

An Evaluation of Graywater Reuse Utilizing a Constructed Wetland Treatment System

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ABSTRACT

Increasing demand for conservation of water resources has prompted the notion that the separation of graywater (all wastewater not including toilet and kitchen sources) from sewer effluents through the use of dual-plumbed systems may enable graywater to be reused. Constructed wetland systems for conditioning combined wastewater effluents are widely used, and offer an efficient solution for onsite wastewater treatment of a variety of pollutants. However, limited long-term research has been conducted to determine the effectiveness of such systems specifically on graywater. This paper aims to determine the viability and efficiency of constructed wetlands for graywater treatment, and assess the water quality produced from such systems. The experimental method involves monitoring of specific water quality constituents under varying operating conditions in a prototype constructed graywater wetland. Preliminary findings show the wetland significantly reduces many graywater contaminants including pathogens, biochemical oxygen demands, solids, and nitrogen and phosphorus species.

INTRODUCTION

Conventional wastewater management practices collect all used indoor water into a single pipe leading to the sewer and treat it at a wastewater treatment plant. Mounting pressure to conserve water supplies, however, has led to the suggestion that the separation of wastewater at its source may enable graywater to be reused for such non-potable uses as landscape irrigation and toilet flushing.

Graywater Quantity and Quality Characterization

A general definition of graywater is any residential wastewater which has not come in contact with toilet water. This definition is restricted in the United States where graywater is defined as wastewater not originating from toilets, kitchen sinks, or dishwashers, and that is produced in showers, bathtubs, sinks, and clothes washers (Roesner et al., 2006).

An American Water Works Association (AWWA) sponsored study of water usage in 14 North American cities found that on average over 50% of all residential indoor water demands generate graywater (Mayer et al., 1999). This same study showed that outdoor irrigation constituted the largest of all total residential potable water demands, and that while highly variable depending on geographical location, on average over 50% of all residential potable water is used for landscape irrigation. Considering this large demand and the fact that the source water for outdoor irrigation water need not be of the same quality as indoor potable water, reusing graywater for outdoor irrigation offers a substantial and attractive water savings. In addition to landscape irrigation, recycled graywater is a potential source for other demands not requiring potable source water such as toilet flushing.

Graywater recycling in Europe and Australia is gaining in popularity; however, in the U.S. the practice is not yet commonplace. The degree to which graywater reuse can reduce household potable water demand is variable depending on geographical location, landscaping preferences, and personal water use habits. Rose, 1991; Karpiscak, 1990; and the City of Los Angeles, 1992 among others have estimated that reusing graywater for outdoor irrigation and toilet flushing could reduce household water demand by 25 – 50%.

The chemical, physical, and microbial qualities of graywater are highly variable depending on the source, and are influenced by many factors including the number of household occupants, types of cleaners and personal care products used, grooming and hygiene habits, and sink waste disposal practices (Eriksson et al., 2002). Concentration ranges for common water quality constituents and pathogen indicators compiled from three studies are listed in Table 1.

Constructed Wetlands

Constructed wetlands are treatment systems that replicate natural wetlands to improve water quality through physical, chemical, and biological treatment mechanisms (Kadlec and Knight, 1996), and are commonly employed to treat municipal wastewater (Metcalf and Eddy, 2003; U.S. Environmental Protection Agency (USEPA), 1999; Hammer, 1989). Not only can constructed wetlands provide important water quality improvements with low energy and maintenance requirements, they can also offer pleasing aesthetics, ecological benefits, and wildlife habitat (USEPA, 1999).

While treatment wetlands have been shown to effectively treat whole wastewater, their effectiveness in treating graywater has had limited research, especially in the United States. However, past studies involving graywater wetland treatment have shown promising pollution removal efficiencies (Dallas, 2004; Gross, 2007; Frazer-Williams, 2005).

Constructed wetlands can take on various designs, with two of the most common being the free water surface (FWS) and the subsurface flow (SF) wetland. FWS wetlands closely resemble natural wetlands in both appearance and function, and

feature elements typical of a natural wetland such as emerging vegetation and open-water areas (USEPA, 1999). SF wetlands, on the other hand, resemble natural wetlands very little, but instead contain a bed of media such as gravel or sand in which aquatic plants are rooted. Water passes through the media and root zone, but is not exposed to the surface, and is therefore not visible or accessible by humans or wildlife.

Table 1: Graywater quality characterization

Reference	Eriksson et al., 2003	Rose et al., 1991	Casanova et al., 2001
Source	Composite, Range	Composite, Mean	Composite, Mean
pH	7.6 - 8.6	6.54	7.47
BOD ₅ , mg/L	26 - 130		64.85
Total Suspended Solids, mg/L	4 - 207		35.09
Turbidity, NTU		76.3	43
Ammonia, mg/L	0.02 - 0.42	0.74	
Nitrate, mg/L	<0.02 - 0.26	0.98	
Total Nitrogen, mg/L	3.6 - 6.4	1.7	
Orthophosphate, mg/L		9.3	
Total Phosphorus, mg/L	0.28 - 0.779		
Sulfate, mg/L		22.9	59.59
Chloride, mg/L		9	20.54
Alkalinity, mg/L		158	
Total Coliform, CFU/100mL	6.0×10^3 - 3.2×10^5	2.8×10^7	8.03×10^7
Fecal Coliform, CFU/100mL		1.82×10^4 - 7.94×10^6	5.63×10^5
<i>E. Coli</i> , CFU/100mL	<100 - 2800		

MATERIALS AND METHODS

Wetland Design

To evaluate the potential of graywater wetland treatment, a prototype graywater wetland and two dual-plumbed facilities were constructed at Colorado State University. The graywater wetland is a tandem wetland system consisting of a FWS wetland cell followed SF wetland cell. The combination of both a FWS and a SF wetland type was designed to enhance water contaminant removal, and to allow for each wetland type to be evaluated individually. Out of initial public safety concerns, effluent from the prototype system is currently routed to a sanitary sewer; however, future plans call for the effluent to be reused for non-potable demands.

FWS and SF wetland cells are arranged in series with the FWS being upstream of the SF (Figure 1) so that the FWS provides the bulk area for sediment settling and prevents clogging of the gravel matrix in the SF. Also, since the FWS is exposed to the atmosphere and the SF is not, having the FWS upstream of the SF also allows an aerobic/anaerobic flow progression. The wetland includes flow distributing and collection headers to prevent flow short circuiting, diversion berms to prevent surface water runoff intrusion, and impermeable liners to restrict groundwater flux.

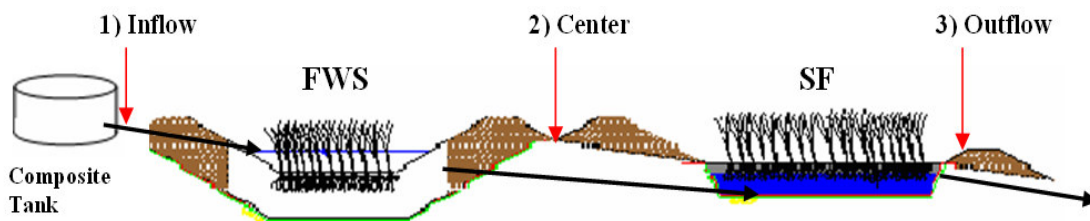


Figure 1: Graywater wetland schematic and sampling locations.

Graywater is provided to the wetland system from several of sources: lavatory sink water from a dual-plumbed office/laboratory facility, lavatory sink and shower water from a residential dormitory, and whole graywater (all wastewater except toilet and kitchen sources) from a single-family residence. Graywater from the office/laboratory facility is piped directly to the wetland. Graywater from the dormitory and residence is collected in batches onsite and hauled to the wetland where it is dispensed via metering pump. Hauling graywater proved necessary since the office/laboratory facility is not yet fully occupied and does not produce the flow rate of graywater desired. Hauled graywater is mixed with the graywater stream from the office/laboratory building before flowing to the wetland. A storage tank is provided just upstream of the wetland inlet, which is sized to collect approximately one day's flow volume, and it thus used to collect a daily composite of inflow.

Common Cattails (*Typha latifolia*) are planted in the FWS cell, and have been established since September, 2007. The SF is planted with Hardstem Bulrush (*Scirpus acutus*), which have been established since June, 2008.

Flow and Water Quality Monitoring

Flow and water quality measurements are made at three locations (Figure 1): the inflow to the FWS at the composite tank (Site 1; raw graywater influent), between the FWS and SF (Site 2; center; FWS effluent/SF influent), and the outflow of the SF (Site 3; system effluent). Site 1 is taken from the composite tank, and represents a daily composite. Sites 2 and 3 are located in manholes and are not composited.

Flow meters are located at each sampling site. The flow metering system features a dosing vessel that collects inflowing water until it is full, at which time a pump is activated which pumps the water through an inline, turbine flow meter. This design is necessary to accommodate the low flows produced by the office/laboratory building (down to 19 L/day), while being capable of handling large flow events (as in the case of heavy precipitation entering the wetland) with high solids concentrations. No data

recording hardware is used; instead, readings of the cumulative flow at each location are collected manually, and the flow computed as the difference in cumulative flows from two sequential readings divided by the time between readings. A counter switch is provided to count the number of times the dosing vessel fills and empties, which can be used in redundancy to compute flow.

Sampling was conducted starting in September, 2008. Sampling commenced weekly for four weeks, after which samples were collected every three weeks. Water quality measurements evaluated the physical, chemical, and biological composition of the raw and treated graywater (Table 2), and included measurements of the solids, carbon, nitrogen, phosphorus, and pathogen indicator content of the water. These measurements were chosen to evaluate the wetlands' treatment efficiency in removing such constituents, as well as determine the quality of the effluent produced from the system. In addition to the measurements listed in Table 2 other water quality measurements have been commenced to test for different pathogenic indicator species and trace organics. Standard analytical methods (Eaton et al., 1998) were used for all analyses, and quality assurance samples (blanks, duplicate analyses, and standards) were analyzed at a rate of 10%.

Table 2: Water quality measurements and analytical methods used to determine the treatment performance of the graywater wetland system.

Parameter	Analytical Method	Standard Method #
Ammonia	Ion Selective Electrode	4500-NH ₃ D
5-day Biochemical Oxygen Demand (BOD ₅)	5-day; Dissolved Oxygen Probe	5210 B
Dissolved Oxygen (DO)	Membrane Electrode	4500-O G
<i>E. Coli</i>	Enzyme Substrate	9223 B
Nitrate	Ion Chromatography	4110 B
Orthophosphate	Ion Chromatography	4110 B
pH	Potentiometric Probe	4500-H ⁺ B
Specific Conductivity	Electrical Conductivity	2510 B
Temperature	Thermometer	2550 B
Total Dissolved Solids (TDS)	Gravimetric, Dried at 103-105 C	2540 C
Total Nitrogen (TN)	UV Persulfate Digestion and Oxidation w/ Flow Injection	4500-N B
Total Organic Carbon (TOC)	Heater-Persulfate Oxidation	5310 C
Total Phosphorus (TP)	Colorimetric; Persulfate Digestion	4500-P H
Total Suspended Solids (TSS)	Gravimetric, Dried at 103-105 C	2540 D
Turbidity	Nephelometric	2130 B

RESULTS

Flow Monitoring

During the sampling period, graywater inflow to the wetland system averaged 318 L/day (Site 1, Figure 2). This inflow rate is averaged over two distinct periods. Prior to December 11, 2008 hauled graywater was collected from the dormitory and the average flow rate of inflow was 346 L/day. After December 11, the dormitory was unoccupied, graywater was collected from the single family residence, and the inflow averaged 154 L/day. For the entire monitoring period, flow between the FWS and SF wetlands (Site 2) averaged 282 L/day, and the system outflow (Site 3) averaged 245 L/day. Differences in flow rates between monitoring stations result from precipitation additions and losses attributed to seepage over the wetlands' liners and evapotranspiration. Losses diminished as weather cooled and the vegetation became dormant.

Wetland volumes were used to compute the hydraulic residence times (HRTs) in each wetland cell. The FWS volume was estimated at 2.0 m³, assuming a porosity of 0.8 for the established cattails. SF volume was 2.9 m³ assuming a porosity of 0.3 for the gravel and plant root matrix. Using these volumes and the average flows previously given, an average HRT of 6.3 days and 10.3 days were computed for the FWS and SF cells respectively over the entire monitoring period.

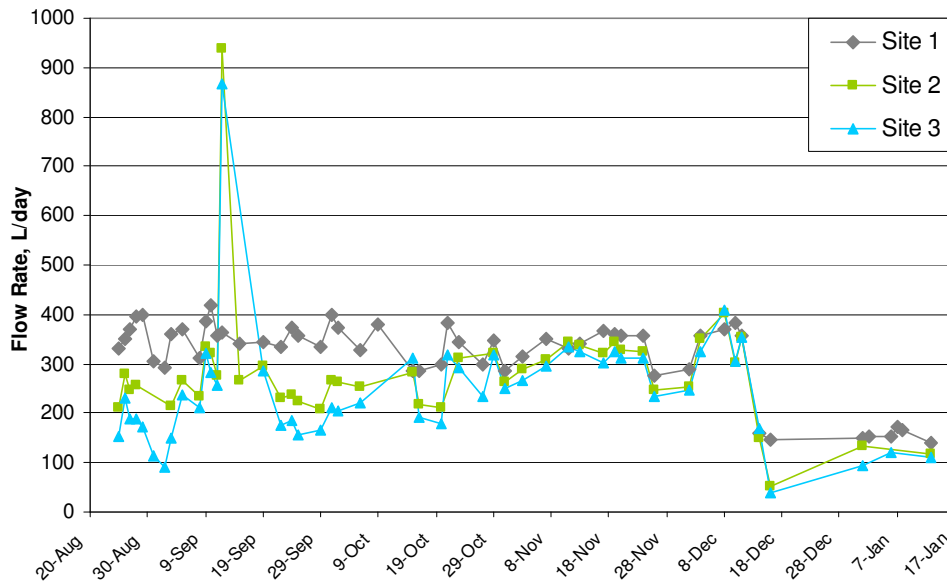
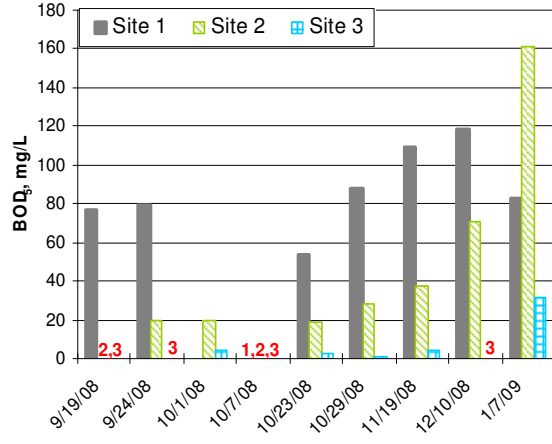
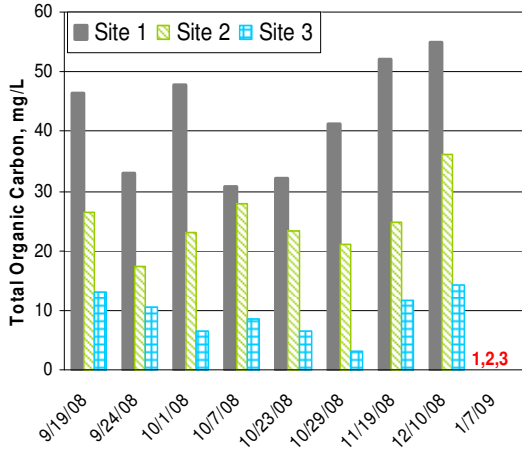


Figure 2: Flow rates measured at the graywater wetland system. The large flow rate increase at Sites 2 and 3 on 9/12/08 results from a precipitation event.

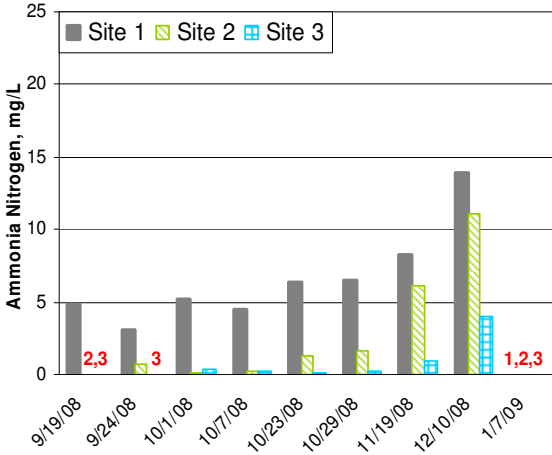
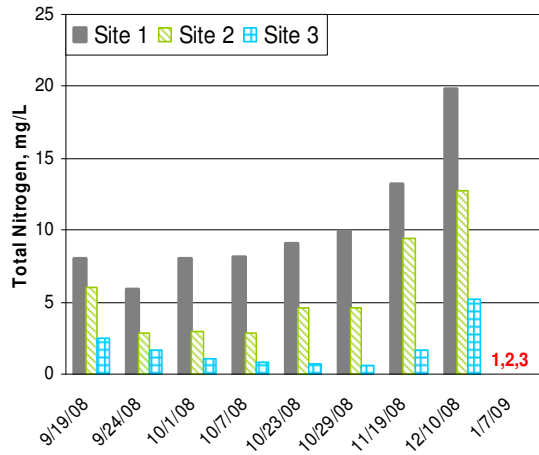
Water Quality Monitoring

Nine water quality sampling events were conducted over the monitoring period. All sampling sites were monitored during each sampling event except the first two; to allow for steady state conditions, Sites 2 and 3 were omitted from the first sampling event and Site 3 was omitted from the second event. Selected water quality measurements are presented subsequently (Figure 3 and 4; Table 3).



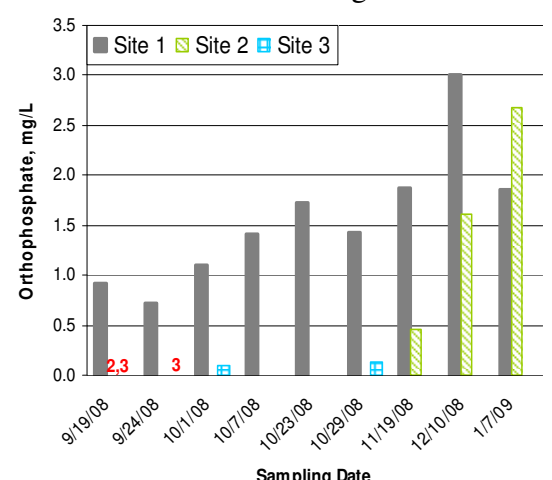
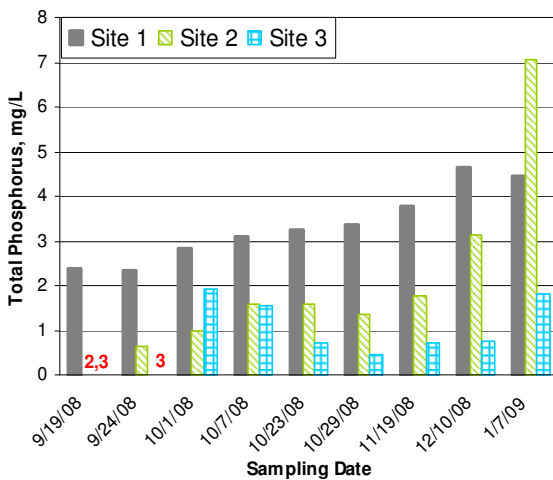
Total Organic Carbon

BOD₅



Total Nitrogen

Ammonia Nitrogen



Total Phosphorus

Orthophosphate

Figure 3: Average concentrations of carbon, nitrogen, and phosphorus water quality constituents at three sampling locations in the graywater wetland taken over nine sampling events. Numbers in red represent erred or omitted measurements.

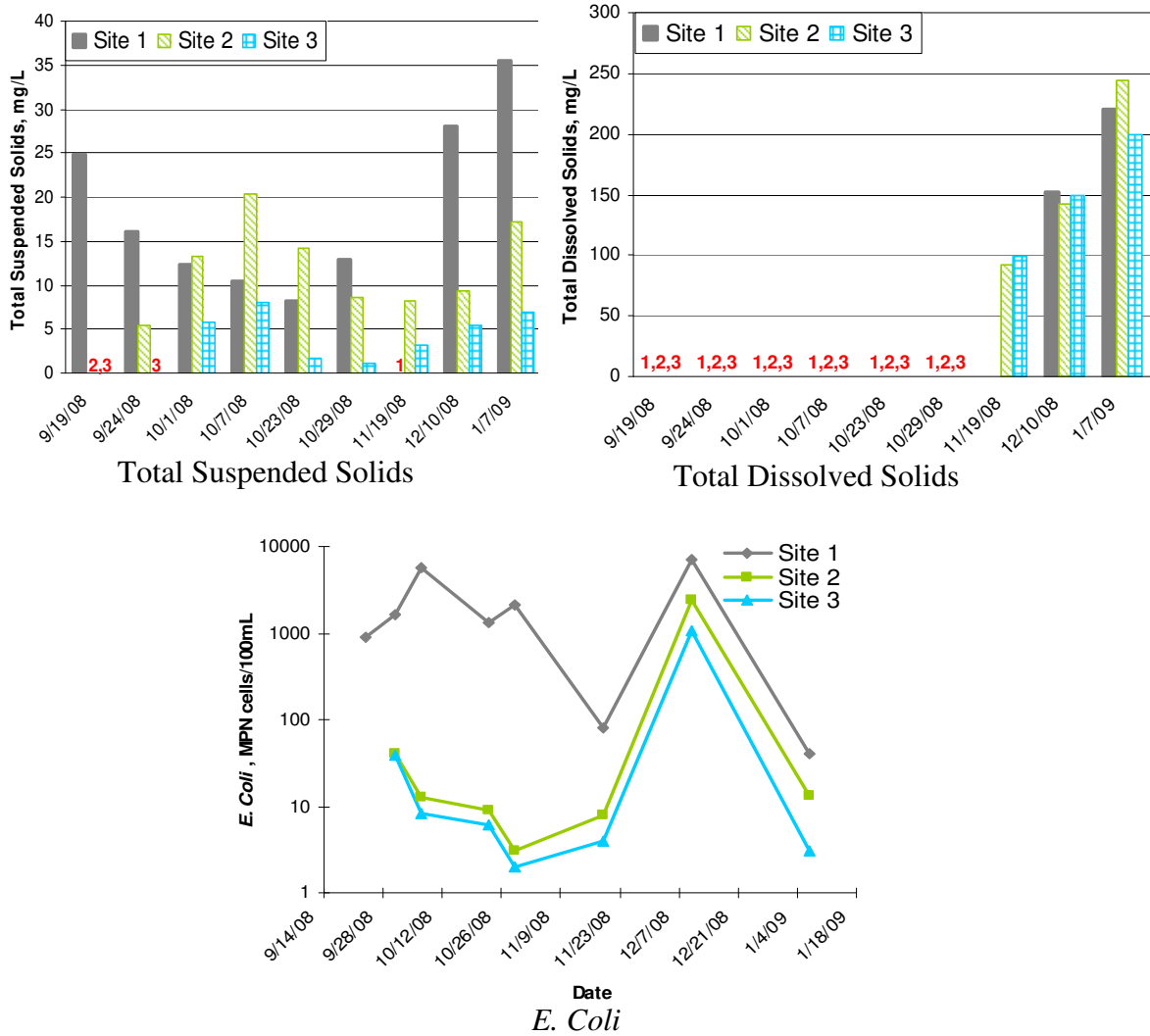


Figure 4: Average values of solids and pathogen indicator measurements at three monitoring locations in the graywater wetland. Red numbers represent erred or omitted measurements.

Table 3: Field measurements taken at graywater wetland.

		Site 1	Site 2	Site 3
Dissolved Oxygen, mg/L	Range	0.02 - 0.17	0.89 - 5.46	0.82 - 2.96
	Mean	0.11	2.65	2.18
pH	Range	6.0 - 6.7	6.3 - 6.9	6.3 - 6.8
	Mean	6.3	6.7	6.5
Specific Conductivity, uS/cm	Range	197 - 348	235 - 409	256 - 404
	Mean	232	276	299
Turbidity, NTU	Range	8.1 - 58.2	5.6 - 46.0	1.5 - 18.5
	Mean	27.4	17.7	7.9

Removal efficiencies were computed for each wetland cell and for the total system (Table 4), and were calculated from the average concentration values for all sampling events. Pathogen levels were shown to decrease approximately 0.8 and 0.4 orders of magnitude on average through the FWS and SF wetlands respectively. Removal efficiencies for all constituents were generally greatest in the FWS.

Table 4: Average removal efficiencies of various constituents in the graywater wetland. Values presented exclude the January 7, 2009 sampling event.

	FWS	SF	Total
BOD ₅	63%	33%	96%
TOC	41%	37%	78%
TN	44%	39%	83%
TP	50%	18%	68%
Turbidity	42%	31%	73%
TSS	30%	44%	74%
<i>E. coli</i>	85%	9%	93%

DISCUSSION

As determined from repeat water quality analysis in the prototype wetland, treatment of graywater via constructed wetlands demonstrates great potential. Effluent water has shown to be of the quality suitable for reuse, as in the case of *E. coli* levels, which were shown to be below recommended single-sample levels for primary contact waters according to USEPA, 1986 for all but one sample. It should be noted that the one sample out of compliance was taken while significant ice had formed on the wetlands, greatly reducing the wetland's HRT. This problem is only expected in the winter when graywater reuse for irrigation is not needed.

Water quality monitoring is expected to continue through 2009, which should shed light on the long-term performance of the graywater wetland. Expanded water quality analysis, including those of additional pathogenic indicators and trace organics will further evaluate the graywater wetland's treatment potential.

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