0.04
TIC, mg/L	40.96	45.33	52.45	52.43	54.70	56.48	51.13	54.07
DOC, mg/L	41.66	19.35	16.90	13.50	12.34	11.47	8.76	6.87
DOC Stnd Dev	0.23	0.05	0.13	0.08	0.07	0.07	0.08	0.08
DIC, mg/L	44.20	46.93	49.99	45.30	46.98	46.62	56.93	48.15
SOC, mg/L	3.56	5.16	2.54	1.77	1.68	1.23	0.24	-0.29
COD, mg/L	204.67	99.03	73.17	51.91	45.56	38.80	19.94	7.61
BOD, mg/L	63.09	29.26	20.98	14.18	12.14	9.98	3.94	0.10

	IN_0928	EF_0928_0hr	EF_0928_30min	EF_0928_1hr	EF_0928_2hr	EF_0928_3hr	EF_0928_8hr	EF_0928_24hr
TDS, mg/L	330.00	358.00	365.00	366.00	369.00	375.00	390.00	379.00
DO, mg/L	1.28	5.84	5.74	5.93	6.43	6.40	6.76	6.90
Temp, C	20.40	20.00	21.30	21.40	23.50	22.60	19.50	20.40
Turbidity, NTU	30.00	9.18	3.80	2.03	0.77	0.19	0.00	0.00
TOC, mg/L	29.18	14.25	11.53	10.41	8.90	7.22	5.53	6.17
TOC Stnd Dev	0.45	0.17	0.06	0.11	0.12	0.05	0.07	0.09
TIC, mg/L	32.68	41.13	38.51	45.56	46.83	44.19	44.27	48.32
DOC, mg/L	25.39	11.54	10.74	9.42	8.37	6.97	5.25	5.42
DOC Stnd Dev	0.85	0.03	0.02	0.03	0.05	0.06	0.11	0.08
DIC, mg/L	30.13	37.92	34.79	36.69	37.46	38.60	46.31	42.38
SOC, mg/L	3.78	2.72	0.79	0.99	0.53	0.24	0.27	0.74
COD, mg/L	122.82	46.71	32.82	27.13	19.41	10.84	2.21	5.48
BOD, mg/L	36.88	12.51	8.06	6.24	3.77	1.02	0.50	0.10

	IN_1002	EF_1002_0hr	EF_1002_30min	EF_1002_1hr	EF_1002_2hr	EF_1002_3hr	EF_1002_8hr	EF_1002_24hr
TDS, mg/L	361.00	336.00	335.00	350.00	345.00	350.00	365.00	354.00
DO, mg/L	1.65	5.41	5.87	5.74	5.94	5.60	6.62	7.42
Temp, C	20.00	18.70	18.70	18.50	19.10	20.30	19.10	16.90
Turbidity, NTU	70.70	13.40	4.68	2.12	0.61	0.05	0.00	0.00
TOC, mg/L	29.65	17.42	11.09	8.71	6.77	5.51	4.70	4.48
TOC Stnd Dev	0.22	0.14	0.10	0.05	0.01	0.02	0.07	0.03
TIC, mg/L	38.49	36.48	35.03	34.62	36.51	33.28	37.96	32.38
DOC, mg/L	24.31	12.77	8.94	7.59	6.08	4.78	4.24	4.15
DOC Stnd Dev	0.04	0.03	0.04	0.05	0.04	0.13	0.06	0.04
DIC, mg/L	34.37	29.61	30.12	33.29	33.82	29.18	35.13	30.39
SOC, mg/L	5.34	4.66	2.15	1.12	0.69	0.73	0.45	0.33
COD, mg/L	125.26	62.88	30.59	18.45	8.58	2.11	0.40	0.20
BOD, mg/L	37.66	17.69	7.35	3.46	0.30	0.20	0.10	0.05

	IN_1003	EF_1003_0hr	EF_1003_30min	EF_1003_1hr	EF_1003_2hr	EF_1003_3hr	EF_1003_8hr	EF_1003_24hr
TDS, mg/L	287.00	304.00	317.00	309.00	329.00	320.00	330.00	331.00
DO, mg/L	1.06	5.43	5.85	5.73	5.51	5.64	6.52	8.51
Temp, C	19.70	19.80	19.70	19.80	21.70	20.40	17.80	17.40
Turbidity, NTU	35.60	14.70	9.27	6.14	3.41	1.93	0.15	0.00
TOC, mg/L	110.23	59.30	37.36	30.54	24.17	19.03	12.43	6.53
TOC Stnd Dev	0.67	0.49	0.33	0.07	0.07	0.04	0.11	0.07
TIC, mg/L	25.84	30.09	29.68	32.63	33.30	31.94	34.92	30.31
DOC, mg/L	94.34	53.35	36.25	27.10	22.46	18.29	11.71	5.93
DOC Stnd Dev	1.93	0.43	0.08	0.08	0.06	0.10	0.13	0.03
DIC, mg/L	24.87	28.40	27.25	26.89	28.58	30.38	27.46	27.91
SOC, mg/L	15.89	5.95	1.11	3.44	1.71	0.75	0.72	0.60
COD, mg/L	536.15	276.44	164.55	129.77	97.31	71.10	37.42	7.36
BOD, mg/L	169.23	86.07	50.24	39.11	28.71	20.32	9.53	0.50

	IN_1010	EF_1010_0hr	EF_1010_30min	EF_1010_1hr	EF_1010_2hr	EF_1010_3hr	EF_1010_8hr	EF_1010_24hr
TDS, mg/L	292.00	291.00	296.00	292.00	290.00	293.00	306.00	303.00
DO, mg/L	2.00	5.50	5.90	6.23	5.51	6.23	6.69	8.07
Temp, C	16.60	15.80	16.10	17.40	18.20	17.80	15.20	13.40
Turbidity, NTU	45.50	17.50	9.8606.04	6.04	3.33	1.57	0.17	0.00
TOC, mg/L	122.66	76.54	50.17	39.15	30.28	24.80	17.79	8.28
TOC Stnd Dev	1.06	0.50	0.74	0.30	0.47	0.14	0.12	0.06
TIC, mg/L	27.49	27.00	25.29	29.30	29.13	27.08	27.05	25.34
DOC, mg/L	104.68	64.44	41.43	33.62	26.71	22.87	16.15	7.61
DOC Stnd Dev	2.33	0.21	0.27	0.04	0.07	0.25	0.11	0.06
DIC, mg/L	23.94	24.19	27.05	27.38	26.27	27.14	26.09	23.74
SOC, mg/L	17.98	12.09	8.74	5.54	3.58	1.93	1.64	0.67
COD, mg/L	599.54	364.33	229.89	173.70	128.46	100.49	64.76	16.26
BOD, mg/L	189.53	114.22	71.17	53.17	38.69	29.73	18.29	2.76

	IN_1025	EF_1025_0hr	EF_1025_30mi	EF_1025_1hr	EF_1025_2hr	EF_1025_3hr	EF_1025_8hr	EF_1025_24hr	EF_1025_48hr
TDS, mg/L									
DO, mg/L									
Temp, C									
Turbidity, NTU	`	21.50	9.97	6.50	3.58	2.51	0.88		
TOC, mg/L	180.91	118.34	76.81	65.86	50.76	44.15	29.09	13.08	6.98
TOC Stnd Dev	0.71	0.35	0.12	0.82	0.54	0.33	0.18	0.05	0.04
TIC, mg/L	21.65	20.51	25.10	27.94	31.57	35.06	43.60	21.95	17.17
DOC, mg/L	144.65	105.92	68.12	60.46	47.46	40.26	25.63	12.52	6.13
DOC Stnd Dev	0.49	0.37	0.29	0.33	0.18	0.35	0.25	0.09	0.04
DIC, mg/L	18.48	20.80	23.19	27.07	30.70	32.63	43.28	24.37	17.67
SOC, mg/L	36.27	12.41	8.69	5.40	3.31	3.88	3.46	0.56	0.85
COD, mg/L	896.59	577.50	365.73	309.87	232.91	199.16	122.39	40.74	9.63
BOD, mg/L	284.66	182.48	114.67	96.78	72.13	61.33	36.74	10.60	0.64

	IN_1107	IN_1107_spike	EF_1107_0hr	EF_1107_30mi	EF_1107_1hr	EF_1107_2hr	EF_1107_3hr	EF_1107_8hr	EF_1107_24hr
TDS, mg/L	293.00	388.00	356.00	355.00	352.00	356.00	364.00	410.00	492.00
DO, mg/L	1.85		4.82	4.74	4.42	4.28	4.30	3.43	7.59
Temp, C				19.60	19.60	20.20	19.50	17.50	14.80
Turbidity, NTU	63.40		34.10	32.80	31.70	25.00	21.10	17.80	7.14
TOC, mg/L		217.97	168.18	159.32	153.03	123.84	110.51	61.71	44.49
TOC Stnd Dev		2.47	0.22	0.78	1.85	1.10	0.11	0.17	0.42
TIC, mg/L		25.04	21.76	23.32	23.79	25.68	28.35	39.28	55.38
DOC, mg/L		181.65	139.30	120.86	119.32	111.38	95.64	56.10	36.09
DOC Stnd Dev		2.00	1.41	2.05	3.16	1.78	2.14	0.41	0.27
DIC, mg/L		23.88	20.57	21.54	23.41	25.94	26.40	40.42	50.79
SOC, mg/L		36.33	28.88	38.46	33.71	12.46	14.87	5.61	8.40
COD, mg/L		1085.58	831.68	786.48	754.41	605.54	537.60	288.72	200.91
BOD, mg/L		345.17	263.87	249.40	239.13	191.45	169.70	90.01	61.89

	EF_0207_24	IN_020814	EF_020814_0hr	EF_020814_30min	EF_020814_1hr	EF_1107_2hr	EF_020814_3hr	EF_020814_8hr	EF_020814_24hr
TDS, mg/L	313.00	291.00	293.00	292.00	294.00	291.00	282.00		313.00
DO, mg/L	7.90	1.16	7.40	7.33	7.79	7.52	7.60		7.90
Temp, C									
Turbidity, NTU	0.00	13.20	5.11	2.23	0.95	0.45	0.00	0.00	0.00
TOC, mg/L	4.34	50.33	18.87	10.84	7.74	6.11	5.37	4.77	6.50
TOC Stnd Dev	0.02	0.68	0.14	0.04	0.05	0.01	0.01	0.05	0.39
TIC, mg/L	10.90	24.43	19.93	18.80	20.44	19.67	18.28	17.07	13.43
DOC, mg/L	4.11	44.12	12.89	8.01	6.46	5.81	5.04	4.55	5.38
DOC Stnd Dev	0.02	0.37	0.04	0.06	0.04	0.01	0.02	0.04	0.17
DIC, mg/L	9.96	21.55	22.37	20.52	19.76	18.28	16.14	15.78	15.17
SOC, mg/L	0.23	6.21	5.98	2.83	1.28	0.30	0.33	0.21	1.12
COD, mg/L	0.50	230.68	70.28	29.31	13.50	5.20	1.43	1.00	7.21
BOD, mg/L	0.10	71.42	20.06	6.94	1.88	0.70	0.40	0.10	0.80

Appendix 6 Supplemental data for plots/figures and tables

This appendix presents data for producing plots / figures and tables for Chapters 4, 5, and 6 in this dissertation. The purpose of this appendix is to provide data necessary for readers or researchers who are interested in further evaluating the plots / figures and tables presented in the main body of this dissertation for their own purposes. It is noted that for field data, all Sample IDs represent the date when samples were collected. All IDs were arranged in the following way:

- Month (one or two digits, depending on the month. For example, January has one digit; while October has two digits),
- Date (two digits), and
- Year (two digits).

For example, a sample ID is "50813" means that the sample was collected on May 8, 2013. The tables presented in this appendix follow the same order of presentation arrangement as the original figures / plots or tables in this main body of dissertation.

Chapter 4

Table 10 Turbidity data used for producing Fig. 4.2 and Fig. 4.5

Sample ID	Influent	0.25hr	0.5hr	0.75hr	1hr	2hr	3hr	8hr
50813	22.0	4.5	3.1	2.0	1.2	0.4	0.4	0.2
51013	17.0	4.6	2.4	1.6	0.9	0.7	0.3	-
42013	36.3	18.6	6.5	4.8	3.2	1.5	0.9	-
51313	15.0	4.3	2.6	1.7	1.2	0.3	0.2	0.0
51513	22.0	5.4	2.0	0.9	0.5	0.1	0.1	0.0
51713	20.6	4.9	2.7	1.4	0.9	0.2	0.0	-
52013	13.2	5.7	3.4	2.0	1.5	0.5	0.2	0.2
42413	26.0	7.6	6.0	3.7	3.0	0.8	0.5	0.1
42613	21.0	5.2	4.2	2.3	1.7	0.7	0.4	0.2
50113	32.0	7.1	3.3	1.9	1.3	0.7	0.6	0.3
50313	24.0	7.6	4.9	3.3	2.3	0.6	0.5	-
Average, NTU	22.6	6.9	3.7	2.3	1.6	0.6	0.4	0.1
Std. Dev., NTU	6.9	4.1	1.5	1.1	0.9	0.4	0.3	0.1

Table 11 bDOC data used for producing Fig. 4.2

Sample ID	Influent	0.25hr	0.5hr	0.75hr	1hr	2hr	3hr	8hr
50813	10.41	2.69	2.43	1.57	1.50	0.57	0.00	0.20
51013	16.56	6.24	3.76	2.96	2.36	1.08	0.23	0.00
42013	13.13	6.79	5.38	4.13	3.29	1.55	0.18	0.00
51313	10.60	4.13	2.95	2.35	1.82	0.93	0.45	0.00
51513	21.52	5.55	2.99	2.37	1.90	1.01	0.05	0.00
51713	13.68	3.62	2.73	1.77	1.32	0.59	0.24	0.00
52013	9.57	4.85	4.08	2.69	2.47	1.56	0.94	0.00
42413	13.27	5.42	4.28	3.39	2.65	1.50	0.98	0.00
42613	15.03	6.26	4.60	3.88	2.95	1.41	0.58	0.00
50113	9.52	3.18	1.63	0.89	0.65	0.19	0.00	0.56
50313	5.87	2.94	1.70	1.36	1.06	0.73	0.12	0.00
42413	13.27	5.42	4.28	3.39	2.65	1.50	0.98	0.00
42613	15.03	6.26	4.60	3.88	2.95	1.41	0.58	0.00
Avg. m/L	12.88	4.87	3.49	2.66	2.12	1.08	0.41	0.06
Std. Dev. mg/L	3.89	1.41	1.18	1.05	0.81	0.45	0.37	0.16

Table 12 TOC data used for producing Fig. 4.3

		Influent		Effluent (3 hr)	
	Sample ID	Initial	Final	Initial	Final
TOC 10-days, mg/L	33113	34.83	19.36	5.38	5.38
Removal		1	0.56	0.15	0.15
TOC 5-days, mg/L	51013	41.50	14.76	8.55	7.29
Removal		1	0.36	0.21	0.18

Table 13 DOC data used for producing Fig. 4.3

Sample ID	Influent	0.25hr	0.5hr	0.75hr	1hr	2hr	3hr	8hr
Recirculation flow rate = 15 L/min								
50813	15.98	8.26	8.00	7.15	7.07	6.15	5.57	5.77
51013	23.46	13.14	10.66	9.86	9.26	7.98	7.13	6.92
51113	15.01	10.07	9.15	8.10	7.66	6.75	6.66	6.04
Avg, mg/L	18.15	10.49	9.27	8.37	8.00	6.96	6.45	6.24
Std. Dev., mg/L	4.63	2.46	1.33	1.37	1.13	0.93	0.80	0.60
Avg. Removal	0.00	0.46	0.52	0.57	0.58	0.64	0.67	0.67
Std. Dev. removal	0.00	0.03	0.03	0.02	0.03	0.03	0.03	0.05
Recirculation flow rate = 19 L/min								
42013	18.03	11.69	10.28	9.03	8.19	6.45	5.08	4.90
51313	18.12	11.65	10.47	9.86	9.33	8.45	7.96	7.52
51513	29.48	13.51	10.95	10.32	9.86	8.97	8.01	7.96
51713	21.88	11.82	10.93	9.97	9.52	8.79	8.44	8.20
52013	16.25	11.53	10.76	9.37	9.15	8.24	7.62	6.68
Avg, mg/L	20.75	12.04	10.68	9.71	9.21	8.18	7.42	7.05
Std. Dev., mg/L	5.29	0.83	0.29	0.51	0.63	1.01	1.34	1.33
Avg. Removal	0.00	0.40	0.46	0.51	0.54	0.59	0.63	0.65
Std. Dev. removal	0.00	0.10	0.11	0.09	0.09	0.08	0.09	0.07
Recirculation flow rate = 26 L/min								
42413	20.95	13.10	11.96	11.07	10.33	9.18	8.66	7.68
42613	20.23	11.46	9.80	9.08	8.16	6.61	5.78	5.20
50113	15.98	9.64	8.09	7.35	7.10	6.65	6.46	7.02
50313	11.77	8.84	7.60	7.26	6.96	6.63	6.02	5.90
Avg, mg/L	17.23	10.76	9.36	8.69	8.14	7.27	6.73	6.45
Std. Dev., mg/L	4.25	1.91	1.97	1.80	1.56	1.28	1.32	1.11
Avg. Removal	0.00	0.36	0.45	0.49	0.52	0.56	0.60	0.61
Std. Dev. removal	0.00	0.08	0.07	0.08	0.08	0.10	0.09	0.10

Table 14 Particulate organic carbon data used for producing Fig. 4.5

	Influent	0hr	0.25hr	0.5hr	0.75hr	1hr	2hr	3hr	8hr
50813	13.96	9.03	3.67	1.97	1.68	1.17	0.73	0.67	0.35
51013	14.71	9.31	5.98	4.30	3.28	2.27	0.90	0.13	0.44
42013	18.70	13.01	7.95	4.89	3.84	2.55	1.39	1.11	1.10
51313	10.41	8.44	3.04	1.58	0.90	0.77	0.28	0.09	0.43
51513	12.03	11.22	4.71	2.23	1.38	0.63	0.56	0.55	0.18
51713	16.45	12.15	4.46	2.55	1.38	0.52	0.25	0.15	0.00
52013	13.54	10.89	6.10	3.71	2.64	1.94	1.08	1.04	0.26
42413	14.63	10.57	5.15	3.19	2.04	1.80	0.95	0.33	0.31
42613	12.87	10.88	4.31	2.79	1.86	1.08	0.60	0.62	0.33
50113	20.42	14.85	4.62	2.52	1.65	1.39	0.64	0.77	0.37
50313	20.42	14.85	4.62	2.52	1.65	1.39	0.64	0.77	0.37

Table 15 Normalized bDOC concentration calculated from Eq.4.5 to produce Fig. 4.5(a)

Hydraulic retention time (θ), hr	0.06	0.3	1	1.5	3
Treatment time, hours	Normalized bDOC Concentration				
0	1	1	1	1	1
1	0.21	0.27	0.44	0.54	0.72
2	0.04	0.07	0.20	0.29	0.52
3	0.01	0.02	0.09	0.16	0.37
4	0.00	0.01	0.04	0.09	0.27
5	0.00	0.00	0.02	0.05	0.19
6	0.00	0.00	0.01	0.03	0.14
7	0.00	0.00	0.00	0.01	0.10
8	0.00	0.00	0.00	0.01	0.07
9	0.00	0.00	0.00	0.00	0.05
10	0.00	0.00	0.00	0.00	0.03

Table 16 Normalized bDOC concentration calculated from Eq.4.5 to produce Fig. 4.5 (b)

Length (L), m	0.1	0.15	0.3	0.5	2
Treatment time, hours	Normalized bDOC Concentration				
0	1	1	1	1	1
1	0.39	0.27	0.13	0.08	0.05
1.2	0.32	0.21	0.09	0.05	0.03
1.4	0.26	0.16	0.06	0.03	0.02
1.6	0.22	0.12	0.04	0.02	0.01
1.8	0.18	0.09	0.03	0.01	0.01
2	0.15	0.07	0.02	0.01	0.00
3	0.06	0.02	0.00	0.00	0.00
4	0.02	0.01	0.00	0.00	0.00
5	0.01	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00

Table 17 Normalized bDOC concentration calculated from Eq.4.5 to produce Fig. 4.5 (c)

Area (A), m^2	0.2	0.4	0.68	1.5	3
Treatment time, hours	Normalized bDOC Concentration				
0	1	1	1	1	1
1	0.63	0.42	0.27	0.12	0.06
2	0.39	0.18	0.07	0.01	0.00
3	0.25	0.08	0.02	0.00	0.00
4	0.16	0.03	0.01	0.00	0.00
5	0.10	0.01	0.00	0.00	0.00
6	0.06	0.01	0.00	0.00	0.00
7	0.04	0.00	0.00	0.00	0.00
8	0.02	0.00	0.00	0.00	0.00
9	0.02	0.00	0.00	0.00	0.00
10	0.01	0.00	0.00	0.00	0.00

Table 18 Normalized bDOC concentration calculated from Eq.4.5 to produce Fig. 4.5 (d)

Area (k), m^2	0.5	1	3	5.8	12
Treatment time, hours	Normalized bDOC Concentration				
0	1	1	1	1	1
1	0.86	0.75	0.46	0.27	0.12
2	0.75	0.57	0.21	0.07	0.02
3	0.65	0.43	0.10	0.02	0.00
4	0.56	0.32	0.05	0.01	0.00
5	0.48	0.24	0.02	0.00	0.00
6	0.42	0.18	0.01	0.00	0.00
7	0.36	0.14	0.00	0.00	0.00
8	0.31	0.10	0.00	0.00	0.00
9	0.27	0.08	0.00	0.00	0.00
10	0.23	0.06	0.00	0.00	0.00

Table 19 Retail price range estimate for a SB-VFW system to be sold in the US used in this thesis used in discussions in Section 4.3.3 and Chapter 6

Component	**Quantity**	**Lower-bound cost range**		**Quantity**	**Upper-bound Cost range**	
		unit cost, $	**Total, $**		**Unit cost, $**	**Total, $**
Containers	2	50	100	2	70	140
Filter media	10	7	70	10	7	70
Recirculation pump	1	90	90	1	90	90
Bilge pump	1	67	67	2	67	134
Ball valve	4	8	32	3	8	24
Check valves	3	8	24	4	8	32
Soil mix	2	28	56	2	28	56
Irrigation timer	0	70	0	1	61	61
Pump start relay	0	40	0	3	40	120
Soil basket	6	7	42	6	8	48
Float switch	0	40	0	1	40	40
Collection tank	1	50	50	1	70	70
Nylon screen	1	5	5	1	5	5
Downspout	2	10	20	2	10	20
Plumbing fittings	1	50	50	1	135	135
Pipes	1	20	20	1	20	20
Labor assembly	4	25	100	4	25	100
Materials, total			626			1065
contingency, 20%			145			233
Transportation, 10%			87			140
Overhead, 30%			287			461
Profit, 25%			311			500
Retailed price			**1563**			**2509**

Note: treatment volume summed to be 560 GPD, collection and reservoir tanks sizes were 88 gallons each. All material prices were obtained from homedepot.com.

Table 20 Data inputs used for calculating the breakeven period (Eq. 4.6) and return on investment (Eq. 4.7) for manual and automated SB-VFW systems with different daily treatment volumes to create Fig. 4.8 and Fig. 4.9.

Daily treatment volume, m^3	Annual water saving, US$	No. of cycles	Daily electricity consumption, kWh	Annual electricity consumption, kWh	Total Costs, US$	Annual filter costs, $
2.12	2290	7	2.11	769	163	100
1.82	1963	6	2.03	742	157	100
1.51	1636	5	1.96	715	152	100
1.21	1309	4	1.88	688	146	100
0.91	982	3	1.81	661	140	100
0.61	654	2	1.74	634	134	100
0.30	327	1	1.66	606.92	129	100
0.23	245	1	1.66	607	129	100

Note: water +sewer charges, \$2.96/m^3 (LADWP, 2013), sump pump power rate = kW (actual pump used in the field study (Section 4.2.2); sump pump pumping time per cycle = 0.4 hr; recirculation pump power rating = 0.07 kW; recirculation time per cycle = 3 hr; controllers power rating = 0.03 kW; Electricity rates = \$0.21/kWh (LADWP, 2013). A manual system did not have a controller, thus controller power consumption = 0 kWh

Table 21 Breakeven period calculated using Eq. 4.6 and the data inputs in Table 11 (above) to produce Fig. 4.8

Daily treatment volume, m^3	Breakeven period, capital cost = \$1,000	Breakeven period, capital cost = \$1,500	Breakeven period, capital cost = \$2,000	Breakeven period, capital cost = \$2,500
2.12	0.50	0.74	0.99	1.23
1.82	0.59	0.88	1.17	1.47
1.51	0.73	1.08	1.44	1.81
1.21	0.95	1.41	1.88	2.35
0.91	1.37	2.02	2.70	3.37
0.61	2.41	3.55	4.76	5.95
0.30	10.34	14.89	20.30	25.38
0.23	67.01	79.17	119.63	149.54

Table 22 Return-on-investment calculated using Eq. 4.7 and the data inputs in Table 11 (above) to produce Fig. 4.9

Daily treatment volume, m^3	Return-on-investment, capital cost = $1,000	Return-on-investment, capital cost = $1,500	Return-on-investment, capital cost = $2,000	Return-on-investment, capital cost = $2,500
2.12	200%	135%	101%	81%
1.82	168%	114%	85%	68%
1.51	137%	92%	69%	55%
1.21	105%	71%	53%	43%
0.91	73%	50%	37%	30%
0.61	41%	28%	21%	17%
0.30	10%	7%	5%	4%
0.23	1%	1%	1%	1%

Chapter 5

Table 23 bDOC data for non-BBL graywater used for producing Fig. 5.2 (a)

Sample ID	Influent	0.5hr	1hr	2hr	3hr	8hr	24hr
Non-BBL							
71413	84.85				16.43		2.18
71513	59.46				7.67		3.85
71613	78.75				21.64		
100313	90.34	32.25	23.10	18.46	14.29	7.71	1.93
101013	100.68	37.43	29.62	22.71	18.87	12.15	3.61
Average, mg/L	78.35	34.84	26.36	18.46	15.01	7.71	2.89
Std. Dev., mg/L	15.34	3.67	4.61	3.00	5.30	3.14	1.36

Table 24 bDOC data for BBL graywater used for producing Fig. 5.2 (a)

Sample ID	Influent	0.5hr	1hr	2hr	3hr	8hr	24hr
72513	11.42	3.42	2.04	1.10	0.34	0.68	1.18
72613	15.95				0.21		
72913	35.44	8.67	6.08	3.77	2.46		0.63
73013	28.32	6.73	4.29	2.88	1.79	0.50	1.18
73113	16.08	5.03	2.91	1.81	0.90	0.04	0.45
80113	21.26	3.50	2.72	1.81	1.03	0.15	0.44
80213	22.30	7.06	5.13	2.91	1.92	0.09	0.34
80313	21.71	6.66	4.51	2.60	1.53	0.14	0.22
80713	19.94	6.26	4.99	4.05	1.85	0.16	0.11
81213	11.51	3.09	2.02	0.97	0.67	0.20	0.74
81513	15.60	6.47	5.40	3.78	2.70	0.39	0.60
81713	13.42	3.83	2.14	1.04	0.45	0.03	0.42
82613	17.53	4.73	3.30	1.78	1.33	0.20	0.58
82713	19.35	6.89	4.83	2.68	1.78	0.08	0.06
82813	27.57	10.31	6.24	3.83	2.22	0.27	0.11
90313	24.40	11.53	6.74	3.60	2.37	1.47	1.99
91513	19.39		4.54		2.30		
91613						1.32	0.77
91713	6.31		1.79		0.36	0.20	0.55
92813	20.39	5.74	4.42	3.37	1.97	0.25	0.42
100213	20.31	4.94	3.59	2.08	0.78	0.24	0.15
20814	40.12	4.01	2.46	1.81	1.04	0.55	1.38
Average, mg/L	20.40	6.05	4.01	2.55	1.43	0.37	0.62
Std. Dev., mg/L	7.65	2.28	1.49	1.01	0.77	0.39	0.48

Table 25 Turbidity data for non-BBL graywater used for producing Fig. 5.2 (b) and Fig. 5.3

Sample ID	Influent	0.5hr	1hr	2hr	3hr	8hr	24hr
71413	26.10				2.82		0.19
71513	19.00				0.99	0.11	0.00
100313	35.60	9.27	6.14	3.41	1.93	0.15	0.00
101013	45.50	9.86	6.04	3.33	1.57	0.17	0.00
Average, NTU	31.55	9.57	6.09	3.37	1.83	0.14	0.05
Std. Dev., NTU	11.52	0.42	0.07	0.06	0.77	0.03	0.10

Table 26 Turbidity data for BBL graywater used for producing Fig. 5.2 (b) and Fig. 5.3

Sample ID	Influent	0.5hr	1hr	2hr	3hr	8hr	24hr
71013	29.90				0.23		
71213	22.80				0.00		0.00
72513	15.00	5.20	2.10	0.55	0.40	0.00	0.00
72613	24.00				0.15		
72913	35.00	4.50	2.40	0.80	0.50	0.00	
73013	24.00	5.50	2.50	0.70	0.30	0.00	0.00
73113	20.00	3.60	1.60	0.40	0.15	0.00	0.00
80113	21.00	3.20	1.60	0.65	0.20	0.00	0.00
80213	15.30	3.20	1.80	0.50	0.15	0.00	0.00
80313	16.20	3.32	1.64	0.41	0.13	0.00	0.00
80713	14.50	2.48	1.57	0.58	0.38	0.00	0.00
81213	23.60	4.22	2.18	0.82	0.26	0.00	0.00
81513	14.30	3.95	2.24	0.77	0.35	0.00	0.00
81713	9.95	3.17	1.70	0.41	0.08	0.00	0.00
82513	17.40	5.76	3.13	1.21	0.49	0.00	0.00
82613	12.90	2.63	1.27	0.38	0.12	0.00	0.00
82713	14.80	2.74	1.44	0.47	0.19	0.00	0.00
82813	28.40	6.66	3.27	0.95	0.30	0.00	0.00
90313	24.00	16.30	8.56	3.11	1.18	0.00	0.00
91513	17.30		2.13		0.29	0.00	0.00
91613	25.20		2.71		0.46	0.00	0.00
91713	14.70		0.67		0.00		0.00
Average, NTU	19.21	4.72	2.33	1.00	0.30	0.00	0.00
Std. Dev., NTU	6.16	3.31	1.63	0.66	0.25	0.00	0.00

Table 27 Turbidity data for BBL graywater used for producing Fig. 5.3

Sample ID	Influent	0.5hr	1hr	2hr	3hr	8hr	24hr
72513	23.41	10.07	7.79	5.92	5.32	5.32	5.92
72613	26.21				4.46		
72913	51.51	14.63	11.96	8.74	7.84		5.39
73013	41.78	12.58	9.60	7.46	6.46	5.17	5.22
73113	25.83	10.95	8.46	6.61	5.79	4.85	4.76
80113	30.53	8.93	7.60	6.13	5.43	4.25	4.78
80213	31.80	12.20	9.96	7.73	6.18	4.31	4.54
80313	35.61	11.89	9.67	7.28	6.50	4.69	4.83
80713	35.62	12.85	10.55	8.79	7.08	4.77	4.72
81213	24.02	8.13	7.20	5.87	5.35	4.90	4.92
81513	27.86	12.82	11.33	8.39	7.40	4.71	4.94
81713	21.02	8.38	6.86	5.76	4.72	4.12	4.96
82513	30.57	20.09	16.04	12.42	10.88	7.45	5.27
82613	27.90	10.47	8.80	6.16	5.37	4.20	4.76
82713	36.36	13.86	10.96	7.76	6.97	4.84	4.74
82813	40.07	18.14	12.88	8.86	7.25	5.16	4.81
90313	31.70	17.84	13.03	8.58	7.73	6.00	6.12
91513	28.40		9.30		6.84		
91713	13.78		6.12		4.87	4.46	4.54
92813	29.18	11.53	10.41	8.90	7.22	5.53	6.17
100213	29.65	11.09	8.71	6.77	5.51	4.70	4.48
Average, NTU	28.14	11.42	9.09	7.00	5.96	4.59	4.64
Std. Dev., NTU	10.03	4.29	3.13	2.39	1.96	1.50	1.43

Table 28 Dissolved oxygen data for BBL graywater with cross flow media (CFM) used for producing Fig. 5.5

Sample ID	Influent	1hr	3hr	8hr	24hr
82513	1.6	4.8	5.0	5.7	5.7
82613	2.4	5.8		4.7	5.8
82713	1.6			6.7	6.6
82813	1.1	5.2	4.9	6.3	6.6
90313	1.3				
91513	1.6	6.1	6.4	7.0	7.5
91613	1.6	6.1	6.4	7.0	7.5
91713	1.7	6.4	6.4		8.8
92813	1.3	5.9	6.4	6.8	6.9
100213	1.7	5.7	5.6	6.6	7.4
Average, mg/L	1.6	5.7	6.2	6.3	7.0
Std. Dev., mg/L	0.3	0.5	0.7	0.8	1.0

Table 29 Dissolved oxygen data for BBL graywater without cross flow media (CFM) used for producing Fig. 5.5

Sample ID	Influent	1hr	3hr	8hr	24hr
81213	2.03	3.76	3.6	4.4	5.22
81513	1.29	3.26	3.9	4.3	4.9
81713	1.65	4.57	3.54	4.21	4.87
Average, mg/L	1.66	3.86	4.10	4.30	5.00
Std. Dev., mg/L	0.37	0.66	0.19	0.10	0.19

Table 30 NH_4-N data used for producing Fig. 5.6

Treatment time	Influent	3 hr	8 hr	24 hr
Normal BBL graywater				
82513	4.68	1.15	0.05	0.02
82613	3.66	0.88	0.04	0.06
82713	8.13	2.23	0.06	0.08
82813	4.74	2.56	0.28	0.08
Average, mg/L	5.30	1.70	0.11	0.06
Std. Dev., mg/L	1.95	0.82	0.11	0.03
BBL graywater spiked with BBL detergent				
92613	2.51	0.70	0.08	0.04
92713	2.71	1.15	0.12	0.10
Average, mg/L	2.61	0.93	0.10	0.07
Std. Dev., mg/L	0.14	0.32	0.03	0.04
Treatment of a new BBL graywater batch after discharge of detergent spiked graywater				
92813	1.71	0.38	0.09	0.08

Table 31 NO_3-N data used for producing Fig. 5.6

Treatment time	Influent	3 hr	8 hr	24 hr
82513	0.13	4.11	6.40	6.65
82613	0.12	2.34	3.73	4.62
82713	0.19	0.47	2.34	7.61
82813	0.08	2.97	3.66	4.83
Average, mg/L	0.13	2.47	4.03	5.93
Std. Dev., mg/L	0.05	1.52	1.70	1.45
BBL graywater spiked with BBL detergent				
92613	0.20	0.24	0.17	0.15
92713	0.13	0.16	0.13	0.24
Average, mg/L	0.17	0.20	0.15	0.19
Std. Dev., mg/L	0.05	0.05	0.03	0.07
Treatment of a new BBL graywater batch after discharge of detergent spiked graywater				
92813	0.21	0.20	0.27	1.28

Table 32 TOC data used for producing Fig. 5.7 (a)

TOC	Sample ID	Influent	0.5hr	1hr	2hr	3hr	8hr	24hr
Day 1	92613	84.31	32.55	26.25	21.74	18.36	13.95	8.59
Day 2	92713	45.23	19.44	15.27	14.03	12.70	9.00	6.58
Day 3	92813	29.18	11.53	10.41	8.90	7.22	5.53	6.17
Normal	72513	23.41	10.07	7.79	5.92	5.32	5.32	5.92
Normal	72613	26.21				4.46		
Normal	72913	51.51	14.63	11.96	8.74	7.84		5.39
Normal	73013	41.78	12.58	9.60	7.46	6.46	5.17	5.22
Normal	73113	25.83	10.95	8.46	6.61	5.79	4.85	4.76
Normal	80113	30.53	8.93	7.60	6.13	5.43	4.25	4.78
Normal	80213	31.80	12.20	9.96	7.73	6.18	4.31	4.54
Normal	80313	35.61	11.89	9.67	7.28	6.50	4.69	4.83
Normal	80713	35.62	12.85	10.55	8.79	7.08	4.77	4.72
Normal	81213	24.02	8.13	7.20	5.87	5.35	4.90	4.92
Normal	81513	27.86	12.82	11.33	8.39	7.40	4.71	4.94
Normal	81713	21.02	8.38	6.86	5.76	4.72	4.12	4.96
Normal	82513	30.57	20.09	16.04	12.42	10.88	7.45	5.27
Normal	82613	27.90	10.47	8.80	6.16	5.37	4.20	4.76
Normal	82713	36.36	13.86	10.96	7.76	6.97	4.84	4.74
Normal	82813	40.07	18.14	12.88	8.86	7.25	5.16	4.81
Normal	90313	31.70	17.84	13.03	8.58	7.73	6.00	6.12
Normal	91513	28.40		9.30		6.84		
Normal	91613						5.80	5.06
Normal	91713	13.78		6.12		4.87	4.46	4.54
Normal	100213	29.65	11.09	8.71	6.77	5.51	4.70	4.48
Normal	Average, mg/L	28.14	11.42	9.09	7.00	5.96	4.59	4.64
Normal	Std. Dev., mg/L	10.03	4.29	3.13	2.39	1.96	1.50	1.43

Table 33 TOC data used for producing Fig. 5.7 (b), Normal load average data is presented in Table 18 in this Appendix

Turbidity	Sample ID	Influent	0.5hr	1hr	2hr	3hr	8hr
Day 1	92613	82.2	11.2	6.54	3.5	2.33	0.35
Day 2	92713	33.5	5.1	3.43	1.41	0.82	0.1
Day 3	92813	30	3.8	2.03	0.77	0.19	0

Table 34 bDOC data used for producing Fig. 5.8 (a)

Sample ID	Influent	0.5hr	1hr	2hr	3hr	8hr	24hr
	bDOC, mg/L						
100313	90.34	32.25	23.10	18.46	14.29	7.71	1.93
101013	100.68	37.43	29.62	22.71	18.87	12.15	3.61
102513	140.65	64.12	56.46	43.46	36.26	21.63	8.52
110713	177.65	123.00	110.00	100.00	91.64	52.10	32.09
	Normalized bDOC						
100313	1	0.36	0.26	0.20	0.16	0.09	0.02
101013	1	0.37	0.29	0.23	0.19	0.12	0.04
102513	1	0.46	0.40	0.31	0.26	0.15	0.06
110713	1	0.69	0.62	0.56	0.50	0.29	0.18

Table 35 Turbidity data used for producing Fig. 5.8 (b)

Sample ID	Influent	0.5hr	1hr	2hr	3hr	8hr	24hr
	Turbidity, NTU						
100313	35.60	9.27	6.14	3.41	1.93	0.15	0.00
101013	45.50	9.86	6.04	3.33	1.57	0.17	0.00
102513	21.50	9.97	6.50	3.58	2.51	0.88	0.40
110713	63.40	32.80	28.00	24.00	21.10	17.80	7.14

Chapter 6

Table 36 Material cost estimate per bathroom for installing drains to allow graywater collection presented in Table 6.2

	A	B	C	D	E	F	G	
1		Unit cost, $	Component quantity per bathroom	number of bathroom	Component quantity per collection tank	Number of tanks (collection + reservoir)	Total costs, $	Formula
3	3in ABS pipe /10 ft	21	1	2	1	2	42	=B3*C3*D3
4	Elbow, 3 inch	3	4	2			24	=B4*C4*D4
5	Elbow, 4 inch	10			4		40	=B5*E5
6	Valves, 3 inch	48			2		96	=B6*E6
7	Tee, 4-4-3 inch	12			1		12	=B7*E7
8	Tee, 4-4-4 inch	9			1		9	=B8*E8
9	Tee, 4-4-2 inch	14			1		14	=B9*E9
11						**Total**	**237**	=SUM(G2:G9)
						Cost per bathroom	**~120**	

Note: All component unit prices were obtained online from homedepot.com. The component types and quantities presented above were developed on a best reasonable estimate basis for the purpose of the economic study presented in Chapter 6. The component types and quantity needed in a real situation can vary significantly depending on the site situation.

Table 37 Material cost estimate for indoor distribution system for reusing treated graywater for toilet flushing in Table 6.2

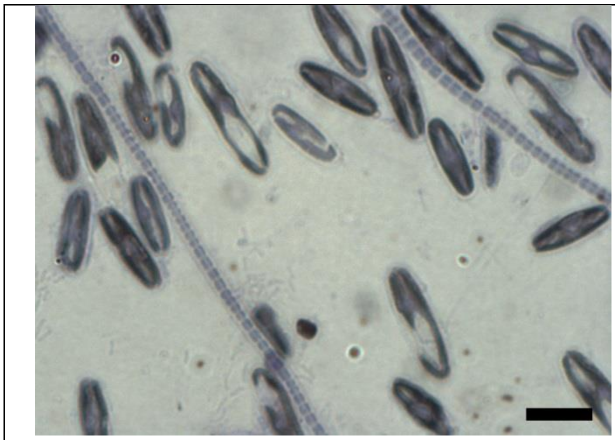
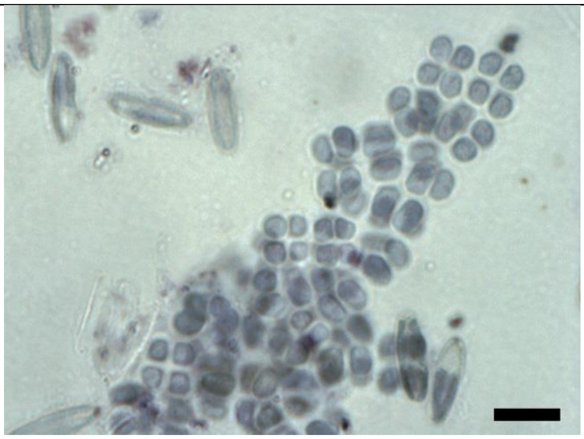
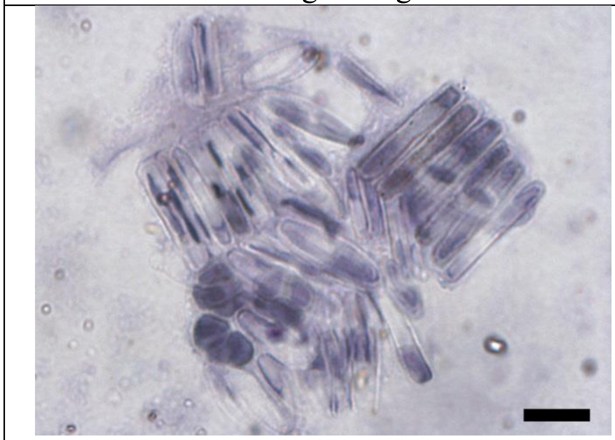
	A	B	C	D	E	Formula
1	Toilet water supply	Unit price, $	Component quantity per bathroom	number of bathroom	Total, $	
	1st 2 toilets					
2	Purple tubing (100 ft), $	70	3	2	420	=B2*C2*D2
3	Pipe fittings	100	1	2	200	= B3*C3*D3
4	Jet pump to pressurize water	300	1		300	= B4*C4
				Total	**920**	= SUM(E2:E4)
	Each additional toilets					
5	Purple tubing (100 ft), $	70	1		70	= B5*C5
6	Pipe fittings	10	1		10	= B6*C6
				Total	**80**	= SUM(E5:E6)

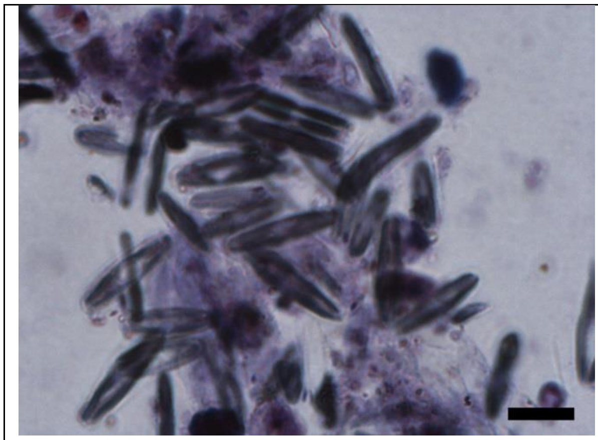
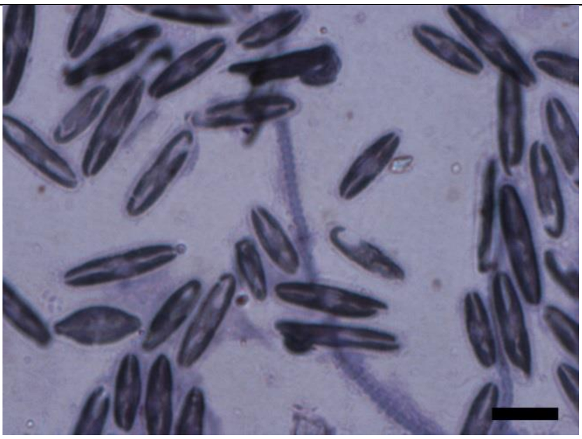
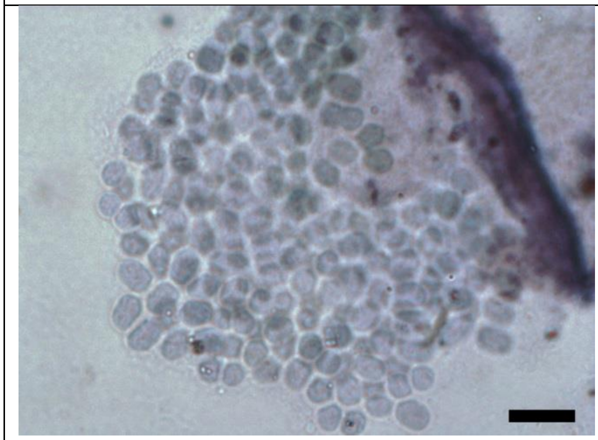
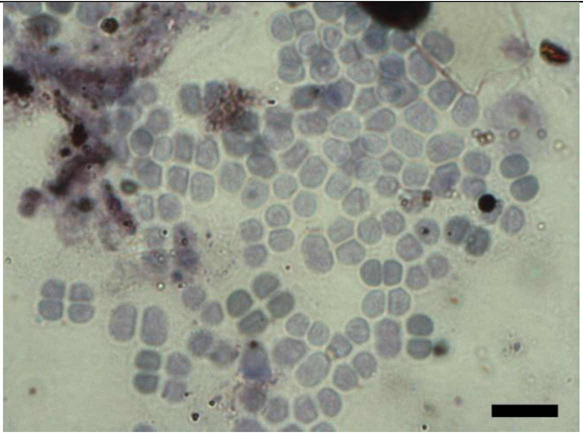
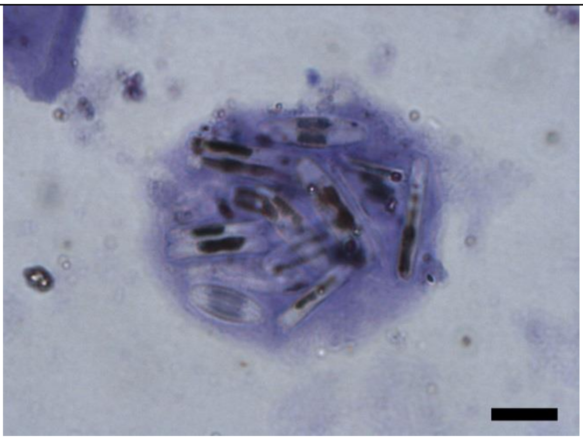
Note: All component unit prices were obtained online from homedepot.com. The component types and quantities, and lump sum pipe fitting cost estimates presented above were developed on a best reasonable estimate basis for the purpose of the economic study presented in Chapter 6. The component types and quantity, and lump sum pipe fitting cost needed in a real situation can vary significantly depending on the site situation.

Appendix 8 Biofilm images

This appendix provides additional biofilm images of representation sampled from the SB-VFW system during the treatment of graywater containing bio-based laundry (BBL) detergent (**Table 1**) and non-bio-based laundry (non-BBL) detergent (**Table 2**). The sampling procedure and additional images are presented in **Chapter 5**. The images below show that microorganisms in the treatment system after treatment of BBL and non-BBL were predominantly protozoa and algae.

Table 38 Microscopic images of biofilm collected from the plastic media when the treatment system was treating non-BBL graywater. Scale bars are 10 µm.

 Diatoms and two strings of algae	 A cluster of algae and diatoms
 Diatoms aligned in parallel	 Diatoms, algae

 A cluster of diatoms	 A cluster of diatoms and a chain of algae
 A cluster of diatoms	 A cluster of diatoms
 Diatoms	 A cluster of diatoms

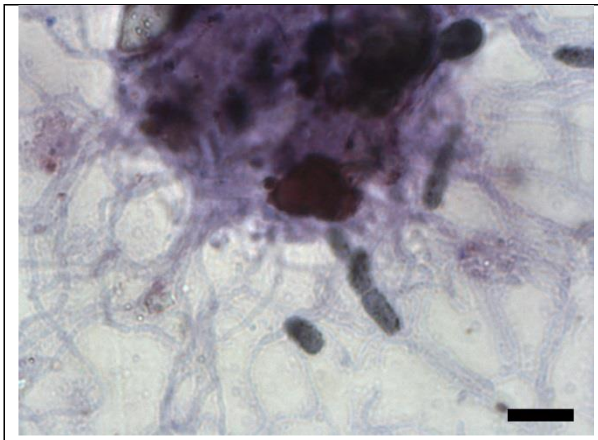
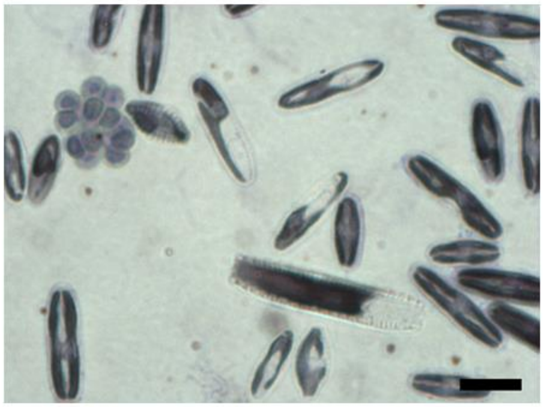
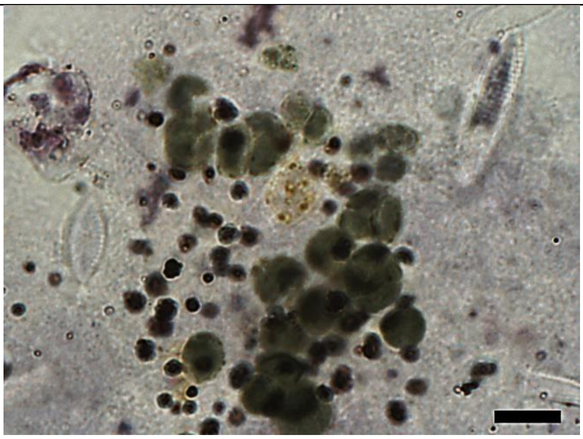
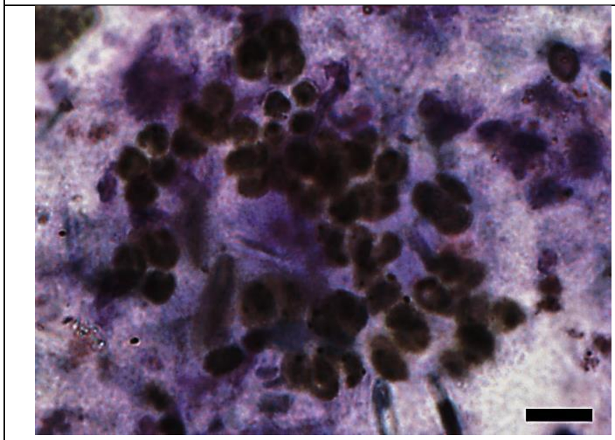
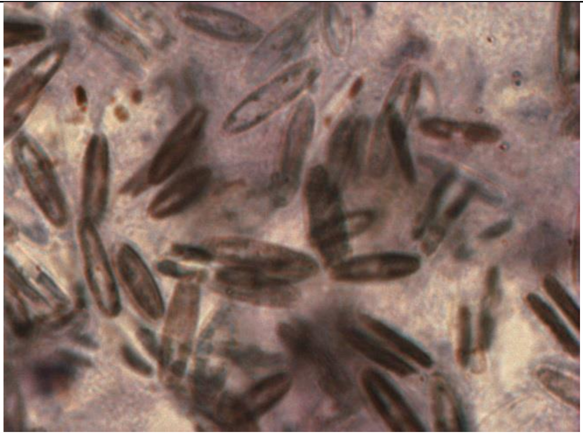
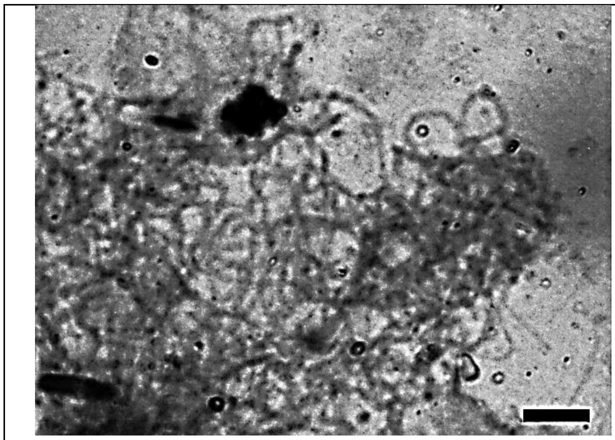
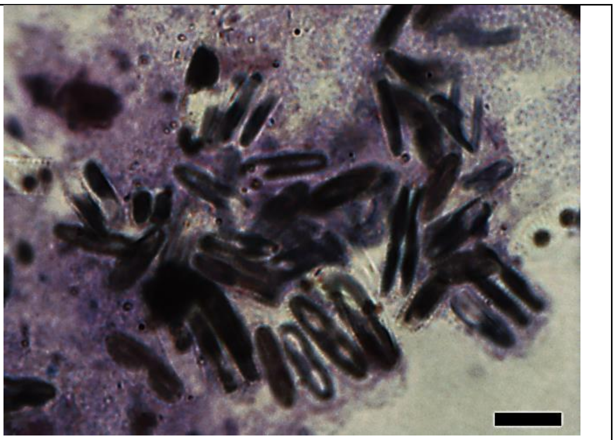
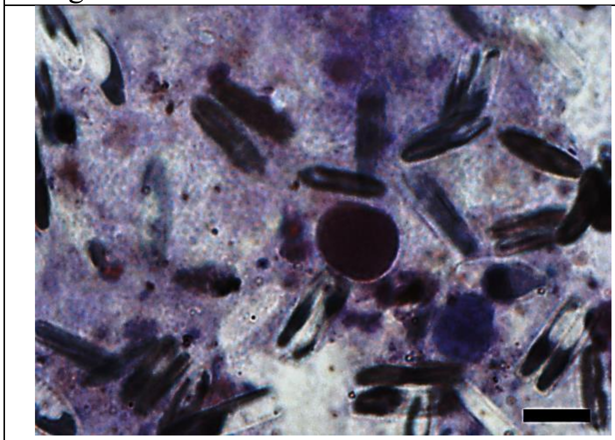
 Fungi	 Diatoms

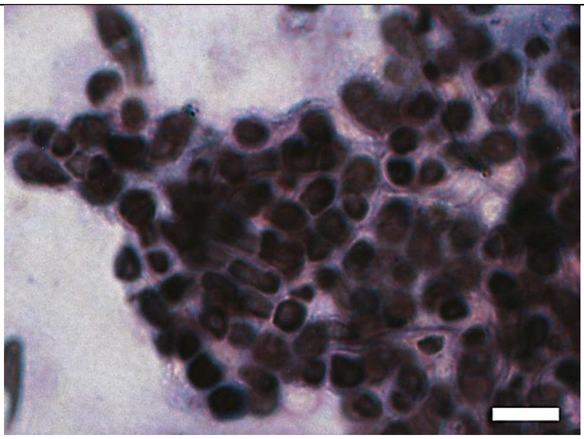
Table 39 Microscopic images of biofilm collected from the plastic media when the treatment system was treating non-BBL graywater. Scale bars represent 10 µm.

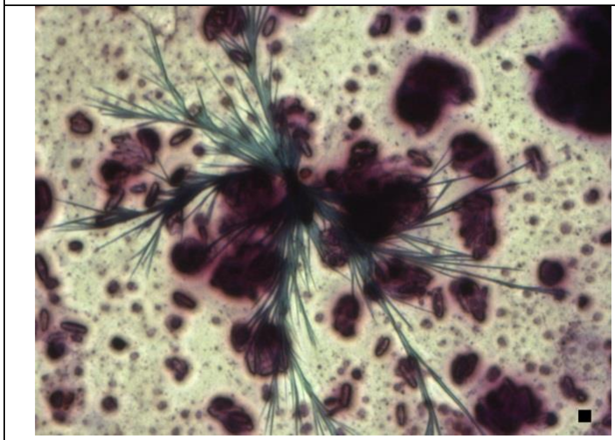
 A cluster of soil diatoms	 A cluster of diatoms and algae
 A cluster of algae and protozoa	 Diatoms

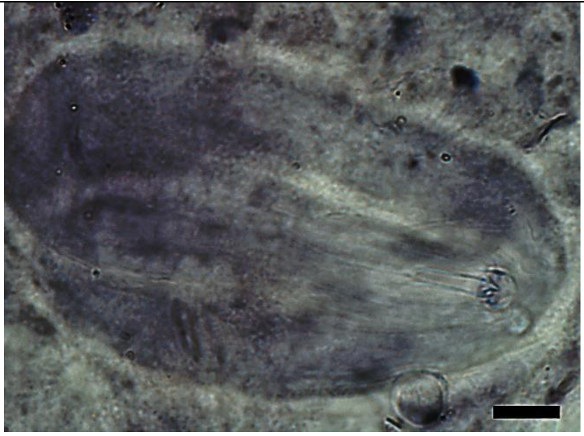

Fungi

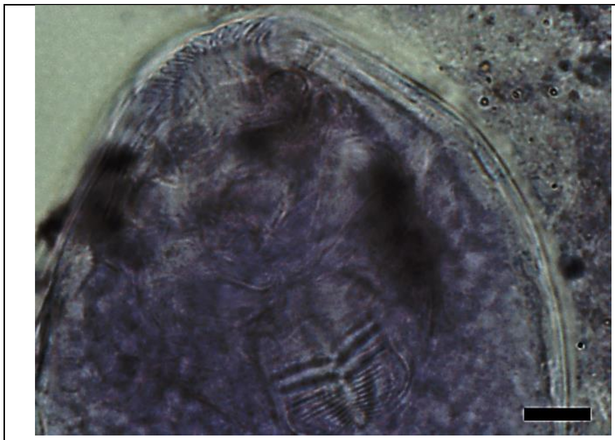
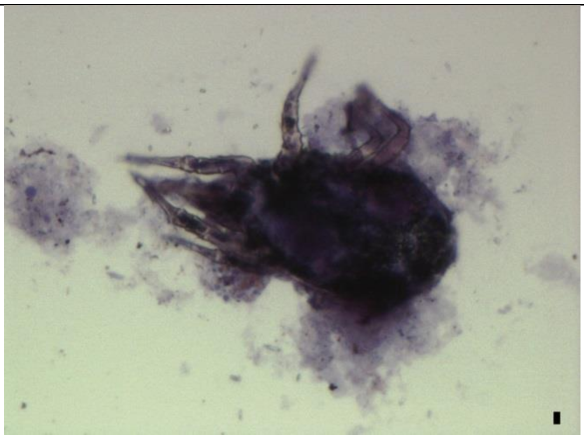
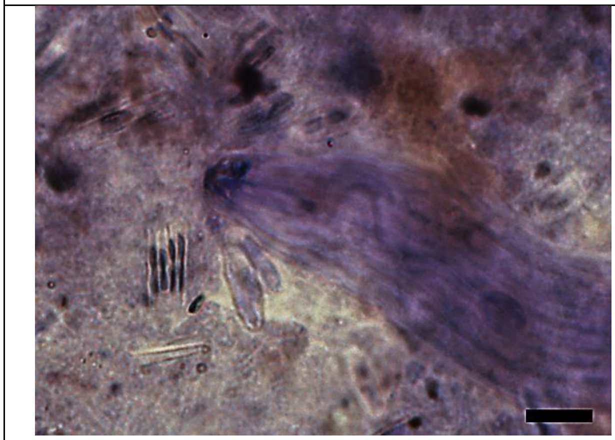

A cluster of diatoms


Diatoms


A cluster of algae


A plant surrounded by a cluster of diatoms


Larval or embryonic round Nematode

 Nematode	 An insect
 Nematode and other microorganisms	 Nematode

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