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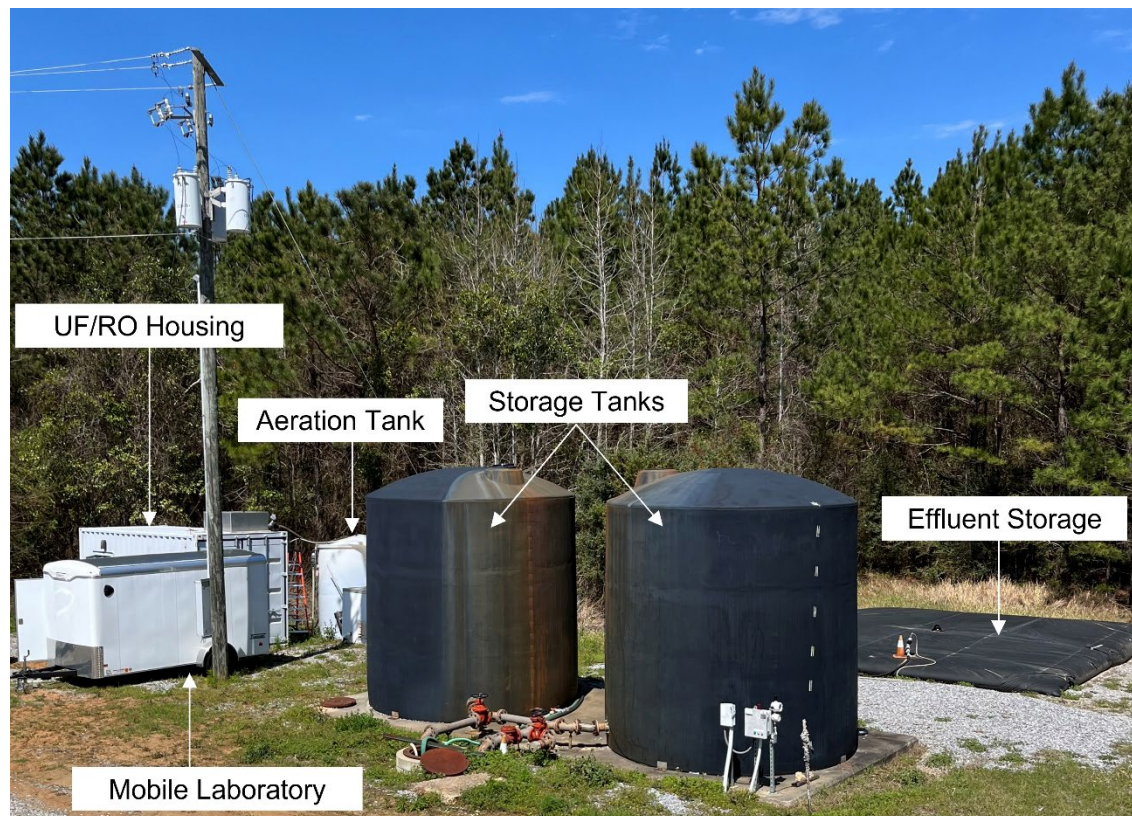
Environmental Security Technology Certification Program (ESTCP)

Employing Ultrafiltration and Reverse Osmosis (UF/RO) for Treatment of Source-Separated Graywater

ER-201636

Chris S. Griggs, Scott A. Waisner, Jacob Lalley, Sarah Grace Zetterholm, Sheila McLeod, Edith Martinez-Guerra, Max Wamsley, Luke A. Gurtowski, Susan Bailey, Roy Wade, and Steve Pranger

April 2024



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Abstract

In field operating environments, military units must ensure access to a critical water supply to maintain mission readiness. Increasing complexity of logistics and costs to transport water and climate change are driving the development and demonstration of water treatment units. The treatment unit described uses ultrafiltration (UF) and reverse osmosis (RO) membrane technologies with a disinfection step to treat low-strength graywater from shower facilities at Camp Shelby Joint Force Training Center in Hattiesburg, Mississippi. Samples were collected from human shower sampling events. During the demonstration, greater than 100,000 gal. of graywater were treated, supplied by two battalion training rotations over a 6-month period. Characterization of the source graywater continued throughout the system demonstration.

Based on the literature, these are among the largest source-separated graywater sampling events to date. The combined treatment train of UF/RO met all compliance metrics for all analytes of interest for potability and met nonpotable metrics except for special use cases in three states. Both the quality of the treated water and the effective volume gains from an 85% multiplier effect directly support DoD water sustainment goals for both installations and operational environments.

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Preface

This study was conducted for the Environmental Security Technology Certification Program (ESTCP) under ER-201632, “Distributed System for Efficient Recovery of Wastewater.”

The work was performed by the Environmental Engineering Branch of the Environmental Processes and Engineering Division, US Army Engineer Research and Development Center, Environmental Laboratory (ERDC-EL). At the time of publication, Dr. Michael Rowland was chief, and Mr. Warren Lorentz was chief. The deputy director of ERDC-EL was Dr. Brandon J. Lafferty and the director was Dr. Edmond J. Russo Jr.

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COL Christian Patterson was the commander of ERDC, and Dr. David W. Pittman was the director.

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1 Introduction

1.1 Background

Viable water resources are gradually becoming scarcer throughout our planet. Up to 37% of the world's population will be living in water-scarce countries by the year 2025 (Boyjoo et al. 2013). Optimization of these resources is crucial to balance society's water needs with emergent climate change factors and increases in population and urbanization. While large-scale solutions could potentially relieve some of the water demand, reuse and recycling of regularly consumed water resources of significant volumes appears to be the most suitable alternative to help shorten and close the water cycle. Consumed water reenters the water cycle after undergoing treatment in a wastewater treatment plant (WWTP). A majority of the WWTP influent is graywater, a characteristically less polluted and less demanding type of wastewater for in situ recycling (Ramon et al. 2004). Graywater includes all domestic wastewater except toilet wastewater (blackwater). Graywater is classified as either high strength (kitchen and laundry) or low strength (bath, shower, and washbasins). Low-strength graywater is commonly referred to as light graywater. When light graywater has kitchen or laundry water introduced to it, it becomes a higher-strength graywater that is referred to as dark graywater. Light graywater possesses physical and chemical contaminants but shows lower organic matter and thermotolerant coliforms (De Gisi et al. 2016).

Graywater reuse regulations and contaminant concentrations are considered when determining best treatment technology options. Technologies for treating these contaminants include physical, chemical, biological, and natural treatment systems with disinfection stages added for pathogen removal. Graywater treatment and reuse are normally regulated by local entities. There is growing demand for research and regulatory action that supports the potential for safe graywater reuse.

1.1.1 Graywater Characteristics

Currently there is still a significant data gap regarding the composition of different types of graywater, making it difficult to evaluate its potential applications for reuse and the required treatment technology. There is evident variability among the characteristics of graywater sources reported in the literature. Overall graywater has some similar constituents to those of domestic wastewater; however, the nutrient concentrations are typically

much lower (Sievers et al. 2016). Because graywater makes up around 50%–80% of all domestic wastewater depending on location (Etchepare and van der Hoek 2015; Maimon et al. 2010), researchers are searching for ways to purify and reuse this potential water source. Utilizing graywater for select purposes can reduce consumption of environmental water sources and the amount of wastewater discharged to the environment.

Although it is commonly used for irrigation of plants, graywater could be collected and repurified for use as a freshwater source, which could significantly decrease the cost and consumption of fresh water. Some of the known characteristics of graywater are similar to those of raw wastewater (Hrudey and Raniga 1983), including temperature, turbidity, suspended solids, chemical oxygen demand (COD), biochemical oxygen demand (BOD), total organic carbon (TOC), pH, nutrients, heavy metals, bacteria, protozoa, helminths, and viruses (Etchepare and van der Hoek 2015). However, laundry and kitchen water can have high concentrations of microbial contaminants, oil and grease, foodborne pathogens, and opportunistic pathogens. Therefore, there can be a lot of variability in graywater chemistry depending on the initial usage. Table 1 shows characteristics of graywater based on usage in individual homes (note: CFU is colony-forming unit).

Table 1. Graywater characteristics by usage in individual homes (Li et al. 2009).*

Graywater Source	pH	BOD (mg/L)	COD (mg/L)	Total Coliforms (CFU/ 100 mL)	Fecal Coliforms (CFU/ 100 mL)	<i>E. coli</i> (CFU/ 100 mL)
Bathroom	6.4–8.1	50–300	100–633	10–2.4E+07	0–3.4E+05	82.7
Laundry	7.1–10	48–472	231–2,950	200.5–7E+05	50–1.4E+03	—
Kitchen	5.9–7.4	536–1,460	26–2,050	>2.4E+08	—	200
Mixed	6.3–8.1	47–466	100–700	56–8.0E+07	0.1–1.5E+08	—

Typically, 24–32 gal./day/person (gpd/p) of graywater are produced; however, the composition and usage of graywater is very dependent on lifestyle and location (Li et al. 2009). There is wide variation in graywater composition by country and level of economic development. Low-income homes can produce as low as 4 gpd/p, and some parts of Asia produce upwards of 86 gpd/p (Oteng-Peprah et al. 2018). According to US

* For a full list of the spelled-out forms of the units of measure used in this document and their conversions, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office, 2016), 248–52 and 345–47, <https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf>.

Environmental Protection Agency (US EPA) WaterSense standards (US EPA 2024), an average user showers for 8.2–10.4 min with a flow of 2 gal./min, contributing 16–21 gal. per shower, which represents approximately 17% of annual residential indoor water use in the United States. This translates into more than 1.2 trillion gal. of water consumed with a shower duration and volume that has remained constant since 1999. Therefore, source-separated shower water represents a large and predictable volume of water source.

1.1.2 Biological Contaminants in Graywater

Common contaminants found in bathtub and shower wastewater include hair, bacteria, solids from skin, oil and grease, soap, and detergent residue. However, this type of graywater contains low concentrations of BOD, nitrogen, and phosphorus and is considered the cleanest source of graywater (Bodnar et al. 2014; Oron et al. 2014). Although it is the cleanest stream, the concentrations of coliforms can exceed 1×10^7 CFU/100 mL (De Gisi et al. 2016). One of the biggest problems in the reuse of graywater, especially in dark graywater, is the presence of pathogenic organisms (Etchepare and van der Hoek 2015). The treatment of graywater into a drinkable water source is difficult due to the large variety of physical, chemical, and biological contaminants. Biological contamination of water is a major concern due to its acute hazard to human health. Biological contaminants include bacteria, viruses, and protozoa. Most of the bacteria listed are indicators of fecal contamination, which can result in food poisoning, necrosis, and various types of infections. Fecal coliforms, *E. coli*, and enterococci have been shown to proliferate in graywater (Zapater et al. 2011). Similarly, protozoa present in graywater can negatively affect human health. Viruses can also result in stomach problems; respiratory illnesses; malaise; and hand, foot, and mouth disease.

Several studies on the investigation of different bacteria and pathogens in untreated graywater have been completed. A quantitative microbial risk assessment (QMRA) model was used in Australia (Barker et al. 2013) to estimate the norovirus disease burden associated with consumption of graywater-irrigated lettuce, indicating that limiting the use of untreated graywater to light graywater could reduce annual disease burden by up to 1,000-fold. Shi et al. (2018) also conducted a QMRA to estimate public health risks for graywater reuse, and it was concluded that treated bathroom graywater can be safely reused for toilet flushing and food-crop irrigation within US EPA annual infection benchmark ($\leq 10^{-4}$ person/year).

The hazard of using untreated graywater for toilet flushing is that graywater aerosols are produced after a single toilet flushing. These aerosols can be inhaled by humans, which brings in harmful constituents (Lim et al. 2015). These problematic microorganisms can be removed or inactivated if the appropriate treatment is used. According to Benami et al. (2016), chlorine is the option of choice due to its polymicrobial and residual disinfection capabilities. March et al. (2004) published the first study in which treated graywater was successfully used for toilet flushing in a hotel. The treatment system was based on sedimentation, filtration, and disinfection using hypochlorite injected in two stages. It also recommended the filtration and chlorination of bathroom graywater if the effluent will be used for toilet flushing.

Probably the main pathway for microorganisms to affect public health is via food ingestion. With toilet flushing and irrigation being the common uses of recycled graywater, crops can be contaminated during irrigation. Farmers and consumers can be affected through the spreading of diseases, such as cholera and typhoid (Tauxe et al. 2002). For example, Jackson et al. (2009) found significant concentrations of staphylococcus externally on vegetables that were irrigated with graywater, which is not an unexpected result after several studies reporting high numbers of traditional fecal indicators in graywater. Gorgich et al. (2020) detected fecal coliform in small quantities in lettuce leaves and on the surface of carrots. However, it is recognized that *E. coli* is not an ideal indicator organism for pathogens because the coliform group is susceptible to regrowth. Ottoson and Stenstrom (2003) suggested that guidelines for graywater recirculation and reuse should not be based on thermotolerant coliforms as a hygienic parameter because of the large input of nonfecal coliforms and/or regrowth of coliforms.

According to O'Toole et al. (2012), most of these studies are focusing on fecal indicators and only a few selected pathogens have been targeted, which may not be a good predictor of human health risks. Because of this concern, researchers have investigated the characterization of bacterial composition from various points throughout a graywater recycling system using high throughput metagenomic profiling techniques to identify microbial compositions of these graywater sources. This investigation concluded that a relatively consistent set of genera associated with skin are the dominant human-associated bacteria in graywater. The study showed that shower graywater contained distinct genera common to wastewater

infrastructure. The abundance and relative stability of these infrastructure-associated organisms make them good candidates to be used as endogenous markers of treatment process efficacy.

1.1.3 Chemical Contaminants in Graywater

In addition to common chemical contaminants present in graywater (e.g., BOD, COD, organics, and nutrients), sink and shower source-separated graywater can also contain micropollutants coming from personal care and pharmaceutical products; for example, ethylhexyl methoxycinnamate from UV-filter/sunscreen, triclosan from toothpaste, and surfactants from shampoo. Although triclosan in combination with sodium fluoride was approved by the Food and Drug Administration to aid in the prevention of caries, plaque, and gingivitis, toothpaste containing triclosan is no longer commercially available. Parabens are common preservatives used in personal care products and pharmaceuticals and are of great interest due to their estrogenic potency (Andersen et al. 2007). They have been found to be linked to an increased risk of breast cancer and reproductive toxicity. People who wear makeup everyday have been found to have 20 times the levels of propylparaben in their urine when compared to those who do not wear makeup (Berger 2018). Parabens in graywater also come from moisturizers, deodorants, shaving gels, toothpastes, and skin cleansers (Stoiber 2019). Other contaminants to consider during graywater testing are phthalates. Like parabens, phthalates have estrogenic potency and are linked to endocrine disruption. They are industrial plasticizers commonly used in hairsprays, soaps, shampoos, and perfumes.

1.2 Objective

The objective of this study is to investigate the implementation of a physical treatment system coupled with a disinfection step to treat graywater with low organic matter content, often associated with shower water. Source-separated sink and shower water collected from two training events at Camp Shelby Joint Forces Training Center (CSJFTC) south of Hattiesburg, Mississippi, was treated using a physical treatment system design based on the feed water source characteristics. The results demonstrate the treatment efficiency of a physical treatment system of light graywater. This demonstration was conducted to fill data gaps and provide scientifically sound options for adoption of treatment systems for reuse of treated graywater.

1.3 Approach

1.3.1 Graywater Treatment Technologies

A wide variety of techniques have been tested to determine the most effective method for treating graywater. However, choosing the optimal method of treatment is determined by the application, location, and cost of graywater treatment. Physical, chemical, and biological treatment may all be necessary when treating graywater depending on the source. Turbidity is used as an indicator of how much physical contamination is in the water. The turbidity of graywater in high income countries was around 25 nephelometric turbidity unit (NTU), and the turbidity needs to be less than 2 NTU according to the EPA (Ghaitidak & Yadav 2013). Methods to treat these specific contaminants are critical to making graywater safe for reuse. The most challenging of these contaminants is nitrogen and phosphorus. Filtration, adsorption, chlorination, ultraviolet disinfection, chemical spiking, and membranes are all examples of methods that can be used for graywater treatment.

Many forms of biological reactors could be applied to the treatment of graywater: moving-bed biofilm reactor (MBBR), membrane bioreactor (MBR), sequencing batch reactor (SBR), up-flow anaerobic sludge blanket, and biological activated membrane bioreactor. However, discrepancies exist between the recommended use of biological treatment for shower graywater. Some researchers argue that graywater contains more nonbiodegradable material than sewage, limiting the effectiveness of biological processes to treat it and suggest that extensive biological treatment of graywater is required to meet mandatory water quality standards (Nolde 2000). BOD is the measurement of how much dissolved oxygen can be used by microorganisms. Graywater needs to have a minimum BOD to be viable for biological treatment. Typically, a BOD₅/COD ratio of at least 0.5 is required for biological treatment. For low-strength, source-separated shower water, the BOD₅/COD ratio is around 0.46 as reported in the literature, which is similar to the 0.57 reported in this study, making it an ideal candidate for membrane treatment.

Ramon et al. (2004) studied the use of direct filtration (ultrafiltration [UF] and nanofiltration) to treat graywater for in situ reuse, concluding that direct dense-membrane filtration is a favorable technology for source-separated graywater treatment; however, it still needs optimization of the molecular weight cut-off to achieve better results. Reverse osmosis (RO)

water purification system technologies are often used in military field exercises for rapid treatment and reuse capabilities for rejection of salts and low molecular weight organic substances (HQDA 2005). The effectiveness of reverse osmosis treatment has been demonstrated for reduction of COD, especially with a prefiltration step (Boddu et al. 2016). In this study, the use of an optimized UF/RO system was employed based on the site specific BOD₅/COD ratio and similar water chemistry in Table 2 (note: TDS is total dissolved solids).

Table 2. Source-separated graywater chemistry.

Analyte	Ramon et al. (2004)	Lalley et al. (2023) ^a
COD (mg/L)	170	287.6
BOD ₅ (mg/L)	78	163.4
BOD ₅ /COD	0.46	0.57
Turbidity (NTU)	23	59.6
TDS (mg/L)	599	617

^aAverage of values over the course of the experiment.

1.3.2 Guidance for Reuse

For this demonstration, a comprehensive inventory of reuse standards was compiled and results for all relevant parameters were closely monitored. There are no federal regulations governing water reuse, but guidance and best practices are provided by a combination of military, US federal, and state documents. There are individual guidelines for reuse meeting potability standards, and all other forms of reuse.

For potable reuse, military guidelines can be found in USAPHC (2014) *Water Reuse in Contingency Operations* and Technical Bulletin (TB) MED 577 (HQDA 2005). USAPHC (2014) guidelines for greywater reuse outline standards that meet potability standards, but only are used for showering. However, TB MED 577 has short-term potability military field water standards for direct potable reuse. Most of the shared parameters for TB MED 577 are stricter than USAPHC (2014), so if water quality meets both standards it can be used for direct potable reuse. US Federal guidelines for indirect potable reuse can be found in US EPA (2012). The combined guidelines for all three documents can be found in Table 3.

be used for all 50 states. To broaden the potential application for gray-water reuse posttreatment, high treatment goals based on potable water regulations were set for the system being evaluated in this study.

Table 4. Proposed treatment goals used for system evaluation based on published nonpotable reuse standards from 35 states.

Criteria	Value	Units
Total Coliform	<2.2	CFU/100 mL
Fecal Coliform	<2.2	CFU/100 mL
<i>E. Coli</i>	<1	CFU/100 mL
Total Nitrogen	<10 ^a	mg-N/L
Total Suspended Solids (TSS)	<5	mg/L
Turbidity	<1 ^b	NTU
BOD	<2	mg/L
Free Residual Chlorine	1–4	mg/L
Chlorine Disinfection Contact Time	>15	Min
UV Transmittance	>90	% at 254 nm
pH	6.5–8.5	

^aException for Maryland Class IV reuse at 1 mg N/L.

^bExceptions for Hawaii and Idaho, which have a membrane requirement for certain reuse applications with a limit of <0.2 NTU. This limit is below detection limits and is therefore not a practical criterion for reuse.

Regarding the use of a standard for ammonia, there are no action levels or maximum contaminant levels set by the US EPA at this time. The concentration of ammonia that exists in drinking water has been determined by the US EPA not to be a risk. However, ammonia should be monitored for other potential reuse applications because it can be harmful to aquatic life. Nitrate is also monitored to determine whether the total nitrogen exceeds the limit for other reuse applications.

2 Materials and Methods

2.1 Demonstration Site and Sampling Events

The graywater reuse treatment system demonstration took place at Camp Shelby Joint Forces Training Center south of Hattiesburg, Mississippi. The system was situated at a contingency operating location (COL), where training units shower and use sinks, and the water streams are collected separately. Samples were collected from shower events. The largest sampling events included treatment of shower water from two battalions over the course of 6 months.

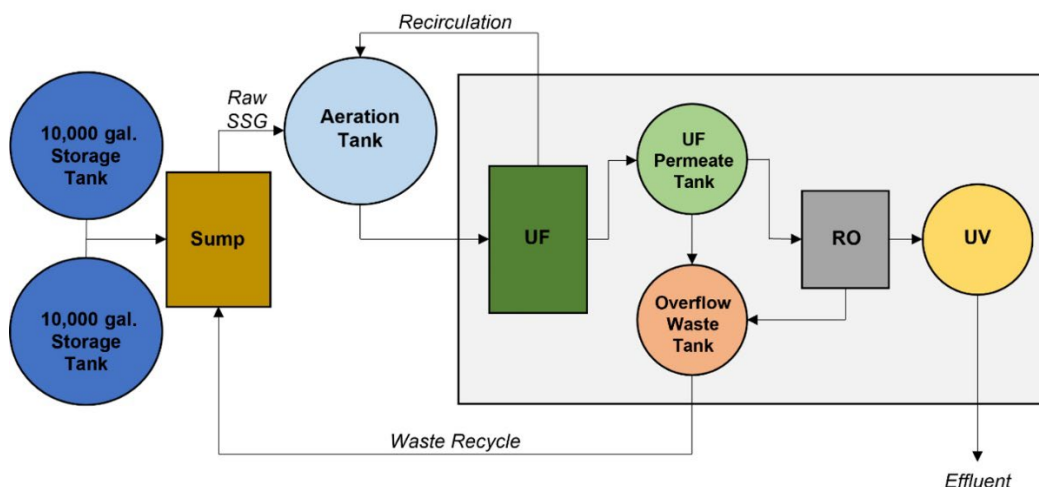
2.2 Graywater Treatment System

The graywater reuse system was designed and constructed by SUEZ Water Technologies & Solutions (Figure 2; note: SSG is source-separated graywater). The system includes a raw feed sump that collects water from COL underground culverts, which houses a submersible pump for water transfer to two existing 10,000 gal. storage tanks that store untreated graywater influent and a raw feed submersible pump to transfer graywater to the water treatment pilot system. The pilot water treatment system is housed in an 8 × 20 ft shipping container, which protects the UF unit, RO unit, and disinfection equipment from the elements. The UF unit consists of Zee-Weed 500 Hollow Fiber polyvinylidene fluoride Membranes (Suez Water Technologies and Solutions, Greenville, South Carolina) with a 0.4 µm pore size and self-priming horizontal centrifugal pumps (Pacer, Lancaster, Pennsylvania; model: GNOK1-1/2-2ALN D.5C). The RO system consists of a Model 4,400-Suez E4 Series 60 Hz with a centrifugal pump (American Stainless Pumps, Carson, California; model: SSP), a 60 Hz pump (Tonkaflo, Chicago, Illinois; model: SS1809x), and high rejection sea water membranes (GE Element, Boston, Massachusetts; models: AP90 and AG90).

A UV water purification system (Hallett, UV Pure, Toronto, Ontario, Canada) was implemented as a polishing step in the treatment train. The bioreactor used for degradation of BOD consists of an aeration tank located outside the main treatment unit housing and a blower that is housed in a small weather-proof container; 1 in. aluminum flowmeters were placed on the inlet to the blivet and treatment system (Great Plains Industries, Wichita, Kansas; model numbers: A109GMA100NA1 and A109GMA025NA1).

Finally, the treated effluent from the system was collected in a collapsible 25,000 gal. bladder tank or blivet.

Figure 2. Schematic of the treatment system.



Water samples were collected at major points along the treatment train including pretreatment, postultrafiltration, and postreverse osmosis purification and UV disinfection.

2.3 Water Quality Analysis

Water quality parameters for all samples collected were analyzed at Air Water and Soil Laboratories, Inc. in Richmond, Virginia using the methods described in Table 5. The parameters were compared to the treatment goals described in Table 3 and 4.

Table 5. Sampling detection methods.*

Analysis	Parameter	Method
Metals (Total) by EPA 200 Series Methods	Hardness as CaCO ₃	SM22 2340B-2011 (SMC 2012b)
Wet Chemistry Analysis	Alkalinity	SM22 2330B-2011 (SMC 2012a)
	Ammonia as N	EPA350.1 R2.0 (US EPA 1993c)
	BOD	SM22 5210B-2011 (SMC 2012f)

* For a full list of the spelled-out forms of the chemical elements used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office, 2016), 265, <https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf>.

Table 5 (cont.). Sampling detection methods.

Analysis	Parameter	Method
Wet Chemistry Analysis (cont.)	Nutrients	EPA300.0 R2.1 (US EPA 1993b)
	MBAS ^a	SM22 5540C-2011 (SMC 2012i)
	Phosphorus, Total	SM 4500-PE (SMC 2012e)
	Specific Conductance	SM22 2510B-2011 (SMC 2012c)
	TDS	SM22 2540C-2011 (SMC 2012d)
	TKN ^b as N	EPA351.2 R2.0 (US EPA 1993d)
	TOC	SM22 5310C-2011 (SMC 2012h)
	Turbidity	EPA180.1 (US EPA 1993a)
Microbiological Analysis	<i>E. Coli</i> (MPN ^c)	Colilert 18 Quanti-Tray System
USGS National Water Quality Laboratory	Micropollutants	Zaugg et al. 2007

^aMBAS = methylene blue active substances assay.

^bTKN = total Kjeldahl nitrogen.

^cMPN = most probable number.

3 Results and Discussion

3.1 Source-Water Characterization

Before the system design was finalized, baseline characteristics were determined for the source-separated shower and sink water from the site. The water was found to possess similar organic matter and nutrients content to values seen in light graywater by Ramon et al. 2004 (Table 2). Use of only physical processes for treatment of this graywater was based on the results of the initial baseline characterization, which indicated that biological and chemical treatment processes were not necessarily required to treat this graywater. Ramon et al. (2004) and Ghaitidak et al. (2013) indicated that filtration treatment processes appear to be feasible with greater than 90% removal recorded for TSS, BOD, COD, surfactants, total nitrogen, total phosphorus, *E. coli*, calcium, and magnesium; greater than 70% removal for ammonia; and greater than 50% removal for potassium. Based on this information, it was determined that filtration coupled with other physiochemical treatment processes should be sufficient to treat light graywater. Ultrafiltration followed by reverse osmosis and an additional UV disinfection step was selected as the treatment train for the graywater during this demonstration.

Characterization of the source graywater occurred throughout the system demonstration. Graywater was supplied by two battalions training over a 6-month period. During this demonstration, more than 100,000 gal. of source-separated sink and shower water was treated. Based on what was found in the literature, these are among the largest source-separated graywater sampling events to date. The data from this event is valuable because it represents the range of feed water characteristics for normal sink and shower water use practices by a military unit. The characteristics of the raw graywater during the training events are summarized in Table 6. The *E. coli* numbers are skewed low due to the upper limit of the analytical method being reached for many samples. Additional samples of the source water were collected later for microbial analysis. The samples were diluted prior to analysis to estimate the upper limit of *E. coli* in the feed water. The results of the two samples were 2,010 and 4,960 CFU/100 mL.

Table 6. Raw graywater characteristics during the pilot study.

Analyte	Average	Std Dev	Min	Max
COD (mg/L)	287.6	529.4	17.6	1,690
BOD (mg/L)	163.4	323.0	11.3	1,090
MBAS (mg/L)	0.76	0.73	< 0.10	2.50
TOC (mg/L)	29.1	25.9	6.3	98.8
NH ₃ (mg-N/L)	8.93	6.10	1.24	22.6
Nitrate (mg-N/L)	0.73	1.12	< 0.10	3.94
PO ₄ (mg/L)	8.04	8.32	2.34	37.7
TDS (mg/L)	617.4	251	250	1,230
Turbidity (NTU)	59.6	147.8	2.63	626
<i>E. coli</i> (MPN/100 mL)	3,542.3	9,740	5	41,100

A summary of the findings includes COD, BOD, and NH₃ values consistent with recorded literature values for domestic shower water as the result of soaps and the presence of urine (Santos et al. 2014). The slight variations from the literature are a result of spiking events occurring in the real-world samples. This can be seen from the high standard deviations for some analytes but were included to reflect the actual surges present in real-world samples. Elevated *E. coli* counts, high turbidity, and high dissolved solids concentrations were also recorded.

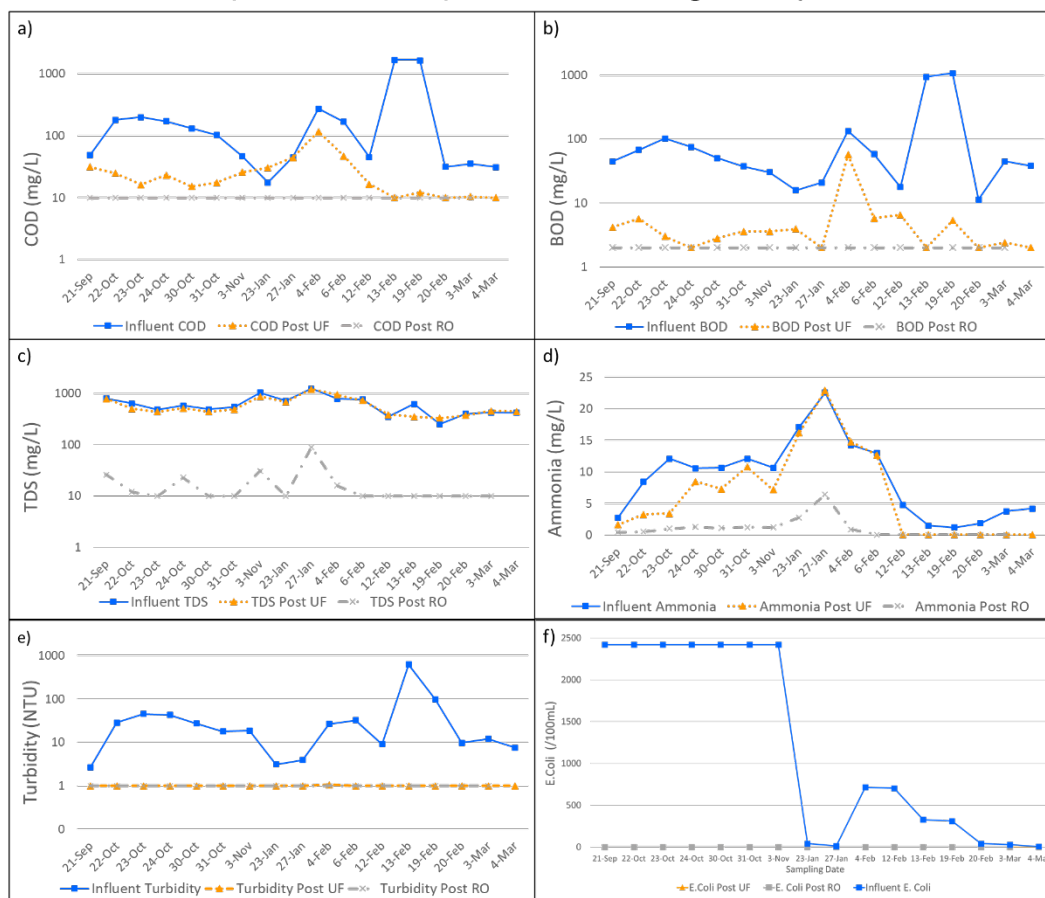
3.2 Effluent Water Quality Results

3.2.1 Performance Assessment Criteria

The water quality necessary for reuse is dependent on the intended use of the treated water. The water quality treatment goals were evaluated against the potability standards found in Table 3 and the nonpotable reuse standards in Table 4.

Water treatment was performed solely as a demonstration exercise without actual reuse of the treated water. Because the effluent from the system was not used, no chlorination took place and no attempt to measure chlorine demand was made. Chlorine demand is rarely measured in the field. *E. coli* was substituted as a surrogate for total coliforms. Figure 3 gives a visual representation of the effects of the UF/RO system on the influent and provides insight on the importance of using reverse osmosis for this treatment instance relating to these contaminants.

Figure 3. Concentrations of *A*, COD; *B*, BOD; *C*, TDS; *D*, ammonia; *E*, turbidity; and *F*, *E. coli* of the raw influent, UF permeate, and RO permeate. Note the logarithmic y-scale in *A–C*, *E*, and *F*.



3.2.2 Ultrafiltration

Post ultrafiltration, on average compliance metrics for BOD, TDS, turbidity, and *E. coli* were met for potability standards while metrics for TOC failed, as seen in Table 7. During spiking events with much higher-than-normal influent concentrations, compliance metrics were failed once for BOD, once for TDS, and once for turbidity. *E. coli* concentrations always met potability requirements. Compliance standards for nonpotable reuse were met on average for *E. coli*, turbidity, and total nitrogen, but failed for all other metrics.

Table 7. Average ultrafiltration results.

Analyte	Average	Standard Deviation	Average Percent Removal (%)
COD (mg/L)	27.2	25.0	90.5
BOD ₅ (mg/L)	6.7	12.7	95.9
MBAS (mg/L)	0.21	0.24	72.7
TOC (mg/L)	8.4	7.9	71.3

Table 7 (cont.). Average ultrafiltration results.

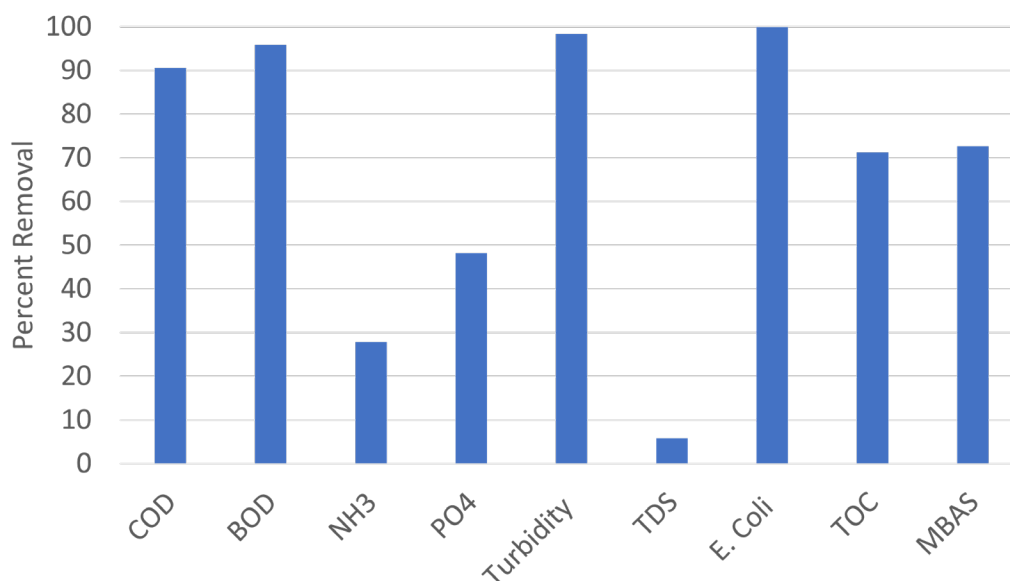
Analyte	Average	Standard Deviation	Average Percent Removal (%)
NH ₃ (mg-N/L)	6.44	6.8	27.9
Nitrate (mg-N/L)	2.54	3.5	-247 ^a
PO ₄ (mg/L)	4.17	2.6	48.1
TDS (mg/L)	581.6	238	5.8
Turbidity (NTU)	1.0	0.01	98.3
<i>E. coli</i> (MPN/100 mL)	ND ^b	—	99.9

^aNegative due to the formation of nitrate in the UF unit from the biological oxidation of ammonia to nitrate.

^bND = nondetect.

The removal efficiency of the ultrafiltration unit for the measured parameters are illustrated in Figure 4. The unit was highly effective at reducing concentrations of BOD, turbidity, and *E. coli*. The unit was moderately effective for the removal of COD, TOC, and methylene blue active substances (MBAS) (surfactants). The unit was ineffective for the removal of ionic nitrogen and phosphate species and dissolved solids in general. The results appear to indicate moderate removal of ammonia, but this was due to biological oxidation of ammonia to nitrate.

Figure 4. Average removal efficiency of analytes by UF unit.



3.2.3 Ultrafiltration and Reverse Osmosis

Since ultrafiltration alone was not sufficient to meet reuse guidelines, RO removal needed evaluation. The analytical results for samples collected from the RO effluent during the 6-month course of the study are provided

in Table 8. Compliance metrics were met on average for all analytes of interest for potable standards. Throughout the course of the field demonstration, no metric exceeded the potability standards during a spiking event. This demonstrates that the system can successfully handle variable spiking events to treat the influent. For nonpotable reuse, compliance standards were met for all analytes in almost all cases. One exception was total nitrogen concentration of combined ammonia and nitrate exceeding the limit for Class IV reuse in Maryland by 0.24 mg N/L. The other exception was turbidity, which exceeded membrane requirements in Hawaii and Idaho (which are below the method detection limit).

Table 8. Average reverse osmosis results.

Analyte	Average	Standard Deviation	Average Percent Removal (%)
COD (mg/L)	<10.0	0	>96.5
BOD ₅ (mg/L)	<2.0	0	>98.8
MBAS (mg/L)	<0.10	0	>86.9
TOC (mg/L)	<1.0	0.02	>96.5
NH ₃ (mg-N/L)	1.12	1.54	87.5
Nitrate (mg-N/L)	0.12	0.04	84.1
PO ₄ (mg/L)	0.33	0.85	98.6
TDS (mg/L)	19	19.6	97.0
Turbidity (NTU)	<1.0	0	>98.3
<i>E. coli</i> (MPN/100 mL)	ND	0	>99.9

The fraction of the influent concentration of each measured parameter removed by the ultrafiltration and reverse osmosis units is illustrated in Figure 5. The unit was highly effective at consistently reducing concentrations of COD, BOD, turbidity, and *E. coli* to their respective method detection limits. Total removal efficiencies for these analytes not being at or near 100% are due to the method detection limits being significant compared to the influent concentrations. The unit is less effective for the removal of dissolved solids, TOC, and MBAS. As stated previously, while the results appear to indicate moderate removal of ammonia, this was due to biological oxidation of ammonia to nitrate. It is apparent that the RO unit can provide significant removal of the nitrogen, phosphorus, and dissolved species not treated well by the UF unit.

Figure 5. Average removal efficiency of analytes by UF and RO units combined.

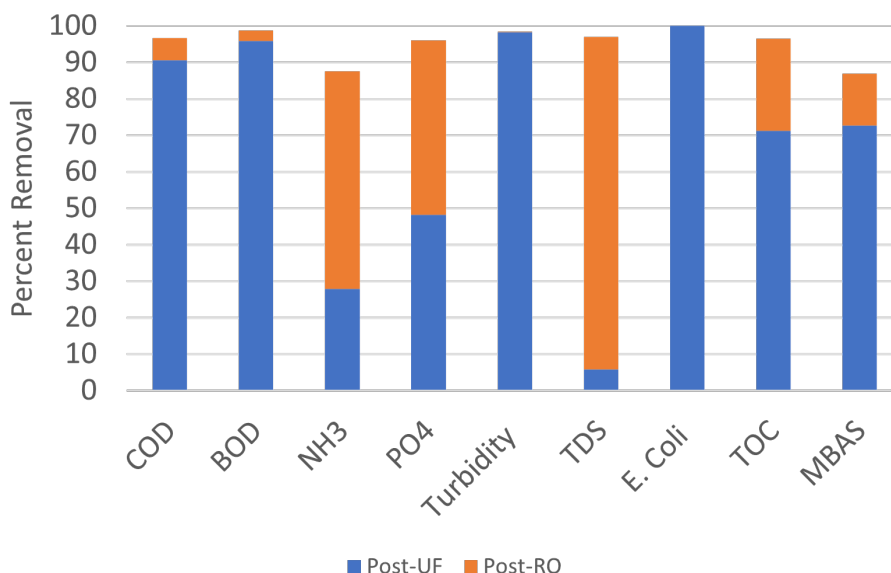
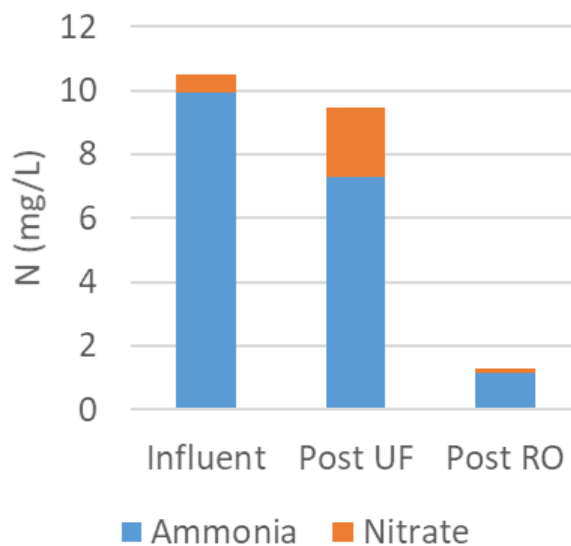


Figure 6 illustrates the fate of ammonia and nitrate through the system. This figure makes it apparent that the UF system does not remove these nitrogen species well, but it does provide some biological oxidation of the ammonia. The RO system does remove greater than 75% of the combined concentrations of ammonia and nitrate remaining after the UF system.

Figure 6. Fate of ammonia and nitrate in the system.



3.2.4 Micropollutants

One set of samples were collected and analyzed for micropollutants. The purpose of this was to determine what micropollutants may be encountered in graywater from field showers and sinks. The results are presented in Table 9. The sources for the six highest concentration chemical compounds found in the graywater were personal care products applied to the skin and compounds commonly found in human urine. The highest concentration compound was DEET, which is commonly used in insect repellent. Cholesterol and caffeine are commonly found in human waste. Hexahydrohexamethyl cyclopentabenzopyran (HHCB), also known as galaxolide, is a musk odorant commonly used in colognes and perfumes. Diethyl phthalate is commonly used in skin care products (e.g., cosmetics, perfume, hair spray, nail polish, soap, detergent, and lotions). And triethyl citrate is frequently used in deodorants.

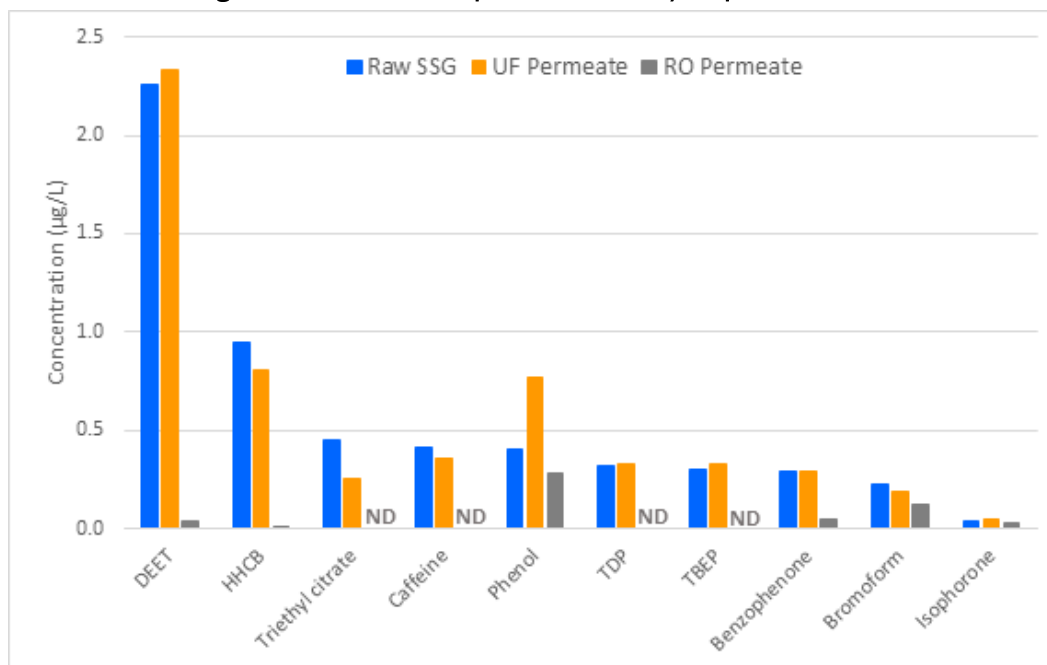
Table 9. Micropollutants detected in graywater.

Analyte		Concentration (ug/L)				
CAS	Name	DL	RL	RAW	UF	RO
134-62-3	N,N-diethyl-meta-toluamide (DEET)	0.020	0.040	2.260	2.330	0.040
57-88-5	Cholesterol	0.800	1.600	2.050	ND	ND
1222-05-5	Hexahydrohexamethyl cyclopentabenzopyran (HHCB)	0.020	0.040	0.947	0.810	0.008
84-66-2	Diethyl phthalate	0.200	0.400	0.620	ND	ND
77-93-0	Triethyl citrate (ethyl citrate)	0.020	0.040	0.446	0.250	ND
58-08-2	Caffeine	0.040	0.080	0.416	0.360	ND
108-95-2	Phenol	0.080	0.160	0.400	0.771	0.278
13674-87-8	Tris(dichloroisopropyl) phosphate	0.160	0.320	0.316	0.332	ND
78-51-3	Tri(2-butoxyethyl) phosphate	0.320	0.640	0.304	0.331	ND
360-68-9	3-beta-Coprostanol	0.800	1.600	0.290	ND	ND
119-61-9	Benzophenone	0.040	0.080	0.290	0.290	0.050
486-56-6	Cotinine	0.040	0.080	0.227	ND	ND
75-25-2	Bromoform	0.080	0.160	0.227	0.191	0.124
87-86-5	Pentachlorophenol	0.800	1.600	0.160	ND	ND
21145-77-7	Acetyl-hexamethyl-tetrahydro-naphthalene (AHTN)	0.020	0.040	0.099	ND	ND
78-59-1	Isophorone	0.025	0.050	0.037	0.051	0.025
115-86-6	Triphenyl phosphate	0.040	0.080	0.020	0.027	ND
581-42-0	2,6-Dimethylnaphthalene	0.020	0.040	ND	0.041	ND
120-72-9	Indole	0.020	0.040	ND	ND	0.029
89-78-1	Menthol	0.160	0.320	ND	ND	0.048

Note: CAS = Chemical Abstract Service; DL = detection limit; and RL = reporting limit.

Figure 7 illustrates the change in concentrations of micropollutants resulting from ultrafiltration and reverse osmosis treatment. UF resulted in some removal of a limited number of these contaminants, while RO effectively reduced most contaminants to very low levels, typically nondetectable. In several cases, ultrafiltration alone can treat the influent to acceptable standards, but this is not the case for all the micropollutants present. Because of this, the reverse osmosis process is necessary for thorough treatment of micropollutants such as DEET, HHCB, and so forth. It is worth noting that the UF/RO treatment was unable to fully treat phenol or bromoform.

Figure 7. Detected micropollutants and UF/RO performance.



The presence of these compounds in the concentrations found are not normally cause for concern; however, they can be of concern when direct reuse of the water for potable purposes, as a source for drinking water, is considered. Direct reuse of treated wastewater results in a partially closed loop of the water source and can result in significant increases in the concentration of these micropollutants if they are not effectively destroyed or removed during treatment. Some of these contaminants may be destroyed by a UV or ozonation disinfection step, but reverse osmosis appears to be the best treatment option to ensure adequate removal. Removal or destruction prior to disinfection by chlorination is recommended due to the possibility of forming unanticipated chlorination byproducts with the micropollutants.

3.3 Water Recovery

Graywater treatment by ultrafiltration alone does not create any significant loss of water, so recovery can be considered near 100%. If this treatment is sufficient to meet the water quality standards for direct reuse, then it would represent a near infinite source of water. However, the purpose of this demonstration was to treat light graywater to meet standards required for potable reuse. To do this, the addition of a reverse osmosis step following treatment by ultrafiltration is required.

Sequential UF and RO treatment of the light graywater in this demonstration resulted in a product water of a quality suitable for potable purposes and it removed micropollutants to a sufficient level to prevent their buildup in a semiclosed-loop water supply. However, two issues must be considered when using RO. The first is level of recovery and loss. The second is the increased concentrations of contaminants of concern in the reject or waste stream from the RO system, which may make disposal of the waste stream problematic. A balance must be struck between the level of water recovery and the level of contaminants in the waste stream. Ideally the goal is to achieve the highest level of recovery possible while maintaining levels of contaminants in the waste stream that are below the limits set for unrestricted discharge to the environment.

When reusing water, the additional water gained is more than just the recovery rate achieved by the RO unit. The ultimate multiplier effect is many times higher due to the water being used many times. This is illustrated in Figure 8, in which a water recovery rate of 85% multiplies the effective volume of useable water by a factor of 6.5. To estimate the water multiplier, you start with an initial volume of water (1.0), which is also the Current volume of water in your system at the beginning. Each time the Current volume is treated, some water is recovered for reuse and some is rejected as waste. The recovered water from each cycle becomes the new Current volume for the next cycle and is also added to the Total volume. The water rejected as waste from each is added to the Reject volume, which begins at zero. The Reject volume can also be calculated by subtracting the Current volume from the initial volume put into the system. These calculations do not factor in dead volumes in the water distribution and wastewater treatment systems. Water multipliers for several recovery rates are included in Table 10.

Figure 8. Water volume multiplier for 85% water recovery rate.

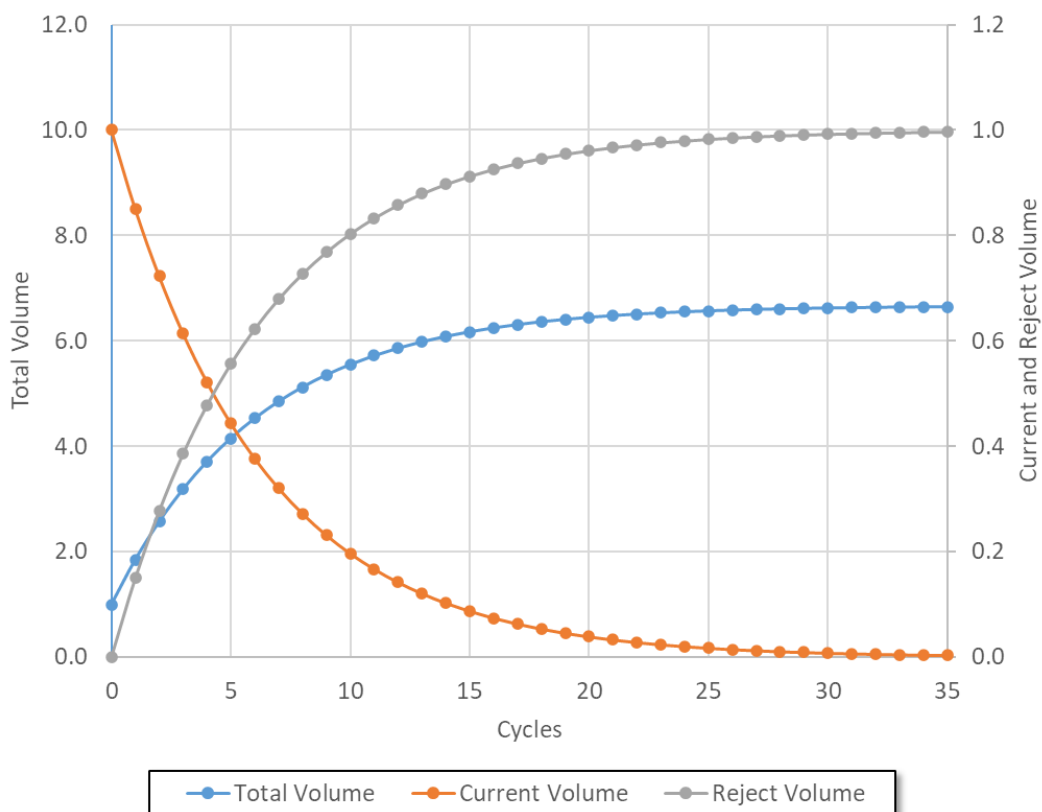


Table 10. Volume multipliers versus RO recovery rates.

Recovery Rate	Volume Multiplier
50%	2.0
60%	2.5
70%	3.33
75%	4.0
80%	5.0
85%	6.5

Several of the parameters measured during the test are typically regulated for discharge to the environment. Among those are BOD, COD, ammonia, nitrate, phosphate, turbidity, and fecal coliforms. Because turbidity and fecal coliforms are effectively eliminated by the UF system, they are not of concern when considering the waste stream from the RO system. Reverse osmosis systems recover about 50% of the water as permeate for each stage of reject treatment. This means the estimated recovery for a 1-stage system is 50%, for a 2-stage system is 75%, and for a 3-stage system is

87.5%. The level of recovery attempted is typically determined by the level of total dissolved solids in the water being treated.

The RO system was operated at a water recovery rate of 75% most of the time, but occasionally, the unit was pushed to recovery rates exceeding 80%. The estimated concentration of rejected compounds can be calculated using Equation 1.

$$C_r = \frac{C_i - C_p}{1 - R}, \quad (1)$$

where

C_r = concentration in the reject stream,

C_i = concentration in the influent,

C_p = concentration in the permeate stream, and

R = water recovery rate.

The estimated concentration of compounds in the reject stream are presented in Table 11 using three different rates of water recovery and average effluent concentrations from the UF and RO units during the demonstration. Nondetect values in the RO permeate were assumed to be zero to produce a conservative (high) estimate of concentrations in the reject stream.

Table 11. Estimated concentrations in the RO reject stream.

Analyte	Avg UF Effluent	Avg RO Permeate	Reject @ $R = 50\%$	Reject @ $R = 60\%$	Reject @ $R = 75\%$
COD (mg/L)	27.2	<10.0	34.4	43.0	68.8
BOD (mg/L)	6.7	<2.0	9.4	11.8	18.8
NH ₃ -N (mg/L)	6.44	1.12	10.6	13.3	21.3
NO ₃ -N (mg/L)	2.54	0.12	4.84	6.05	9.7
PO ₄ (mg/L)	4.17	0.33	7.68	9.6	15.36
TDS (mg/L)	581.6	19	1,125	1,407	2,250

The reject stream cannot be discharged into the environment based on the potable and nonpotable standards in Tables 3 and 4. Light graywater such as that encountered during this demonstration can be effectively treated by reverse osmosis only with minimal prefiltration; however, the concentration increase in the reject stream is one of the main factors necessitating use of a biological treatment and/or ultrafiltration process before the

reverse osmosis process. Pretreatment by UF allows a higher recovery rate RO system to be used while still maintaining a waste stream potentially suitable for discharge.

4 Conclusions

The demonstrated water treatment unit combining ultrafiltration followed by reverse osmosis provided for the treatment of low-strength graywater from source-separated shower water from Tactical Training Base (TTB)#4 at CSJFTC. The system was situated at a COL, where training units shower and use sinks and water from each source was collected separately. Graywater was supplied by two large training events that occurred over a 6-month period. During the demonstration, more than 100,000 gal. of source-separated sink and shower water were treated. Characterization of the source graywater continued throughout the system demonstration. Based on a review of the literature, these are among the largest source-separated graywater sampling events to date. The data from this event is valuable because it represents the range of feed water characteristics for normal sink and shower water use practices by a military unit. Primary findings and conclusions from this study include the following:

- Graywater from source-separated shower water is low strength with a BOD/COD ratio of 0.57; therefore, ultrafiltration followed by reverse osmosis with an additional UV disinfection step is an effective treatment train for this feedwater.
- UF treatment alone is highly effective at reducing concentrations of BOD, turbidity, and *E. coli*; moderately effective for the removal of COD, TOC, and MBAS (surfactants); and insufficient for the removal of ionic nitrogen and phosphate species and dissolved solids in general.
- The combined treatment train of UF and RO met all compliance metrics for potable reuse. For nonpotable reuse, all compliance standards that currently exist in 35 states were met, except for special use cases on total nitrogen in one state and turbidity in two states.
- RO appears to be an effective treatment option to ensure adequate removal for most of the micropollutants detected.
- When reusing water, the additional water gained is more than just the recovery rate achieved by the RO unit. The ultimate multiplier effect is many times higher due to the water being used many times.
- A water recovery rate of 85% multiplies the effective volume of useable water by a factor of 6.5, creating a significant reduction in the volumes required.

5 Proposed Future Treatment Train

The water treatment unit as designed performed very well and produced a high-quality water effluent. Because of the low BOD levels of the graywater from the showers and sinks, biological activity in the ultrafiltration unit was insufficient to remove nutrients such as ammonia, nitrate, and phosphate. If concentrations of these nutrients become an issue, particularly for discharge of the RO reject stream, an additional step or change in operation may be necessary to remove these contaminants. Introduction of a material such as clinoptilolite, which is a zeolite, into the system would potentially help with further removal of NH_3 . These changes would allow the water produced by the system to be used for every potential reuse explored in the guidelines.

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Appendix: Supplementary Data

Table A-1 Ultrafiltration effluent results.

	21-Sep	22-Oct	23-Oct	24-Oct	30-Oct	31-Oct	3-Nov	23-Jan	27-Jan	4-Feb	6-Feb	12-Feb	13-Feb	19-Feb	20-Feb	3-Mar	4-Mar
COD (mg/L)	31.40	24.80	16.20	23.10	15.20	17.60	25.90	30.40	44.20	117.00	46.90	16.60	10.00	12.10	10.00	10.40	10.00
BOD (mg/L)	4.20	5.70	3.00	2.00	2.80	3.60	3.60	3.90	2.00	57.10	5.80	6.50	2.00	5.30	2.00	2.40	2.00
NH ₃ (mg/L)	1.66	3.30	3.46	8.51	7.32	10.80	7.22	16.20	22.90	14.80	12.70	0.10	0.10	0.10	0.10	0.10	0.10
PO ₄ (mg/L)	4.29	0.90	1.25	2.23	1.31	3.89	9.21	5.98	10.00	6.80	4.83	6.27	3.01	1.83	2.18	3.26	3.59
Turbidity (NTU)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.05	1.00	1.00	1.00	1.00	1.00	1.00	1.00
TDS (mg/L)	783.00	497.00	439.00	510.00	440.00	486.00	863.00	680.00	1,200.00	944.00	719.00	383.00	348.00	331.00	370.00	452.00	442.00
<i>E. coli</i> (MPN/10,000 mL)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
TOC (mg/L)	9.00	8.90	7.30	7.00	4.30	4.90	7.50	7.80	11.70	37.60	14.30	4.90	3.20	3.30	2.90	4.00	3.70
MBAS (mg/L)	0.10	0.23	0.23	0.20	0.21	0.20	0.18	0.10	0.10	1.14	0.27	0.10	0.10	0.10	0.10	0.10	0.10
Nitrate (mg/L)	0.74	0.10	0.10	0.10	0.10	0.35	0.10	0.10	0.17	0.10	0.10	11.60	7.24	4.52	5.42	5.42	7.00

Note: COD = chemical oxygen demand; BOD = biochemical oxygen demand; NTU = nephelometric turbidity unit; TDS = total dissolved solids; MPN = most probable number; TOC = total organic carbon; and MBAS = methylene blue active substances.

Table A-2 Reverse osmosis effluent results.

UF	21-Sep	22-Oct	23-Oct	24-Oct	30-Oct	31-Oct	3-Nov	23-Jan	27-Jan	6-Feb	12-Feb	13-Feb	19-Feb	20-Feb	3-Mar	4-Mar
COD	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	1.00	10.00	10.00	10.00	10.00	10.00
BOD	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
NH ₃	0.47	0.58	1.07	1.32	1.14	1.28	1.24	2.81	6.44	0.94	0.10	0.10	0.10	0.10	0.10	0.10
PO ₄	0.10	0.06	0.06	0.06	0.06	0.06	0.18	0.06	0.44	0.06	0.19	0.06	0.06	0.10	3.59	0.06
Turbidity	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
TDS	26.00	12.00	10.00	23.00	10.00	10.00	31.00	10.00	90.00	16.00	10.00	10.00	10.00	10.00	10.00	10.00
<i>E. Coli</i>	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
TOC	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.10	1.00	1.00	1.00	1.00	1.00	1.00	1.00
MBAS	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Nitrate	0.12	0.10	0.10	0.10	0.10	0.10	0.21	0.10	0.10	0.10	0.22	0.11	0.10	0.10	0.10	0.10

Note: UF = Ultrafiltration

Abbreviations

BOD	Biochemical oxygen demand
CAS	Chemical Abstract Service
CFU	Colony-forming unit
COD	Chemical oxygen demand
COL	Contingency operating location
CSJFTC	Camp Shelby Joint Force Training Center
DL	Detection limit
gpd	Gallons per day
gpd/p	Gallons per day per person
HHCB	Hexahydrohexamethyl cyclopentabenzopyran
HQDA	Headquarters, Department of the Army
MBAS	Methylene blue active substances
MBBR	Moving-bed biofilm reactor
MBR	Membrane bioreactor
MPN	Most probable number
ND	Nondetect
NTU	Nephelometric turbidity unit
QMRA	Quantitative microbial risk assessment
RL	Reporting limit
RO	Reverse osmosis
SBR	Sequencing batch reactor
SMC	Standard Methods Committee

TB	Technical bulletin
TDS	Total dissolved solids
TOC	Total organic carbon
TSS	Total suspended solids
TTB	Tactical training base
UF	Ultrafiltration
US EPA	US Environmental Protection Agency
USAPHC	US Army Public Health Command
WWTP	Wastewater treatment plant

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14. ABSTRACT In field operating environments, military units must ensure access to a critical water supply to maintain mission readiness. Increasing complexity of logistics and costs to transport water and climate change are driving the development and demonstration of water treatment units. The treatment unit described uses ultrafiltration (UF) and reverse osmosis (RO) membrane technologies with a disinfection step to treat low-strength graywater from shower facilities at Camp Shelby Joint Force Training Center in Hattiesburg, Mississippi. Samples were collected from human shower sampling events. During the demonstration, greater than 100,000 gal. of graywater were treated, supplied by two battalion training rotations over a 6-month period. Characterization of the source graywater continued throughout the system demonstration. Based on the literature, these are among the largest source-separated graywater sampling events to date. The combined treatment train of UF/RO met all compliance metrics for all analytes of interest for potability and met nonpotable metrics except for special use cases in three states. Both the quality of the treated water and the effective volume gains from an 85% multiplier effect directly support DoD water sustainment goals for both installations and operational environments.							
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