8-2012

The Effect of Granular Activated Carbon Pretreatment and Sand Pretreatment on Microfiltration of Greywater

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Recommended Citation

Christopher, David, "The Effect of Granular Activated Carbon Pretreatment and Sand Pretreatment on Microfiltration of Greywater" (2012). *All Theses*. 1463.
https://tigerprints.clemson.edu/all_theses/1463

THE EFFECT OF GRANULAR ACTIVATED CARBON PRETREATMENT AND SAND PRETREATMENT ON MICROFILTRATION OF GREYWATER

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Civil Engineering

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by
David Mark Christopher
August 2012

Accepted by:
Dr. Cindy Lee, Committee Chair
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Dr. Nadim Aziz

ABSTRACT

Around the world, water scarcity is driving people to practice water reuse. One form of water reuse is the recycling of greywater, which is household wastewater excluding toilet waste. With adequate treatment, greywater may be recycled onsite for applications that do not require potable water, such as irrigation or toilet flushing. Membrane filtration (including microfiltration (MF)) is one option for greywater treatment. The small footprint, modular nature, and predictable performance of MF make it an attractive option. However, direct MF of greywater can lead to rapid membrane fouling. This thesis investigated two possible pretreatments for reducing membrane fouling and improving effluent water quality: granular activated carbon (GAC) and silica sand. To test these pretreatments, synthetic greywater (representing effluent from bathroom sinks and showers) was prepared using a recipe from NSF/ANSI Standard 350 and then treated using a pressure-driven MF membrane in a dead-end configuration. Samples were taken before pretreatment, after pretreatment, and after microfiltration and analyzed for four parameters: turbidity, total organic carbon (TOC), chemical oxygen demand (COD), and surfactants. Membrane flux was also monitored. The results indicate that for the given experimental conditions, GAC and sand pretreatments improved effluent water quality but did not significantly reduce membrane fouling. GAC was more effective than sand at removing surfactants, while sand was more effective than GAC at removing turbidity. GAC and sand were comparable in their ability to remove TOC and COD once the flows through the columns had stabilized (i.e., within one minute). After microfiltration (MF), samples that had been pretreated with GAC exhibited the lowest level of contamination in all categories. Nevertheless, according to guidelines published by the US Environmental Protection Agency the final treated effluent was unsuitable for direct reuse because it exceeded the recommended threshold for TOC. (Currently there is no recommended threshold for water reuse regarding surfactants.) These results imply that physical treatment alone may be insufficient to remove contaminants from greywater, especially dissolved contaminants such as surfactants, which are prevalent in greywater. Future research could investigate the effect of different operating conditions (e.g., longer pretreatment contact time, upflow configuration through GAC, different membrane types), different pretreatment setup (e.g., dual layer pretreatment media with both GAC and sand), and incorporation of a biological component (i.e., allowing biofilm to develop on filter media or using a membrane bioreactor instead of strict membrane filtration).

DEDICATION

To Jesus Christ, my Creator, Redeemer, Savior, Shepherd, King, Comforter, Advocate, Friend – the one true and living God.

ACKNOWLEDGMENTS

This research was supported by the National Science Foundation, under Grant No. NSF-1011478. The views and conclusions contained in this document are those of the writers and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the National Science Foundation.

The author would like to thank Dr. Martin Page of the US Army Corps of Engineers Construction Engineering Research Laboratory (USACE-CERL) for serving as an internship mentor and an external reviewer of this thesis. In addition, the author would like to acknowledge the following individuals for their helpful contributions, without which this work would not have been possible:

- Dr. Cindy Lee
- Dr. David Ladner
- Anne Cummings
- Karen Lanning
- Martha Zglinicki
- Kenneth Dunn
- Kristi Baker
- Jaclyn Ellerie
- Muriel Steele
- Meric Selbes
- Ademola Bakenne
- Viet Dang
- Diana Delach
- Aliece Wilson

TABLE OF CONTENTS

TITLE PAGE....i

ABSTRACT....ii

DEDICATION....iv

ACKNOWLEDGMENTS....v

LIST OF TABLES....iv

LIST OF FIGURES....vi

LIST OF ABBREVIATIONS....viii

1. INTRODUCTION AND CRITICAL LITERATURE REVIEW....1

    Background on greywater reuse....3
    Discussion of sustainability....13
    Membrane filtration....20
    Summary of key points....23

2. EXPERIMENTAL METHODS....24

    Experimental objectives....24
    Overview....24
    Experimental apparatus....29
    Preparation of NSF/ANSI 350 challenge water....32
    Sampling of raw (untreated) challenge water....36
    Pretreatment step (filtration columns)....37
    Treatment step (microfiltration)....39
    Water quality methods....42

3. EXPERIMENTAL RESULTS AND DISCUSSION 46

Terminology 46
Pretreatment column flow rate 47
Limits and goals for reuse 48
Turbidity removal 48
TOC removal 53
COD removal 59
Surfactant removal 65
Flux through membrane 70

4. CONCLUSIONS AND FUTURE WORK 73

Treatment effectiveness and effluent suitability for reuse 73
Implications for designers 75
Future research 75

APPENDICES 77

APPENDIX A 78

Experimental background – internship at CERL 78

APPENDIX B 80

Fabrication of experimental apparatus 80

APPENDIX C 85

COD analysis procedure (closed reflux, colorimetric method) 85

APPENDIX D 89

TOC analysis procedure 89

APPENDIX E 93

Surfactant analysis procedure 93

APPENDIX F 96

Raw data – Turbidity 96

APPENDIX G 99

Raw data – TOC 99

APPENDIX H 102

Raw data – COD 102

APPENDIX I 105

Raw data – Surfactants 105

APPENDIX J 108

Raw data – Flux across membrane 108

REFERENCES 128

LIST OF TABLES

Table 1. List of components for pretreatment. 27

Table 2. List of components for membrane filtration. 28

Table 3. Reagents used to create synthetic "bathing source" challenge greywater. 34

Table 4. Turbidity removal results. 49

Table 5. Turbidity levels in pretreatment effluent. 52

Table 6. TOC removal results. 55

Table 7. TOC levels in pretreatment effluent. 58

Table 8. COD removal results. 60

Table 9. COD levels in pretreatment effluent. 63

Table 10. Surfactant removal results. 66

Table 11. Surfactant levels in pretreatment effluent. 69

Table 12. Dilutions required for creating COD standards. 86

Table 13. Raw turbidity data for samples receiving GAC pretreatment. 96

Table 14. Raw turbidity data for samples receiving sand pretreatment. 97

Table 15. Raw TOC data for samples receiving GAC pretreatment. 99

Table 16. Raw TOC data for samples receiving sand pretreatment. 100

Table 17. Raw TOC data for samples receiving no pretreatment. 101

Table 18. Raw COD data for samples receiving GAC pretreatment. 102

Table 19. Raw COD data for samples receiving sand pretreatment. 103

Table 20. Raw COD data for samples receiving no pretreatment. 104

Table 21. Raw surfactant data for samples receiving GAC pretreatment. 105

Table 22. Raw surfactant data for samples receiving sand pretreatment......................106

Table 23. Raw surfactant data for samples receiving no pretreatment. 107

Table 24. Raw flux data for samples receiving GAC pretreatment. 108

Table 25. Raw flux data for samples receiving sand pretreatment. 117

Table 26. Raw flux data for sample receiving no pretreatment. 123

LIST OF FIGURES

Figure 1. Photograph of experimental setup. 25

Figure 2. Diagram of experimental setup during pretreatment phase. 27

Figure 3. Diagram of experimental setup during membrane filtration phase. 28

Figure 4. Detail of pretreatment column construction. 31

Figure 5. Photograph of primary ingredients in challenge water recipe. 36

Figure 6. Turbidity removal results. Error bars represent ± 1 standard deviation. Sample size was eight (for all values before pretreatment), three (for GAC and Sand after pretreatment), or two (for No pretreatment after MF). 49

Figure 7. Turbidity levels in pretreatment effluent. Error bars represent ± 1 standard deviation. Sample size was three (both for GAC pretreatment and Sand pretreatment). 52

Figure 8. TOC removal results. Error bars represent ± 1 standard deviation. Sample size was 11 (for all values before pretreatment), six (for GAC after pretreatment), or two (for Sand after pretreatment, Sand after MF, and No pretreatment after MF). All measurements were made in triplicate. 55

Figure 9. TOC levels in pretreatment effluent. Error bars represent ± 1 standard deviation. Sample size was six (for GAC pretreatment at time = 0), two (GAC at time = 50), four (GAC at time = 90), two (for Sand pretreatment at time = 0 and time = 50), or one (for Sand at time = 180). All samples were measured in triplicate..58

Figure 10. COD removal results. Error bars represent ± 1 standard deviation. Sample size was eight (for all values before pretreatment), three (for GAC after pretreatment and after MF), or two (for Sand after pretreatment, Sand after MF, and No pretreatment after MF). All samples were measured in triplicate.60

Figure 11. COD levels in pretreatment effluent. Error bars represent ± 1 standard deviation. Sample size was three (for GAC pretreatment), or two (for Sand pretreatment). All samples were measured in triplicate.................................63

Figure 12. Surfactant removal results. Error bars represent ± 1 standard deviation. Sample size was eight (for all values before pretreatment), four (for GAC after pretreatment), six (for GAC after MF), two (for Sand after pretreatment), one (for Sand after MF), or two (for No pretreatment after MF). All but four of the samples were measured in triplicate (see APPENDIX I)...................................66

Figure 13. Surfactant levels in pretreatment effluent. Error bars represent ± 1 standard deviation. Sample size was four (for GAC pretreatment), two (for Sand at time = 0 and time = 50), or one (for Sand at time = 40). All samples (except two for GAC) were measured in triplicate...69

Figure 14. Membrane flux results. Error bars represent ± 1 standard deviation. Sample size was five (for GAC pretreatment), two (for Sand pretreatment), or one (for No pretreatment). 71

LIST OF ABBREVIATIONS

Average	Avg
Chemical oxygen demand	COD
Construction Engineering Research Lab	CERL
Cubic inch(es)	in^3
Degrees Celsius	°C
Distilled deionized	DDI
Empty bed contact time	EBCT
Environmental Protection Agency	EPA
Foot (feet)	ft
Gallon(s)	gal
Inch(es)	in
Linear alkylbenzene sulfonate	LAS
Liter(s)	L
Liters per square meter per hour	lmh
Milligram(s)	mg
Milliliter(s)	mL
Minute(s)	min
Molar	M
Molecular weight cut-off	MWCO

Nanometer(s)	nm
Nephelometric turbidity units	NTU
Polyvinyl chloride	PVC
Standard deviation	SD
Total organic carbon	TOC
Ultrafiltration	UF
United States Army Corps of Engineers	USACE

CHAPTER 1

INTRODUCTION AND CRITICAL LITERATURE REVIEW

As the world population grows and the average standard of living increases (Rosling, 2010), the fixed amount of freshwater resources on earth becomes more and more strained. In some places, all available water resources have already been exploited and there is still a net shortage of water. For example, China already has an estimated annual water shortage of 40 billion cubic meters (Zhang and Tan, 2010) and residents in the capital city of Jordan are reported to receive less than 100 liters (26 gallons) of water per person per day, all delivered on just one or two days each week (Al-Jayyousi, 2004). Clearly, water is not as abundant as one might assume.

To deal with increasing water scarcity, one of two things must happen: either new freshwater sources must be developed, or the existing (and growing) water demand must be reduced. Often, as in the case of China, developing new natural sources is infeasible, so mitigating demand is the only alternative.

One means for managing freshwater demand is to reuse water within a home or business. Water reuse has been implemented in one form or another for hundreds of years (Metcalf & Eddy et al., 2007) but has become increasingly prevalent (and necessary) in recent years. Metcalf & Eddy (2007) predicts that using water only once is a rapidly disappearing luxury. By extracting more than one use out of a given volume of water, the total quantity of water required for a building is reduced. Therefore, it has been suggested that “dilute nonfecal wastes” be recycled whenever possible (Lehr, 1987). Water recycled in this manner is often called “greywater” because after the first use, the water is no longer clean and potable but is also not on par with sewage (known as “blackwater”), since toilet waste is excluded from greywater by definition. There is a general perception that greywater is not as polluted as blackwater (Birks and Hills, 2007; Nghiem et al., 2006; Ramon et al., 2004). The validity of this perception is questionable (Birks and Hills, 2007), but it prevails nonetheless.

Greywater reuse is part of a larger movement toward sustainability that has been gaining momentum in recent years (Anastas, 2003). Sustainable development is defined as that which meets the needs of the present generation without compromising the ability of future generations to do the same (Brundtland, 1987). Sustainability can be further defined within the framework of “the triple bottom line” of social, economic, and environmental sustainability (Smith, 2004). For a technology or system to be sustainable, it must address all three spheres. Often the environmental sphere is highlighted (e.g., (Anastas and Zimmerman, 2003)) while the other spheres are neglected. However, sustainability is ultimately intended to support human life and wellbeing (Brundtland, 1987), so environmental protection that hinders economic and societal development is insufficient and even counterproductive.

The purpose of the critical literature review is to analyze the existing literature on greywater treatment and reuse within the framework of sustainability (social, economic, and environmental), considering both greywater reuse in general and current greywater reuse systems in particular. Special note will be made of areas of literature that are conflicting, incomplete, or missing, and membrane filtration will be highlighted as a treatment option that is viable and worthy of further research and development.

Background on greywater reuse

Greywater characteristics

Definition

Greywater is spelled and defined in various ways. Spellings include “greywater” (e.g., (Al-Jayyousi, 2003; Christova-Boal et al., 1996; Mandal et al., 2011; Nghiem et al., 2006)), “graywater” (e.g., (Casanova, 2001; Ramon et al., 2004)), “grey water” (e.g., (Ghunmi et al., 2011a)), and “gray water” (e.g., (Lehr, 1987)), none of which is incorrect (Ludwig, 2006). Because it seems that “greywater” will become the standard international spelling (James, 2010), the remainder of this thesis assumes the spelling “greywater.”

Greywater is broadly defined as “untreated household wastewater which has not been contaminated by toilet waste“ (WHO-ROEM, 2006), but precise definitions are varied. In any case, the definition of greywater revolves around which wastewater streams are included in the reuse system.

Sources

There is agreement that water from baths, showers, and hand basins (i.e., non-kitchen sinks) qualifies as greywater. However, there is disagreement over the categorization of other sources of water such as clothes washers, dishwashers, and kitchen sinks (see Figure 1). To acknowledge this discrepancy, some authors have adopted a sub-categorization of “light” greywater and “dark” greywater (e.g., (Lazarova et al., 2003; Birks and Hills, 2007)) or “low load” greywater and “high load” greywater (Ramon et al., 2004). Light (or low load) greywater includes water from baths, showers, and hand basins, while dark (high load) greywater includes water from clothes washers, dishwashers, and kitchen sinks. Toilet water, as black water, is always excluded.

Applications

The two most common applications of greywater are irrigation (typically using a sub-surface distribution system to minimize human contact with the water) (Al-Jayyousi, 2004; Christova-Boal et al., 1996; Karpiscak et al., 1990; Nghiem et al., 2006) and toilet flushing (Christova-Boal et al., 1996; Lazarova et al., 2003; Nghiem et al., 2006). However, other uses that have been proposed include clothes washing, car washing, window washing, and groundwater recharge (Ghunmi et al., 2011a) as well as ornamental fountains, recreational impoundments, lakes and ponds, air conditioning, process water, fire protection, construction (Li et al., 2009), and pavement cleansing (Nghiem et al., 2006). In essence, any use that does not result in direct human contact may be considered (Abu-Ashour and Jamrah, 2008).

Li et al. (2009) proposed categorizing greywater reuse applications into two primary categories: (1) recreational impoundments and lakes, and (2) urban reuses and agricultural irrigation, with each category subdivided into (a) restricted uses and (b) unrestricted uses, based on the associated human health risk.

Potential benefits

Homeowner perspective

Potential benefits to homeowners who reuse greywater include reduced monthly water costs, reduced monthly wastewater/sewage costs, pride in their improved environmental stewardship, as well as any application-specific benefits (e.g., produce grown using irrigation, clean cars washed with greywater, etc.). Most people decide to install greywater systems not because of economic incentives (these may or may not be present) but because of their desires to protect the natural environment and to have greater freedom during times of water rationing and drought (Sheikh, 2010).

Whole-system perspective

From the perspective of a drinking water utility, the water savings offered by greywater could result in a lower demand for potable water, with a corresponding reduction in the need for freshwater withdrawal from reservoirs and aquifers, for chemical purchase and storage, and for sludge creation and disposal.

Treatment

Treatment requirements

Although greywater is generally perceived as cleaner than raw sewage (due to the reduction in fecal matter) (Nghiem et al., 2006; Ramon et al., 2004), studies have shown that greywater can contain significant levels of indicator organisms such as total coliforms, *E. coli* and fecal enterococci (Birks and Hills, 2007), as well as salmonella (Mandal et al., 2011). Sometimes pathogens are present at concentrations comparable with raw sewage (Casanova, 2001). In addition, there are multiple physical and chemical contaminants present. Thus, researchers generally recommend that greywater be treated to some degree prior to use (Al-Jayyousi, 2004; Maimon et al., 2010). However, it should also be noted that the composition of greywater varies drastically from location to location based on personal habits, cultural mores, climactic effects, and other factors (Mandal et al., 2011; Ramon et al., 2004). Therefore, some greywater sources will be more contaminated than others, and even from a single source, temporal fluctuations should be expected.

For irrigation, one concern with greywater from clothes washers and dishwashers is that high concentrations of surfactants from detergents may accumulate in soil over time and adversely alter soil properties, potentially making the soil hydrophobic (Wiel-Shafran et al., 2006). While household detergents are often required to contain biodegradable surfactants, some results suggest that soil particles can absorb the surfactants strongly enough to inhibit biodegradation (Wiel-Shafran et al., 2006).

Also, with the potentially high concentration of surfactants in greywater, surfactants may accumulate faster than they can be biodegraded. However, Wiel-Shafran et al. observed hydrophobicity in soils comprised entirely of sand. Other authors assert that under normal favorable conditions (i.e., a soil incorporating natural organic matter), the topsoil layer functions as a very effective filtering mechanism that can remove surfactants and other contaminants (Feiden and Winkler, 2006; Ludwig, 2006). Another concern regarding irrigation with laundry water is the presences of salts from detergents (Christova-Boal et al., 1996). Alfiya et al. (2012) observed elevated salt levels in soils irrigated with laundry greywater but also noted that periodic excess irrigation rinsed the accumulated salts out of the soils.

With kitchen sinks, one concern is that the high nutrient content may enable pathogens to survive longer in the soil and thus created a more severe public health risk. Abu-Ashour and Jamrah (2008) found a significant relationship between the survival of bacteria in soil irrigated with greywater and the greywater source (kitchen sinks represented the longest survival times at 15 days). However, the nutrients in kitchen sink water may also serve to correct nutrient imbalances in the overall greywater composition and so facilitate more effective biological treatment . Thus, although some sources choose to exclude kitchen sink water from greywater systems in order to avoid the potential influx of pathogens, high organic loadings, and detergents (Maimon et al., 2010), kitchen sink effluent should be considered on a case-by-case basis.

Related concerns apply to greywater that is reused for toilet flushing. Because toilet flushing presents an opportunity for human contact (especially unintentional contact by visitors who are unaware that the bathroom contains a greywater system), some believe that toilet water should be treated to near-potable water standards – more highly treated than greywater used for subsurface irrigation (Sheikh, 2010). Others, particularly the public, may perceive toilet flushing as less “personal” than the irrigation of food crops (Lazarova et al., 2003), and thus expect less treatment. This disparity of interpretation may warrant an educational campaign to help align public perception with empirical findings.

Birks and Hills (2007) claim that that the presence of traditional indicator organisms does not always correspond to a high level of pathogens, and thus traditional indicator organisms are not valid for greywater use, despite their popularity and effectiveness for potable water use. However, Birks and Hills (2007) fail to supply an alternative indicator organism or method to replace the traditional ones. Because this is an area with many public health ramifications, further research into this topic is imperative.

Greywater can also contain physical and chemical contaminants, such as phosphorus (primarily from detergents, which may be excluded from some greywater streams) (Birks and Hills, 2007), chlorides, turbidity, and BOD (biological oxygen demand). The concentrations of the last three contaminants normally fall somewhere between raw sewage and treated wastewater (Casanova, 2001). One study found that the major pollutants in shower greywater were suspended solids and organic matter (Ramon et al., 2004).

Greywater treatment

Treatment options

As with conventional wastewater treatment (Metcalf & Eddy et al., 2003), greywater treatment mechanisms can be divided into three primary categories: physical, chemical, and biological. Li et al (2009) provides a thorough review of existing treatment options under each category.

Physical processes include filtration and settling/sedimentation. Some authors report that while helpful for pretreatment purposes, physical processes alone cannot adequately treat greywater for reuse (Friedler and Alfiya, 2010; Ghunmi et al., 2011a; Li et al., 2009). However, others contend that some physical processes, such as standalone membrane filtration, are viable for decentralized greywater treatment and reuse (Friedler and Alfiya, 2010; Nghiem et al., 2006; Ramon et al., 2004). (Membrane filtration is discussed in detail below.)

With the exception of disinfection, chemical processes are not widely used with greywater; prior studies found them unable to produce effluent suitable for direct reuse, especially with more highly contaminated greywater (Li et al., 2009). However, coagulation and ion exchange are two chemical treatment processes that may be used (Li et al., 2009).

Biological processes receive conflicting reviews in the literature. One source claims that the effectiveness of biological treatment is limited because of the relatively low amount of biodegradable organic matter as well as the nutrient imbalance in greywater (Al-Jayyousi, 2003). However, another suggests that the most simple, affordable, and efficient treatment systems should be comprised largely of biological treatment units, followed by disinfection (Ghunmi et al., 2011b). Li et al. (2009) suggests a technique that may reconcile these seemingly disparate views: depending on the nature of the kitchen sink effluent (which can vary significantly from site to site), mixing the kitchen sink water with other greywater sources may remedy the nutrient imbalance and enable biological treatment.

Treatment selection

To efficiently manage the risks presented by greywater reuse while minimizing the amount of treatment necessary, greywater sources should be paired with appropriate end uses (Al-Jayyousi, 2003). Christova-Boal (1996) suggests using bathroom, shower, and hand basin greywater to irrigate gardens, while reserving laundry greywater (with its elevated salt levels from detergents) for toilet flushing.

However, greywater systems popularized in California distribute laundry effluent directly into subsurface irrigation basins, and long-term users of these systems (eight or more years) report no detrimental effects to local biota. On the contrary, they report that plants appear healthier and more fruitful than before the system was installed (Allen, 2011). The anecdotal belief is that rainwater flushes salts and surfactants from the soil before they accumulate to harmful levels. At the time of writing, empirical studies were underway to investigate those claims (Allen, 2012).

Thus, there are multiple ways to reuse treated greywater. A context-sensitive decision should be made, since each design scenario is unique. Once an end use has been chosen, treatment methods should be selected and designed to elevate the water quality to required levels (but no further, to avoid overtreatment).

Design criteria

Various greywater standards or design criteria have been proposed, but they have not been consolidated into any universally-recognized set of standards; perhaps this is one of the sources of confusion surrounding greywater (Al-Jayyousi, 2003; Sheikh, 2010). Additionally, some of the existing guidelines may not specify where in the water reuse cycle the indicator organism measurements should be taken/applied, thus adding to the confusion (Dixon et al., 1999).

Dixon et al. (1999) calls for the development of a set of greywater reuse criteria (relating to “system sizing, treatment, maintenance requirement and operation”) based on the following conditions:

- Residence time of greywater in the system kept to a minimum in order to minimize microbial proliferation;
- Human exposure to greywater kept to a minimum;
- Odor kept to a minimum;

- Biofilm prevented; and
- Components clearly labeled.

Additionally, it has been proposed that the recycled greywater itself should fulfill four criteria: hygienic safety, aesthetics, environmental tolerance, and technical and economic feasibility (Al-Jayyousi, 2003; Li et al., 2009; Nolde and Dott, 1991). In an effort to elucidate these broad criteria, Li et al. (2009) proposed a set of water quality standards for greywater based on the reuse application.

For the application of home garden irrigation, Al-Jayyousi (2004) recommends secondary treatment plus filtration and pathogen reduction (with the filtration necessary to facilitate the pathogen reduction). Pathogen reduction could be accomplished by chlorination or by detention in lagoons. For those systems utilizing a filter, Christova-Boal (1996) describes the ideal disposable filter as one that is cheap, efficient, in-line, cartridge-based, and provides a large surface area (to maximize time between filter changes).

Greywater systems must also balance accessibility and sustainability (Maimon et al., 2010). For accessibility that encourages wider use, greywater recycling should be simple and affordable. Wider usage would increase overall water savings. Meanwhile, environmental husbandry and public health protection must not be neglected (Maimon et al., 2010).

Discussion of sustainability

In isolation, greywater reuse cannot be defined as sustainable – it must be incorporated with other responsible water practices to achieve optimum sustainability (Parkinson et al., 2005). Thus, other techniques such as xeriscaping, rainwater catchment, low-flow fixtures and appliances, composting toilets, etc. should also be considered when designing a project for sustainable water management. Greywater reuse must be considered holistically (and critically) within the system's social, economic, and environmental context (Anastas, 2003).

Social sustainability

Public health

Ludwig (2006) argues that since there are no reported cases of sickness due to greywater reuse – despite thousands of operational systems – greywater reuse must not pose a significant public health risk if done properly. However, Sheikh (2010) points out that the absence of public health investigations related to greywater makes this statistic (or non-statistic) only marginally meaningful. Nevertheless, personal interviews conducted by the author provide anecdotal evidence that public health risks are minimal if basic precautionary procedures are followed (Allen, 2011; Benninger, 2011; Gomes, 2011; Lara, 2011; Nicolaus, 2011; Yaffe, 2011). Of course, empirical evidence is preferable to anecdotal evidence (empirical data collection is currently underway in

California to verify these anecdotal accounts (Allen, 2012)), but until empirical data becomes available, anecdotal reports can be informative.

Other sources claim that there is a public health risk inherent in greywater because it contains significant levels of various contaminants. Casanova (2001) found total coliforms, fecal coliforms, and *Pseudomonas aeruginosa* in greywater to fall in the range typical of raw wastewater, while other contaminants such as fecal streptococci, turbidity, biological oxygen demand (BOD), total suspended solids (TSS), and chlorides to fall somewhere between raw wastewater and secondary effluent.

One way of reconciling these two seemingly disparate views is found in a conceptual model of risk given by Dixon et al. (1999). The concept is that risk is proportional to the product of hazard and exposure ($risk = hazard \times exposure$), which means that risk is reduced not only by removing hazards (e.g., treating greywater to inactivate pathogens) but also by limiting human contact with the greywater (e.g., via subsurface irrigation methods). Therefore, while Casanova (2001) may be correct in identifying the public health *hazards* associated with untreated greywater, Ludwig (2006) and others may also be correct in saying that greywater poses a low *risk* to human health so long as *exposure* is kept to a minimum.

Public acceptance

Designs for water conservation or reuse are successful only if they are correctly implemented and operated. Because the performance of greywater systems is inherently dependent on user behaviors and user behaviors are influenced by education, Tarantini and Ferri (2003) highlight education as a crucial element in achieving water sustainability. Also, Al-Jayyousi (2004) explains that knowledge ultimately resides in the user (not in a collection of information) and is gained through action. Thus, one task that must be organized – perhaps by water utilities – is the creation of a context within which knowledge may be created, shared, and accumulated (Al-Jayyousi, 2004). If water utilities embrace greywater and want their clients to do the same, then the utilities must reach out to facilitate education.

Additionally, public acceptance for greywater tends to increase where there are external factors driving people toward choosing greywater of their own volition. Sandman (1995) and Sheikh (2010) explain how voluntary risks (e.g., driving a car, where one is in control) are more palatable to people than involuntary risks (e.g., riding on a plane, where the pilot is in control). Factors that lead people to choose greywater of their own volition may include drought and water rationing, increases in water prices, and a desire to be environmentally responsible (Sheikh, 2010). Also, public acceptance is generally higher for toilet flushing than for more "personal" uses such as vegetable irrigation (Lazarova et al., 2003; Camp Dresser & McKee, 2004, 224).

Social justice

In studies cited by Al-Jayyousi (2004), it was shown that using greywater to irrigate small home gardens can measurably reduce poverty by reducing food expenditures for families (up to 44% for the poorest families). Additionally, greywater reuse for home gardening improved the sense of independence, self-confidence, and environmental awareness of women participating in a pilot project in Ain El Baida (a suburb of Tufileh, Jordan) (Al-Jayyousi, 2004). Thus, greywater reuse can serve as a liberating technology, helping lower-income users escape from poverty. The key question then becomes one of accessibility – how accessible is greywater reuse to potential lower class users?

Economic sustainability

For homeowners

Although cost savings is not the primary motivation for most homeowners who reuse greywater (Sheikh, 2010), public-relations campaigns often claim that greywater reuse systems will pay for themselves eventually. For example, simple greywater treatment systems in the United Kingdom are reported to have payback periods of eight years (Jefferson et al., 2000). This view is so prevalent that many people take it for granted: residents of Melbourne, Australia, said that they would only be interested in greywater reuse if the system had a short (two to four year) payback period (Christova-Boal et al., 1996).

However, when Memon et al (2005) performed a rigorous whole-life cost analysis on greywater recycling systems, they found that all of the small-scale system scenarios they had analyzed would result in a net <u>cost</u> over the life of the system. The net present value of these costs ranged from approximately £2,000 to approximately £3000, or approximately US$3,800 to US$5,800 (based on a conversion factor of 1.9224

USD per 1 British Pound Sterling, which was effective on 11 March 2005 when the Memon et al. paper was published). The only system that offered a net economic benefit for the owners was a large-scale system that was 100% efficient (i.e., provided all of the water necessary for flushing toilets) (Memon et al., 2005). Of course, the study only considered toilet flushing and ignored other possible applications such as irrigation. Nevertheless, the economic sustainability of greywater reuse could be improved by conducting further research and development to help reduce system costs.

It should be noted that less sophisticated greywater systems can be installed for a lower cost than those described in Memon et al. (2005) (Ludwig, 2006). These sacrifice water quality for simplicity and affordability; therefore it would be necessary to limit human exposure to the reused water in order to minimize risk (see Public health discussion above).

For water utilities

Parkinson et al. (2005) modeled the effects of domestic water conservation (i.e., low-flush toilets, greywater reuse, and rainwater reuse) on urban sewer systems and found both positive and negative effects. Notably, greywater reuse was the most likely (of the three technologies modeled) to cause increased sediment deposition in sewer lines due to decreased wastewater flow velocities. Presumably, increased sediment deposition would impair sewer functionality and incur higher maintenance costs. Greywater reuse also caused the most concentrated wastewater stream in terms of suspended solids (SS), biological oxygen demand (BOD), chemical oxygen demand

(COD), and nitrogen as ammonia (Parkinson et al., 2005). However, the increased concentrations were not problematic and even resulted in a slight (but insignificant) increase in treatment efficiency at the central wastewater treatment plant.

Nevertheless, Sheikh (2010) predicts that even widespread greywater reuse is unlikely to have a significant impact on water and wastewater utilities. One reason is that homeowners who have enough land to consider irrigating with greywater will likely not have a city sewer connection; they are more likely to be rural residents who have their own septic system. Another reason is that the number of homes reusing greywater will likely never become a majority of the population, so although individual homeowners may enjoy significant water savings (in terms of percentage) from greywater reuse, the municipality will not see such drastic reductions (Sheikh, 2010).

Environmental sustainability

Small-scale perspective

As noted previously, there is a reported risk of surfactant accumulation in soil that has been irrigated with greywater (Wiel-Shafran et al., 2006). Also, there is a chance that poorly managed greywater can run off into surface waters, or soak through the soil into groundwater aquifers, in both cases potentially contaminating freshwater sources.

Large-scale perspective

Through a large-scale life-cycle assessment, Tarantini and Ferri (2003) found that the largest environmental impact from water and wastewater systems (with the exception of eutrophication) comes from the production of electricity needed for pumps. Their study found that widespread domestic water conservation (using both rainwater and greywater reuse) resulted in a net decrease in primary energy production, representing increased environmental sustainability. It should be noted that a portion of the calculated energy savings came from detergent production, because the harvested rainwater was used for dishwashing and reduced the need for detergent (compared with tap water) (Tarantini and Ferri, 2003). These energy savings would only be realized if homeowners were cognizant of this interdependency and altered their behavior to take advantage of it. Other potential environmental benefits might include reduction or deceleration in ground subsidence caused by aquifer over-withdrawal; reductions in the amount of chemicals mined for water treatment; and reductions in sludge volumes that must be deposited in landfills, both from water treatment and wastewater treatment.

Comparing risks vs. benefits

People are more likely to accept known, voluntary risks over unknown, involuntary risks (Sandman, 1995; Sheikh, 2010). Therefore, although there may be legitimate risks associated with reusing untreated greywater, homeowners may be willing to accept these risks if they expect a benefit such as improved freedom from water restrictions, improved sense of environmental stewardship, or reduced water bills. However, if a landlord or municipality mandates greywater reuse among unwilling tenants, or if a neighbor's greywater system overflows onto the property of someone else (forcing that person to encounter greywater against their will), the perceived acceptability of the risk will be greatly reduced (Sheikh, 2010).

By definition, sustainable projects must balance present risks with future risks. This means that mitigating risks to present occupants (e.g., by avoiding human contact with greywater) may not imply sustainability if there are risks presented to future occupants (e.g., in the form of hydrophobic/infertile soil due to accumulation of contaminants such as surfactants). A holistic evaluation must be performed to determine whether the potential benefits outweigh the probable risks.

Membrane filtration

Viability

Some authors claim that despite their helpfulness for pretreatment purposes, physical processes alone (including filtration) cannot adequately treat greywater for reuse (Friedler and Alfiya, 2010; Ghunmi et al., 2011a; Li et al., 2009). However, others contend that standalone membrane filtration is a viable option for decentralized greywater treatment and reuse (Friedler and Alfiya, 2010; Nghiem et al., 2006; Ramon et al., 2004). The reasons for each viewpoint are described in detail below.

Benefits of membrane filtration

The primary advantage of using membrane filtration to treat greywater is simplicity (Ramon et al., 2004). Particularly in decentralized configurations where untrained homeowners may be responsible for system maintenance, greywater treatment systems must be straightforward and easy to maintain. The only continual maintenance requirement of a filtration unit is filter cleaning and replacement, which a non-technical user can perform with minimal instruction. Thus the suggested guidelines (Christova-Boal et al., 1996) [see Design criteria discussion above] seek to make disposable filters accessible to nonprofessional owner-operators.

Membrane filtration is also an efficient option (Ramon et al., 2004). Because of the small footprint required, membrane filtration can be used in many retrofit situations where space is limited. This efficiency translates to savings not only in space but also in physical materials required for construction.

Furthermore, membrane filtration units offer a form of modularity that biological treatment does not. If a component in a membrane filtration system fails, the user can purchase and install a replacement immediately. However, if a biological treatment system is incapacitated by a system shock, the user must start over by re-growing the colony of microorganisms, which may take days or weeks (Water for the World). This may be unacceptable in certain contexts.

Finally, membrane filtration, when performed properly, can provide reliable and consistent water quality (Nghiem et al., 2006). Although greywater composition can vary greatly (even from an individual source over time), membrane filters can produce predictable effluent quality throughout their life, though admittedly their lifespans may be shortened if certain mixtures of contaminants are present which induce more rapid fouling (Friedler and Alfiya, 2010; Oschmann et al., 2005).

Disadvantages of membrane filtration

The most salient disadvantage of standalone filtration is its lack of a disinfectant residual. While filtration can itself be a disinfection mechanism (Madaeni, 1999), the filtered effluent is prone to microbial regrowth if not used immediately, and immediate reuse might not be practical in realistic scenarios (e.g., toilet flushing – the water must be stored until the toilet is flushed).

Additionally, direct membrane filtration may have difficulty achieving the desired BOD effluent levels (Ramon et al., 2004). This is due to the fact that most greywater contaminants are either colloidal (Ramon et al., 2004) or dissolved (Friedler and Alfiya, 2010) – capturing these contaminants with a filter would require advanced filtration with ultra-small pore sizes. Among the most difficult contaminants to remove by direct membrane filtration are surface active agents, also known as surfactants (Ramon et al., 2004).

Finally, membrane filtration is an active process requiring a constant input of electricity to power pumps and sensors. Until this electrical load is provided through renewable sources, the high energy requirements for membrane filtration prevent it from being entirely sustainable.

Summary of key points

Greywater reuse is one part of a larger movement toward sustainability and must be viewed within the larger context of social, economic, and environmental sustainability. Public perception regarding the sustainability of greywater reuse is not always in agreement with empirical findings. Therefore education and dialogue are critical for achieving true sustainability. Ongoing research is also warranted.

With the diversity of situations in which greywater may be reused, sustainability must be analyzed on a case-by-case basis. This type of rigorous analysis may be beyond the capabilities of individual homeowners. Thus, there is a need for a standardized set of design criteria which could be adapted to any greywater reuse project to facilitate a sustainable outcome. The beginnings of such criteria may be found in the literature (Al-Jayyousi, 2003; Christova-Boal et al., 1996; Dixon et al., 1999; Nolde and Dott, 1991). Furthermore, a third-party certification body such as NSF International could certify greywater treatment units based on their intended application; the NSF/ANSI 350 standard seeks to do just that (NSF International, 2011).

Membrane filtration is one promising treatment option that is gaining popularity. Further research to help increase the efficiency and longevity of filter systems would be beneficial. Specifically, identifying a way to remove surfactants from the greywater stream could help solve one of the most difficult challenges with direct membrane filtration systems for greywater (Ramon et al., 2004).

CHAPTER 2

EXPERIMENTAL METHODS

Experimental objectives

The preceding literature review provided a broad context for this experiment. However, an internship that the author completed in the summer of 2011 ultimately motivated the objectives for the thesis (see APPENDIX A). For the purpose of this thesis, the experimental objectives were as follows:

1. To determine whether GAC or sand pretreatment would significantly reduce the flux decline observed when performing microfiltration of greywater.
2. To determine whether GAC or sand pretreatment would significantly improve the effluent water quality produced by microfiltration of greywater.

Overview

The experimental setup (shown in Figure 1 below and diagrammed in Figure 2 and Figure 3) was designed to accommodate a two-phase treatment system.

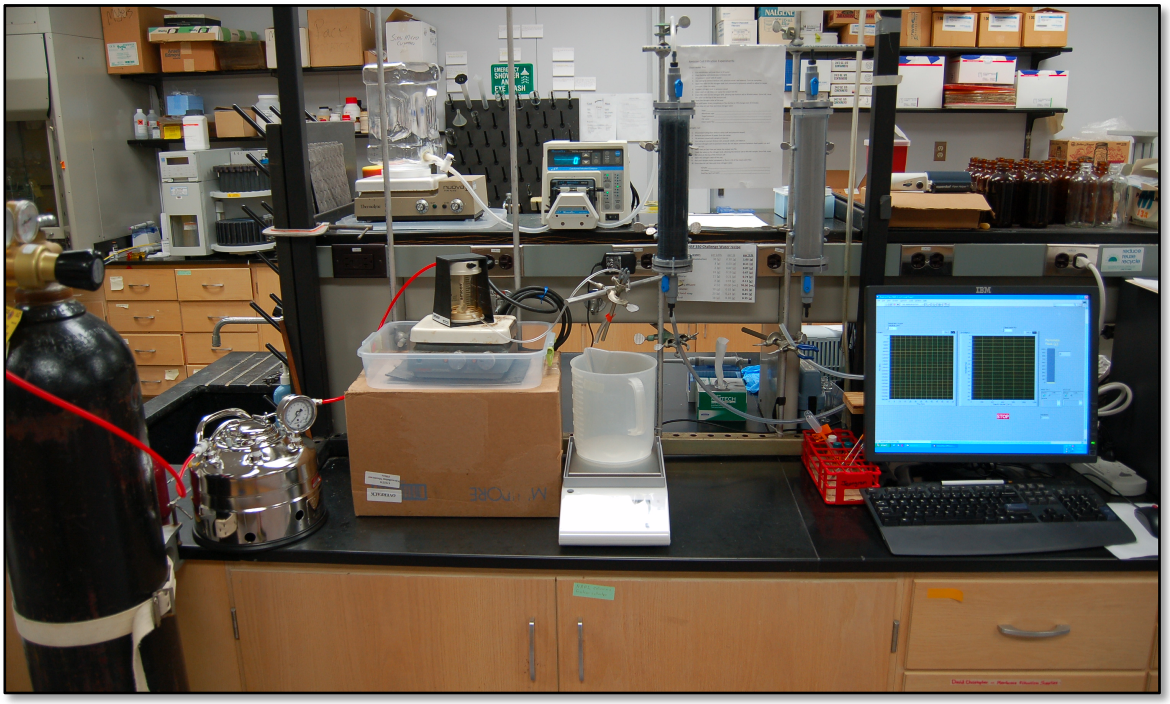


Figure 1. Photograph of experimental setup.

Phase one was **pretreatment**. During this phase, the synthetic greywater was pumped from the reservoir through a pretreatment column at a fixed flow rate by means of a peristaltic pump. The treated effluent was captured in an empty pressure vessel.

Phase two was **membrane filtration**. During this phase, pretreated water in the pressure vessel was filtered through a low-pressure membrane and captured in a container. The pressure source driving the filtration was a tank of compressed nitrogen gas outfitted with a pressure regulator. Flux through the membrane was calculated by monitoring (electronically) the accumulated mass in the container.

Samples were taken at each step of the process (i.e., before treatment, after pretreatment, and after membrane filtration). These samples were then analyzed to quantify each of the experimental parameters (turbidity, total organic carbon (TOC), chemical oxygen demand (COD), and surfactants).

Each of the components and steps introduced above are further explained below.

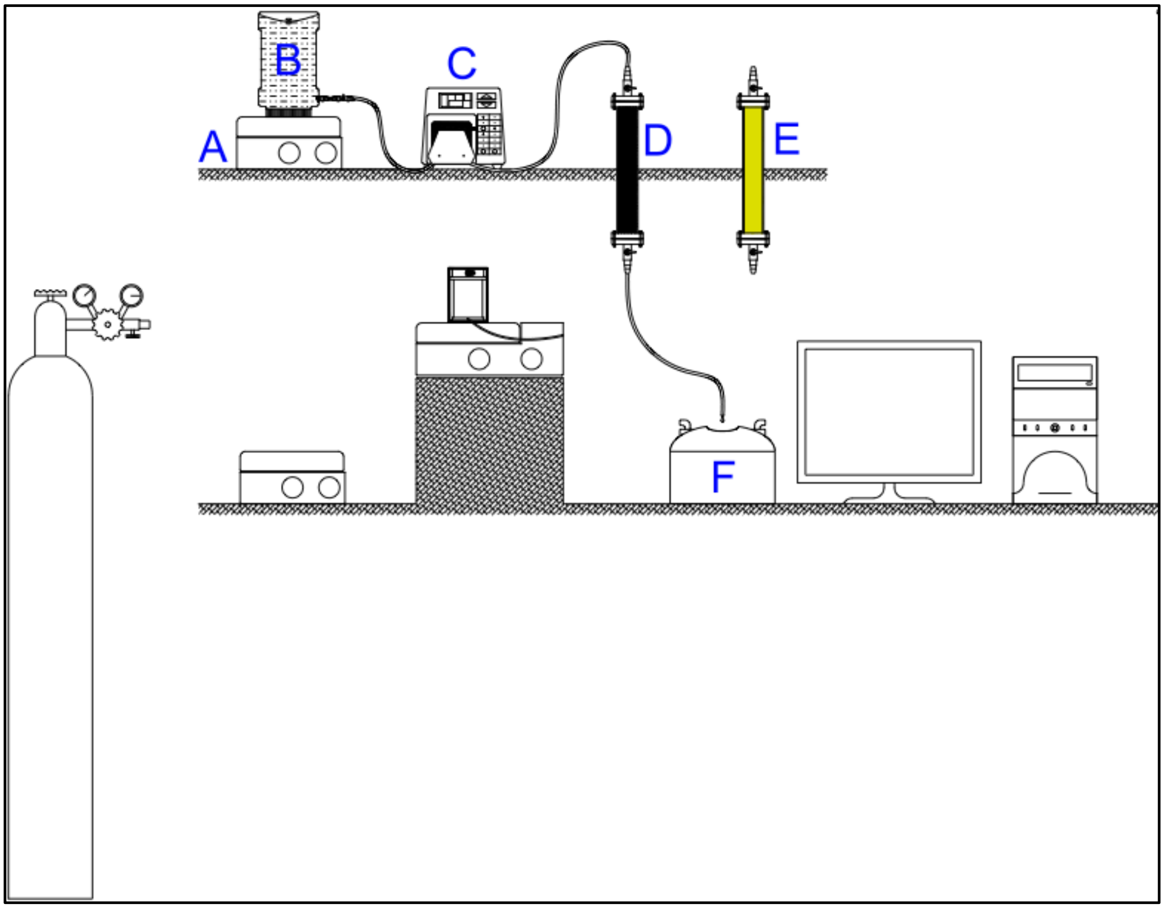


Figure 2. Diagram of experimental setup during pretreatment phase.

Table 1. List of components for pretreatment.

Component labels correspond to those in Figure 2 above.

Label	Component name
A	Stir plate
B	Reservoir
C	Peristaltic pump

Label	Component name
D	GAC column
E	Sand column
F	Empty pressure vessel

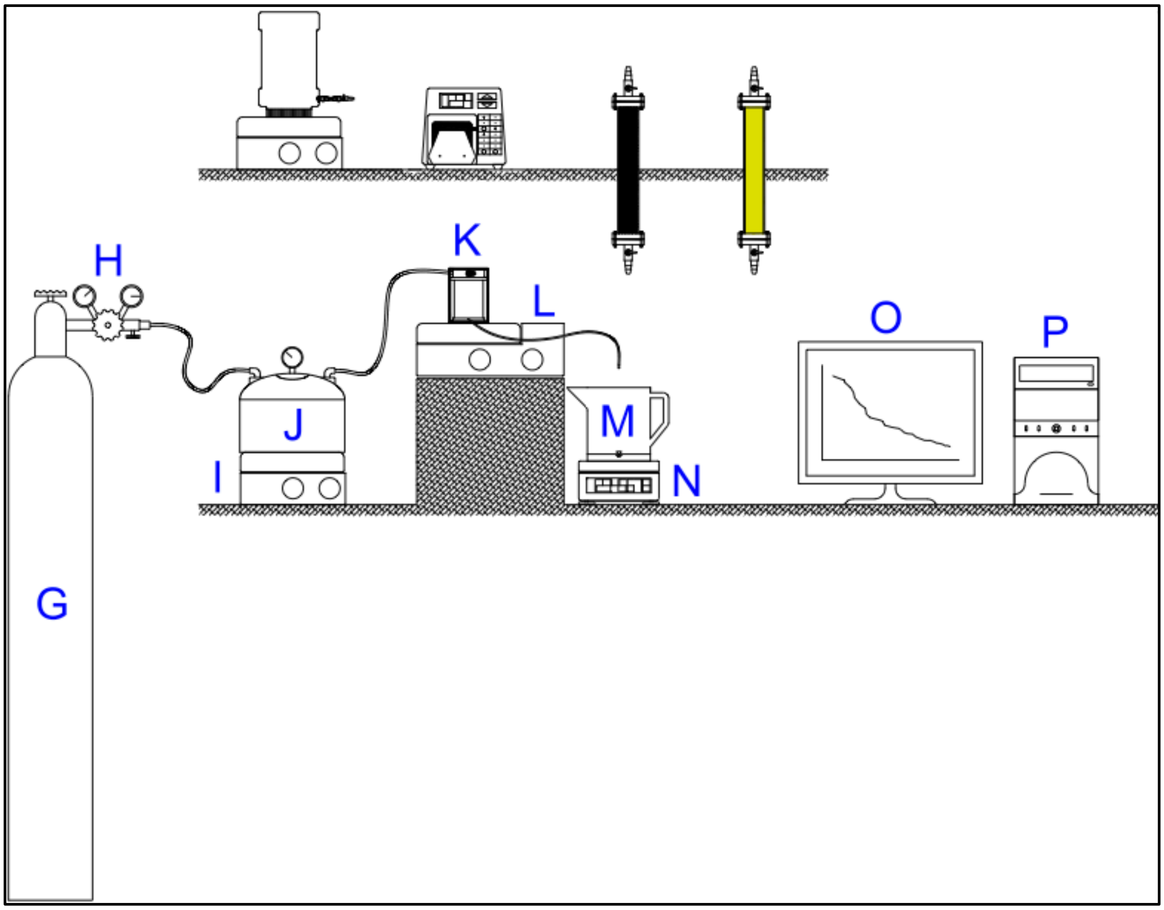


Figure 3. Diagram of experimental setup during membrane filtration phase.

Table 2. List of components for membrane filtration.

Component labels correspond to those in Figure 3 above.

Label	Component name	Label	Component name
G	Nitrogen gas tank	L	Stir plate
H	Gas pressure regulator	M	Container
I	Stir plate	N	Electronic balance
J	Dispensing pressure vessel	O	Computer monitor
K	Membrane filtration cell	P	Desktop computer

Experimental apparatus

Detailed descriptions of the component parts and the fabrication process for each experimental apparatus are given in APPENDIX B, including manufacturer catalog numbers. The following is a general summary of that information.

Reservoir

A reservoir for mixing NSF/ANSI 350 challenge water, using a stir plate and magnetic stir bar, was constructed from a 1-gallon wide-mouth plastic jar. The lid of the reservoir served as a weigh boat for measuring reagents, and once screwed together, the entire reservoir assembly (body and lid) rested on a stir plate, with the lid of the reservoir on the bottom. This placed the stir bar in direct contact with the reagents that had been measured into the lid of the reservoir.

Pressure vessel

A one-gallon (3.78 liter) Millipore stainless steel pressure vessel outfitted with a pressure gauge and quick-disconnect couplings was used to dispense feed water into the Amicon MF cell for microfiltration. This vessel was continuously stirred during the microfiltration process via a magnetic stir bar placed inside the vessel.

Connection to gas tank

The gas tank was connected to the dispensing pressure vessel using quick-disconnect fittings and crack-resistant polyethylene tubing, which allowed rapid assembly and disassembly. The pressure regulator remained connected to the gas tank at all times.

Pretreatment columns

Two 12-inch long pretreatment columns were constructed using clear PVC pipe with an internal diameter of two inches. Figure 4 below shows the dimensions of the columns. At each end of each pretreatment column was a ¼ inch barbed fitting for connecting ¼ inch inner diameter Masterflex tubing. A valve controlled the flow at each end of the column.

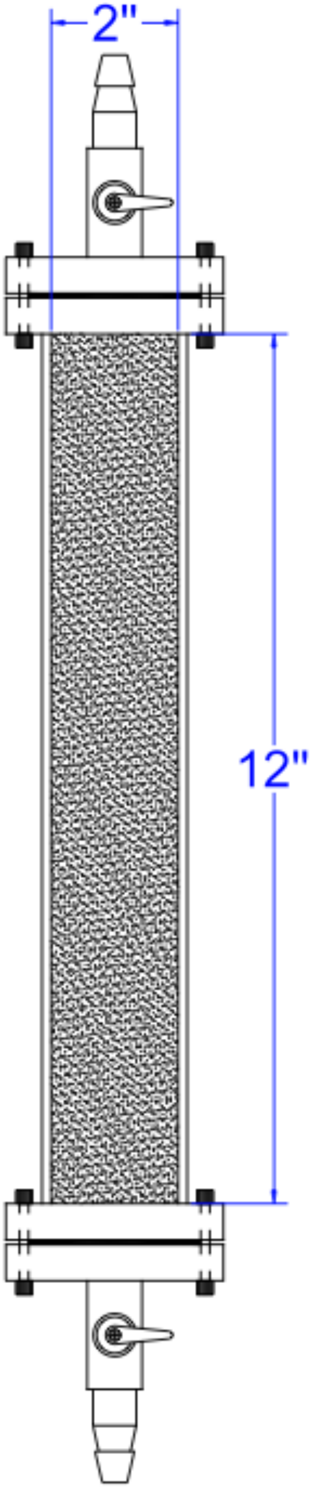


Figure 4. Detail of pretreatment column construction.

MF cell

An Amicon microfiltration (MF) cell (Amicon Stirred Cell, Model 8200, 200 mL capacity, 63.5 mm diameter, pressure driven, Millipore catalog number 5123) was assembled in a dead-end configuration as recommended by the manufacturer. Feed water was delivered from the pressure vessel (described above) via ¼ inch polyethylene tubing, and treated effluent was collected through $^{3}/_{32}$ inch laboratory tubing.

Preparation of NSF/ANSI 350 challenge water

Justification

Guidelines published by the NSF – “The public health and safety company” – are internationally recognized performance standards (Gordon, 2008). The newly published *NSF/ANSI Standard 350-1 – Onsite residential and commercial water reuse treatment systems* (NSF International, 2011) is directly relevant to the field of greywater treatment and reuse, because greywater treatment systems fall within the category of onsite water reuse treatment systems. Because this standard is one of the first attempts to certify (and thus standardize) greywater treatment systems, the criteria in NSF/ANSI 350 are a reasonable baseline for future research.

“Bathing source” greywater was selected for analysis because the original context surrounding this treatment scheme (i.e., bathroom sink greywater) falls within the “bathing source greywater” classification as the NSF/ANSI 350 standard defines it. For the sake of simplicity, the recipe for Bathing Source Challenge Water (tabulated on page 12 of the Standard) was scaled linearly to create 3.5-liter batches, as shown in Table 3 below.

The formula recommended in the NSF/ANSI 350 standard (p.12) was treated as a fixed recipe, without attempting to fine-tune the resultant mixture to meet specified criteria. This was a deviation from the recommendations given on page 13 of the standard. However, it was deemed necessary in order to streamline the testing process and enable a single person (the author) to perform all of the necessary tasks for testing and subsequent data collection.

Procedure

With the upside-down lid of the reservoir serving as a weigh boat, the reagents listed in Table 3 (below) were carefully weighed on an electronic balance (Mettler Toledo precision balance, model MS3002S, 0.01 g readability).

Table 3. Reagents used to create synthetic "bathing source" challenge greywater.

Adapted from section 8.1.2.1.1 of NSF/ANSI 350 standard

Reagent type	Reagent specifications	Quantity per 3.5L batch
Body wash with moisturizer	Johnson's Body Care 24 Hour Body Lotion, 20 fl. oz. UPC: 3-8137-005241-8	1.05 g
Toothpaste	Colgate Fluoride Toothpaste Great Regular Flavor, 6.4 oz. UPC: 0-35000-50900-0	0.11 g
Deodorant	Gillette Odor Shield Antiperspirant/ Deodorant; All Day Clean, 2.6 oz. UPC: 0-47400-50019-8	0.07 g
Shampoo	Suave Naturals Shampoo Daily Clarifying, 22.5 fl. oz. UPC: 0-79400-76750-9	0.67 g
Conditioner	Suave Naturals Conditioner Refreshing Waterfall Mist, 15 fl. oz. UPC: 0-79400-92290-8	0.74 g
Lactic acid	EMD Lactic acid, 85% GR ACS Product number LX0020-6 Received 12/4/2009, Opened 01/27/2010	0.11 g
Secondary effluent	Effluent water was collected from the Pendleton Waste Treatment Plant after the final clarifier but before disinfection.	70.0 mL
Bath cleaner	Lysol Disinfectant Bathroom Cleaner Island Breeze® Scent, 32 fl. oz. UPC: 0-19200-02699-4	0.35 g
Liquid hand soap	Dial Gold Hand Soap with Moisturizer Antibacterial, 9.375 fl. oz. UPC: 0-17000-08507-4	0.81 g
Test dust	ISO 12103-1, A2 - Fine test dust Purchased from Powder Technology, Inc., 14331 Ewing Avenue, South, Burnsville, MN 55306	0.35 g

After all of the reagents except the secondary effluent had been measured into the lid of the reservoir, a five-gallon plastic reservoir of secondary effluent was removed from the refrigerator and rotated 90° (to move the spout from facing upwards to facing sideways) immediately before dispensing 70.0 mL of the effluent into a 100 mL plastic graduated cylinder. This effluent sample was poured into the empty reservoir body, the reservoir was filled to the 3.5-liter mark with cold tap water, a two-inch Teflon-coated magnetic stir bar was added to the jar, and finally the lid containing the measured reagents was screwed onto the top of the jar. This entire assembly was inverted and placed onto the stir plate (Barnstead/Thermolyne *nuova II* Stir Plate, Model No. SP18425) for mixing.

The stir plate was turned on to highest speed setting (10 out of 10) and allowed to stir for at least three hours. During this time, the ventilation hole remained sealed (to prevent evaporation) and the sampling valve was kept closed.

Figure 5. Photograph of primary ingredients in challenge water recipe.

Cold tap water was used to prepare the challenge water because the stir plate stirring the challenge water tended to become warm as a result of stirring for three hours or more. Thus the challenge water was always warmed to room temperature before usage and sampling. Hot tap water would have introduced excessive heat into the system.

Sampling of raw (untreated) challenge water

After the three hour mixing period had passed but before any treatments were applied, the sampling valve was opened briefly to flush a small portion of test dust that always tended to settle in the neck of the sampling valve (this undesirable settling was unavoidable). Then, by opening the sampling valve again, samples of the raw challenge water were collected in either plastic or glass sample vials and labeled based on the analysis that would be performed (e.g., TOC, COD, turbidity, surfactants).

Pretreatment step (filtration columns)

Procedure

After the small sample of untreated water had been collected, a length (approximately two feet) of flexible plastic tubing (Masterflex platinum-cured silicone tubing, size L/S 17) was used to connect the effluent valve of the mixing reservoir to the influent valve of one of the filtration columns (either GAC or sand) by means of the peristaltic pump. A second length of tubing was connected to the effluent valve at the bottom the column and positioned so that it would drain into the empty pressure vessel placed below the column (see Figure 2).

For pretreatment, the flow rate on the peristaltic pump was set to 1000 mL/min (1 L/min), the tape covering the ventilation hole was removed, and the pump was turned on. The challenge water (continuously stirred within the reservoir) was pumped at this fixed rate from the reservoir into the pretreatment column until the reservoir was as empty as possible (there was some raw water left in the reservoir due to the offset between the sampling valve opening and the bottom of the reservoir). Toward the end of each run (once the water level in the reservoir dropped below the level of the effluent valve), the reservoir was manually tilted to one side to allow the remaining water to flow into the valve as much as possible.

During the pretreatment step described in the previous paragraph, multiple samples were collected, typically at 10-second intervals. A multi-track stopwatch program on the computer was used to synchronize the timing of sample collection. Samples were collected in turbidimeter vials, tested for turbidity as soon as possible, and then divided into other sample vials for further testing (COD, TOC, and surfactants). Samples to be tested for COD were preserved by acidifying them with two or three drops (depending on the sample volume) of 2M sulfuric acid (H_2SO_4). Similarly, samples to be tested for TOC were preserved by acidifying them with two or three drops (depending on the sample volume) of 2M hydrochloric acid (HCl). After addition of the acid, the sample vials were capped and inverted at least seven times, then placed into a refrigerator until testing. Samples to be tested for surfactants were refrigerated without acidification (as per the Hach colorimeter procedures manual (Hach Company, 2009)).

After the pretreatment pumping was finished, the tubing connected to the influent valve of the pretreatment column was disconnected. Then, once the effluent flow from the column had slowed from a steady stream to a drip, the tubing was also removed from the effluent valve. Both the influent and effluent valves were left open so that water could drain freely while the column was not in use; an empty beaker was placed below the column to catch any remaining effluent.

Empty bed contact time

The empty bed contact time (EBCT) value for the pretreatment columns was chosen indirectly, based on the capabilities of the peristaltic pump that was available in the lab and the dimensions of the PVC pipe that housed the pretreatment columns. The goal was to use even measurements to facilitate construction of the apparatus and replication of the experiment in the future if necessary.

Thus, the pretreatment columns were constructed as cylinders with a height and inner diameter of 12 inches and 2 inches, respectively. These dimensions seemed reasonable for a pretreatment column intended for use under a bathroom sink. The total volume for each column was thus 37.7 in^3, or 0.618 L. Also, a constant flow rate of 1 L/min was chosen, producing an empty bed contact time (EBCT) of

$$Volume\ of\ column = 0.618\ L$$

$$Flow\ rate\ through\ column = 1.0\ \frac{L}{min}$$

$$EBCT = \frac{Volume\ of\ column}{Flow\ rate\ through\ column} = \frac{0.618\ L}{1.0\ \frac{L}{min}}$$

$$\boldsymbol{EBCT = 0.618\ min} \tag{1}$$

Treatment step (microfiltration)

Membrane soaking

In preparation for microfiltration (MF), an unused membrane (MF membrane, mixed cellulose esters, hydrophilic, 0.22 µm, white; Millipore catalog number

GSWP09000) was modified to a 2 ½ inch diameter using a round arch punch (round arch punch, 2 ½ inch diameter, purchased from Brettun's Village Leather online) and a plastic cutting board (small cutting board, 8 in x 12 in, purchased from Brettun's Village Leather online). A 600 mL beaker was filled approximately to the 200 mL mark with distilled water, and the cut membrane was submerged in the water to soak for at least 30 minutes.

Clean water run

After the 30-minute soaking period, the membrane was placed in the MF cell. The pressure vessel (as described above) was filled with distilled water up to the level where the sidewalls joined the rounded top of the vessel, and then the vessel was connected to the filtration cell using plastic pressure tubing (crack-resistant polyethylene tubing, 0.170 in inner diameter, ¼ in outer diameter, 0.04 in wall thickness, red; McMaster-Carr catalog number 5181K231). Approximately eight inches of effluent tubing (Tygon® laboratory tubing, formulation R-3603, Saint-Gobain Performance Plastics, $^{3}/_{32}$ in inner diameter, $^{5}/_{32}$ in outer diameter; VWR catalog number 63010-010) was connected to the effluent port of the membrane cell and positioned so that it would drain into an empty 3-liter plastic container located on the electronic balance.

With the nitrogen gas tank still disconnected from the pressure vessel, the pressure regulator was adjusted to the target pressure of 10 psi and then the gas flow valve was closed completely. Next, the LabVIEW program was opened on the computer and the membrane diameter (2.5 in, or 63.5 mm) was input in the appropriate box on the “Front Panel” of the program. The program was then initiated by pressing the “Start” button and a file name and location were specified. Next, the gas tank was connected to the pressure vessel, the gas flow valve was opened slightly to allow the membrane cell to fill with distilled water, and then the pressure relief valve on the top of the membrane cell was closed. After this, the gas flow valve was opened completely (to allow gas pressure to reach the target value of 10 psi) and the stir plate housing the membrane cell was turned on, stirring the stir bar within the cell at speed 2 out of 7 (Corning Laboratory Stirrer/Hotplate, Model PC-320).

The flux through the membrane was calculated automatically in the LabVIEW program by dividing the volumetric flow rate through the membrane (in units of cubic meters per second) by the cross sectional area of the membrane (in units of square meters). After unit conversions, the flux value was reported in the standard units of lmh, or liters per square meter per hour.

Distilled water was allowed to run through the membrane for approximately ten minutes and then the program was stopped and the gas flow valve was closed. By importing the LabVIEW output data into Microsoft Excel, the average clean water flux value was calculated by taking the average of the flux values during the last two minutes of the clean water run.

After the clean water run was completed, all tubes were disconnected from the pressure vessel and membrane cell, and all distilled water was removed from the system. Once the empty pressure vessel had finished drying, it was used to collect effluent from the pretreatment run.

Sample run

After the pressure vessel was filled with effluent from the pretreatment process, the membrane filtration process was repeated using sample water instead of distilled water. In order to keep the sample water well-mixed during the filtration process, the pressure vessel was placed on top of a stir plate, a stir bar was placed inside the pressure vessel, and the stir plate was set to stir at setting 5 out of 9. All other steps were followed as explained previously in the clean water run section.

The sample run was allowed to continue for at least 20 minutes or until the flux values appeared to stabilize, whichever came later. The LabVIEW program was then stopped and the system was depressurized. Samples of final effluent water were collected and analyzed for turbidity, surfactants, TOC, and COD. As described previously, samples to be analyzed for TOC and COD were acidified and refrigerated to preserve them until analysis could be performed.

Water quality methods

Turbidity

Samples were collected in Hach turbidimeter sample cells (lab turbidimeter sample cells; Hach product number 2084900) and analyzed for turbidity using a Hach ratio turbidimeter (2100N laboratory turbidimeter; Hach product number 4700000).

Before taking any sample readings, the turbidimeter was allowed to warm up for at least 30 minutes and then the accuracy of the turbidimeter was checked by comparing the turbidity readings to the values of known standards (StablCal® turbidity standards calibration kit, sealed vials; Hach product number 2662105).

The experimental sample cells were prepared by following a three-step procedure for each vial immediately before taking a reading. First, the sample cell was rapidly inverted seven times to mix the contents. Second, the outside of the cell was thoroughly dried and cleaned using a lint-free wipe. Third, the outside of the cell was thoroughly polished using a sample cell oiling cloth (Hach product number 4707600).

Immediately after completing the three preparatory steps, the sample cell was placed into the turbidimeter. The turbidity reading was taken as the average of (a) the first value displayed by the turbidimeter, and (b) the highest value ultimately displayed by the turbidimeter. It should be noted that this is not the method officially recommended by the turbidimeter manufacturer; the manufacturer recommends waiting until the reading has stabilized before recording the value (Hach Company, 2012a). However, due to the high quantity of suspended particles that tended to settle quickly within the samples (especially for samples of the challenge water before pretreatment), it was determined that this method provided a value more representative of the true turbidity of the samples.

COD (closed reflux, colorimetric method)

The chemical oxygen demand (COD) of the synthetic greywater was measured before pretreatment, after pretreatment, and after microfiltration. The *Closed Reflux, Colorimetric Method* (provided in APPENDIX C) was used in conjunction with COD reagent vials distributed by Bioscience Inc. This method involved adding a 2.5 mL sample to the reagent vial, digested for two hours at 150°C, allowed to cool to room temperature, and then analyzed for absorbance at 440 nm using a spectrophotometer (Milton Roy Spectronic 20D, Item number 333175). A calibration curve was created using samples of known concentration and then used to determine the values of all other samples. In all cases, the stock solutions of known concentration were dated and used within two weeks of their initial preparation.

TOC

The TOC (total organic carbon) levels in the greywater were measured before pretreatment, after pretreatment, and after microfiltration using a Shimadzu TOC analyzer (model TOC-V CSH). APPENDIX D provides a detailed explanation of the procedure. TOC samples were diluted (typically to one-fifth of their original concentration) in order to avoid fouling the TOC analyzer with excess residue. These dilutions were noted and taken into consideration when calculating the true TOC concentrations reported for each sample. Stock solutions of known value were also used to create a calibration curve for each batch of TOC samples analyzed. Using Microsoft Excel 2011 and the TREND() function, linear interpolation was used to calculate the concentrations of each sample based on the known values in the calibration curve. In order to avoid residual contamination between readings, samples were loaded into the analyzer in order of increasing concentration, and blank samples consisting only of DDI (distilled deionized) water were placed before and after each set of samples.

Surfactants

Surfactants were measured using a portable colorimeter and *Method 8028: Surfactants, Anionic* (also known as the *Crystal Violet Method*) (Hach Company, 2009). The procedures are given in their entirety in APPENDIX E. In brief, a sample was collected, diluted to 300 mL, and placed into a separatory funnel with a sulfate buffer solution. Prepackaged violet dye was added to the mixture, and then 30 mL of benzene was added. After a 30-minute reaction period, the water was discarded and the amount of dye that had partitioned into the benzene was measured using a Hach portable colorimeter. The colorimeter converted this reading to a measure of anionic surfactants (in terms of mg/L as LAS).

Flux decline

The flux data collected using the LabVIEW program was normalized by dividing each sample flux value by the average clean water flux value for that membrane:

$$Normalized\ flux = \frac{Sample\ flux}{Average\ clean\ water\ flux} \times 100\% \qquad (2)$$

This put the flux in terms of a percentage so that results from multiple runs could be compared equitably.

CHAPTER 3

EXPERIMENTAL RESULTS AND DISCUSSION

Terminology

The following results report contaminant levels before pretreatment, after pretreatment, and after microfiltration (MF). It should be noted that the “after pretreatment” values represent samples collected at slightly different times depending on the parameter in question. For TOC, COD, and surfactants, the values represent samples collected immediately after effluent began flowing from the pretreatment columns (i.e., early effluent). For turbidity, the values represent samples collected 10 seconds after effluent began flowing from the pretreatment columns. This is because turbidity values (especially for sand pretreatment) were initially high but dropped to a lower, stable value within 10 seconds. Thus it seemed that the 10-second turbidity reading was more representative of the pretreatment performance.

Furthermore, it should be noted that the feed water for microfiltration treatment was the entire 3.5-liter batch of pretreated sample water, not merely the early effluent from the pretreatment columns. Thus, there may be some minor discrepancy between the values reported for “after pretreatment” and the values that were actually present in the feed water for microfiltration. However, this discrepancy is believed to be insignificant.

Ultimately, the decision was made to report the early effluent quality because those values would be most useful for future researchers and designers. The 3.5 L batch size was chosen arbitrarily to facilitate the logistics of this experiment, and it was kept constant only for the sake of experimental consistency. However, not every flow through a greywater treatment system will be fixed at 3.5 L. In fact, influent flow volumes will vary appreciably. However, every flow through the system will produce some amount of "early effluent," and designers will be interested in knowing the composition of this effluent. Thus, the early effluent values were report in this thesis.

Finally, in the data tables, "average value" refers to the arithmetic mean as calculated using the AVERAGE() function in Microsoft Excel 2011, and "standard deviation" refers to the standard deviation of the population of all relevant values as calculated using the STDEV.P() function in Microsoft Excel 2011.

Pretreatment column flow rate

In this experiment, the flow rate through the pretreatment columns was fixed at 1 L/min, or 0.26 gal/min. Since 1998, the maximum flow rate for new faucets has been limited to 8.3 L/min, or 2.2 gal/min (US EPA, 2007). That maximum is significantly above the value used in this experiment, which is admittedly a potential source of error. However, the term "challenge water" (NSF International, 2011) highlights the fact that the prescribed recipe of synthetic greywater is conservative (i.e., more contaminated than average bathroom sink or shower effluent). Therefore the higher contamination level in the challenge water may compensate for the lower flow rate used in this experiment.

Limits and goals for reuse

In three of the graphs below, a band of yellow shading is shown between two horizontal dashed lines. These dashed lines indicate (a) the maximum permissible contaminant level for which a water sample may be reused (the “limit for reuse”) and the recommended contaminant level for water reuse (the “goal for reuse”). These reuse limits are drawn from a document published by the US EPA entitled “Guidelines for Water Reuse” (authored by Camp Dresser & McKee (2004) in cooperation with the US EPA). These limits are non-binding recommendations and are based on a survey of current practices around the world. Since the US EPA is a widely regarded authority in matters of water treatment, these limits were chosen as the standard of comparison for the results of this research.

Turbidity removal

The results for removal of turbidity are shown in Figure 6 below. The data used to generate the graph are shown in Table 4, and all of the turbidity data collected in the course of the experiment are given in **APPENDIX F.** The 30 NTU limit for reuse and 0.1 NTU goal for reuse indicated in Figure 6 come from US EPA Guidelines for Water Reuse (Camp Dresser & McKee, 2004).

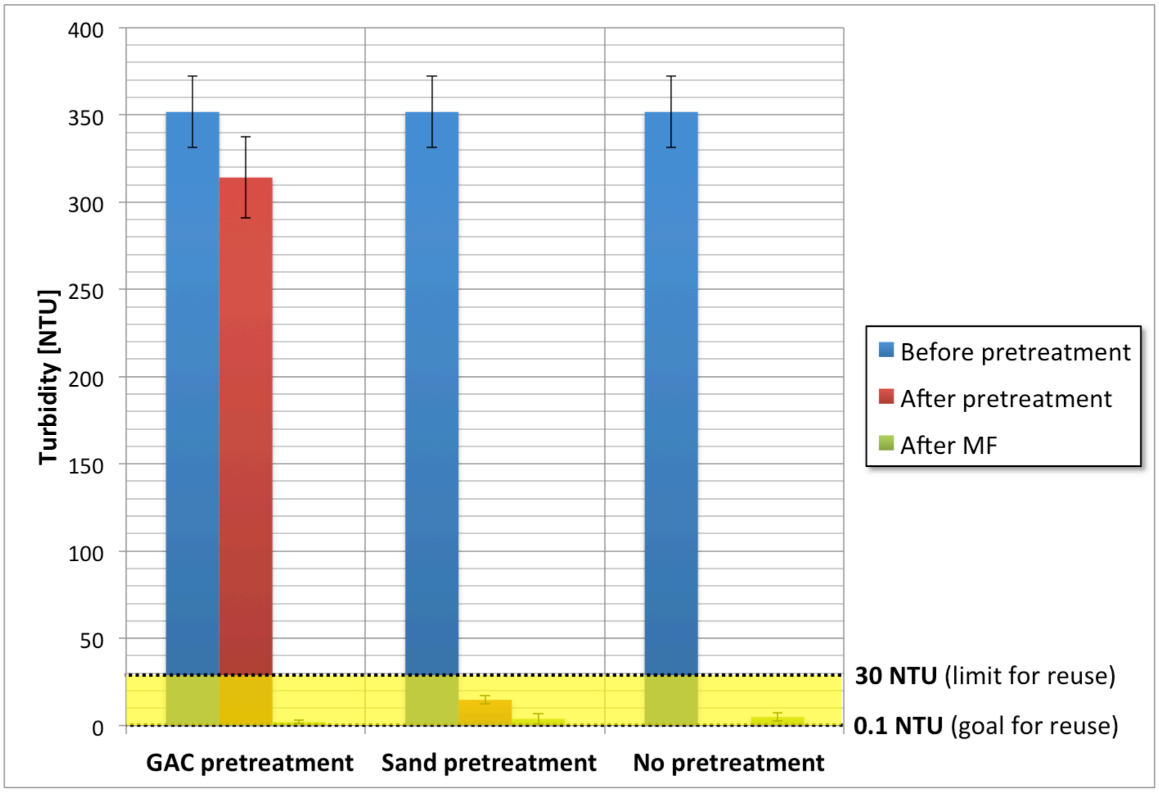


Figure 6. Turbidity removal results. Error bars represent ± 1 standard deviation. Sample size was eight (for all values before pretreatment), three (for GAC and Sand after pretreatment), or two (for No pretreatment after MF).

Table 4. Turbidity removal results.

Units are [NTU] unless noted otherwise	**GAC pretreatment**		**Sand pretreatment**		**No pretreatment**	
	Average value	Standard deviation	Average value	Standard deviation	Average value	Standard deviation
Before pretreatment	352	20 (5.8%)*	352	20 (5.8%)	352	20 (5.8%)
After pretreatment**	314	23 (7.4%)	15	2.3 (15.7%)	NA	NA
After MF	2.0	0.9 (47.2%)	3.8	3.0 (78.3%)	4.9	2.5 (50.7%)

*Percentages denote relative standard deviation (i.e., standard deviation divided by average value).

**These represent values 10 seconds after pretreatment effluent began flowing.

NA = not applicable

Figure 6 shows that GAC pretreatment provided little removal of turbidity from the challenge water, with an average reduction of 11% (not statistically significant). In comparison, sand pretreatment provided greater turbidity removal, with a mean reduction of 96%, to produce an effluent averaging 15 NTU (±2.3 NTU). These results closely parallel those of Friedler and Alfia (2010), who reported that a sand filter treating greywater produced a consistent effluent quality of 15 NTU (±7.0 NTU).

The result is likely due to the larger average grain size of the GAC compared to the sand (3.6 mm vs 0.6 mm, respectively). The suspended particles causing the turbidity were likely trapped within the sand matrix by straining, sedimentation or inertial impaction, interception, adhesion, and/or flocculation (Metcalf & Eddy et al., 2003). However, most of the turbidity-causing particles were able to flow uninhibited through the GAC matrix; the slight removal observed by GAC was likely due to adsorption onto GAC particles at locations where the flow path of the challenge water changed direction and the particles collided with the GAC due to momentum (i.e., inertial impaction).

After pretreatment, microfiltration (MF) removed a significant portion of all remaining turbidity from the samples; all MF effluent samples had average turbidity values below 5 NTU, which agrees with previous studies that found MF membranes highly effective at removing turbidity from greywater (Ramon et al., 2004; Kim et al., 2009). On average, the highest final turbidity was observed in samples receiving no pretreatment, the second highest turbidity in samples receiving sand pretreatment, and the lowest final turbidity in samples receiving GAC pretreatment. However, due to high standard deviation values this trend was not statistically significant. The high variations are attributed to the small values being measured, which are near the lower detection limit of the turbidimeter that was used (detection range 0 – 4000 NTU, per Hach Company (2012b)).

Although bacterial concentrations were not directly measured in this experiment, turbidity values can serve as a surrogate for bacterial contamination, because bacteria often sorb onto the suspended particles that cause turbidity. Thus, removal of turbidity often corresponds to removal of bacteria (Baderia and Toshniwal, 1969; Wang et al., 2004) and bacterial spores (Ndiongue et al., 2000). Therefore, while pathogen concentrations were not measured in this study, it is hypothesized that membrane filtration caused a significant reduction in pathogenic organisms that could have been present in the water. From a public health and safety perspective, pathogenic organisms are a primary concern with wastewater treatment and reuse, therefore further research is warranted in order to confirm or reject the hypothesis stated above.

The results above are concerned with average turbidity values in the challenge water before pretreatment, after pretreatment, and after MF. In contrast, Figure 7 and Table 5 (below) show specific turbidity values in the pretreatment effluent as a function of time. For the purpose of these results, the measurement of time began as soon as the wetting front of challenge water had proceeded through the pretreatment column and began to exit the effluent valve at the bottom.

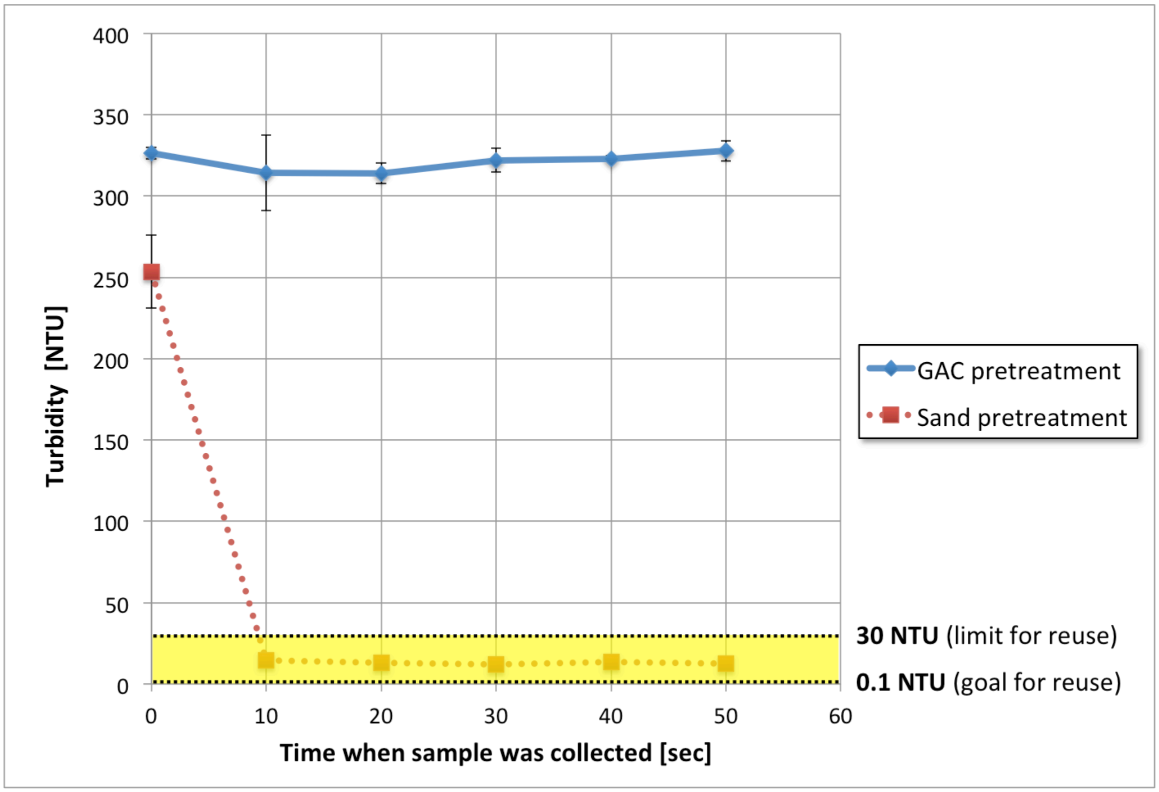


Figure 7. Turbidity levels in pretreatment effluent. Error bars represent ± 1 standard deviation. Sample size was three (both for GAC pretreatment and Sand pretreatment).

Table 5. Turbidity levels in pretreatment effluent.

Units are [NTU] unless noted otherwise	**GAC pretreatment**		**Sand pretreatment**	
	Average value	Standard deviation	Average value	Standard deviation
0 sec	326	3.5 (1.1%)*	253	22.4 (8.9%)
10 sec	314	23.3 (7.4%)	15	2.3 (15.7%)
20 sec	314	6.3 (2.0%)	13	2.4 (18.7%)
30 sec	322	7.3 (2.3%)	12	2.0 (16.4%)
40 sec	323	1.9 (0.6%)	14	3.7 (27.4%)
50 sec	328	6.2 (1.9%)	13	1.8 (14.3%)

*Percentages denote relative standard deviation (i.e., standard deviation divided by average value).

Figure 7 shows that GAC pretreatment removed only minor amounts of turbidity from the water (effluent turbidity ranged from 314 to 328 NTU, compared to the raw water turbidity of 352 NTU) and the turbidity in the GAC effluent was essentially stable. In contrast, the effluent turbidity from the sand pretreatment column began relatively high but quickly dropped to approximately 15 NTU and then remained stable.

These results suggest that suspended particles are trapped within the sand column matrix but then washed out at the beginning of subsequent runs. Because the columns were exposed to the atmosphere and allowed to drain and dry between runs, the dehydration-rehydration process within the sand filter may have caused the turbidity particles to break down into smaller particles that could more easily pass through the column, which explains the consistently relatively high turbidity values at the beginning of each run followed by lower stable values.

In the case of the GAC column, little turbidity was captured in the first place, so no initial spike was observed. In fact, after a statistically-insignificant initial drop, the turbidity values from the GAC pretreatment began to gradually increase with time, suggesting that adsorbed particles on the GAC granules may have begun to slough off as the pretreatment run progressed.

TOC removal

The results for removal of TOC are shown in Figure 8 below. The data used to generate the graph are listed in Table 6, and all of the TOC data collected in the course of the experiment are given in APPENDIX G. The 10 mg/L limit for reuse and 1 mg/L goal for reuse indicated in Figure 8 come from US EPA Guidelines for Water Reuse (Camp Dresser & McKee, 2004).

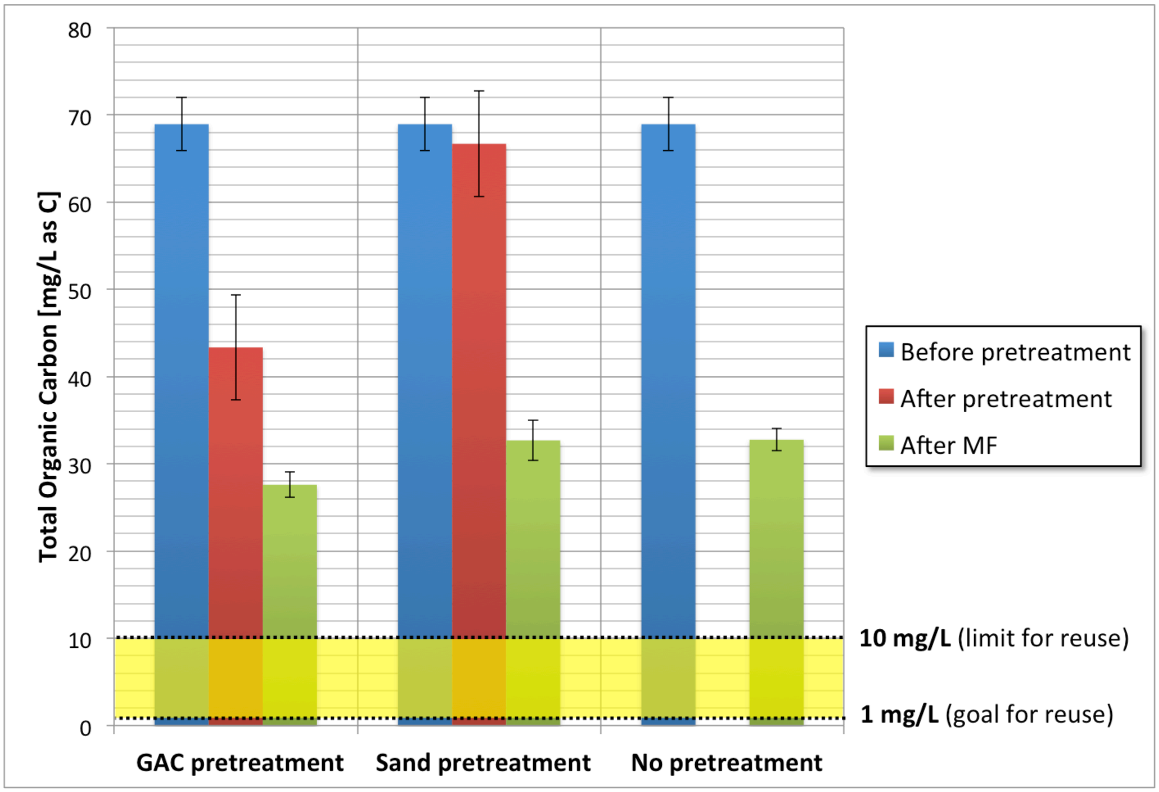


Figure 8. TOC removal results. Error bars represent ± 1 standard deviation. Sample size was 11 (for all values before pretreatment), six (for GAC after pretreatment), or two (for Sand after pretreatment, Sand after MF, and No pretreatment after MF). All measurements were made in triplicate.

Table 6. TOC removal results.

Units are [mg/L as C] unless noted otherwise	**GAC pretreatment**		**Sand pretreatment**		**No pretreatment**	
	Average value	Standard deviation	Average value	Standard deviation	Average value	Standard deviation
Before pretreatment	68.9	3.0 (4.4%)*	68.9	3.0 (4.4%)	68.9	3.0 (4.4%)
After pretreatment**	43.3	6.0 (13.9%)	66.7	6.0 (9.1%)	NA	NA
After MF	27.6	1.5 (5.3%)	34.3	3.1 (8.9%)	32.8	1.3 (3.8%)

*Percentages denote relative standard deviation (i.e., standard deviation divided by average value).

**These represent values immediately after pretreatment effluent began flowing.

NA = not applicable

Figure 8 shows that GAC pretreatment removed a significant portion of the total organic carbon (TOC) from the raw water (37% average removal), whereas the reduction due to sand pretreatment was not statistically significant. This agrees with prior research, which found that GAC removed TOC more effectively than sand in rapid gravity filters (which was effectively what was used in this experiment) (Hyde et al., 1987). Furthermore, after microfiltration (MF) was applied, no significant difference between the samples receiving sand pretreatment and those receiving no pretreatment was observed. However, GAC pretreatment led to a significantly lower TOC concentration in the final MF effluent (16% lower than samples receiving no pretreatment, on average). Samples that received no pretreatment had a final TOC value averaging 32.8 mg/L as C, which agrees with prior research that found shower greywater subjected to ultrafiltration (UF) to have an effluent organic carbon concentration in the range of 20 to 30 mg/L (Bhattacharyya et al., 1978). (The slight discrepancy can be attributed to the smaller pore size in the UF membranes compared to MF membranes.)

These results suggest that most of the TOC in the challenge water was in a dissolved form, especially when the TOC results are compared with the turbidity results (Figure 6). The sand column was able to capture the majority of the suspended particulate matter (turbidity), however it was unable to remove TOC. In contrast, GAC had a larger grain size and was unable to remove much turbidity from the water, but it successfully removed over one third of the TOC. Finally, even after microfiltration through a membrane with an average pore size of 0.22 µm, 48% of the original TOC was still present in the MF effluent (when no pretreatment was applied). These results are all consistent with the presence of dissolved organic contaminants.

Many of the constituents in the challenge water formula were personal care products or cleaning products that dissolved readily in water. These included shampoo, hand soap, body wash, bathroom cleaner, and lactic acid. Other constituents such as conditioner and toothpaste would dissolve in the presence of physical mixing. During the experiment, deodorant would not dissolve unless it first came in contact with the lactic acid or bathroom cleaner; thus the author intentionally placed these components in contact with each other to promote as much deodorant dissolution as possible when preparing the challenge water. Since every effort was made to create a homogenized challenge water mixture that had all of its constituents thoroughly dissolved, the TOC results conform to the expected pattern.

Figure 9 and Table 7 below show the TOC levels measured in the pretreatment effluent over time.

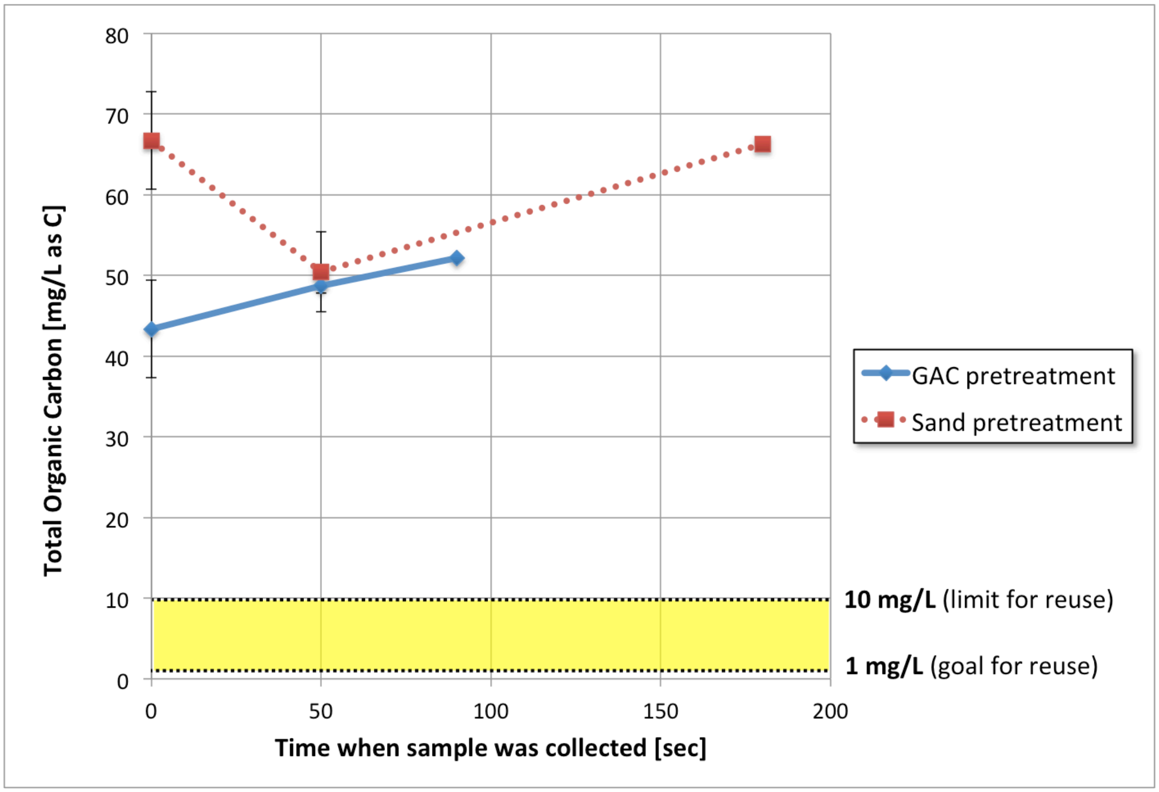


Figure 9. TOC levels in pretreatment effluent. Error bars represent ± 1 standard deviation. Sample size was six (for GAC pretreatment at time = 0), two (GAC at time = 50), four (GAC at time = 90), two (for Sand pretreatment at time = 0 and time = 50), or one (for Sand at time = 180). All samples were measured in triplicate.

Table 7. TOC levels in pretreatment effluent.

Units are [mg/L as C] unless noted otherwise	**GAC pretreatment**		**Sand pretreatment**	
	Average value	Standard deviation	Average value	Standard deviation
0 sec	43.3	6.0 (13.9%)*	66.7	6.0 (9.1%)
50 sec	48.7	0.9 (1.8%)	50.4	4.9 (9.8%)
90 sec	52.1	2.9 (5.6%)	NA	NA
180 sec	NA	NA	66.2	1.0 (1.5%)

*Percentages denote relative standard deviation (i.e., standard deviation divided by average value).

NA = not applicable

Figure 9 shows that although the GAC pretreatment initially provided a significantly lower TOC removal than sand pretreatment, after 50 seconds of continuous flow through the columns, the TOC values in the effluent became effectively identical. After that point, both pretreatment effluent streams began to increase in TOC concentration as time passed. (Unfortunately, the final samples for sand pretreatment and GAC pretreatment were collected at different times, preventing a direct comparison of the two later values. However both of the later samples showed a statistically significant increase in TOC over the 50-second value.)

COD removal

The results for removal of COD are shown in Figure 10 below. The data used to generate the graph are listed in Table 8, and all of the COD data collected in the course of the experiment are given in APPENDIX H. The 90 mg/L limit for reuse and 20 mg/L goal for reuse indicated in Figure 10 come from US EPA Guidelines for Water Reuse (Camp Dresser & McKee, 2004).

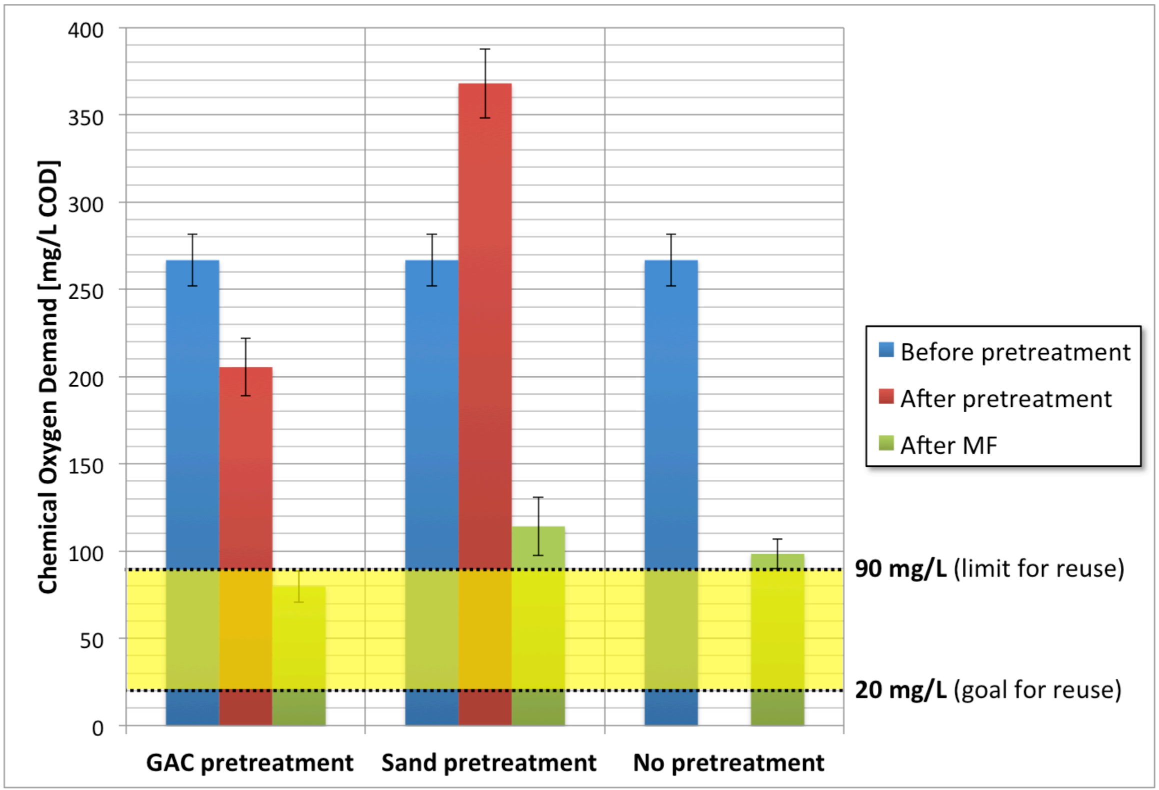


Figure 10. COD removal results. Error bars represent ± 1 standard deviation. Sample size was eight (for all values before pretreatment), three (for GAC after pretreatment and after MF), or two (for Sand after pretreatment, Sand after MF, and No pretreatment after MF). All samples were measured in triplicate.

Table 8. COD removal results.

Units are [mg/L COD] unless noted otherwise	**GAC pretreatment**		**Sand pretreatment**		**No pretreatment**	
	Average value	Standard deviation	Average value	Standard deviation	Average value	Standard deviation
Before pretreatment	266.8	14.8 (5.5%)*	266.8	14.8 (5.5%)	266.8	14.8 (5.5%)
After pretreatment**	205.4	16.5 (8.1%)	368.1	19.8 (5.4%)	NA	NA
After MF	79.6	9.1 (11.4%)	114.2	16.9 (14.8%)	98.4	8.5 (8.7%)

*Percentages denote relative standard deviation (i.e., standard deviation divided by average value).

**These represent values immediately after pretreatment effluent began flowing.

NA = not applicable

As shown in Figure 10, pretreatment with GAC reduced COD by an average of 23% (a significant reduction), whereas pretreatment with sand actually increased COD by an average of 38% (a significant increase). It should be noted that these values represent the COD values in the initial effluent exiting of the pretreatment columns. Figure 11 (below) shows that COD levels in the sand pretreatment effluent declined and ultimately converged with the GAC effluent values after 50 seconds of continuous flow through the pretreatment columns. However, it should also be noted that continuous flow regimes would not be expected in an actual greywater installation. Rather, intermittent flows would be expected.

After microfiltration (MF), samples that had received GAC pretreatment exhibited significantly lower COD values than those receiving sand pretreatment or no pretreatment. On average, GAC pretreated samples had 19% less COD than samples receiving no pretreatment, while sand pretreated samples had 16% more COD than samples receiving no pretreatment. Samples receiving no pretreatment had an average final concentration of 98 mg/L COD (compared to the untreated value of 267 mg/L COD); this closely matches the results found by Šostar-Turk et al. (2005), who found that the COD of greywater could be reduced from 280 mg/L to 130 mg/L via ultrafiltration (UF).

Due to the small pore size of the MF membranes used in this experiment (0.22 µm), the COD present in MF effluent that had received no pretreatment may be taken to represent the dissolved portion of the COD. Thus, the results indicate that 37% of the

COD present in the challenge water was in a dissolved form. This is roughly half of the value observed by Friedler and Alfiya (2010), who recorded a 75% dissolved portion of COD in the greywater stream coming from washbasins in a school cafeteria. The discrepancy is likely due to differences in source water composition. Furthermore, they did not observe an initial spike of COD in sand filter effluent as was observed in the present study; however, Friedler and Alfiya (2010) manually backwashed their filter between runs. This supports the hypothesis that the initial COD spike was due to residue from prior runs being washed out of the filter in the early effluent.

Figure 11 and Table 9 below show the COD levels measured in the pretreatment effluent over time.

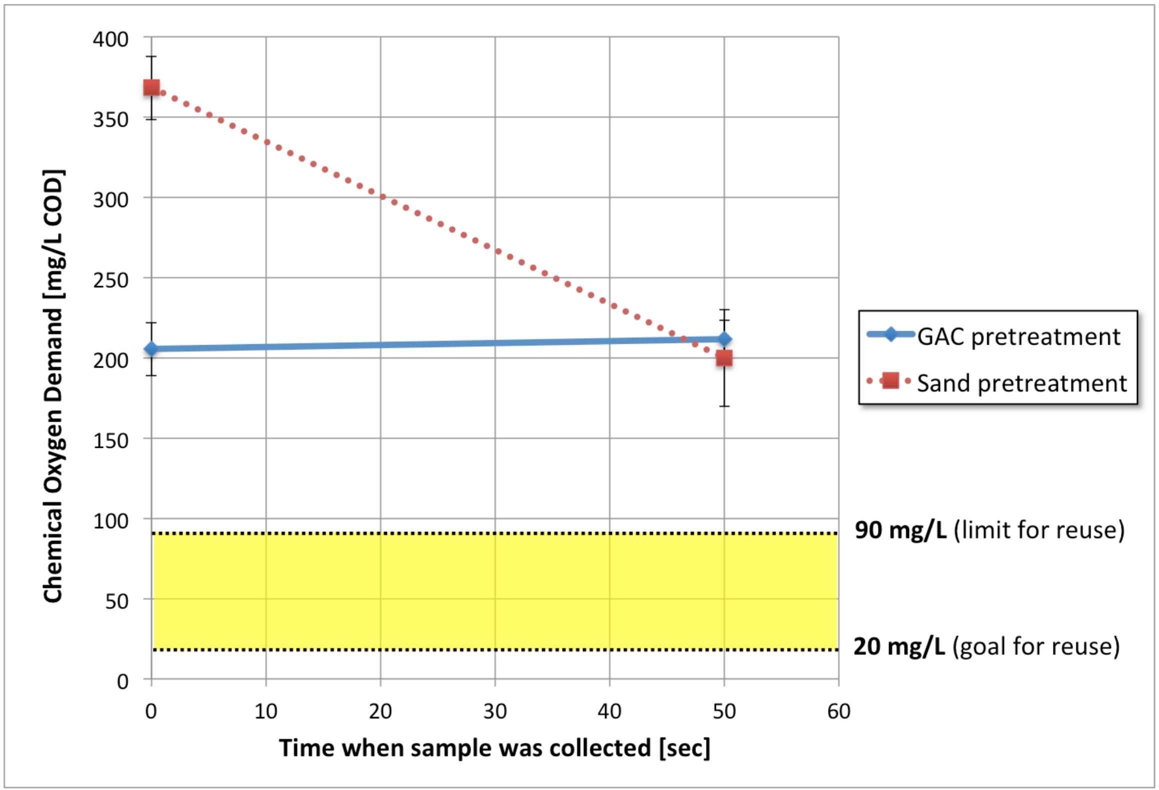


Figure 11. COD levels in pretreatment effluent. Error bars represent ± 1 standard deviation. Sample size was three (for GAC pretreatment), or two (for Sand pretreatment). All samples were measured in triplicate.

Table 9. COD levels in pretreatment effluent.

Units are [mg/L COD] unless noted otherwise	**GAC pretreatment**		**Sand pretreatment**	
	Average value	Standard deviation	Average value	Standard deviation
0 sec	205.4	16.5 (8.1%)*	368.1	19.8 (5.4%)
50 sec	211.8	11.4 (5.4%)	199.8	30.2 (15.1%)

*Percentages denote relative standard deviation (i.e., standard deviation divided by average value).

The temporary spike in COD immediately following sand pretreatment could indicate mineral contamination in the sand. The sand column was rinsed with tap water before initial use, but residual contamination could have remained. The presence of inorganic compounds or minerals would explain the high COD levels without a correspondingly high level of TOC, which is the pattern seen when Figure 8 and Figure 10 are compared. Furthermore, despite being allowed to drain freely between runs, the sand column retained some moisture in the interstices between the sand grains at all times. During the time between runs (a period which averaged approximately four days), mineral particles would have had the opportunity to dissolve into the stagnant water, and then this mineral-laden water would have been washed out in the initial effluent of the next pretreatment run.

Another possibility is that the smaller pore sizes in the sand column captured particulate matter from the greywater and this particulate matter degraded into smaller particles during the resting period between runs. These smaller particles would have been washed out at the beginning of the next run. However, this is unlikely because such a scenario would be expected to cause a corresponding spike in TOC levels in the early effluent (due to the fact that most of the personal care products in the greywater are made of organic constituents), and such a spike was not observed.

The data from samples that received no pretreatment show that MF removed 63% of COD from the challenge water, on average. The remaining 37% of COD passed through the filter, which suggests that at least one third of the chemical oxygen demand came from dissolved constituents, while the remaining two thirds were either particulate matter (captured by physical straining on the filter surface) or dissolved matter that adsorbed to the surface of the membrane due to electrostatic attractive forces.

Surfactant removal

The results for removal of surfactants are shown in Figure 12 below. The data used to generate the graph are listed in Table 10, and all of the surfactant data collected in the course of the experiment are given in APPENDIX I. Figure 12 does not indicate a surfactant concentration goal or limit for reuse because no such limits presently exist in the literature.

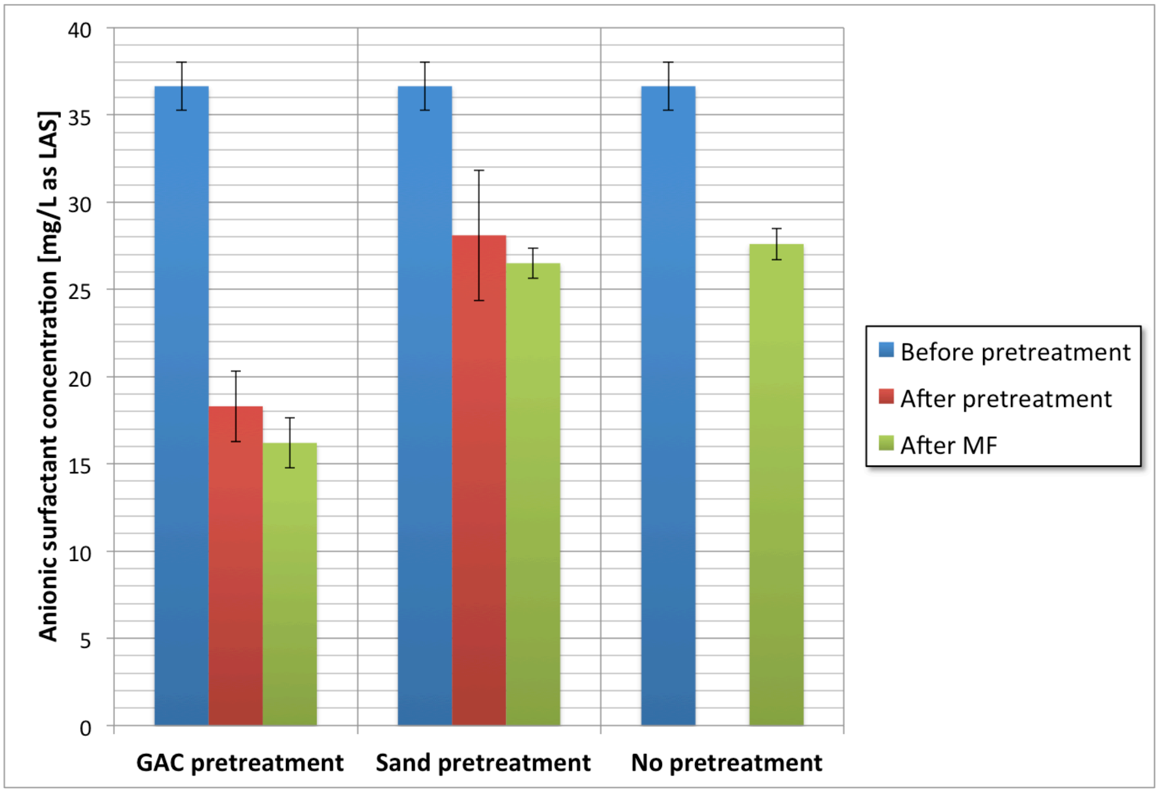


Figure 12. Surfactant removal results. Error bars represent ± 1 standard deviation. Sample size was eight (for all values before pretreatment), four (for GAC after pretreatment), six (for GAC after MF), two (for Sand after pretreatment), one (for Sand after MF), or two (for No pretreatment after MF). All but four of the samples were measured in triplicate (see APPENDIX I).

Table 10. Surfactant removal results.

Units are [mg/L as LAS] unless noted otherwise	**GAC pretreatment**		**Sand pretreatment**		**No pretreatment**	
	Average value	Standard deviation	Average value	Standard deviation	Average value	Standard deviation
Before pretreatment	36.6	1.4 (3.7%)*	36.6	1.4 (3.7%)	36.6	1.4 (3.7%)
After pretreatment**	18.3	2.0 (11.1%)	28.1	3.7 (13.3%)	NA	NA
After MF	15.8	1.2 (7.5%)	26.5	0.9 (3.2%)	27.6	0.9 (3.3%)

*Percentages denote relative standard deviation (i.e., standard deviation divided by average value).

**These represent values immediately after pretreatment effluent began flowing.

NA = not applicable

It should be noted from the outset that the surfactant levels reported in this thesis are for anionic surfactants only; cationic and nonionic surfactants were not considered. This is important because the charge of a surfactant plays a significant role in determining adsorption rates onto membranes (Boussu et al., 2007). Anionic surfactants are the most common surfactants in general detergents such as for laundry and dishwashing (Amoozegar et al., 2005), and a study of greywater composition in Sneek, the Netherlands, found 76% of the surfactants present in household greywater to be anionic, 3% to be cationic, and 21% to nonionic (Hernández Leal et al., 2011). Therefore anionic surfactants are a reasonable approximation of the total surfactant load in greywater. Throughout this thesis, any references to surfactants should be taken to mean anionic surfactants unless noted otherwise.

As shown in Figure 12, the majority (75%) of the surfactants in the challenge water were able to pass through the MF membrane when no pretreatment was applied. This suggests that most of the surfactants present in the challenge water were smaller than the molecular weight cut-off (MWCO) of the membrane. The MWCO represents the lowest molecular weight for which a solute would be 90% retained by the membrane (Cole-Parmer, 2006); unfortunately the MWCO value for these membranes was not published by the manufacturer. The remaining 25% of surfactants that were captured by the membrane could have been captured via adsorption within the pores and/or adsorption on the membrane surface.

On average, GAC pretreatment removed 50% of surfactants from the challenge water, while sand pretreatment removed only 23% of surfactants. Furthermore, after pretreatment had been applied, microfiltration did little to further reduce the surfactant concentrations: GAC-pretreated samples saw a 7% additional removal and sand samples saw a 4% additional removal (neither of which was statistically significant) compared to the untreated value. The difference in effluent concentrations between sand-pretreated samples and non-pretreated samples was insignificant.

Figure 13 and Table 11 below show the surfactant levels measured in the pretreatment effluent over time.

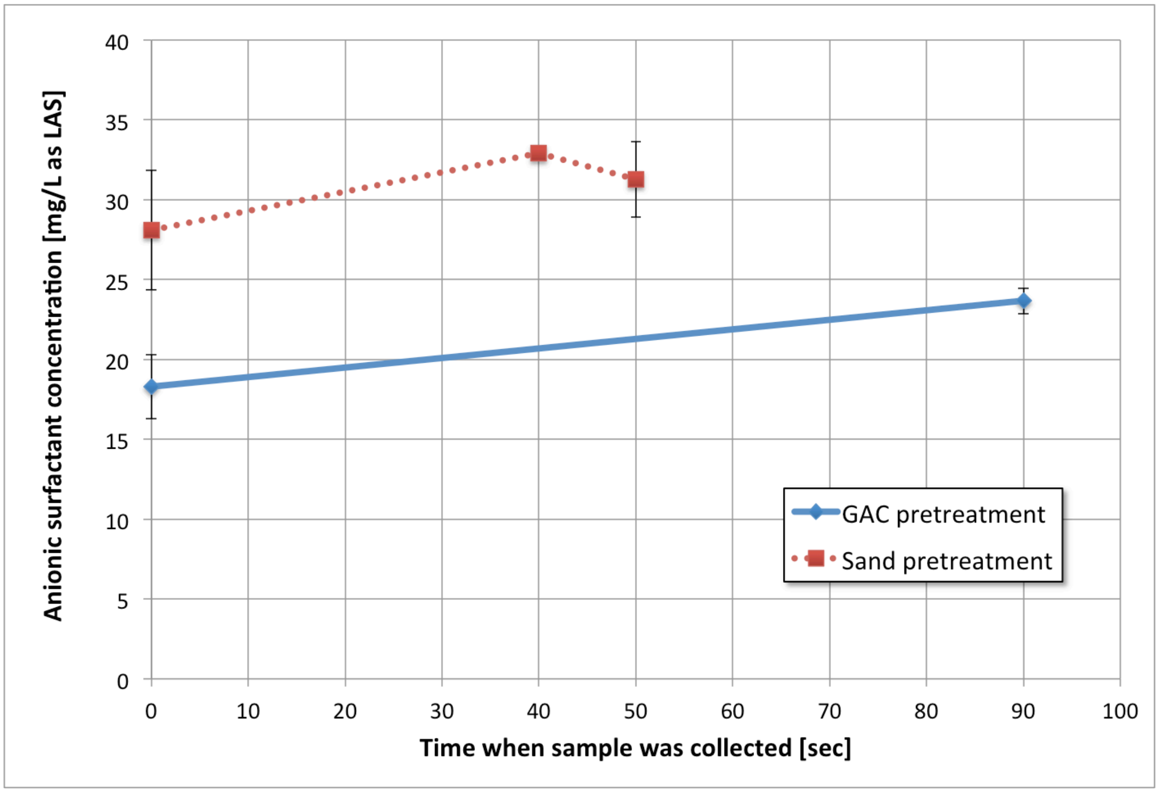


Figure 13. Surfactant levels in pretreatment effluent. Error bars represent ± 1 standard deviation. Sample size was four (for GAC pretreatment), two (for Sand at time = 0 and time = 50), or one (for Sand at time = 40). All samples (except two for GAC) were measured in triplicate.

Table 11. Surfactant levels in pretreatment effluent.

Units are [mg/L as LAS] unless noted otherwise	**GAC pretreatment**		**Sand pretreatment**	
	Average value	Standard deviation	Average value	Standard deviation
0 sec	18.3	2.0 (11.1%)*	28.1	3.7 (13.3%)
40 sec	NA	NA	32.9	0.3 (0.9%)
50 sec	NA	NA	31.3	2.4 (7.6%)
90 sec	23.7	0.8 (3.4%)	NA	NA

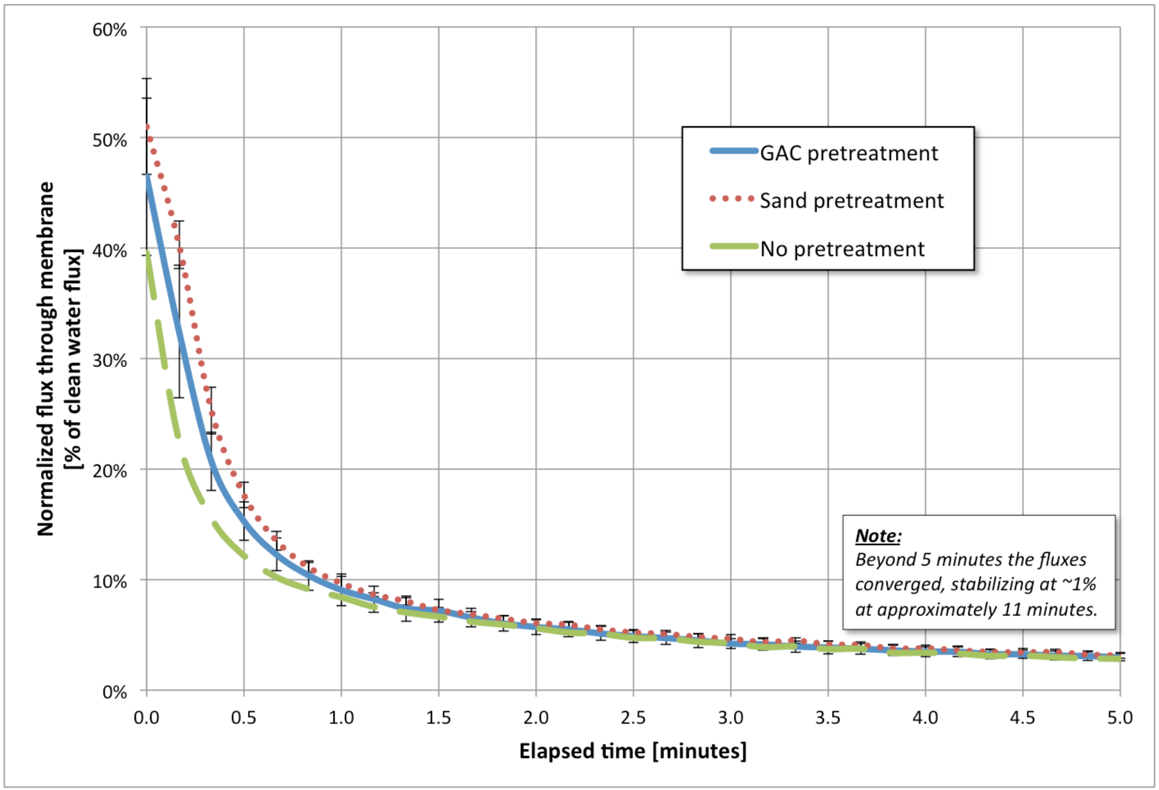
*Percentages denote relative standard deviation (i.e., standard deviation divided by average value).

NA = not applicable

As seen in Figure 13, surfactant levels in both the GAC-pretreated effluent and the sand-pretreated effluent tended to rise gradually over time. (This trend was only statistically significant for GAC pretreatment.) This suggests that both the sand and GAC had a carrying capacity for capturing surfactants, and as time went on and the columns became saturated with surfactants, more and more of the surfactants in the raw water began to pass through into the effluent (indicating breakthrough). Since the specific greywater scenario for this experiment (hand washing at public restroom sinks) involves low flows applied intermittently, the decrease in surfactant retention over time may not be a severe problem as long as enough time passed between hand washings to allow the columns to regenerate. However, for longer or more continuous flows, this trend could have negative consequences such as foaming in the toilets during flushing.

Flux through membrane

Figure 14 below shows the average membrane performance as measured in normalized flux through the membrane. For each microfiltration run, the flux (in units of lmh, or liters per square meter per hour) was monitored in 10-second intervals and recorded in Microsoft Excel 2011. These absolute flux values were then divided by the clean water flux value for the respective membrane to arrive at a normalized flux value. This enabled an equitable comparison of flux values generated using different membranes.



Note:
Beyond 5 minutes the fluxes converged, stabilizing at ~1% at approximately 11 minutes.

Figure 14. Membrane flux results. Error bars represent ± 1 standard deviation. Sample size was five (for GAC pretreatment), two (for Sand pretreatment), or one (for No pretreatment).

Figure 14 shows that the membranes fouled quickly in all cases, with flux falling below 10% of the clean water flux within one minute regardless of the pretreatment type. Average fluxes were slightly different at early times; however the difference between GAC and sand pretreatment was not statistically significant. The ranking of initial flux values followed the same pattern as the turbidity levels in the water being filtered; i.e., the higher the turbidity in the pretreated samples, the lower the initial flux. This indicates that particulate matter in the samples was a primary fouling mechanism, especially at early times. However, the magnitude of turbidity levels in the feed water did not directly correspond to the magnitude in differences of flux observed, therefore the dissolved portion of the sample must have also played a role in fouling. Prior research indicates that high surfactant concentrations can form micelles and exacerbate membrane fouling (Oschmann et al., 2005; Boussu et al., 2007; Lee et al., 2008; Sagle et al., 2009; Kaya et al., 2011).

CHAPTER 4

CONCLUSIONS AND FUTURE WORK

Treatment effectiveness and effluent suitability for reuse

The results indicate that for the given experimental conditions, granular activated carbon and sand pretreatments improved effluent water quality but did not significantly reduce membrane fouling. GAC was more effective than sand at removing surfactants, while sand was more effective than GAC at removing turbidity. GAC and sand were comparable in their ability to remove TOC and COD once the flows through the columns had stabilized (i.e., within one minute). After microfiltration (MF), samples that had been pretreated with GAC exhibited the lowest level of contamination in all categories. Nevertheless, guidelines published by the US EPA (Camp Dresser & McKee, 2004) state that the final treated effluent was unsuitable for direct reuse because it exceeded the recommended threshold for TOC. (Currently there is no recommended threshold for water reuse regarding surfactants.)

However, considering the proposed reuse application in this study (toilet flushing), the treated effluent may actually have been safe for reuse. While the TOC and surfactant values were high even after microfiltration, the turbidity values were consistently low and within the EPA proposed range. This turbidity reduction implies that a significant bacterial reduction likely also took place during treatment (Baderia and Toshniwal, 1969; Ndiongue et al., 2000). Furthermore, the rated pore size of the microfiltration membranes was 0.22 µm, a size which normally captures helminth eggs, Giardia lamblia cysts, cryptosporidium oocysts, algae, bacteria, and some viruses (Mihelcic et al., 2009). Therefore from a public health and safety perspective, the effluent was likely suitable for toilet flushing. However, before implementing any such reuse, the removal of pathogens should be confirmed through testing specifically for pathogens rather than relying solely on turbidity as a surrogate; this is an area for future research. Furthermore, the water reuse guidelines are based not only on health and safety considerations but also on aesthetics and public acceptability (Camp Dresser & McKee, 2004). Therefore, this treatment configuration is not recommended in its current form due to the possibility that the effluent could be perceived as objectionable by the public (because of odor, foaming, etc.).

Even if the final MF effluent quality had been within acceptable limits, the rapid membrane fouling would have rendered the system unacceptable. A rapidly-fouling membrane-based treatment system would require frequent monitoring and maintenance, which would incur labor and material costs that could quickly eclipse any cost savings from water reduction. Economic viability was not the focus of this experiment; however, the results clearly indicate that the current setup is not completely efficient.

It should be noted that this project considered a worst-case scenario: high volumes of highly-fouling challenge water applied infrequently. Improved performance could be expected from this setup in a less extreme situation.

Implications for designers

The results of this research provide a number of implications for greywater treatment system designers. First, the use of GAC as an adsorbent was effective in removing a significant portion (but not all) of the anionic surfactants from raw greywater. This fact could be useful in preventing foaming in toilets and other turbulent reuse applications. If more than 50% surfactant removal was required, a longer EBCT could be prescribed and an upflow design through the GAC could be used to increase contact between the greywater and the GAC granules. However, any proposed design should be pilot tested before widespread implementation.

Another implication is that physical treatment alone may be insufficient to remove all contaminants from the greywater stream, particularly those contaminants that exist in a dissolved state. Other researchers have come to the same conclusion (Pidou et al., 2007; Li et al., 2009). Although GAC was capable of capturing some dissolved constituents through adsorption, a significant portion still passed through to the final effluent. Therefore additional treatment, such as biological or chemical treatment, may be required to produce a satisfactory effluent.

Future research

Much research has been performed regarding membrane filtration lately due to its rising prominence in the water and wastewater treatment fields. Further research could investigate ways to reduce energy requirements for membrane filtration (such as low-pressure filtration, more efficient or passive pumping methods, etc.), since electricity production for pumping is currently the largest source of the environmental damage caused by water and wastewater treatment (Tarantini and Ferri, 2003). Additionally, the optimum type of membrane material for greywater treatment should be investigated, because different membranes exhibit different propensities for fouling and for withstanding chemical attacks (Koo et al., 2011).

Because of the complementary capabilities of GAC and sand, it may be advantageous to combine them into a dual-layer pretreatment filter. Indeed, this configuration has already been applied to drinking water (Ndiongue et al., 2000; Wang et al., 2011); future research could apply this configuration to greywater treatment.

Future studies may also consider the effect of continuous flow (this experiment was run in discrete batches), long-term biofilm buildup (this experiment allowed only short-term buildup, if any), and/or differing operating conditions. For example, an increased empty bed contact time (EBCT) or an upflow configuration through the GAC pretreatment column (as mentioned in the previous section) are parameters that may be explored.

In addition, future studies should include bacteriological counts (instead of relying on turbidity as a surrogate) to verify the magnitude of the health risk associated with reusing treated greywater. In light of claims that traditional indicator organisms are not representative of greywater quality (Birks and Hills, 2007), a study should be performed to identify indicator organisms that are more suitable for greywater.

APPENDICES

APPENDIX A

Experimental background – internship at CERL

After performing the literature review, I participated in a ten-week summer internship at the US Army Corps of Engineers Construction Engineering Research Lab (USACE-CERL) in Champaign, Illinois, under the direction of Dr. Martin Page. I was assigned to help Dr. Martin Page on a greywater treatment system design project for an external client (Sloan Valve Company). The project was governed by a CRADA (Cooperative Research and Development Agreement), so I am unable to disclose many details of the design to those not involved in the project. Additionally, once I left the facility in August I was unable to receive updates regarding the design development process except in the most general terms. However, in broad terms, the goal of the design process was to develop a treatment system for greywater generated in the sinks of a public bathroom (i.e., through hand washing) to use for flushing toilets in the same bathroom.

There were various ways to approach this problem and Dr. Page was considering both a bioreactor and a GAC biofilter as possible options. During the internship I used data published by Young and Xu (2008) and Metcalf & Eddy (2003) to develop a numerical model (not included in this thesis) for predicting the performance of a bioreactor for treating greywater. The model aided Dr. Page and his colleagues in making design decisions.

Since one of the challenges in using membranes to treat greywater is the high surfactant load (Ramon et al., 2004), Dr. Page wondering if using an adsorbent (such as GAC) might help improve performance. This suggestion interested me, so I decided to use my masters research to investigate the benefit (if any) of using an adsorbent such as GAC (granular activated carbon) as pretreatment before performing membrane bioreactor treatment.

Ultimately, due to logistical constraints and recommendations from faculty experienced in membrane filtration (namely Dr. David Ladner), my system was redesigned to use simple membrane filtration rather than a full membrane bioreactor. However, the general concept of using an adsorbent to enhance the performance of a membrane filter still applied. Such a setup has been used to treat drinking water (Wang et al., 2004; Zuo Jinlong, 2010) but had not yet been applied to greywater for the purpose of reuse.

APPENDIX B

Fabrication of experimental apparatus

Reservoir preparation

A reservoir (for mixing NSF/ANSI 350 challenge water using a stir plate and magnetic stir bar) was constructed from a 1-gallon wide-mouth plastic jar (Mainstays Canister, polyethylene terephthalate, Wal-Mart UPC 0-71691-43914-1). The lid of the reservoir served as a weigh boat for measuring reagents, and once screwed together, the entire reservoir assembly (body + lid) rested upside down on a stir plate; this allowed the stir bar to be in direct contact with the reagents that had been measured into the lid of the reservoir.

A ½” hole was drilled through the side of the reservoir in order to house a ¼” ID (internal diameter) plastic barbed adapter (nylon single-barbed tube fitting with through-wall adapter, ¼” ID, McMaster-Carr catalog number 2974K831). The hole for this adapter was drilled as close to the lid as possible so that when the reservoir assembly was inverted, the adapter – serving as a sampling port – would be as close as possible to the bottom of the water column. This adapter was then connected to a plastic three-way valve (barbed) by means of short length of ¼” ID tubing (Masterflex platinum-cured silicone tubing, size L/S 17).

For ventilation and pressure relief purposes, a small (< ¼" diameter) hole was drilled into the bottom of the reservoir (when inverted, this hole would be on the top of the assembly). When not in use, this hole was covered/sealed using a small section of clear office tape. Also, the body of the reservoir was marked at the 1-liter, 2-liter, 3-liter, and 3.5-liter levels using a fine-tip permanent marker for future reference.

Pressure vessel configuration

The standard pressure vessel assembly (RC800 Mini-Reservoir, Millipore catalog number 6028) was unavailable, so an alternative assembly was recommended by the technical support staff of the manufacturer. The components described below were combined to create a comparable (and in fact, superior) configuration:

- **Pressure vessel** (Millipore dispensing pressure vessel, 1 gallon capacity, stainless steel; Millipore catalog number XX6700P01)
- **Pressure gauge** (Millipore pressure gauge, ¼" ASME; Millipore catalog number XX6700L15)
- **Pressure relief valve** (Millipore vent/relief valve, 7 bar, ASME; Millipore catalog number XX6700L24)
- **Quick-disconnect fittings** (Acetyl quick-disconnect coupling socket, ⅛" coupling, ¼" NPT thread, with valve; McMaster-Carr catalog number 5012K31)
- **Plumber's sealant tape** for all threaded connections

Connection from gas tank to pressure vessel

The nitrogen gas tank was connected to the pressure vessel using the following assembly (listed in the order of connection), with all threaded connections sealed using plumber's sealant tape:

- **Gas tank** (tank of compressed nitrogen, industrial grade, National Welders catalog number NI300)
- **Pressure regulator** (VWR® multistage gas regulator with neoprene diaphragms, for use with argon, nitrogen, helium; delivery pressure range 0-50 psi; VWR catalog number 55850-474)
- **Brass coupling** (¼" brass pipe coupling, purchased from Lowe's)
- **Quick-disconnect tube adapter** (acetal quick-disconnect coupling socket, ⅛" coupling, 1/4" male NPT, with valve; McMaster-Carr catalog number 5012K31)
- **Quick-disconnect tube coupling** (acetal quick-disconnect coupling plug, ⅛" coupling, for 1/4" tube outer diameter, with valve; McMaster-Carr catalog number 5012K41)
- **Plastic tubing** (crack-resistant polyethylene tubing, 0.170" inner diameter, 1/4" outer diameter, 0.04" wall thickness, red; McMaster-Carr catalog number 5181K231)
- **Quick-disconnect tube coupling** (as described above)
- **Quick-disconnect tube adapter** (as described above)
- **Pressure vessel** (as described on page 29)

Pretreatment column construction

Two pretreatment columns were constructed from 2” ID pipes (clear PVC) cut to 12” long. Figure 4 (p.31) illustrates the final product that is described in the following paragraphs.

Circular polycarbonate flanges were epoxied onto each end of each pipe, leaving approximately ⅛” of the pipe extending beyond the flanges (to hold an O-ring for sealing purposes). Round sheets of 30-mesh wire screen (lightweight particle filtering stainless steel woven wire cloth, type 304, 30x30 mesh, 0.0095" wire diameter, 12"x12" sheet; McMaster-Carr catalog number 9238T532) cut to approximately 2¼” diameter were placed over the top and bottom opening of each pipe (one screen per end) to prevent loss of the filter media during usage. A round polycarbonate cover plate (cut to match the outer diameter of the polycarbonate flange) was placed on top of the screen and O-ring. The cover plate was bolted to the flange using a series of screws (zinc-plated alloy steel socket head cap screws, 8-32 thread, 1¼" length; McMaster-Carr catalog number 90128A201) drilled into the flange.

A ¼” hole was tapped into the center of each cover plate, and a ¼” ball valve (Miniature PVC high-flow ball valve, ¼” NPT female x ¼” NPT male; McMaster-Carr catalog number 45975K26) was screwed into the hole. A plastic barbed adapter (Nylon single-barbed tube fitting adapter, tube to male threaded pipe; McMaster-Carr catalog number 5463K247) was then screwed into the free end of the valve. For the experiment, ¼” ID flexible plastic tubing was connected to the adapter. One of the columns was filled with GAC (granular activated carbon; activated charcoal, untreated, granular, 4-8 mesh; Sigma-Aldrich catalog number C2764-2.5KG) and the other was filled with sand (American Foundry Society – Grain Fineness Number 24-38). Then they were screwed shut (as described above) and clamped to a support apparatus; they were clamped in a vertical orientation (i.e., with the longitudinal axis of the columns perpendicular to the floor).

APPENDIX C

COD analysis procedure (closed reflux, colorimetric method)

Acknowledgement

The following procedure was adapted from the instructions for the Bioscience accu-TEST low range (5-150 mg COD/L) COD test (with twist cap vials) by Dr. David Freedman of Clemson University and further edited by the author of this thesis. (*Note: because the reagents used in this procedure contained sulfuric acid, chromium, silver, and mercury, they were handled with care and disposed of as hazardous waste*).

Preparation of Standards

Approximately 0.5 g of KHP (potassium hydrogen phthalate, $KOCOC_6H_4$-2-COOH, molecular weight 204.22 g/mol; Crystal AR (ACS), primary standard; VWR catalog number BDH0260-125G) was dried in a 120°C oven for several hours and then cooled in a desiccator.

It is known that KHP contains 1.1752 mg COD per mg KHP. Therefore, a stock solution of 500 mg/L COD was prepared by dissolving 0.4250 g of KHP in 1 L of distilled deionized (DDI) water. The actual mass of the KHP added was recorded.

Standards were prepared by making the following dilutions:

Table 12. Dilutions required for creating COD standards.

Standard [mg/L COD]	Dilution of stock solution
150	15.0 mL diluted to 50.0 mL
125	25.0 mL diluted to 100.0 mL
100	20.0 mL diluted to 100.0 mL
50	10.0 mL diluted to 100.0 mL
10	2.0 mL diluted to 100.0 mL

Analysis of the standards and samples

The COD heating block was preheated to 150°C (approximately one hour) and for each sample to be analyzed, a COD digestion reagent vial was obtained and numbered to allow for later sample identification.

With the author wearing gloves, lab coat, and eye protection, the samples and standards were digested in the following manner:

1. The cap of a COD digestion reagent vial was removed. Holding the vial at a 45° angle pointing away from the researcher's body, 2.5 mL of sample were slowly added into the vial, allowing the sample to run down the side of the vial. The sample formed a layer on top of the reagents.
2. The vial cap was replaced tightly.
3. Using a heat resistant glove, the vial was held over a sink by its cap and inverted gently several times to mix the contents. The temperature of the vial increased

rapidly. The outside of the COD vial was rinsed with DI water and wiped clean with a lab wipe.

4. The vials were placed in the preheated (150°C) COD heating block and heated for two hours. The temperature of the heating block temperature was checked periodically. If the heat block temperature dropped below 150°C, the reaction time was extended to compensate for the reduced reactor temperature.
5. The vials were carefully removed from the heating block and placed in a rack to cool.
6. Each vial was inverted several times while still warm.
7. The vials were left undisturbed until they had cooled to room temperature and any precipitate had settled.
8. The COD for the standards was determined with a Spec 20 spectrophotometer using phototube CEA 95 with the pale green (almost clear) filter.
    a. The spectrophotometer was turned on using the front left knob and allowed to warm up for at least 15 minutes.
    b. The spectrophotometer wavelength control was adjusted to 440 nm using the large knob at the upper right of the machine.
    c. The empty sample compartment was covered and the zero control was adjusted for a reading of exactly 0% transmittance using the front left knob.
    d. The spectrophotometer was switched to absorbance mode.

    e. The 150 mg/L COD standard was inserted into the sample compartment. The full scale control was adjusted using the front right knob, for a meter reading of exactly 0% absorbance.
    f. The absorbance of each standard and sample was read twice, rotating the tube 90° between readings. The average reading for each tube was recorded.
    g. A calibration curve was prepared by plotting the absorbance of the standards versus their known concentrations and fitting a best-fit line to the data (using Microsoft Excel).
9. The sample absorbances were compared to the calibration curve to determine the COD concentration of each sample. These concentrations were recorded.

APPENDIX D

TOC analysis procedure

TOC (total organic carbon) was measured using a Shimadzu TOC analyzer (model TOC-V CSH) outfitted with a Total Nitrogen Measuring Unit (model TNM-1) and an autosampler (model ASI-V). The following procedure was performed for each analysis:

1. It was verified that the pressure in the gas tank serving the TOC analyzer was greater than or equal to 400 psi. If this condition was not met, a replacement tank was installed before proceeding.
2. On the desktop computer connected to the TOC analyzer, all open instances of the TOC software (TOC-Control V, Version 2.00) were closed. If the TOC analyzer was not already powered on, it was powered on at this point using the button on the bottom right corner of the unit.
3. On the computer's desktop screen, the shortcut icon labeled "TOC-V Sample Table Editor" was double clicked. With the "username" field still blank, the "OK" button was clicked.
4. From within the TOC software, the "NEW" icon was clicked, "TC/IC/TN catalyst" was selected, and the "OK" button was clicked. This step generated a blank spreadsheet.

5. In the new (blank) spreadsheet, the button immediately to the right of Row 1 was right-clicked, the “Insert” option was clicked, and then “Multiple Samples” was selected.
6. Under the “Method” option, “NPOC_TN.met” was selected, and then the “Next” button was clicked.
7. The number of samples was input, taking into consideration (a) the actual number of samples to be analyzed, plus (b) at least five additional spaces for DDI (distilled deionized) water at the beginning of the tray, (c) 6 additional spaces for TOC calibration samples, (d) one additional space for DDI water, (e) 6 additional spaces for TN calibration samples, and (f) further additional DDI spaces at the end of the tray to wash the instrument after the analyses had been completed. The “Finish” button was clicked. At the next screen (preview of tray), the “OK” button was clicked.
8. Next, the “Connect” button was clicked, which began the instrument warm-up process (approximately 30 minutes in duration). At this point, the sample tray was loaded with all samples to be analyzed, and standard checks were performed:
    a. The gas pressure gauge was tapped to ensure that the needle had not become stuck.
    b. The fluid levels in the water reservoirs were verified, and additional DDI water was added as necessary to completely fill the reservoirs.

    c. The gas pressure within the instrument was verified to be 200 psi.
    d. It was verified that gas was flowing through the instrument.
    e. All DDI samples were filled to the neck of the sample vial with DDI water.

9. A datasheet was created, listing all of the spaces on the loading tray and their respective samples. Samples were loaded so that the most dilute samples were analyzed first and the most concentrated samples were analyzed last (but before the final DDI samples).
10. The sample tray was loaded into the machine. A check was performed to verify that all vials were properly seated in the tray. The plastic cover was placed on the analyzer over the sample tray.
11. On the computer program, it was verified that the “Monitor” indicator lines were all green (indicating that the machine was ready) and the “Ready” indicator was visible in the top right corner of the screen.
12. In the blank spreadsheet previously created, all sample names were entered (i.e., transcribed from the handwritten list previously created).
13. The “Save” icon was clicked, the desired destination folder was located on the computer, the file type was set to “*.t32”, and the “Save” button was clicked.
14. A final check was performed by clicking on all tabs in the software screen and verifying that all “Monitor” indicator lines showed green.

15. The “Start” icon was clicked to initialize the analysis. Before proceeding to the next step, it was verified (by listening for the characteristic sound of the machine) that the analysis had indeed begun.
16. Using the Microsoft Access file on the desktop of the computer, a new entry was created in the electronic logbook for the TOC analyzer.
17. After the analysis was complete, the results were saved to an Excel spreadsheet and the machine was powered off using the “Shutdown” icon.
18. A calibration curve was generated in Microsoft Excel 2011 and used to calculate the TOC values of all samples.

APPENDIX E

Surfactant analysis procedure

Surfactants were measured using a portable colorimeter (HACH DR890; Hach product number 4847000) and *Method 8028: Surfactants, Anionic* (also known as the *Crystal Violet Method*). The procedure, which was performed under a fume hood, was as follows:

1. The PRGM button on the DR890 was pressed. This activated the Program menu.
2. The buttons “2, 6, ENTER” (no quotes) were pressed on the DR890 to select program number 26.
3. One milliliter (1 mL) of sample was pipetted into a clean 1000 mL graduated cylinder using an Eppendorf Research Plus 100 – 1000 µL pipette (Eppendorf catalog number 3120000062), then the graduated cylinder was filled to the 300 mL mark with distilled water. The graduated cylinder was manually agitated for 10 seconds to blend its contents. The 300 mL diluted sample was then poured into a clean 500 mL separatory funnel.
4. 10 mL of sulfate buffer solution (Hach product number 45249) was added to the funnel. The funnel was stoppered and shaken for five seconds.
5. The contents of one detergent reagents powder pillow (Hach product number 100868) were added to the funnel. The funnel was stoppered and shaken until the powder was dissolved (approximately five to ten seconds).

6. Thirty milliliters (30 mL) of benzene was added to the funnel. The funnel was stoppered and shaken gently for one minute, taking care not to create an emulsion.
7. The funnel was placed in a support stand.
8. On the DR890, the buttons “TIMER” and “ENTER” were pressed to initiate a 30-minute waiting period.
9. After the timer beeped, the stopper was removed from the funnel and the bottom water layer was removed (and ultimately discarded as hazardous waste).
10. The top benzene layer was drained into a clean sample cell (glass, 25 mm round, 10-20-25 mL marks; Hach product number 2401906).
11. Another sample cell was filled with pure benzene to serve as a blank. Once filled, this blank was labeled and reused until the entire experiment was completed.
12. The outside of the blank sample cell was wiped clean using a lint-free disposable wipe (Kimtech delicate task wipers, VWR catalog number 500030-631), and the blank was placed into the cell holder of the DR890. The cap of the DR890 was used to cover the sample cell tightly.
13. On the DR890, the “ZERO” button was pressed to zero the instrument.
14. Once the instrument display showed all zeros, the blank was removed from the DR890. The outside of the prepared sample cell was wiped clean using a lint-free disposable wipe and placed into the cell holder. The sample cell was again tightly covered with the cap of the DR890.

15. The “READ” button on the DR890 was pressed, and the level of surfactants (measured in mg/L of anionic surfactants (LAS)) was recorded.
16. The sample was disposed of as hazardous waste.
17. To prepare for subsequent tests,
    a. The 1000 mL graduated cylinder was rinsed five times with distilled water (manually agitating the water inside the cylinder each time) and then the top edge (inside and outside) of the cylinder was wiped dry using a lint-free disposable wipe.
    b. Separatory funnels were rinsed with acetone, allowed to air dry under the fume hood, and then scrubbed three times with hot tap water, scrubbed one time with hot tap water and soap, rinsed once with hot tap water, and rinsed three times with distilled water. They were either allowed to air dry overnight or were placed in a drying oven until dry and then allowed to cool to room temperature. Stopcocks and stoppers were washed in a similar manner (but never oven-dried).

APPENDIX F

Raw data – Turbidity

GAC pretreatment

Table 13. Raw turbidity data for samples receiving GAC pretreatment.

Sampling time	Sampling date			Average value*	Standard deviation**	
	13-Jun	18-Jun	25-Jun			
Before pretreatment	340.5	354	352	348.8	5.95	1.7%
After pretreatment (0 sec)	326	331	322	326.2	3.47	1.1%
After pretreatment (10 sec)	291	346	306	314.2	23.3	7.4%
After pretreatment (20 sec)	322	314	306	313.8	6.33	2.0%
After pretreatment (30 sec)	325	329	312	322.0	7.26	2.3%
After pretreatment (40 sec)	326	323	321	323.0	1.87	0.6%
After pretreatment (50 sec)	333	331	319	327.7	6.18	1.9%
After MF	0.662	2.67	2.64	1.99	0.939	47%

*All values in this table are in units of NTU unless noted otherwise.

** Percentages denote relative standard deviation (i.e., standard deviation divided by average value).

Sand pretreatment

Table 14. Raw turbidity data for samples receiving sand pretreatment.

Sampling time	Sampling date			Average value*	Standard deviation**	
	11-Jun	15-Jun	20-Jun			
Before pretreatment	338	358	363	353	10.9	3.1%
After pretreatment (0 sec)	285	239	236	253	22.4	8.9%
After pretreatment (10 sec)	11.9	14.8	17.5	14.7	2.31	15.7%
After pretreatment (20 sec)	9.88	13.6	15.8	13.1	2.44	18.7%
After pretreatment (30 sec)	9.95	13.9	***	11.9	1.95	16.4%
After pretreatment (40 sec)	8.92	13.8	18.0	13.6	3.71	27.4%
After pretreatment (50 sec)	10.8	14.4	NA	12.6	1.80	14.3%
After pretreatment (180 sec)	NA	NA	22.5	22.5	NA	NA
After MF	****	0.833	6.86	3.85	3.01	78.3%

*All values in this table are in units of NTU unless noted otherwise

**Percentages denote relative standard deviation (i.e., standard deviation divided by average value).

***This value was measured one day later as 24.2 NTU, but that value was discarded because (a) it was not collected at the same time as all other samples (due to limited sample cell availability that day) and (b) it seemed not to fit the trend established by the other points.

****During this run the dispensing pressure vessel was (unintentionally) not continuously stirred, therefore the measured MF value of 0.535 NTU was believed to be erroneously low. Thus, that value was discarded.

NA = not applicable

No pretreatment

Sampling time	Sampling date		Average value*	Standard deviation**	
	22-Jun	28-Jun			
Before MF	392	317	355	37.5	10.6%
After MF	2.41	7.37	4.89	2.48	50.7%

*All values in this table are in units of NTU unless noted otherwise
**Percentages denote relative standard deviation (i.e., standard deviation divided by average value).

APPENDIX G

Raw data – TOC

GAC pretreatment

Table 15. Raw TOC data for samples receiving GAC pretreatment.

Sample date	Before PT*	After PT (0 sec)	After PT (50 sec)	After PT (90 sec)	After MF
17-May	68.8	44.4	NA	46.5	25.4
	68.9	45.2	NA	48.7	24.8
	68.4	45.4	NA	48.5	25.1
22-May	73.1	48.7	NA	52.8	29.4
	72.0	50.3	NA	55.3	29.1
	73.4	49.9	NA	57.1	29.4
26-May	71.2	47.4	NA	51.0	26.9
	71.0	47.1	NA	52.5	26.6
	70.4	48.0	NA	52.5	27.4
30-May	70.0	47.5	NA	52.9	27.3
	70.2	46.4	NA	54.9	27.5
	69.6	48.5	NA	52.5	27.2
13-June	64.7	37.5	47.9	NA	28.6
	63.8	35.8	48.9	NA	26.9
	63.2	37.1	49.0	NA	27.8
18-June	63.8	35.8	47.4	NA	29.5
	65.0	32.2	48.7	NA	29.3
	64.6	33.2	50.1	NA	28.6
Average value	68.4	43.3	48.7	52.1	27.6
Standard deviation**	3.3 (4.8%)	6.0 (13.9%)	0.9 (1.8%)	2.9 (5.6%)	1.5 (5.3%)

Note: All values are in units of mg/L as C, unless noted otherwise.
*PT = pretreatment
**Percentages denote relative standard deviation (i.e., standard deviation divided by average value).
NA = not applicable

Sand pretreatment

Table 16. Raw TOC data for samples receiving sand pretreatment.

Sample date	Before PT*	After PT (0 sec)	After PT (50 sec)	After PT (180 sec)	After MF
11-June	64.0	**	45.7	NA	***
	65.2	**	45.5	NA	***
	66.8	**	45.4	NA	***
15-June	71.2	60.8	54.3	NA	37.3
	70.2	61.8	56.6	NA	33.8
	71.1	59.9	55.1	NA	32.5
20-June	70.8	71.8	NA	65.1	30.8
	70.7	70.7	NA	66.2	30.8
	71.6	75.2	NA	67.5	31.0
Average value	69.1	66.7	50.4	66.2	32.7
Standard deviation****	2.7 (4.0%)	6.0 (9.1%)	4.9 (9.8%)	1.0 (1.5%)	2.3 (7.2%)

Note: All values are in units of mg/L as C, unless noted otherwise.
*PT = pretreatment
**This sample accidentally captured residual tap water that had remained in the column after the preparatory rinse, therefore the values were discarded because they were erroneously low and not representative of pretreatment effluent. The discarded values were 8.36, 7.08, and 8.16 mg/L as C.
***The dispensing pressure vessel was (unintentionally) not continuously stirred during this MF run, therefore the effluent values were not comparable with value from other runs and were discarded. The discarded values were 36.0, 37.9, and 38.8 mg/L as C.
****Percentages denote relative standard deviation (i.e., standard deviation divided by average value).
NA = not applicable

No pretreatment

Table 17. Raw TOC data for samples receiving no pretreatment.

Sample date	Before MF	After MF
22-June	66.6	34.0
	71.5	31.3
	69.2	31.2
28-June	70.0	34.6
	71.9	32.8
	72.4	32.8
Average value	70.3	32.8
Standard deviation*	2.0 (2.8%)	1.3 (3.8%)

Note: All values are in units of mg/L as C, unless noted otherwise.

*Percentages denote relative standard deviation (i.e., standard deviation divided by average value).

APPENDIX H

Raw data – COD

GAC pretreatment

Table 18. Raw COD data for samples receiving GAC pretreatment.

Sample date	Before PT*	After PT (0 sec)	After PT (50 sec)	After MF
13-June	269	203	211	91
	270	202	206	79
	270	178	203	74
18-June	261	208	204	75
	256	200	214	63
	260	203	199	79
25-June	291	245	222	95
	282	213	238	85
	278	197	209	76
Average value	271	205	212	80
Standard deviation**	10.8 (4.0%)	16.5 (8.1%)	11.4 (5.4%)	9.1 (11.4%)

Note: All values are in units of mg/L COD, unless noted otherwise.

*PT = pretreatment

**Percentages denote relative standard deviation (i.e., standard deviation divided by average value).

Sand pretreatment

Table 19. Raw COD data for samples receiving sand pretreatment.

Sample date	Before PT*	After PT (0 sec)	After PT (50 sec)	After PT (180 sec)	After MF
11-June	261	**	174	-	***
	269	**	166	-	***
	258	**	169	-	***
15-June	293	383	229	-	129
	288	386	230	-	137
	286	388	230	-	126
20-June	263	367	-	222	99
	239	338	-	231	97
	238	346	-	211	96
Average value	266	368	200	221	114
Standard deviation****	18.8 (7.1%)	19.8 (5.4%)	30.2 (15.1%)	8.0 (3.6%)	16.9 (14.8%)

Note: All values are in units of mg/L COD, unless noted otherwise.
*PT = pretreatment
**This sample accidentally captured residual tap water that had remained in the column after the preparatory rinse, therefore the values were discarded because they were erroneously low and not representative of pretreatment effluent. The discarded values were 2, 9, and 11 mg/L COD.
***The dispensing pressure vessel was (unintentionally) not continuously stirred during this MF run, therefore the effluent values were not comparable with value from other runs and were discarded. The discarded values were 117, 112, 112 mg/L COD.
****Percentages denote relative standard deviation (i.e., standard deviation divided by average value).

No pretreatment

Table 20. Raw COD data for samples receiving no pretreatment.

Sample date	Before MF	After MF
22-June	254	109
	247	88
	255	86
28-June	273	103
	279	99
	262	106
Average value	262	98
Standard deviation*	11.0 (4.2%)	8.5 (8.7%)

Note: All values are in units of mg/L COD, unless noted otherwise.

*Percentages denote relative standard deviation (i.e., standard deviation divided by average value).

APPENDIX I

Raw data – Surfactants

GAC pretreatment

Table 21. Raw surfactant data for samples receiving GAC pretreatment.

Sample date	Before PT*	After PT (0 sec)	After PT (90 sec)	After MF
17-May	39.0	22.5	24.0	14.4
22-May	34.2	14.7	22.8	19.2
	-	-	-	16.8
	-	-	-	17.1
26-May	36.6	18.0	23.7	15.9
	33.6	17.7	22.5	15.3
	37.2	17.4	24.3	14.1
30-May	35.4	18.6	22.8	15.9
	38.4	18.3	24.3	17.4
	36.0	19.2	24.9	15.9
Average value	36.3	18.3	23.7	16.2
Standard deviation**	1.8 (4.9%)	2.0 (11.1%)	0.8 (3.4%)	1.4 (8.8%)

Note: All samples were analyzed at a 300x dilution and then the measured values were multiplied by a factor of 300 to arrive at the true (original) sample value. All values shown in this table represent the full, undiluted value, and are in units of mg/L as LAS unless noted otherwise.

*PT = pretreatment

**Percentages denote relative standard deviation (i.e., standard deviation divided by average value).

Sand pretreatment

Table 22. Raw surfactant data for samples receiving sand pretreatment.

Sample date	Before PT*	After PT (0 sec)	After PT (40 sec)	After PT (50 sec)	After MF
11-June	36.0	**	-	27.8***	****
	34.5	**	-	28.2***	****
	37.8	**	-	32.4	****
15-June	37.8	34.2	-	32.4	
	37.5	30.3	-	33.3	
	38.1	30.3	-	33.6	
20-June	36.3	24.6	32.7	-	25.5
	36.3	24.3	32.7	-	26.4
	36.9	24.9	33.3	-	27.6
Average value	36.8	28.1	32.9	31.3	26.5
Standard deviation*****	1.1 (3.0%)	3.7 (13.3%)	0.3 (0.9%)	2.4 (7.6%)	0.9 (3.2%)

Note: All samples were analyzed at a 300x dilution and then the measured values were multiplied by a factor of 300 to arrive at the true (original) sample value. All values shown in this table represent the full, undiluted value, and are in units of mg/L as LAS unless noted otherwise.

*PT = pretreatment

**This sample accidentally captured residual tap water that had remained in the column after the preparatory rinse, therefore the values were discarded because they were erroneously low and not representative of pretreatment effluent. The discarded values were 4.5, 3.6, and 2.1 mg/L as LAS (all of these values also fell below the estimated detection limit for the HACH colorimeter).

***These samples were analyzed using a 150x dilution instead of a 300x dilution.

****The dispensing pressure vessel was (unintentionally) not continuously stirred during this MF run, therefore the effluent values were not comparable with value from other runs and were not measured.

*****Percentages denote relative standard deviation (i.e., standard deviation divided by average value).

No pretreatment

Table 23. Raw surfactant data for samples receiving no pretreatment.

Sample date	Before MF	After MF
22-June	-	27.3
	-	26.4
	-	27.0
28-June	37.2	28.8
	36.9	27.3
	37.2	28.8
Average value	37.1	27.6
Standard deviation*	0.1 (0.4%)	0.9 (3.3%)

Note: All samples were analyzed at a 300x dilution and then the measured values were multiplied by a factor of 300 to arrive at the true (original) sample value. All values shown in this table represent the full, undiluted value, and are in units of mg/L as LAS unless noted otherwise.

*Percentages denote relative standard deviation (i.e., standard deviation divided by average value).

APPENDIX J

Raw data – Flux across membrane

GAC pretreatment

Table 24 below lists all of the raw flux data collected for samples receiving GAC pretreatment. It should be noted that the clean water flux (CWF) values (given in units of lmh, or liters per square meter per hour) listed in the top row correspond to the sample data for the dates immediately below each entry. Each column represents one MF run. The percentages listed in the table represent the sample flux as a percentage of the corresponding clean water flux, as described on page 45.

In the table, Avg refers to the average value of sample entries in that row, SD refers to the standard deviation of the sample entries in that row, and SD% refers to the relative standard deviation (i.e., SD divided by Avg).

Table 24. Raw flux data for samples receiving GAC pretreatment.

CWF: [lmh]	4513	4582	4566	4962	4604

Time [min]	22-May	26-May	30-May	13-Jun	18-Jun	Avg	SD	SD%
0.0	47%	36%	52%	56%	41%	46%	7%	15.3%
0.2	41%	22%	31%	34%	34%	32%	6%	18.5%
0.3	25%	17%	21%	21%	20%	21%	3%	12.7%
0.5	18%	14%	15%	15%	13%	15%	2%	11.3%
0.7	15%	12%	12%	12%	10%	12%	1%	12.1%
0.8	12%	11%	10%	10%	8%	10%	1%	12.9%

1.0	11%	10%	9%	9%	7%	9%	1%	15.7%
1.2	9%	9%	8%	8%	6%	8%	1%	14.4%
1.3	9%	8%	7%	7%	6%	7%	1%	15.6%
1.5	8%	8%	8%	7%	5%	7%	1%	14.2%
1.7	8%	7%	7%	6%	5%	7%	1%	12.8%
1.8	7%	6%	6%	6%	5%	6%	1%	11.3%
2.0	7%	6%	6%	5%	5%	6%	1%	12.2%
2.2	7%	5%	6%	5%	5%	5%	1%	11.9%
2.3	6%	5%	6%	5%	4%	5%	1%	11.9%
2.5	6%	5%	5%	5%	4%	5%	1%	11.8%
2.7	6%	4%	5%	5%	4%	5%	1%	12.2%
2.8	5%	4%	5%	4%	4%	4%	1%	14.4%
3.0	5%	4%	5%	4%	4%	4%	0%	11.2%
3.2	5%	4%	5%	4%	4%	4%	1%	12.9%
3.3	5%	3%	4%	4%	3%	4%	1%	13.1%
3.5	5%	3%	4%	4%	3%	4%	1%	14.9%
3.7	4%	3%	4%	4%	3%	4%	0%	13.3%
3.8	4%	3%	4%	3%	3%	4%	0%	12.8%
4.0	4%	3%	4%	3%	3%	3%	0%	13.3%
4.2	4%	3%	4%	3%	3%	3%	0%	12.4%
4.3	4%	3%	4%	3%	3%	3%	0%	13.1%
4.5	4%	3%	4%	3%	3%	3%	0%	11.9%
4.7	4%	3%	4%	3%	3%	3%	0%	13.4%
4.8	4%	3%	3%	3%	3%	3%	0%	12.9%
5.0	4%	3%	3%	3%	3%	3%	0%	11.3%
5.2	4%	3%	3%	3%	3%	3%	0%	14.6%
5.3	3%	3%	3%	3%	3%	3%	0%	10.2%
5.5	3%	3%	3%	3%	2%	3%	0%	13.4%
5.7	3%	2%	3%	3%	2%	3%	0%	11.7%
5.8	3%	2%	3%	2%	2%	3%	0%	12.6%
6.0	3%	2%	3%	2%	2%	3%	0%	11.2%
6.2	3%	2%	3%	2%	2%	3%	0%	14.2%
6.3	3%	2%	3%	2%	2%	2%	0%	9.8%
6.5	3%	2%	3%	2%	2%	2%	0%	12.5%
6.7	3%	2%	3%	2%	2%	2%	0%	12.6%
6.8	3%	2%	3%	2%	2%	2%	0%	11.0%
7.0	3%	2%	3%	2%	2%	2%	0%	12.4%
7.2	3%	2%	3%	2%	2%	2%	0%	11.9%
7.3	2%	2%	3%	2%	2%	2%	0%	9.7%
7.5	3%	2%	2%	2%	2%	2%	0%	14.0%

7.7	3%	2%	2%	2%	2%	2%	0%	11.4%
7.8	2%	2%	2%	2%	2%	2%	0%	10.4%
8.0	2%	2%	2%	2%	2%	2%	0%	10.2%
8.2	2%	2%	2%	2%	2%	2%	0%	14.6%
8.3	2%	2%	2%	2%	2%	2%	0%	10.6%
8.5	2%	2%	2%	2%	2%	2%	0%	10.1%
8.7	2%	2%	2%	2%	2%	2%	0%	15.4%
8.8	2%	2%	2%	2%	2%	2%	0%	9.1%
9.0	2%	2%	2%	2%	2%	2%	0%	10.2%
9.2	2%	2%	2%	2%	2%	2%	0%	11.8%
9.3	2%	2%	2%	2%	2%	2%	0%	11.8%
9.5	2%	2%	2%	2%	2%	2%	0%	12.1%
9.7	2%	2%	2%	2%	2%	2%	0%	11.5%
9.8	2%	2%	2%	2%	2%	2%	0%	9.4%
10.0	2%	2%	2%	2%	2%	2%	0%	12.4%
10.2	2%	2%	2%	2%	2%	2%	0%	9.9%
10.3	2%	2%	2%	2%	2%	2%	0%	10.1%
10.5	2%	2%	2%	2%	1%	2%	0%	11.6%
10.7	2%	2%	2%	2%	1%	2%	0%	11.5%
10.8	2%	2%	2%	2%	2%	2%	0%	9.1%
11.0	2%	2%	2%	1%	2%	2%	0%	11.2%
11.2	2%	2%	2%	1%	1%	2%	0%	11.2%
11.3	2%	2%	2%	1%	1%	2%	0%	11.7%
11.5	2%	2%	2%	1%	2%	2%	0%	8.5%
11.7	2%	2%	2%	1%	1%	2%	0%	13.3%
11.8	2%	2%	2%	1%	1%	2%	0%	12.6%
12.0	2%	2%	2%	1%	1%	2%	0%	8.4%
12.2	2%	2%	2%	1%	1%	2%	0%	12.8%
12.3	2%	2%	2%	1%	1%	2%	0%	14.4%
12.5	2%	2%	2%	2%	1%	2%	0%	7.7%
12.7	2%	2%	2%	1%	1%	2%	0%	10.0%
12.8	2%	2%	2%	1%	1%	2%	0%	7.7%
13.0	2%	2%	2%	1%	1%	1%	0%	14.5%
13.2	2%	2%	2%	1%	1%	2%	0%	8.0%
13.3	2%	1%	2%	1%	1%	1%	0%	14.0%
13.5	2%	2%	2%	1%	1%	2%	0%	10.5%
13.7	2%	2%	2%	1%	1%	1%	0%	12.0%
13.8	2%	1%	2%	1%	1%	1%	0%	7.3%
14.0	2%	2%	2%	1%	1%	1%	0%	13.0%
14.2	2%	1%	2%	1%	1%	1%	0%	9.7%

14.3	2%	2%	1%	1%	1%	1%	0%	11.6%
14.5	2%	2%	2%	1%	1%	1%	0%	12.1%
14.7	2%	1%	2%	1%	1%	1%	0%	10.3%
14.8	2%	1%	2%	1%	1%	1%	0%	12.9%
15.0	1%	2%	1%	1%	1%	1%	0%	10.6%
15.2	2%	1%	1%	1%	1%	1%	0%	10.3%
15.3	2%	2%	2%	1%	1%	1%	0%	12.6%
15.5	2%	1%	1%	1%	1%	1%	0%	13.0%
15.7	1%	1%	1%	1%	1%	1%	0%	8.9%
15.8	1%	1%	2%	1%	1%	1%	0%	12.8%
16.0	1%	1%	1%	1%	1%	1%	0%	9.9%
16.2	2%	2%	1%	1%	1%	1%	0%	12.0%
16.3	1%	1%	1%	1%	1%	1%	0%	10.4%
16.5	1%	1%	1%	1%	1%	1%	0%	10.7%
16.7	2%	1%	1%	1%	1%	1%	0%	12.3%
16.8	1%	1%	1%	1%	1%	1%	0%	8.0%
17.0	2%	1%	1%	1%	1%	1%	0%	14.0%
17.2	1%	1%	1%	1%	1%	1%	0%	9.4%
17.3	1%	1%	1%	1%	1%	1%	0%	10.9%
17.5	1%	1%	1%	1%	1%	1%	0%	14.3%
17.7	1%	1%	1%	1%	1%	1%	0%	7.5%
17.8	1%	1%	1%	1%	1%	1%	0%	12.8%
18.0	1%	1%	1%	1%	1%	1%	0%	14.5%
18.2	2%	1%	1%	1%	1%	1%	0%	16.2%
18.3	1%	1%	1%	1%	1%	1%	0%	13.2%
18.5	1%	1%	1%	1%	1%	1%	0%	7.5%
18.7	1%	1%	1%	1%	1%	1%	0%	14.3%
18.8	1%	1%	1%	1%	1%	1%	0%	6.1%
19.0	1%	1%	1%	1%	1%	1%	0%	13.2%
19.2	1%	1%	1%	1%	1%	1%	0%	11.6%
19.3	1%	1%	1%	1%	1%	1%	0%	11.9%
19.5	1%	1%	1%	1%	1%	1%	0%	13.7%
19.7	1%	1%	1%	1%	1%	1%	0%	10.8%
19.8	1%	1%	1%	1%	1%	1%	0%	12.9%
20.0	1%	1%	1%	1%	1%	1%	0%	10.3%
20.2	1%	1%	1%	1%	1%	1%	0%	12.2%
20.3	1%	1%	1%	1%	1%	1%	0%	13.5%
20.5	1%	1%	1%	1%	1%	1%	0%	11.1%
20.7	1%	1%	1%	1%	1%	1%	0%	9.0%
20.8	1%	1%	1%	1%	1%	1%	0%	11.5%

21.0	1%	1%	1%	1%	1%	1%	0%	10.5%
21.2	1%	1%	1%	1%	1%	1%	0%	13.7%
21.3	1%	1%	1%	1%	1%	1%	0%	11.3%
21.5	1%	1%	1%	1%	1%	1%	0%	9.1%
21.7	1%	1%	1%	1%	1%	1%	0%	14.7%
21.8	1%	1%	1%	1%	1%	1%	0%	9.9%
22.0	1%	1%	1%	1%	1%	1%	0%	11.7%
22.2	1%	1%	1%	1%	1%	1%	0%	9.8%
22.3	1%	1%	1%	1%	1%	1%	0%	13.7%
22.5	1%	1%	1%	1%	1%	1%	0%	14.0%
22.7	1%	1%	1%	1%	1%	1%	0%	8.3%
22.8	1%	1%	1%	1%	1%	1%	0%	12.8%
23.0	1%	1%	1%	1%	1%	1%	0%	12.2%
23.2	1%	1%	1%	1%	1%	1%	0%	13.0%
23.3	1%	1%	1%	1%	1%	1%	0%	11.0%
23.5	1%	1%	1%	1%	1%	1%	0%	15.4%
23.7	1%	1%	1%	1%	1%	1%	0%	11.4%
23.8	1%	1%	1%	1%	1%	1%	0%	11.7%
24.0	1%	1%	1%	1%	1%	1%	0%	11.4%
24.2	1%	1%	1%	1%	1%	1%	0%	10.0%
24.3	1%	1%	1%	1%	1%	1%	0%	12.4%
24.5	1%	1%	1%	1%	1%	1%	0%	11.2%
24.7	1%	1%	1%	1%	1%	1%	0%	9.3%
24.8	1%	1%	1%	1%	1%	1%	0%	15.1%
25.0	1%	1%	1%	1%	1%	1%	0%	12.6%
25.2	1%	1%	1%	1%	1%	1%	0%	9.3%
25.3	1%	1%	1%	1%	1%	1%	0%	11.8%
25.5	1%	1%	1%	1%	1%	1%	0%	11.1%
25.7	1%	1%	1%	1%	1%	1%	0%	12.4%
25.8	1%	1%	1%	1%	1%	1%	0%	13.3%
26.0	1%	1%	1%	1%	1%	1%	0%	13.1%
26.2	1%	1%	1%	1%	1%	1%	0%	8.4%
26.3	1%	1%	1%	1%		1%	0%	11.0%
26.5	1%	1%	1%	1%		1%	0%	10.2%
26.7	1%	1%	1%			1%	0%	3.5%
26.8	1%	1%	1%			1%	0%	8.3%
27.0	1%	1%	1%			1%	0%	1.4%
27.2	1%	1%	1%			1%	0%	3.6%
27.3	1%	1%	1%			1%	0%	1.7%
27.5	1%	1%	1%			1%	0%	9.8%

27.7	1%	1%	1%			1%	0%	3.9%
27.8	1%	1%	1%			1%	0%	7.1%
28.0	1%	1%	1%			1%	0%	6.3%
28.2	1%	1%	1%			1%	0%	6.5%
28.3	1%	1%	1%			1%	0%	0.6%
28.5	1%	1%	1%			1%	0%	6.3%
28.7	1%	1%	1%			1%	0%	3.0%
28.8	1%	1%	1%			1%	0%	5.8%
29.0	1%	1%	1%			1%	0%	8.5%
29.2	1%	1%	1%			1%	0%	0.6%
29.3	1%	1%	1%			1%	0%	6.1%
29.5	1%	1%	1%			1%	0%	9.0%
29.7	1%	1%	1%			1%	0%	4.5%
29.8	1%	1%	1%			1%	0%	5.9%
30.0	1%	1%	1%			1%	0%	9.1%
30.2	1%	1%	1%			1%	0%	4.3%
30.3	1%	1%	1%			1%	0%	9.8%
30.5	1%	1%	1%			1%	0%	5.9%
30.7	1%	1%	1%			1%	0%	4.0%
30.8	1%	1%	1%			1%	0%	6.2%
31.0	1%	1%	1%			1%	0%	4.1%
31.2	1%	1%	1%			1%	0%	12.1%
31.3	1%	1%	1%			1%	0%	1.8%
31.5	1%	1%	1%			1%	0%	5.2%
31.7	1%	1%	1%			1%	0%	1.9%
31.8	1%	1%	1%			1%	0%	8.9%
32.0	1%	1%	1%			1%	0%	5.1%
32.2	1%	1%	1%			1%	0%	9.7%
32.3	1%	1%	1%			1%	0%	11.2%
32.5	1%	1%	1%			1%	0%	0.6%
32.7	1%	1%	1%			1%	0%	7.1%
32.8	1%	1%	1%			1%	0%	5.1%
33.0	1%	1%	1%			1%	0%	2.8%
33.2	1%	1%	1%			1%	0%	12.5%
33.3	1%	1%	1%			1%	0%	9.1%
33.5	1%	1%	1%			1%	0%	0.5%
33.7	1%	1%	1%			1%	0%	6.1%
33.8	1%	1%	1%			1%	0%	1.7%
34.0	1%	1%	1%			1%	0%	6.0%
34.2	1%	1%	1%			1%	0%	11.1%

34.3	1%	1%	1%			1%	0%	5.1%
34.5	1%	1%	1%			1%	0%	7.1%
34.7	1%	1%	1%			1%	0%	4.4%
34.8	1%	1%	1%			1%	0%	7.1%
35.0	1%	1%	1%			1%	0%	5.5%
35.2	1%	1%	1%			1%	0%	7.4%
35.3	1%	1%	1%			1%	0%	8.2%
35.5	1%	1%	1%			1%	0%	6.0%
35.7	1%	1%	1%			1%	0%	6.6%
35.8	1%	1%	1%			1%	0%	4.4%
36.0	1%	1%	1%			1%	0%	6.2%
36.2	1%	1%	1%			1%	0%	6.3%
36.3	1%	1%	1%			1%	0%	5.0%
36.5	1%	1%	1%			1%	0%	6.8%
36.7	1%	1%	1%			1%	0%	8.3%
36.8	1%	1%	1%			1%	0%	5.2%
37.0	1%	1%	1%			1%	0%	5.2%
37.2	1%	1%	1%			1%	0%	5.1%
37.3	1%	1%	1%			1%	0%	11.0%
37.5	1%	1%	1%			1%	0%	7.1%
37.7	1%	1%	1%			1%	0%	6.6%
37.8	1%	1%	1%			1%	0%	9.3%
38.0	1%	1%	1%			1%	0%	2.8%
38.2	1%	1%	1%			1%	0%	4.4%
38.3	1%	1%	1%			1%	0%	10.0%
38.5	1%	1%	1%			1%	0%	1.9%
38.7	1%	1%	1%			1%	0%	7.6%
38.8	1%	1%	1%			1%	0%	9.2%
39.0	1%	1%	1%			1%	0%	7.1%
39.2	1%	1%	1%			1%	0%	15.2%
39.3	1%	1%	1%			1%	0%	5.2%
39.5	1%	1%	1%			1%	0%	6.5%
39.7	1%	1%	1%			1%	0%	2.8%
39.8	1%	1%	1%			1%	0%	9.8%
40.0	1%	1%	1%			1%	0%	7.3%
40.2	1%	1%	1%			1%	0%	6.9%
40.3	1%	1%	1%			1%	0%	11.8%
40.5	1%	1%	1%			1%	0%	6.8%
40.7	1%	1%	1%			1%	0%	3.0%
40.8	1%	1%	1%			1%	0%	8.8%

41.0	1%	1%	1%			1%	0%	6.5%
41.2	1%	1%	1%			1%	0%	9.6%
41.3	1%	1%	1%			1%	0%	1.5%
41.5	1%	1%	1%			1%	0%	6.2%
41.7	1%	1%	1%			1%	0%	11.7%
41.8	1%	1%	1%			1%	0%	6.2%
42.0	1%	1%	1%			1%	0%	7.3%
42.2	1%	1%	1%			1%	0%	12.0%
42.3	1%	1%	1%			1%	0%	7.6%
42.5	1%	1%	1%			1%	0%	2.2%
42.7	1%	1%	1%			1%	0%	6.5%
42.8	1%	1%	1%			1%	0%	11.2%
43.0	1%	1%	1%			1%	0%	6.1%
43.2	1%	1%	1%			1%	0%	7.2%
43.3	1%	1%	1%			1%	0%	9.3%
43.5	1%	1%	1%			1%	0%	6.2%
43.7	1%	1%	1%			1%	0%	14.2%
43.8	1%	1%	1%			1%	0%	3.9%
44.0	1%	1%	1%			1%	0%	13.6%
44.2	1%	1%	1%			1%	0%	5.1%
44.3	1%	1%	1%			1%	0%	5.2%
44.5	1%	1%	1%			1%	0%	14.2%
44.7	1%	1%	1%			1%	0%	6.0%
44.8	1%	1%	1%			1%	0%	11.3%
45.0	1%		1%			1%	0%	3.5%
45.2	1%					1%		
45.3	1%					1%		
45.5	1%					1%		
45.7	1%					1%		
45.8	1%					1%		
46.0	1%					1%		
46.2	1%					1%		
46.3	1%					1%		
46.5	1%					1%		
46.7	1%					1%		
46.8	1%					1%		
47.0	1%					1%		
47.2	1%					1%		
47.3	1%					1%		
47.5	1%					1%		

47.7	1%					1%		
47.8	1%					1%		
48.0	1%					1%		
48.2	1%					1%		
48.3	1%					1%		
48.5	1%					1%		
48.7	1%					1%		
48.8	1%					1%		
49.0	1%					1%		
49.2	1%					1%		
49.3	1%					1%		
49.5	1%					1%		
49.7	1%					1%		
49.8	1%					1%		
50.0	1%					1%		
50.2	1%					1%		
50.3	1%					1%		
50.5	1%					1%		
50.7	1%					1%		
50.8	1%					1%		
51.0	1%					1%		
51.2	1%					1%		
51.3	1%					1%		
51.5	1%					1%		
51.7	1%					1%		
51.8	1%					1%		
52.0	1%					1%		

Sand pretreatment

Table 25 below lists all of the raw flux data collected for samples receiving sand pretreatment. It should be noted that the clean water flux (CWF) values (given in units of lmh, or liters per square meter per hour) listed in the top row correspond to the sample data for the dates immediately below each entry. Each column represents one MF run. The percentages listed in the table represent the sample flux as a percentage of the corresponding clean water flux, as described on page 45.

The June 11 run was omitted from calculations and graphs because the dispensing pressure vessel was (unintentionally) not continuously stirred during MF, therefore the data from that run were not directly comparable to the data from other runs.

In the table, Avg refers to the average value of sample entries in that row, SD refers to the standard deviation of the sample entries in that row, and SD% refers to the relative standard deviation (i.e., SD divided by Avg).

Table 25. Raw flux data for samples receiving sand pretreatment.

CWF: [lmh]	4760	4414					4611
							(omitted)
Time [min]	15-Jun	20-Jun	Avg	SD	SD%		11-Jun
0.0	55%	47%	51%	4%	8.5%		81%
0.2	42%	38%	40%	2%	5.4%		62%
0.3	27%	23%	25%	2%	8.4%		45%
0.5	19%	17%	18%	1%	6.5%		33%

0.7	14%	13%	14%	1%	6.4%	25%
0.8	12%	11%	11%	0%	3.9%	20%
1.0	10%	9%	10%	1%	6.1%	17%
1.2	9%	8%	9%	0%	2.1%	13%
1.3	8%	8%	8%	0%	4.1%	12%
1.5	7%	7%	7%	0%	2.9%	11%
1.7	7%	7%	7%	0%	3.6%	9%
1.8	7%	6%	6%	0%	4.4%	9%
2.0	6%	6%	6%	0%	4.3%	8%
2.2	6%	6%	6%	0%	4.5%	7%
2.3	6%	5%	5%	0%	6.5%	7%
2.5	5%	5%	5%	0%	4.0%	6%
2.7	5%	5%	5%	0%	6.2%	6%
2.8	5%	4%	5%	0%	6.9%	6%
3.0	5%	4%	5%	0%	8.5%	6%
3.2	5%	4%	4%	0%	9.2%	5%
3.3	5%	4%	4%	0%	5.1%	5%
3.5	4%	4%	4%	0%	6.5%	5%
3.7	4%	4%	4%	0%	7.0%	5%
3.8	4%	3%	4%	0%	9.6%	5%
4.0	4%	3%	4%	0%	8.0%	4%
4.2	4%	3%	4%	0%	10.1%	4%
4.3	4%	3%	3%	0%	7.8%	4%
4.5	4%	3%	3%	0%	9.7%	4%
4.7	4%	3%	3%	0%	6.8%	4%
4.8	4%	3%	3%	0%	10.1%	4%
5.0	3%	3%	3%	0%	7.7%	4%
5.2	3%	3%	3%	0%	13.0%	4%
5.3	3%	3%	3%	0%	9.1%	4%
5.5	3%	3%	3%	0%	9.1%	3%
5.7	3%	3%	3%	0%	10.6%	3%
5.8	3%	2%	3%	0%	9.0%	3%
6.0	3%	2%	3%	0%	12.3%	3%
6.2	3%	2%	3%	0%	8.4%	3%
6.3	3%	2%	3%	0%	10.5%	3%
6.5	3%	2%	3%	0%	10.9%	3%
6.7	3%	2%	2%	0%	9.8%	3%
6.8	3%	2%	2%	0%	10.2%	3%
7.0	3%	2%	2%	0%	13.0%	3%
7.2	3%	2%	2%	0%	10.5%	3%

7.3	2%	2%	2%	0%	10.2%	3%
7.5	3%	2%	2%	0%	10.7%	3%
7.7	2%	2%	2%	0%	12.0%	3%
7.8	2%	2%	2%	0%	13.5%	2%
8.0	2%	2%	2%	0%	7.4%	2%
8.2	2%	2%	2%	0%	12.8%	2%
8.3	2%	2%	2%	0%	12.3%	2%
8.5	2%	2%	2%	0%	11.5%	2%
8.7	2%	2%	2%	0%	8.6%	2%
8.8	2%	2%	2%	0%	14.8%	2%
9.0	2%	2%	2%	0%	16.3%	2%
9.2	2%	2%	2%	0%	9.0%	2%
9.3	2%	2%	2%	0%	10.2%	2%
9.5	2%	2%	2%	0%	14.4%	2%
9.7	2%	2%	2%	0%	12.1%	2%
9.8	2%	1%	2%	0%	14.3%	2%
10.0	2%	2%	2%	0%	11.0%	2%
10.2	2%	1%	2%	0%	15.9%	2%
10.3	2%	1%	2%	0%	12.0%	2%
10.5	2%	1%	2%	0%	12.0%	2%
10.7	2%	1%	2%	0%	10.3%	2%
10.8	2%	1%	2%	0%	15.0%	2%
11.0	2%	1%	2%	0%	16.5%	2%
11.2	2%	1%	2%	0%	11.1%	2%
11.3	2%	1%	2%	0%	12.4%	2%
11.5	2%	1%	1%	0%	17.7%	2%
11.7	2%	1%	2%	0%	13.6%	2%
11.8	2%	1%	1%	0%	14.6%	2%
12.0	2%	1%	1%	0%	15.5%	2%
12.2	2%	1%	1%	0%	12.4%	2%
12.3	2%	1%	1%	0%	15.3%	2%
12.5	2%	1%	1%	0%	13.2%	2%
12.7	2%	1%	1%	0%	15.0%	2%
12.8	2%	1%	1%	0%	10.9%	2%
13.0	2%	1%	1%	0%	6.8%	2%
13.2	2%	1%	1%	0%	16.7%	2%
13.3	1%	1%	1%	0%	7.4%	2%
13.5	2%	1%	1%	0%	12.4%	2%
13.7	2%	1%	1%	0%	14.2%	2%
13.8	1%	1%	1%	0%	2.7%	2%

14.0	1%	1%	1%	0%	8.6%	2%
14.2	2%	1%	1%	0%	11.9%	2%
14.3	1%	1%	1%	0%	6.8%	2%
14.5	2%	1%	1%	0%	12.9%	2%
14.7	1%	1%	1%	0%	11.2%	2%
14.8	1%	1%	1%	0%	7.6%	2%
15.0	1%	1%	1%	0%	8.0%	2%
15.2	1%	1%	1%	0%	8.4%	2%
15.3	1%	1%	1%	0%	5.0%	1%
15.5	1%	1%	1%	0%	15.0%	2%
15.7	1%	1%	1%	0%	9.5%	1%
15.8	1%	1%	1%	0%	9.9%	1%
16.0	1%	1%	1%	0%	9.9%	2%
16.2	1%	1%	1%	0%	10.4%	1%
16.3	1%	1%	1%	0%	6.3%	1%
16.5	1%	1%	1%	0%	10.1%	1%
16.7	1%	1%	1%	0%	6.5%	1%
16.8	1%	1%	1%	0%	9.9%	1%
17.0	1%	1%	1%	0%	7.6%	1%
17.2	1%	1%	1%	0%	10.6%	1%
17.3	1%	1%	1%	0%	8.8%	1%
17.5	1%	1%	1%	0%	10.2%	1%
17.7	1%	1%	1%	0%	6.7%	1%
17.8	1%	1%	1%	0%	4.2%	1%
18.0	1%	1%	1%	0%	11.7%	1%
18.2	1%	1%	1%	0%	6.9%	1%
18.3	1%	1%	1%	0%	7.8%	1%
18.5	1%	1%	1%	0%	9.0%	1%
18.7	1%	1%	1%	0%	9.5%	1%
18.8	1%	1%	1%	0%	10.7%	1%
19.0	1%	1%	1%	0%	3.6%	1%
19.2	1%	1%	1%	0%	10.4%	1%
19.3	1%	1%	1%	0%	11.1%	1%
19.5	1%	1%	1%	0%	4.0%	1%
19.7	1%	1%	1%	0%	6.0%	1%
19.8	1%	1%	1%	0%	9.9%	1%
20.0	1%	1%	1%	0%	15.0%	1%
20.2	1%	1%	1%	0%	0.5%	1%
20.3	1%	1%	1%	0%	9.0%	1%
20.5	1%	1%	1%	0%	12.7%	1%

20.7	1%	1%	1%	0%	4.1%	1%
20.8	1%	1%	1%	0%	7.2%	1%
21.0	1%	1%	1%	0%	11.3%	1%
21.2	1%	1%	1%	0%	11.0%	1%
21.3	1%	1%	1%	0%	7.9%	1%
21.5	1%	1%	1%	0%	6.0%	1%
21.7	1%	1%	1%	0%	7.9%	1%
21.8	1%		1%			1%
22.0	1%		1%			1%
22.2	1%		1%			1%
22.3	1%		1%			1%
22.5	1%		1%			1%
22.7	1%		1%			1%
22.8	1%		1%			1%
23.0	1%		1%			1%
23.2	1%		1%			1%
23.3	1%		1%			1%
23.5	1%		1%			1%
23.7	1%		1%			1%
23.8	1%		1%			1%
24.0	1%		1%			1%
24.2	1%		1%			1%
24.3	1%		1%			1%
24.5	1%		1%			1%
24.7	1%		1%			1%
24.8	1%		1%			1%
25.0	1%		1%			1%
25.2	1%		1%			1%
25.3	1%		1%			1%
25.5	1%		1%			
25.7	1%		1%			
25.8	1%		1%			
26.0	1%		1%			
26.2	1%		1%			
26.3	1%		1%			
26.5	1%		1%			
26.7	1%		1%			
26.8	1%		1%			
27.0	1%		1%			
27.2	1%		1%			

27.3	1%		1%			
27.5	1%		1%			
27.7	1%		1%			
27.8	1%		1%			
28.0	1%		1%			
28.2	1%		1%			
28.3	1%		1%			
28.5	1%		1%			
28.7	1%		1%			
28.8	1%		1%			
29.0	1%		1%			
29.2	1%		1%			
29.3	1%		1%			

No pretreatment

Table 26 below lists all of the raw flux data collected for the sample receiving no pretreatment. It should be noted that the clean water flux (CWF) value (given in units of lmh, or liters per square meter per hour) listed in the top row corresponds to the sample data for the date immediately below that entry. The percentages listed in the table represent the sample flux as a percentage of the corresponding clean water flux, as described on page 45.

Table 26. Raw flux data for sample receiving no pretreatment.

CWF: [lmh]	4467

Time [min]	22-Jun
0.0	40%
0.2	23%
0.3	16%
0.5	12%
0.7	10%
0.8	9%
1.0	8%
1.2	8%
1.3	7%
1.5	7%
1.7	6%
1.8	6%
2.0	6%
2.2	5%
2.3	5%
2.5	5%
2.7	5%

2.8	4%
3.0	4%
3.2	4%
3.3	4%
3.5	4%
3.7	4%
3.8	3%
4.0	3%
4.2	3%
4.3	3%
4.5	3%
4.7	3%
4.8	3%
5.0	3%
5.2	3%
5.3	3%
5.5	2%
5.7	3%
5.8	2%
6.0	2%
6.2	2%
6.3	2%
6.5	2%
6.7	2%
6.8	2%
7.0	2%
7.2	2%
7.3	2%
7.5	2%
7.7	2%
7.8	2%
8.0	2%
8.2	2%
8.3	2%
8.5	2%
8.7	2%
8.8	2%
9.0	2%
9.2	2%
9.3	2%

9.5	2%
9.7	2%
9.8	2%
10.0	2%
10.2	2%
10.3	2%
10.5	2%
10.7	2%
10.8	2%
11.0	2%
11.2	2%
11.3	1%
11.5	2%
11.7	1%
11.8	1%
12.0	1%
12.2	2%
12.3	1%
12.5	1%
12.7	1%
12.8	2%
13.0	1%
13.2	1%
13.3	1%
13.5	1%
13.7	1%
13.8	1%
14.0	1%
14.2	1%
14.3	1%
14.5	1%
14.7	1%
14.8	1%
15.0	1%
15.2	1%
15.3	1%
15.5	1%
15.7	1%
15.8	1%
16.0	1%

16.2	1%
16.3	1%
16.5	1%
16.7	1%
16.8	1%
17.0	1%
17.2	1%
17.3	1%
17.5	1%
17.7	1%
17.8	1%
18.0	1%
18.2	1%
18.3	1%
18.5	1%
18.7	1%
18.8	1%
19.0	1%
19.2	1%
19.3	1%
19.5	1%
19.7	1%
19.8	1%
20.0	1%
20.2	1%
20.3	1%
20.5	1%
20.7	1%
20.8	1%
21.0	1%
21.2	1%
21.3	1%
21.5	1%
21.7	1%
21.8	1%
22.0	1%
22.2	1%
22.3	1%
22.5	1%
22.7	1%

22.8	1%
23.0	1%
23.2	1%
23.3	1%
23.5	1%
23.7	1%
23.8	1%
24.0	1%
24.2	1%
24.3	1%
24.5	1%
24.7	1%
24.8	1%
25.0	1%
25.2	1%
25.3	1%
25.5	1%
25.7	1%
25.8	1%
26.0	1%
26.2	1%
26.3	1%
26.5	1%
26.7	1%
26.8	1%
27.0	1%
27.2	1%
27.3	1%
27.5	1%
27.7	1%
27.8	1%
28.0	1%
28.2	1%
28.3	1%
28.5	1%
28.7	1%
28.8	1%
29.0	1%
29.2	1%

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