THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

DEPARTMENT OF ENGINEERING SCIENCE AND MECHANICS

ANALYSIS OF THE REMOVAL CAPABILITIES OF INTERMITTENTLY AND CONTINUOUSLY RUN SLOW SAND FILTERS

TIMOTHY MICHAEL BYRNE

SPRING 2010

A thesis
submitted in partial fulfillment
of the requirements
for a baccalaureate degree
in Engineering Science
with honors in Engineering Science

Reviewed and approved* by the following:

Brian A. Dempsey
Professor of Environmental Engineering
Thesis Supervisor

Clifford J. Lissenden
Professor of Engineering Science and Mechanics
Honors Adviser

Judith A. Todd
P.B. Breneman Department Head Chair
Professor, Department of Engineering Science and Mechanics

* Signatures are on file in the Schreyer Honors College and Engineering Science and Mechanics Offic

ABSTRACT

Over 80,000 household scale intermittent slow sand filters (SSF) have been installed in 20 different countries. However, case studies reveal that the operating removal performance does not comply with design expectations and can be variable. Therefore, additional study, better characterization, and design improvements are needed. In this study, both continuous and intermittent SSFs were operated for a duration of 110 days. Performance was monitored in terms of conventional parameters (turbidity, BOD, COD, coliform organisms, etc.) and by changes in the composition of organic matter (TOC and content of organic acids and other organic fractions) in the influent and the effluents. The continuous-flow SSF was operated with 91 cm of head, and, after providing at least 24 hours for maturing, flow ranged from 350 to 20 ml/min (1150 to 65 $Lm^{-2}hr^{-1}$loading rate). The intermittent flow SSF was charged with 20 L per day, and, after maturing, the flow typically ranged between 55 and 29 ml/min (181 to 72 $Lm^{-2}hr^{-1}$ loading rate) during a single run, due to changing hydraulic head. Removals for the conventional parameters showed that effective biological and physical treatment was achieved within the SSFs. As expected, the continuous-flow SSF performed marginally better than the intermittent-feed SSF. Both hydraulic modes provided good removal of organic acids, but hydrophilic base/neutrals were consistently produced in the columns. Unexpectedly, removal of total organic carbon (TOC) increased with increasing flow in the continuously run SSF, but the reverse occurred with the intermittently run filter. This could have been due to better penetration of O_2 and nutrients and thus a deeper bio-filter layer in the continuous-flow SSF, and due to shearing of organic matter with increased flow in the intermittent-feed SSF. The results are consistent with several other studies completed on both municipal and pilot scale SSFs, while they are in conflict with a small number of investigations. These results indicate that intermittent SSF could be improved with better flow control, including reeducated fluctuation in flow rate.

Keywords: slow sand filtration, biosand filter, intermittent, organic fractionation, removal

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ACKNOWLEDGEMENTS

The author would like to thank Hyunchul Kim for all of his help with lab acclimation and, especially, for pivotal help in performing organic fractionation. Also, David Faulds was instrumental in collecting supplies for the experimental set up. Thanks also to John Fox for help with running lab tests and tending the pilot columns for a couple of weekends. Likewise, the author would like to thank Janalyn Sheetz, the author’s fiancée, for support and tending the pilot columns on one occasion. In addition, the author would like to express gratitude to Dr. Dempsey for the opportunity to pursue research on what he is passionate about, as well as, key guidance and advising throughout the course of the research project.

ABBREVIATIONS AND ACRONYMS

SSF	Slow Sand Filter
POU	Point-of-use
THM	Tri-halo Methane
THMFP	Tri-halo Methane Formation Potential
HAA	Haloacetic Acids
TDS	Total Dissolved Solids
TOC	Total Organic Carbon
DOC	Dissolved Organic Carbon
NPDOC	Non-purgeable Dissolved Organic Carbon
POC	Particulate Organic Carbon
NOM	Natural Organic Matter
MW	Molecular Weight
COD	Chemical Oxygen Demand
BOD	Biochemical Oxygen Demand
WHO	World Health Organization
NGO	Non-governmental Organization
UN	United Nations
MDG	Millennium Development Goal
EfOM	Effluent Organic Matter
HPO	Hydrophobic
HPI	Hydrophilic
TPI	Transphilic
b/n	Base/neutral
Cont	Continuous-flow
Int	Intermittent-flow

Chapter 1

INTRODUCTION

1.1. Slow Sand Filtration

Though slow sand filtration is one of the oldest modern water treatment technologies, its use is still very relevant almost two centuries after its conception. Slow sand filtration is well suited for water treatment for small and developing communities attributable to simplicity of design, passive mechanisms, and relative ease of operation and maintenance (Hendricks, 1991). For small water supplies, slow sand filtration is often a better alternative than rapid sand filtration, which has helped to preserve its importance to society and scientific research.

An adaptation discovered by Dr. David H. Manz at the University of Calgary in the early 1990's has allowed slow sand filtration to function even with an intermittent supply (Duke et al., 2006). These "demand operated slow sand filters" afford the same treatment mechanisms as traditional flow systems, but do not require water to be continuously supplied to the biological layer, or schmutzdecke, which forms on top of the sand (Manz, 2004). This mechanism enables slow sand filtration to be an effective method for point of use (POU) water treatment, especially relevant in the developing world. POU systems can be designed to a household scale and used as an effective water quality improvement system, especially when safe water is not available. The World Health Organization (WHO) reports that approximately 1.1 billion people in the developing world do not have access to safe sources of drinking water, so effective and available treatment technologies, such as slow sand filtration, are needed to address this huge need (WHO, 2004). An estimated 500,000 people currently use up to 80,000 household SSF units worldwide, but only a handful of field and lab studies have monitored their performance and studied their treatment mechanisms (Elliot et al., 2006) (Stauber et al., 2009). Case studies reveal 83-99% removal of pathogens and greater than 50% reduction in diarrheal diseases when using SSF, but these values need to be higher and more consistent if the provision of safe water is to be guaranteed by this technology (Stauber et al., 2009).

1.2. Conventional Parameters of Filter Performance

There is a need for more research to be conducted to allow a better understanding of the removal mechanisms and capabilities of intermittent slow sand filtration. The typical parameters which are used to give an indication of maturation to proper filter performance are turbidity removal, total coliform removal, and headloss development. Turbidity is believed to be a carrier of nutrients involved in biological metabolism and its removal is an indication of proper filtration of particles (Farooq & Al-Yousef, 1993). Also, high levels of effluent turbidity could signify that particles such as bacteria and viruses are passing through. Total coliform bacteria are indicator organisms linked to fecal contamination but also include organisms native to the environment. Fecal coliform organisms are a subgroup of total coliform referring specifically to "thermotolerant" organisms which inhabit the intestines of warm-blood animals. Removal of fecal and total coliform is correlated to removal of human pathogenic microorganisms transported by fecal contamination. Lower than expected removals of pathogens can be attributed to poor bio-layer performance, high flow rates (low retention time), and transport mechanisms. Pathogen transport through the filter can be influenced greatly by the nature of the organic content in the source water. Natural organic matter (NOM), which originates from plant and biomass degradation, can facilitate transport of pathogens, as well as metals and synthetic organic chemicals, by protection from degradation and adsorption.

1.3. Natural Organic Matter

The impact of source water organic chemistry on the performance of household scale SSFs has not yet been investigated. Natural organic matter (NOM and total organic carbon (TOC) are lumped parameters representing all of the organic compounds in water. A 1992 study conducted by Collins et al. reported on the removal of NOM from traditional SSFs, but the performance of intermittent SSFs has yet to be extensively tested. NOM and humic substances are historically the focus of organic contaminant removal due to their potential to form trihalomethanes (THM) and haloacetic acids (HAA) when combined with halogen disinfectants (Collins et al, 1992). Household SSFs can experience similar risks as POU systems and often employ chlorine tablets or diluted household bleach for final disinfection (CAWST, 2009). In addition, small rural systems primarily use chlorine as a final disinfection because it is inexpensive and effective. In fact, chlorine is the most used water treatment technology in the world (Burch & Thomas, 1998). Water treatment in developing countries is primarily facilitated by NGO's, and their major emphasis for rural areas in developing countries is on chlorine bleach, slow sand filters, and ceramic filters (Burch & Thomas, 1998). Therefore, removal of NOM precursors to THM formation is likely important at all scales of slow sand filtration. Understanding the mechanisms of NOM removal in intermittent SSFs is essential to reduction of formation of halogenated organics, known carcinogens, and to understanding the transport of contaminants and pathogens through the filter.

In addition, NOM can add to negative aesthetic properties in water. Sensory perception of water is closely linked to consumer acceptance and confidence in a drinking water source. Consequently, when treated water has an unsatisfactory taste, consumers often seek alternative, better tasting water sources, which may offer a greater risk of disease (Whelton et al, 2007). Organic contaminants caused by algal blooms, soil microorganisms, and agriculture such as geosmin, 2-methylisoborneol (MIB), and volatile organic compounds are known to add taste and odor at low threshold concentrations. In addition, humic materials from plant and soil decay often add color to source waters, which must be removed during the water treatment processes (Thurman, 1985). The character of organic content of the water and the specific SSF removal of TOC can be explored using an organic fractionation technique to operationally distinguish between several size and functionality criteria.

1.4. Objectives and Organization

The aim of this paper is to explore the performance of continuous and intermittent slow sand filtration, analyzing a worst-case scenario influent (settled plant effluent from the Pennsylvania State University Waste Water Treatment Plant). The specific objective was to compare the performance of the continuously and intermittently run SSFs to find similarities, strengths, and weakness for each flow regime. Filter performance and maturation was primarily monitored by recording flow rate, turbidity, chemical oxygen demand (COD), and coliform organism removal throughout the filter operation period. In addition, several other surrogate parameters were measured occasionally such as conductivity, total dissolved solids (TDS), alkalinity, and total hardness. Organic fractionation was also performed on four occasions to further characterize filter performance. Grab samples for organic fractionation were sequentially separated by particle size (suspended solids: > 1μm, colloids: 1 μm-20nm, dissolved organic matter: < 20 nm), and then functionality (HPO/HPI/TPI acids, HPO base/neutrals, TPI base/neutrals, HPI base/neutrals).

1.5. Impact of Research

Slow sand filtration has already been implemented globally (over 20 countries) and has shown evidence to be a feasible technology for decrease in occurrence of diarrheal disease caused by lack of water hygiene and sanitation. Diarrheal disease is a very serious health concern in much of the world, accounting for 4 % of the global disease burden with an annual death toll of 1 million. In addition, the average child in developing countries is affected by 3 to 4 cases annually (Stauber et al., 2009). The huge burden caused by contaminated drinking water has led the UN to include improvement of access to safe water in its Millennium Development Goals (MDG). Slow sand filtration will be and has been an effective tool in working toward the third target of MDG 6 which seeks "to halve by 2015 the population which lacks sustainable access to safe drinking water and basic sanitation." In addition, intermittent slow sand filtration is a POU technology which requires little to no energy or transport for operation, which makes it a very low impact treatment technology as it can be decentralized. POU SSFs can also be highly economically sustainable because they are built with locally available materials for a cost less than 25 US dollars. Additional operation and maintenance costs are minimal.

However, POU SSFs may not always be the best solution, and research is needed to understand consistency and effectiveness. For instance, in rural China an NGO installed a slow sand filtration system to treat water contaminated with industrial pollutants, but Dr. Wu Zucheng, professor of environmental science and engineering at Zhejiang University, was skeptical about their ability to remove industrial contaminants. Dr. Zucheng explained that the slow sand filtration system might “too primitive” to deal with the complicated waste streams (Tremblay, 2010). In addition, nearly every case study conducted on household scale slow sand filtration recommends post disinfection after filtration because of performance fluctuation. Therefore, more research is needed to characterize and improve the overall performance of intermittent SSFs. Chlorination also creates the need for prevention of disinfection by-products, which are known carcinogens, to assure the long term safety of drinking water. The simplicity of construction, operation, and maintenance of intermittent slow sand filtration offers hope for providing safe drinking water to those 1.1 billion who still lack it, but the complexities of the treatment mechanisms must be understood in order to ensure that the technology will provide a sustainable solution.

Chapter 2

REVIEW OF RELEVANT LITERATURE

2.1. History of Slow Sand Filtration

The use of slow sand filtration to increase water quality dates back to the early nineteenth century in England, where it was primarily used to improve aesthetics. In fact, the importance of SSFs even precedes the discovery of water-borne pathogens by Dr. John Snow in 1854 (Fox et al., 1994). Continual progress in disease epidemiology in the nineteenth century created a realized need for drinking water regulation and treatment. Consequently, this need sparked the fast growth of slow sand filtration, and many plants were installed throughout Europe. In 1872, the town of Poughkeepsie, New York installed the first recorded SSF plant in the United States (Fox et al, 1994). However, by the 1940s only approximately 100 SSF plants were in operation in the United States compared to around 3000 rapid sand filter plants. Throughout the next couple decades, SSF plants were rarely installed in the US though many were continuing to be constructed throughout the world.

However, reinvestigation of the technology began in the US around 1980 for use in small communities due to its ease of operation and maintenance, low cost, and effectiveness in removing microbial contaminants (Fox et al, 1994). For these same reasons, NGOs around the world have concentrated efforts on using SSF for water treatment in developing countries. In addition, the development of the household scale intermittent SSF, or the Biosand filter, in the early 1990s has allowed for widespread distribution in developing countries. Over 80,000 intermittent household scale filters have been installed in more than 20 countries across the globe (Duke et al., 2006). In fact, more than 10 case studies have been published within the last decade on the effectiveness of house scale SSF's across the world, primarily focusing on fecal coliform removal and sustainability of performance and use within the studied communities (CAWST, 2008).

2.2. Design of Slow Sand Filtration

Conventional slow sand filtration is gravity-driven treatment through porous media, involving four major components: supernatant water storage, a filter bed, an underdrain, and a flow control system, as shown in **Figure 2-2-1** (Fox, 1994).

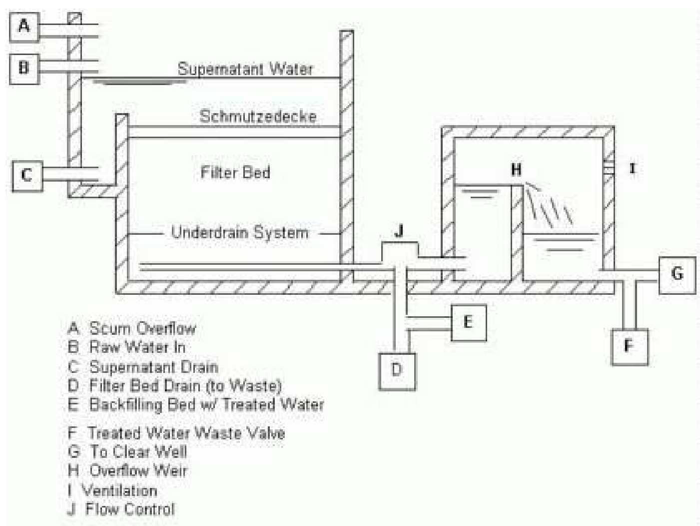

Figure 2-2-1: Design of Conventional Slow Sand Filter (Rust, 1996)

2.2.1. Supernatant Water Storage

The primary importance of the supernatant water is to provide a pressure head to drive the influent water through the porous filter bed, according to Darcy's Law. The resulting high retention time in the supernatant water before entering the filter also allows settling of solids and biological treatment at the interface with the filter media (Fox et al., 1994).

2.2.2. The Filter Bed

The filter bed functions as the location of the vast majority of the treatment. It is composed of sand with an effective diameter of approximately 0.2-0.3 mm and a uniformity coefficient between 1.5 and 3.0 (Hendricks, 1991). The porous sand layer creates a large surface area for particle trapping and attachment as well as biological growth. The thick biological layer or schmutzdecke ("dirt covering") which forms on the surface and top several inches of the sand layer concentrates mechanisms of biodegradation and bioadsorption to form an intensified treatment zone for organics, pathogens, and particulate matter (Fox et al, 1994). As the water percolates deeper into the filter bed, further adsorption occurs in the sand media along with yet more biological breakdown and attachment. However, the large majority of the biomass is found within the top 10-20 cm of the filter bed (Collins et al., 1992).

2.2.3. The Underdrain and Flow Control Systems

The underdrain system supports the filter media, prevents sand grains from escaping the bed, and ensures uniform outflow across the entire filter bed area (Fox et al, 1994). At the start of a run, the filter is backfilled through the underdrain to remove gas bubbles which could cause air binding in the filter media. The flow control system is either located before or after the filter bed and operates to allow constant flow or head, ensuring the filter

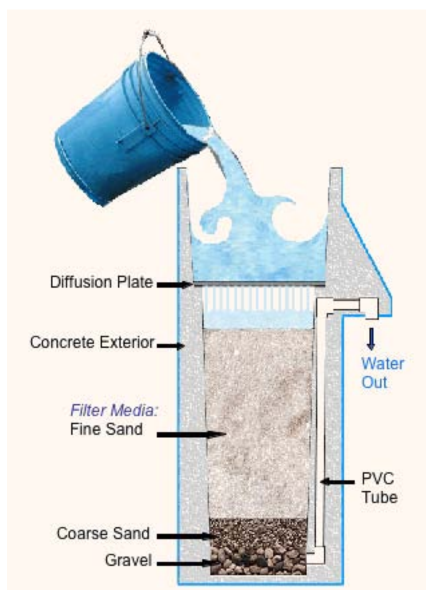

Figure 2-2-2: Design of Intermittent Slow Sand Filter (Duke, 2006)

media remains saturated so that the biological layer can remain metabolically active and aerobically respiring.

2.2.4. Design of Intermittent SSFs

Demand-operated (intermittent) slow sand filters have slightly modified components, which allow for several key performance differences highlighted in **Table 2-2-1**. The raised water outlet maintains a water level of around 5 cm for optimal oxygen and nutrient diffusion to the schmutzdecke, shown in **Figure 2-2-2** (Manz, 2004). Also, filters can be cleaned without scraping and removal of filter media, which allows filter performance to be relatively unaltered after the cleaning procedure.

	Traditional (continuous-flow)	**Demand Operated (intermittent-flow)**
Operation	- Stopping and starting alters performance - Large volume of treated water storage needed	- Unaffected by intermittent use - Minimization of water storage and waste - Retrofittable with other treatment and with different construction materials
Maintenance	- Requires removal and eventual replacement of media - Time and labor intensive cleaning - Must run water to waste until ripened	- No media removal or replacement - Cleaning does not impact filter performance - Little to no waste water produced
Performance	- Parasites: up to 100% - Bacteria: up to 99% - Turbidity: < 1 NTU - Arsenic: NA	- Parasites: up to 100% - Bacteria: up to 99% - Turbidity: <1 NTU - Arsenic: up to 100%
Design	- Large structures – several meter filter bed and supernatant water storage - Construction on-site with large skilled work force - Foundation needed	- Compact – 1 to 2 meters height - Minimum construction if on-site with small skilled work force - Construction can be off-site - Minimal foundation needed
Loading Rate	150-300 litres/m^2/hr	Up to 600 litres/m^2/hr

Table 2-2-1: Comparison of Traditional and Demand Operated Slow Sand Filtration (Manz, 2004)

2.3. Mechanisms of Removal

2.3.1. Typical Removal Efficiencies of Conventional Parameters

Intermittent and continuous SSFs are expected to function under the same basic mechanisms of performance. It would then be logical to assume that their removal capabilities would be similar; however, observed differences have been reported. **Table 2-3-1** compares some values found in the literature for turbidity and coliform removal of SSFs. As shown, values from the literature suggest that continuous filters offer more consistent and better removal of turbidity and coliform organisms than intermittent filters. The comparisons between continuous and intermittent filters cannot completely conclusive as the influent water qualities and design parameters varied between studies, but the overall trends suggest marginally better performance from SSFs in the continuous flow mode.

COD values have been used a baseline parameter for the amount of organic compounds removed by a filter, as a complement to TOC values. Palmateer et al. (1999) found COD values to be largely additive with a production of 1-8 mg/l COD in the effluent from the intermittent filter used. This is the opposite of the organic removal found using TOC values in **Table 2-3-1** for continuous flow filters.

Study	Effluent Tubidity (NTU)		Turbidity Removal (%)		Coliform Removal (%)		Bed Depth (m)	D_{eff} (mm)	U
	Int	Cont	Int	Cont	Int	Cont			
Farooq & Al-Yousef, 1993 (pilot)	--	0.10-0.18	--	91	--	93	0.55	0.31	2
	--	0.05-0.30	--	92	--	>96	1.05	0.31	2
	--	0.05-0.40	--	95	--	>99	1.35	0.31	2
	--	0.13-0.43	--	87	--	93	0.55	0.56	1.64
	--	0.13-0.40	--	89	--	97	1.05	0.56	1.64
	--	0.10-0.26	--	92	--	>97	1.35	0.56	1.64
Malley et al., 1991 (pilot)	--	0.25-0.75	--	65-80	--	--	0.406	0.34	2
Collins et al., 1994 (municipal)	--	0.26	--	27.8	--	--	0.7	0.3	2.3
	--	0.15	--	70	--	--	0.64	0.27	2
	--	0.17	--	43.3	--	--	0.46	0.3	2.7
Elliot et al., 2008 (pilot)	0.65-2.99	--	--	--	75-99.9	--	0.4	0.19–0.22	3.5-4
Stauber et al., 2009 (field)	--	--	red.	--	83	--	0.4	0.15-0.55	2-4 or >4
Earwaker, 2006 (field)	<5	--	--	--	87.9	--	0.46	0.15-0.35	low
Duke and Baker, 2006 (field)	0.9	--	85	--	99	--	0.4	0.15-0.55	2-4 or >4
Buzunis, 1995 (lab)	<1	--	95	--	97	--	--	--	--
Vanderzwaag, 2008 (field)	--	--	88	--	98	--	0.4	0.15-0.55	2-4 or >4

Table 2-3-1: Comparison of Removal of Conventional Parameters

2.3.2. Transport and Attachment

The exact mechanisms of particle removal by slow sand filtration are yet to be completely understood, but there is likely a physical entrapment in the pores between the grains of sand and on the surface of the sand grains. The two major filtration steps are theoretically defined as transport and attachment (Hendricks, 1991). Transport involves the attachment of an ambient particle to a sand grain either by interception, sedimentation, or diffusion. The likelihood of transport to the surface of the sand grain occurring is associated with a collision probability coefficient, η. After collision occurs, removal will not take place unless particle attachment is also achieved. A coefficient of attachment, α, relates the number of attachments to the number of collisions (Hendricks, 1991). The attachment and growth of the biofilm and schmutzdecke in slow sand filtration, transforms from $\alpha = 0$ at start up to approaching $\alpha = 1$ at filter maturity. Filter maturation is by definition the process, lasting 2-3 weeks, in which the biological layer of the SSF ripens to achieve maximum removal efficiency (Palmateer et al., 1999).

2.3.3. Biodegradation

In addition to adsorption through filtration, removal within the filter bed is largely enhanced by biodegradation, the metabolism of influent particulates and soluble compounds. The majority of the microbial population that grows in the filter bed is oligotrophic heterotrophs, which are well adapted to growth utilizing diverse carbon sources (Eighmy et al., 1992). Chemolithotrophic microbes can allow some oxidation and removal of inorganic compounds, such as nitrates (Aslan, 2008). The general mechanism for metabolism of biodegradable NOM is separation of small aromatic compounds from larger fulvic and humic substances, enzymatic alteration, and mineralization to CO_2 (Eighmy et al., 1992). Collins et al. (1992) found an inverse relation between bacterial population size and filter depth as well as positive correlations between filter biomass and organic THM precursor removal.

2.4. Organic Chemistry of Source Waters

2.4.1. Natural Organic Matter

Throughout the hydrological cycle, drinking water source waters accumulate NOM from both natural and anthropogenic activity. Plant and soil matter leach into the water creating color, taste, and odor. In addition, NOM is the primary precursor to disinfection byproducts such as trihalomethanes (THMs) and haloacetic acids (HAAs), which are widely recognized to be harmful or even carcinogenic. NOM can be further classified as particulate organic carbon (POC) and dissolved organic carbon (DOC), which are inherently divided at a size of 0.45 micrometers as seen in **Figure 2-4-1.**

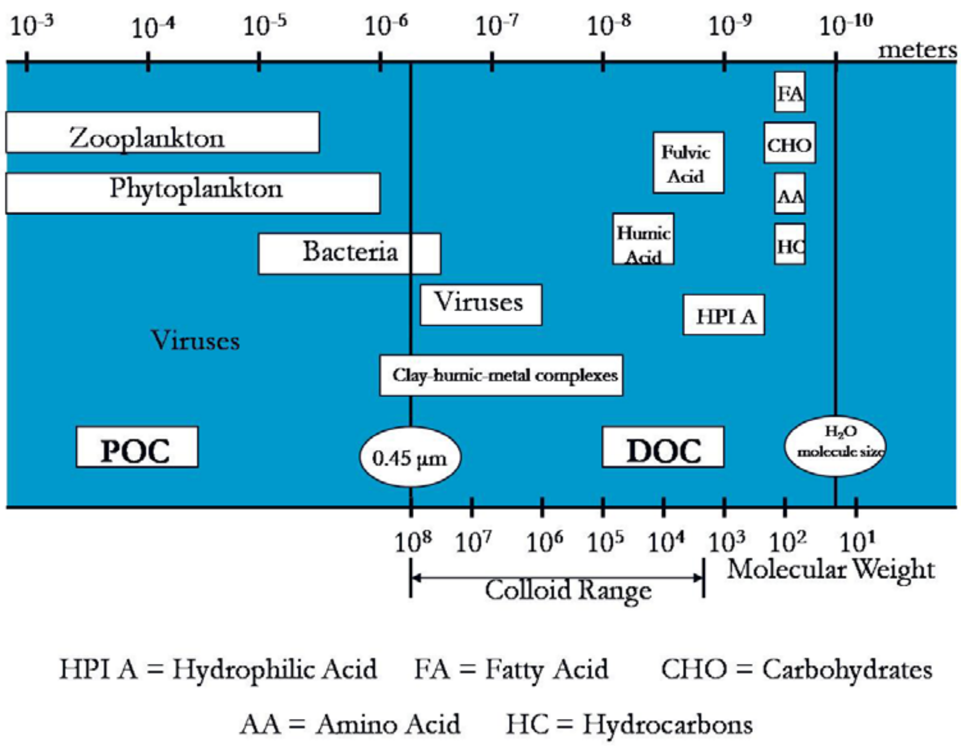

Figure 2-4-1: Distribution of Organic Carbon Size (Thurman, 1985)

NOM is most common in the anionic soluble form (DOC), though compounds can also be associated with particles, such as clays (Veissmann, 2009). The main constituents of DOC in natural waters are polymeric organic acids, classified as humic substances, along with hydrophilic acids and polysaccharides (Thurman, 1985). Humic substances, which are further classified as humic and fulvic acids, are operationally isolated using a weak-base ion exchange resin and are nonvolatile. Humic acids precipitate, where as fulvic acids stay in solution at a pH of 2 or less (Thurman, 1985).

2.4.2. Removal of NOM

POC, such as algae and bacteria, encounter high removal rates in slow sand filtration, where as higher fractions of DOC pass through. However, biodegradable organics such as carbohydrates, carboxylic acids, amino acids, and hydrocarbon fractions are treatable with around 50% removal efficiency by SSF (Thurman, 1985) (Fox et al, 1994). The majority of biodegradable DOC is already metabolized by biota in the natural waters, so the removal of TOC is only 15-19 %, according to USEPA investigative study recorded by Fox et al (1984) using several pilot scale SSFs across the United States (Logsdon, 2008). Similar investigations in England found 15% reduction in TOC for pilot and full scale SSF as seen in **Table 2-3-1** (Rachwal et al, 1988).

Trihalomethane formation potential (THMFP) is likely the most investigated and regulated characteristic of NOM when post treatment chlorination is used. THMs originate largely from humic materials, which are often inadequately removed by SSF (Demspey, 1994). Humic substances are, on average, composed of 50% carbon, 4-5% hydrogen, 35-40% oxygen, and 1% nitrogen, forming carboxylic acids, phenolic and alcoholic hydroxyl groups, and keto functional groups (Thurman, 1985). Humic substances are extremely important to NOM removal as they can constitute up to 40-60% of the DOC in a surface water source.

Low removal rates are attributed to the low solubility and inertness to biodegradation of humic materials, which are the stable end products of the breakdown of plant life. Humic materials, however, are removed more effectively at high molecular weights (MW) in contrast to low MWs (Dempsey, 1994). M.R. Collins et al (1994) found in a study of multiple municipal full and pilot scale SSFs in the Northeast US that low MW NOM with MW 5000-500 and <500 kDa achieved the highest mass removal rates.

Schmutzdecke bacterial isolates readily biodegrade lower MW organic compounds, such as monoaromatics. Large hydrophobic and humic materials are removed primarily by adsorption, while smaller hydrophilic materials, such as carbohydrates, aldehydes, and simple organic acids are more affected by biodegradation (Thurman, 1985). The largest removals seen by the filters were hydrophobic-humic substances (most THM reactive) attributed to adsorption, whereas hydrophilic removal did increase when temperatures were warmer and metabolic activity was greater in the schmutzdecke (Collins, 1992). In addition, humic substances with high carboxylic acid concentrations were not effectively removed due to high charge density (Collins et al., 1986).

Source and Location	DOC Removal	UV Abs Removal	THMFP Removal
Mallevaile & Cournarie (1982), France	10%	10%	-
Fox et. al (1984), OH	19%	-	18%
Rachwal et al. (1988), London	15%	12%	23%
Collins et al. (1992), MA & CT	12-33%	17-40%	9-27%
Dempsey et al. (1994), PA	19%	23%	29%

Table 2-3-1: Comparison of NOM Removals by SSFs

2.4.3. NOM Functionality

NOM is a water quality parameter that is characterized by a huge variety of organic compounds that can not be easily individually identified. Therefore, some operational categories are commonly used in order to understand some of the important properties of the organic content of a water sample. Organic compounds can be related to their willingness to donate or accept protons: acid, bases, and neutrals, and related to their polarity and solubility in water: hydrophobic (HPO), transphilic (TPI), and hydrophilic (HPI). The major acidic functional groups in NOM are carboxylic acids, enolic hydrogen, phenolic hydroxyl, and quinone. The major basic functional groups are amines and amides. The major neutral functional groups are alcoholic hydroxyls, ethers, ketones, aldehydes, esters, and lactones (Thurman, 1985). Each of these functional groups can also be classified based on their polarity, such as a carboxylic acid group is a hydrophilic acid group which would increase solubility if substituted for a non-polar moiety. The sum of the interactions of the functional groups determines the functionality of the molecule. HPOs would be expected to adhere to non-polar surfaces, where as HPIs prefer to dissociate into aqueous solution or become associated with a polar surface, such as an ion exchange medium with the opposite charge.

Organic acids are often a large fraction of NOM in surface waters and are subsequently also the largest cause of harmful chlorinated disinfection by products. Neutral functional groups such as aldehydes and ketones can form compounds which affect taste and odor. The overall charge of the organic compounds largely affects the adsorption onto the largely HPO sand particles and onto HPI, TPI, and HPO NOM. Contaminant adsorption onto NOM can either enhance or retard transport through the porous filter media. HPO contaminants which preferentially bind to high MW, HPO NOM compounds will likely be adsorbed into the filter media, where as HPI contaminants such as metals could receive increased transport when bound with low MW, HPI NOM compounds (Steinberg, 2003). Overall, NOM can have a large or small or even negative impact on mediating transport of inorganic, organic, and microbial contaminants through the filter media.

2.5. Improvement of Organic Removal

Slow sand filtration has been historically deficient at removing organic compounds from source waters, especially non-biodegradable dissolved organic carbons. However, there are many pretreatment processes which can aid in the removal of organic matter. The most studied method is preozonation. Pretreatment with ozone results in decomposition to more biodegradable components and has experimentally resulted in 7-20% increases in DOC removal efficiency in laboratory pilot scale studies (Dempsey et al., 1994) (Mallevialle & Cournarie., 1982) (Rachwal et al., 1988). However, ozone technologies are often not accessible for the small water supplies which consider use of slow sand filtration. Therefore, low cost absorbents such as activated carbons, biomaterials, and novel polymers may be a more feasible option for increased removal of NOM and trace organics. Eighmy et al. (1992) found that surface amendments to increase NOM removal efficiency do not markedly affect the microbial population dynamics and distribution of the schmutzdecke.

One biomaterial, the seed of the Moringa oleifera plant, has received a lot of scientific attention within the past two decades for its ability as a coagulant and antimicrobial agent. The Moringa oleifera plant is native to Northern India but grows well in tropical, semi-arid climates akin to Africa, Central and South America, and Southern Asia. Often called the “miracle tree,” it has multiple uses for nutrition, cooking, water treatment, and even biofuel. When the seeds of the plant are pressed to harvest the precious oil contained, 60% (by weight) of the seed is considered the waste of the oil extraction process. This remaining “seed cake” contains cationic proteins which can be beneficial for coagulation and adsorption of turbidity and contaminants in drinking water. One batch test study found the seed cakes to be effective in removal of hydrophobic organic pollutants, the type which are most persistent in the environment (Boucher et al., 2007). The main constituents of the seed cakes are cellulose, lignin, and hemi-cellulose, which have potential for adsorption of organic contaminants (Boucher et al., 2008). Hydrophobic organic contaminants such as pesticides are trapped in the residual immobilized oil within the press cake matrix. However, these results are from batch test studies, and column studies have not been conducted but the potential is promising. The adsorption properties should allow relatively high fluxes without mass transfer limitations, and packed columns could provide several equilibrium stages which could increase removal efficiency (Boucher et al., 2007). Even if Moringa is not feasible as a filter media addition, pre-coagulation with Moringa before slow sand filtration may provide enhanced removal of organics.

Chapter 3

MATERIALS AND METHODS

3.1. Experiment Design

3.1.1. Slow Sand Filter Pilot Columns

All slow sand filter runs were conducted in the Stan and Flora Kappe Environmental Engineering Laboratory at the Pennsylvania State University Waste Water Treatment Plant. The pilot filter columns used in this study were 6 inch diameter (A = 0.196 ft^2 = 0.0182 m^2) clear polymer columns fitted with sealed end caps containing barbed ports. Vinyl tubes were attached to the barbed ports to control the head of the filters and to transport the filter effluent to a drain (see **Figure 3-1-1**). The continuously operated slow sand filter was run at a constant hydraulic head of about 0.91 m. The intermittent filter received a 20 L daily charge of water. The hydraulic head was selected to fluctuate from 51 cm at the highest level to the 5 cm resting level, where the filter remained in between daily charges. The pore volume of the filter beds was found to be about 2.5 L.

3.1.2. Design of the Continuous SSF

The continuous filter was designed to operate at a constant hydraulic head. A settling tank was designed to remove any large solids and volatilize any remaining chlorine residual. After several prototype design concepts, a design which used a float valve and two 55 gallon drums was selected. The float valve was connected to a line which pumped treated WWTP effluent to the Kappe lab. The two settling barrels were connected to each other with bulk-head fittings and a section of 2” PVC pipe. The WWTP effluent entered at the top of the first barrel and passed through the second barrel to the continuous filter column. A section of 1” ID vinyl tubing allowed further settling of finer floc particles before entering the continuous filter supernatant water storage through a barbed port. The water level of the barrels was designed to provide the level of hydraulic head for the connected SSF pilot column, as shown in **Figure 3-1-1**.

3.1.3. Design of the Intermittent SSF

The intermittent SSF was designed using a column identical to the one used in the continuous flow design except with a shorter height. A 5 gallon bucket was mounted on the column to provide around 0.5 m of hydraulic head at the maximum water height and a larger storage volume without an enormous increase in initial hydraulic head. The diffuser used, as shown in **Figure 3-1-1** was placed about 0.23 m above the resting water level, which was designed to be 5 cm in accordance with the Manz BSF design (Elliot et al., 2008).

Following construction of the filter columns and experimental set up, the columns were backfilled to prevent airlocking. The filters were initiated in December and run for 18 days. Then, columns were sporadically batched and observed throughout the semester break. Following the semester break, the columns were allowed to stabilize and various parameters were measured to assess the removal capabilities throughout the remainder of the filter operation.

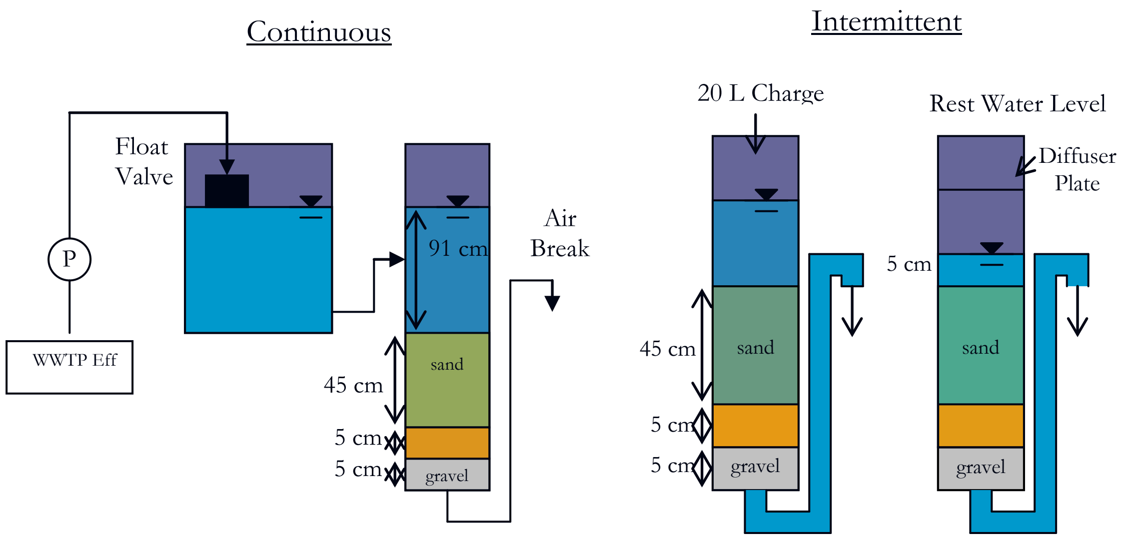

Figure 3-1-1: Continuous and Intermittent Pilot Column Design

3.1.4. Design of the Filter Media

The slow sand filter media was selected to be similar to the POU Biosand filter used in Elliot, et al (2008). **Table 3-2-1** details a comparison of the filter media selections for various slow sand filtration studies. A depth of 45 cm for the fine sand media was selected to emulate the typical media design parameters used in the household scale intermittent slow sand filters. This level is also within a viable range for municipal slow sand filters and was likewise used for the continuously run SSF test column. In addition, 5 cm of sieved and washed gravel (2-10mm) was used as a base, and 5 cm of pre-washed Quikrete Play Sand (No. 113) was used in the rough sand layer. The gravel and the rough sand functioned primarily to prevent the fine sand media from escaping through the outlet portal in the bottom of the filter column. The fine sand media used was filter sand from Ricci Bros. Sand Co., Port Norris, NJ (CAS. No.14808-60-7). The filter sand was composed of 99.4% SiO_2, 0.13% Al_2O_3, < 0.03% of CaO, Fe_2O_3, K_2O, TiO_2, Na_20, and MgO. Sieve analysis revealed the sand to have an effective diameter of 0.355 mm and a uniformity coefficient of 1.47 (see Appendix). These values were on the fringe of typical parameters used for slow sand filtration applications, yet flow through the sand was as expected.

Study	**Sand**			**Gravel**	
	Depth(m)	**Eff. Size (mm)**	**U**	**Depth (m)**	**Eff. Size (mm)**
Biosand filter	0.40	0.15-0.55	<4	0.1	—
Conventional filter	>0.8	0.15-0.35	<2	0.1	—
Dempsey et al. (1991)	1.0	0.22	1.38	0.2	0.3-1.5
Malley et al. (1991)	0.41	0.34		0.15	Pea size
Collins et al. (1994): Springfield	0.79	0.30	2.3		
West Hartford	0.67	0.27	2.0	—	—
New Haven	0.46	0.30	2.7	—	—
Pilot columns	0.38	0.25-0.45	1.8-3.4	0.15	3-18
Elliot et al. (2002)	0.40	0.19-0.22	3.5-4	—	—
This Study	0.45	0.355	1.47	0.05	2-10

Table 3-2-1: Comparison of Sand Characteristics between Studies

3.1.5. Cleaning of the Slow Sand Filters

When flow rate values stabilized and decreased below the desired values (less than a loading rate of 80 $Lm^{-2}hr^{-1}$), a "swirl and dump" cleaning process was employed (CAWST, 2009). The contents of the upper 2-4" of sand were mixed into the supernatant water, and the supernatant water was scooped and dumped. In this process some of the organic matter and biomass which was fouling the filter was removed. Flow rates instantly increased to values similar to the beginning of the filter runs. The two major run cycles studied began with cleaning procedures on day 52 and day 79 of filter operation.

3.1.6. Selection of Source Water

The source water used was the plant effluent from the Penn State University Waste Water Treatment plant located at 501 University Drive, State College, PA 16801. The plant effluent was a viable source in terms of quantity and quality. It was good emulation of the typical types of relatively high quality surface waters required for slow sand filtration (see **Table 4.1.1** for the characteristics of the source water). The WWTP plant effluent is chlorinated and discharged to a spray field. However, analysis of the effluent line which was pumped to the Kappe lab in the WWTP office building indicated negligible free and total chlorine values. Likewise, retention times in the uncovered settling drums antecedent to filtration were between 8.4 hours to 10.5 days, which provided ample time for kinetic dissipation of any residual chlorine. However, flow rate and total coliform values on a select few days indicate some possible spikes in chlorine residual, which had minor but unappreciable effects on the filter performance.

3.2. Sampling and Analytical Techniques

3.2.1. Chemical and Microbiological Analysis

Grab samples were collected for chemical and microbiological analysis from the raw water settling tank and from the effluents of each pilot column. Throughout the pilot column operation turbidity (NTU), chemical oxygen demand (COD), and fecal and total coliform values were regularly assessed to monitor maturation and performance. A HACH 2100P Turbidimeter was used to measure turbidity in NTU. COD was measured using HACH COD low range digestion vials, a HACH COD digester block, and a HACH DR/2010 Portable Datalogging Spectrophotometer. Plate enumeration counts using the membrane filtration technique with HACH m-Coliblue 24 reagent were used for fecal and total coliform analysis.

A 5-day biochemical oxygen demand (BOD) test was also conducted to establish the biodegradable fraction of the COD. Analysis was performed using the HACH BODTrak apparatus with addition of HACH BOD nutrient packets. Grab samples were immediately measured for pH, and alkalinity values were measured within 24 hours. TDS and total conductivity values were measured on grab samples within one week of collection using the Thermo Orion Model 115 A+ conductivity probe. Hardness values were obtained using a Perkin-Elmer Optima 5300 ICP-ES (inductively couple plasma emission spectrometer). Calibration curves were determined using synthetic standards from high quality standards.

3.2.2. Organic Fractionation

Organic fractionation was achieved using several steps without pH manipulation as described in Kim and Dempsey (2008) with one addition: a XAD-4 column to separate TPI b/ns. The first two steps involve size separation (>1.0 μm, 1.0 μm-20 nm, < 20nm). Next, removals were based on functionality with removal of, respectively, organic acids, HPO b/ns, and TPI b/ns, leaving TPI b/ns. This process is illustrated in Figure 3.2.

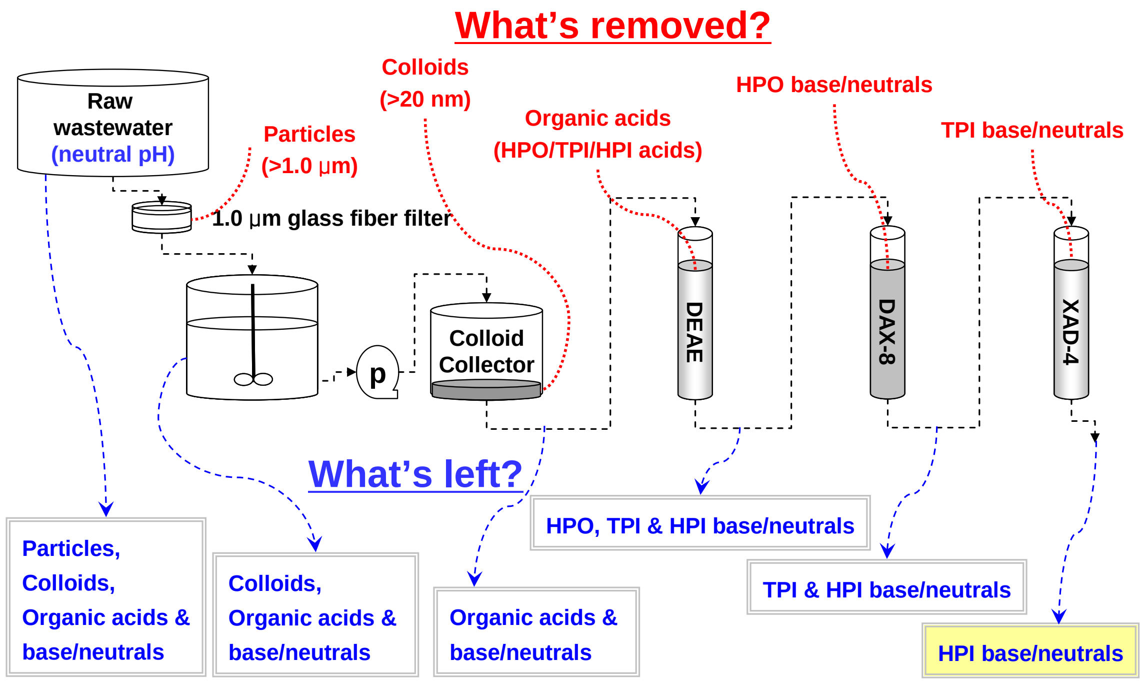

Figure 3-2-1: Organic Fractionation System (Kim & Dempsey)

Grab samples were taken from the raw water, after the 1.0 μm filter, after the colloid collector, after DEAE, after DAX-8, and after XAD-4 to be analyzed for NPDOC. A Shimazdu TOC analyzer was used for analysis of NPDOC. Subsequent analysis of fractional amounts derived from the NPDOC analysis was performed in Microsoft Excel.

Chapter 4

RESULTS AND DISCUSSION

4.1. Characteristics of the Source Water

4.1.1. Chemical and Physical Parameters

The raw water used during the pilot column studies was found to have several water quality characteristics which were very similar to common surface waters such as turbidity, pH, and TOC (Malley et al, 1991) (Collins et al., 1994). However, some qualities such as hardness and alkalinity were analogous to groundwater sources, which are the largest portion of the source waters used in the State College area. High hardness and alkalinity was also evidenced by cementation in the top layers of the slow sand filter columns, caused by precipitation of $CaCO_3$ and binding between the sand particles. An observed raise in pH, correlating to a decrease in $CaCO_3$ solubility, also supports the presence of cementation. This may have increased the filter media headloss, causing the flow to decline more rapidly throughout a filter run. Similar maintenance concerns have been found in other slow sand filtration beds (Logdon, 2008).

The water quality parameters also fluctuated throughout the duration of the 109 day filter operation period. The average, high, and low values can be found in **Table 4-1-1**. These fluctuations are within the range of water quality reported for other pilot studies (Collins et al., 1994), and thus the use of well-treated wastewater effluent in this study appeared to be a good representation of poor-quality water that might be used as a source water for SSF in some cases. Though some fluctuation was found in physical parameters of the source water, the amount of TOC and the composition of the TOC remained relatively constant throughout the filter operation (see APPENDIX).

	Geometric Mean	Standard Deviation
Turbidity (NTU)	0.88	0.25
COD (mg/L)	19.6	5.3
BOD (mg/L)	7.3	2.2
TOC (mg C/L)	4.711	0.406
TDS (mg/L)	747	38.2
Conductivity (μS)	1529	78.4
pH	7.5	0.16
Alkalinity (mg/L as $CaCO_3$)	194	10.6
Hardness (mg/L as $CaCO_3$)	273	7.91
Fecal Coliform/100ml	6.2	17.7
Total Coliform/100ml	173.8	137.0

Table 4-1-1: Source Water (University WWTP) Parameters

4.1.2. Total Organic Carbon Composition of Source Water

After organic fractionation, the average TOC of the settled source water was found to be largely composed of organic acids (56.6% ± standard deviation). TPI and HPI b/ns were also significant portions with 19.9% and 21.6%, respectively. HPO b/ns were a small percentage, and particles and colloids were nearly negligible sources of TOC.

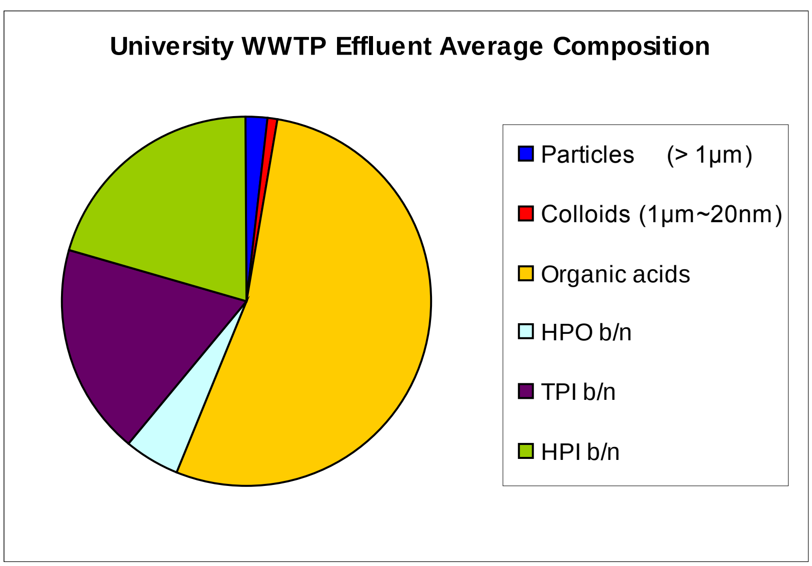

Figure 4-1-1: University WWTP Organic Fraction Distribution

Average University WWTP Effluent				
Fraction	TOC mg C L^{-1}	SD, mg C L^{-1}	Distribution (%)	SD, %
Particles (> 1μm)	-0.095	0.460	-1.92	9.75
Colloids (1μm~20nm)	-0.052	0.370	-0.90	7.85
Organic acids	2.681	0.403	56.56	8.55
HPO b/n	0.224	0.333	4.77	7.05
TPI b/n	0.944	0.220	19.86	4.67
HPI b/n	1.023	0.071	21.64	1.50
Sum	4.725	0.309	100.00	6.55

Table 4-1-2: Average Composition of the University WWTP Effluent

4.1.3. Comparison with TOC Composition of UAJA EfOM

In contrast, settled WWTP effluent from State College's second WWTP, the University Area Joint Authority (UAJA), was found to have a different composition of TOC especially with regard to the percentage as organic acids and a greater amount of TOC (17.8 mg/L) (Kim & Dempsey, 2008). At first look, there appears to be a significantly smaller percentage of organic acids in the University WWTP effluent, as shown in **Figure 4-1-2**. However, TPI b/ns were not analyzed in the fractionation of the UAJA effluent. The sum of HPI and TPI b/ns in the University WWTP effluent and HPI/TPI b/n in the UAJA EfOM were similar. The percentages of particles, and colloids were much higher in the UAJA EfOM, probably due to much longer settling time in the feed to the SSF system. The UAJA WWTP utilizes alum coagulation which is effective for removal of larger organic acids (Kim & Dempsey, 2008). The University WWTP does not use coagulation as part of the secondary treatment process. Common microbial degradation pathways with carboxylic and phenolic acid intermediates may be a source of the high content of organic acids in the University WWTP Effluent added during the biological treatment processes of the secondary treatment (Collins et al., 1994).

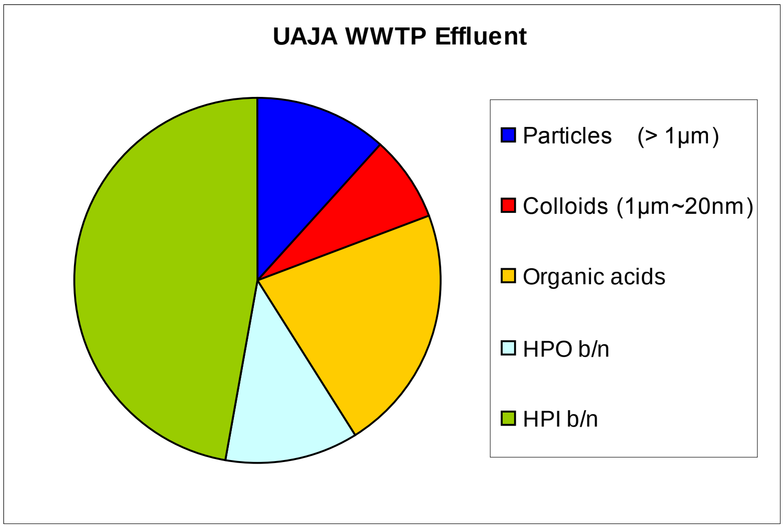

Figure 4-1-2: University Area Joint Authority WWTP Effluent Compositions (Kim & Dempsey, 2008)

UAJA WWTP Effluent				
Fraction	TOC mg C L^{-1}	SD, mg C L^{-1}	Distribution (%)	SD, %
Particles (> 1μm)	2.10	0.45	11.80	2.53
Colloids (1μm~20nm)	1.30	0.38	7.30	2.13
Organic acids	3.90	0.3	21.91	1.69
HPO b/n	2.10	0.25	11.80	1.40
HPI b/n	8.40	0.12	47.19	0.67
Sum	17.80	0.24	100	1.35

Table 4-1-3: UAJA WWTP Effluent Average Composition (Kim & Dempsey, 2008)

4.2. General Removal Capabilities: Continuous vs. Intermittent

4.2.1. Flow Characteristics for Filter Operation Period

Upon initiation, the flow rates of the pilot filters were closely monitored to understand the maturation cycles of both hydraulic modes, as shown in **Figure 4-1-3**. The initial flow rates were very high, but the flow quickly decreased within the first 10 days. During this time period, particles and microorganisms from the source water accumulated in the upper region of the sand to form the schmutzdecke bio-layer. This filter maturation was evidenced by increased removal of turbidity and coliforms and decreased flow rate.

On day 12, the first cleaning procedure took place, wherein some of the particles and floc contributing to filter fouling were removed. In addition, some of the resident microorganisms were removed, but majority of the maturing bio-layer within the top 10-20 cm of sand was likely maintained. After the semester break, which lasted from day 20 to day 41, the matured filters were cleaned and started into two highly monitored clean-to-clean cycles where the majority of the data for the following analysis was collected. By this time, the biological communities had significant time to mature and acclimate, and filter behavior was as expected.

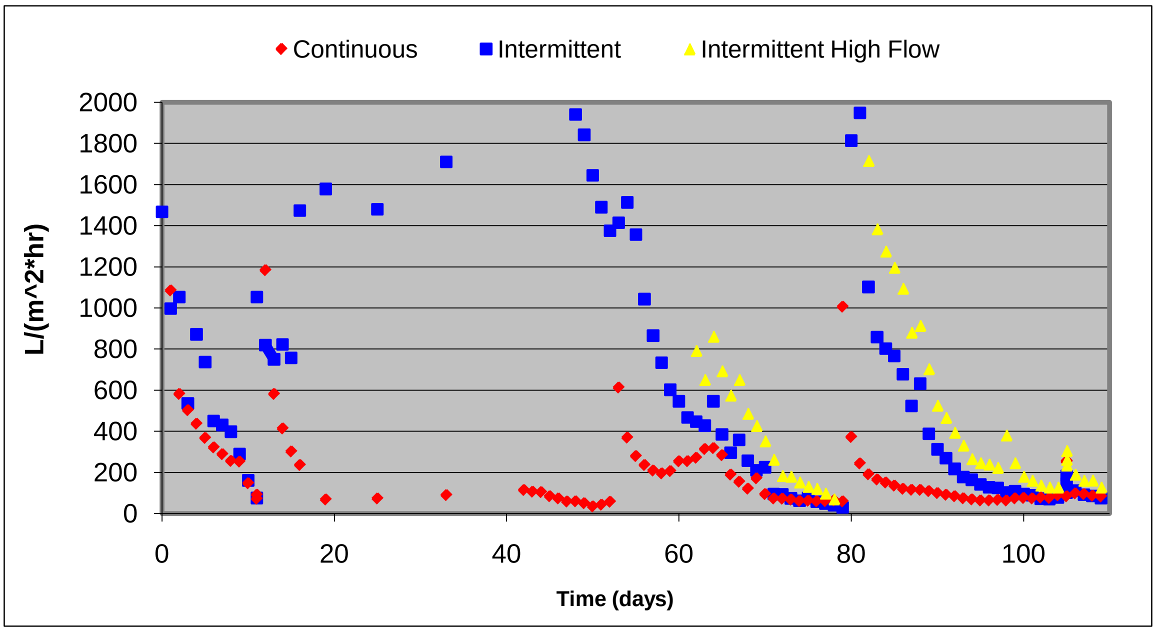

Figure 4-2-1: Loading Rate vs. Time through the entire filter operation

4.2.2. Definition of Run 1 and Run 2

The first studied filter run (Run 1) was started on day 52 with the cleaning of the continuous filter and the partial cleaning of the already fast flowing intermittent filter. Day 52 was arbitrarily selected once the filter was confirmed to be mature based on removal abilities. Run 1 ended on day 79 as both filters neared the defined operational flow rate limit of 10 mL/min (32.9 L/m^{2}hr) (CAWST, 2009). Run 2, therefore, began on Day 79 and continued until day 109 when the flow values once again neared the operational limit. This flow cycle could continue indefinitely if more time were permitted for observation and analysis.

High hydraulic head (18"), high flow rate values for the intermittent filter were recorded as "intermittent high flow" for Run 2, but not for Run1. The standard head values for all data points labeled "intermittent" and "intermittent low flow" was 12.5". There are two major causes likely for the abrupt increases in flow rates, including chlorine content spike and sampling from the bottom ports of the columns leading to excessive head conditions which took 1-3 days to equilibrate after return to normal operating conditions.

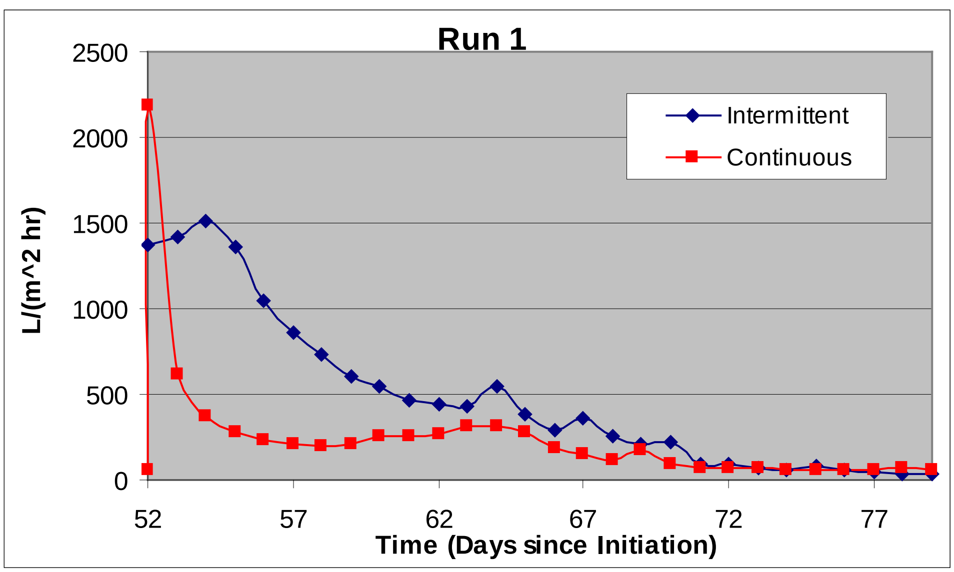

Figure 4-2-2: Loading Rate vs. Time for Run 1

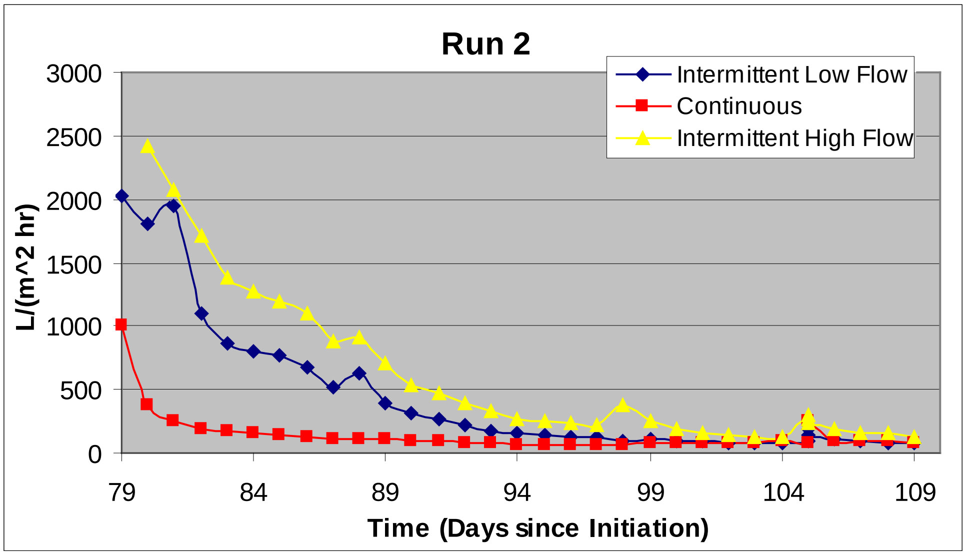

Figure 4-2-3: Loading Rate vs. Time for Run 2

4.2.3. Removals of Contaminants during Run 1 and Run 2

Three typical, characteristic filter performance parameters were closely monitored throughout the duration of both Run 1 and Run 2. The three monitored parameters were turbidity, COD, and coliform removal (Farooq & Al-Yousef, 1993). For all three parameters, removal efficiencies decreased significantly after the cleaning procedure and returned quickly to previous values.

4.2.4. Turbidity Removal

The continuous SSF consistently achieved higher removal efficiencies in comparison to the intermittent as shown in **Figure 4-2-4**. Proper filter operation was evidenced by consistent reduction in turbidity to below 0.6 NTU for both hydraulic modes during normal performance. Turbidity removal was relatively constant, with consistent trends observed between the continuous and intermittent columns. However, even the highest values were still lower than the values typically seen in most conventional slow sand filters, but these often have deeper sand beds and more consistent flow rates (Farooq & Al-Yousef, 1993). The improvement of turbidity removal with time is likely due to enhanced entrapment of particles, greater adsorption at lower flow rates, and mature sand particle surface properties (Elliot et al., 2008). Also, the low turbidity of the raw water limited the removal capacity of the filters and often determined the removal efficiency as the effluent turbidity values remained relatively constant.

The intermittent filter consistently performed worse than the continuous filter due to its rapidly varying hydraulic loading conditions throughout filtration of a daily charge. Even at analogous flow rate values, the continuous filter consistently recorded higher removal efficiencies than the intermittent. Similarly, the coliform removal values show similar trends though they are not as drastic.

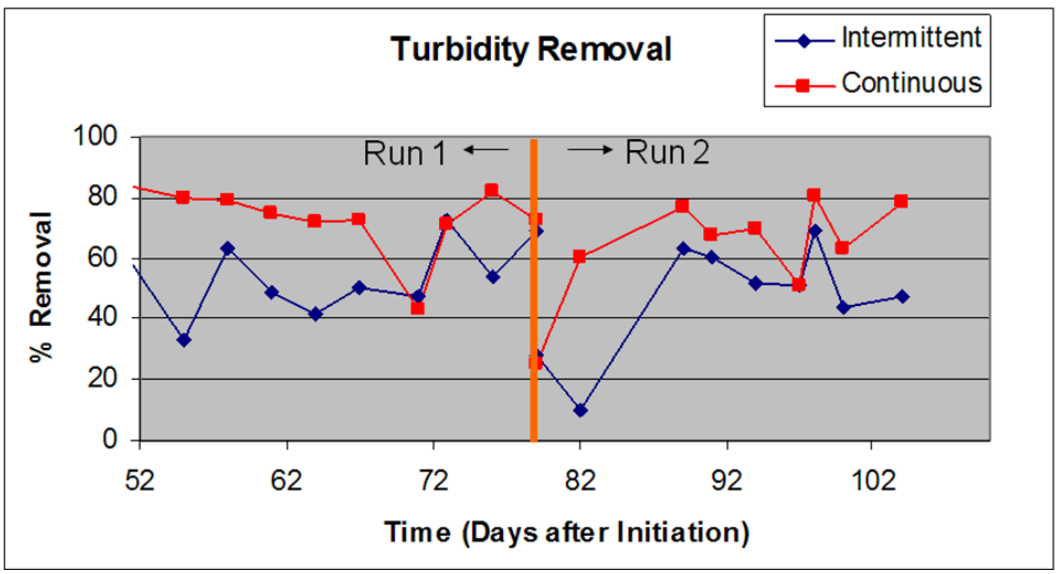

Figure 4-2-4: Turbidity removal within pilot SSF columns

4.2.5. Coliform Removal

Over 97% removal of coliform organisms were achieved during the 2nd continuously-fed SSF run, while >90% removal was only achieved for the 2nd intermittently-fed SSF after 100 days of operation. The Biosand filter manual recommends safe filter loading rates to be less than 400 $L/m^2 * hr^{-1}$ which was reached around day 90 in filter run 2, so excessive flow rate likely limited removal efficiency in the intermittent initially. In addition, the ratio of fecal to total coliform organisms within the coliform organism plate count of the raw water was often very low. During the 2^{nd} run, the highest influent fecal coliform count was 6 with an average of 1.8. Conversely, the highest influent total coliform was 478 with an average of 316. On all but two occasions, fecal coliform microorganisms were not found in the discharge from either SSF. Therefore, both human pathogenic and other native microorganisms were effectively removed from the raw water by die-off, predation in the bio-layer, adsorption, or entrapment (Eighmy et al., 1992). Elliott et al. (2008) suggests the importance of retention time for microbiological reduction and emphasizes the importance of the stationary period. In fact, since a large volume of water is retained with the pores of the sand filter during the stationary period for the intermittent filter, a significant percentage of the removal may occur during this period and would be evident in the beginning of the discharge of the following day.

The continuous filter consistently outperformed the intermittent in coliform removal, likely due to the variance in flow conditions and the higher flow rates which decreased the retention times, and, hence, the microbial removal ability. The intermittent filter underperformed the Biosand filter used in Elliott et al. (2008) in terms of the overall $\log_{10}$ reductions, but the overall removal trends were similar.

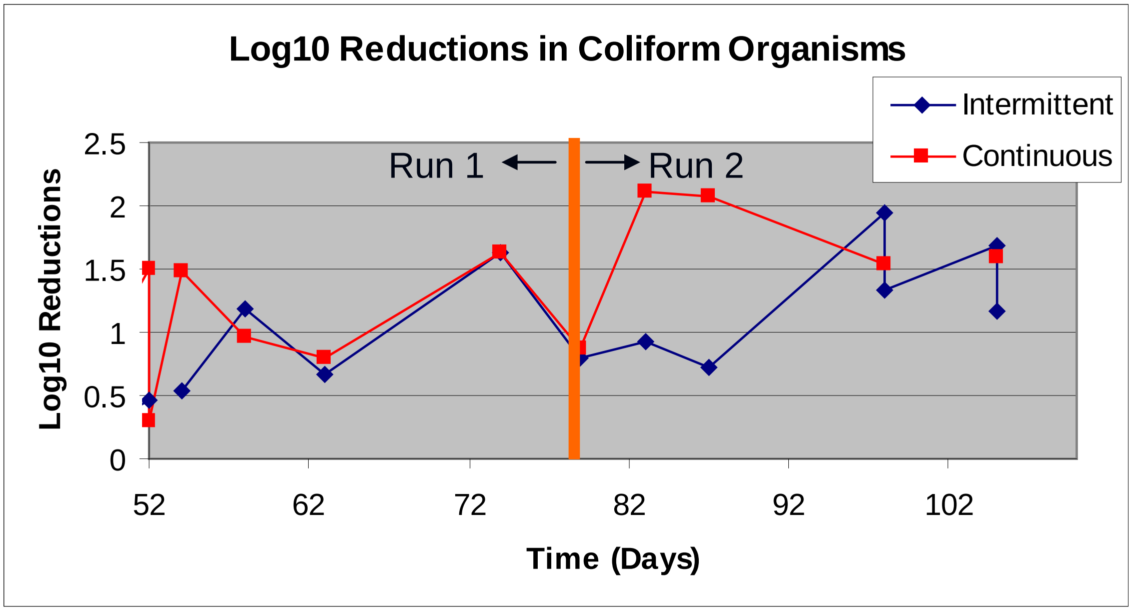

Figure 4-2-5: Coliform removal within pilot SSF columns

4.2.6. Chemical Oxygen Demand Removal

COD is a not traditional water quality parameter for monitoring slow sand filtration performance, but consistent reductions were observed though the efficiencies fluctuated. **Figures 4-2-6 and 4-2-7** provide a good baseline for the further analysis of the organic removal capabilities of the continuous and intermittent slow sand filters. One clear obsevation is the noticable drop in COD removal directly following cleaning. Therefore, the performance of all three parameters (turbidity, coliforms, and COD) confirm the caveat to run the filter to waste for 1-2 days after a cleaning procedure..

COD is a relatively complex water quality parameter which is often used to predict the effect of a WWTP effluent on the dissolved oxygen content of a surface water due to chemical oxidation. COD also gives a quick and easy indication of the organic content of a water sample. As expected, the removal values of COD were low, between 10-40%, which is consistent with the literature. COD is representative of the organic compounds in a water which are reduced by a strong oxidant, but some compounds such as aromatic hydrocarbons and alkanes are not accounted for, as they are highly unreactive. However, many of these organic compounds accounted for in the COD would not be naturally biodegraded, so the BOD fraction of the COD is another important factor to be mentioned.

The BOD to COD ratio was between 0.3-0.4 which is typical forEfOM at the University WWTP. The ratio may fluctuate . BOD removal through the SSFs was from 58-78% . These high values indicate the presence of an active microbial community within the filter. In addition, when examining the correlation the relationship between COD and TOC a slight correlation was found as shown in **Figure 4-2-8**. The average COD to TOC ratio was found to be 4.0 $\pm$ 0.3, which is slightly less than the 64 g O_2/ 12 g TOC ratio for a fully reduced TOC. This is unlikely, as the TOC was definitely not largely methane, so interferences such as nitrites and sulfides may have provided some influence on the COD readings. This interference could have led to the high variability observed in the removal efficiencies. However, there was some observed correlation between TOC and COD as shown in **Figure 4-2-8** which indicates some consistency and accuracy of the COD results. Also, this may indicate that the TOC may have been composed of moderately reduced organic acids and other organic compounds. The analysis of TOC and organic fracations to follow will provide an even better picture of the organic removal capabilites in relation to time during filter run and flow rate.

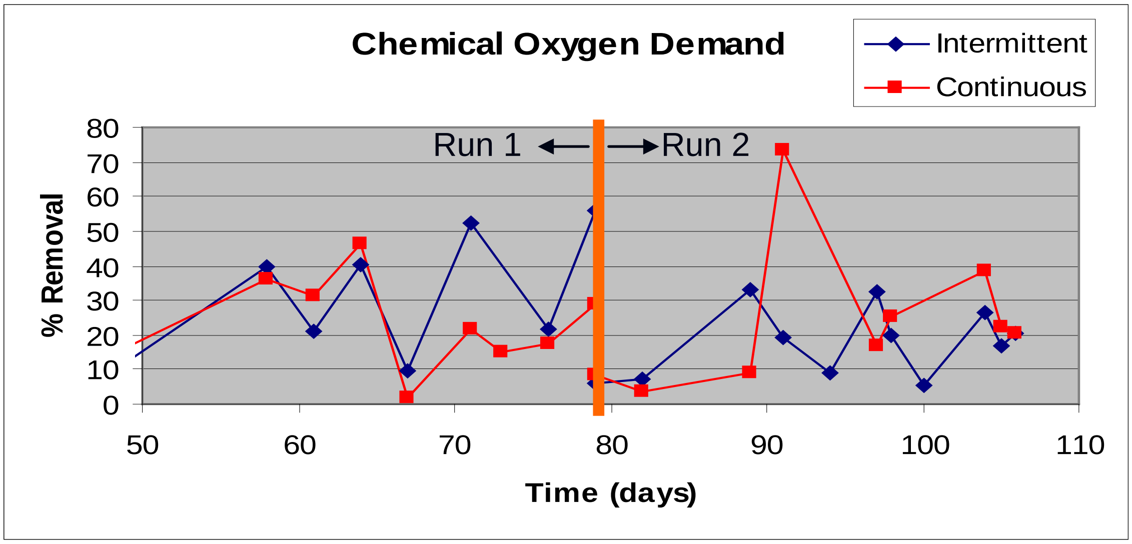

Figure 4-2-6: COD removal within pilot SSF columns

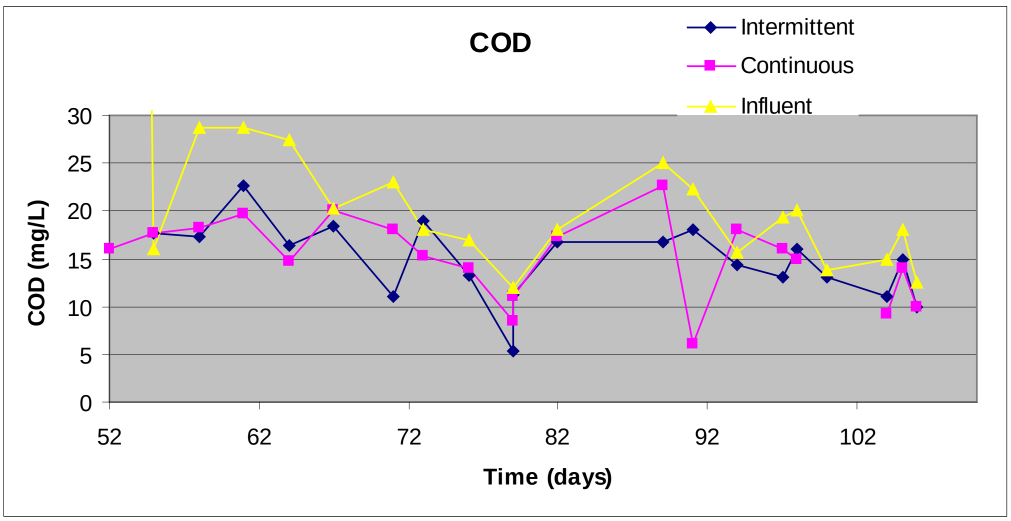

Figure 4-2-7: COD plots for SSF influent and effluents

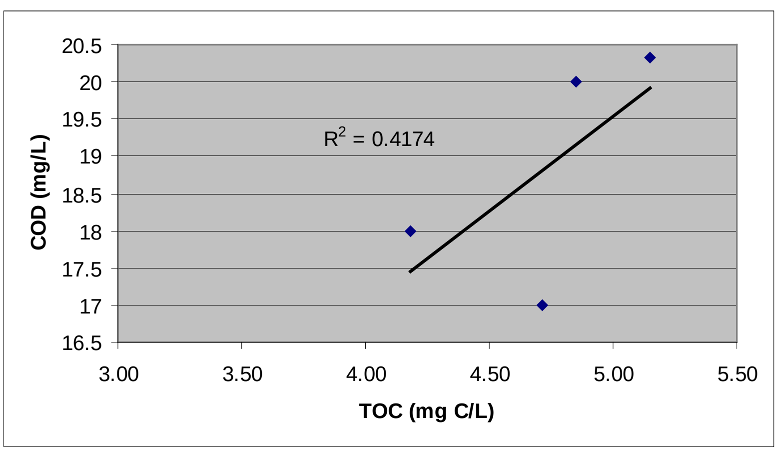

Figure 4-2-8: Correlation between COD and TOC values for University WWTP

4.3. Removal of Total Organic Carbon and Organic Fractions

4.3.1. Overview of TOC and Organic Fraction Removal Results

Organic fractionation analysis was performed on the influent and effluent flows on days 68, 76, 98 and 105. These days were representative of stabilized conditions towards the end of Runs 1 and 2. The results were relatively consistent when compared between trials, with the largest discrepancies occurring in the day 98 results. The recorded results for the particles and colloids were very low and sometimes slightly negative, which could be anomalous due to initially very low concentrations in the influent.. Control samples were analyzed by running distilled water through the fractionation system, but the results were inconclusive about the effect of the colloid collector and 1.0 μm filter on the TOC reading. The 1.0 μm filter, however, consistently added a small amount of TOC. Therefore, confidence in the accuracy of the particle and colloid values is relatively low. The majority of the data analysis was conducted on the dissolved organic carbon (DOC) fractions and turbidity was used to indicate removal of particles and colloids.

4.3.2. TOC and Organic Fraction Removal: Day 68

The first trial of organic fractionation resulted in a 9.4% removal of TOC in the continuous filter which was largely attributed to HPO b/n and organic acid removals. Conversely, the intermittent filter actually added TOC in this trial, caused by a higher flow rate and release of HPI and TPI b/ns from the filter bed. The removal of organic acids was the most significant removal achieved during the trial with values of 25.0% and 18.3% for the intermittent and continuous filters, respectively.

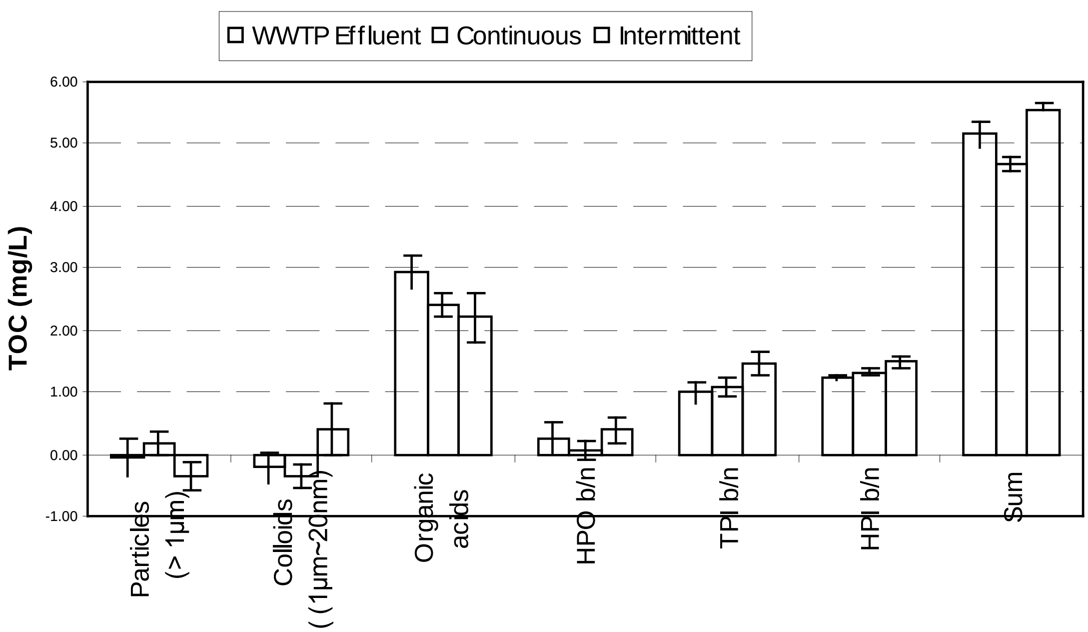

Figure 4-3-1: Day 68 Organic Fractionation Results

4.3.3. TOC and Organic Fraction Removal Rate: Day 76

With lower flow rates than day 68, both the continuous and intermittent filters experienced positive TOC removal rates with 3.6% and 6.7%, respectively. Once again, HPI b/ns were once again released by the filters. Also, organic acids were removed with values similar to the previous trials. The continuous removed 23.4% where as the intermittent removed 24.9% of organic acids. In this case, TPI b/ns were also removed in this flow regime, with moderate decreases in the already low content of the HPO b/ns in the raw water.

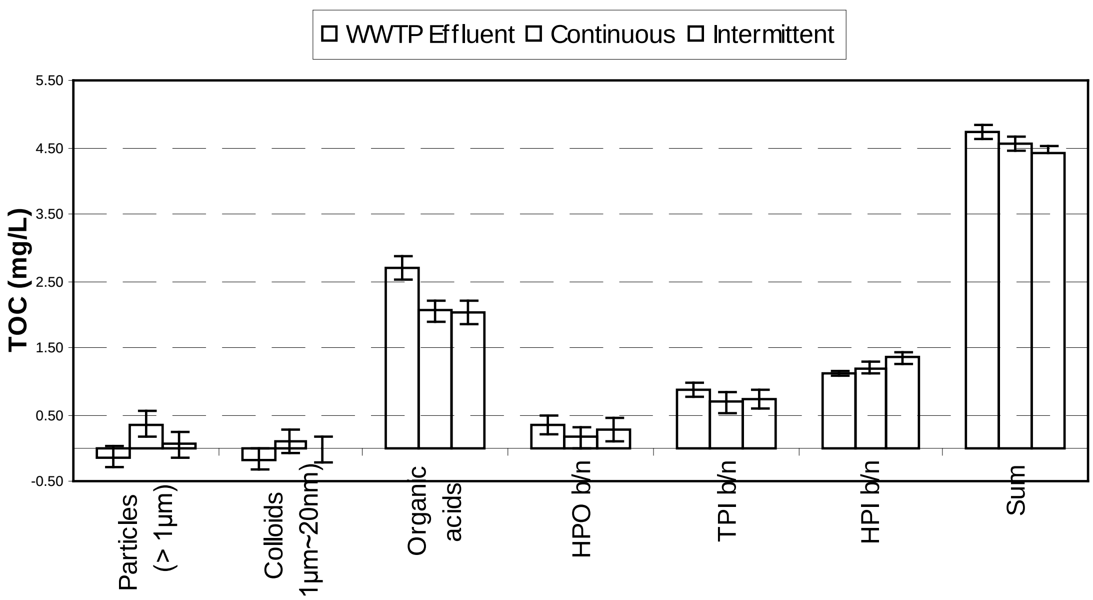

Figure 4-3-2: Day 76 Organic Fractionation Results

4.3.4. TOC and Organic Fraction Removal Rate: Day 98

During this trial a two point flow profile was conducted for the intermittent filter. The high flow condition was more than 3.5 times greater than the low flow condition. Therefore, the TOC removal rate of 15.3% versus 5.3% for the intermittent low and high flow conditions indicates a possible correlation between flow rate and TOC removal throughout duration of a daily filter dosing. The TOC removal of the continuous was slightly lower than the intermittent low flow condition at 12.6%. However, the one major irregularity with this trial is the very high removal of organic acids observed in the continuous and intermittent low flow samples. Also, the HPO b/ns were added by the column in addition to the typical release of HPI b/ns.

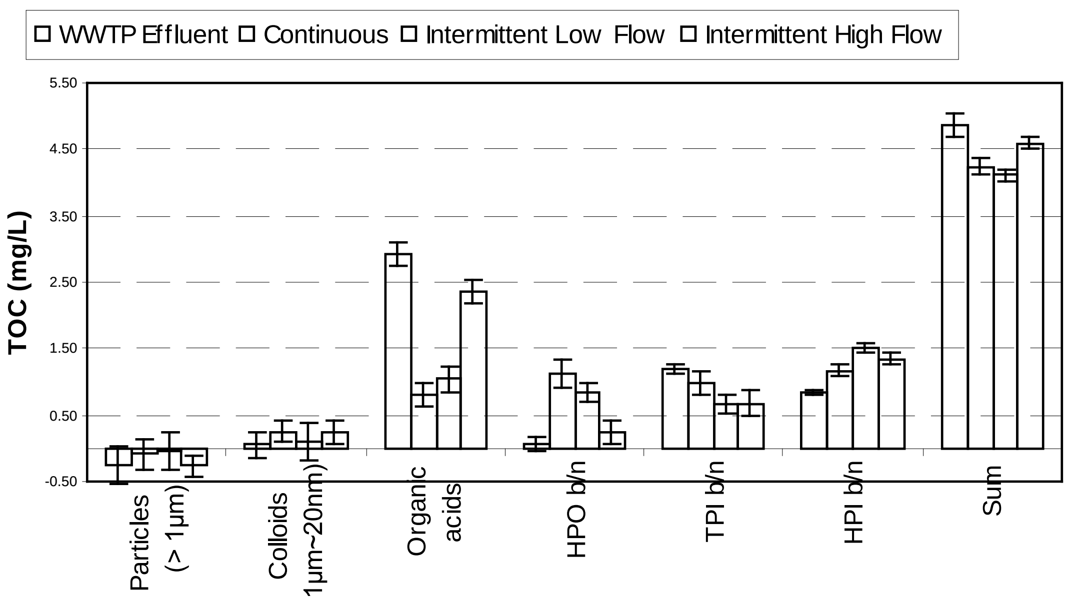

Figure 4-3-3: Day 98 Organic Fractionation Results

4.3.5. TOC and Organic Fraction Removal: Day 105

The final trial provides values similar to those recorded in the first two trials. In addition, the TOC removal rates in the low flow versus the high flow intermittent were 6.3% and 15.9%, respectively. The TOC removal of the continuous filter was 16.3%. The organic acids were removed in similar proportions for all three flow regimes at 21.4%, 20.5%, and 20.6% for the continuous, intermittent high flow, and intermittent low flow, respectively. HPI b/ns were the largest source of TOC addition in the high flow condition of the intermittent filter which subtracted from the overall TOC removal. Once again, the HPI b/ns were consistently released by the filter beds and HPO b/ns were a small portion of TOC in the raw water and an insignificant source of TOC removal.

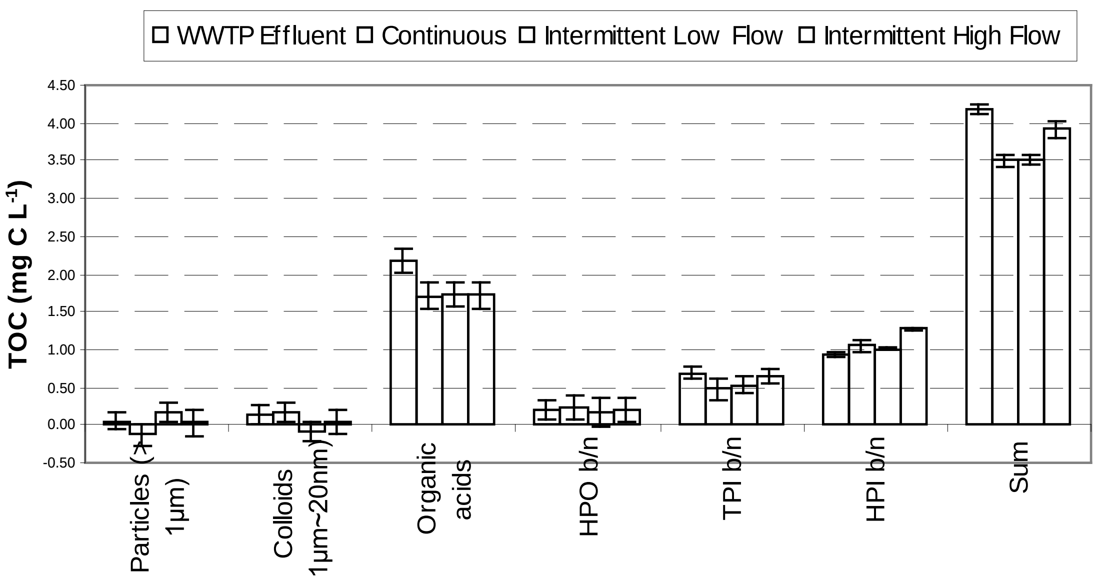

Figure 4-3-4: Day 105 Organic Fractionation Results

4.3.6. Trends in TOC and Organic Fraction Removal

As expected the most conclusive observations where found in the dissolved fractions of the TOC, with consistent reduction of organic acids and addition of HPI b/ns.

In addition, HPO b/ns were a relatively small source of TOC in the raw water. Only on day 98 was there any significant release of HPO b/ns from the filters. TPI b/ns were more or less removed in every trial at small to insignificant levels. The role of the TPI b/ns in the NOM characteristics and the transport with the filter bed is not well known. The TPI separation was a new step added to the novel fractionation system developed by Kim and Dempsey.

Net importation and exportation of both bacteria and TOC is expected from microbial metabolism, temperature effects, nutrient and oxygen availability, fluid flow shear, and localized sloughing (Eigmy et al., 1994). Therefore, as seen in the fraction results some fractions were primarily exported (HPI b/ns) while others were adsorbed, metabolized, or transformed to some degree (organic acids and TPI b/ns). In fact, both temporal and spatial variance in biomass are an expected, inborn characteristic of slow sand filtration (Elliot et al., 2008).

4.3.7. Relationship between Flow Rate and TOC Removal

Preliminary observation of the fractionation data presented the possibility of a relationship between the flow rate of the filter and the TOC removal. In addition, Elliot et al. (2008) found microbial reductions were to increase slightly at the low flow rate versus the high head, high flow rate condition in an intermittent Biosand filter. Collins et al. posited that filter loading rates had little impact on DOC removal rates. In fact, the highest removal rates were observed for the fastest flow rates, attributed to more efficient transport mechanisms and higher attachment probabilities. Logsdon, however, reports declining rates of total coliform and turbidity removal with increasing filtration rate in continuous slow sand filters (2008).

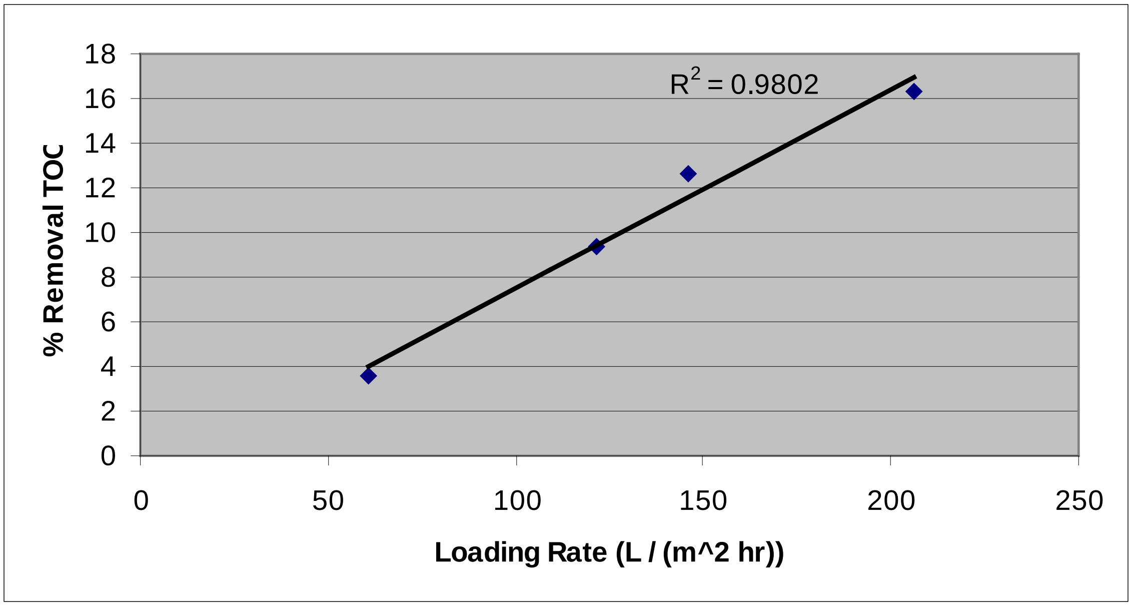

Figure 4-3-5: TOC % Removal Rates for the Continuous Filter at Different Loading Rates

In fact, the continuously run pilot filter column exhibited similar behavior to the findings of Collins et al. (1992) with a high correlation between increasing TOC removal with increasing flow rate. **Figure 4-3-5** illustrates this trend, where each of the four data points represents, x, the loading rate measured during the collection of fractionation grab sample matched with, y, the corresponding TOC removal percentage.

Conversely, the intermittent filter showed a correlation between increasing TOC removal with decreasing flow rate as observed during the two fractionation trials preformed during Run 2 as shown in **Figure 4-3-6**. However, unlike the continuous filter the difference between the high and low flow conditions within a single charge period involved significant variance in flow in a short time period. Where as, in the continuous filter the different flow regimes were arrived at very gradually throughout the maturation of the filter within the run. Therefore, the transport of nutrients and oxygen may actually be improved to a level that the increase in biomass activity is greater than any shearing and sloughing caused by the increased flow rate. In fact in continuous municipal and pilot scale filters the filter bed biomass volume is the largest determiner of removal of NOM.

The previously mentioned set of mechanisms does not seem to be the ruling fundamentals for intermittent filter, as its flow conditions are very different. Since the change in flow rate occurs on the time scale of hours versus a time scale of days, the biomass does not have the time to acclimate to the heightened loading of nutrients and oxygen. Therefore, the effect of shearing and sloughing may have greater effects in the intermittent filter with these sudden initiations of high flow rate on a dormant biomass. But as the flow rate decreased towards the end of a daily charge, the TOC removal efficiency improved significantly due to increased retention time. Retention time is a value commonly linked with increased removal efficiencies because kinetic reactions are given more time to react to a greater completion, however, the increased retention time in the continuous filter decreased the TOC removal. Regardless, retention time plays a key role in the organic removal abilities of intermittent slow sand filter, and it should therefore be heavily considered in design.

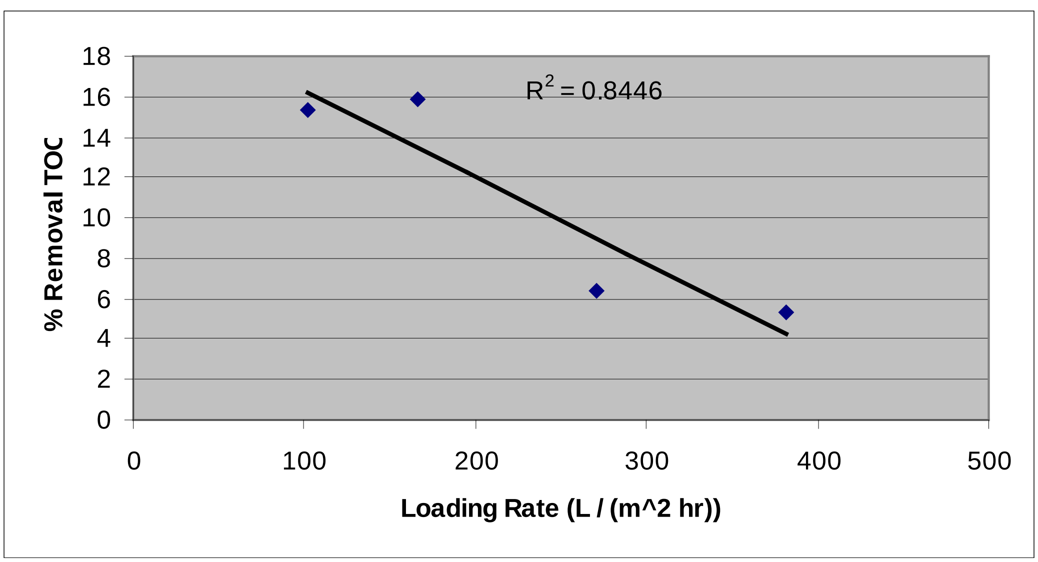

Figure 4-3-6: TOC % Removal Rates for the Intermittent Filter at Different Loading Rates

Chapter 5

CONCLUSIONS AND FUTURE WORK

5.l. Conclusions

5.1.1. Performance of Intermittent-flow SSF

- After maturation, 40-76% of turbidity was removed, with effluents always less than 0.7 NTU.
- Coliform removals between 70.7% and 98.8% were observed.
- The intermittent-flow SSF underperformed the continuous-flow SSF for the typical filtration parameters of the turbidity and coliform reduction, as expected.
- All three parameters significantly dropped in removal efficiency after cleaning, which confirms the need to wait 1-2 days before safe use.
- 58% to 76% of BOD was removed, which was less than the values observed for the continuous filter. This confirms biodegradation as the main source of organic removal.
- TOC removal decreased with increased flow, likely due to shearing and decrease retention times for biological activity.

5.1.2. Performance of Continuous-flow SSF

- After maturation, 51-82% turbidity removal was observed with effluent values always less than 0.52 NTU.
- Coliform removals between 83.8% and 99.2% were observed.
- 68% to 78% of BOD was removed, attributed to a more active and acclimated biological layer than the intermittent, as there is much less fluctuation in loading rates.

- TOC removal increased with increased flow, possibly due to improved transport of O_2 and nutrients to the bio-layer

5.1.3. Removal of Organic Fractions

- Organic acids were consistently removed within both flow regimes, which correlates with reduction in DBP formation.
- HPI b/n concentrations increased in the SSF effluents compared to influents. This net production of TOC could create TOC removal values lower than actual treatment efficiencies for the filter media.
- Significant color a persistent odor remained in the effluent likely caused by DOC not removed by the filter.
- TPI b/n were consistently removed by the filters, where as HPO b/n behaved sporadically likely due to adsorption effects and interactions with other HPO particles and surfaces in the filter media

5.1.4. Cementation of Filter Sand

- An increase in pH between the effluent (pH = 7.2) and influent (pH = 7.5) provided evidence supporting the cementation of the upper layer of sand within both filter columns This phenomena has been encountered in various other slow sand filters, and it did not greatly affect the flow.
- Similarly, high hardness and alkalinity values of the source water were found, which is not typical of surface waters, but confirms the precipitation of $CaC0_3$

5.1.5. Additional Findings

- The WWTP effluent from the Penn State University Waster Water Treatment Plant has a higher percentage of organic acids than the UAJA effluent

- The lower percentage of organic acids seen in the UAJA EfOM is likely due to the use of alum coagulation.
- The high level of biological treatment and the different source waters for the University WWTP may have lead to a higher organic acid content then seen in the UAJA effluent.
- Different WWTPs have different fractional compositions of EfOM which is important to the selection of tertiary treatment to be used.
- SSF is most effective for treating the organic acid content of EfOM

5.2. Recommendations for Operation and Maintenance

The previous results indicate that the microbial population may need more gradual acclimation to a source water and high flow rate, so any ability to improve the consistency of the flow rate would help to establish more even removal abilities throughout a daily charge. In addition, water should be run to waste or refiltered until at least 1 to 2 days after a cleaning session. Source waters with aesthetic problems should be pretreated or post-treated to ensure water that is drinkable, as intermittent SSF does little to remove color, taste, and odor. Post chlorination should minimize the chlorine demand applied to reduce the amount of DBP's formed as there will likely be sufficient NOM for the chlorine to react with.

5.3. Future Work

The major areas of future work which could be pursued involve the flow conditions of the intermittent filter and improvement of the organic removal. A detailed profile of the removal rates throughout the duration of the decreasing head intermittent filter run would be valuable to document. Also, a study on the effect of the stationary time between intermittent runs could help to optimize the effectiveness of the filters, as a majority of the water discharged during a daily charge of a typical Biosand filter is water remaining in the pore volume of the filter from the previous day. Treatment during this stationary phase would be interesting to investigate.

Also, pre and post treatment schemes would be valuable to pursue in order to improve the efficiency and consistency of slow sand filtration. *Moringa oleifera* offers promising potential as a coagulant, filter media, and source for cheap activated carbon. Other biomaterials such as pumice could be valuable adsorbents for DOC to obtain the treatment not offered by traditional slow sand filtration. Preozonation has proved to provide marginal improvements but a low cost, available alternative would be better suited to improve the 80,000 household scale slow sand filters already in use and the thousands more that are yet to be build.

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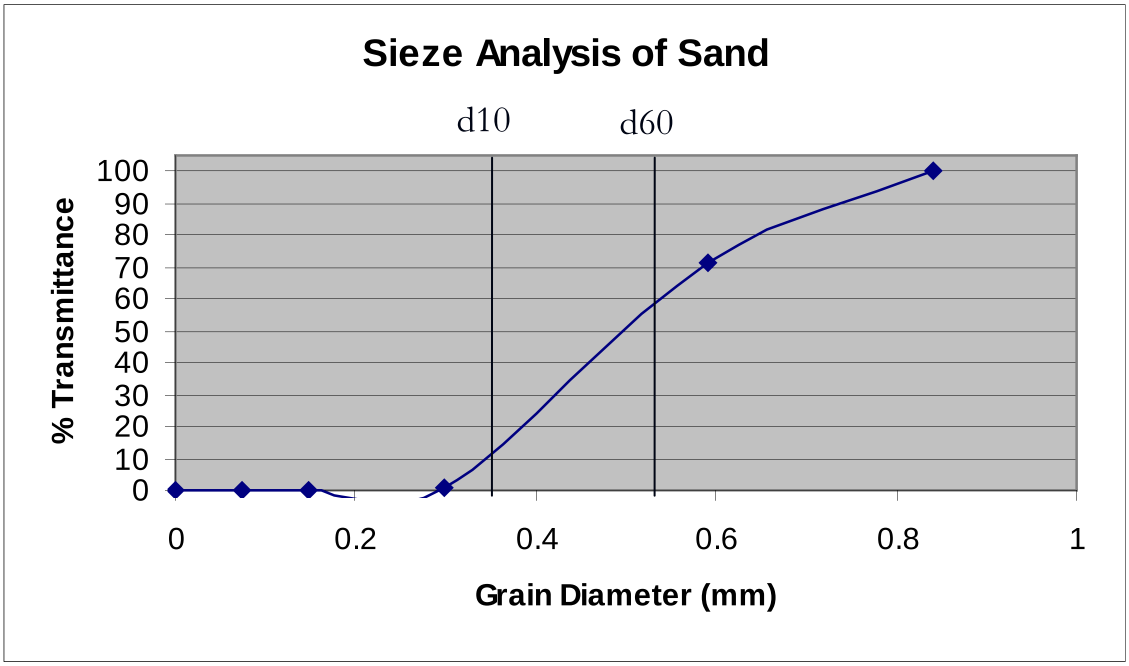
APPENDIX

Sieve Analysis Results for Filter Bed Sand:



Organic Fractionation Data:

PSU WWTP Effluent Day 68				
Fraction	TOC mg C L^{-1}	SD, mg C L^{-1}	Distribution (%)	SD, %
Particles (> 1µm)	-0.05	0.31	-0.95	6.02
Colloids (1µm~20nm)	-0.22	0.24	-4.35	4.66
Organic acids	2.95	0.27	57.18	5.24
HPO b/n	0.26	0.25	5.07	4.85
TPI b/n	1.00	0.17	19.45	3.30
HPI b/n	1.22	0.04	23.60	0.78
Sum	5.15	-	100	-

PSU WWTP Effluent Day 76				
Fraction	TOC mg C L^{-1}	SD, mg C L^{-1}	Distribution (%)	SD, %
Particles (> 1µm)	-0.14	0.16	-2.88	3.39
Colloids (1µm~20nm)	-0.18	0.16	-3.77	3.39
Organic acids	2.69	0.18	56.98	3.82
HPO b/n	0.35	0.14	7.44	2.97
TPI b/n	0.88	0.1	18.62	2.12
HPI b/n	1.11	0.04	23.62	0.85
Sum	4.72	-	100	-

PSU WWTP Effluent Day 98				
Fraction	TOC mg C L^{-1}	SD, mg C L^{-1}	Distribution (%)	SD, %
Particles (> 1µm)	-0.24	0.28	-4.99	5.77
Colloids (1µm~20nm)	0.05	0.2	1.09	4.12
Organic acids	2.92	0.17	60.14	3.50
HPO b/n	0.08	0.11	1.61	2.27
TPI b/n	1.21	0.07	24.84	1.44
HPI b/n	0.84	0.03	17.31	0.62
Sum	4.85	-	100	-

PSU WWTP Effluent Day 105				
Fraction	TOC mg C L^{-1}	SD, mg C L^{-1}	Distribution (%)	SD, %
Particles (> 1µm)	0.05	0.11	1.12	2.63
Colloids (1µm~20nm)	0.14	0.12	3.42	2.87
Organic acids	2.17	0.17	51.96	4.07
HPO b/n	0.21	0.13	4.95	3.11
TPI b/n	0.69	0.07	16.53	1.67
HPI b/n	0.92	0.03	22.01	0.72
Sum	4.18	-	100	-

Percent Removals of Organic Fractions:

Day		Flow Rate (ml/min)	% TOC	% Particles	% Colloids	% Organic Acid	% HPO b/n	% TPI b/n	% HPI b/n removal
68	Cont	121.71	9.39	477.55	-57.59	18.33	76.63	-7.49	-7.89
68	Int	256.58	-7.82	-624.49	273.66	25.02	-47.89	-44.11	-21.88
76	Cont	60.53	3.60	358.09	155.06	23.41	56.13	21.53	-7.36
76	Int	57.57	6.68	137.50	91.01	24.86	22.79	16.74	-20.74
98	Cont	145.72	12.63	62.81	-384.91	72.52	-1347.44	19.34	-39.17
98	Int High	381.58	5.32	-10.33	-350.94	19.02	-203.85	44.32	-60.83
98	Int Low	101.97	15.31	84.30	-111.32	64.50	-969.23	45.06	-78.93
105	Cont	206.25	16.29	382.98	-14.69	21.36	-14.01	31.11	-13.91
105	Int High	270.56	6.34	27.66	76.92	20.63	2.90	5.64	-38.15
105	Int Low	166.12	15.91	-234.04	151.05	20.49	16.43	23.59	-9.02

Raw Date for Mineral and Metal Analysis (Int L = Intermittent Low Flow Effluent, Int H = Intermittent High Flow Effluent, Cont = Continuous Flow Effluent):

Sample Day	Source	Al (ppm)	Ca (ppm)	Fe (ppm)	Mg (ppm)	Si (ppm)
105	Int L	0.02	55.4	0.01	26.8	3.73
	Cont	0.02	55.0	0.01	26.4	3.76
	Influent	0.08	56.8	0.03	27.1	3.76
107	Int L	0.02	57.2	0.01	27.3	3.94
	Int H	0.01	58.0	<.01	27.7	3.94
	Cont	0.01	57.5	0.02	27.5	3.81
	Influent	0.12	57.3	0.03	27.4	3.81
110	Int L	<.01	59.0	< .01	28.4	3.95
	Int H	0.01	57.9	< .01	27.8	3.97
	Cont	0.02	58.8	0.01	28.4	3.88
	Influent	0.07	59.6	0.03	28.9	3.88

Academic Vita

Timothy Byrne
The Department of Engineering Science and Mechanics
tmb5093@psu.edu

Education:

The Pennsylvania State University, University Park, PA 2006-2010
B.S. in Engineering Science, Environmental Engineering minor
Schreyer Honors College

Research Experience:

Schreyer Honors College Undergraduate Thesis *March 2009 - May 2010*
Undergraduate Researcher- Primary Investigator

- Designed and implemented the experimental setup for continuous and intermittent flow pilot slow sand filter columns
- Characterized matter removal using organic fractionation, COD, TOC, and turbidity

Virginia Tech NSF Interdisciplinary Watershed Sciences and Engineering REU *Summer 2009*
Undergraduate Research Fellow

- Designed and implemented experiments to analyze the effect of water quality, especially water hardness, on drinking water taste
- Created and tested dozens of synthetic mineral and hard waters using AAS, ICP-MS, and alkalinity titrations
- Organized and performed dozens of IRB sanctioned sensory testing sessions with faculty, staff, students, and community members

PSU Engineering Science and Mechanics Undergraduate Research Experience *Summer 2008*
Undergraduate Research Assistant

- Designed a process to embed piezoelectric fibers in carbon fiber reinforced polymer for use in guided wave structural health monitoring
- Developed and implemented an individual work plan to meet research goals which involved effective communication and collaboration with graduate students, professors, and professionals

Work Experience:

PSU Department of Civil and Environmental Engineering *Spring 2010*
Grading Assistant

- Evaluated and corrected seven homework assignments for half of a section of 120 students in CE 371: Water and Wastewater Design

Architectural Testing, Inc. *Summer 2007 and Winter 2008*
Support Staff

- Worked as part of a team to accomplish tear down and set up of acoustical, thermal, and environmental tests of various architectural building supplies as directed by a supervisor

Voith Siemens Hydroelectric Generation Inc. *Summer 2006*
Support Staff

- Helped to maintain the machine shop of an electrical and mechanical design and manufacturing firm that produces turbines and generators for hydroelectric power

Awards, Honors, and Leaderships

- Second Place, Undergraduate Poster Session, The 13th Annual Environmental Chemistry Student Symposium (Spring 2010)
- Evan Pugh Scholar Award (Spring 2009 and 2010)
- Member of Tau Beta Pi Engineering Honors Society (Spring 2009-present)
- PSU College of Engineering Richard A. McQuade Memorial Scholarship (Fall 2009 and Spring 2010)
- Engineering Science and Mechanics Centennial Award (Fall 2009)
- Virginia D. Bear Eagle Scout Scholarship (Fall 2009)
- Voith Hydropower Generation, Inc. Scholarship Award (4 years)
- President’s Freshman Award (Spring 2007)
- Best Design Communication Award at the PSU Design Expo (Fall 2006)
- Dean’s List (7 semesters to date)
- Eagle Scout Award, Boys Scouts of America
- Reformed University Fellowship Small Group Leader (Fall 2008 – present)

Activities and Interests

- Penn State Club Ultimate team member
- Penn State Intramurals: Soccer, Flag Football, Volleyball, and Arena Football
- Penn State Concert Band (Fall and Spring 2007)
- Oakwood Presbyterian Church member
- Reformed University Fellowship
- Hearthside Nursing Home ministry
- Ballroom and Salsa Dancing