Passive Membrane Systems for Small Communities

by

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Abstract

Submerged hollow fibre ultrafiltration (SHFUF) is an established drinking water treatment technology viable for community-scale use. It can effectively treat surface water up to 4-log removal of colloids, pathogenic bacteria, and viruses. However, current use of SHFUF in small/ remote communities is hindered by the system's complexity and high construction and operating costs. The present study focuses on the development of a novel and simple SHFUF system that can operate passively and with limited mechanical complexity for the production of drinking water in small/ remote communities.

The experimental program was divided into four main stages; each stage was instrumental in eliminating component of a SHFUF system that contributes to its complexity (ie. backwash, permeate pump, aeration and recovery cleaning) and achieving an optimized state feasible for a small community use. Surface water containing 6-7 ppm dissolved organic carbon (DOC) was used for the pilot-scale experiments.

In Stage 1, the contributions of periodic backwash in SHFUF were assessed through a comparative study of with and without backwash systems at sub-critical fluxes of 10, 20 and 30 L/m^2h. While the benefits of backwash were clearly observed at 30 L/m^2h, backwash was less necessary at lower permeate fluxes. At 10 L/m^2h, flux was successfully maintained over the 2-month operation without backwash, indicating that backwash can be eliminated when operating at a low flux. Elimination of backwash reduces power requirements, increases throughput, and simplifies the system. In Stage 2, further simplification to the system was achieved through gravity permeation at a constant hydrostatic pressure. Gravity permeation at 10 L/m^2h could be maintained with a head of 37 mbar. In stage 3, further reduction in energy consumption was achieved through operations under reduced air sparging conditions. Although reduced aeration decreased the permeate flux that could be maintained, this decrease can be compensated by proportionally increasing the number of membrane modules. In stage 4, recovery cleaning was confirmed to recover all of the permeability loss during the 2-month operation. Results from the present study confirm that technical complexity and energy requirements of SHFUF can be substantially reduced and made feasible for use in small/ remote communities.

Preface

This dissertation is original, unpublished, independent work by the author, Patricia Oka.

Table of Contents

List of Tables

List of Figures

Nomenclature

θ	Angle between liquid surface and the capillary wall
[xx]	Concentration of xx
ΔP	Transmembrane pressure
μ	Dynamic viscosity of water
μ_{20}	Dynamic viscosity of water at 20°C
μ_T	Dynamic viscosity of water at T°C
∞	Infinity
AUC	Area under the curve
B	Membrane permeability
B/B_i	Normalized membrane permeability
B_i	Initial membrane permeability normalized to 1
B_s	Normalized membrane permeability at steady state
C_F	Particles concentration in bulk liquid
C_M	Particles concentration at membrane surface
C_p	Particles concentration in the permeate
CPWDU	Community potable water dispensing units
d	Diameter of the pore
Da	Dalton
DI	De-ionized water
Dia.	Diameter
DOC	Dissolved organic carbon
F	Feed
F_t	Total mass of NOM in feed at time t
GE	General Electric
H	Hydrostatic head
HCl	Hydrochloric acid
HMW	High molecular weight
HPLC	High performance liquid chromatography
HS	Humic substances

ID	Inner diameter
J	Flux
Jo	Initial operating flux
J_{OP}	Operating flux
k	Membrane integrity constant
K	Fouling coefficient
K_b	Complete blocking fouling coefficient
K_c	Cake fouling coefficient
K_i	Intermediate fouling coefficient
K_s	Standard fouling coefficient
K_{tot}	Total fouling coefficient
LMA	Low molecular weight acid
LMH	Litre per m^2 per hour
LMN	Low molecular weight neutrals
lpcd	Litres per capita per day
lpd	Litre per day
MBR	Membrane biological reactor
MCF	Macrofiltration
MF	Microfiltration
MW	Molecular weight
MWCO	Molecular weight cut-off
n	Number of data points
NaClO	Sodium Hypochlorite
NF	Nanofiltration
NOM	Natural organic matter
NTU	Nephelometric Turbidity Units
Ø	Diameter
OCD	Organic carbon detection
OD	Outter diameter
ON/OFF	On/Off aeration cycle ratio
P	Permeate

PEG	Polyethylene glycol
p_F	Pressure at the feed side of the membrane
POE	Point-of-entry
POU	Point-of-use
p_p	Pressure at the lumen side of the membrane
PSS	Polystyrene sulfonate
PT	Pressure transducer
P_T	Transmembrane pressure at temperature T°C
P_t	Total mass of NOM in permeates at time t
Q	Flow
Qfeed	Flow into the pressurized-vessel
Qin	Influent flow
Qout	Effluent flow
R	Total resistance
R^2	Coefficient of determination
R_i	Initial concentration of a NOM in system reactor
R_{IR}	Irreversible fouling resistance coefficient
R_m	Membrane resistance coefficient
RO	Reverse Osmosis
R_R	Reversible fouling resistance coefficient
R_t/R_0	Relative membrane resistance
R_{TH}	Theoretical concentration of a NOM in system reactor
s	Standard error
s/m^2	Seconds per square meter
SHFUF	Submerged Hollow Fibre Ultrafiltration
SRT	Solid retention time
SSR	Residual sum of squares
S_t	HPLC signal response at time t
t	Time
T.AUC	Total area under the curve
TMP	Transmembrane pressure

TOC	Total organic carbon
UF	Ultrafiltration
USB	Universal serial bus
UV254	Ultraviolet absorption at 254 nm
V	Volume
V_{F_t}	Total volume fed to the system reactor between two sampling dates
V_P	Total volume filtered
V_W	Total volume wasted
VBA	Visual Basic for Application
W	Waste
W_t	Total mass of NOM in waste at time t
ZW-1000	ZeeWeed®-1000 membrane
ZW-500	ZeeWeed®-500 membrane

Acknowledgements

The completion of this thesis would not be possible without the contributions of many people that I truly respect and care about. For that, I would like to take the opportunity to express my sincere gratitude to them.

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Dedication

This thesis is dedicated to my mother, to whom I gratefully owe my love and fascination for engineering.

This thesis is also dedicated to my father, who envisioned my future and devoted his life and prayers to it.

1. Introduction

Submerged hollow fibre ultrafiltration (SHFUF) is an established drinking water treatment technology viable for community-scale use. It is capable of removing colloids, pathogenic bacteria, and viruses in water up to a log removal value (LRV) of four. However, the adoption of SHFUF for small-scale water treatment in small communities or rural areas is currently hindered by the complexity and costs of the system. As stated by USEPA in their *Drinking Water Treatment for Small Communities* report, the most significant requirements of small systems are low construction and operating costs, simple operation, high adaptability to part-time operations and low maintenance (States, 1994). While the context of a membrane treatment gives a promising outcome of steady high quality drinking water production, its operation requires the availability of skilled operators, a large capital expenditure and a high energy input that rural areas may not have.

Fortunately, in the recent decade, research studies have collectively discovered the potential of membrane systems to operate and self-maintain for an extended period through operations under sub-critical flux conditions. Under sub-critical flux conditions flux has been reported to remain constant and fouling was not observed (Howell, 1995; Wang et al., 2008a). Furthermore, cake layer that forms on the membrane surface under these conditions tends to grow in thickness rather than density (Akhondi et al., 2014) due to the development of cavities, channel networks, and heterogeneous structures that decreases the resistance of the fouling layer and stabilizes the operating flux (Peter-Varbanets et al., 2011).

The first attempt in developing a simple membrane system has only been recently explored through the development of a completely self-sustained, ultra-low pressure flat-sheet membrane system (Boulestreau et al., 2012; Peter-Varbanets et al., 2010). Similar attempts toward system simplification and energy reduction in SHFUF have not been done due to their susceptibility to fouling in the absence of fouling controls, such as backwash and aeration.

1.1 Aims and Objectives

The objectives of the present research was to develop a novel and simple SHFUF system that can operate passively and with limited mechanical complexity for the production of drinking water in small/ remote communities. In meeting the objectives, performance examination on the novel system was done with respect to the effects of operating flux, backwashing, air sparging, as well as, recovery cleaning on the long term operation of the system under sub-critical flux conditions. In conjunction to this, the study attempted to shed some light on the fouling and biological mechanisms governing the operation of the system.

1.2 Thesis Structure

The discussion of the relevant studies by others is compiled in Chapter 2. Chapter 3 outlines the research questions that drive the direction of the study. Chapter 4 describes in detail the materials and methods adopted to conduct and answer the proposed research questions. The obtained data and analyses are presented and discussed comprehensively in Chapter 5. The engineering application of the present study is further discussed in Chapter 6. Finally, the conclusions from the present study are presented in Chapter 7.

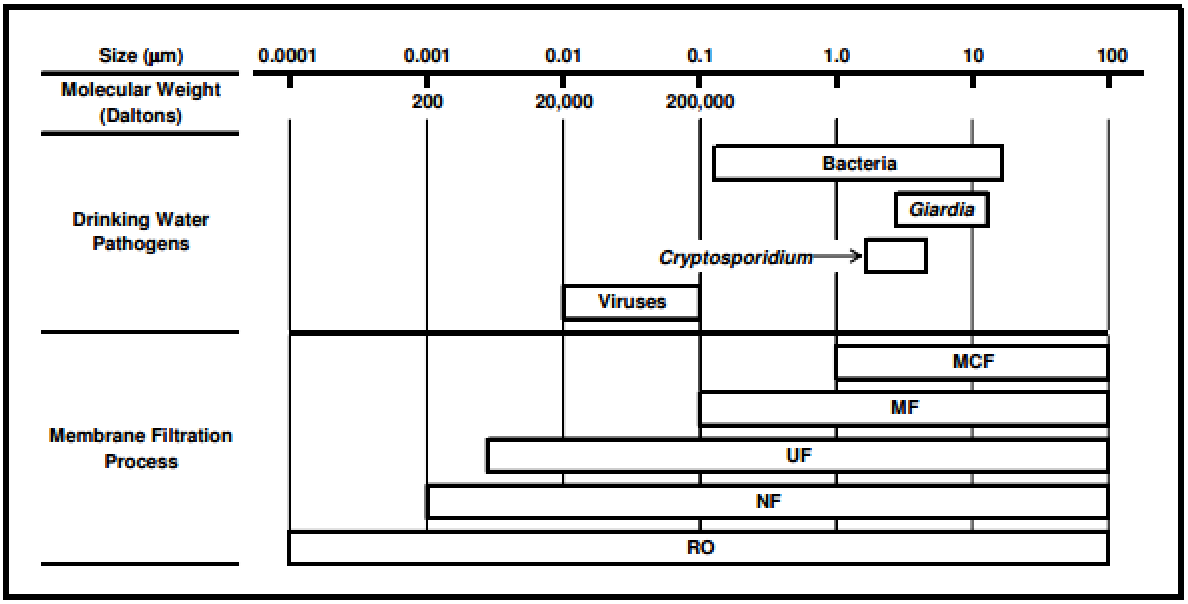
2 Literature Review

2.1 Membrane Filtration in Drinking Water Treatment

Although the first membrane manufacturing and industrial application was started in the 1920s in Germany, the use of membrane filtration in drinking water treatment did not gain popularity until more than 70 years later. During this time, the use of membranes in water treatment had only been considered in some European countries, such as France and Netherlands, who pioneered its use in water treatment in the 1970s. The widespread adoption of membrane treatment was hampered by the high capital and operating costs of the systems. In addition, the extent of treatment by the membrane was viewed to be excessive for the drinking water standard at the time, thereby presenting a poor business case for the use of membranes in water treatment projects.

In the 1990s, a series of serious *Cryptosporidium* outbreaks occurred in major cities throughout the world. One outbreak in 1993 which affected 403,000 people in Milwaukee, US, became the catalyst to the development of a more stringent drinking water legislation. The new legislation mandated membrane treatment for high risk sources. This created volume and competitiveness in the membrane market in the late 1990s, making membrane technologies more economical in the following years (Pearce, 2011).

Today, the use of membranes in drinking water treatment includes a range of applications from the removal of solutes through reverse osmosis (RO) and nanofiltration (NF) to the removal of fine particles through ultrafiltration (UF) and microfiltration (MF). For fresh water treatment applications, membrane filtration is usually performed using either UF or MF treatment, where contaminants are removed through size exclusion. Therefore, it is essential to properly select the pore-size specification for effective treatment. Figure 1 displays the operating spectrums of the different types of membrane treatment. Aside from pore-size, the success of the treatment itself is dependent on the operability of other variables, including membrane permeability and process stability (Pearce, 2011), which vary depending on the type and configuration of the system. Unless indicated otherwise, the following discussion focuses on membranes used for fresh water treatment (ie. MF and UF).



**MCF = Macrofiltration Membrane*

Figure 1 Membrane Filtration Spectrum (USEPA, 2005)

There are three categories of membrane geometries used in water treatment: tubular, flat sheet and hollow fibre. Hollow-fibre membranes are the most commonly used type, largely due to its high packing density and backwash ability. Applications of flat-sheet membranes as a single layer or spiral-wound, are more challenging compared to hollow fibre because of the propensity of these membranes for pore-clogging and limited backwash ability. Whereas, applications of tubular membranes are common in small systems with highly turbid waters due to its low packing density and niche on high tolerance of high cross-flow velocity (MWH, 2005).

In water treatment, membrane modules can be configured as either external or internal. An external membrane system uses pressurized vessels to house the membrane. A positive pressure is applied to the feed side of the membrane to provide the driving force for the liquid to permeate through the membrane. High pumping capacity and piping complexity are usually associated with an external membrane system. On the other hand, an internal membrane system (also known as submerged system, as addressed from this point on) combines both the raw feed and membrane modules in one tank. A negative pressure or suction is applied to the permeate side of the membrane to provide the driving force for the liquid to permeate through the membrane (MWH, 2005; Pearce, 2011). External and submerged membrane configurations are illustrated in Figure 2.

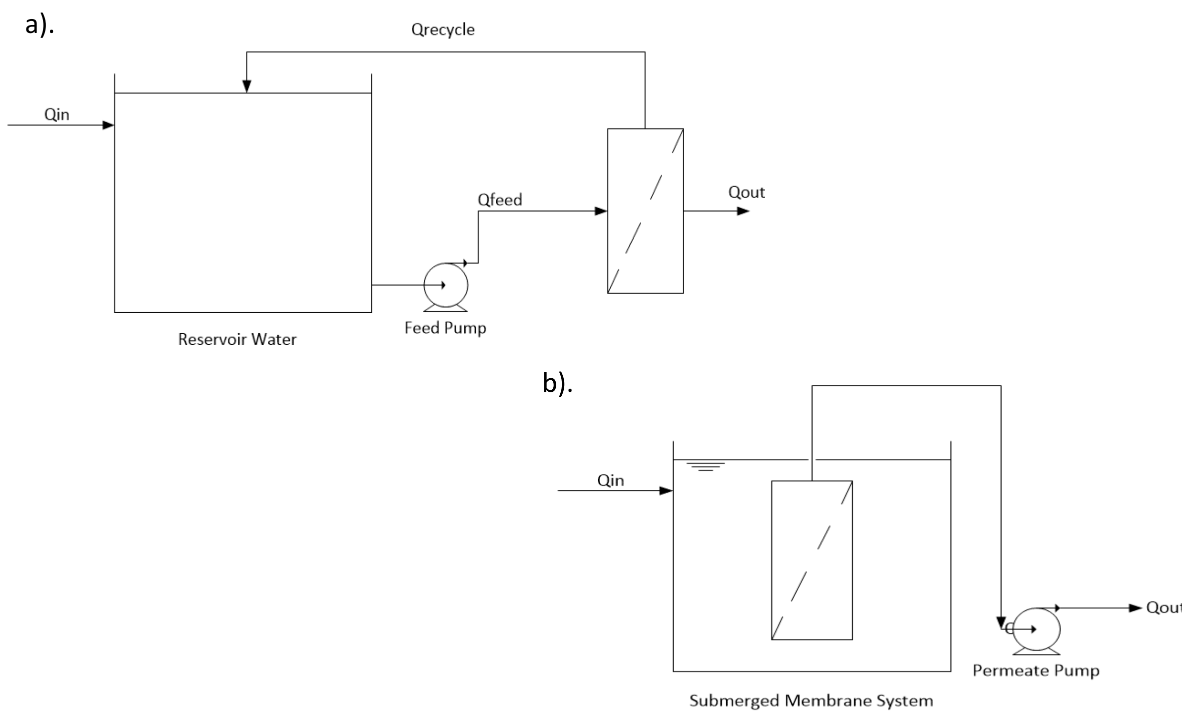


Figure 2 Typical Membrane System Configurations
(a). External Membrane Configuration; b). Submerged Membrane Configuration)

2.2 Submerged Hollow Fibre Ultrafiltration Membrane (SHFUF)

Submerged systems consists of membrane modules immersed in an open raw water tank. Hollow fibre membrane modules are commonly used in submerged systems because of their high surface area and backwash ability (Peinemann and Nunes, 2010). Permeate is generally extracted out of the tank from the top of the modules using a negative pressure generated by a permeate pump. Particles greater than the membrane pore-size are retained at the surface, while permeate is collected on the other side (*lumen*) of the membrane. A portion of the permeate collected is pumped back to backwash the modules and the remainder is collected for drinking use. Figure 3 depicts a typical schematic diagram of a submerged hollow fibre membrane system. Unless indicated otherwise, the following discussion focuses on SHFUF membranes.

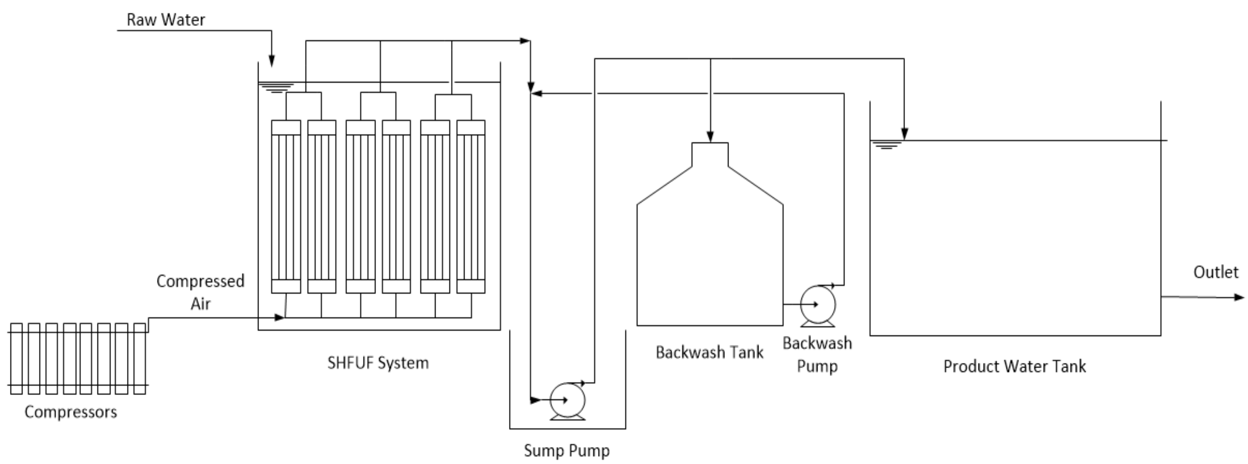


Figure 3 Process Diagram of a Typical Submerged Membrane System

Generally, air is added at the base of the membranes to generate turbulent air and liquid two-phase flow at the surface of the membrane. This turbulence creates shear forces between the bulk liquid and the retained particles at the membrane surface, eroding and preventing further build-up of retained material (ie. foulants). Figure 4 illustrates the eroding of the foulants by aeration in a submerged system.

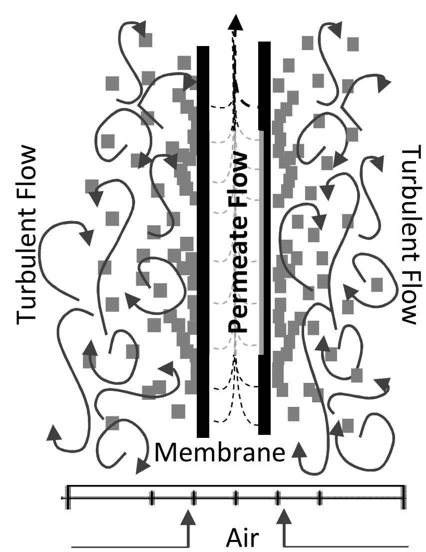


Figure 4 Typical hydrodynamic conditions in SHFUF operation

The application of SHFUF in water treatment has become increasingly popular for both operational and economic reasons. For example, the submerged configuration of the system allows it to operate with a relatively low energy consumption and low system complexity compared to its predecessor, the external membrane systems (Pearce, 2011). Furthermore, the high surface area and packing density of the hollow fibres allows for higher productivity compared to other types of membranes given the overall footprint.

SHFUF systems can be operated under constant flux or constant pressure (MWH, 2005; Pearce, 2011). Over time, particle accumulation at the membrane surface under constant pressure increases the resistance to the permeate flow, resulting in the reduction of permeate flux. Whereas under constant flux operation, particle accumulation increases the resistance to the permeate flow, resulting in the increase of trans-membrane pressure (TMP).

To prevent excessive accumulation of retained material at the membrane surface, SHFUF units are equipped with various fouling prevention features and maintenance programs, such as air scour, periodic backwash and recovery cleaning. Although effective, these fouling controls substantially increase the complexity and cost of membrane systems.

2.3 Membrane Fouling in SHFUF systems

Fouling is the accumulation of particles or solutes at the membrane surface (Field, 2010). It largely results from particle size exclusion by the pores and chemical/electrical attractions that may exist between retained material and the membrane (Cho J., 1999; Jermann, Pronk, Meylan, & Boller, 2007; Pearce, 2011). In SHFUF systems, fouling tendency is often affected by the high fibre packing density, which limits *two-phase flow* at the membranes surface (Yeo et al., 2006). Furthermore, operating conditions and feed characteristics also play a significant role in SHFUF fouling (Aimar and Bacchin, 2010; Tang et al., 2011). The presence of fouling is commonly manifested by an increase in resistance to permeate through a membrane. The relationship between permeate and resistance is presented in Equation 1.

Equation 1

$$J = \frac{\Delta P}{\mu\,(R_M + R_{IR} + R_R)}$$

where, J is volumetric water flux through the membrane, L/m^2.h

ΔP is the transmembrane pressure (TMP), bar

μ is dynamic viscosity of water, kg/m.s

R_M is membrane resistance coefficient, m^{-1}

R_{IR} is irreversible fouling resistance coefficient, m^{-1}

R_R is reversible fouling resistance coefficient, m^{-1}

Another indicator of fouling is the reduction in membrane permeability, which is inversely proportional to the total increase in membrane resistance as expressed in Equation 2.

Equation 2

$$B = \frac{\mu J}{\Delta P} = \frac{1}{(R_M + R_{IR} + R_R)}$$

where, B is membrane permeability, meters.

Fouling forms through different mechanisms as illustrated in Figure 5. *Adsorption* can occur with and without the presence of permeate flux. It is typically driven by specific interactions between the membrane and the solute/ particles in the bulk feed. *Pore blocking* (intermediate or complete) occurs as a result of the migration of particles towards the membrane via permeate flux and their entrapment in the membrane pores. The migration of particles towards the membrane by permeate flux may also result in foulant accumulation at the surface of the membrane, known as *cake deposition*. The degree of accumulation, however, depends on the balance between convective transport of solutes towards the membrane and back-diffusion transport, which is discussed in Section 2.5.

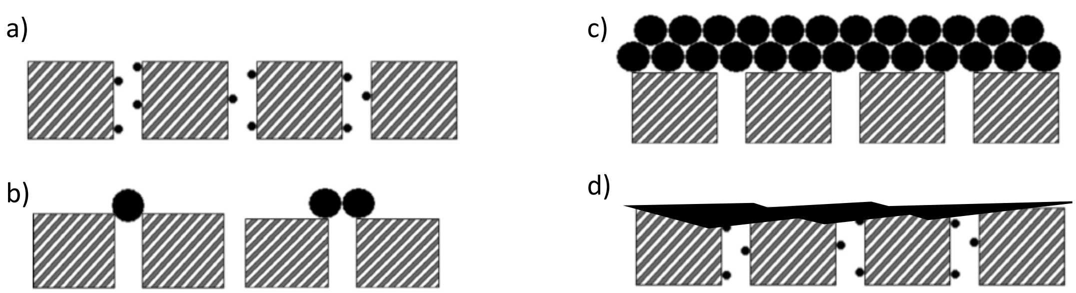


Figure 5 Typical Fouling Mechanisms in Membrane Treatment
(a) Adsorption, b) Pore Blocking, c) Cake Deposition, d) Gel Formation)

In some cases, fouling may occur from a combination of different mechanisms depending on system conditions and presence of specific foulant constituents (Bolton et al., 2006). Many studies have attempted to identify different fouling mechanisms, individually and in combinations, for the purposes of understanding the effects of different operating conditions and/or foulant constituents on membranes performance (Bolton et al., 2006). Table 1 and Table 2 summarize the individual and combined fouling models for constant pressure operation as derived by Bolton et.al. (2006).

Table 1 Summary of the Four Constant Pressure Individual Fouling Models

Single Fouling Mechanism	Equation	Fitted Parameter	Reference
Standard	$V = \left(\frac{1}{J_0 t} + \frac{K_s}{2}\right)^{-1}$	K_s (L/m^2)	Equation 3
Intermediate Blocking	$V = \frac{1}{K_i} + \ln(1 + K_i J_0 t)$	K_i (L/m^2)	Equation 4
Complete Blocking	$V = \frac{J_0}{K_b} + (1 - \exp(-K_b t))$	K_b (hr^{-1})	Equation 5
Cake	$V = \frac{1}{K_C J_0}\left(\sqrt{1 + 2K_c J_0^2 t} - 1\right)$	K_c (m^{4}hr/L^2)	Equation 6

Table 2 Summary of the Four Constant Pressure Combined Fouling Models

Combined Fouling Mechanisms	Equation	Fitted Parameters	Reference
Cake – Complete	$V = \frac{J_0}{K_b}\left(1 - \exp\left(\frac{-K_b}{K_c J_0^2}\left(\sqrt{1 + 2K_C J_0^2 t} - 1\right)\right)\right)$	K_c (m^{4}hr/L^2) K_b (hr^{-1})	Equation 7
Cake - Intermediate	$V = \frac{1}{K_i}\ln\left(1 + \frac{K_i}{K_c J_0}\left((1 + 2K_c J_0^2)^{1/2} - 1\right)\right)$	K_c (m^{4}hr/L^2) K_i (L/m^2)	Equation 8
Complete - Standard	$V = \frac{J_0}{K_b}\left(1 - \exp\left(\frac{-2K_b t}{2 + K_s J_0 t}\right)\right)$	K_b (hr^{-1}) K_s (L/m^2)	Equation 9
Intermediate - Standard	$V = \frac{1}{K_i}\ln\left(1 + \frac{2K_i J_0 t}{2 + K_s J_0 t}\right)$	K_i (L/m^2) K_s (L/m^2)	Equation 10
Cake - Standard	$V = \frac{2}{K_s}\left(\beta\, cos\left(\frac{2\pi}{3} - \frac{1}{3} arccos(\alpha)\right) + \frac{1}{3}\right)$ Where, $\alpha = \frac{8}{27\beta^3} + \frac{4K_s}{3\beta^3 K_c J_0} - \frac{4K_s^2 t}{3\beta^3 K_c}$ $\beta = \sqrt{\frac{4}{9} + \frac{4K_s}{3K_c J_0} + \frac{2K_s^2\, t}{3K_c}}$	K_c (m^{4}hr/L^2) K_s (L/m^2)	Equation 11 Equation 12 Equation 13

Whatever the driving mechanism may be, all fouling leads to a rise in the membrane's hydraulic resistance, which may or may not be reversible. Over time, foulants may transform physically through compression and/or chemically through biodegradation, leading to further fouling (Field, 2010; Pearce, 2011; Rodríguez et al., 2012). The following section introduces different fouling constituents commonly found in source waters and their effects on membrane fouling.

2.4 Fouling Constituents in Surface Water Sources Affecting UF Performance and Permeate Quality

There are four broad categories of raw water constituents that have been documented to cause fouling : particulates, inorganic, organic, and micro-biological organisms (Field, 2010; Pearce, 2011). Particulate foulants are defined as undissolved organic and/or inorganic matter that have the ability to block or blind the membrane surface. Inorganic foulants in water sources are typically dissolved materials, which tend to precipitate on the membrane surface under certain conditions. In water treatment, inorganic foulants may be present as coagulant residuals from the upstream processes in the treatment plants (Pearce, 2011). Organic foulants, also known as natural organic matter (NOM), include both undissolved and dissolved materials (MWH, 2005). However, it is the dissolved components of organic foulants that have been widely known to cause rapid membrane fouling. Fouling by NOM is usually through adsorption and pore blocking, which can be irreversible through regular hydrodynamic fouling control, such as air scour and backwash (Aoustin et al., 2001; Fan et al., 2001; Kimura et al., 2006).

In a typical natural surface water, NOM consists of 60-90% of hydrophobic humic substances (HS), 10-15% of hydrophilic high molecular weight (HMW) substances and 25-40% of hydrophilic low molecular weight (LMW) substances (Peter-Varbanets et al., 2011; Thurman, 1985; Y. Choi, 2003). Any NOM constituents can be responsible for membrane fouling and flux decline. However, recent studies have confirmed that the hydrophilic portion of the NOM is responsible for most of the fouling (Jarusutthirak, 2002; Jermann et al., 2007; Kimura et al., 2004; Lin et al., 2000). Within this portion of the NOM, both the high and the low molecular weight substances of the hydrophilic group play a role in the fouling of UF membranes. The HMW materials (ie. polysaccharides and protein) often foul membranes through cake deposition and pore blocking at the membrane surface, whereas, low molecular neutrals tend to adsorb onto the membrane pores (Jarusutthirak et al., 2002; Speth et al., 2000). Overtime, microbial communities in the system excrete extracellular material and establish colonies, forming a *biofilm*. This is known as biological fouling (MWH, 2005; Pearce, 2011; Qu et al., 2013; Wang et al., 2008b).

Several studies have reported that the presence of young and thin biofilm can act as pre-coat to the membrane surface, which minimizes further fouling and enables long-term membrane operation (Peter-Varbanets et al., 2010; Ye et al., 2011). However, the long-term presence and accumulation of biofilm is also known to compromise permeate quality as the biofilm hydrolyzes into soluble material that is permeable through the membrane. The rate at which hydrolysis occurs is proportional to the mass of volatile solids in the biofilm (Derlon et al., 2014). Nonetheless, biofilm is easily removable through recovery cleaning using chemical agents, such as chlorine (MWH, 2005). Figure 6 was adopted from Derlon et al.'s study to illustrate the contribution of biofilm to permeate quality.

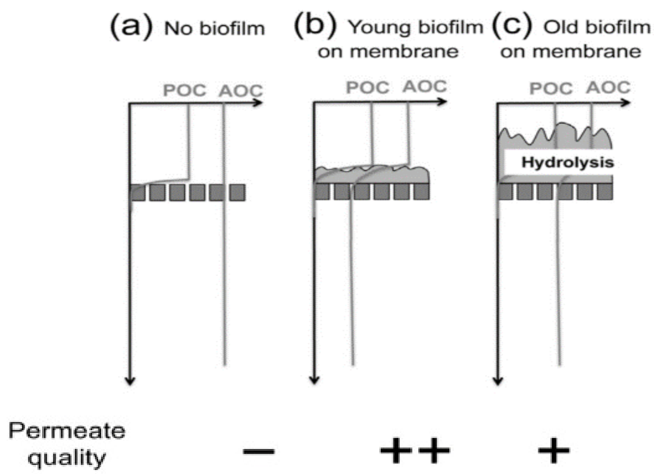


Figure 6 Illustration of the Effect of Biofilm formation on Permeate Quality during an Ultra-low Gravity Permeation by Derlon et al. in 2014: a). Case of membrane system without biofilm, b) Case of young and thin biofilm developed on a membrane, c). Case of an old and thick biofilm on a membrane (Derlon et al., 2014).

2.5 Fouling Control

The degree of fouling in submerged systems is a complex function of feed characteristics, membrane properties and operating conditions (Aimar and Bacchin, 2010; Raffin et al., 2012; Tang et al., 2011). Due to the many variables affecting fouling, fouling controls can be implemented in many ways, both directly or indirectly. Direct methods may include adding turbulence promoters, implementing pulsed or reverse flow, rotating/ vibrating membranes, air scour, periodic cleaning and backwash. Indirect methods include pre-treatment of feed water, membrane surface treatment/ modification, and selection of appropriate operating mode (Akhondi et al., 2014). The following sections discuss the three most common fouling controls used in a submerged hollow fibre system.

2.5.1 Periodic Backwash

Backwash is an operational approach that reduces foulant deposition by the reversal of permeation flow, going outwardly from the membrane's lumen to the feed wall side. The cyclical outward direction of the flow dislodges foulants inside the pores and detaches deposition at the membrane's surface. Detaching and dislodging foulants from the membrane surface not only reduces the resistance to the permeate flow, but also the effect of the *concentration polarization* mechanism on the membrane, which would otherwise enhance mass flux toward the membranes in the reactor (Pearce, 2011).

Backwash cycles are usually programmed to occur 1 to 4 times per hour (Pearce, 2011), but can vary over a greater range depending to the membrane product. Every cycle of backwash allows both detachment and reorganization of the foulant structure to maintain a *sustainable flux,* which is a flux at which fouling rate is operationally and economically acceptable (Guglielmi et al., 2007; Ognier et al., 2004). The implementation of backwash is proven to improve and prolong the usability of membranes (Akhondi et al., 2014). However, the efficiency of backwash may decrease over time due to the inability of the reversed flow to dislodge or displace all foulants.

The efficiency of backwash is limited by both the amount of product loss and the energy required to reverse the flow (Psoch and Schiewer, 2005). A study by Akhondi et al. in 2014 demonstrated that for a given volume, higher backwash flux provides greater cleaning efficiency than longer backwash duration (Akhondi et al., 2014). A study led by Chua in 2003 demonstrated that optimum backwash flux was approximately twice the flux of the permeate flow, beyond which no further improvement was observed (Chua et al., 2003).

2.5.2 Air Scour

Air scour or *sparging* is an operational approach that reduces foulant deposition by increasing air/water turbulent at the surface of the membrane, hence enhancing hydrodynamic conditions around the membrane surface. The introduction of air bubbles at the bottom of the reactor, directly below the membranes, produces sub-turbulent or turbulent conditions near and at the membrane's surface. The rising bubbles generate secondary flows in their wake and entrain bulk liquid that results in fiber sway, resulting shear forces and eroding foulant layers at the membrane's surface (Cabassud et al., 1997; Wu et al., 1999; Zularisam et al., 2006). Inducing air scour during backwash is also a common practice that has been confirmed beneficial to enhance fouling removal and backwash efficiency. It is understood that while backwash detaches the particles from the membrane, air scour removes these particles away from the membrane into the bulk feed (Bessiere et al., 2009; Serra et al., 1999).

The benefits of air scouring application in membrane systems have been comprehensively studied. A comparison study conducted by Judd et al. in 2001 confirmed that dual-phase cross-flow brought by the introduction of air results in a significantly higher pseudo-state permeate flux than a single-phase cross-flow filtration under constant-pressure operation (Judd et al., 2001). The higher steady-state flux achieved indicates that there is less foulant deposition on the membrane under dual-phase cross-flow (Ducom et al., 2002). Berubé and Lei (2006) observed an optimum point beyond which an increase in bulk cross-flow through air scour above 0.3 m/s will not give further improvement to the system performance.

2.5.3 Sub-Critical Flux Operation

Another approach for fouling controls in membrane systems is to operate below *critical flux* (Psoch and Schiewer, 2005). Critical flux is an operating flux below which increase in TMP over time does not occur (ie. no fouling) and above which the opposite is observed (Wang et al., 2008b). The concept of critical flux was first introduced by Field et al. in 1995 for MBR applications, where *sub-critical flux* conditions in MBR operations were achieved with the assistance of air sparging alone. As a result, a 12-month continuous operation was achieved without backwashing and chemical cleaning (H. Ishida, Y. Yamada, 1993).

The application of critical-flux by means of hydrodynamic modifications in drinking water treatment has since been studied and confirmed to have benefits in fouling prevention. Bérubé and Lei (2006) reported the significant reduction of fouling occurrences as the *flux index* is lowered to less than zero (Figure 7). Flux index is the difference between the operating flux and the critical flux. Sub-critical conditions can be achieved by operating under a constant low flux or pressure, where the mass transport of foulants in the direction of the membrane through the convective flow of permeate is minimized. The lower mass transport also reduces compaction of foulants on the membrane surface, allowing the foulant layer to grow in thickness and porosity rather than density while a steady transmembrane pressure is maintained (Akhondi et al., 2014; Rodríguez et al., 2012).

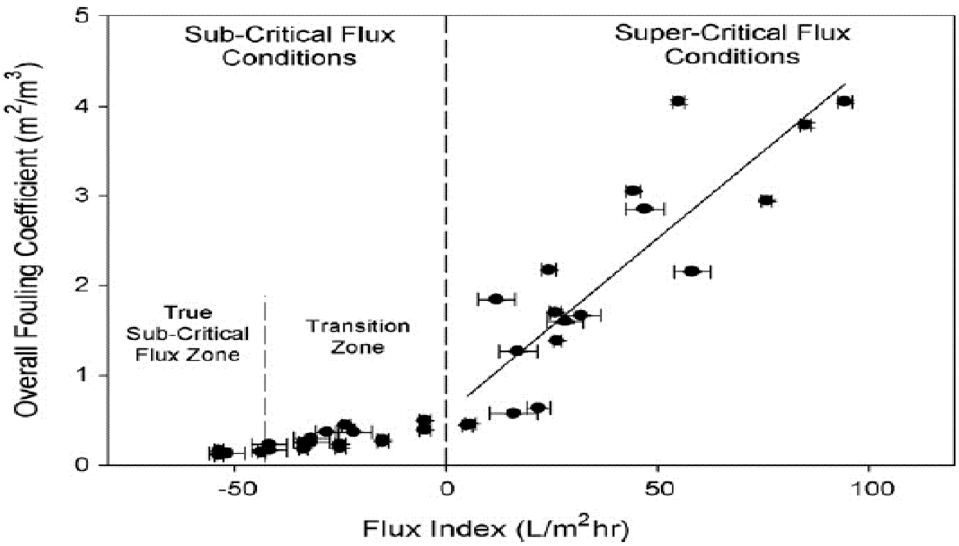


Figure 7 Fouling coefficient across different flux indexes (Bérubé et al., 2008)

2.6 Passive Membrane Filtration

The definition of *passive filtration* comes from the biomedical field, which defines the self-sustained physical transport process of biochemical and other atomic substances across the cell membranes of an organism (Pont and Bonting, 1981). The self-sustained characteristic enables the system to operate without any additional driving force other than the mechanical properties of the system, such as the growth of entropy in the system. In the case of membrane application, the enabling properties would be the given hydrostatic head, the membrane's surface characteristics, and the resulting vacuum from the pressure difference across the membrane. The application of this passive filtration concept in an actual membrane operation is intended to reduce the system's dependency on additional driving forces (e.g. pumps) and user maintenance (e.g. monitoring and cleaning).

Coupling the passive filtration concept with the concept of sub-critical flux operation is understood to have complementary effects in the reduction of both energy consumption and user maintenance requirements that has historically made conventional SHFUF systems complex and expensive. A way of combining the two concepts is by operating membrane permeation under a constant, ultra-low hydrostatic pressure driven by gravity. Over time, the system is expected to reach a steady-state at a very low operating flux, at which point the system will become stable and self-sustained, such as observed by P.H. Hodgson (1994), Howell (1995) and Wu et al. (1999). This particular phenomena was confirmed in a pilot study by Peter-Varbanets et al. in 2010, which investigated the potential suitability of a gravity-driven, flat-sheet membrane operation for decentralized drinking water treatment. In their research, a 40-cm hydrostatic pressure was applied to induce continuous permeation on a dead-end operated UF flat-sheet membrane. No additional control features, such as air sparging, backwash or chemical cleaning, were added to maintain the stability of the system. Under this ultra-low pressure, the growth in fouling thickness was observed to be counteracted by biological activity. This activity makes the fouling structure porous, maintaining a low fouling resistance and a steady-state permeate flux (Peter-Varbanets et al., 2011). The system proposed by Peter-Varbanets et al. (2010) was field tested in Annet-sur-Marne, France and Ogunjini, South Africa to provide sufficient drinking water for 100-200 people. Their results produced insights on other aspects affecting the system's operation, such as pre-treatment of high turbid waters (>100 NTU) and daily wastage for a better flux stabilization (Boulestreau et al., 2012). . Figure 8 illustrates the process diagram of the gravity system developed by Peter-Varbanets in 2010.

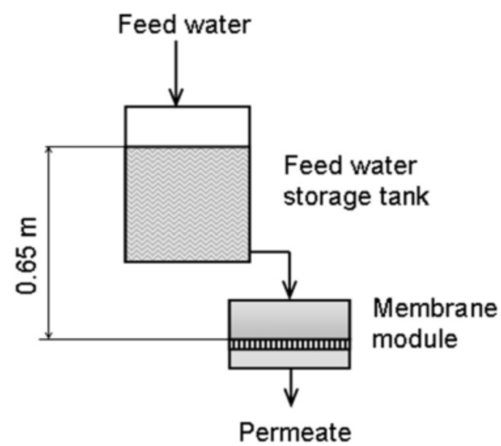


Figure 8 Schematic presentation of the dead-end UF system (Peter-Varbanets et al., 2010)

3 Knowledge Gap and Objectives of Present Study

The idea to simplify and develop a more affordable membrane system has only been explored recently with the development of a completely self-sustained, ultra-low pressure flat-sheet membrane system (Boulestreau et al., 2012; Peter-Varbanets et al., 2010). Similar attempts toward system simplification and energy reduction in SHFUF have not been done due to their susceptibility to fouling in the absence of fouling controls, such as backwash and aeration. Therefore, the main **objective** of the present study is to develop a novel and simple SHFUF system that can operate passively and with limited mechanical complexity for the production of drinking water in small/ remote communities. In meeting the objective, the present study will attempt to address the following research questions:

I. Can process complexity of the conventional SHFUF system be simplified without compromising the operational stability?
   A. Is it possible to eliminate periodic backwash?
      i. What are the contributions of periodic backwash in SHFUF operation under sub-critical flux condition?
      ii. Can backwash be completely eliminated under sub-critical flux condition?
   B. Is it possible to eliminate the use of permeate pump using passive membrane filtration (ie. gravity-driven) and still achieve a steady flux?
      i. Does fouling behave similarly in sub-critical flux operations under constant flux (ie. pumped flow) and constant pressure (ie. gravity driven)?
      ii. What is the magnitude of permeate flux that can be sustained?
   C. Is it possible to eliminate air sparging in passive membrane filtration used in I-B for further system simplification?
      i. What are the contributions of air sparging in passive membrane filtration under sub-critical flux conditions?
      ii. Can air sparging be completely eliminated in passive membrane filtration?

II. What are the impacts of recovery cleaning on hollow-fibre modules and their performance?
   A. Is recovery cleaning capable to recover all of the loss permeability from a long-term operation?
   B. Does acclimatization help to improve membrane performance?

III. What are the mechanisms that govern the performance of the passive membrane system used in I-B?

IV. What are the predominant fouling mechanism(s) in passive membrane system?

A. Does air sparging frequency affect the predominant fouling mechanism?

V. What are the contributions of biological communities in passive membrane filtration?

i. Is there evidence that biomass accumulation occurs during passive permeation?

ii. Does this biomass accumulation in the system reactor help the removal of organics?

4 Material and Methods

4.1 Experimental Program

The experimental program was divided into four main stages that investigated the contributions of: 1). periodic backwash, 2). constant-pressure permeation, 3). air sparging, and 4). recovery cleaning in SHFUF operations under sub-critical flux conditions. Each stage was instrumental in eliminating one complex aspect of SHFUF system and bringing it closer to an optimized state that is feasible for a small community use. Table 3 summarizes the complete experimental program of the present study and Figure 9 illustrates the evolution of the system from each stage to the next.

Table 3 Operational Conditions of the Three-stage Experimental Program

Parameter of Interest	Reactor	Flux (LMH)	Operation Type	Aeration	Backwash	Daily Wasting
1. Periodic Backwashing	A	10 20 30	Constant Flux	3.8 L/min Continuous	10-min/ 4-hr filtration	none
	B	10 20 30	Constant Flux	3.8 L/min Continuous	none	none
2. Constant-Pressure Permeation	C	10 13 16	*Constant Pressure	3.8 L/min Continuous	none	10 %V
3. Air Sparging	D[1]	10	*Constant Pressure	3.8 L/min 25mins off/ 5 mins on	none	10 %V
	E	10	*Constant Pressure	3.8 L/min 4hrs off/ 5 mins on	none	10 %V
	F	10	*Constant Pressure	3.8 L/min 4hrs off/ 30 mins on	none	10 %V
	G	10	*Constant Pressure	No Aeration	none	10 %V
4. Recovery Cleaning	D[2]	10	*Constant Pressure	3.8 L/min 25 mins off/ 5 mins on	none	10 %V

*vacuum pressure provided by gravity

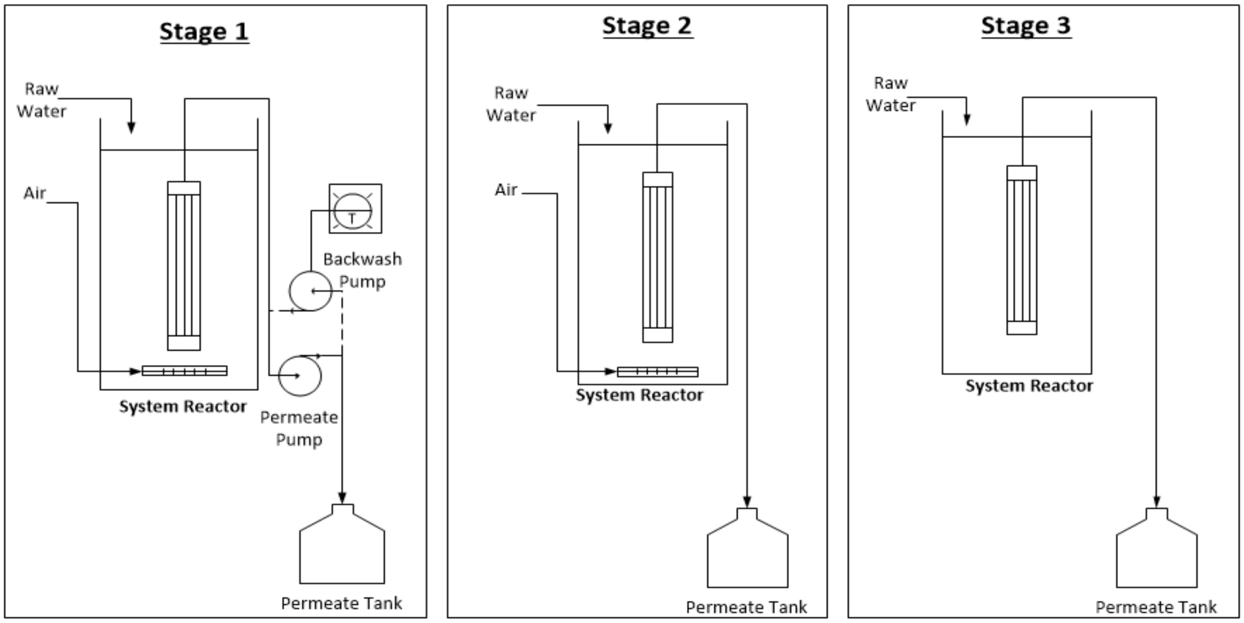


Figure 9 Simplification of the complex SHFUF into a simple system over the span of the research

For all of the experimental stages, laboratory data such as temperature, production volume and transmembrane pressure were recorded daily. Water samples were collected every 2 to 5 days from all components of the treatment, including feed tank, system reactor and permeate flasks. Each sample was analyzed for its carbon content using total and dissolved organic carbon (TOC-DOC) analysis and its size exclusion chromatography using high performance liquid chromatography (HPLC) analysis.

4.2 Pilot-scale Submerged Hollow-Fibre Membrane System

The pilot-scale submerged hollow-fibre membrane systems used in the present study are illustrated in Figure 15, Figure 17, and Figure 18. In general, the systems consisted of a feed water tank, a system reactor, membrane modules and a permeate collection unit. Depending on the investigated conditions, the systems would be equipped to conduct periodic backwash, pump permeate, and aerate. This section discusses in detail each component that made up the pilot-scale systems used in Stages 1 through 4.

The feed water system of the pilot-scale consisted of one peristaltic pump (Masterflex) and an enclosed feed tank of 450 mm ID by 570 mm tall with a removable lid. Throughout the study, the liquid level in the reservoir was maintained at an elevation that is sufficient to continuously provide feed to the system reactor for a period of three days. The feed flow to the system reactor was supplied at a rate that was close to the permeation rate to maintain constant operating level.

The system reactor was an open cylindrical tank with an inside diameter of 155 mm and a total reactor height of 1,270 mm. A working depth of 1,000 mm was adopted to create sufficient freeboard. The total operating volume of the system reactor was approximately 19 litres. Water temperature inside the system reactor was measured daily using an alcohol based thermometer (Fisher Scientific 15-030 or CanLab D67412), which was installed inside the reactor. The system reactor was also equipped with a discharge valve at the bottom of the tank for daily wasting, which was started in Stage 2. Also added in Stage 2 was an overflow line to maintain a consistent head for a stable siphon flow of permeate. Figure 10 illustrates details of the design of the system reactor.

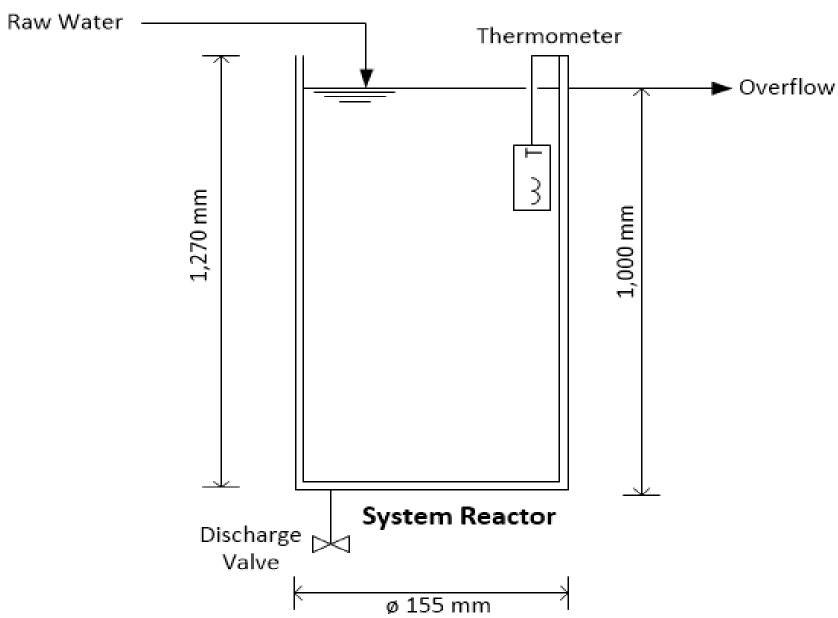


Figure 10 System Reactor Configuration

Inside the system reactor was a set of membrane modules made with ZeeWeed® 500 hollow-fibres (GE Water and Process Technologies, Oakville, Canada), which are non-ionic and hydrophilic UF membranes. Their physical properties are summarized in Table 4. Each membrane module consisted of three 510 mm-long membrane fibres that were potted together into bulkheads. The bulkheads were 50 mm-long ¼" OD rigid tubing. One of bulkheads was open to allow permeate flow, whereas the other was sealed with epoxy glue. A total effective fibre length between the bulkheads was 430 mm, creating a total effective membrane surface area of 0.00717 m^2 per bundle. Figure 13 details the configuration of the membrane module.

Table 4 Membrane Module Properties of the Present Study

Membrane Properties	Unit	Value
Outside Dia.	mm	1.77
Nominal pore Dia.	um	0.04
Typical TMP	psi	1-8
Number of Strands	unit	3
Length	mm	430
Total Filtration Area	m^2/ module	0.00717

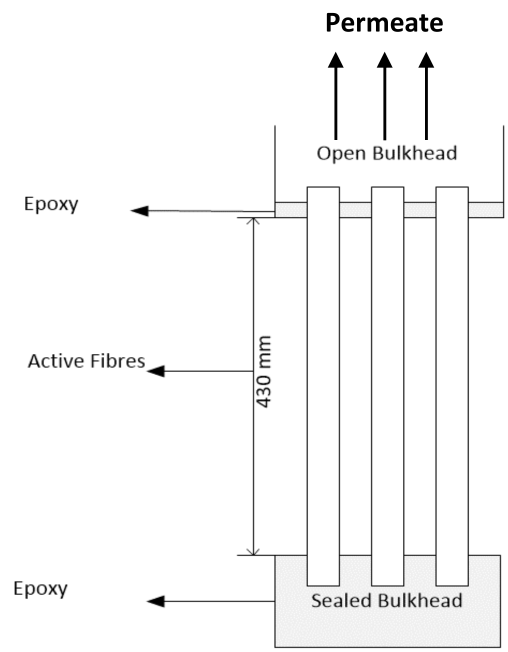


Figure 11 Membrane Potting Configuration

For each experiment, a total of three membrane modules were made and mounted on a three-legged membrane stand. Depending on the operation conditions, the three modules may or may not operate as triplicates. Each module was secured with an adjustable membrane holder on either ends with a pot-to-pot distance of 420 mm, or 98% of membrane looseness, to allow sufficient freedom for fibre movement and avoid membrane agglutination. Figure 12 details the installment of the modules onto the membrane stand.

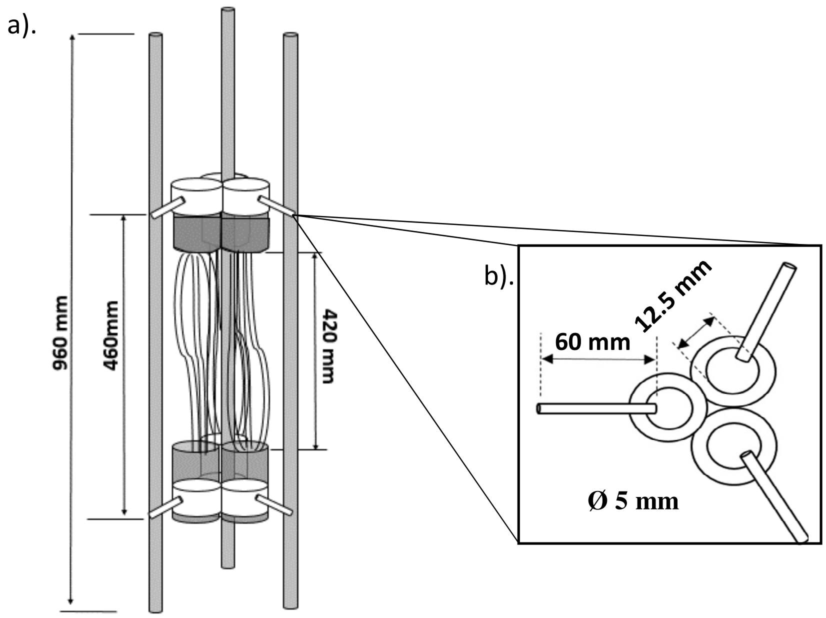


Figure 12 Membrane Stand Design and Installation

(a) Membrane Modules Arrangement, b). Design Criteria of the Adjustable Membrane Holder)

Permeation in Stage 1 was generated with a Masterflex pump (series 7520-35 and 7528-30 for Reactor A and B, respectively) with four Masterflex head pumps, specifically configured to produce the fluxes of interest. The configuration was as follows: one size-13 head pump (7013-21) to create 10 LMH, two size-13 head pumps (7013-21) to create 20 LMH, and one size-14 head pump (7014-21) to create 30 LMH. Within each of the permeate lines, resistance to permeate flow was measured using Omega Engineering Inc. pressure transducer (Model PX243A-15BG5V) and recorded by HOBOware U12 data logger every 3 minutes. Permeation in Stages 2 through 4 was driven by a constant hydrostatic pressure and resistance to permeate was stable.

Fouling control through periodic backwashing (ie. in Stage 1) was performed by reversed flow of the permeate pump every 4 hours for 10 minutes at the same permeating fluxes, such that backwash flow was equal to the permeate flow. Fouling control through air sparging was provided by a sparger with three 1/8”-diameter orifices, located below the membrane modules. A normally-closed solenoid valve and a timer was added into the system in Stages 3 and 4 to conduct intermittent aeration in the system reactor. Figure 13 depicts the configuration of the system aeration.

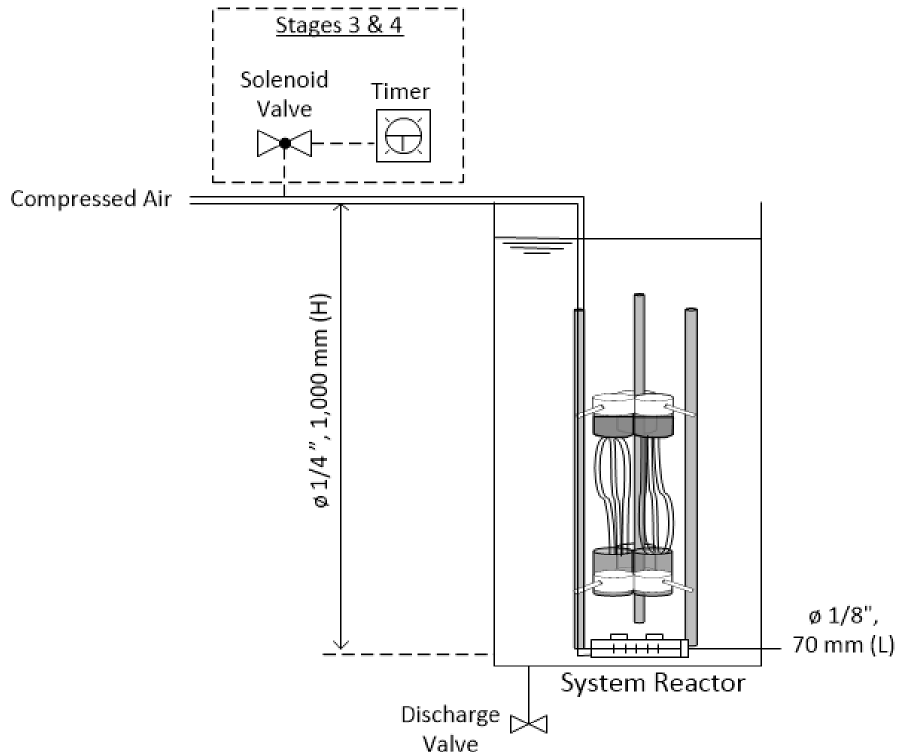


Figure 13 Configuration of the System Aeration

Permeate collection generally consisted of a 5-litre flask per permeate line and an electronic balance (Denver Instrument MXX-10). In stages 2 through 4, a graduated cylinder with an overflow line into the permeate flask was added to maintain the hydrostatic head difference (refer to Figure 14). The weight of the produced permeate was taken once a day. Total volume filtered given time was calculated from multiplying the permeate weight by the density of water. Permeate flux was calculated daily using Equation 14.

Equation 14

$$J = \frac{V_p}{t \ x \ A}$$

where, *J* is operating flux, L/m^2.h

V_p is volume of permeate, litres

t is filtration time, hours

A is total filtration time, m^2.

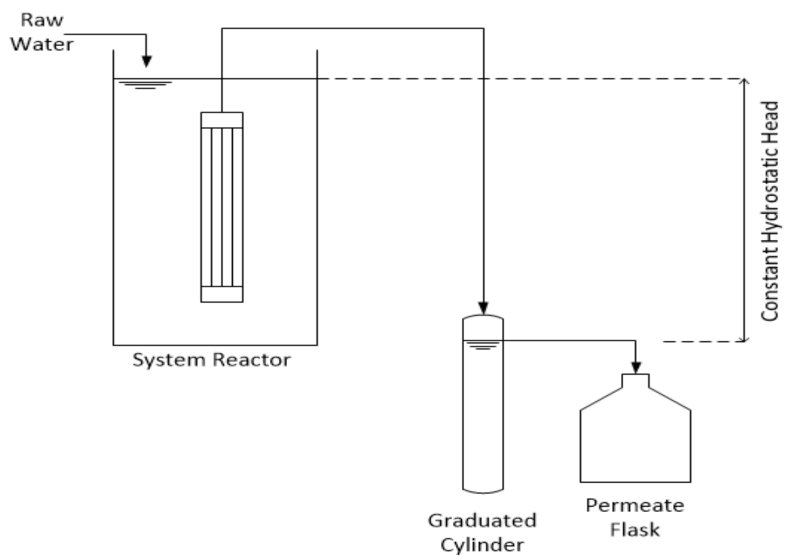


Figure 14 Establishment of constant hydrostatic pressure in SHUFUF System Stages 2 through 4

4.3 Source Water

Raw water used in this study was surface water from Jericho pond, located approximately 1 km south of the Jericho beach. Jericho pond is a typical run-off water pond that also serves as a natural habitat for ducks, blackbirds and fish. Its subjection to quality change due to seasonal changes and biological activities makes it an ideal representation of a typical surface water source. Raw water was collected once every 3 weeks. Approximately 2 m^3 of water was collected in total over the one-year research period.

Immediately after the collection, water was transported back to UBC Environmental Engineering Lab and filtered through a 100 µm screen. Pre-treated water was then analyzed for total organic carbon (TOC) and dissolved organic carbon (DOC) contents as per Section 4.6.1, after which they were stored in a refrigerator at 4^{o}C until the time to use. Prior to use, the water was warmed to room temperature, diluted with tap water to a DOC concentration of approximately 6-7 ppm, and tested for DOC and TOC. Table 5 summarizes the dissolved and total organic content in the raw Jericho Pond water.

Table 5 TOC and DOC of Raw Jericho Pond Water

Sampling Date	Volume (L)	DOC (ppm)	TOC (ppm)
03-Sep-13	90	22.9	32.0
30-Sep-13	113	17.0	28.3
05-Nov-13	90	14.5	23.8
04-Dec-13	113	13.1	18.5
23-Dec-13	113	12.5	18.6
10-Jan-13	158	10.6	16.3
23-Jan-14	135	9.5	14.2
06-Feb-14	158	8.6	11.3
20-Feb-14	158	9.0	12.6
06-Mar-14	158	7.9	9.6
14-Mar-14	113	8.7	10.5
27-Mar-14	158	7.2	10.6
17-Apr-14	135	11.1	16.6
29-Apr-14	158	12.4	18.5
09-May-14	113	12.5	18.2
Total	1,958	11.3	16.4

4.4 Experimental Setup

4.4.1 Stage 1: Contributions of Periodic Backwash in Long-Term SHFUF Operations under Sub-Critical Flux Conditions

Two parallel experiments, with and without backwash, were conducted at constant low-fluxes. Each reactor contained three independent modules operating at fluxes of 10, 20 and 30 LMH for an extended period of 2 months. Backwash was controlled with a timer to occur every 4 hours for a duration of 10 minutes at the applied permeating fluxes. A continuous aeration at 3.8 L/min was adopted throughout the stage. Daily wasting was not incorporated in this stage. Figure 15 depicts the process diagram of Stage 1.

Given that the system reactor and membrane module configuration were directly adopted from a previous study by Bérubé & Lei (2006), the system was assumed to inherit the same estimated critical flux of 98.1 ± 2.8 LMH with the presence of a continuous aeration at 3.8 L/min. The fluxes of 10, 20 and 30 LMH considered in the present study were therefore sub-critical. Figure 16 was directly adopted from Bérubé & Lei (2006) to highlight the sub-critical zone that was considered in the present study.

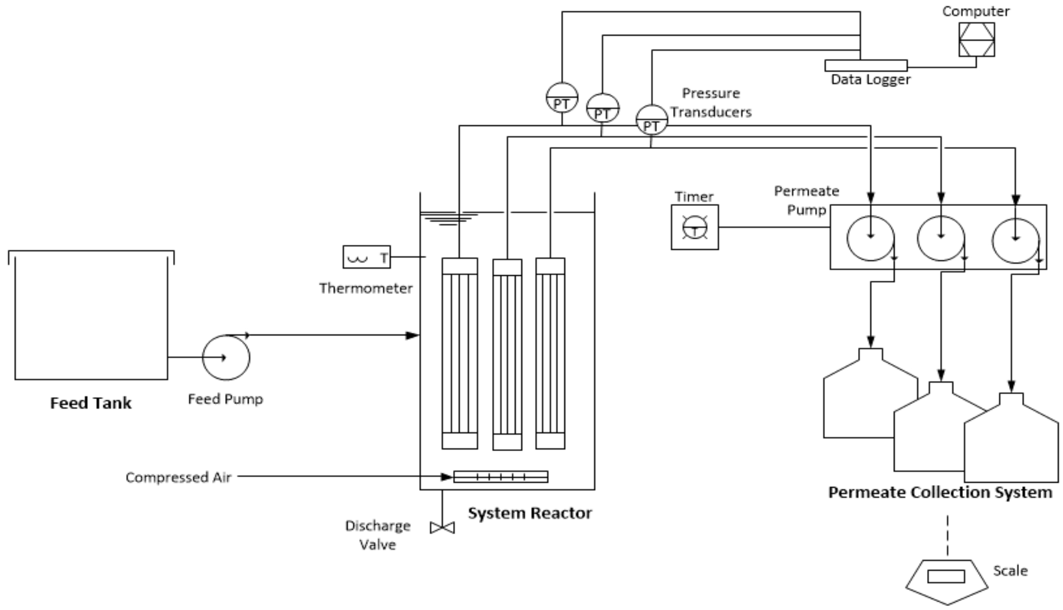


Figure 15 Schematic of the Pilot-scale Submerged Membrane System Assessing the Benefits Backwash under Constant Low-Flux Operation

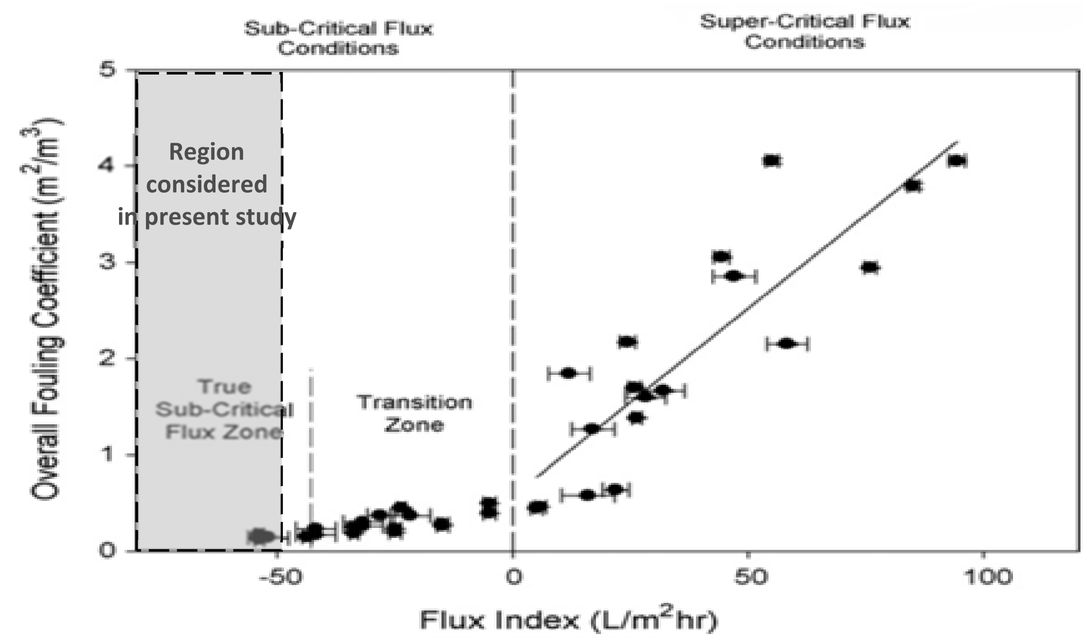


Figure 16 Range of Flux Index Investigated in the Present Study

4.4.2 Stage 2: Contributions of Constant-Pressure Permeation in Long-Term SHFUF Operations under Sub-Critical Flux Conditions

Stage 2 was conducted with the understanding that backwash did not provide any significant improvement to SHFUF performance under constant low flux of 10 LMH in Stage 1 and thus, can be eliminated. The pilot-scale system used in Stage 2 was an identical setup to that in Stage 1, without the presence of periodic backwash, pressure transducers and permeate pump. A hydrostatic head was adopted to provide a continuous siphon flow of permeate by means of pressure difference. In order to maintain a constant hydrostatic head, an overflow line was added to the system reactor to recycle any excess feed to the reservoir tank. Three independent membrane modules were installed in the reactor to operate independently at constant heads (H) equivalent to 10, 13 and 16 LMH. Note that because the intrinsic membrane resistance varied from membrane module to membrane module, the relationship between flux and applied hydrostatic head was not linear. The hydrostatic head needed to generate fluxes of 10, 13, and 16 LMH were determined to be 37, 73 and 73 mBar (or 38, 74 and 74 cm), respectively. A continuous aeration at 3.8 L/min was adopted throughout the experiment. A solid retention time (SRT) of 10 days was adopted by wasting 10% of the system reactor's operating volume each day. Figure 17 depicts the process diagram of Stage 2. Items identified in grey are those removed from the setup used during Stage 1.

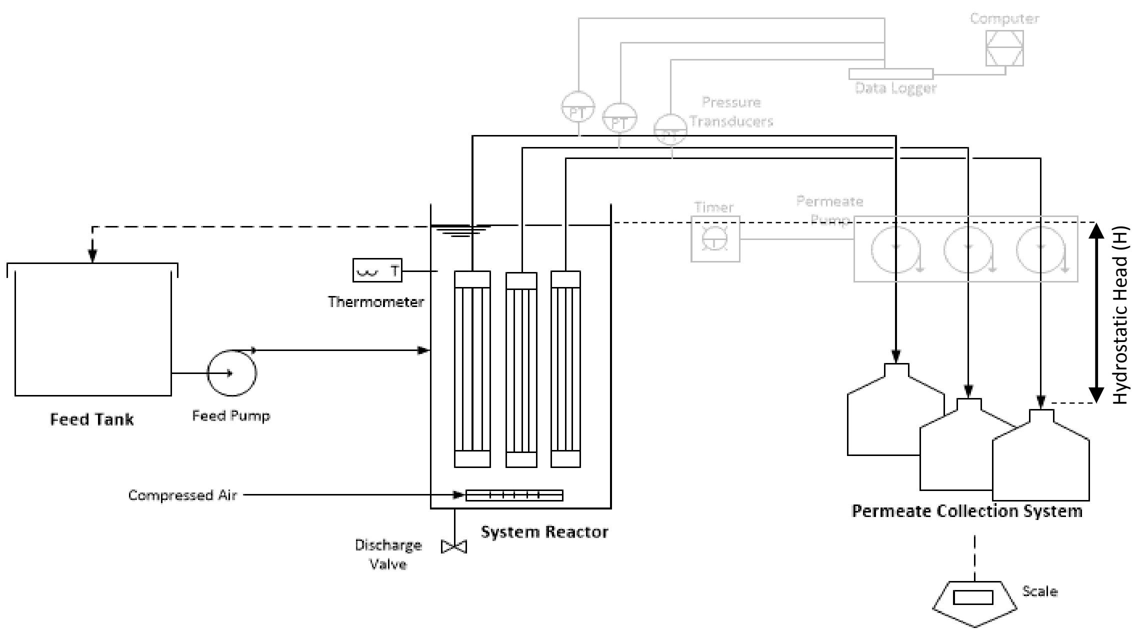


Figure 17 Schematic of the Pilot-scale Submerged Membrane System Operating as Passive Membrane System at 10, 13 and 16 LMH

Prior to applying the experimental conditions, the membrane modules were acclimatized with continuous aeration for 20 days, which consisted of 10 days of priming at a constant flux of 10 LMH and 10 days of gravity permeation at a constant head of 76 cm or approximately 25 LMH. The priming period was meant to establish a consistent pressure difference for siphon (ie. gravity) flow, and the high-flux permeation period was meant to ensure the presence of biofilm at the membrane surface. Biofilm is believed to help the establishment of steady-state conditions in the system reactor.

4.4.3 Stage 3: Contributions of Air Sparging in Long-Term SHFUF Operations under Sub-Critical Flux Conditions

Stage 3 was conducted with the understanding that in Stage 2, 1). a continuous and stable passive permeation was achievable through siphon mechanism and 2). 10 LMH operating flux was maintainable through an extended operation of passive permeation. The pilot-scale system used in Stage 3 were made identical to Stage 2, except for the addition of a timer and a solenoid valve to control the different aeration conditions in the system reactor. Four aeration conditions were investigated: *no aeration,* intermittent aeration cycles of *25 minutes off – 5 minutes on*, *4 hours off – 30 minutes on* and *4 hours off – 5 minutes*. Experiments for each condition investigated were performed with three identical membrane modules (ie. triplicates) operating at a constant head (H) equivalent to 10 LMH. A 10%-volume daily wasting was conducted during aeration, except for conditions with no aeration. Prior to each experimental condition, membrane modules were acclimatized as in Stage 2 with continuous aeration. Figure 18 depicts the process diagram of Stage 3. Items identified in grey are those removed from the setup used during Stage 2.

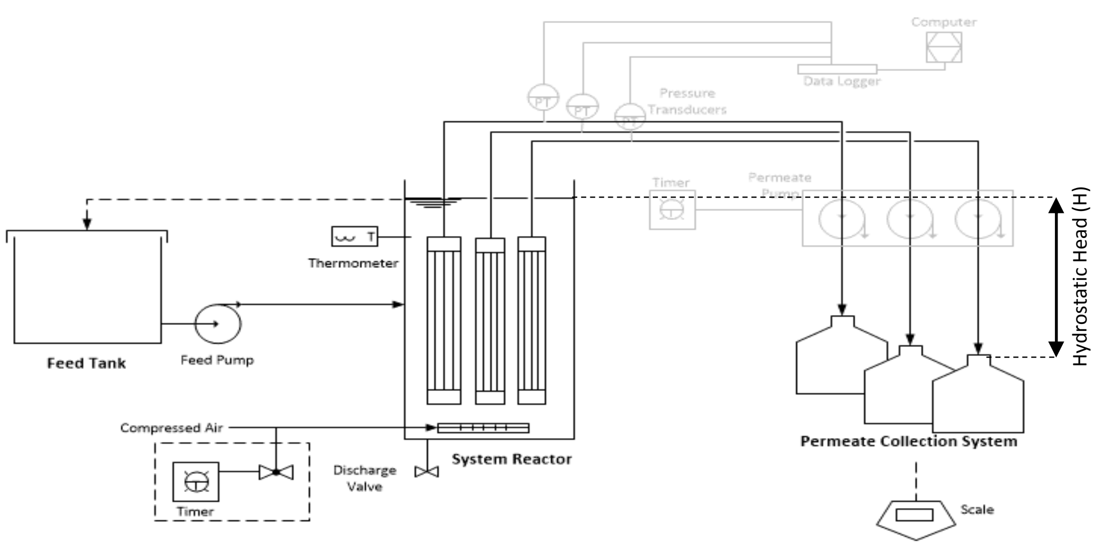


Figure 18 Schematic of the Pilot-scale Submerged Membrane System Operating as Passive Membrane System with Intermittent Aeration

4.4.4 Stage 4: Contributions of Membrane Recovery Cleaning in Long-Term SHFUF Operations under Sub-Critical Flux Conditions

The pilot-scale system used in Stage 4 was identical to that used in Stage 3 (refer to Figure 18). Stage 4 was conducted to investigate the effectiveness of recovery cleaning on modules after an extended operation. Recovery cleaning was performed on three membrane modules from Stage 3's *25 minutes on – 5 minutes off* at the end of its 2-month operation. Membrane recovery cleaning was conducted through a complete drainage of the system reactor, which was then refilled with a solution containing 500-ppm NaClO. NaClO permeation was conducted for 4 hours by gravity, after which the tank was drained and refilled with new raw water feed. The membranes were directly put back into operation without acclimatization.

4.5 Quality Control

4.5.1 Membrane Integrity Testing

Membrane integrity tests were conducted prior to starting each experiment. Membrane integrity tests were done by submerging and pressurizing each module to 10 psi with air while submerged in de-ionized (DI) water. Pressure was monitored in the air line using a pressure transducer connected to a data logger and a standby computer. Any observable bubbles released from the module would indicate that the module was breached, in which case the module would have to be repaired or completely replaced with a new one. Figure 19 illustrates the laboratory set-up for membrane integrity test.

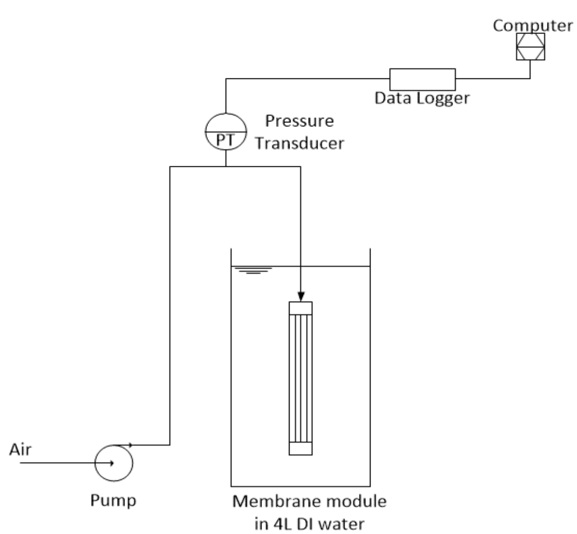


Figure 19 Membrane Integrity Testing

4.5.2 Membrane Cleaning

A new membrane module was used for each experiment, except for the experiments performed in Stage 4. Each new membrane module was chemically cleaned before the start of each experiment to ensure complete removal of any preservatives. Sodium hypochlorite solution (NaClO) was used as follows.

1. A new membrane module is placed in an enclosed container filled with a 750-ppm NaClO solution (25 ml NaClO at 6% and 1,975 ml distilled water) for 16 hours.
2. This solution is then filtered through the module at -4.1 psi for 20 minutes.
3. The container is then drained and a fresh 50-ppm NaClO solution (1.7ml NaClO at 6% and 1,998.3 ml distilled water) is added and then filtered through the module for 20 minutes at -4.1 psi.
4. The cleaned membrane module is stored in a 50-ppm NaClO solution until used.

Prior to using, each module was rinsed three times and filtered at -4.1 psi for 20 minutes with DI water.

4.5.3 Clean Water Tests

An overnight clean water test (approximately 20 hours) was conducted before the start of each experiment using DI water at the operating flux of interest. Throughout the test, transmembrane pressure was measured and recorded by a data logger. The long duration of clean water flux was adopted to ensure the achievement of a steady-state TMP by the modules. The filtered water was circulated back into the feed container to maintain a constant water level throughout the experiment.

The initial membrane resistance was back-calculated with Equation 1 using the known permeate flux and the obtained steady-state clean water TMP as inputs. Since fouling does not occur when filtering DI water, membrane resistance (R_m) is equivalent to the total filtration resistance (R). The complete data obtained from the clean water tests is available in Appendix A.

4.5.4 Transmembrane Pressure

Measured transmembrane pressures were collected and updated daily from the data logger using a visual basic for applications (VBA) algorithm (Appendix B). Upon using the data, TMP values were normalized to a temperature of 20^{o}C using Equation 15 to account for slight daily temperature fluctuation in the room.

Equation 15

$$P_{20^oC} = \frac{P_T \mu_{20^oC}}{\mu_T}$$

where, P_{20^oC} is the normalized TMP at 20°C, N/m^2

P_T is the obtained TMP at temperature T°C, N/m^2

μ_{20^oC} is water viscosity at 20°C, Ns/m^2

μ_T is water viscosity at T°C, Ns/m^2.

Water viscosity value at T°C was estimated using the three regression models listed below over the range of temperatures observed during the present study (17 to 28°C).

Equation 16

$$\mu_{T_{15-20^oC}} = -2.76\text{x}10^{-5}\text{T} + 1.55\text{x}10^{-3}$$

Equation 17

$$\mu_{T_{20-25^oC}} = -2.17\text{x}10^{-5}\text{T} + 1.44\text{x}10^{-3}$$

Equation 18

$$\mu_{T_{25-30^oC}} = -2.00\text{x}10^{-5}\text{T} + 1.40\text{x}10^{-3}$$

4.5.5 Sampling

Operating samples were collected from feed tank, system reactor and permeate flasks every 3 to 5 days throughout the duration of each experiment. The feed tank was sampled at mid-depth after fully-stirring the contents of the tank. System reactors without daily wasting (Stages 1 and 2) were sampled at approximately 25 cm below the height of the liquid level. System reactors with daily wasting (Stages 2 through 4) were sampled at the discharge point during daily wasting. Permeate samples were taken directly from the permeate flask. All samples were collected in a beaker that that had previously been rinsed with the sample.

4.6 Analytical Methods

4.6.1 Total and Dissolved Organic Carbon (TOC and DOC)

TOC and DOC samples were analyzed in a batch every 7 to 10 days. For dissolved organics quantification, each sample was filtered with a 0.45 μm nylon filter prior to the analysis and preserved with one drop of 10% hydrochloric acid (HCl) solution. Quantification of organic carbon was conducted with instrument IL 550 TOC-TN by Hach and run by software OmniTOC4.5, according to their user manuals.

Three blanks and six different concentration standard solutions at 1, 2, 10, 20, 40 and 50 ppm were included in each batch of the DOC/TOC analyses. The standards were made from diluting a 1,000-ppm stock solution of 0.5312 grams of potassium hydrogen phthalate in 250 ml of H_3PO_4 to the concentrations of interest with DI water. During the analysis, a total volume of 0.25 ml was extracted from each sample vial for carbon detection.

The presence of carbon in each sample was reported in total integrated area (arbitrary unit) by the instrument. The linear relationship that occurs between the integrated area and organic carbon concentration in the standards was used to normalize the measurement variability among the samples within each run. A typical linear relationship between the areas and organic concentrations are projected in Appendix C.

4.6.2 High Performance Liquid Chromatography (HPLC)

Size exclusion chromatography was performed on a batch of samples every 3 weeks. Prior to the analyses, each sample was filtered with a 0.45 um nylon filter. Size exclusion was conducted with a 20 mm ID x 250 mm stainless steel TSKgel column of 30-µm silica-based resin and a series of instruments, including: Waters 717plus autosampler, Waters 600 controller, Waters 2410 refractive index detector, Waters 486 tunable absorbance detector (programed to operate at 254 nm), Sievers 900 portable TOC analyzer and Sievers inorganic carbon remover.

Two blanks and six at 10-ppm calibration standards (four polyethylene glycol (PEG) solutions of 600, 1500, 3300, 6000 Da in molecular weight and two polystyrene sulfonate (PSS) solutions of 15000 and 41000 Da) were included in each batch of samples analyzed. An aqueous buffer (5.0 KH_2PO_4 and 4.5 $Na_2HPO_4.7H_2O$ in 2 litres of DI water) was used in isocratic mode at 1 ml/minute. Run time was 100 minutes to accommodate TOC analyzer cycles, during which time a total volume of 1 ml was extracted from each sample vial for analysis.

Presence of total organic materials and organic materials absorbing UV_{254} were identified by the peaks produced in the analysis. The retention times at which the peaks occur are linearly correlated with the Log_{10} of their molecular weights. A typical calibration curve obtained from the analyzed standards in each batch was available in Appendix C.

4.7 Data Analysis Methods

4.7.1 Quantification of Fouling Effects on Membrane Performance

The occurrence and progress of fouling was confirmed by the reduction in membrane permeability over time. System performance for each of the investigated conditions was presented through the plotting of relative membrane permeability (B/B_i) over volume filtered and time. Equation 2 was used to calculate the membrane permeability given flux and constant hydrostatic head.

Comparison of system performances between conditions was conducted through a pairwise comparison. The difference between the two compared targets was calculated for each obtained data point (governed by time or volume filtered), from which an overall mean difference was then calculated. The variant of the mean was presented with 95% confidence interval using the standard equation below.

Equation 19

$$\pm 95\% = t_{\propto/2} \times \frac{s}{\sqrt{n}}$$

where, *t* is the t distribution

α is the degree of freedom

s is standard error

n is number of data points.

4.7.2 Determination of the Pre-dominant Fouling Mechanisms

The pre-dominant fouling mechanism(s) was determined through data modelling using the individual and combined fouling models developed by Bolton, Lacasse, & Kuriyel (2006) for a constant-pressure system, as presented in Table 1 and Table 2. Throughout the analysis, volume was represented in litres, flux was in LMH and time was in hours. The fit the models in each data set was analyzed using a statistical software package of SigmaPlot 12 by Systat Software Inc.

Essential parameters, such as residual sum of squares (SSR), coefficient of determination (R^2) of the model, as well as the fitted parameters' standard errors (s), t-statistics and p-values, were evaluated to determine the validity of the analysis. For comparison, all models considered were ranked based on how well they could be fitted to the measured data (ie. lowest to highest SSR values). The complete statistical reports of the top 5 models are available in Appendices F through J.

4.7.3 NOM Characterization and Quantification

Responses from both the UV_{254}-detection (UVD) and organic carbon detection (OCD) were compiled and synchronized using a VBA algorithms for Excel, which is available in Appendix B. Profiles obtained from HPLC were characterized according to a study by Huber et al. in 2011, as illustrated in Figure 20. The detectable peaks of A to E mark the typical surface water characteristics, which include the presence of biopolymers, humic substances (HS), building blocks, low molecular-weight acid (LMA), and low molecular-weight neutrals (LMN), respectively. The signal response in the y-axis signifies the strength of the corresponding NOM constituent, which was identifiable by the i^{th} minute of travel time (retention time) defined in x-axis.

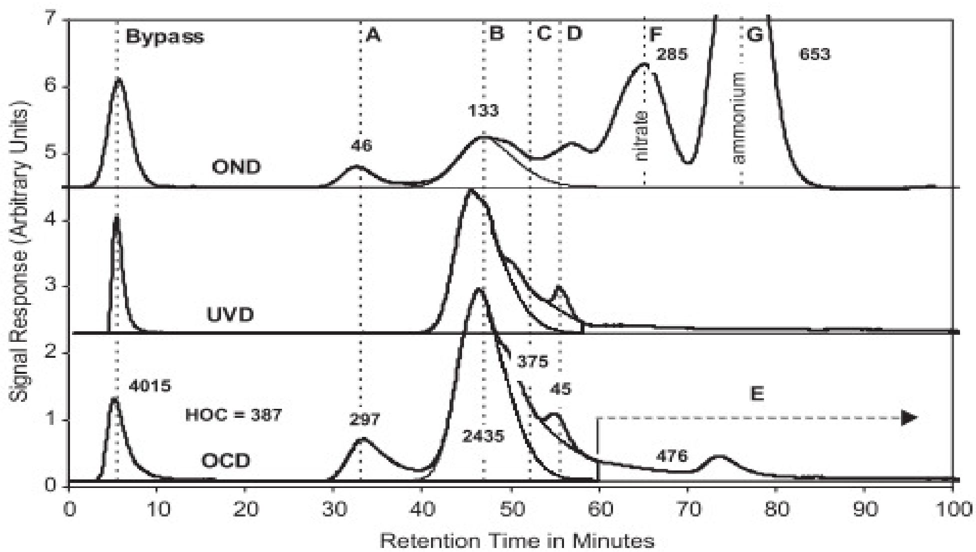


Figure 20 Chromatogram of a typical surface water with responses for organic carbon detection (OCD), UV-detection at 254 nm (UVD) and organic nitrogen detection (OND). Source: Huber et al., 2011

NOM quantification was, conducted via integration of the area under the curve. Equation 20 was used to integrate the total area under the curve over the 100-minute total retention time.

Equation 20

$$Total\ Area\ Under\ The\ Curve\ (T.AUC) = \sum_{i=0}^{t} \frac{S_{t_i} - S_{t_{i+1}}}{Ln\ (S_{t_i} - S_{t_{i+1}})}\ x\ (\ t_{i+1} - t_i\ )$$

where, *T.AUC* quantifies the total signal received for NOM in a water sample, unitless

t_i is the i^{th} measurement of time in minutes during the 100-minute retention time,

S_t is the signal response at the corresponding time, unitless.

Estimations on the contribution of each NOM type in T.AUC can be done by truncating the integrated water profile according to the time range during which each peak was received. Table 6 summarizes the time windows for each NOM in the investigated waters. The intermediate peaks of humic substances, building blocks and LMA were combined into a single HS peak.

Table 6 Ranges of Retention Time for the Different NOM Types in the Water Samples

Natural Organic Matters	**Retention Time (mins)**
High Molecular Weight (HMW)	$19 \le x \le 36$
Humic Substances (HS)	$36 < x \le 59$
Low Molecular Neutrals (LMN)	$x > 59$

Using the defined time boundary, the total response received for each NOM type was calculated using Equation 21 to Equation 23.

Equation 21

$$AUC\ HMW = \sum_{i=19}^{36} \frac{S_{t_i} - S_{t_{i+1}}}{Ln\ (S_{t_i} - S_{t_{i+1}})}\ x\ (\ t_{i+1} - t_i\ )$$

Equation 22

$$AUC\ \ HS = \sum_{i=37}^{59} \frac{S_{t_i} - S_{t_{i+1}}}{Ln\ (S_{t_i} - S_{t_{i+1}})}\ x\ (\ t_{i+1} - t_i\ )$$

Equation 23

$$AUC\ LMN = \sum_{i=60}^{100} \frac{S_{t_i} - S_{t_{i+1}}}{Ln\ (S_{t_i} - S_{t_{i+1}})}\ x\ (\ t_{i+1} - t_i\ )$$

where, the summation of these AUC's is also equal to T.AUC.

NOM quantification was calculated using the linear relationship that exists between the total area under the curve (T.AUC) and the measured DOC in ppm from Section 4.6.1, as also displayed by Figure 21. The concentration of any NOM type can be calculated using Equation 24 given the availability of DOC measurements, such as in the case of feed tank and system reactor samples.

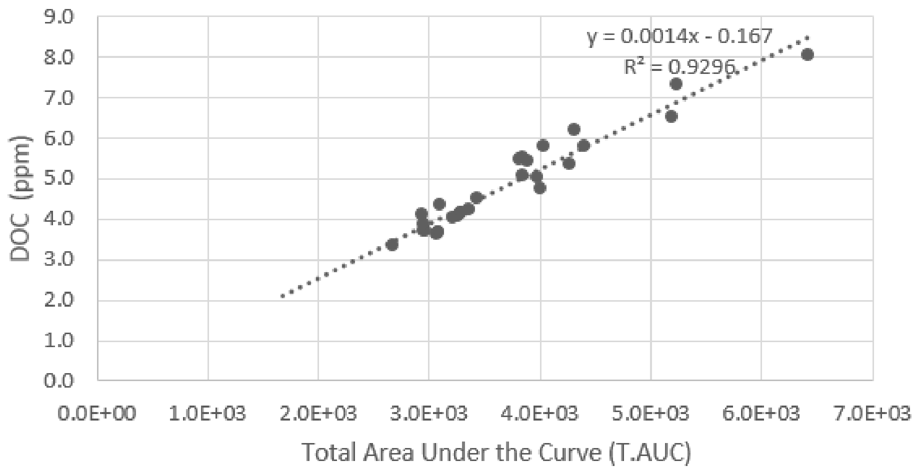


Figure 21 Typical Linear Correlation found between the measured DOC in ppm and calculated AUC from HPLC analyses on the feed and system reactor samples

Equation 24

$$\text{[NOM Type] in feed or reactor} = \frac{AUC\ NOM\ Type}{T.AUC}\ x\ DOC_{Sample}$$

where, *[NOM Type]* is the concentration of a specific NOM type of interest, ppm and

DOC_{sample} is the measured DOC concentration of the sample in question, ppm.

In the case of permeates, where DOC measurements were not conducted, NOM concentrations were estimated from the calculated NOM concentrations of the corresponding system reactor on the day of interest. Equation 25 was used to estimate the NOM concentration in permeates.

Equation 25

$$\text{[NOM Type] in Permeate} = \frac{AUC\ NOM\ Type\ in\ Permeate}{AUC\ NOM\ Type\ in\ Reactor} \text{ x [NOM Type] in Reactor}$$

4.7.4 Mass Balance of NOM throughout the Passive Membrane System

A mass balance calculation was conducted to estimate the theoretical concentrations of NOM in the system reactor in the absence of biological activity. The difference between the theoretical and the measured values indicate the contributions of biological activities during the extended operation passive membrane system. Throughout the analysis, the system reactor was assumed to be fully mixed. Figure 22 illustrates the input-output flows of the system reactor.

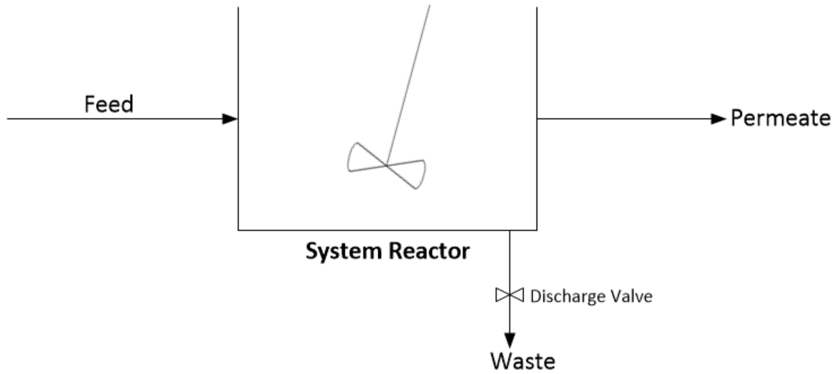


Figure 22 Schematic Diagram

The total mass of NOM fed to the system reactor was estimated by summing the products of each measured NOM concentration in feed and the corresponding total volume discharged over the span of the experiment (ie. 60 days), as expressed in Equation 26 and Equation 27.

Equation 26

$$F = \sum_{t=1}^{60\,days} \left([F_t] \ x \ V_{F_t} \right)$$

Where, *F* is the estimated cumulative mass of NOM in feed over the span of the experiment, milligrams

t is n^th sampling day

$[F_t]$ is NOM concentration in feed at time t, ppm

V_{F_t} is the total volume fed to the system reactor between two sampling dates, litres.

Equation 27

$$V_{F_t} = \left(\sum_{t-1}^{t} V_P + V_W \right)$$

Where, V_P is the total volume filtered, litres and

V_w is the total volume wasted, litres.

The mass of NOM permeated through the membrane between sampling intervals was estimated by accounting the permeate production from all modules used in the experiment using Equation 28.

Equation 28

$$P = \sum_{t=1}^{60\,days} \left(\sum_{i=1}^{n} \left([P_t] \ x \ \Delta \sum_{t-1}^{60} V_P \right) \right)$$

Where, *P* is the estimated cumulative mass of NOM permeated through the membrane over the span of the experiment, mg

n is the total number of membrane modules in an experiment and

$[P_t]$ is the NOM concentration in permeates at time t, ppm.

The mass of NOM wasted was estimated similarly as both the feed and permeates. Equation 29 was used to estimate the total mass of NOM wasted throughout an operation, where $[R_t]$ is the reactor concentration at time t.

Equation 29

$$W = \sum_{t=1}^{60\,days}(\,[R_t]\,x\,\Delta\sum_{t-1}^{60}V_W)$$

Where, *W* is the estimated cumulative mass of NOM wasted over the span of the experiment, mg

$[R_t]$ is the NOM concentration in waste at time t, ppm.

Therefore, the theoretical cumulative NOM mass (R_{TH}) in system reactor at any time during the operation can be calculated using Equation 30. R_{TH} should only be used as a trend indicator of biological activity in the system reactor rather than an exact quantification.

Equation 30

$$R_{TH} = \sum_{t=1}^{60\,days}(F_t - P_t + W_t) + R_{t-1} \qquad , \quad R_{TH} \geq 0$$

Where, R_{TH} is constrained to be equal or greater than zero, mg

F_t is total mass of NOM in feed at time t, mg

P_t is total mass of NOM in permeates at time t, mg

W_t is total mass of NOM in waste at time t, mg

R_{t-1} at t = 1 is the mass of NOM in system reactor at initial time.

5 Results, Data Analysis and Discussion

Chapter 5 presents and discusses the experimental results obtained from the SHFUF pilot-scale trials. The chapter is divided into two sections, 1). long-term fouling mitigations in in SHFUF systems and 2). presence of organic material in passive membrane operations. Together, the two sections will attempt to comprehensively answer the research questions proposed in Chapter 3.

5.1 Long Term Fouling Mitigation in SHFUF systems

5.1.1 Contributions of Backwash to Fouling Control in Long-term SHFUF operation under Sub-Critical Flux Conditions

The benefits of backwash in long-term, constant low-flux operations were assessed through a comparative study of two parallel pilot-scale SHFUF systems operating with (Reactor A) and without (Reactor B) periodic backwash. Both systems were operated until either the membrane's maximum operable transmembrane pressure (8 psi) was reached or a maximum of 2 operating months was reached. The objective of Stage 1 of the present study was to determine whether the elimination of periodic backwash is possible in a low-flux SHFUF operation. The elimination of periodic backwash is expected to simplify the system and significantly reduce the system's energy requirements and operating costs. The performances of the two pilot systems at different operating fluxes (10, 20 and 30 LMH) were evaluated by comparing the rate at which membrane permeability was lost with respect to volume filtered. Figure 23 present the declining normalized permeability over volume filtered for the two pilot systems operating at sub-critical fluxes.

At 30 LMH, a gradual decline in the normalized permeability with respect to volume filtered was observed in both of the reactors, with and without backwash. The continuous decline over time observed in both Figure 23a and Figure 23b suggest a growing fouling rate even with the presence of periodic backwash. However, the total filtration volume that could be achieved by the reactor with backwash was five times that of the reactor without backwash. The higher permeability observed in the reactor with backwash resulted from the partial removal of foulants by the periodic backwash. As expected, the periodic backwash was able to improve hydrodynamic conditions within the reactor by dislodging foulants from the membrane surface and pores.

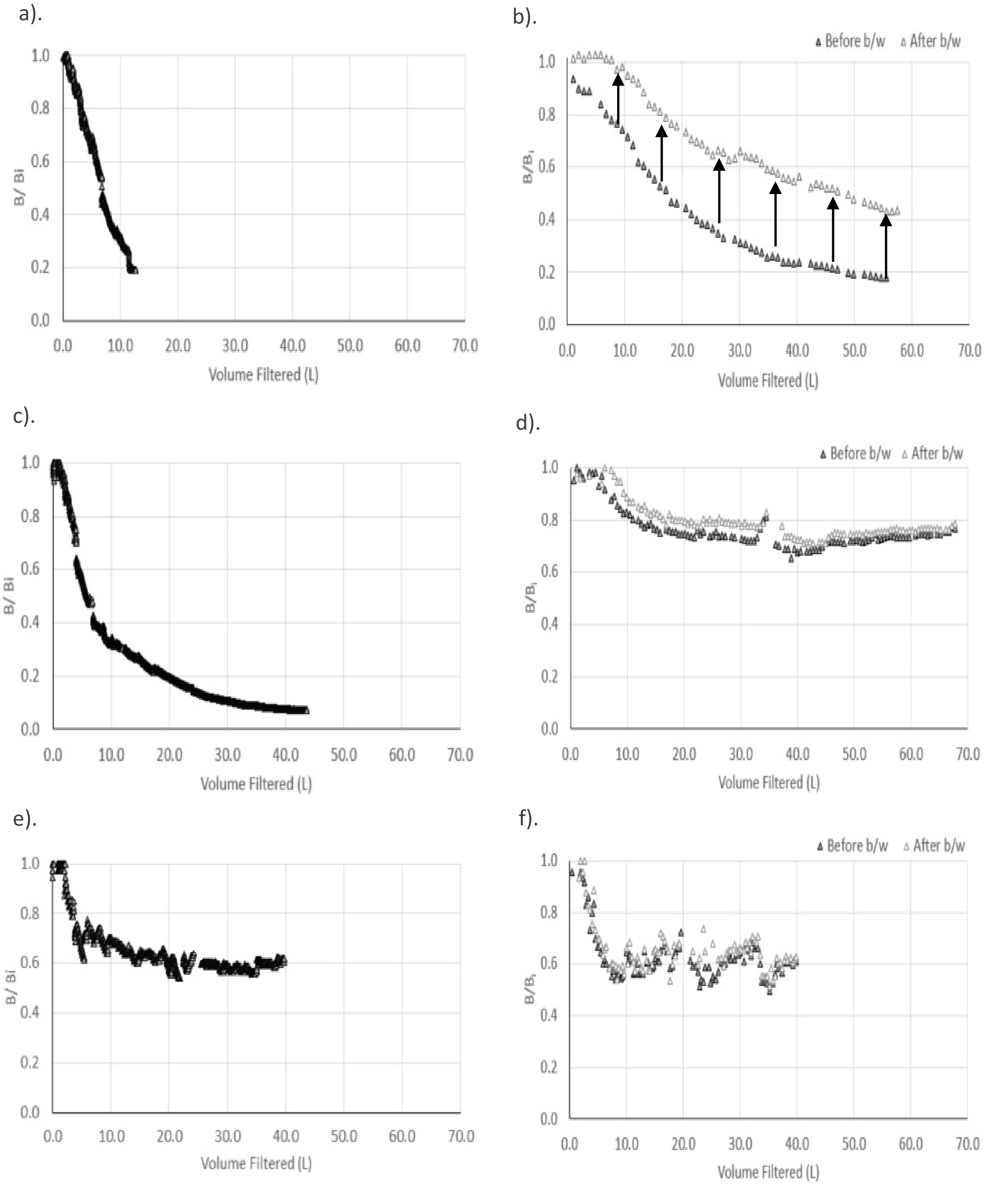


Figure 23 Reduced Membrane Permeability over Volume Filtered for both With and Without Backwash Operations
(a). 30 LMH without Backwash, b). 30 LMH with backwash, c). 20 LMH without Backwash, d). 20 LMH with Backwash, e). 30 LMH without Backwash, and f). 30 LMH with Backwash)

At 20 LMH, a gradual decline in the normalized permeability with respect to volume filtered was again observed for reactors with and without backwash. The rate at which permeability declined, as illustrated by Figure 23c and Figure 23d, was lower than that observed at 30 LMH. Moreover, a steady state was reached in the reactor with backwash at a normalized permeability (B/B_i) of 0.75. Consequently, the 8 psi termination point was never reached in the reactor with backwash. Over the 2-month period the reactor with backwash produced approximately 70 L of filtered water, while the reactor without backwash produced 45 L of filtered water. The steady-state condition that was reached indicated that at this operating flux, backwash was still instrumental in enhancing the system's hydrodynamic conditions through the establishment of a *critical-flux* condition, where fouling ceased to occur. Subsequently, the impacts of backwash on membrane permeability was not as prominent as was observed at 30 LMH.

At 10 LMH, an initial decline in the normalized permeability with respect to volume filtered was observed in reactors with and without backwash prior to reaching a similar steady state at a normalized permeability (B/B_i) of 0.6. Consequently, the 8 PSI termination point was also never reached by either reactor (refer to Figure 23e and Figure 23f). Over the 2-month period, both reactors produced 40 L of filtered water. The short *stabilization period* during the first 8 L of production indicated that fouling still occurred even during an extremely low-flux filtration. A number of studies have suggested that some initial fouling does occur under low-flux filtration and is largely the cause of concentration polarization development (Marshall et al., 1996; Miller et al., 2013). Nonetheless, the low operating flux significantly limited the rate and amount of particle mass travelling toward the membrane (Pearce, 2011), which enabled the system to reach steady-state conditions without backwash. The normalized permeability after backwash was observed to be exactly the same as that of prior backwash. The results from Stage 1 indicate that at 10 LMH periodic backwash can be safely eliminated without any significant impact on membrane's fouling rate.

5.1.2 Contributions of Constant-Pressure Permeation in Long-Term SHFUF Operations under Sub-Critical Flux Conditions

Fouling during constant-pressure SHFUF operation without backwash was assessed by operation using gravity-driven permeation (ie. siphoning) at a constant hydrostatic head. The alteration of the system to a gravity flow without backwash reduces system's complexity and costs, making it more suitable for remote applications. The objectives of this stage were 1). to assess if fouling was similar under constant-pressure and constant-flux operation, and therefore allowing gravity to be used to provide the driving force for permeation through the membrane and 2). to closely investigate the magnitude of permeate flux that can be sustained in passive membrane filtration, which was previously identified between 10 and 20 LMH in Stage 1. Three hydrostatic heads that generate fluxes of 10, 13 and 16 LMH were considered in Stage 2. Prior to operation at the fluxes of interest, all three modules were acclimatized through 10 days of priming and 10 days of 75mBar gravity-permeation.

Figure 24 illustrates the progression of normalized membrane permeability over volume treated for 10, 13 and 16 LMH post acclimatization period. The complete permeability data obtained in Stage 2 can be found in Appendix D.

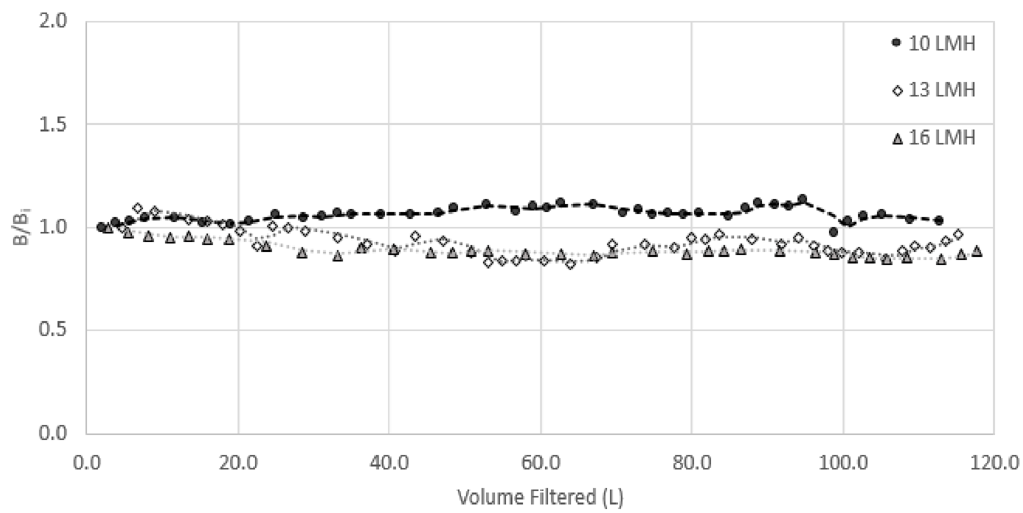


Figure 24 Normalized Membrane Permeability of Gravity Permeation at 10, 13, and 16 LMH Post-Acclimatization Period

After the acclimatization period, the 10 LMH module had completely reached steady-state conditions, normalized membrane permeability was constant at B/B_i of approximately 1 for the 2-month operation. The steady-state permeability observed under gravity permeation (ie. constant-pressure) was similar to that achieved under constant-flux conditions observed in Stage 1. Miller et al. (2013) reported that below a threshold flux, fouling is similar for both constant-pressure and constant-flux operations. This confirms the similar fouling behaviour observed in both constant-flux (Stage 1) and constant-pressure (Stage 2) operations at 10 LMH, which was a sub-critical flux.

At the intermediate fluxes of 13 and 16 LMH, a steady-state conditions were not immediately observed after the acclimatization period as the normalized permeability (B/B_i) continued to decline to a steady-state value of 0.8. These results indicate that at 13 and 16 LMH, the steady-state permeability that can be sustained is lower than that which can be sustained at 10 LMH.

Overall, the results from Stage 2 indicate that 1). fouling behaviour in constant-pressure system is similar to that in constant-flux under sub-critical flux conditions, 2). gravity force is sufficient to sustain a continuous SHFUF operation, thus can be used for permeation, and 3). 10 LMH was observed to be the optimum flux that can immediately establish steady-state conditions at a high normalized permeability.

5.1.3 Contributions of Air Sparging in Long-Term SHFUF Operations under Sub-Critical Flux Conditions

The contributions of air sparging in passive membrane filtration was assessed through a comparative study of four parallel pilot-scale gravity driven systems operating at 10 LMH under intermittent air sparging cycles of *25 minutes off – 5 minutes on* in Reactor D, *4 hours off – 30 minutes on* in Reactor E, and *4 hours off – 5 minutes on* in Reactor F and under *no air sparging* in Reactor G. The elimination of air sparging in passive membrane system is expected to further reduce cost and complexity. The objective of Stage 3 of the present study was to assess 1). the contributions of air sparging in passive membrane filtration as a fouling control and 2). the feasibility of operating passive membrane filtration with complete absence of air sparging. All experiments were conducted in triplicate, except for one of the conditions investigated for which the experiment was conducted in duplicate. Each reactor was acclimatized as in Stage 2 prior to operating at a hydrostatic pressure equivalent to 10 LMH and under reduced aeration. Figure 25 illustrates the progression of normalized membrane permeability over volume post-acclimatization under different air sparging conditions. The complete permeability data obtained in Stage 3 can be found in Appendix E.

After the acclimatization period, the normalized membrane permeability was observed to decline with respect to the volume filtered for the four conditions investigated in this stage. The extent of the decline increased as air sparging was decreased. Following the initial rapid decline, the rate at which the normalized membrane permeability (B/B_i) decreased reduced. For all conditions investigated, the normalized membrane permeability either reached or trended towards a steady state of approximately 0.2. A reduction in the rate of decline to a steady state was also reported by Miller at al. (2014). For all conditions investigated, the decline in the normalized permeability with respect to the volume filtered could be modeled using the exponential relationship presented in *Equation 31*. The fit of the model to the obtained data is also presented in Figure 25.

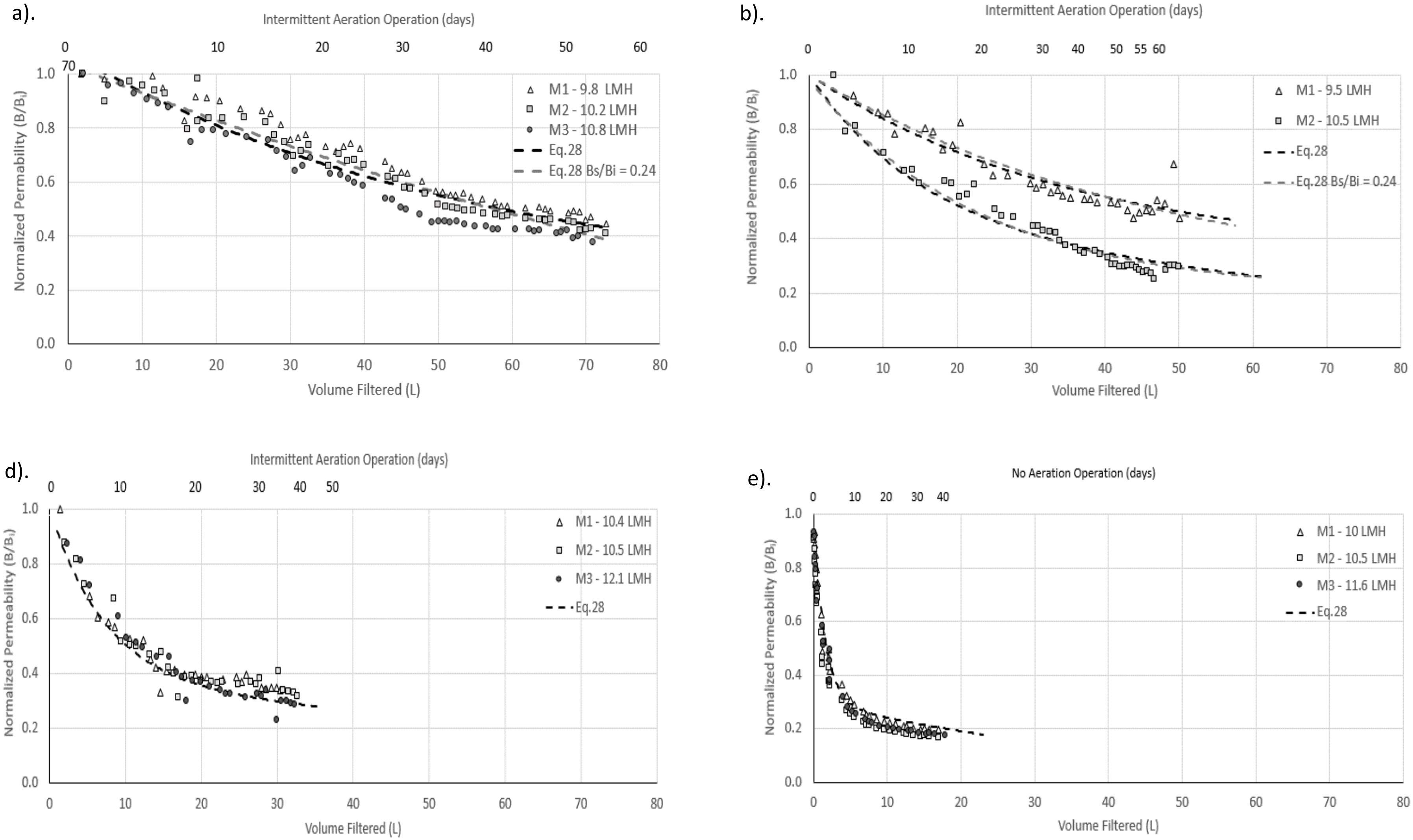


Figure 25 Reduced Normalized Membrane Permeability over Time
(a). 25 Minutes off – 5 Minutes on; b). 4 Hours off – 30 Minutes on; c). 4 Hours off – 5 Minutes on; and d). No Air Sparging)

Equation 31

$$\frac{B}{B_i} = B_s + \left(\Delta \frac{B}{B_i}\right) exp^{-KV}$$

where, $\frac{B}{B_i}$ is normalized permeability at a given volume, unitless

B_s is normalized membrane permeability at steady state, m

$\Delta \frac{B}{B_i}$ is change in normalized membrane permeability prior to reaching steady state, unitless

K is fouling coefficient, L^{-1}

V is volume filtered, L.

For the two conditions with the least air sparging (ie. no air sparging and intermittent cycle of *4 hours off – 5 minutes on*)*,* steady-state conditions appeared to have been reached after filtering approximately 20 and 30 L, respectively. For these conditions, the normalized membrane permeabilities at steady state were estimated to be 0.22±0.004 and 0.26±0.003, respectively, by fitting *Equation 31* to the measured data. These B_s values were equivalent to 2 and 2.7 LMH, respectively, and are lower than the steady-state flux of 4 LMH that was obtained by Boulestreau et al. (2012) and Peter-Varbanets, Margot, Traber, & Pronk (2011) in their similar gravity-operated flat-sheet membrane system with no aeration. The difference in result from the present study and those reported by others is likely due to differences in organic content of the waters investigated, which ranged between 2.0 to 2.7 ppm DOC in Peter-Varbanets et al.'s and Boulestreau et al.'s study and 6.0 to 7.0 ppm DOC in the present study.

For the other two conditions with higher air sparging (ie. *25 minutes off – 5 minutes* on and *4 hours off – 30 minutes on)*, steady state conditions were not reached during the two-month operation. As a result, *Equation 31* alone was not able to estimate the normalized membrane permeability at steady state without an assumed constraint. Since the normalized permeability of the two conditions appeared to trend towards a steady state value similar to that observed for the previous conditions with the least air sparging, a constraint of B_s equalled to the averaged normalized permeabilities of the two conditions with the least air sparging (0.24±0.007) was applied to produce a representative model for the two higher air sparging conditions. The fit of the assumed model to the measured data was close to that of the model without the constraint, supporting the validity of the assumption (refer to Figure 25a and Figure 25b). The four fitted models representing the different extent of reduced air sparging are presented in Figure 26 with respect to the system with continuous air sparging for a direct performance comparison. Their fitted parameters and errors are summarized in Table 7.

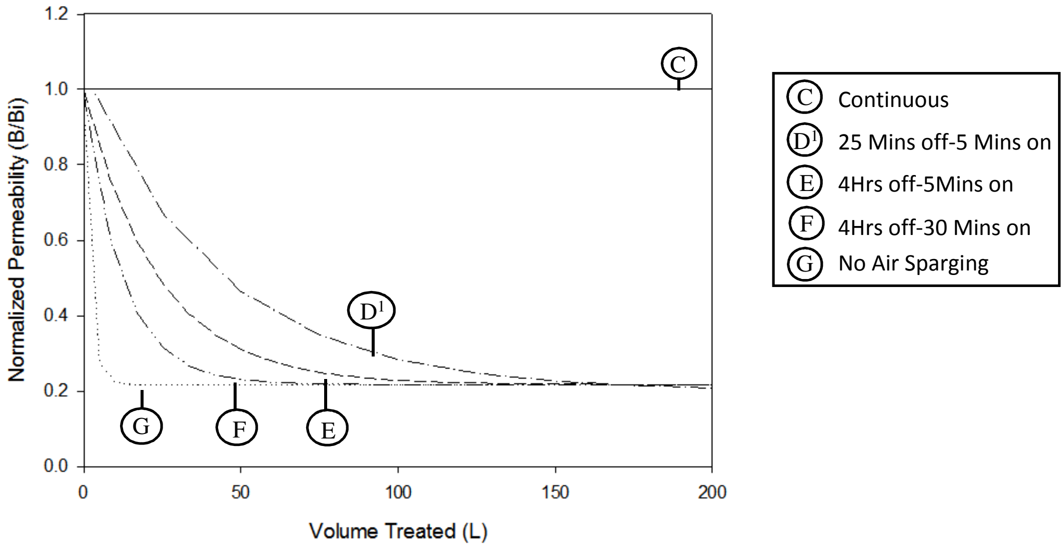


Figure 26 Effect of Reduced Air Sparging Conditions on Membrane Permeability

Table 7 Fitted Values of the Exponential Regression Model for Each of the Reduced Air Sparging Conditions

			B_s		$\Delta\frac{B}{B_i}$		-K	
Reactor	**Conditions**	**ON/OFF Ratio**	**Mean**	**±95%**	**Mean**	**±95%**	**Mean**	**±95%**
C	**Continuous**	∞	1.04	0.01	0.02	0.01	2.96×10^{-18}	0.003
D^1	**25min off/ 5 mins on**	0.20	0.24*	N/A	0.84	0.004	0.023	0.0013
E	**4hrs off/ 30 mins on**	0.13	0.24*	N/A	0.78	0.005	0.043	0.0003
F	**4hrs off/ 5 mins on**	0.02	0.26	0.003	0.74	0.003	0.109	0.002
G	**No Air Sparging**	0.00	0.22	0.004	0.78	0.004	0.544	0.0178

*assumed normalized permeability at steady-state

The above results suggest that the extent of total permeability drop with aeration that is less than continuous is the same regardless the on/off ratio, as all of the reduced aeration conditions eventually reached the same steady-state permeability that was approximately 24% of the initial permeability. This residual permeability, nonetheless, allows long-term operation of a passive membrane filtration at a lower, but steady flux. The contributions of aeration were clearly observed in the rate at which steady state conditions were reached (ie. fouling coefficient) by the different aeration conditions. Figure 27 illustrates the correlation between fouling coefficient and ON/OFF ratio of the aeration. Providing a small amount of aeration, such as 5 minutes every 4 hours, was enough to decrease the fouling rate by over 80%. Any reduction in fouling positively impacts the capacity of the system in terms of volumetric throughput.

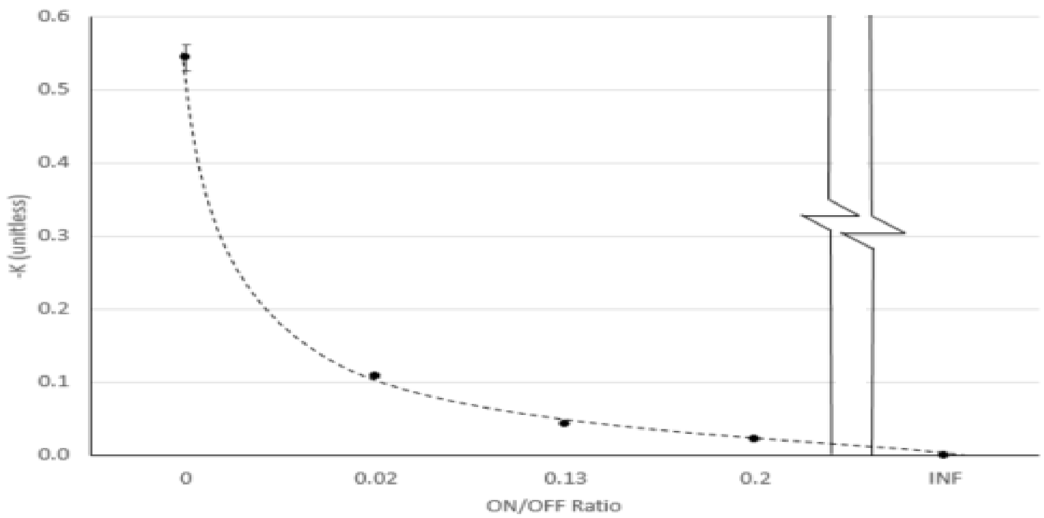


Figure 27 Reducing Fouling Rate with Increasing Air Sparging Frequencies

5.1.4 Contributions of Recovery Cleaning on Membrane Modules and Operation

The final stage of the present study was conducted to investigate the contributions of 1). recovery cleaning on the restoration of membrane permeability and 2). acclimatization on the long-term operation of passive membrane systems. Modules from the system with reduced aeration of *25 Minutes off – 5 Minutes on* were cleaned (see Section 4.4.4) and returned to operation without acclimatization. Figure 28 presents the change in the normalized membrane permeability before and after recovery cleaning.

The efficiency of cleaning was demonstrated by the complete recovery of membrane permeability after cleaning. Without the acclimatization, the initial permeability of the cleaned membrane modules was 45% greater than that observed following acclimatization. The difference in the membrane permeability was expected, likely due to the contribution of foulants pre-coating the membrane during the acclimatization period. At this higher permeability, the system was fouling at a proportionally higher rate. Equation 31 was fitted to the measured data to determine the steady-state permeability and the fouling rate before and after-recovery cleaning. Table 8 compares the fitted values of the three modules operated with recovery cleaning. The fouling rate (-K) was observed to be greater following recovery cleaning and without acclimatization. Also, the normalized membrane permeability at steady state was greater following recovery cleaning and without acclimatization. Despite the difference in fouling rates and system stability, both pre- and post-recovery operations produced the same throughput over the 2-month span.

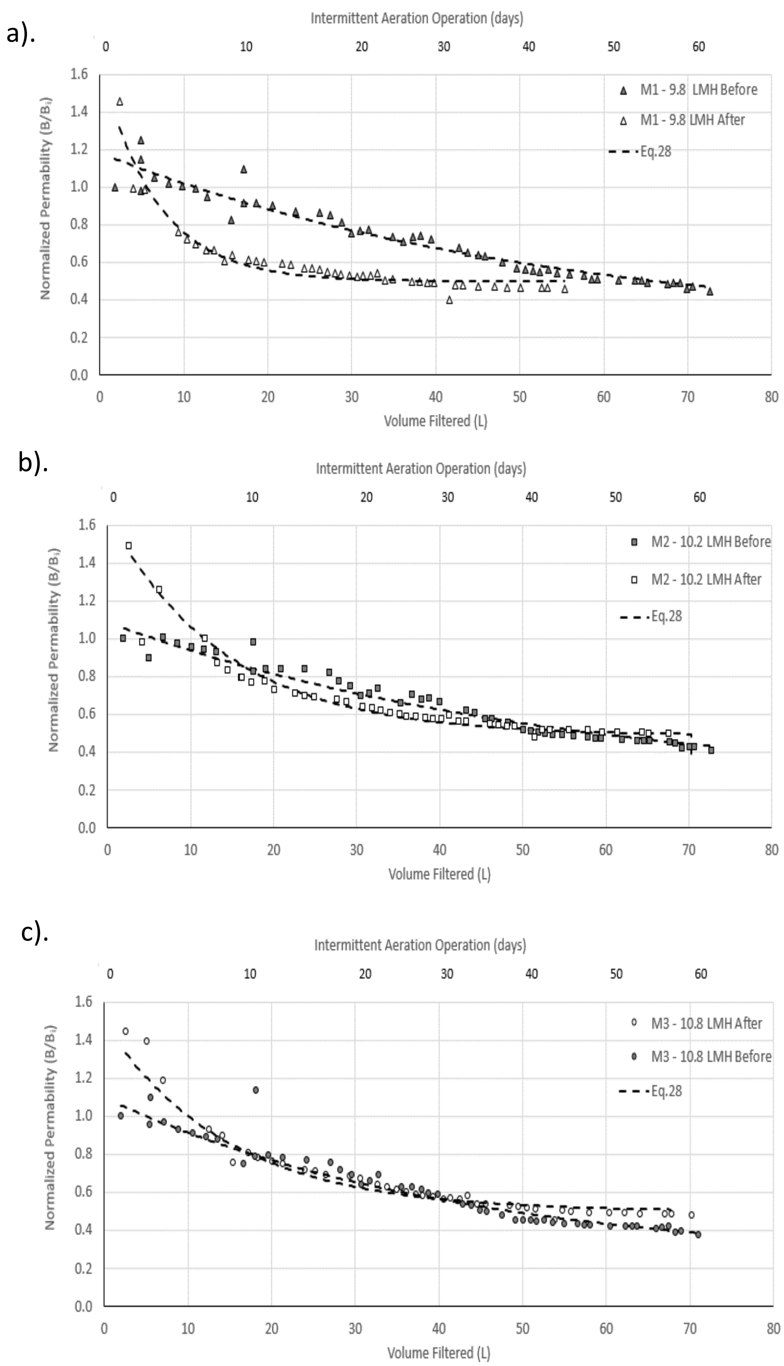


Figure 28 Reduced Permeability over Volume Filtered for the 25 Minutes off – 5 Minutes on Modules After Recovery Cleaning (a). Module 1, b) Module 2, c). Module 3)

Overall, results indicated that acclimatization did not improve membrane performance as was claimed by Ye et al. (2011). In fact, acclimatization appeared to hinder the occurrence of sustainable conditions, leading to a lower steady-state permeability. It should, however, be noted that different acclimatization approaches were not considered in the present study. It is possible that other acclimatization methods (e.g. lower fluxes/gravity pressure and shorter periods) may be beneficial to membrane performance.

Table 8 Fitted Values of the Exponential Regression Model for Before and After Recovery

Parameters	**9.8LMH**		**10.2 LMH**		**10.8 LMH**	
	Before	**After**	**Before**	**After**	**Before**	**After**
$\frac{B}{B_i}$	0.24±N/A*	0.50±0.003	0.24±N/A*	0.50±0.006	0.24±N/A*	0.34±0.002
$\Delta\frac{B}{B_i}$	0.96±0.006	1.16±0.022	0.84±0.004	0.99±0.015	0.88±0.004	0.81±0.007
-K	0.02±0.0002	0.15±0.004	0.02±0.001	0.07±0.002	0.02±0.0002	0.07±0.001

*assumed

5.1.5 Fouling Mechanisms in Passive Membrane Operations

An analysis to determine the predominant fouling mechanisms governing passive membrane filtration was conducted by fitting the individual (Table 1) and combined (Table 2) fouling models defined by Bolton et al. (2011) to the measured data. The predominant fouling mechanisms were assumed to be the ones for which the corresponding fouling model best-fit the measured data. The best fit was determined by the coefficient of determination (R^2) and residual sum of squares (SSR) of the fitted models, while also considering the resulting statistic indicators, such as standard errors (s), t-statistics and p-value. The complete statistical reports are provided in Appendices F through J.

According to the analysis, all the investigated conditions were predominately governed by the same models. Four possible models, *cake-complete*, *cake*, *cake-intermediate*, and *cake-standard,* were identified to share the same likelihood to govern the system under different air sparging conditions. Figure 29 presents the fit of these models with the obtained data. However, the negative complete-blocking coefficients (K_b) obtained from fitting cake-complete model in the data sets suggest an impossible hypothesis of de-blocking of the pores during the operation of passive membrane filtration. Furthermore, the statistical analysis of both the cake-intermediate and cake-standard models revealed high standard errors, low t-statistics and p-values of 1 on the fitted intermediate- (K_i) and standard-blocking (K_s) coefficients. This implies uncertainties to the actual contributions of the intermediate- or standard-blocking mechanisms in membrane fouling during passive filtration. On the other hand, cake coefficient (K_c) consistently fit the data with low standard errors, high t-statistics and p-value of <0.0001 for both the individual and combined model analyses. From this examination, cake formation was determined to be the predominant mechanism governing the fouling of passive membrane filtration in all of the investigated operating conditions. Thus, it can be concluded that fouling predominantly occurs at the membrane surface despite the air sparging conditions. Table 9 summarizes the results of the individual and combined model analyses.

Table 9 Fitted Parameters for the Single and Combined Fouling Models

		Air ON/OFF Ratios								
		0			0.02			0.13		
Rank	**Model**	**R^2**	**SSR**	**Fitted Parameters**	**R^2**	**SSR**	**Fitted Parameters**	**R^2**	**SSR**	**Fitted Parameters**
1	Cake	0.96	35	$K_c = 8.50±0.14$	0.96	171	$K_c = 1.73±0.02$	0.96	359	$K_c = 1.29±0.01$
2	Cake-Intermediate	0.96	35	$K_i = 2.90x10^{-9}±3.00x10^{-2}$ $K_c = 8.25±0.26$	0.96	173	$K_i = 2.41x10^{-10}±4.03\ x10^{-4}$ $K_c = 1.70±0.01$	0.96	362	$K_i =5.64x10^{-10}±3.51x10^{-4}$ $K_c = 1.27±0.02$
3	Cake-Standard	0.96	35	$K_s =5.02x10^{-6}±3.87x10^{10}$ $K_c = 8.93±0.15$	0.96	173	$K_s = 1.04x10^3±9.88\ x10^4$ $K_b = 1.82±0.02$	0.96	365	$K_s = 4.52x10^6±2.94x10^{10}$ $K_c = 1.36±0.01$
4	Intermediate	0.53	440	$K_i = 0.94±0.03$	0.52	2002	$K_i = 0.29±0.01$	0.53	4051	$K_i =0.21±3.10x10^{-3}$
5	Intermediate - Standard	0.53	440	$K_i = 0.94±0.07$ $K_s = 1.39x10^{-18}±2.0810^{-4}$	0.52	2002	$K_i = 0.29±0.02$ $K_s = 7.01x10^{-19}±1.01x10^{-4}$	0.53	4051	$K_i =0.21±0.01$ $K_s = 8.66x10^{-20}±5.84x10^{-5}$
6	Standard	0.14	812	$K_s = 0.29±0.01$	0.16	3540	$K_s= 0.08±2.00x10^{-3}$	0.16	7277	$K_s = 0.06±1.05x10^{-3}$
7	Complete - Standard	0.14	812	$K_b= 4.00x10^{-4}±4.24\ x10^3$ $K_s = 0.29±4.24x10^2$	0.16	3540	$K_b = 1.00x10^{-4}±2.42x10^3$ $K_s = 0.08±2.43x10^2$	0.25	6511	$K_b= 4.57x10^{-16}±7.98x10^4$ $K_s = 0.061±0.00$
8	Complete	0.06	887	$K_b = 1.57±0.08$	0.11	3700	$K_b = 0.42±0.01$	0.12	7617	$K_b = 0.31±0.01$
9*	Cake-Complete	1.00	1	$K_b = -1.34±0.27$ $K_c = 23.49±0.35$	1.00	8	$K_b = -0.38±0.01$ $K_c = 3.89±0.04$	0.99	67	$K_b = -0.28±0.01$ $K_c = 2.80±0.05$

*Invalid results due to the negative fitted K_b

Table 9 Fitted Parameters for the Single and Combined Fouling Models (Continued)

		Air ON/OFF Ratios								
		0.2			0.2**			Infinity		
Rank	**Model**	**R^2**	**SSR**	**Fitted Parameters**	**R^2**	**SSR**	**Fitted Parameters**	**R^2**	**SSR**	**Fitted Parameters**
1	Cake	0.94	134	$K_c = 0.71 \pm 0.01$	0.94	714	$K_c = 0.79 \pm 0.01$	0.86	5735	$K_c = 0.36 \pm 0.01$
2	Cake-Intermediate	0.94	1359	$K_i = 1.61x10^{-10} \pm 2.20x10^{-4}$ $K_c = 0.70 \pm 0.01$	0.94	722	$K_i = 2.16x10^{-11} \pm 2.12x10^{-4}$ $K_c = 0.78 \pm 1.97x10^{-3}$	0.86	5779	$K_i = 1.20x10^{-10} \pm 5.27x10^{-4}$ $K_c = 0.35 \pm 0.01$
3	Cake-Standard	0.94	1369	$K_s = 5.02x10^{3} \pm 1.34x10^{6}$ $K_c = 0.75 \pm 0.01$	0.94	727	$K_s = 923.17 \pm 9.49x10^{4}$ $K_c = 0.84 \pm 0.01$	0.85	5807	$K_s = 1.27x10^{7} \pm 3.29\ x10^{11}$ $K_c = 0.38 \pm 0.01$
4	Intermediate	0.50	11602	$K_i = 0.16 \pm 2.58x10^{-3}$	0.51	6284	$K_i = 0.18 \pm 3.08x10^{-3}$	0.46	21426	$K_i = 0.11 \pm 2.48x10^{-3}$
5	Intermediate - Standard	0.50	11602	$K_i = 0.16 \pm 0.01$ $K_s = 1.39x10^{-19} \pm 5.49x10^{-5}$	0.51	6284	$K_i = 0.18 \pm 0.01$ $K_s = 2.21x10^{-19} \pm 6.05x10^{-5}$	0.46	21426	$K_i = 0.11 \pm 0.01$ $K_s = 1.77x10^{-19} \pm 9.30x10^{-5}$
6	Standard	0.11	20410	$K_s = 0.05 \pm 9.61x10^{-4}$	0.14	10883	$K_s = 0.05 \pm 1.09x10^{-3}$	0.15	34061	$K_s = 0.03 \pm 8.99\ x10^{-4}$
7	Complete-Standard	0.11	20410	$K_b = 8.72x10^{-5} \pm 2.29x10^{3}$ $K_s = 0.05 \pm 2.29x10^{2}$	0.14	10883	$K_b = 1.22x10^{-5} \pm 3.68x10^{2}$ $K_s = 0.05 \pm 3.68x10^{1}$	0.15	34061	$K_b = 2.67x10^{-5} \pm 1.63x10^{3}$ $K_s = 0.03 \pm 1.63x10^{2}$
8	Complete	0.06	21603	$K_b = 0.25 \pm 0.01$	0.09	11581	$K_b = 0.27 \pm 0.01$	0.08	36798	$K_b = 0.18 \pm 0.01$
9*	Cake - Complete	0.99	152	$K_b = -0.29 \pm 0.01$ $K_c = 1.98 \pm 0.03$	1.00	21.6	$K_b = -0.29 \pm 3.48x10^{-3}$ $K_c = 1.98 \pm 0.02$	0.99	90	$K_b = -0.75 \pm 0.01$ $K_c = 3.03 \pm 0.05$

*Invalid results due to the negative fitted K_b

**After Cleaning (Reactor D^2)

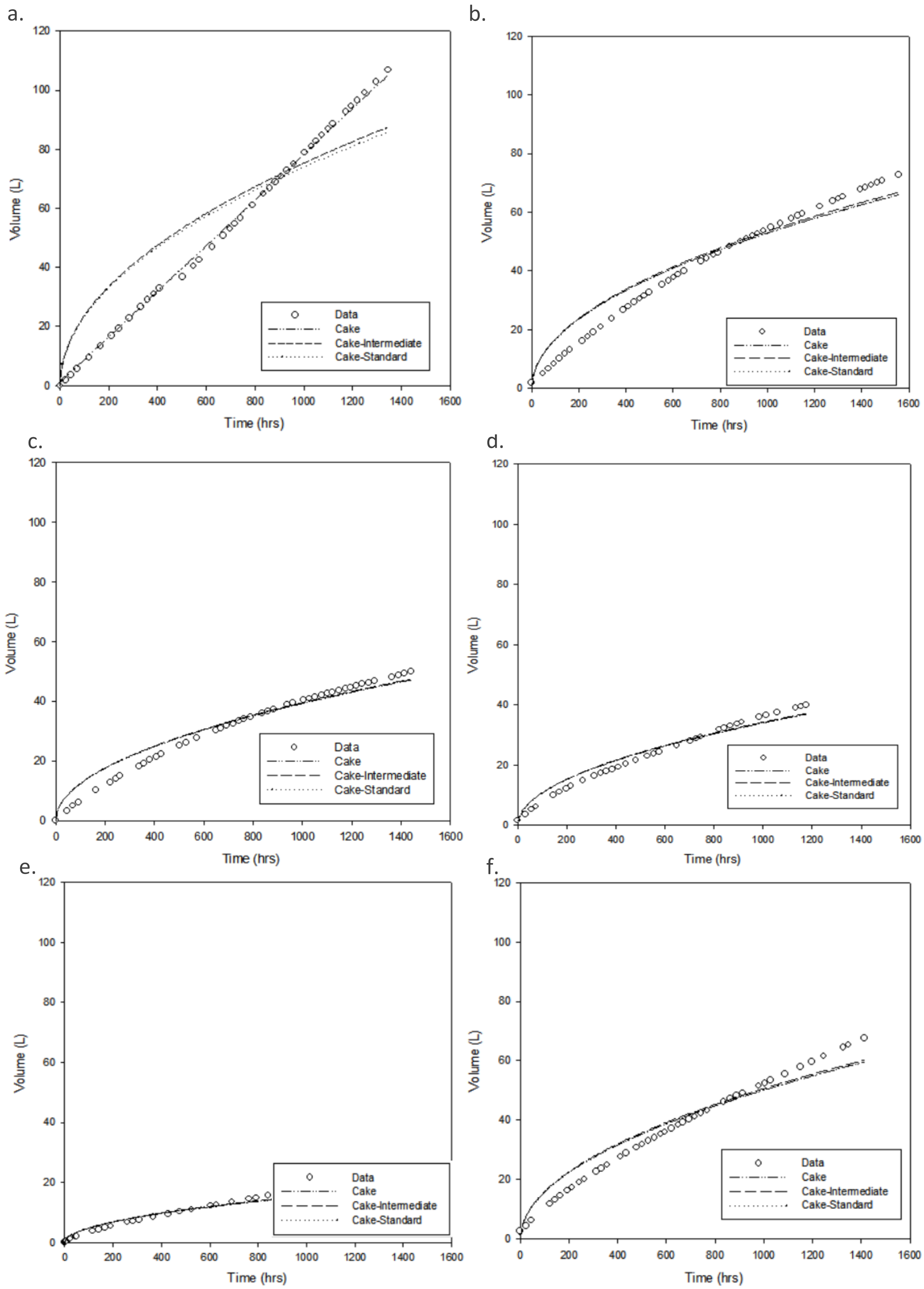


Figure 29 Top Ranked Models Fitted to the Measured Data for the Different Air Sparging Conditions (a). infinity Air ON/OFF ratio, b). 0.2 Air ON/OFF Ratio, c). 0.13 Air ON/OFF Ratio, d). 0.02 Air ON/OFF Ratio, e). 0 Air ON/OFF Ratio, f). 0.2 Air ON/OFF Ratio After Recovery Cleaning)

5.2 Natural Organic Material (NOM) in Passive Membrane Operations

5.2.1 Accumulation of NOM in System Reactor

Dissolved organic carbon (DOC) and total organic carbon (TOC) analyses were conducted to quantify the proportion of particulate and dissolved organic component in the feed water. Size exclusion chromatography analyses using high performance liquid chromatography (HPLC) were conducted to characterize the composition of the soluble natural organic matter (NOM) in the feed. The objective was to determine the stability of the different NOM constituents within the system during long-term operation.

The DOC and TOC of the feed water was 6.31±0.54 ppm and 11.47±2.39 ppm, respectively. The NOM was categorized into three major soluble fractions consisting of 1). biopolymers or high molecular weight substances (HMW), 2). humic substances (HS) and 3). low molecular weight neutrals (LMN). Figure 30 illustrates the typical size exclusion chromatograms of the raw feed water during different seasons.

The NOM concentration in the feed water was highest during high rainfall seasons (i.e. spring and winter), where high runoff tends to increase the mobilization of humic substances (Uyak et al., 2008) into the pond, from which the raw feed water was collected. The HS accounted for approximately 70 to 86% of the total NOM, whereas HMW and LMN accounted for 20% and 13% of the total NOM, respectively. These proportions are consistent with those reported by others for typical natural surface waters (Peter-Varbanets et al., 2011; Thurman, 1985; Y. Choi, 2003). Table 10 summarizes the concentration and percent contribution of each NOM fraction to the DOC content.

Table 10 Averaged Concentrations of High Molecular Weight, Humic Substances and Low Molecular Weight Neutrals Contents in Feed Water

Season	**Concentration (ppm)**				**Percent Contribution (%)**		
	HMW	**HS**	**LMN**	**Total**	**HMW**	**HS**	**LMN**
Fall 2013	0.94	3.72	0.72	5.38	17%	69%	13%
Winter 2013	0.50	5.29	0.35	6.14	8%	86%	6%
Spring 2014	1.67	5.02	0.59	7.29	23%	69%	8%
Summer 2014	0.76	4.92	0.43	6.10	12%	81%	7%

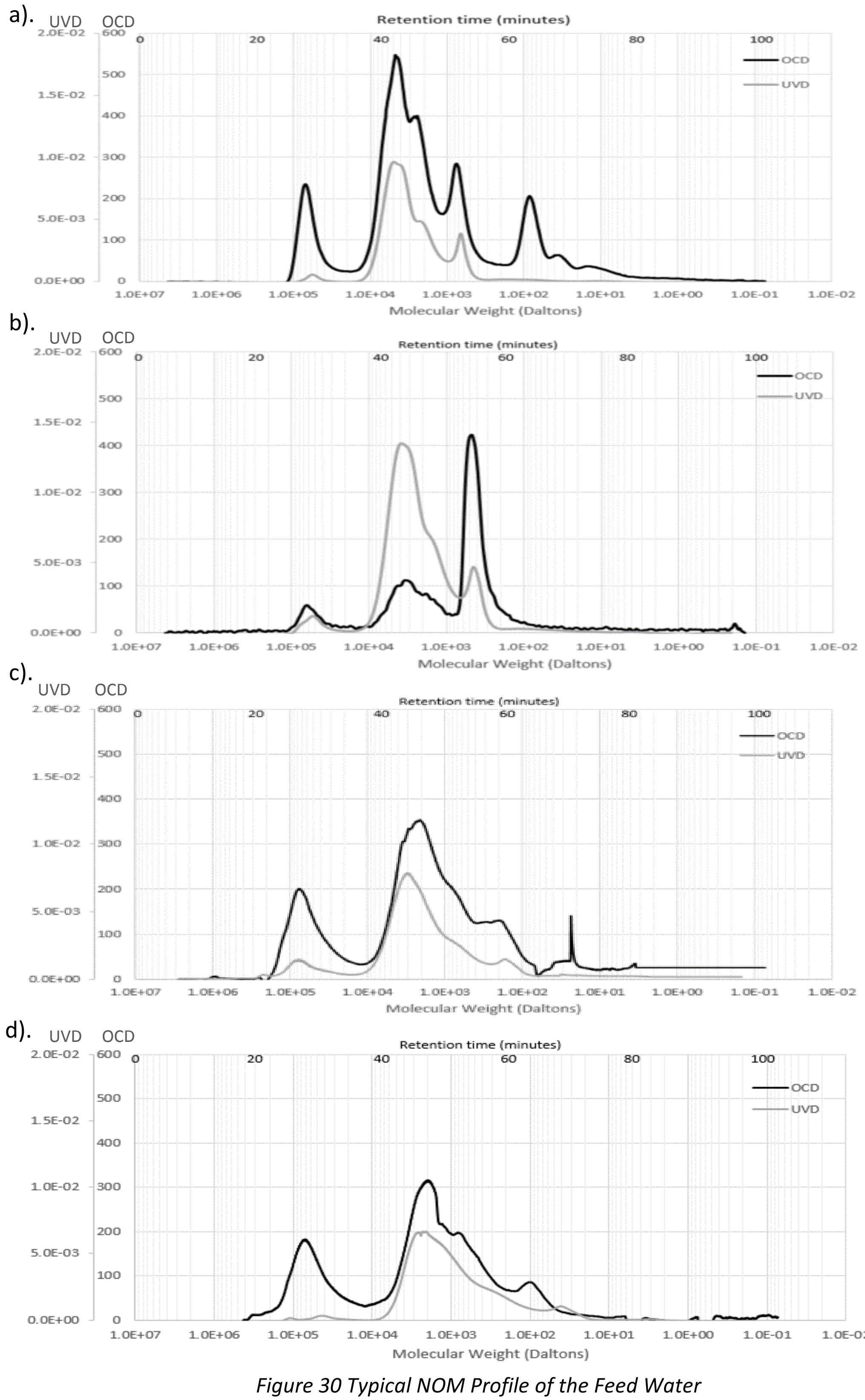


Figure 30 Typical NOM Profile of the Feed Water
(a). Fall 2013, b). Winter 2013, c). Spring 2014, d). Summer 2014)
Response signals from both the 254 nm ultraviolet (UVD_{254}) and organic carbon detections (OCD) are reported in arbitrary units.

For the reactors with no wasting (ie. SRT of infinity), the NOM concentration increased over time, especially with respect to HMW and HS. UF membranes can effectively retain HMW and some of the larger HS. Therefore the accumulation of HMW and some HS was expected in the system. A total HMW accumulation of 2.37±1.11 ppm and 1.69±0.54 ppm, as well as HS of 3.40±1.31 ppm and 2.98±1.13 ppm were observed with and without backwash, respectively. For the reactors with daily wasting (ie. SRT of 10 days), the NOM concentration in the system reactors was similar to that of the concentration of the feed, and therefore NOM did not accumulate. This results indicate that the daily wasting of 10% of the operating volume was sufficient to prevent the accumulation of NOM in the system reactor. The differences between the feed water and system reactor concentrations for HMW, HS, and LMN are summarized in Figure 31a, b and c.

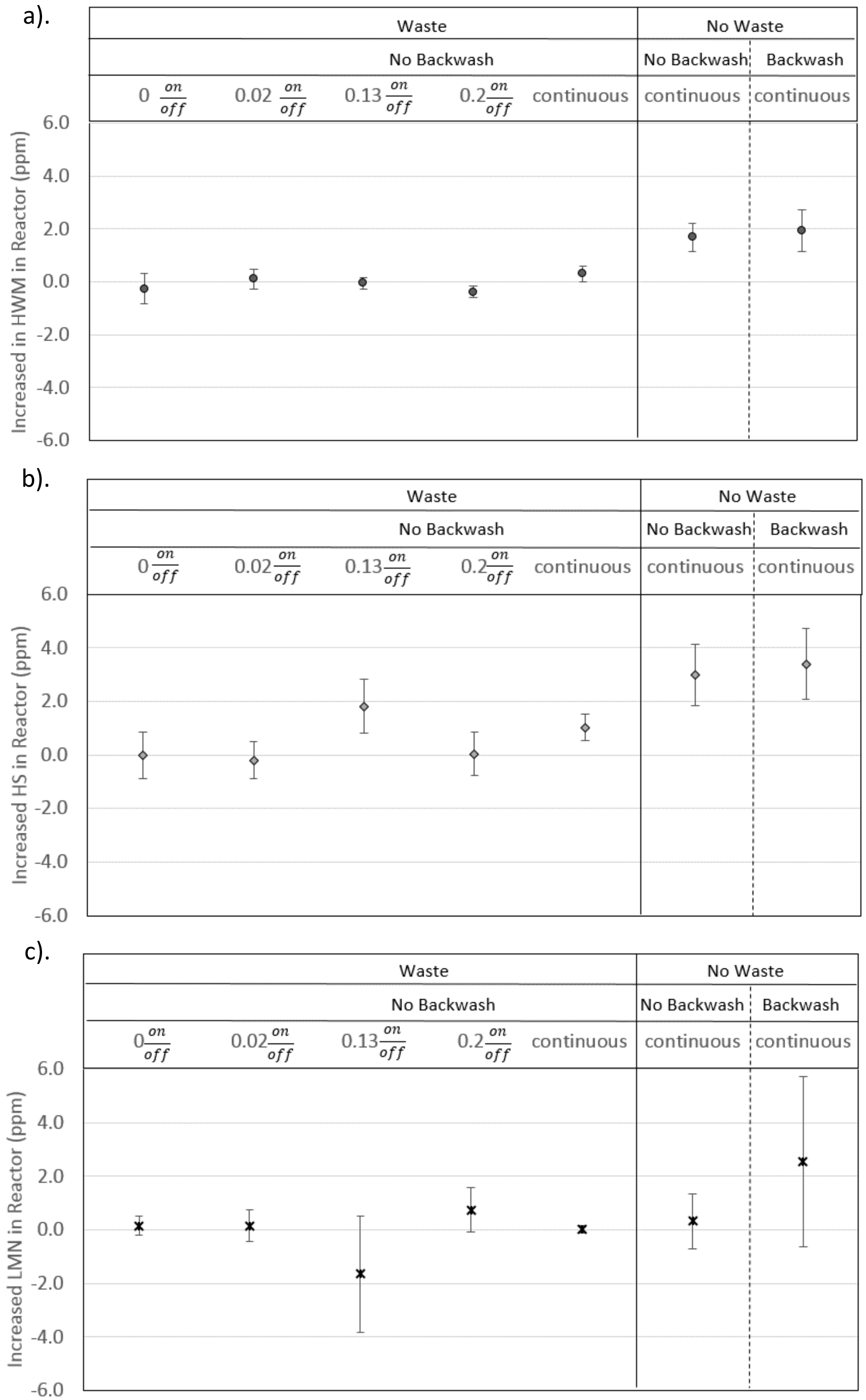


Figure 31 Differences in Organic Content between System Reactor and Feed Tank under Different Operation Conditions: with and without wasting, backwash and different on/off frequencies of air sparging (a). HMW, b). HS, c). LMN)

5.2.2 Removal of NOM during Treatment

NOM characterization and quantification was done on the permeates for each condition investigated to determine the overall NOM removal during treatment. As previously discussed, an increase in the concentration of HMW and HS occurred in the system reactors without daily wasting. This increase had an effect on the overall NOM removal. With wasting, the NOM concentration in permeates was equal or less than then concentration in the feed water, which was similar to the concentration in the system reactor. Whereas without wasting, the NOM concentration in the permeate was higher than the concentration in the feed water especially with respect to HS. Figure 32 illustrates typical NOM profiles observed with and without wasting.

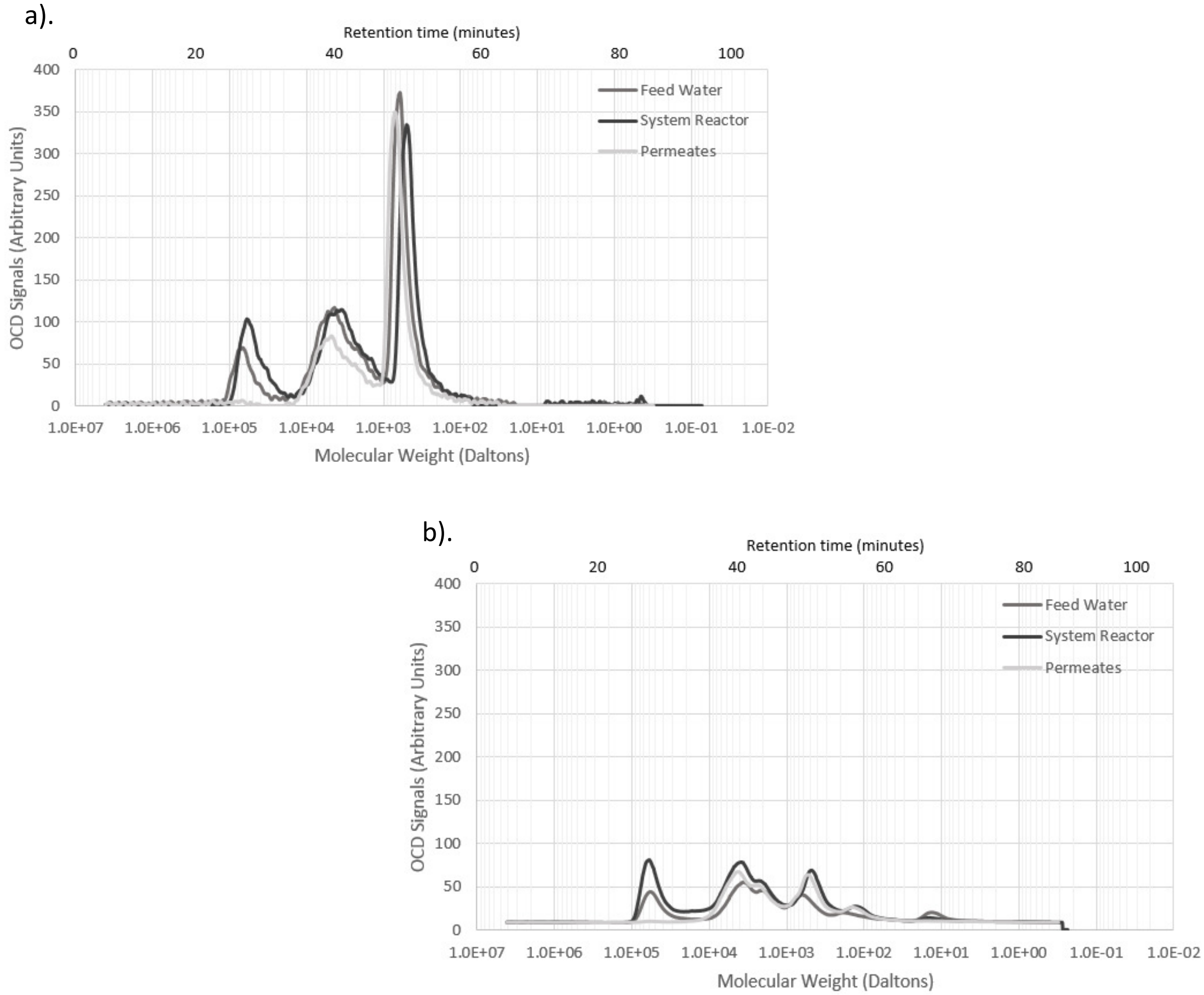


Figure 32 Typical NOM Profile at the Different Stages of Treatment (a). With Wasting and b). Without Wasting)

The differences between the feed and permeate concentrations for HMW, HS and LMN are summarized in Figure 33. Overall, HMW were effectively removed both with and without wasting. This was expected because UF membranes can effectively retain HMW. With wasting, the concentration of HS and LMN in the feed and permeate were generally the same, indicating that these NOM components were not effectively removed with wasting, which is consistent with results presented in Section 5.1.2. However, without wasting, the concentration of HS in the permeate was greater than that in the feed. The overall increase in HS during treatment likely resulted from the hydrolysis of material retained by the UF membranes (ie. particulate organic material, HMW and larger HS) into smaller material with a molecular weight similar to that of HS (Derlon et al., 2014; Niaounakis, 2014). The concentration of LMN in the feed and permeate were generally the same, indicating that LMN were not effectively removed without wasting. This is consistent with the results presented in Section 5.1.2.

Although the dissolved NOM components were not all effectively removed to an appreciable extent, the total concentration of organic matter decreased substantially during treatment from 11.47±2.39 ppm to 5.23±0.79 ppm and 6.84±0.02 ppm, with and without wasting, respectively. Table 11 summarizes the observed removal of the different NOM components for the different operating conditions investigated.

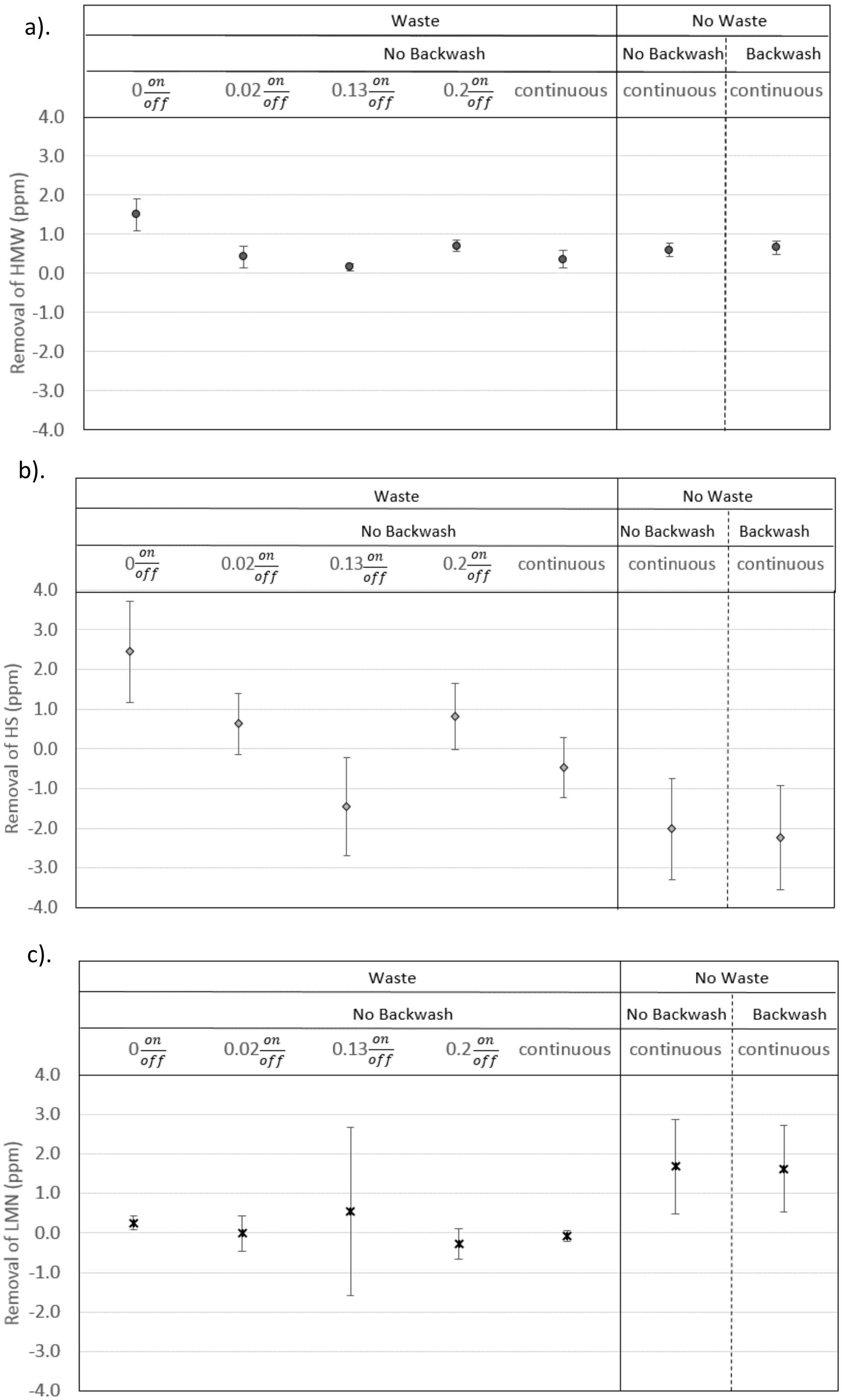


Figure 33 Mean Removal of Organics under Different Operating Conditions: with and without wasting, backwash and different on/off frequencies of air sparging (a). HWM, b). HS, c). LMN)

Table 11 Summary of the Pairwise Comparison between the Feed Water, System Reactor, Permeates to Determine Consistency of Raw Water Feed and Overall NOM Removal

	With Wasting										**Without Wasting**			
	Without Backwash												**With Backwash**	
Air (ON/OFF)	**0**		**0.02**		**0.13**		**0.2**		**Continuous**		**Continuous**		**Continuous**	
Δ in Reactor	mean	±95%	mean	±95%	mean	±95%	mean	±95%	mean	±95%	mean	±95%	mean	±95%
HMW (ppm)	-0.25	0.56	0.10	0.37	-0.05	0.21	-0.38	0.21	0.42	0.34	1.69	0.54	2.37	1.11
HS (ppm)	-0.02	0.86	-0.20	0.69	1.82	1.00	0.04	0.81	1.03	0.48	2.98	1.13	3.40	1.31
LMN (ppm)	0.16	0.35	0.16	0.59	-1.65	2.16	0.75	0.82	-0.34	0.54	-0.07	1.24	2.56	3.17
NOM Removal	mean	±95%	mean	±95%	mean	±95%	mean	±95%	mean	±95%	mean	±95%	mean	±95%
HMW (ppm)	1.50	0.396771	0.43	0.27	0.16	0.10	0.70	0.15	0.31	0.24	0.60	0.18	0.59	0.21
HS (ppm)	2.45	1.267199	0.63	0.78	-1.46	1.23	0.82	0.82	-1.17	1.19	-2.12	1.30	-2.27	1.26
LMN (ppm)	0.26	0.165882	-0.01	0.46	0.55	2.12	-0.27	0.38	0.23	0.56	1.68	1.19	1.62	1.10
%NOM Removal	mean	±95%	mean	±95%	mean	±95%	mean	±95%	mean	±95%	mean	±95%	mean	±95%
HMW	88%	8%	84%	26%	35%	12%	90%	6%	86%	283%	59%	11%	58%	16%
HS	5%	22%	27%	17%	13%	59%	35%	18%	13%	21%	-60%	43%	-67%	41%
LMN	-54%	149%	66%	97%	61%	167%	53%	221%	52%	89%	-22%	147%	-30%	149%

5.2.3 Degradation of NOM in System Reactor

A mass balance was performed to determine if NOM degradation occurred during treatment. The extent of the degradation was quantified based on the difference between the measured and the theoretical NOM concentrations in the system over time. The theoretical NOM concentration in the system was estimated based on the difference between the mass input of NOM into the system through the feed and the mass output of NOM out of the system through the permeate and daily wasting. The results from the mass balance analysis are presented in Figure 34. The complete mass balance calculations are available in Appendices K through Q for all of the conditions investigated.

Figure 34a and Figure 34b illustrate the increasing trend of the HMW's theoretical concentration over time that was projected for all conditions investigated, while the HMW's measured concentration remained relatively constant. The greater theoretical concentration than the measured indicates that degradation of HMW occurred during treatment. Peter-Varbanets et al. (2010) also claimed that cavities within the foulant layer are formed by biological activity during passive membrane filtration. The observed HMW degradation is, therefore, likely to result from biological activity.

Figure 34c and Figure 34d illustrate the declining trend of the HS' theoretical concentration over time that was projected for all conditions investigated, while the HS' measured concentration remained relatively constant. The lower theoretical than measured concentration indicates that HS were generated over time. These results are consistent with those presented in Section 5.2.2 that indicated the increase in the permeate's HS concentration due to the hydrolysis of material retained by the UF membranes into smaller material with a molecular weight similar to that of HS.

Figure 34e and Figure 34f illustrate the increasing trend of the LMN's theoretical concentration over time projected for conditions investigated, while the LMN's measured concentration remained low and constant. The higher theoretical concentration than measured indicates that degradation of LMN occurred during treatment. Overall, the mass balance analysis confirmed the biodegradation of NOM during treatment.

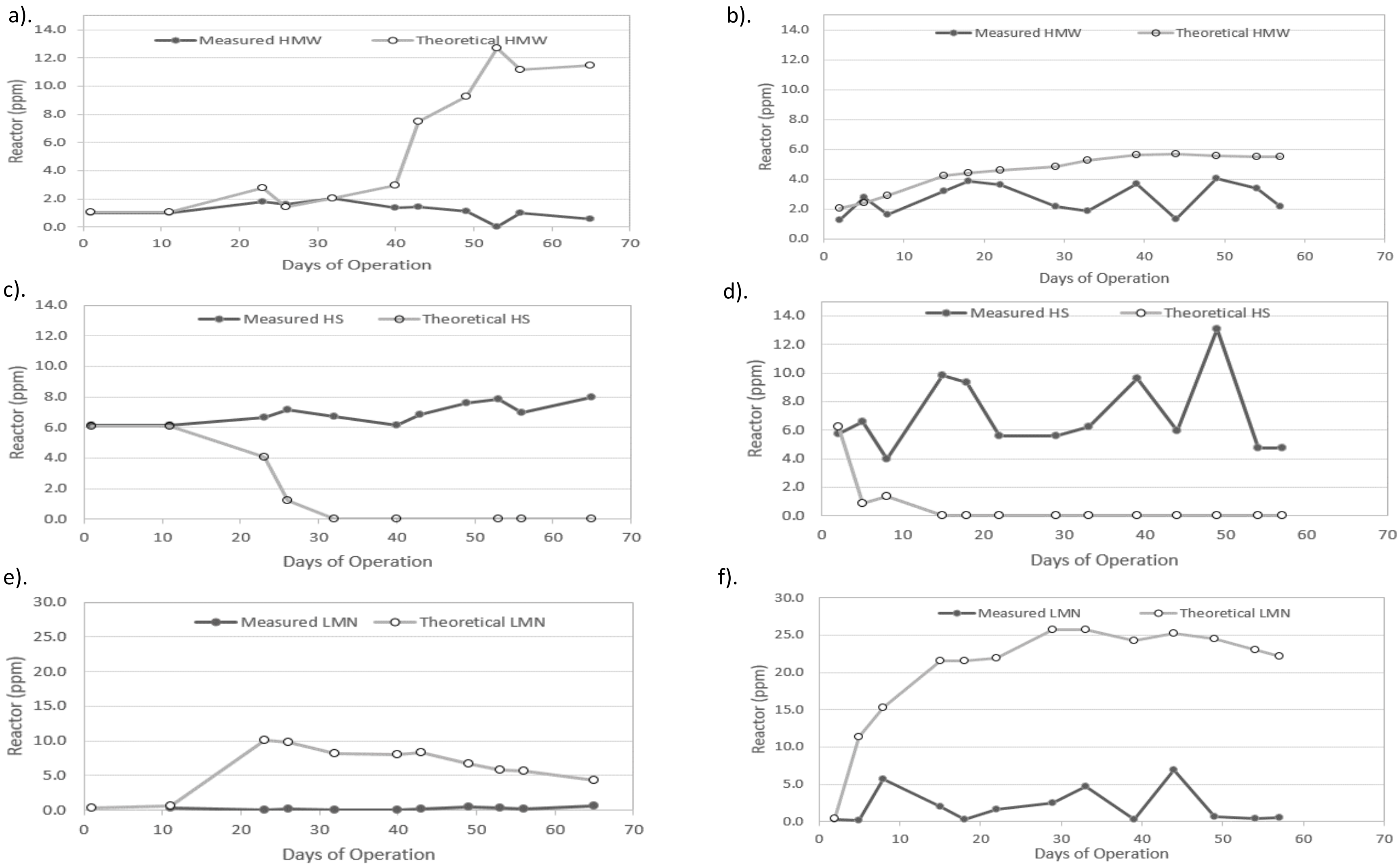


Figure 34 Typical Trends of Measured and Theoretical NOM over Time for the Wasting and Non-Wasting Reactors (a). HMW in a Wasting Reactor, b). HMW in a Non-Wasting Reactor, c). HS in a Wasting Reactor, d) HS in a Non-Wasting Reactor, e). LMN in a Wasting Reactor, f). LMN in a Non-Wasting Reactor)

6 Prototype Design of Passive Membrane Filtration

The results from the present study were used to develop preliminary prototype designs of passive membrane treatment systems suitable for remote communities. Three prototype sizes were considered to provide potable water to 1). single households, 2). a group of five household and 3). a community of 20 household. An illustration of the prototype is provided in Figure 35.

The proposed design considers a hollow fibre module submerged within a cylindrical casing. The cylindrical casing is approximately 81 cm in height and 0.8 cm in diameter. The module is made of made of 70-cm long strands of ZW-1000 hollow fibres (GE Water and Process Technologies, Oakville, Canada) potted into cylindrical bulkheads at both ends, which will be installed with 98% looseness (or 27 cm installment length). A gravity head of approximately 40 cm is applied to provide the driving force for permeation through the membranes, giving an initial flux of approximately 10 LMH. A controlled raw feed rate is provided by either a pump or a gravity-fed system.

An air inlet located at the bottom of the reactor is used for sparging. For the initial prototype development, continuous aeration is considered for fouling control. As determined in the present study, continuous air sparging at 0.009 $m^3/m^2/s$ is sufficient to enable sustainable operation at the flux of 10 LMH. Without continuous aeration, the steady-state flux would lower to approximately 2.5 LMH (Section 5.1.3). Therefore, operation without air sparging would be possible but would require that the membrane fibres be quadrupled to compensate for the lower sustainable flux.

Ten percent of the system reactor's volume is to be manually wasted every day to avoid NOM accumulation in the system, which could lead to a reduced treatment efficiency (Section 5.2.2). A permeate collection tank is connected at the bottom of the system to store the filtered water.

The proposed design provides 40, 600 and 4000 litres per day (lpd) of filtered water for 1, 5 and 20 households, respectively. These estimations were made based on the assumption of 4 people per household at 10 litres per capita per day (lpcd) of drinking and cooking water (for the single household system) and 50 lpcd of drinking, cooking and sanitary water (for the 5 and 20 household systems). A summary of the design assumptions and capacity for the prototypes is presented in Table 12.

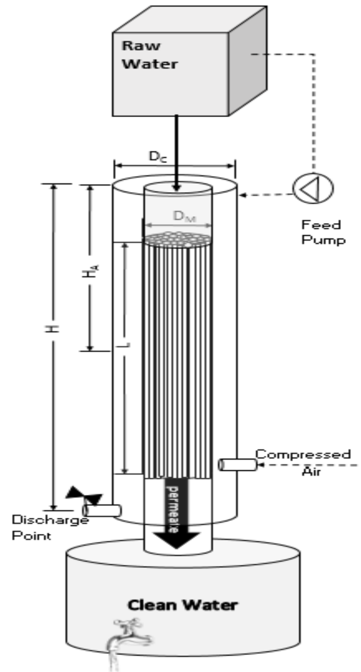


Figure 35 Prototype Diagram with 135 lpcd capacity and an option to be gravity-fed

Table 12 Proposed Designs and Capacity for Prototype

		Unit	Lab Set-Up	1 Household	5 Households	20 Households
Membrane Fibre Properties			ZW 500	ZW 1000	ZW 1000	ZW 1000
	Nominal pore Dia.	um	0.04	0.02	0.02	0.02
	Outside Dia.	mm	1.77	0.95	0.95	0.95
	Length (L)	mm	430	700	700	700
	Filter Area/ strand	m^2/ strand	0.0024	0.0021	0.0021	0.0021
	# of strands	strands	3	80	907	7,978
	Total Filter Area	m^2	0.007	0.17	1.90	16.67
	Strand Area	mm^2/strand	2.46	0.71	0.71	0.71
	Total packing Area	mm^2	7	57	643	5,655
Treatment Capacity	Static Head (H_A)	mm	370	370	370	370
	Permeate Flux	$L/m^2.h$	10	10	10	10
	Production	L/day	2	40	600	4,000
System Reactor						
	Height (H)	mm		813	813	813
	Cassette ID (D_c)	mm		8	29	85
Permeate Collector	dia	m		0.4	1.0	2.0
	height	m		0.3	0.7	1.3
	Freeboard	m		0.5	0.5	0.5
	Dia : H			1.5	1.5	1.5
Aeration	Air rate	L/min	3.8	88	1,004	8,829
		$L/m^2/min$	530	530	530	530
		$m^3/m^2/s$	0.009	0.009	0.009	0.009

7 Conclusions

1. The permeate flux had a significant effect on the efficacy of backwashing. As the permeate flux decreased the need for backwashing to minimize fouling diminished. At a permeate flux of 10 LMH, long term operation could be achieved without backwash.

2. At a hydrostatic head producing an equivalent to 10 LMH, fouling during constant-pressure operations was similar to that for constant-flux operations. Constant-pressure, gravity operations with a hydrostatic head of 37mbar could be used to sustain operation at 10 LMH.

3. Continuous air sparging was required to maintain a permeate flux of 10 LMH. Reducing the extent of air sparging reduced the permeate flux that could be maintained. For all reduced air sparging conditions investigated, the permeate flux that could be maintained was approximately 2.5 LMH.

4. The complexity of a SHFUF can be simplified by eliminating backwash (conclusion 1), operating with gravity flow (conclusion 2), and eliminating/reducing the need of air sparging (conclusion 3) without compromising the long-term operational stability of the system.

5. Recovery cleaning could effectively recover the decrease in permeability which occurred during long-term operations.

6. Acclimatization method adopted in the present study did not help to improve membrane performance. Its adoption hindered the occurrence of sustainable conditions, leading to a lower steady-state permeability.

7. Modeling suggested that fouling was predominantly governed by cake formation for all conditions investigated.

8. A mass balance analysis indicated that NOM degradation occurred during treatment and that the degradation resulted from biological activity.

9. NOM accumulation in the system without wasting negatively affected the overall treatment efficiency. The total NOM removal achieved by the reactors with wasting was 4.63±2.41 ppm, while that without wasting was 6.25±3.18 ppm.

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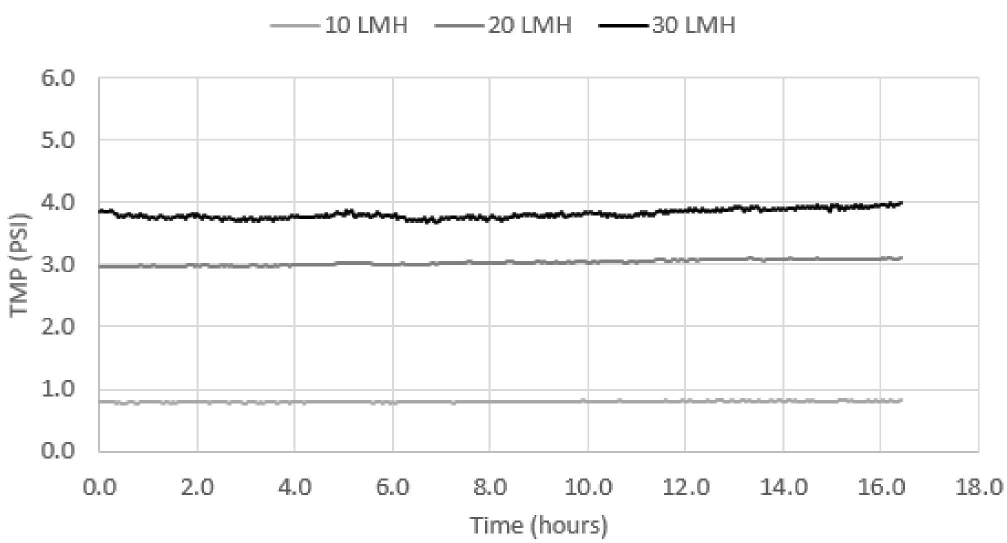
Appendix A : Clean Water Fluxes and Initial Membrane Resistances

I. Stage 1

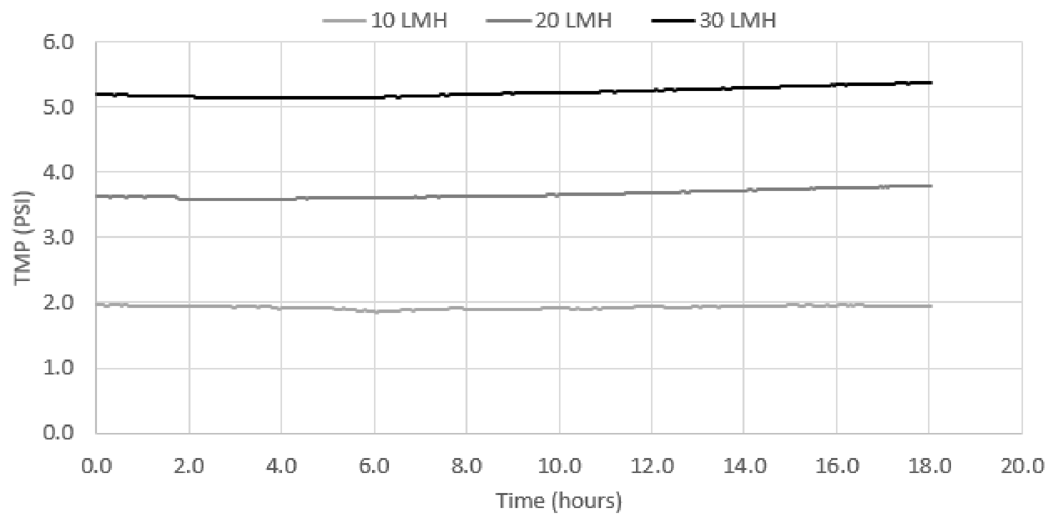
<u>Reactor A : Without Backwash</u>

J_0 (LMH)	10.00	20.00	30.00
J_0 ($m^3/m^2.s$)	2.77778E-06	5.56E-06	8.33E-06
Avg. ΔP (N/m^2)	5,488	20,885	26,254
μ (Ns/m^2)	0.001002	0.001002	0.001002
R_m (m^2/m^3)	1.97E+12	3.75E+12	3.14E+12



<u>Reactor B : With Backwash</u>

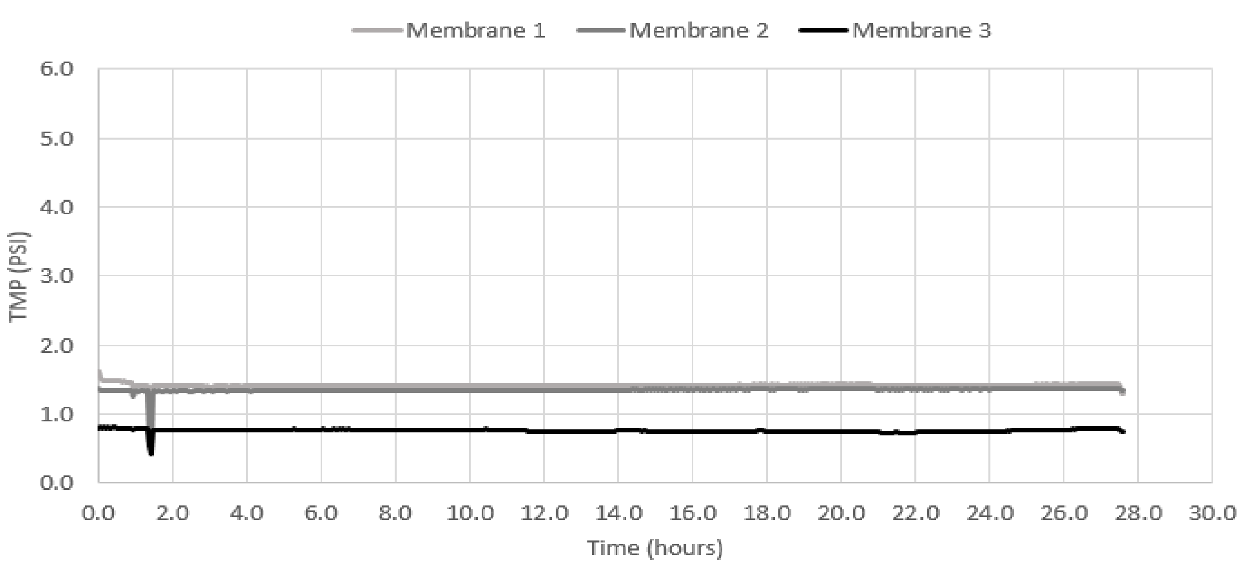
J_0 (LMH)	10.00	20.00	30.00
J_0 ($m^3/m^2.s$)	2.78E-06	5.56E-06	8.33E-06
Avg. ΔP (N/m^2)	13,275	25,233	36,005
μ (Ns/m^2)	0.001002	0.001002	0.001002
R_m (m^2/m^3)	4.77E+12	4.53E+12	4.31E+12



II. Stage 2

<u>Reactor C : Passive Membrane Permeation</u>

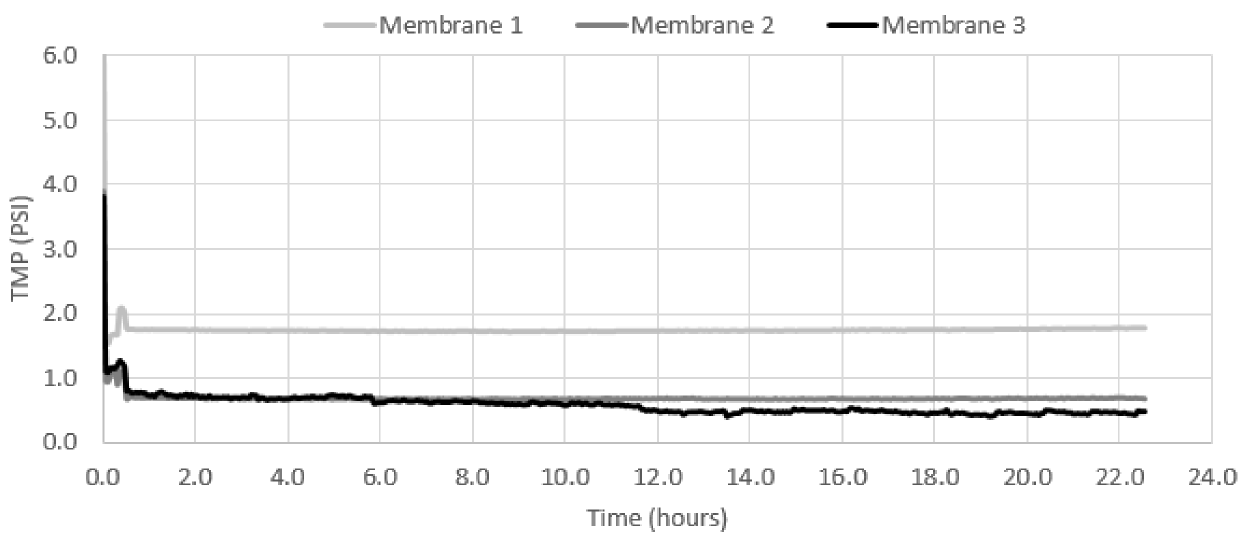
J_0 (LMH)	**9.20**	**9.20**	**9.20**
J_0 ($m^3/m^2.s$)	2.56E-06	2.56E-06	2.56E-06
Avg. ΔP (N/m^2)	8,549	7,171	5,861
μ (Ns/m^2)	0.001002	0.001002	0.001002
R (m^2/m^3)	1.13E+12	3.48E+11	7.20E+09



III. Stage 3

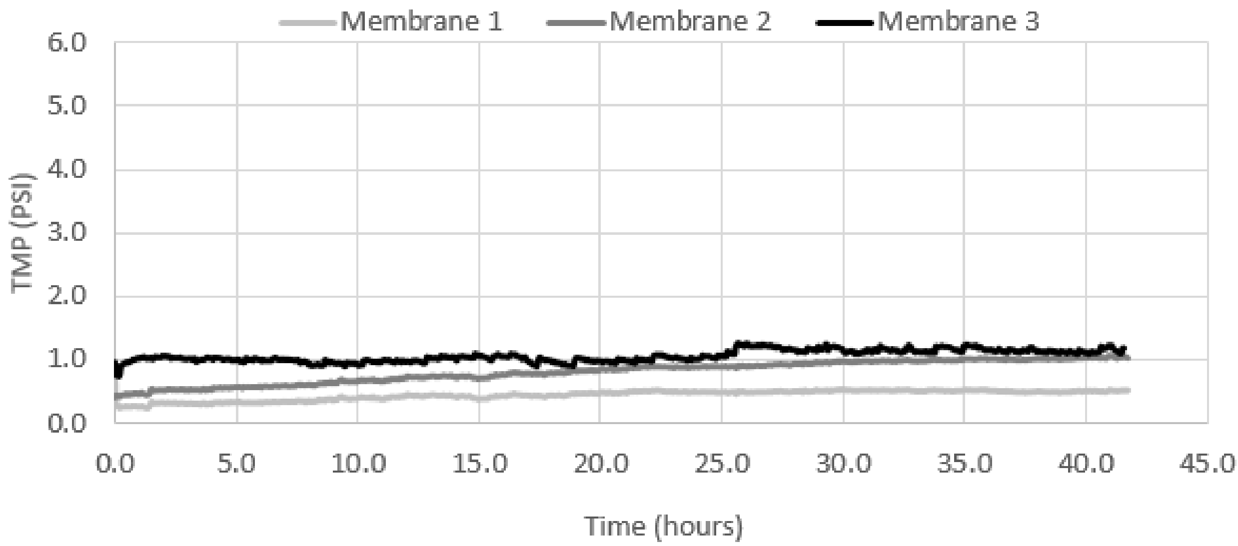
Reactor D[1] : 25 Minutes Off – 5 Minutes On

J_0 (LMH)	**12.13**	**12.13**	**12.13**
J_0 ($m^3/m^2.s$)	3.37E-06	3.37E-06	3.37E-06
Avg. ΔP N/m^2	11,947	4,756	4,078
μ (Ns/m^2)	0.001002	0.001002	0.001002
R (m^2/m^3)	3.54E+12	1.41E+12	1.21E+12



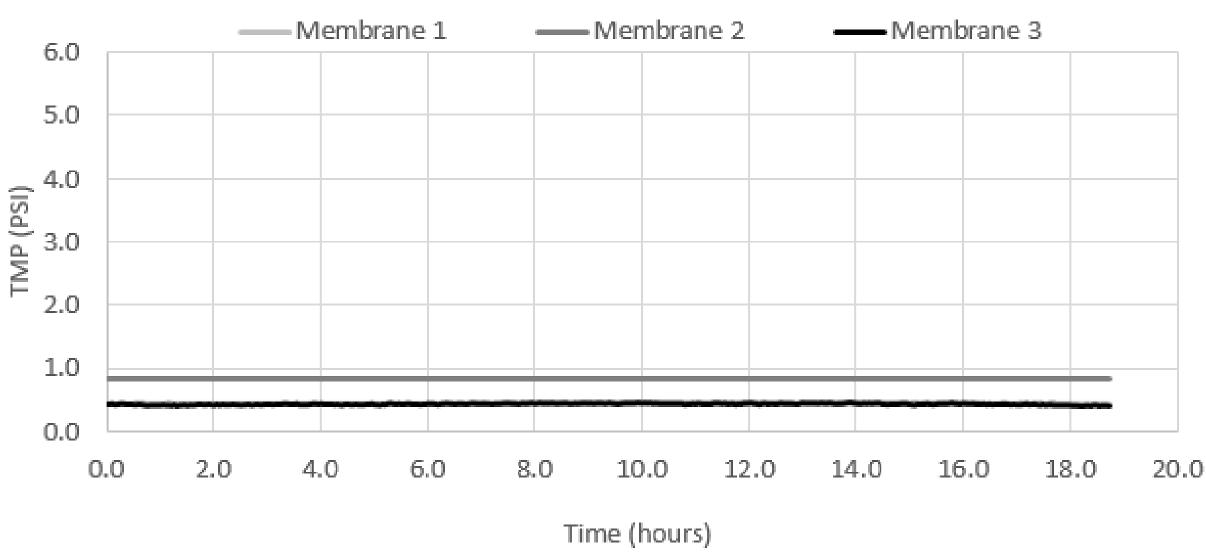
Reactor E : 4 Hours Off – 30 Minutes On

J_0 (LMH)	**10.50**	**10.50**	**10.50**
J_0 ($m^3/m^2.s$)	2.92E-06	2.92E-06	2.92E-06
Avg. ΔP N/m^2	3,390	6,772	7,891
μ (Ns/m^2)	0.001002	0.001002	0.001002
R (m^2/m^3)	1.16E+12	2.32E+12	2.70E+12



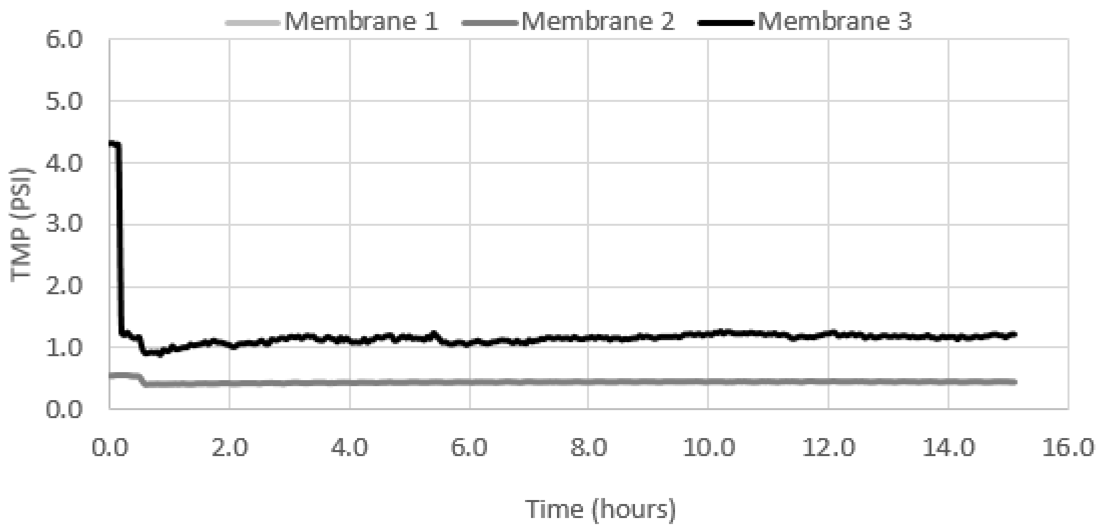
Reactor F : 4 Hours Off – 5 Minutes On

J_0 (LMH)	**10.60**	**10.60**	**10.60**
J_0 ($m^3/m^2.s$)	2.94E-06	2.94E-06	2.94E-06
Avg. ΔP (N/m^2)	3,083	5,737	2,961
μ (Ns/m^2)	0.001002	0.001002	0.001002
R_m (m^2/m^3)	1.04E+12	1.94E+12	1.00E+12



Reactor G : No Aeration

J_0 (LMH)	**10.80**	**10.80**	**10.80**
J_0 ($m^3/m^2.s$)	3.00E-06	3.00E-06	3.00E-06
Avg. ΔP (N/m^2)	3,104	2,975	8,215
μ (Ns/m^2)	0.001002	0.001002	0.001002
R (m^2/m^3)	1.03E+12	9.90E+11	2.73E+12



Appendix B: Excel Visual Basic for Applications (VBA) Commands

1. **<u>HOBOware datalog transfer:</u>** was used to compile transferred csv file from HOBOware data logger into the master spreadsheet for data analysis. Calculations and analyses in the spreadsheet were automatically updated by the macros every time the transfer was done.

```
Sub UpdateData()
Dim LastRow As Long

'Open Workbooks

   Workbooks.Open Filename:="R1_Exp2F.csv"
   Windows("R1_Exp2F.csv").Activate

'Delete Blank Cells
   Columns("C").SpecialCells(xlCellTypeBlanks).EntireRow.Delete

' UpdateData Macro

   Range("A3:C3", Range("A3:C3").End(xlDown)).Select
   Selection.Copy

   Windows("EXP2_DataLog.xlsm").Activate
   ActiveWorkbook.Sheets("R1_EXP2").Activate
   Range("A32203").Select
   ActiveSheet.Paste

'Close csv File
   Windows("R1_Exp2F.csv").Activate
   Workbooks("R1_Exp2F.csv").Close SaveChanges:=False

'Update External Calculations

   LastRow = Range("A3").End(xlDown).Row
   Range("F18375:L18375").AutoFill Destination:=Range(Range("F18375"), Range("L" & LastRow))

End Sub
```

2. **Backwash Data sorting** : was used to sort through the logged pressure data and separate the before and after backwash transmembrane pressures. This was required for backwash benefits analysis.

```
Sub Backwash ()
Dim i As Integer
Last = Cells(Rows.Count, “E”).End(xlUp).Row
For i = Last To 1 Step -1
        If (Cells(i, “E”).Value = “” Then
                Cells (i, “E”).Delet Shift :=xlUp
        End If
Last2 = Cells(Rows.Count, “f”).End(xlUp).Row
For ii = Last2 To 1 Step -1
        If (Cells(ii, “f”).Value = “” Then
                Cells(ii, “f”). Delete Shift :=xlUp
        End If
   Next ii
   MsgBox “You’re Done!!”

End Sub
```

3. **HPLC's UV Data Transfer** : was used to compile and organize all of the arw files, which contained the distinct UV absorbance data of each sample, into the HPLC master spreadsheet.

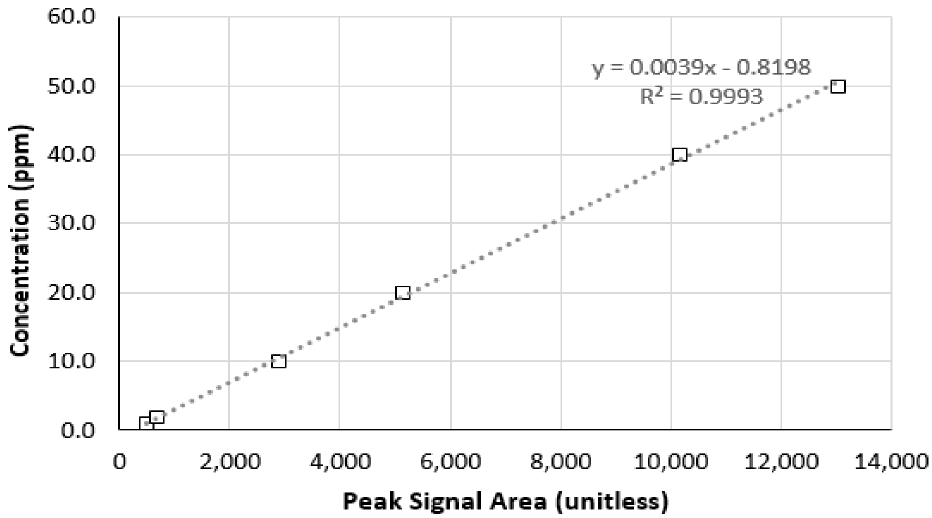
```
Sub DataTransfer()

Dim File As String
Dim emptyColumn As Long
Dim Data As Workbook
Dim destination As Worksheet
Dim Name As String

'1. Open arw file: change the address of the file
File = Dir("C:\Users\Patricia Oka\Documents\School\Classes\MASc THESIS\Data\Exp3\hplc\Feb 11
Calibration\" & "*.arw")

Do While Len(File) > 0
'2. Input the name you gave to this file "xxxx.xlsm"
If File = "HPLC_CalibrationFeb11.xlsm" Then
Exit Sub
End If

Set Data = Workbooks.Open(File)
Name = Mid(ActiveWorkbook.Name, 2, 5)

'copy data
ActiveSheet.Range("B3", ActiveSheet.Range("b3").End(xlDown)).Select
Selection.Copy

'paste: Change the name of the file the same as above "xxx.xlsm"
Windows("HPLC_CalibrationFeb11.xlsm").Activate
Range("a4").End(xlToRight).Offset(0, 1).Select
ActiveSheet.Paste

Application.SendKeys ("N")

Range("a4").End(xlToRight).Offset(-1, 0).Value = Name

Data.Close SaveChanges:=False

File = Dir
Loop

End Sub
```

4. **HPLC's TOC Data Transfer** : was used to sort through the compiled TOC data for the purposes of extracting the values for the data of interest given the start and end analysis times.

```
Sub tocTransfer()

    Dim Mini As Double, Maxi As Double
    Dim RowMini As Long, RowMaxi As Long
    Dim MyRg As Range
    Dim LastRow As Long
    Dim Counter As Long

    Sheets("toc").Activate
    Counter = 1

'This loop runs until there is nothing in the Next column is Empty
Do
    Mini = Range("C4").Offset(0, Counter - 1)
    Maxi = Range("D4").Offset(0, Counter - 1)

    Sheets("TOCRaw").Activate
    LastRow = Range("B" & Rows.Count).End(xlUp).Row
    Set MyRg = Range("B:B")
    RowMini = Application.WorksheetFunction.Match(Mini, MyRg)
    RowMaxi = Application.WorksheetFunction.Match(Maxi, MyRg)
    Range("C" & RowMini & ":" & "C" & RowMaxi).Copy
    Sheets("TOC").Activate
    Range("A5").End(xlToRight).Offset(0, 1).Select
    ActiveSheet.Paste
    Counter = Counter + 1

Loop Until IsEmpty(ActiveCell.End(xlUp).Offset(0, 1))

    End Sub
```

Appendix C : Instrument Calibration Curves

Organic Carbon Analysis

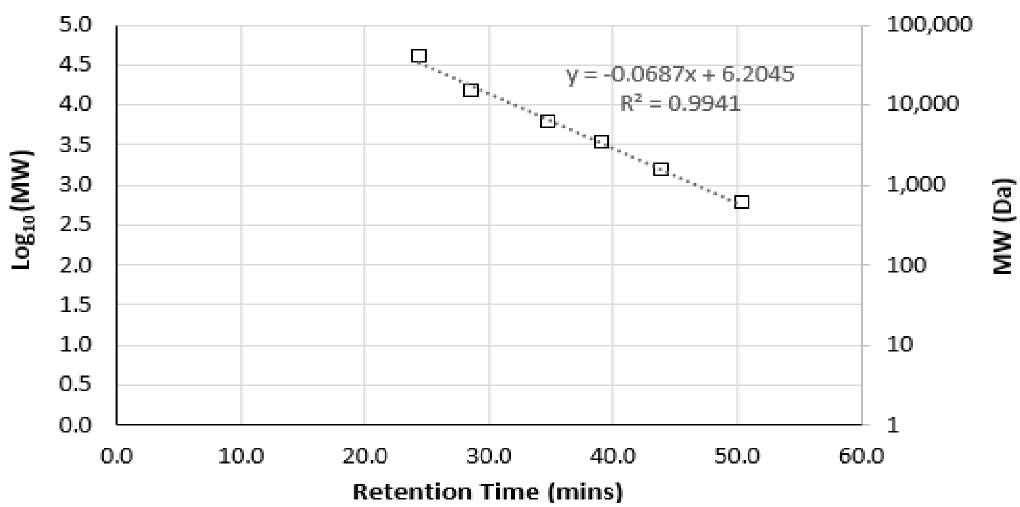


A typical Calibration Curve of the Standards with Concentrations Ranging from 1 to 50 ppm

High Performance Liquid Chromatography (HPLC)

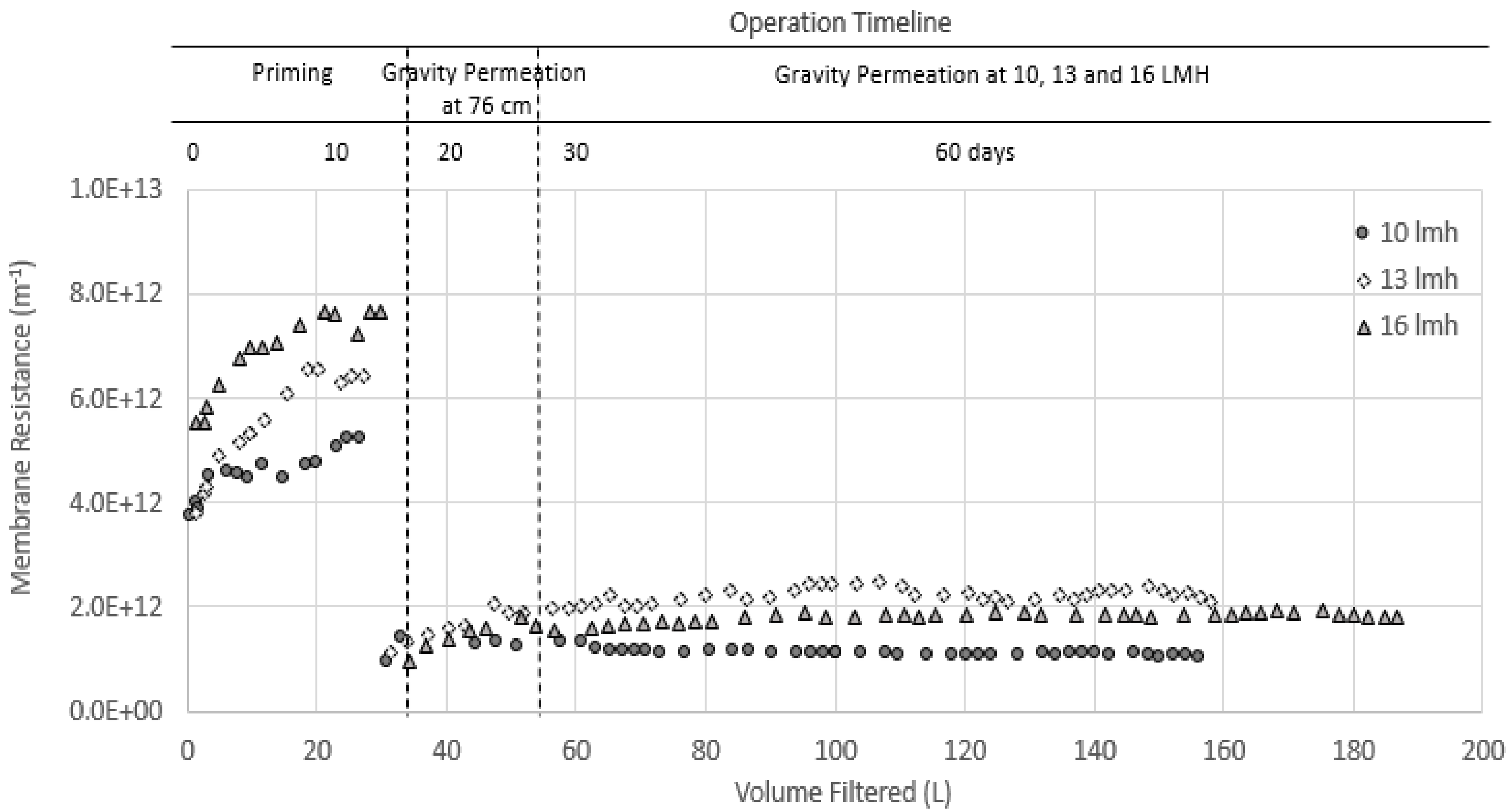
Typical Retention Times in Minutes for the Six Different Molecular Weight Standards

Standard Solution	MW (Da)	$\log_{10}$(MW)	Retention Time (mins)
PEG	600	2.78	50.40
PEG	1500	3.18	43.93
PEG	3300	3.52	39.13
PEG	6000	3.78	34.80
PSS	15000	4.18	28.60
PSS	41000	4.61	24.33



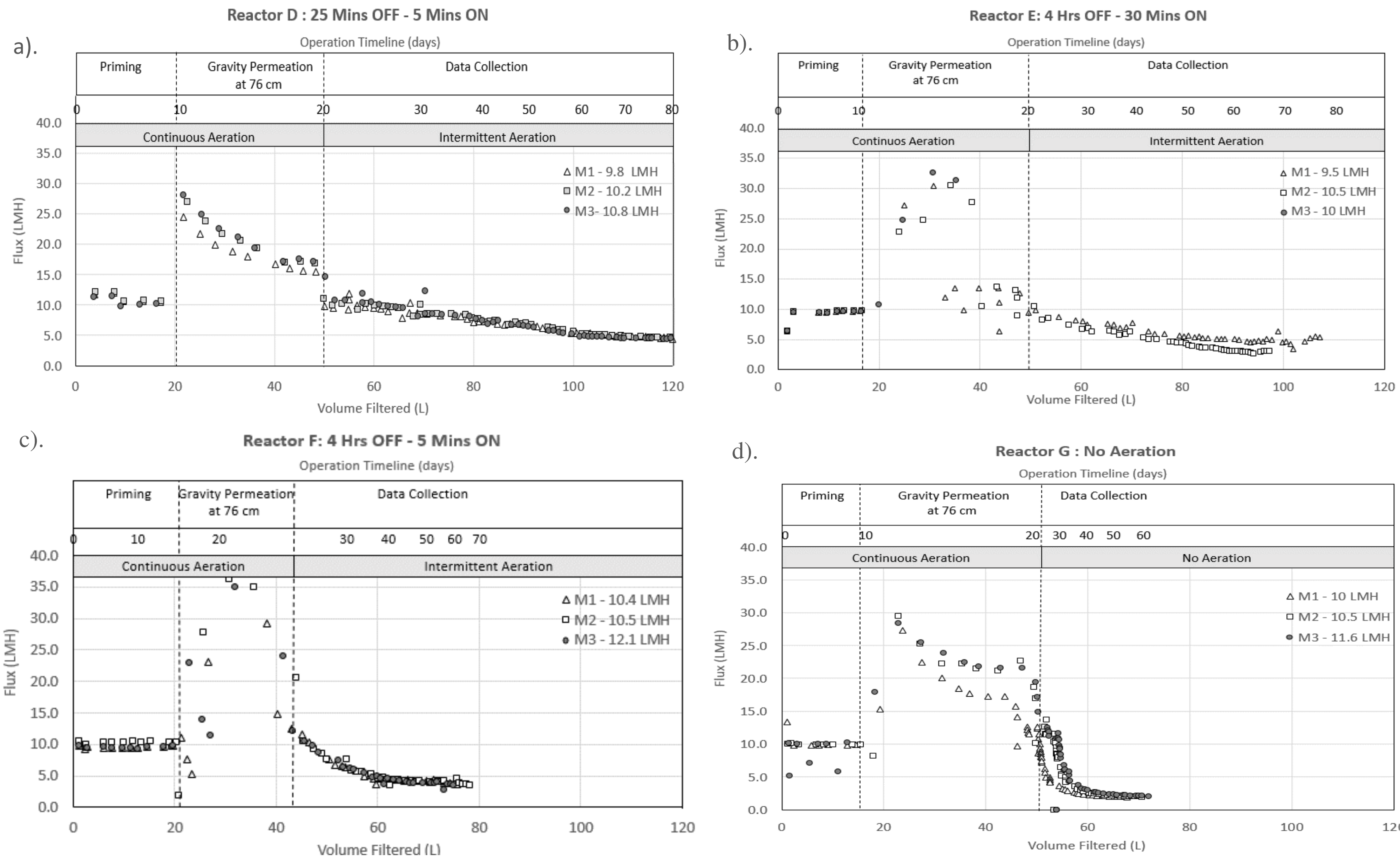
A typical Logarithm curve of Standards' Molecular Weights versus Retention Time

Appendix D: Complete Resistance Data for Stage 2



Resistance Plot for the Different Operating Stages in Stage 2's Constant-Pressure Passive Membrane Filtration

Appendix E: Flux Reduction in Stage 4



Permeate Flux Reduction over Volume Filtered under Different Aeration Frequencies
(a). 25 Minutes off – 5 Minutes on; b). 4 Hours off – 30 Minutes on; c). 4 Hours off – 5 Minutes on; and d). No Aeration)

Appendix F: Statistical Reports of the Fouling Models for Continuous Aeration

Model's Fit Error and Estimated Parameter Values for Passive Membrane Permeation with Continuous Aeration

Model	SSR	Fitted Parameter Values	s
Cake-Complete	$9.01x10^{1}$	K_b = -0.746,	0.0331
		K_c = 3.03	0.1512
Cake	$5.73x10^{3}$	K_c = 0.362	0.0226
Cake- Intermediate	$5.78x10^{3}$	K_i = $1.20x10^{-10}$,	0.0017
		K_c = 0.350	0.0408
Cake- Standard	$5.81x10^{3}$	K_s = $1.27x10^{7}$,	$1.0629x10^{12}$
		K_c = 0.383	0.0243
Intermediate	$2.14x10^{4}$	K_i = 0.108	0.0080
Intermediate - Standard	$2.14x10^{4}$	K_i = 0.108,	0.0234
		K_s = $1.77x10^{-19}$	0.0003
Standard	$3.41x10^{4}$	K_s = 0.0345	0.0029
Complete - Standard	$3.41x10^{4}$	K_b= $2.67x10^{-5}$,	5266.2123
		K_s = 0.0345	526.6482
Complete	$3.68x10^{4}$	K_b = 0.179	0.0158

1. **Cake Complete**

Nonlinear Regression **Sunday, July 13, 2014, 11:19:55 AM**

Equation: User-Defined, Cake-Complete

f = 10/a*(1-exp(-a/(b*100)*(sqrt(1+2*b*100*x)-1)))

R	Rsqr	Adj Rsqr	Standard Error of Estimate
0.9989	0.9977	0.9977	1.5402

	Coefficient	Std. Error	t	P
a	-0.7455	0.0331	-22.5528	<0.0001
b	3.0349	0.1512	20.0741	<0.0001

Analysis of Variance:

	DF	SS	MS
Regression	2	157535.6947	78767.8474
Residual	38	90.1455	2.3723
Total	40	157625.8403	3940.6460

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	1	39831.6776	39831.6776	16790.6676	<0.0001
Residual	38	90.1455	2.3723		
Total	39	39921.8232	1023.6365		

Statistical Tests:

Normality Test (Shapiro-Wilk) Failed (P = 0.0014)

W Statistic= 0.8952 Significance Level = 0.0500

Constant Variance Test Passed (P = 0.3875)

Fit Equation Description:

```
[Variables]
x = col(1)
y = col(2)
reciprocal_y = 1/abs(y)
reciprocal_ysquare = 1/y^2
reciprocal_pred = 1/abs(f)
reciprocal_predsqr = 1/f^2
'Automatic Initial Parameter Estimate Functions
first(q) = if(size(q)<10,size(q)-1,int(0.9*size(q)))
ylast(q) = mean(q[data(first(q),size(q))])
[Parameters]
```

a = ylast(y) ''Auto {{previous: -0.745484}} {{MinRange: 6}} {{MaxRange: 18}}

b = if(x50(x,y,.5)-min(x)>0, -ln(.5)/(x50(x,y,.5)-min(x)), 1) ''Auto {{previous: 3.03486}}

[Equation]

f = 10/a*(1-exp(-a/(b*100)*(sqrt(1+2*b*100*x)-1)))

fit f to y

''fit f to y with weight reciprocal_y

''fit f to y with weight reciprocal_ysquare

''fit f to y with weight reciprocal_pred

''fit f to y with weight reciprocal_predsqr

[Constraints]

b>0

[Options]

tolerance=0.0000000001

stepsize=1

iterations=200

Number of Iterations Performed = 40

2. **Cake**

Nonlinear Regression **Wednesday, July 23, 2014, 4:02:46 PM**

Equation: User-Defined, 3Cake

f = 1/(10*a)*((1+2*a*100*x)^(1/2)-1)

R	Rsqr	Adj Rsqr	Standard Error of Estimate
0.9254	0.8563	0.8563	12.1264

	Coefficient	Std. Error	t	P
a	0.3620	0.0226	16.0065	<0.0001

Analysis of Variance:

	DF	SS	MS
Regression	1	151890.9316	151890.9316
Residual	39	5734.9087	147.0489
Total	40	157625.8403	3940.6460

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	0	34186.9145	(+inf)	(+inf)	(NAN)
Residual	39	5734.9087	147.0489		
Total	39	39921.8232	1023.6365		

Statistical Tests:

Normality Test (Shapiro-Wilk) Failed (P = 0.0036)

W Statistic= 0.9095 Significance Level = 0.0500

Constant Variance Test Passed (P = 0.3214)

Fit Equation Description:

[Variables]

x = col(1)

y = col(2)

reciprocal_y = 1/abs(y)

reciprocal_ysquare = 1/y^2

reciprocal_pred = 1/abs(f)

reciprocal_predsqr = 1/f^2

'Automatic Initial Parameter Estimate Functions

F(q) = ape(x,y,1,0,1)

[Parameters]

a = F(0)[2] ''Auto {{previous: 0.362012}} {{MinRange: -4.5}} {{MaxRange: 1.5}}

[Equation]

f = 1/(10*a)*((1+2*a*100*x)^(1/2)-1)

fit f to y

''fit f to y with weight reciprocal_y

''fit f to y with weight reciprocal_ysquare

''fit f to y with weight reciprocal_pred

''fit f to y with weight reciprocal_predsqr

[Constraints]

a>0

[Options]

tolerance=0.0000000001

stepsize=1

iterations=200

Number of Iterations Performed = 7

3. Cake-Intermediate

Nonlinear Regression **Sunday, July 13, 2014, 11:22:20 AM**

Equation: User-Defined, Cake-Intermediate

f = 1/a*Ln(abs(1+a/(b*10)*((1+2*b*100*x)^(0.5)-1)))

R	Rsqr	Adj Rsqr	Standard Error of Estimate
0.9248	0.8553	0.8514	12.3317

	Coefficient	Std. Error	t	P
a	1.2005E-010	0.0017	7.0872E-008	1.0000
b	0.3500	0.0408	8.5730	<0.0001

Analysis of Variance:

	DF	SS	MS
Regression	2	151847.1829	75923.5914
Residual	38	5778.6574	152.0699
Total	40	157625.8403	3940.6460

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	1	34143.1658	34143.1658	224.5228	<0.0001
Residual	38	5778.6574	152.0699		
Total	39	39921.8232	1023.6365		

Statistical Tests:

Normality Test (Shapiro-Wilk) Failed (P = 0.0035)

W Statistic= 0.9091 Significance Level = 0.0500

Constant Variance Test Passed (P = 0.0807)

Fit Equation Description:

[Variables]

x = col(1)

y = col(2)

reciprocal_y = 1/abs(y)

reciprocal_ysquare = 1/y^2

reciprocal_pred = 1/abs(f)

reciprocal_predsqr = 1/f^2

'Automatic Initial Parameter Estimate Functions

F(q) = ape(x,exp(y),1,0,1)

[Parameters]

a = 0.1 ' {{previous: 1.20048e-010}}

b = 1 ' {{previous: 0.349981}}

[Equation]

f = 1/a*Ln(abs(1+a/(b*10)*((1+2*b*100*x)^(0.5)-1)))

fit f to y

''fit f to y with weight reciprocal_y

''fit f to y with weight reciprocal_ysquare

''fit f to y with weight reciprocal_pred

''fit f to y with weight reciprocal_predsqr

[Constraints]

a>0

b>0

[Options]

tolerance=0.0000000001

stepsize=0.5

iterations=200

Number of Iterations Performed = 49

4. Cake-Standard

Nonlinear Regression **Thursday, July 24, 2014, 12:12:17 AM**

Equation: User-Defined, Cake-standard

a=sqrt(4/9+4*d/(30*e)+2*d^2*x/(3*e))

b=2/(9*(4/9+4*d/(30*e)+2*d^2*x/(3*e))^1.5)*(4/3+d/(10*e)-d^2*x/e)

f = 2/d*(a*cos(2.09-0.33*arccos(b))+1/3)

R	**Rsqr**	**Adj Rsqr**	**Standard Error of Estimate**
0.9244	0.8546	0.8507	12.3614

	Coefficient	**Std. Error**	**t**	**P**
d	12653940.4201	1.0629E+012	1.1905E-005	1.0000
e	0.3825	0.0243	15.7600	<0.0001

Analysis of Variance:

	DF	SS	MS
Regression	2	151819.3031	75909.6516
Residual	38	5806.5372	152.8036
Total	40	157625.8403	3940.6460

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	1	34115.2860	34115.2860	223.2623	<0.0001
Residual	38	5806.5372	152.8036		
Total	39	39921.8232	1023.6365		

Statistical Tests:

Normality Test (Shapiro-Wilk) Failed (P = 0.0037)

W Statistic= 0.9097 Significance Level = 0.0500

Constant Variance Test Passed (P = 0.3260)

Fit Equation Description:

```
[Variables]
x = col(1)
y = col(2)
reciprocal_y = 1/abs(y)
reciprocal_ysquare = 1/y^2
reciprocal_pred = 1/abs(f)
reciprocal_predsqr = 1/f^2
'Automatic Initial Parameter Estimate Functions
first(q) = if(size(q)<10,size(q)-1,int(0.9*size(q)))
ylast(q) = mean(q[data(first(q),size(q))])
[Parameters]
```

```
d = 0.05 ' {{previous: 1.26539e+007}}
e = 0.71 ' {{previous: 0.38254}}
[Equation]
a=sqrt(4/9+4*d/(30*e)+2*d^2*x/(3*e))
b=2/(9*(4/9+4*d/(30*e)+2*d^2*x/(3*e))^1.5)*(4/3+d/(10*e)-d^2*x/e)
f = 2/d*(a*cos(2.09-0.33*arccos(b))+1/3)
fit f to y
''fit f to y with weight reciprocal_y
''fit f to y with weight reciprocal_ysquare
''fit f to y with weight reciprocal_pred
''fit f to y with weight reciprocal_predsqr
[Constraints]
[Options]
tolerance=0.0000000001
stepsize=1
iterations=200
```

Number of Iterations Performed = 9

5. **Intermediate – Standard**

Nonlinear Regression **Tuesday, July 22, 2014, 2:45:21 PM**

Equation: User-Defined, 2Intermediate

f = if(x>0, 1/a*ln(abs(1+a*10*x)), 0)

R	**Rsqr**	**Adj Rsqr**	**Standard Error of Estimate**
0.6807	0.4633	0.4633	23.4389

	Coefficient	**Std. Error**	**t**	**P**
a	0.1078	0.0080	13.4463	<0.0001

Analysis of Variance:

	DF	SS	MS
Regression	1	136199.8984	136199.8984
Residual	39	21425.9419	549.3831
Total	40	157625.8403	3940.6460

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	0	18495.8813	(+inf)	(+inf)	(NAN)
Residual	39	21425.9419	549.3831		
Total	39	39921.8232	1023.6365		

Statistical Tests:

Normality Test (Shapiro-Wilk) Failed (P = 0.0275)

W Statistic= 0.9370 Significance Level = 0.0500

Constant Variance Test Passed (P = 0.4980)

Fit Equation Description:

[Variables]

x = col(1)

y = col(2)

reciprocal_y = 1/abs(y)

reciprocal_ysquare = 1/y^2

reciprocal_pred = 1/abs(f)

reciprocal_predsqr = 1/f^2

'Automatic Initial Parameter Estimate Functions

F(q) = ape(ln(abs(x)),y,1,0,1)

[Parameters]

a = F(0)[2] ''Auto {{previous: 0.107808}}

```
[Equation]
f = if(x>0, 1/a*ln(abs(1+a*10*x)), 0)
fit f to y
''fit f to y with weight reciprocal_y
''fit f to y with weight reciprocal_ysquare
''fit f to y with weight reciprocal_pred
''fit f to y with weight reciprocal_predsqr
[Constraints]
[Options]
tolerance=0.0000000001
stepsize=1
iterations=200
```

Number of Iterations Performed = 13

Appendix G: Statistical Reports of the 5 Best-Fit Fouling Models for 25 Minutes Off – 5 Minutes On

Model's Fit Error and Estimated Parameter Values for Passive Membrane Permeation with ON/OFF Air Ratio of 0.20, Before Recovery Cleaning.

Model	SSR	Fitted Parameters values*	s
Cake-Complete	$1.52x10^2$	K_b = -0.291 , K_c = 1.98	0.0215 0.1037
Cake	$1.34x10^3$	K_c = 0.713	0.0235
Cake- Intermediate	$1.36x10^3$	$K_i = 1.61x10^{-10}$, K_c = 0.696	0.0008 0.0177
Cake-Standard	$1.37x10^3$	$K_s = 5.02x10^3$, K_c = 0.751	4898964.7397 0.0254
Intermediate	$1.16x10^4$	K_i = 0.159	0.0094
Intermediate - Standard	$1.16x10^4$	K_i = 0.159, $K_s = 1.39x10^{-19}$	0.023 0.0002
Standard	$2.04x10^4$	K_s = 0.0487	0.0035
Complete - Standard	$2.04x10^4$	$K_b = 8.72x10^{-5}$, K_s = 0.0487	8344.44468.38 34.5430
Complete	$2.16x10^4$	K_b = 0.251	0.0193

I. Before Cleaning

1. Cake - Complete

Tuesday, July 08, 2014, 12:16:31 AM

Equation: User-Defined, Cake-Complete

f = 10/a*(1-exp(-a/(b*100)*(sqrt(1+2*b*100*x)-1)))

R	Rsqr	Adj Rsqr	Standard Error of Estimate
0.9967	0.9934	0.9933	1.7626

	Coefficient	Std. Error	t	P
a	-0.2808	0.0215	-13.0849	<0.0001
b	1.8945	0.1037	18.2671	<0.0001

Analysis of Variance:

	DF	SS	MS
Regression	2	101128.7056	50564.3528
Residual	49	152.2246	3.1066
Total	51	101280.9302	1985.9006

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	1	22863.5671	22863.5671	7359.6188	<0.0001
Residual	49	152.2246	3.1066		
Total	50	23015.7916	460.3158		

Statistical Tests:

Normality Test (Shapiro-Wilk) Failed (P = 0.0004)

W Statistic= 0.8977 Significance Level = 0.0500

Constant Variance Test Failed (P = <0.0001)

Fit Equation Description:

```
[Variables]
x = col(1)
y = col(2)
reciprocal_y = 1/abs(y)
reciprocal_ysquare = 1/y^2
reciprocal_pred = 1/abs(f)
reciprocal_predsqr = 1/f^2
'Automatic Initial Parameter Estimate Functions
first(q) = if(size(q)<10,size(q)-1,int(0.9*size(q)))
ylast(q) = mean(q[data(first(q),size(q))])
[Parameters]
a = ylast(y) ''Auto {{previous: -0.28078}} {{MinRange: 6}} {{MaxRange: 18}}
b = if(x50(x,y,.5)-min(x)>0, -ln(.5)/(x50(x,y,.5)-min(x)), 1) ''Auto {{previous: 1.89447}}
[Equation]
```

f = 10/a*(1-exp(-a/(b*100)*(sqrt(1+2*b*100*x)-1)))

fit f to y

''fit f to y with weight reciprocal_y

''fit f to y with weight reciprocal_ysquare

''fit f to y with weight reciprocal_pred

''fit f to y with weight reciprocal_predsqr

[Constraints]

b>0

[Options]

tolerance=0.0000000001

stepsize=1

iterations=200

Number of Iterations Performed = 28

2. <u>Cake</u>

Nonlinear Regression **Wednesday, August 06, 2014, 3:23:36 PM**

Equation: User-Defined, 3Cake

f = 1/(10*a)*((1+2*a*100*x)^(1/2)-1)

R	Rsqr	Adj Rsqr	Standard Error of Estimate
0.9704	0.9416	0.9416	5.1851

	Coefficient	Std. Error	t	P
a	0.7130	0.0235	30.3992	<0.0001

Analysis of Variance:

	DF	SS	MS
Regression	1	99936.6740	99936.6740
Residual	50	1344.2562	26.8851
Total	51	101280.9302	1985.9006

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	0	21671.5354	(+inf)	(+inf)	(NAN)
Residual	50	1344.2562	26.8851		
Total	50	23015.7916	460.3158		

Statistical Tests:

Normality Test (Shapiro-Wilk) Failed (P = 0.0023)

W Statistic= 0.9212 Significance Level = 0.0500

Constant Variance Test Failed (P = <0.0001)

Fit Equation Description:

```
[Variables]
x = col(1)
y = col(2)
reciprocal_y = 1/abs(y)
reciprocal_ysquare = 1/y^2
reciprocal_pred = 1/abs(f)
reciprocal_predsqr = 1/f^2
'Automatic Initial Parameter Estimate Functions
F(q) = ape(x,y,1,0,1)
[Parameters]
a = F(0)[2] ''Auto {{previous: 0.713015}} {{MinRange: -4.5}} {{MaxRange: 1.5}}
[Equation]
f = 1/(10*a)*((1+2*a*100*x)^(1/2)-1)
fit f to y
''fit f to y with weight reciprocal_y
''fit f to y with weight reciprocal_ysquare
''fit f to y with weight reciprocal_pred
''fit f to y with weight reciprocal_predsqr
```

[Constraints]

a>0

[Options]

tolerance=0.0000000001

stepsize=1

iterations=200

Number of Iterations Performed = 8

3. **Cake-Intermediate**

Nonlinear Regression **Tuesday, July 08, 2014, 12:22:37 AM**

Equation: User-Defined, Cake-Intermediate

f = 1/a*Ln(abs(1+a/(b*10)*((1+2*b*100*x)^(0.5)-1)))

R	Rsqr	Adj Rsqr	Standard Error of Estimate
0.9700	0.9410	0.9398	5.2660

	Coefficient	Std. Error	t	P
a	1.6052E-010	0.0008	2.0368E-007	1.0000
b	0.6961	0.0177	39.2468	<0.0001

Analysis of Variance:

	DF	SS	MS
Regression	2	99922.1389	49961.0694
Residual	49	1358.7913	27.7304
Total	51	101280.9302	1985.9006

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	1	21657.0003	21657.0003	780.9831	<0.0001
Residual	49	1358.7913	27.7304		
Total	50	23015.7916	460.3158		

Statistical Tests:

Normality Test (Shapiro-Wilk) Failed (P = 0.0024)

W Statistic= 0.9216 Significance Level = 0.0500

Constant Variance Test Failed (P = <0.0001)

Fit Equation Description:

```
[Variables]
x = col(1)
y = col(2)
reciprocal_y = 1/abs(y)
reciprocal_ysquare = 1/y^2
reciprocal_pred = 1/abs(f)
reciprocal_predsqr = 1/f^2
'Automatic Initial Parameter Estimate Functions
F(q) = ape(x,exp(y),1,0,1)
[Parameters]
a = 0.1 ' {{previous: 1.60516e-010}}
b = 1 ' {{previous: 0.696074}}
[Equation]
f = 1/a*Ln(abs(1+a/(b*10)*((1+2*b*100*x)^(0.5)-1)))
fit f to y
''fit f to y with weight reciprocal_y
''fit f to y with weight reciprocal_ysquare
''fit f to y with weight reciprocal_pred
''fit f to y with weight reciprocal_predsqr
[Constraints]
a>0
b>0
[Options]
tolerance=0.0000000001
```

stepsize=0.5

iterations=200

Number of Iterations Performed = 31

4. Cake-Standard

Nonlinear Regression **Wednesday, July 23, 2014, 11:31:07 PM**

Equation: User-Defined, Cake-standard

a=sqrt(4/9+4*d/(30*e)+2*d^2*x/(3*e))

b=2/(9*(4/9+4*d/(30*e)+2*d^2*x/(3*e))^1.5)*(4/3+d/(10*e)-d^2*x/e)

f =2/d*(a*cos(2.09-0.33*arccos(b))+1/3)

R	Rsqr	Adj Rsqr	Standard Error of Estimate
0.9698	0.9405	0.9393	5.2860

	Coefficient	Std. Error	t	P
d	5024.5663	4898964.7397	0.0010	0.9992
e	0.7512	0.0254	29.6182	<0.0001

Analysis of Variance:

	DF	SS	MS
Regression	2	99911.7891	49955.8946
Residual	49	1369.1411	27.9417
Total	51	101280.9302	1985.9006

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	1	21646.6505	21646.6505	774.7090	<0.0001
Residual	49	1369.1411	27.9417		
Total	50	23015.7916	460.3158		

Statistical Tests:

Normality Test (Shapiro-Wilk) Failed (P = 0.0023)

W Statistic= 0.9209 Significance Level = 0.0500

Constant Variance Test Failed (P = <0.0001)

Fit Equation Description:

```
[Variables]
x = col(1)
y = col(2)
reciprocal_y = 1/abs(y)
reciprocal_ysquare = 1/y^2
reciprocal_pred = 1/abs(f)
reciprocal_predsqr = 1/f^2
'Automatic Initial Parameter Estimate Functions
first(q) = if(size(q)<10,size(q)-1,int(0.9*size(q)))
ylast(q) = mean(q[data(first(q),size(q))])
[Parameters]
d = 0.05 ' {{previous: 5024.57}}
e = 0.71 ' {{previous: 0.751211}}
[Equation]
f =2/d*(a*cos(2.09-0.33*arccos(b))+1/3)
a=sqrt(4/9+4*d/(30*e)+2*d^2*x/(3*e))
b=2/(9*(4/9+4*d/(30*e)+2*d^2*x/(3*e))^1.5)*(4/3+d/(10*e)-d^2*x/e)
fit f to y
''fit f to y with weight reciprocal_y
''fit f to y with weight reciprocal_ysquare
''fit f to y with weight reciprocal_pred
''fit f to y with weight reciprocal_predsqr
[Constraints]
[Options]
```

tolerance=0.0000000001

stepsize=1

iterations=200

Number of Iterations Performed = 283

5. **Intermediate**

Nonlinear Regression **Wednesday, August 06, 2014, 3:22:23 PM**

Equation: User-Defined, 2Intermediate

f = if(x>0, 1/a*ln(abs(1+a*10*x)), 0)

R	Rsqr	Adj Rsqr	Standard Error of Estimate
0.7042	0.4959	0.4959	15.2330

	Coefficient	Std. Error	t	P
a	0.1586	0.0094	16.9302	<0.0001

Analysis of Variance:

	DF	SS	MS
Regression	1	89678.7339	89678.7339
Residual	50	11602.1963	232.0439
Total	51	101280.9302	1985.9006

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	0	11413.5953	(+inf)	(+inf)	(NAN)
Residual	50	11602.1963	232.0439		
Total	50	23015.7916	460.3158		

Statistical Tests:

Normality Test (Shapiro-Wilk) Failed (P = 0.0047)

W Statistic= 0.9294 Significance Level = 0.0500

Constant Variance Test Passed (P = 0.1467)

Fit Equation Description:

```
[Variables]
x = col(1)
y = col(2)
reciprocal_y = 1/abs(y)
reciprocal_ysquare = 1/y^2
reciprocal_pred = 1/abs(f)
reciprocal_predsqr = 1/f^2
'Automatic Initial Parameter Estimate Functions
F(q) = ape(ln(abs(x)),y,1,0,1)
[Parameters]
a = F(0)[2] ''Auto {{previous: 0.158583}}
[Equation]
f = if(x>0, 1/a*ln(abs(1+a*10*x)), 0)
fit f to y
''fit f to y with weight reciprocal_y
''fit f to y with weight reciprocal_ysquare
''fit f to y with weight reciprocal_pred
''fit f to y with weight reciprocal_predsqr
[Constraints]
[Options]
tolerance=0.0000000001
stepsize=1
iterations=200
```

Number of Iterations Performed = 13

II. After Cleaning

1. Cake-Complete

Nonlinear Regression **Tuesday, July 08, 2014, 12:34:13 AM**

Equation: User-Defined, Cake-Complete

f = 10/a*(1-exp(-a/(b*100)*(sqrt(1+2*b*100*x)-1)))

R	**Rsqr**	**Adj Rsqr**	**Standard Error of Estimate**
0.9992	0.9983	0.9983	0.7353

	Coefficient	**Std. Error**	**t**	**P**
a	-0.2910	0.0115	-25.3098	<0.0001
b	1.9846	0.0538	36.9190	<0.0001

Analysis of Variance:

	DF	**SS**	**MS**
Regression	2	67350.1010	33675.0505
Residual	40	21.6262	0.5407
Total	42	67371.7272	1604.0887

Corrected for the mean of the observations:

	DF	**SS**	**MS**	**F**	**P**
Regression	1	12705.5422	12705.5422	23500.2859	<0.0001
Residual	40	21.6262	0.5407		
Total	41	12727.1683	310.4187		

Statistical Tests:

Normality Test (Shapiro-Wilk) Failed (P = 0.0009)

W Statistic= 0.8927   Significance Level = 0.0500

Constant Variance Test   Failed   (P = 0.0075)

Fit Equation Description:

```
[Variables]
x = col(1)
y = col(2)
reciprocal_y = 1/abs(y)
reciprocal_ysquare = 1/y^2
reciprocal_pred = 1/abs(f)
reciprocal_predsqr = 1/f^2
'Automatic Initial Parameter Estimate Functions
first(q) = if(size(q)<10,size(q)-1,int(0.9*size(q)))
ylast(q) = mean(q[data(first(q),size(q))])
[Parameters]
a = ylast(y) ''Auto {{previous: -0.290979}} {{MinRange: 6}} {{MaxRange: 18}}
b = if(x50(x,y,.5)-min(x)>0, -ln(.5)/(x50(x,y,.5)-min(x)), 1) ''Auto {{previous: 1.98458}}
[Equation]
f = 10/a*(1-exp(-a/(b*100)*(sqrt(1+2*b*100*x)-1)))
fit f to y
''fit f to y with weight reciprocal_y
''fit f to y with weight reciprocal_ysquare
''fit f to y with weight reciprocal_pred
''fit f to y with weight reciprocal_predsqr
[Constraints]
b>0
[Options]
tolerance=0.0000000001
stepsize=1
iterations=200
```

Number of Iterations Performed = 33

2. Cake

Nonlinear Regression **Thursday, July 24, 2014, 1:20:32 PM**

Equation: User-Defined, 3Cake

f = 1/(10*a)*((1+2*a*100*x)^(1/2)-1)

R	Rsqr	Adj Rsqr	Standard Error of Estimate
0.9715	0.9439	0.9439	4.1737

	Coefficient	Std. Error	t	P
a	0.7938	0.0257	30.8411	<0.0001

Analysis of Variance:

	DF	SS	MS
Regression	1	66657.4999	66657.4999
Residual	41	714.2273	17.4202
Total	42	67371.7272	1604.0887

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	0	12012.9411	(+inf)	(+inf)	(NAN)
Residual	41	714.2273	17.4202		
Total	41	12727.1683	310.4187		

Statistical Tests:

Normality Test (Shapiro-Wilk) Failed (P = 0.0037)

W Statistic= 0.9135 Significance Level = 0.0500

Constant Variance Test Passed (P = 0.1190)

Fit Equation Description:

[Variables]

```
x = col(1)
y = col(2)
reciprocal_y = 1/abs(y)
reciprocal_ysquare = 1/y^2
reciprocal_pred = 1/abs(f)
reciprocal_predsqr = 1/f^2
'Automatic Initial Parameter Estimate Functions
F(q) = ape(x,y,1,0,1)
[Parameters]
a = F(0)[2] ''Auto {{previous: 0.793829}} {{MinRange: -4.5}} {{MaxRange: 1.5}}
[Equation]
f = 1/(10*a)*((1+2*a*100*x)^(1/2)-1)
fit f to y
''fit f to y with weight reciprocal_y
''fit f to y with weight reciprocal_ysquare
''fit f to y with weight reciprocal_pred
''fit f to y with weight reciprocal_predsqr
[Constraints]
a>0
[Options]
tolerance=0.0000000001
stepsize=1
iterations=200
```

Number of Iterations Performed = 9

3. Cake-Intermediate

Nonlinear Regression **Thursday, July 24, 2014, 1:11:40 PM**

Equation: User-Defined, Cake-Intermediate

f = 1/a*Ln(abs(1+a/(b*10)*((1+2*b*100*x)^(0.5)-1)))

R	Rsqr	Adj Rsqr	Standard Error of Estimate
0.9712	0.9433	0.9418	4.2488

	Coefficient	Std. Error	t	P
a	2.1553E-011	0.0007	3.0802E-008	1.0000
b	0.7768	0.0065	119.2967	<0.0001

Analysis of Variance:

	DF	SS	MS
Regression	2	66649.6396	33324.8198
Residual	40	722.0876	18.0522
Total	42	67371.7272	1604.0887

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	1	12005.0807	12005.0807	665.0207	<0.0001
Residual	40	722.0876	18.0522		
Total	41	12727.1683	310.4187		

Statistical Tests:

Normality Test (Shapiro-Wilk) Failed (P = 0.0032)

W Statistic= 0.9112 Significance Level = 0.0500

Constant Variance Test Failed (P = 0.0418)

Fit Equation Description:

[Variables]

x = col(1)

y = col(2)

reciprocal_y = 1/abs(y)

reciprocal_ysquare = 1/y^2

reciprocal_pred = 1/abs(f)

reciprocal_predsqr = 1/f^2

'Automatic Initial Parameter Estimate Functions

F(q) = ape(x,exp(y),1,0,1)

[Parameters]

a = .1 ' {{previous: 2.15527e-011}}

b = 0.349981 ' {{previous: 0.776815}}

[Equation]

f = 1/a*Ln(abs(1+a/(b*10)*((1+2*b*100*x)^(0.5)-1)))

fit f to y

''fit f to y with weight reciprocal_y

''fit f to y with weight reciprocal_ysquare

''fit f to y with weight reciprocal_pred

''fit f to y with weight reciprocal_predsqr

[Constraints]

a>0

b>0

[Options]

tolerance=0.0000000001

stepsize=0.5

iterations=200

Number of Iterations Performed = 44

4. **Cake-Standard**

Nonlinear Regression **Thursday, July 24, 2014, 1:15:09 PM**

Equation: User-Defined, Cake-standard

a=sqrt(4/9+4*d/(30*e)+2*d^2*x/(3*e))

b=2/(9*(4/9+4*d/(30*e)+2*d^2*x/(3*e))^1.5)*(4/3+d/(10*e)-d^2*x/e)

f = 2/d*(a*cos(2.09-0.33*arccos(b))+1/3)

R	**Rsqr**	**Adj Rsqr**	**Standard Error of Estimate**
0.9710	0.9429	0.9415	4.2625

	Coefficient	Std. Error	t	P
d	923.1748	313672.3129	0.0029	0.9977
e	0.8363	0.0288	29.0144	<0.0001

Analysis of Variance:

	DF	SS	MS
Regression	2	66644.9597	33322.4798
Residual	40	726.7675	18.1692
Total	42	67371.7272	1604.0887

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	1	12000.4009	12000.4009	660.4809	<0.0001
Residual	40	726.7675	18.1692		
Total	41	12727.1683	310.4187		

Statistical Tests:

Normality Test (Shapiro-Wilk) Failed (P = 0.0039)

W Statistic= 0.9141 Significance Level = 0.0500

Constant Variance Test Passed (P = 0.1114)

Fit Equation Description:

```
[Variables]
x = col(1)
y = col(2)
reciprocal_y = 1/abs(y)
reciprocal_ysquare = 1/y^2
reciprocal_pred = 1/abs(f)
reciprocal_predsqr = 1/f^2
'Automatic Initial Parameter Estimate Functions
first(q) = if(size(q)<10,size(q)-1,int(0.9*size(q)))
ylast(q) = mean(q[data(first(q),size(q))])
[Parameters]
```

```
d = 0.05 ' {{previous: 923.175}}
e = 0.71 ' {{previous: 0.836326}}
[Equation]
a=sqrt(4/9+4*d/(30*e)+2*d^2*x/(3*e))
b=2/(9*(4/9+4*d/(30*e)+2*d^2*x/(3*e))^1.5)*(4/3+d/(10*e)-d^2*x/e)
f = 2/d*(a*cos(2.09-0.33*arccos(b))+1/3)
fit f to y
''fit f to y with weight reciprocal_y
''fit f to y with weight reciprocal_ysquare
''fit f to y with weight reciprocal_pred
''fit f to y with weight reciprocal_predsqr
[Constraints]
[Options]
tolerance=0.0000000001
stepsize=1
iterations=200
```

Number of Iterations Performed = 190

5. **Intermediate**

Nonlinear Regression **Thursday, July 24, 2014, 1:19:19 PM**

Equation: User-Defined, 2Intermediate

f = if(x>0, 1/a*ln(abs(1+a*10*x)), 0)

R	Rsqr	Adj Rsqr	Standard Error of Estimate
0.7115	0.5062	0.5062	12.3804

	Coefficient	Std. Error	t	P
a	0.1758	0.0102	17.1758	<0.0001

Analysis of Variance:

	DF	SS	MS
Regression	1	61087.4418	61087.4418
Residual	41	6284.2854	153.2753
Total	42	67371.7272	1604.0887

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	0	6442.8830	(+inf)	(+inf)	(NAN)
Residual	41	6284.2854	153.2753		
Total	41	12727.1683	310.4187		

Statistical Tests:

Normality Test (Shapiro-Wilk) Passed (P = 0.0764)

W Statistic= 0.9520 Significance Level = 0.0500

Constant Variance Test Passed (P = 0.5956)

Fit Equation Description:

[Variables]

x = col(1)

y = col(2)

reciprocal_y = 1/abs(y)

reciprocal_ysquare = 1/y^2

reciprocal_pred = 1/abs(f)

reciprocal_predsqr = 1/f^2

'Automatic Initial Parameter Estimate Functions

F(q) = ape(ln(abs(x)),y,1,0,1)

[Parameters]

a = F(0)[2] ''Auto {{previous: 0.175757}}

[Equation]

```
f = if(x>0, 1/a*ln(abs(1+a*10*x)), 0)
fit f to y
''fit f to y with weight reciprocal_y
''fit f to y with weight reciprocal_ysquare
''fit f to y with weight reciprocal_pred
''fit f to y with weight reciprocal_predsqr
[Constraints]
[Options]
tolerance=0.0000000001
stepsize=1
iterations=200
```

Number of Iterations Performed = 13

Appendix H: Statistical Reports of the 5 Best-Fit Fouling Models for 4 Hours Off – 30 Minutes On

Model's Fit Error and Estimated Parameter Values for Passive Membrane Permeation with ON/OFF Air Ratio of 0.13

Model	SSR	Fitted Parameters values*	s
Cake-Complete	6.69×10^{1}	K_b = -0.277,	0.0280
		K_c = 2.80	0.1702
Cake	3.59×10^{2}	K_c = 1.29	0.0319
Cake- Intermediate	3.62×10^{2}	$K_i = 5.64\times10^{-10}$,	0.0012
		K_c = 1.27	0.0525
Cake-Standard	3.65×10^{2}	$K_s = 4.52\times10^{6}$,	100698884844.8935
		K_c = 1.36	0.0341
Intermediate	4.05×10^{3}	K_i = 0.214	0.0106
Intermediate - Standard	4.05×10^{3}	K_i = 0.214,	0.0305
		$K_s = 8.66\times10^{-20}$	0.0002
Complete - Standard	6.51×10^{3}	$K_b = 4.57\times10^{-16}$,	272999.3933
		K_s = 0.0607	0.0000
Standard	7.28×10^{3}	K_s = 0.0607	0.0036
Complete	7.62×10^{3}	K_b = 0.308	0.0188

1. **Cake-Complete**

Nonlinear Regression **Tuesday, July 08, 2014, 12:42:03 AM**

Equation: User-Defined, Cake-Complete

f = 10/a*(1-exp(-a/(b*100)*(sqrt(1+2*b*100*x)-1)))

R	**Rsqr**	**Adj Rsqr**	**Standard Error of Estimate**
0.9961	0.9923	0.9921	1.2475

Coefficient	**Std. Error**	**t**	**P**	
a	-0.2765	0.0280	-9.8674	<0.0001
b	2.8015	0.1702	16.4552	<0.0001

Analysis of Variance:

	DF	SS	MS
Regression	2	53868.2406	26934.1203
Residual	43	66.9181	1.5562
Total	45	53935.1587	1198.5591

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	1	8575.4425	8575.4425	5510.3757	<0.0001
Residual	43	66.9181	1.5562		
Total	44	8642.3607	196.4173		

Statistical Tests:

Normality Test (Shapiro-Wilk) Failed (P = 0.0025)

W Statistic= 0.9132 Significance Level = 0.0500

Constant Variance Test Passed (P = 0.0706)

Fit Equation Description:

[Variables]

x = col(1)

y = col(2)

reciprocal_y = 1/abs(y)

reciprocal_ysquare = 1/y^2

reciprocal_pred = 1/abs(f)

reciprocal_predsqr = 1/f^2

'Automatic Initial Parameter Estimate Functions

first(q) = if(size(q)<10,size(q)-1,int(0.9*size(q)))

ylast(q) = mean(q[data(first(q),size(q))])

[Parameters]

```
a = ylast(y) ''Auto {{previous: -0.276539}} {{MinRange: 6}} {{MaxRange: 18}}
b = if(x50(x,y,.5)-min(x)>0, -ln(.5)/(x50(x,y,.5)-min(x)), 1) ''Auto {{previous: 2.80147}}
[Equation]
f = 10/a*(1-exp(-a/(b*100)*(sqrt(1+2*b*100*x)-1)))
fit f to y
''fit f to y with weight reciprocal_y
''fit f to y with weight reciprocal_ysquare
''fit f to y with weight reciprocal_pred
''fit f to y with weight reciprocal_predsqr
[Constraints]
b>0
[Options]
tolerance=0.0000000001
stepsize=1
iterations=200
```

Number of Iterations Performed = 31

2. **Cake**

Nonlinear Regression **Thursday, July 24, 2014, 12:24:56 AM**

Equation: User-Defined, 3Cake

f = 1/(10*a)*((1+2*a*100*x)^(1/2)-1)

R	**Rsqr**	**Adj Rsqr**	**Standard Error of Estimate**
0.9790	0.9584	0.9584	2.8574

	Coefficient	**Std. Error**	**t**	**P**
a	1.2887	0.0319	40.4184	<0.0001

Analysis of Variance:

	DF	SS	MS
Regression	1	53575.8982	53575.8982
Residual	44	359.2604	8.1650
Total	45	53935.1587	1198.5591

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	0	8283.1002	(+inf)	(+inf)	(NAN)
Residual	44	359.2604	8.1650		
Total	44	8642.3607	196.4173		

Statistical Tests:

Normality Test (Shapiro-Wilk) Failed (P = 0.0006)

W Statistic= 0.8945 Significance Level = 0.0500

Constant Variance Test Failed (P = 0.0239)

Fit Equation Description:

[Variables]

x = col(1)

y = col(2)

reciprocal_y = 1/abs(y)

reciprocal_ysquare = 1/y^2

reciprocal_pred = 1/abs(f)

reciprocal_predsqr = 1/f^2

'Automatic Initial Parameter Estimate Functions

F(q) = ape(x,y,1,0,1)

[Parameters]

a = F(0)[2] ''Auto {{previous: 1.28865}} {{MinRange: -4.5}} {{MaxRange: 1.5}}

[Equation]

f = 1/(10*a)*((1+2*a*100*x)^(1/2)-1)

fit f to y

''fit f to y with weight reciprocal_y

''fit f to y with weight reciprocal_ysquare

''fit f to y with weight reciprocal_pred

''fit f to y with weight reciprocal_predsqr

[Constraints]

a>0

[Options]

tolerance=0.0000000001

stepsize=1

iterations=200

Number of Iterations Performed = 9

3. <u>Cake-Intermediate</u>

Nonlinear Regression **Tuesday, July 08, 2014, 12:44:47 AM**

Equation: User-Defined, Cake-Intermediate

f = 1/a*Ln(abs(1+a/(b*10)*((1+2*b*100*x)^(0.5)-1)))

R	Rsqr	Adj Rsqr	Standard Error of Estimate
0.9788	0.9581	0.9572	2.9008

	Coefficient	Std. Error	t	P
a	5.6415E-010	0.0012	4.6789E-007	1.0000
b	1.2709	0.0525	24.1955	<0.0001

Analysis of Variance:

	DF	SS	MS
Regression	2	53573.3213	26786.6607
Residual	43	361.8374	8.4148
Total	45	53935.1587	1198.5591

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	1	8280.5233	8280.5233	984.0401	<0.0001
Residual	43	361.8374	8.4148		
Total	44	8642.3607	196.4173		

Statistical Tests:

Normality Test (Shapiro-Wilk) Failed (P = 0.0006)

W Statistic= 0.8927 Significance Level = 0.0500

Constant Variance Test Failed (P = 0.0051)

Fit Equation Description:

[Variables]

x = col(1)

y = col(2)

reciprocal_y = 1/abs(y)

reciprocal_ysquare = 1/y^2

reciprocal_pred = 1/abs(f)

reciprocal_predsqr = 1/f^2

'Automatic Initial Parameter Estimate Functions

F(q) = ape(x,exp(y),1,0,1)

[Parameters]

a = 0.1 ' {{previous: 5.64153e-010}}

b = 1 ' {{previous: 1.27093}}

[Equation]

f = 1/a*Ln(abs(1+a/(b*10)*((1+2*b*100*x)^(0.5)-1)))

fit f to y

''fit f to y with weight reciprocal_y

''fit f to y with weight reciprocal_ysquare

''fit f to y with weight reciprocal_pred

''fit f to y with weight reciprocal_predsqr

[Constraints]

a>0

b>0

[Options]

tolerance=0.0000000001

stepsize=0.5

iterations=200

Number of Iterations Performed = 29

4. <u>**Cake-Standard**</u>

Nonlinear Regression **Thursday, July 24, 2014, 12:19:47 AM**

Equation: User-Defined, Cake-standard

a=sqrt(4/9+4*d/(30*e)+2*d^2*x/(3*e))

b=2/(9*(4/9+4*d/(30*e)+2*d^2*x/(3*e))^1.5)*(4/3+d/(10*e)-d^2*x/e)

f = 2/d*(a*cos(2.09-0.33*arccos(b))+1/3)

R	Rsqr	Adj Rsqr	Standard Error of Estimate
0.9787	0.9578	0.9568	2.9134

	Coefficient	Std. Error	t	P
d	4523119.0642	100698884844.8935	4.4917E-005	1.0000
e	1.3552	0.0341	39.7177	<0.0001

Analysis of Variance:

	DF	SS	MS
Regression	2	53570.1707	26785.0853
Residual	43	364.9880	8.4881
Total	45	53935.1587	1198.5591

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	1	8277.3726	8277.3726	975.1745	<0.0001
Residual	43	364.9880	8.4881		
Total	44	8642.3607	196.4173		

Statistical Tests:

Normality Test (Shapiro-Wilk) Failed (P = 0.0006)

W Statistic= 0.8947 Significance Level = 0.0500

Constant Variance Test Failed (P = 0.0239)

Fit Equation Description:

```
[Variables]
x = col(1)
y = col(2)
reciprocal_y = 1/abs(y)
reciprocal_ysquare = 1/y^2
reciprocal_pred = 1/abs(f)
reciprocal_predsqr = 1/f^2
'Automatic Initial Parameter Estimate Functions
first(q) = if(size(q)<10,size(q)-1,int(0.9*size(q)))
ylast(q) = mean(q[data(first(q),size(q))])
[Parameters]
```

d = 0.05 ' {{previous: 4.52312e+006}}

e = 0.71 ' {{previous: 1.35517}}

[Equation]

a=sqrt(4/9+4*d/(30*e)+2*d^2*x/(3*e))

b=2/(9*(4/9+4*d/(30*e)+2*d^2*x/(3*e))^1.5)*(4/3+d/(10*e)-d^2*x/e)

f = 2/d*(a*cos(2.09-0.33*arccos(b))+1/3)

fit f to y

''fit f to y with weight reciprocal_y

''fit f to y with weight reciprocal_ysquare

''fit f to y with weight reciprocal_pred

''fit f to y with weight reciprocal_predsqr

[Constraints]

[Options]

tolerance=0.0000000001

stepsize=1

iterations=200

Number of Iterations Performed = 10

5. **Intermediate**

Nonlinear Regression **Thursday, July 24, 2014, 12:24:15 AM**

Equation: User-Defined, 2Intermediate

f = if(x>0, 1/a*ln(abs(1+a*10*x)), 0)

R	Rsqr	Adj Rsqr	Standard Error of Estimate
0.7289	0.5312	0.5312	9.5956

	Coefficient	Std. Error	t	P
a	0.2142	0.0106	20.1864	<0.0001

Analysis of Variance:

	DF	SS	MS
Regression	1	49883.8509	49883.8509
Residual	44	4051.3078	92.0752
Total	45	53935.1587	1198.5591

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	0	4591.0529	(+inf)	(+inf)	(NAN)
Residual	44	4051.3078	92.0752		
Total	44	8642.3607	196.4173		

Statistical Tests:

Normality Test (Shapiro-Wilk) Failed (P = 0.0098)

W Statistic= 0.9306 Significance Level = 0.0500

Constant Variance Test Passed (P = 0.2547)

Fit Equation Description:

[Variables]

x = col(1)

y = col(2)

reciprocal_y = 1/abs(y)

reciprocal_ysquare = 1/y^2

reciprocal_pred = 1/abs(f)

reciprocal_predsqr = 1/f^2

'Automatic Initial Parameter Estimate Functions

F(q) = ape(ln(abs(x)),y,1,0,1)

[Parameters]

```
a = F(0)[2] ''Auto {{previous: 0.214202}}
[Equation]
f = if(x>0, 1/a*ln(abs(1+a*10*x)), 0)
fit f to y
''fit f to y with weight reciprocal_y
''fit f to y with weight reciprocal_ysquare
''fit f to y with weight reciprocal_pred
''fit f to y with weight reciprocal_predsqr
[Constraints]
[Options]
tolerance=0.0000000001
stepsize=1
iterations=200
```

Number of Iterations Performed = 13

Appendix I: Statistical Reports of the 5 Best-Fit Fouling Models for 4 Hours Off – 5 Minutes On

Model's Fit Error and Estimated Parameter Values for Passive Membrane Permeation with ON/OFF Air Ratio of 0.02

Model	SSR	Fitted Parameters values*	s
Cake-Complete	7.77	K_b =-0.381, K_c = 3.89	0.0202 0.1283
Cake	$1.71x10^{2}$	K_c = 1.73	0.0531
Cake- Intermediate	$1.73x10^{2}$	K_i = $2.41x10^{-10}$, K_c = 1.70	0.0012 0.0343
Cake-Standard	$1.73x10^{2}$	K_s = 1.04 $x10^{3}$, K_b = 1.82	293937.7702 0.0606
Intermediate	$2.00x10^{3}$	K_i = 0.289	0.0182
Intermediate - Standard	$2.00x10^{3}$	K_i = 0.289, K_s = $7.01x10^{-19}$	0.0468 0.0003
Complete - Standard	$3.54x10^{3}$	K_b = $1.00x10^{-4}$, K_s = 0.0828	7213.7470 721.4330
Standard	$3.54x10^{3}$	K_s= 0.0828	0.0063
Complete	$3.70x10^{3}$	K_b = 0.421	0.0327

1. **Cake-Complete**

Nonlinear Regression **Tuesday, July 08, 2014, 1:00:09 AM**

Equation: User-Defined, Cake-Complete

f = 10/a*(1-exp(-a/(b*100)*(sqrt(1+2*b*100*x)-1)))

R	Rsqr	Adj Rsqr	Standard Error of Estimate
0.9991	0.9981	0.9981	0.4928

	Coefficient	Std. Error	t	P
a	-0.3812	0.0202	-18.8332	<0.0001
b	3.8818	0.1283	30.2629	<0.0001

Analysis of Variance:

	DF	SS	MS
Regression	2	22272.8813	11136.4407
Residual	32	7.7704	0.2428
Total	34	22280.6518	655.3133

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	1	4166.7299	4166.7299	17159.3157	<0.0001
Residual	32	7.7704	0.2428		
Total	33	4174.5003	126.5000		

Statistical Tests:

Normality Test (Shapiro-Wilk) Failed (P = 0.0092)

W Statistic= 0.9113 Significance Level = 0.0500

Constant Variance Test Passed (P = 0.5982)

Fit Equation Description:

```
[Variables]
x = col(1)
y = col(2)
reciprocal_y = 1/abs(y)
reciprocal_ysquare = 1/y^2
reciprocal_pred = 1/abs(f)
reciprocal_predsqr = 1/f^2
'Automatic Initial Parameter Estimate Functions
first(q) = if(size(q)<10,size(q)-1,int(0.9*size(q)))
ylast(q) = mean(q[data(first(q),size(q))])
[Parameters]
```

a = ylast(y) ''Auto {{previous: -0.381185}} {{MinRange: 6}} {{MaxRange: 18}}

b = if(x50(x,y,.5)-min(x)>0, -ln(.5)/(x50(x,y,.5)-min(x)), 1) ''Auto {{previous: 3.88176}}

[Equation]

f = 10/a*(1-exp(-a/(b*100)*(sqrt(1+2*b*100*x)-1)))

fit f to y

''fit f to y with weight reciprocal_y

''fit f to y with weight reciprocal_ysquare

''fit f to y with weight reciprocal_pred

''fit f to y with weight reciprocal_predsqr

[Constraints]

b>0

[Options]

tolerance=0.0000000001

stepsize=1

iterations=200

Number of Iterations Performed = 31

2. **Cake**

Nonlinear Regression **Thursday, July 24, 2014, 12:43:33 AM**

Equation: User-Defined, 3Cake

f = 1/(10*a)*((1+2*a*100*x)^(1/2)-1)

R	Rsqr	Adj Rsqr	Standard Error of Estimate
0.9793	0.9591	0.9591	2.2753

	Coefficient	Std. Error	t	P
a	1.7322	0.0531	32.6094	<0.0001

Analysis of Variance:

	DF	SS	MS
Regression	1	22109.8155	22109.8155
Residual	33	170.8362	5.1769
Total	34	22280.6518	655.3133

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	0	4003.6641	(+inf)	(+inf)	(NAN)
Residual	33	170.8362	5.1769		
Total	33	4174.5003	126.5000		

Statistical Tests:

Normality Test (Shapiro-Wilk) Failed (P = 0.0004)

W Statistic= 0.8578 Significance Level = 0.0500

Constant Variance Test Passed (P = 0.1576)

Fit Equation Description:

[Variables]

x = col(1)

y = col(2)

reciprocal_y = 1/abs(y)

reciprocal_ysquare = 1/y^2

reciprocal_pred = 1/abs(f)

reciprocal_predsqr = 1/f^2

'Automatic Initial Parameter Estimate Functions

F(q) = ape(x,y,1,0,1)

[Parameters]

a = F(0)[2] ''Auto {{previous: 1.73219}} {{MinRange: -4.5}} {{MaxRange: 1.5}}

[Equation]

f = 1/(10*a)*((1+2*a*100*x)^(1/2)-1)

fit f to y

''fit f to y with weight reciprocal_y

''fit f to y with weight reciprocal_ysquare

''fit f to y with weight reciprocal_pred

''fit f to y with weight reciprocal_predsqr

[Constraints]

a>0

[Options]

tolerance=0.0000000001

stepsize=1

iterations=200

Number of Iterations Performed = 10

3. Cake-Intermediate

Nonlinear Regression **Tuesday, July 08, 2014, 1:01:59 AM**

Equation: User-Defined, Cake-Intermediate

f = 1/a*Ln(abs(1+a/(b*10)*((1+2*b*100*x)^(0.5)-1)))

R	**Rsqr**	**Adj Rsqr**	**Standard Error of Estimate**
0.9791	0.9587	0.9574	2.3224

	Coefficient	**Std. Error**	**t**	**P**
a	2.4066E-010	0.0012	1.9681E-007	1.0000
b	1.7016	0.0343	49.6777	<0.0001

Analysis of Variance:

	DF	SS	MS
Regression	2	22108.0554	11054.0277
Residual	32	172.5964	5.3936
Total	34	22280.6518	655.3133

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	1	4001.9039	4001.9039	741.9676	<0.0001
Residual	32	172.5964	5.3936		
Total	33	4174.5003	126.5000		

Statistical Tests:

Normality Test (Shapiro-Wilk) Failed (P = 0.0003)

W Statistic= 0.8515 Significance Level = 0.0500

Constant Variance Test Failed (P = 0.0017)

Fit Equation Description:

[Variables]

x = col(1)

y = col(2)

reciprocal_y = 1/abs(y)

reciprocal_ysquare = 1/y^2

reciprocal_pred = 1/abs(f)

reciprocal_predsqr = 1/f^2

'Automatic Initial Parameter Estimate Functions

F(q) = ape(x,exp(y),1,0,1)

[Parameters]

a = 0.1 ' {{previous: 2.40664e-010}}

b = 1 ' {{previous: 1.70163}}

[Equation]

f = 1/a*Ln(abs(1+a/(b*10)*((1+2*b*100*x)^(0.5)-1)))

fit f to y

''fit f to y with weight reciprocal_y

''fit f to y with weight reciprocal_ysquare

''fit f to y with weight reciprocal_pred

''fit f to y with weight reciprocal_predsqr

[Constraints]

a>0

b>0

[Options]

tolerance=0.0000000001

stepsize=0.5

iterations=200

Number of Iterations Performed = 28

4. Cake-Standard

Nonlinear Regression **Thursday, July 24, 2014, 12:48:27 AM**

Equation: User-Defined, Cake-standard

a=sqrt(4/9+4*d/(30*e)+2*d^2*x/(3*e))

b=2/(9*(4/9+4*d/(30*e)+2*d^2*x/(3*e))^1.5)*(4/3+d/(10*e)-d^2*x/e)

f = 2/d*(a*cos(2.09-0.33*arccos(b))+1/3)

R	**Rsqr**	**Adj Rsqr**	**Standard Error of Estimate**
0.9790	0.9585	0.9572	2.3279

	Coefficient	**Std. Error**	**t**	**P**
d	1041.7596	293937.7702	0.0035	0.9972
e	1.8216	0.0606	30.0545	<0.0001

Analysis of Variance:

	DF	SS	MS
Regression	2	22107.2358	11053.6179
Residual	32	173.4159	5.4192
Total	34	22280.6518	655.3133

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	1	4001.0844	4001.0844	738.3099	<0.0001
Residual	32	173.4159	5.4192		
Total	33	4174.5003	126.5000		

Statistical Tests:

Normality Test (Shapiro-Wilk) Failed (P = 0.0005)

W Statistic= 0.8592 Significance Level = 0.0500

Constant Variance Test Passed (P = 0.1597)

Fit Equation Description:

```
[Variables]
x = col(1)
y = col(2)
reciprocal_y = 1/abs(y)
reciprocal_ysquare = 1/y^2
reciprocal_pred = 1/abs(f)
reciprocal_predsqr = 1/f^2
'Automatic Initial Parameter Estimate Functions
first(q) = if(size(q)<10,size(q)-1,int(0.9*size(q)))
ylast(q) = mean(q[data(first(q),size(q))])
[Parameters]
d = 0.05 ' {{previous: 1041.76}}
e = 0.71 ' {{previous: 1.82162}}
[Equation]
a=sqrt(4/9+4*d/(30*e)+2*d^2*x/(3*e))
b=2/(9*(4/9+4*d/(30*e)+2*d^2*x/(3*e))^1.5)*(4/3+d/(10*e)-d^2*x/e)
```

f = 2/d*(a*cos(2.09-0.33*arccos(b))+1/3)

fit f to y

"fit f to y with weight reciprocal_y

"fit f to y with weight reciprocal_ysquare

"fit f to y with weight reciprocal_pred

"fit f to y with weight reciprocal_predsqr

[Constraints]

[Options]

tolerance=0.0000000001

stepsize=1

iterations=200

Number of Iterations Performed = 150

5. Intermediate

Nonlinear Regression **Thursday, July 24, 2014, 12:43:00 AM**

Equation: User-Defined, 2Intermediate

f = if(x>0, 1/a*ln(abs(1+a*10*x)), 0)

R	Rsqr	Adj Rsqr	Standard Error of Estimate
0.7214	0.5205	0.5205	7.7884

	Coefficient	Std. Error	t	P
a	0.2889	0.0182	15.8591	<0.0001

Analysis of Variance:

	DF	SS	MS
Regression	1	20278.9119	20278.9119
Residual	33	2001.7399	60.6588
Total	34	22280.6518	655.3133

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	0	2172.7605	(+inf)	(+inf)	(NAN)
Residual	33	2001.7399	60.6588		
Total	33	4174.5003	126.5000		

Statistical Tests:

Normality Test (Shapiro-Wilk) Passed (P = 0.0725)

W Statistic= 0.9424 Significance Level = 0.0500

Constant Variance Test Passed (P = 0.6030)

Fit Equation Description:

```
[Variables]
x = col(1)
y = col(2)
reciprocal_y = 1/abs(y)
reciprocal_ysquare = 1/y^2
reciprocal_pred = 1/abs(f)
reciprocal_predsqr = 1/f^2
'Automatic Initial Parameter Estimate Functions
F(q) = ape(ln(abs(x)),y,1,0,1)
[Parameters]
a = F(0)[2] ''Auto {{previous: 0.288906}}
[Equation]
f = if(x>0, 1/a*ln(abs(1+a*10*x)), 0)
fit f to y
''fit f to y with weight reciprocal_y
''fit f to y with weight reciprocal_ysquare
''fit f to y with weight reciprocal_pred
''fit f to y with weight reciprocal_predsqr
```

[Constraints]

[Options]

tolerance=0.0000000001

stepsize=1

iterations=200

Number of Iterations Performed = 11

Appendix J: Statistical Reports of the 5 Best-Fit Fouling Models for No Aeration

Model's Fit Error and Estimated Parameter Values for Passive Membrane Permeation with ON/OFF Air Ratio of 0

Model	SSR	Fitted Parameters values*	s
Cake-Complete	1.40	$K_b = -1.34$, $K_c = 23.5$	0.0773 1.0042
Cake	3.45×10^1	$K_c = 8.50$	0.3959
Cake-Standard	3.49×10^1	$K_s = 5.02 \times 10^6$, $K_c = 8.93$	111766502193.6843 0.4242
Cake- Intermediate	3.50×10^1	$K_i = 2.90 \times 10^{-9}$, $K_c = 8.25$	0.0097 0.7458
Intermediate	4.40×10^2	$K_i = 0.945$	0.0994
Intermediate - Standard	4.40×10^2	$K_i = 0.945$, $K_s = 1.39 \times 10^{-18}$	0.1923 0.0006
Standard	8.12×10^2	$K_s = 0.290$	0.0415
Complete - Standard	8.12×10^2	$K_b = 4.00 \times 10^{-4}$, $K_s = 0.290$	12230.6824 1223.1698
Complete	8.87×10^2	$K_b = 1.57$	0.2414

1. **<u>Cake-complete</u>**

Nonlinear Regression **Monday, July 07, 2014, 10:47:36 PM**

Equation: User-Defined, Cake-Complete

f = 10/a*(1-exp(-a/(b*100)*(sqrt(1+2*b*100*x)-1)))

R	Rsqr	Adj Rsqr	Standard Error of Estimate
0.9993	0.9985	0.9985	0.2157

	Coefficient	Std. Error	t	P
a	-1.3439	0.0773	-17.3815	<0.0001
b	23.4890	1.0042	23.3917	<0.0001

Analysis of Variance:

	DF	SS	MS
Regression	2	2092.5148	1046.2574
Residual	30	1.3955	0.0465
Total	32	2093.9103	65.4347

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	1	938.2979	938.2979	20171.2234	<0.0001
Residual	30	1.3955	0.0465		
Total	31	939.6934	30.3127		

Statistical Tests:

Normality Test (Shapiro-Wilk) Failed (P = 0.0030)

W Statistic= 0.8875 Significance Level = 0.0500

Constant Variance Test Failed (P = 0.0121)

Fit Equation Description:

```
[Variables]
x = col(3)
y = col(4)
reciprocal_y = 1/abs(y)
reciprocal_ysquare = 1/y^2
reciprocal_pred = 1/abs(f)
reciprocal_predsqr = 1/f^2
'Automatic Initial Parameter Estimate Functions
first(q) = if(size(q)<10,size(q)-1,int(0.9*size(q)))
ylast(q) = mean(q[data(first(q),size(q))])
[Parameters]
```

a = ylast(y) ''Auto {{previous: -1.34391}} {{MinRange: 6}} {{MaxRange: 18}}

b = if(x50(x,y,.5)-min(x)>0, -ln(.5)/(x50(x,y,.5)-min(x)), 1) ''Auto {{previous: 23.489}}

[Equation]

f = 10/a*(1-exp(-a/(b*100)*(sqrt(1+2*b*100*x)-1)))

fit f to y

''fit f to y with weight reciprocal_y

''fit f to y with weight reciprocal_ysquare

''fit f to y with weight reciprocal_pred

''fit f to y with weight reciprocal_predsqr

[Constraints]

b>0

[Options]

tolerance=0.0000000001

stepsize=1

iterations=200

Number of Iterations Performed = 38

2. <u>**Cake**</u>

Nonlinear Regression **Thursday, July 24, 2014, 12:57:08 AM**

Equation: User-Defined, 3Cake

f = 1/(10*a)*((1+2*a*100*x)^(1/2)-1)

R	**Rsqr**	**Adj Rsqr**	**Standard Error of Estimate**
0.9815	0.9632	0.9632	1.0555

	Coefficient	**Std. Error**	**t**	**P**
a	8.5026	0.3959	21.4743	<0.0001

Analysis of Variance:

	DF	SS	MS
Regression	1	2059.3763	2059.3763
Residual	31	34.5341	1.1140
Total	32	2093.9103	65.4347

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	0	905.1593	(+inf)	(+inf)	(NAN)
Residual	31	34.5341	1.1140		
Total	31	939.6934	30.3127		

Statistical Tests:

Normality Test (Shapiro-Wilk) Failed (P = 0.0006)

W Statistic= 0.8564 Significance Level = 0.0500

Constant Variance Test Passed (P = 0.1692)

Fit Equation Description:

[Variables]

x = col(1)

y = col(2)

reciprocal_y = 1/abs(y)

reciprocal_ysquare = 1/y^2

reciprocal_pred = 1/abs(f)

reciprocal_predsqr = 1/f^2

'Automatic Initial Parameter Estimate Functions

F(q) = ape(x,y,1,0,1)

[Parameters]

a = F(0)[2] ''Auto {{previous: 8.50261}} {{MinRange: -4.5}} {{MaxRange: 1.5}}

[Equation]

f = 1/(10*a)*((1+2*a*100*x)^(1/2)-1)

fit f to y

''fit f to y with weight reciprocal_y

''fit f to y with weight reciprocal_ysquare

''fit f to y with weight reciprocal_pred

''fit f to y with weight reciprocal_predsqr

[Constraints]

a>0

[Options]

tolerance=0.0000000001

stepsize=1

iterations=200

Number of Iterations Performed = 11

3. Cake-Standard

Nonlinear Regression **Thursday, July 24, 2014, 1:00:50 AM**

Equation: User-Defined, Cake-standard

a=sqrt(4/9+4*d/(30*e)+2*d^2*x/(3*e))

b=2/(9*(4/9+4*d/(30*e)+2*d^2*x/(3*e))^1.5)*(4/3+d/(10*e)-d^2*x/e)

f = 2/d*(a*cos(2.09-0.33*arccos(b))+1/3)

R	Rsqr	Adj Rsqr	Standard Error of Estimate
0.9813	0.9629	0.9616	1.0783

	Coefficient	Std. Error	t	P
d	5023582.1705	111766502193.6843	4.4947E-005	1.0000
e	8.9259	0.4242	21.0401	<0.0001

Analysis of Variance:

	DF	SS	MS
Regression	2	2059.0289	1029.5144
Residual	30	34.8815	1.1627
Total	32	2093.9103	65.4347

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	1	904.8119	904.8119	778.1887	<0.0001
Residual	30	34.8815	1.1627		
Total	31	939.6934	30.3127		

Statistical Tests:

Normality Test (Shapiro-Wilk) Failed (P = 0.0005)

W Statistic= 0.8554 Significance Level = 0.0500

Constant Variance Test Passed (P = 0.1692)

Fit Equation Description:

```
[Variables]
x = col(3)
y = col(4)
reciprocal_y = 1/abs(y)
reciprocal_ysquare = 1/y^2
reciprocal_pred = 1/abs(f)
reciprocal_predsqr = 1/f^2
'Automatic Initial Parameter Estimate Functions
first(q) = if(size(q)<10,size(q)-1,int(0.9*size(q)))
ylast(q) = mean(q[data(first(q),size(q))])
[Parameters]
```

```
d = 0.05 ' {{previous: 5.02358e+006}}
e = 0.71 ' {{previous: 8.92586}}
[Equation]
a=sqrt(4/9+4*d/(30*e)+2*d^2*x/(3*e))
b=2/(9*(4/9+4*d/(30*e)+2*d^2*x/(3*e))^1.5)*(4/3+d/(10*e)-d^2*x/e)
f = 2/d*(a*cos(2.09-0.33*arccos(b))+1/3)
fit f to y
''fit f to y with weight reciprocal_y
''fit f to y with weight reciprocal_ysquare
''fit f to y with weight reciprocal_pred
''fit f to y with weight reciprocal_predsqr
[Constraints]
[Options]
tolerance=0.0000000001
stepsize=1
iterations=200
```

Number of Iterations Performed = 13

4. <u>Cake-Intermediate</u>

Nonlinear Regression **Monday, July 07, 2014, 11:43:24 PM**

Equation: User-Defined, Cake-Intermediate

f = 1/a*Ln(abs(1+a/(b*10)*((1+2*b*100*x)^(0.5)-1)))

R	**Rsqr**	**Adj Rsqr**	**Standard Error of Estimate**
0.9812	0.9627	0.9615	1.0804

	Coefficient	**Std. Error**	**t**	**P**
a	2.8956E-009	0.0097	2.9922E-007	1.0000
b	8.2481	0.7458	11.0591	<0.0001

Analysis of Variance:

	DF	SS	MS
Regression	2	2058.8947	1029.4473
Residual	30	35.0157	1.1672
Total	32	2093.9103	65.4347

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	1	904.6777	904.6777	775.0914	<0.0001
Residual	30	35.0157	1.1672		
Total	31	939.6934	30.3127		

Statistical Tests:

Normality Test (Shapiro-Wilk) Failed (P = 0.0011)

W Statistic= 0.8693 Significance Level = 0.0500

Constant Variance Test Passed (P = 0.4018)

Fit Equation Description:

[Variables]

x = col(3)

y = col(4)

reciprocal_y = 1/abs(y)

reciprocal_ysquare = 1/y^2

reciprocal_pred = 1/abs(f)

reciprocal_predsqr = 1/f^2

'Automatic Initial Parameter Estimate Functions

F(q) = ape(x,exp(y),1,0,1)

[Parameters]

a = 0.1 ' {{previous: 2.89565e-009}}

b = 1 ' {{previous: 8.24812}}

[Equation]

f = 1/a*Ln(abs(1+a/(b*10)*((1+2*b*100*x)^(0.5)-1)))

fit f to y

''fit f to y with weight reciprocal_y

''fit f to y with weight reciprocal_ysquare

''fit f to y with weight reciprocal_pred

''fit f to y with weight reciprocal_predsqr

[Constraints]

a>0

b>0

[Options]

tolerance=0.0000000001

stepsize=0.5

iterations=200

Number of Iterations Performed = 31

5. Intermediate

Nonlinear Regression **Thursday, July 24, 2014, 12:56:41 AM**

Equation: User-Defined, 2Intermediate

f = if(x>0, 1/a*ln(abs(1+a*10*x)), 0)

R	Rsqr	Adj Rsqr	Standard Error of Estimate
0.7293	0.5319	0.5319	3.7668

	Coefficient	Std. Error	t	P
a	0.9446	0.0994	9.5045	<0.0001

Analysis of Variance:

	DF	SS	MS
Regression	1	1654.0642	1654.0642
Residual	31	439.8462	14.1886
Total	32	2093.9103	65.4347

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	0	499.8472	(+inf)	(+inf)	(NAN)
Residual	31	439.8462	14.1886		
Total	31	939.6934	30.3127		

Statistical Tests:

Normality Test (Shapiro-Wilk) Failed (P = 0.0008)

W Statistic= 0.8627 Significance Level = 0.0500

Constant Variance Test Passed (P = 0.4661)

Fit Equation Description:

[Variables]

x = col(1)

y = col(2)

reciprocal_y = 1/abs(y)

reciprocal_ysquare = 1/y^2

reciprocal_pred = 1/abs(f)

reciprocal_predsqr = 1/f^2

'Automatic Initial Parameter Estimate Functions

F(q) = ape(ln(abs(x)),y,1,0,1)

[Parameters]

a = F(0)[2] ''Auto {{previous: 0.944578}}

[Equation]

```
f = if(x>0, 1/a*ln(abs(1+a*10*x)), 0)
fit f to y
''fit f to y with weight reciprocal_y
''fit f to y with weight reciprocal_ysquare
''fit f to y with weight reciprocal_pred
''fit f to y with weight reciprocal_predsqr
[Constraints]
[Options]
tolerance=0.0000000001
stepsize=1
iterations=200
```

Number of Iterations Performed = 8

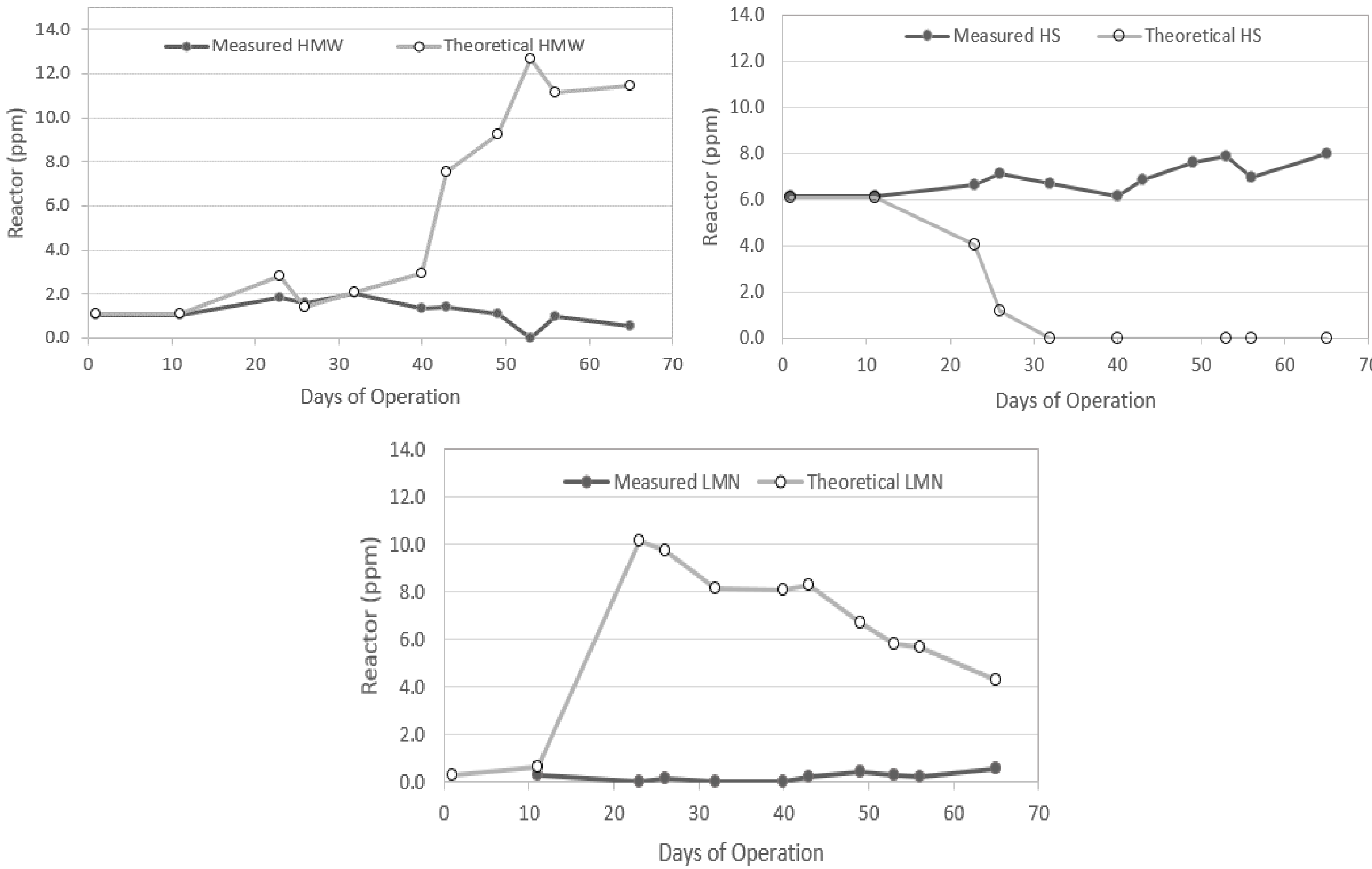
Appendix K: Mass Balance of NOM in a Wasting Passive Membrane System under Continuous Aeration

CONCENTRATION (ppm)

	Feed				Reactor				Theoretical Reactor				Total Permeate				Waste				Permeate 1				Permeate 2				Permeate 3			
Day	Cum Vol. (L)	HMW	HS	LMN	Volume (L)	HMW	HS	LMN	Volume (L)	HMW	HS	LMN	Cum Vol. (L)	HMW	HS	LMN	Cum Vol. (L)	HMW	HS	LMN	Cum Vol. (L)	HMW	HS	LMN	Cum Vol. (L)	HMW	HS	LMN	Cum Vol. (L)	HMW	HS	LMN
1	3.26	0.50	5.29	0.35	18.90	1.01	6.16	0.30	18.90	1.08	6.08	0.31	3.26	0.06	5.71	0.27	0.00	1.01	6.16	0.30	0.26	0.12	6.50	0.34	1.51	0.06	5.52	0.26	1.49	0.04	5.77	0.27
11	76.76	0.50	5.29	0.35	18.90	1.01	6.16	0.30	18.90	1.08	6.08	0.59	76.76	0.06	5.81	0.28	0.00	1.01	6.16	0.30	12.14	0.12	6.50	0.34	24.60	0.06	5.52	0.26	40.01	0.04	5.77	0.27
23	199.90	0.00	5.68	1.82	18.90	1.81	6.65	0.00	18.90	2.79	4.06	10.13	194.23	0.13	6.10	0.38	5.67	1.81	6.65	0.00	30.52	0.41	5.83	0.37	63.54	0.07	5.89	0.13	100.17	0.09	6.31	0.54
26	234.51	0.67	5.34	0.07	18.90	1.59	7.15	0.14	18.90	1.42	1.19	9.73	223.17	0.07	6.05	0.32	11.34	1.59	7.15	0.14	35.20	0.00	5.55	0.00	73.17	0.07	5.89	0.13	114.80	0.09	6.31	0.54
32	323.35	0.55	5.10	0.07	18.90	2.02	6.70	0.01	18.90	2.06	0.00	8.13	300.67	0.12	6.54	0.47	22.68	2.02	6.70	0.01	47.30	0.16	6.13	0.37	98.82	0.09	6.26	0.00	154.54	0.13	6.85	0.81
40	466.20	0.75	6.75	0.00	18.90	1.34	6.16	0.00	18.90	2.93	0.00	8.09	428.40	0.01	4.98	0.01	37.80	1.34	6.16	0.00	69.67	0.00	5.59	0.00	140.53	0.02	5.31	0.02	218.20	0.00	4.55	0.00
43	516.26	0.87	6.04	0.20	18.90	1.42	6.85	0.20	18.90	7.52	#N/A	8.31	472.79	0.06	5.62	0.11	43.47	1.42	6.85	0.20	77.32	0.05	5.48	0.14	154.84	0.07	5.68	0.27	240.63	0.05	5.62	0.00
49	603.97	1.35	5.45	0.00	18.90	1.11	7.62	0.39	18.90	9.26	#N/A	6.68	549.16	0.54	11.09	0.35	54.81	1.11	7.62	0.39	88.97	2.96	13.31	0.57	179.36	0.11	9.62	0.33	280.83	0.10	11.34	0.29
53	658.30	0.04	5.94	0.15	18.90	0.00	7.86	0.29	18.90	12.68	0.00	5.77	595.93	0.44	10.67	0.49	62.37	0.00	7.86	0.29	96.33	2.71	12.58	0.40	194.41	0.00	8.68	0.54	305.20	0.03	11.33	0.49
56	701.97	0.54	5.00	0.35	18.90	0.99	6.94	0.22	19.90	11.13	0.00	5.69	633.93	0.00	7.04	0.26	68.04	0.99	6.94	0.22	102.28	0.03	8.28	0.36	206.66	0.00	6.48	0.36	325.00	0.00	7.02	0.17
65	816.17	0.04	6.00	0.18	18.90	0.54	7.99	0.58	20.90	11.44	0.00	4.27	731.12	0.20	9.05	0.35	85.05	0.54	7.99	0.58	116.14	0.79	10.47	0.71	237.34	0.09	8.75	0.49	377.64	0.10	8.85	0.18
72	915.63	0.54	5.19	0.57	18.90	0.59	5.90	0.11	21.90	9.84	0.00	4.70	817.35	0.01	6.15	0.48	98.28	0.59	5.90	0.11	130.16	0.04	5.71	0.23	265.04	0.00	5.63	0.90	422.14	0.00	6.61	0.30
77	988.71	0.40	5.45	0.33	18.90	0.41	5.07	0.59	22.90	11.41	0.00	5.25	880.98	0.00	3.96	0.02	107.73	0.41	5.07	0.59	140.39	0.00	4.21	0.00	285.64	0.00	4.03	0.00	454.94	0.00	3.84	0.03
82	1059.89	0.40	5.45	0.33	18.90	0.33	5.53	0.22	23.90	12.00	4.12	1.64	942.71	0.64	5.46	1.66	117.18	0.33	5.53	0.22	150.31	0.00	3.77	0.20	305.58	0.00	3.52	0.05	486.82	1.24	7.21	3.12
87	1131.14	0.82	4.23	3.77	18.90	0.20	4.69	0.36	24.90	10.96	3.88	11.44	1004.51	0.09	4.41	0.32	126.63	0.20	4.69	0.36	160.43	0.03	3.73	0.20	325.43	0.11	3.85	0.33	518.66	0.11	4.97	0.35

MASS (mg)

	Feed				Reactor				Theoretical Reactor (Cumulative)				Total Permeate				Waste				Permeate 1				Permeate 2				Permeate 3			
Day	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN
	19.99	1.62	17.22	1.14	141.02	19.06	116.37	5.59	141.35	20.50	115.00	5.85	19.66	0.18	18.60	0.88	0.00	0.00	0.00	0.00	1.79	0.03	1.67	0.09	8.79	0.09	8.31	0.39	9.08	0.06	8.62	0.40
11	451.13	36.58	388.79	25.76	141.02	19.06	116.37	5.59	140.60	52.69	76.67	11.23	451.88	4.39	427.12	20.37	0.00	0.00	0.00	0.00	82.86	1.46	77.31	4.09	134.70	1.30	127.38	6.01	234.32	1.62	222.42	10.27
23	924.22	0.00	699.61	224.61	159.99	34.26	125.73	0.00	240.83	26.87	22.51	191.45	775.99	15.54	716.06	44.40	48.00	10.28	37.72	0.00	121.47	7.48	107.12	6.87	237.11	2.79	229.26	5.07	417.41	5.28	379.68	32.45
26	210.30	23.08	184.84	2.38	167.65	30.01	135.09	2.56	222.89	38.98	0.00	183.91	186.13	1.97	175.01	9.15	50.30	9.00	40.53	0.77	25.98	0.00	25.98	0.00	58.63	0.69	56.69	1.25	101.52	1.28	92.34	7.89
32	508.75	48.72	453.45	6.58	165.01	38.15	126.67	0.19	208.95	55.38	0.00	153.57	553.20	9.42	506.97	36.81	99.01	22.89	76.00	0.11	80.59	1.89	74.17	4.53	162.82	2.22	160.59	0.00	309.79	5.30	272.21	32.28
40	1071.43	107.75	963.68	0.00	141.75	25.25	116.51	0.00	529.23	142.04	234.29	152.90	637.74	0.89	636.18	0.67	113.40	20.20	93.21	0.00	124.98	0.00	124.98	0.00	223.00	0.89	221.43	0.67	289.76	0.00	289.76	0.00
43	356.11	43.68	302.24	10.18	159.97	26.91	129.37	3.69	580.66	175.10	248.44	157.12	256.69	2.56	249.28	4.85	47.99	8.07	38.81	1.11	43.31	0.37	41.89	1.04	86.13	1.00	81.32	3.81	127.26	1.19	126.07	0.00
49	596.45	118.62	477.84	0.00	172.53	21.05	144.02	7.46	365.89	239.72	0.00	126.17	914.46	41.36	846.62	26.48	103.52	12.63	86.41	4.48	196.19	34.44	155.07	6.68	246.75	2.75	235.84	8.16	471.52	4.16	455.71	11.64
53	333.25	2.36	322.60	8.29	154.12	0.00	148.56	5.56	330.62	221.52	0.00	109.11	542.93	20.56	499.24	23.13	61.65	0.00	59.42	2.22	115.51	19.93	92.61	2.97	138.65	0.00	130.51	8.14	288.77	0.63	276.12	12.03
56	257.27	23.40	218.56	15.31	154.12	18.68	131.20	4.23	352.35	239.13	0.00	113.22	277.76	0.18	267.65	9.93	46.23	5.60	39.36	1.27	51.59	0.18	49.25	2.16	83.83	0.00	79.43	4.39	142.34	0.00	138.96	3.38
65	709.86	4.78	684.83	20.26	172.26	10.25	151.01	11.00	304.74	215.52	0.00	89.21	932.83	19.16	879.32	34.36	155.03	9.23	135.90	9.90	165.90	10.98	145.15	9.77	286.10	2.74	268.38	14.98	480.83	5.44	465.78	9.60
72	626.81	54.09	515.87	56.85	124.58	11.11	111.42	2.06	364.19	261.22	0.00	102.97	572.79	0.62	530.52	41.66	87.21	7.77	77.99	1.44	83.91	0.62	80.12	3.17	181.07	0.00	156.08	24.99	307.81	0.00	294.31	13.50
77	451.70	29.58	398.04	24.08	114.75	7.80	95.76	11.19	505.58	286.90	98.35	120.34	252.93	0.00	251.81	1.12	57.37	3.90	47.88	5.60	43.06	0.00	43.06	0.00	82.96	0.00	82.96	0.00	126.90	0.00	125.78	1.12
82	439.98	28.81	387.71	23.46	115.06	6.29	104.54	4.24	408.94	273.02	96.63	39.29	479.10	39.55	337.16	102.38	57.53	3.14	52.27	2.12	39.35	0.00	37.36	1.99	71.20	0.00	70.12	1.08	368.56	39.55	229.69	99.32
87	628.02	58.15	301.44	268.43	99.03	3.72	88.57	6.73	689.59	323.50	81.35	284.74	297.85	5.80	272.44	19.61	49.51	1.86	44.29	3.37	40.10	0.33	37.74	2.03	84.91	2.10	76.33	6.48	172.85	3.37	158.37	11.10



Comparison between Measured and Theoretical NOM Constituents in System Reactor for HMW, HS and LMN over Time for Passive Membrane Filtration under Continuous Aeration and with Daily Wasting

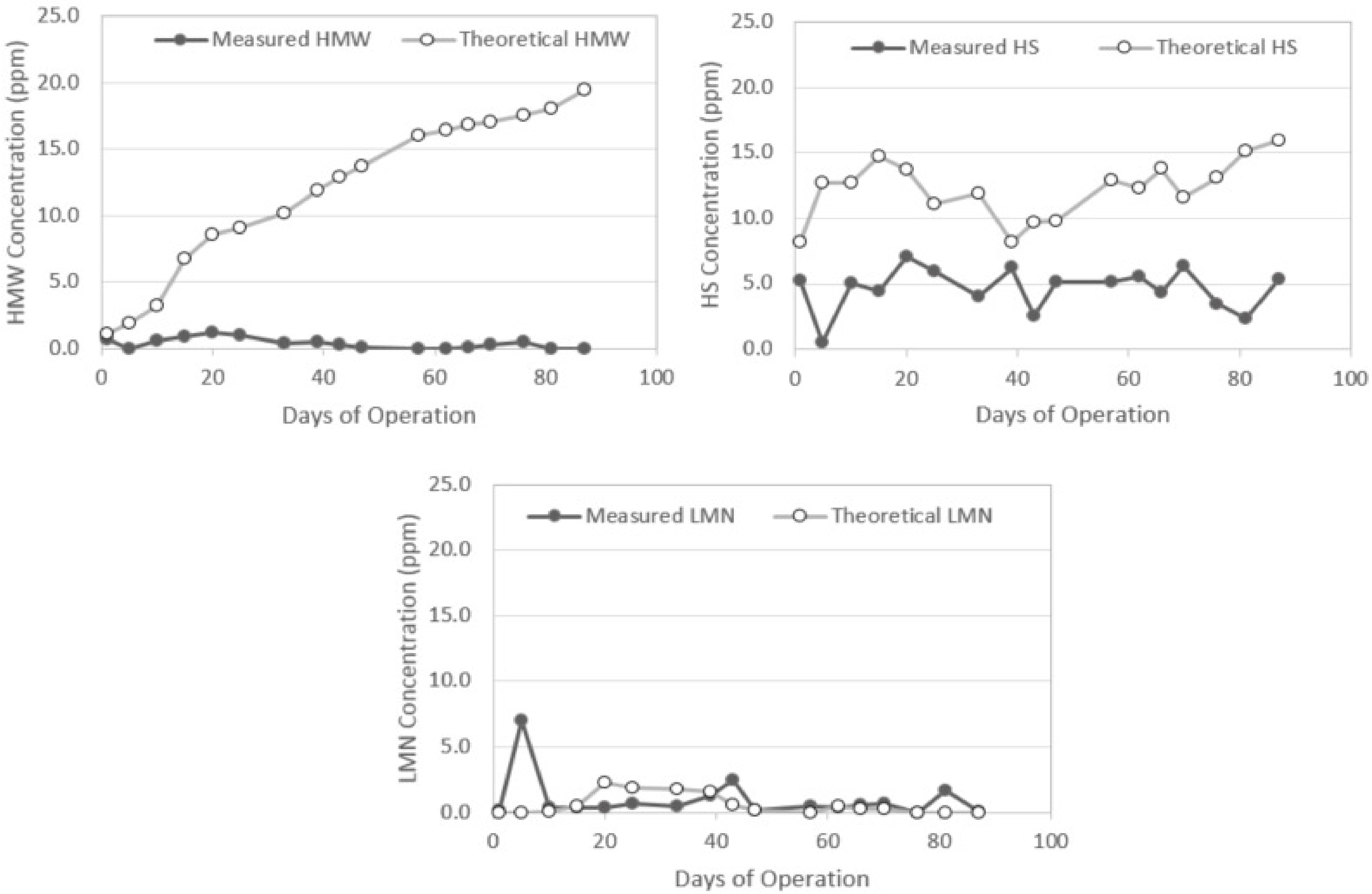
Appendix L : Mass Balance of NOM in a Wasting Passive Membrane System under Intermittent Aeration of *25 Minutes off – 5 Minutes On*

CONCENTRATION (ppm)

	Feed				Reactor				Theoretical Reactor				Total Permeate				Waste				Permeate 1				Permeate 2				Permeate 3			
Day	Cum Vol (L)	HMW	HS	LMN	Volume (L)	HMW	HS	LMN	Volume (L)	HMW	HS	LMN	Cum Vol (L)	HMW	HS	LMN	Cum Vol (L)	HMW	HS	LMN	Cum Vol (L)	HMW	HS	LMN	Cum Vol (L)	HMW	HS	LMN	Cum Vol (L)	HMW	HS	LMN
1	13.48	0.69	5.26	0.15	18.90	0.69	5.26	0.15	18.90	1.12	8.19	0.00	11.59	0.00	0.50	2.40	1.89	0.69	5.26	0.15	4.02	0.00	0.48	0.00	3.72	0.00	0.48	0.00	3.86	0.00	0.50	6.92
5	37.73	0.67	4.93	0.17	18.90	0.04	0.50	7.05	18.90	1.95	12.69	0.00	28.28	0.01	1.84	2.43	9.45	0.04	0.50	7.05	9.71	0.00	0.48	0.00	9.04	0.05	4.74	0.23	9.53	0.00	0.50	6.92
10	84.74	0.67	4.93	0.17	18.90	0.65	5.01	0.35	18.90	3.23	12.70	0.04	65.84	0.03	4.91	0.10	18.90	0.65	5.01	0.35	22.48	0.00	5.29	0.08	21.63	0.05	4.74	0.23	21.73	0.03	4.67	0.00
15	152.36	1.11	4.21	0.36	18.90	0.91	4.44	0.32	18.90	6.76	14.75	0.51	124.01	0.00	3.50	0.21	28.35	0.91	4.44	0.32	42.14	0.00	3.42	0.27	41.74	0.00	3.50	0.20	40.13	0.00	3.59	0.16
20	197.34	1.06	5.37	1.00	18.90	1.20	7.10	0.36	18.90	8.58	13.72	2.25	159.54	0.05	5.46	0.24	37.80	1.20	7.10	0.36	53.61	0.07	5.56	0.00	54.18	0.06	5.64	0.44	51.76	0.03	5.18	0.27
25	231.68	0.59	4.31	0.19	18.90	0.99	5.99	0.71	18.90	9.03	11.12	1.92	184.43	0.09	5.64	0.24	47.25	0.99	5.99	0.71	61.79	0.14	5.06	0.00	62.79	0.00	5.61	0.25	59.85	0.15	6.25	0.47
33	279.05	0.59	4.31	0.19	18.90	0.41	4.01	0.49	18.90	10.15	11.93	1.81	216.68	0.03	3.97	0.11	62.37	0.41	4.01	0.49	72.60	0.05	3.87	0.18	73.58	0.00	4.34	0.02	70.50	0.04	3.70	0.12
39	318.82	1.12	4.72	0.55	18.90	0.55	6.21	1.27	18.90	11.92	8.20	1.63	245.11	0.18	6.61	0.39	73.71	0.55	6.21	1.27	82.21	0.17	7.32	0.48	82.92	0.24	6.52	0.31	79.98	0.12	5.97	0.37
43	332.58	1.57	4.75	0.06	18.90	0.30	2.58	2.48	18.90	12.93	9.69	0.59	251.31	0.00	2.83	0.28	81.27	0.30	2.58	2.48	84.29	0.00	3.26	0.60	84.97	0.00	4.04	0.22	82.05	0.00	1.20	0.00
47	355.67	0.87	4.44	0.12	18.90	0.08	5.17	0.16	18.90	13.75	9.83	0.19	266.84	0.26	3.92	0.59	88.83	0.08	5.17	0.16	89.51	0.00	3.84	0.45	90.07	0.00	2.09	0.82	87.26	0.78	5.78	0.51
57	405.28	0.86	4.71	0.07	18.90	0.00	5.19	0.45	18.90	15.98	12.88	0.00	297.55	0.02	2.53	0.08	107.73	0.00	5.19	0.45	99.99	0.00	1.77	0.00	99.71	0.06	3.54	0.27	97.86	0.00	2.37	0.00
62	427.87	0.43	5.14	0.66	18.90	0.01	5.60	0.34	18.90	16.46	12.32	0.47	310.69	0.05	5.62	0.22	117.18	0.01	5.60	0.34	104.44	0.03	5.35	0.03	103.87	0.08	5.94	0.39	102.39	0.04	5.59	0.24
66	445.75	0.47	4.80	0.03	18.90	0.15	4.35	0.54	18.90	16.84	13.77	0.29	321.01	0.00	2.49	0.00	124.74	0.15	4.35	0.54	107.89	0.00	0.52	0.00	107.16	0.00	3.57	0.00	105.96	0.00	3.39	0.00
70	463.07	0.31	3.55	0.30	18.90	0.28	6.39	0.65	18.90	17.00	11.59	0.27	330.77	0.03	5.57	0.07	132.30	0.28	6.39	0.65	111.19	0.10	6.70	0.00	110.29	0.00	5.03	0.21	109.29	0.00	4.95	0.00
76	491.64	0.55	4.08	0.15	18.90	0.53	3.48	0.00	18.90	17.50	13.16	0.00	348.00	0.01	2.75	1.41	143.64	0.53	3.48	0.00	116.99	0.00	2.52	0.01	115.88	0.01	2.20	0.02	115.14	0.01	3.51	4.12
81	512.82	0.65	4.22	0.23	18.90	0.03	2.28	1.72	18.90	18.09	15.14	0.00	359.73	0.20	2.60	0.19	153.09	0.03	2.28	1.72	120.94	0.00	3.51	0.32	119.70	0.61	3.10	0.25	119.09	0.00	1.21	0.00
87	543.25	1.06	4.44	0.00	18.90	0.01	5.33	0.08	18.90	19.48	15.92	0.00	378.82	0.30	3.13	0.48	164.43	0.01	5.33	0.08	127.35	0.88	4.18	1.43	126.14	0.00	2.48	0.00	125.32	0.01	2.72	0.00

MASS (mg)

	Feed				Reactor				Theoretical Reactor (Cumulative)				Total Permeate				Waste				Permeate 1				Permeate 2				Permeate 3			
Day	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN
1	82.39	9.36	70.94	2.08	115.50	13.12	99.46	2.92	175.88	21.17	154.71	0.00	33.53	0.00	5.75	27.79	11.55	1.31	9.95	0.29	1.91	0.00	1.91	0.00	1.91	0.00	1.91	0.00	29.72	0.00	1.93	27.79
5	139.87	16.20	119.59	4.09	143.38	0.76	9.45	133.18	276.58	36.82	239.76	0.00	71.48	0.24	30.76	40.48	57.35	0.30	3.78	53.27	2.71	0.00	2.71	0.00	26.71	0.24	25.22	1.25	42.06	0.00	2.84	39.23
10	271.19	31.40	231.87	7.92	113.55	12.30	94.62	6.64	301.81	61.09	240.05	0.67	189.19	0.99	184.27	3.93	56.78	6.15	47.31	3.32	68.60	0.00	67.62	0.98	63.19	0.57	59.66	2.95	57.40	0.41	56.98	0.00
15	383.98	75.29	284.44	24.24	107.33	17.29	83.91	6.13	416.22	127.74	278.84	9.64	215.90	0.00	203.70	12.21	53.66	8.64	41.96	3.06	72.48	0.00	67.25	5.24	74.28	0.00	70.32	3.96	69.14	0.00	66.13	3.01
20	333.99	47.57	241.55	44.87	163.76	22.67	134.20	6.89	463.81	162.10	259.25	42.46	204.52	1.87	194.04	8.61	81.88	11.33	67.10	3.45	64.56	0.83	63.73	0.00	76.21	0.69	70.10	5.41	63.74	0.35	60.20	3.19
25	174.68	20.38	147.85	6.46	145.39	18.72	113.29	13.38	417.16	170.75	210.14	36.26	148.64	2.36	140.31	5.97	72.70	9.36	56.65	6.69	42.50	1.12	41.38	0.00	50.52	0.00	48.34	2.18	55.62	1.24	50.59	3.80
33	240.97	28.11	203.95	8.91	92.73	7.73	75.76	9.24	451.43	191.75	225.41	34.28	132.51	0.93	128.08	3.50	74.19	6.19	60.61	7.39	44.33	0.56	41.78	1.99	47.07	0.00	46.82	0.25	41.11	0.38	39.48	1.26
39	254.27	44.67	187.67	21.93	151.71	10.34	117.32	24.05	410.86	225.21	154.90	30.75	203.82	5.00	187.79	11.03	91.03	6.20	70.39	14.43	76.61	1.65	70.32	4.64	65.99	2.25	60.86	2.88	61.22	1.11	56.61	3.51
43	87.71	21.54	65.34	0.83	101.37	5.75	48.69	46.92	438.75	244.45	183.21	11.09	19.27	0.00	17.55	1.72	40.55	2.30	19.48	18.77	8.06	0.00	6.80	1.26	8.74	0.00	8.28	0.46	2.47	0.00	2.47	0.00
47	125.53	20.20	102.46	2.86	102.28	1.56	97.66	3.06	449.23	259.94	185.75	3.54	74.14	4.09	60.86	9.19	40.91	0.62	39.06	1.23	22.40	0.00	20.05	2.35	14.85	0.00	10.67	4.19	36.89	4.09	30.15	2.65
57	279.84	42.70	233.57	3.56	106.60	0.00	98.08	8.52	545.55	302.06	243.49	0.00	80.91	0.58	77.75	2.57	106.60	0.00	98.08	8.52	18.51	0.00	18.51	0.00	37.32	0.58	34.16	2.57	25.08	0.00	25.08	0.00
62	140.93	9.82	116.12	14.99	112.56	0.19	105.88	6.49	552.87	311.14	232.84	8.89	77.33	0.65	73.83	2.85	56.28	0.09	52.94	3.24	24.05	0.12	23.78	0.16	26.67	0.33	24.73	1.61	26.60	0.20	25.31	1.09
66	94.78	8.33	85.84	0.61	95.19	2.80	82.13	10.26	583.91	318.34	260.17	5.39	25.66	0.00	25.66	0.00	38.07	1.12	32.85	4.10	1.81	0.00	1.81	0.00	11.74	0.00	11.74	0.00	12.11	0.00	12.11	0.00
70	72.08	5.33	61.47	5.28	138.35	5.31	120.73	12.31	545.38	321.21	219.08	5.08	55.28	0.34	54.27	0.67	55.34	2.12	48.29	4.92	22.39	0.34	22.05	0.00	16.43	0.00	15.76	0.67	16.46	0.00	16.46	0.00
76	136.47	15.64	116.46	4.37	75.66	9.95	65.71	0.00	579.46	330.78	248.69	0.00	71.83	0.11	47.43	24.29	45.40	5.97	39.43	0.00	14.72	0.00	14.64	0.08	12.45	0.04	12.28	0.13	44.66	0.07	20.52	24.08
81	107.99	13.70	89.39	4.90	76.11	0.59	43.09	32.43	627.92	341.87	286.06	0.00	35.00	2.31	30.47	2.21	38.06	0.29	21.55	16.22	15.14	0.00	13.87	1.26	15.07	2.31	11.81	0.95	4.79	0.00	4.79	0.00
87	167.07	32.10	134.97	0.00	102.22	0.13	100.65	1.44	669.10	368.19	300.91	0.00	74.64	5.70	59.73	9.21	61.33	0.08	60.39	0.87	41.66	5.66	26.81	9.19	15.96	0.00	15.96	0.00	17.01	0.04	16.96	0.02



Comparison between Measured and Theoretical NOM Constituents in System Reactor for HMW, HS and LMN over Time for Passive Membrane Filtration under 25 Minutes off-5 Minutes On Aeration Cycles and with Daily Wasting

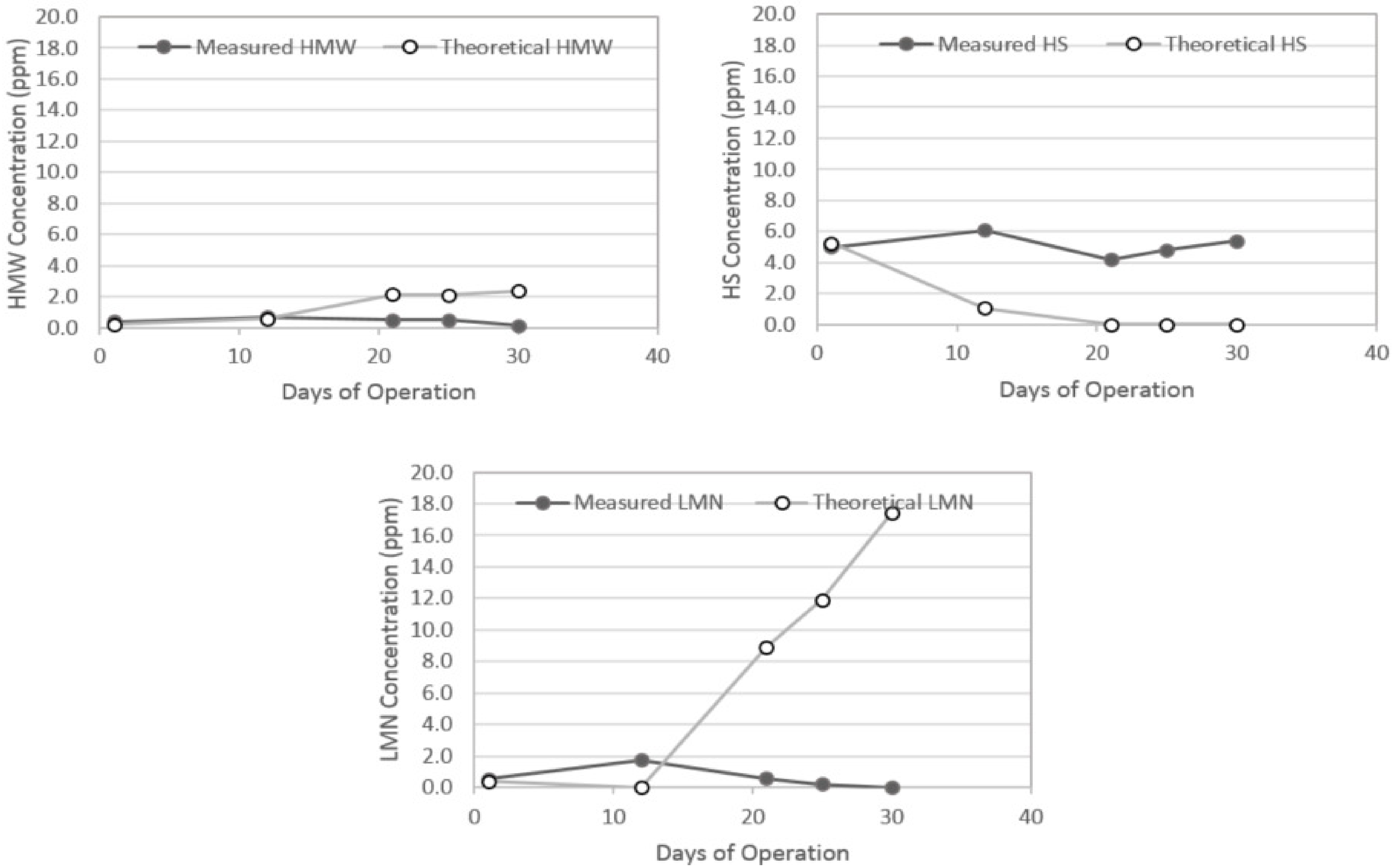
Appendix M : Mass Balance of NOM in a Wasting Passive Membrane System under Intermittent Aeration of *4 Hours off – 30 Minutes On*

CONCENTRATION (ppm)

	Feed				Reactor				Theoretical Reactor				Total Permeate				Waste				Permeate 1				Permeate 2				Permeate 3			
Day	Cum Vol. (L)	HMW	HS	LMN	Volume (L)	HMW	HS	LMN	Volume (L)	HMW	HS	LMN	Cum Vol. (L)	HMW	HS	LMN	Cum Vol. (L)	HMW	HS	LMN	Cum Vol. (L)	HMW	HS	LMN	Cum Vol. (L)	HMW	HS	LMN	Cum Vol. (L)	HMW	HS	LMN
1	5.27	0.36	4.65	0.46	18.90	0.38	4.99	0.56	18.90	0.22	5.24	0.40	3.38	1.25	3.10	1.29	1.89	0.38	4.99	0.56	1.10	0.25	2.83	0.14	1.10	0.15	6.48	0.63	1.18	0.20	2.98	0.04
12	77.45	0.77	5.00	0.00	18.90	0.70	6.10	1.73	18.90	0.59	1.04	0.00	54.77	0.67	6.10	0.44	22.68	0.70	6.10	1.73	17.91	1.01	6.25	0.48	17.91	0.46	6.80	0.66	18.95	0.55	5.31	0.18
21	163.03	0.75	1.51	4.05	18.90	0.51	4.19	0.58	18.90	2.13	0.00	8.89	123.34	0.38	3.47	2.46	39.69	0.51	4.19	0.58	41.39	0.17	4.34	4.25	38.07	0.55	2.45	3.43	43.88	0.43	3.47	0.00
25	192.16	0.19	2.95	2.78	18.90	0.51	4.79	0.21	18.90	2.09	0.00	11.89	144.91	0.11	4.60	1.06	47.25	0.51	4.79	0.21	48.42	0.14	4.41	0.11	46.50	0.07	5.13	0.14	49.99	0.13	4.10	3.41
30	220.11	0.43	2.23	4.03	18.90	0.14	5.37	0.00	18.90	2.36	0.00	17.39	163.41	0.30	5.53	0.48	56.70	0.14	5.37	0.00	54.55	0.22	5.97	0.19	52.85	0.20	5.24	0.17	56.01	0.49	5.40	1.09

MASS (mg)

	Feed				Reactor				Theoretical Reactor (Cumulative)				Total Permeate				Waste				Permeate 1				Permeate 2				Permeate 3			
Day	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN
1	28.80	1.89	24.52	2.40	112.08	7.19	94.36	10.53	110.61	4.12	98.97	7.51	19.06	4.23	10.47	4.36	11.21	0.72	9.44	1.05	3.54	0.27	3.11	0.16	7.99	0.17	7.13	0.69	3.80	0.23	3.51	0.05
12	417.09	55.93	361.17	0.00	1932.95	158.22	1382.53	392.19	30.82	11.09	19.73	0.00	370.65	34.45	313.68	22.52	177.19	14.50	126.73	35.95	130.06	16.96	105.02	8.08	133.20	7.72	114.32	11.16	107.40	9.78	94.34	3.28
21	539.90	63.78	129.36	346.77	2094.58	203.58	1662.15	228.84	208.40	40.30	0.00	168.10	432.49	25.84	237.79	168.86	89.77	8.73	71.24	9.81	205.51	4.03	101.80	99.69	129.56	11.02	49.36	69.17	97.42	10.79	86.63	0.00
25	172.49	5.52	85.95	81.02	2600.06	239.71	2261.84	98.51	264.30	39.57	0.00	224.73	124.50	2.42	99.26	22.81	41.60	3.84	36.19	1.58	32.76	1.00	30.98	0.78	45.05	0.62	43.24	1.20	46.68	0.80	25.04	20.84
30	187.00	11.98	62.29	112.74	3127.20	82.19	3045.01	0.00	373.22	44.55	0.00	328.66	116.86	5.63	102.44	8.80	52.12	1.37	50.75	0.00	39.16	1.37	36.65	1.15	35.72	1.30	33.33	1.10	41.99	2.96	32.47	6.55



Comparison between Measured and Theoretical NOM Constituents in System Reactor for HMW, HS and LMN over Time for Passive Membrane Filtration under 4 hours off-30 Minutes On Aeration Cycles and with Daily Wasting

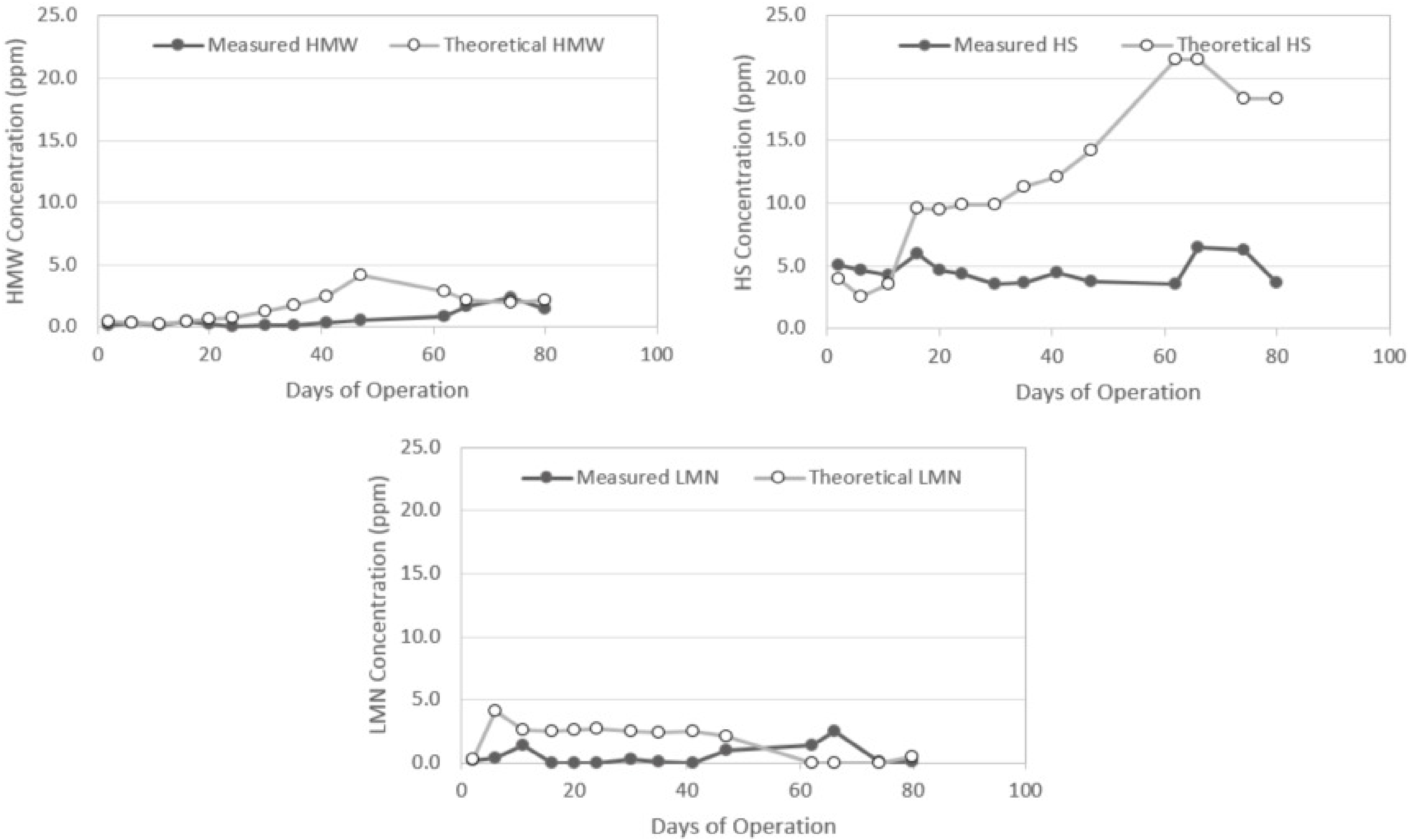
Appendix N: Mass Balance of NOM in a Wasting Passive Membrane System under Intermittent Aeration of *4 Hours off – 5 Minutes On*

CONCENTRATION (ppm)

	Feed				Reactor				Theoretical Reactor				Total Permeate				Waste				Permeate 1				Permeate 2				Permeate 3			
Day	Cum Vol. (L)	HMW	HS	LMN	Volume (L)	HMW	HS	LMN	Volume (L)	HMW	HS	LMN	Cum Vol. (L)	HMW	HS	LMN	Cum Vol. (L)	HMW	HS	LMN	Cum Vol. (L)	HMW	HS	LMN	Cum Vol. (L)	HMW	HS	LMN	Cum Vol. (L)	HMW	HS	LMN
6	40.18	0.10	3.04	2.78	18.90	0.33	4.70	0.35	18.90	0.36	2.55	4.08	28.84	0.04	3.78	0.06	11.34	0.33	4.70	0.35	9.7	0.09	3.49	0.00	9.5	0.00	3.70	0.19	9.6	0.04	4.14	0.00
11	69.92	0.27	6.42	0.00	18.90	0.17	4.27	1.38	18.90	0.23	3.54	2.60	49.13	0.44	6.50	0.74	20.79	0.17	4.27	1.38	16.5	0.09	4.24	0.00	16.2	0.76	6.20	0.21	16.4	0.49	9.07	2.02
16	123.63	0.16	6.26	0.00	18.90	0.39	5.98	0.00	18.90	0.49	9.59	2.51	93.39	0.00	3.74	0.04	30.24	0.39	5.98	0.00	40.2	0.00	3.67	0.00	36.8	0.00	3.83	0.09	0.0	0.00	3.79	0.87
20	145.30	0.24	5.05	0.64	18.90	0.24	4.69	0.00	18.90	0.60	9.51	2.64	107.50	0.09	5.36	0.81	37.80	0.24	4.69	0.00	47.3	0.00	4.38	0.00	43.8	0.19	6.34	1.62	0.0			
24	166.33	0.13	4.47	0.13	18.90	0.00	4.35	0.01	18.90	0.73	9.88	2.69	120.97	0.02	4.01	0.13	45.36	0.00	4.35	0.01	53.5	0.03	4.40	0.28	51.1	0.00	3.68	0.00	0.0			
30	196.45	0.42	3.66	0.05	18.90	0.13	3.58	0.25	18.90	1.26	9.95	2.50	139.75	0.06	3.65	0.13	56.70	0.13	3.58	0.25	62.1	0.09	3.22	0.00	61.2	0.04	4.01	0.23	0.0			
35	217.79	0.54	3.63	0.04	18.90	0.15	3.61	0.12	18.90	1.77	11.34	2.43	151.64	0.04	1.44	0.09	66.15	0.15	3.61	0.12	67.6	0.04	2.16	0.20	67.7	0.04	0.83	0.00	0.0			
41	241.74	0.78	5.17	0.10	18.90	0.37	4.49	0.00	18.90	2.50	12.13	2.52	164.25	0.06	4.60	0.05	77.49	0.37	4.49	0.00	73.3	0.06	4.66	0.04	74.5	0.06	4.55	0.06	0.0			
47	263.89	1.69	5.49	0.11	18.90	0.51	3.73	0.96	18.90	4.17	14.22	2.05	175.06	0.02	3.67	0.03	88.83	0.51	3.73	0.96	78.3	0.00	3.64	0.00	80.4	0.03	3.69	0.06	0.0			
62	315.25	0.00	5.64	0.10	18.90	0.88	3.53	1.34	18.90	2.83	21.46	0.00	198.07	0.01	2.30	0.36	117.18	0.88	3.53	1.34	88.2	0.02	2.47	0.00	93.5	0.01	2.18	0.64	0.0			
66	328.11	0.00	5.64	0.00	18.90	1.60	6.45	2.45	18.90	2.18	21.54	0.00	203.37	0.02	4.18	0.70	124.74	1.60	6.45	2.45	90.3	0.03	4.51	0.00	96.7	0.02	3.97	1.16	0.0			
74	352.16	1.36	3.69	0.15	18.90	2.33	6.31	0.07	18.90	1.95	18.37	0.00	212.30	0.21	5.97	1.05	139.86	2.33	6.31	0.07	94.0	0.41	5.01	2.17	101.9	0.07	6.65	0.26	0.0			
80	372.01	1.02	3.55	0.48	18.90	1.40	3.63	0.05	18.90	2.13	18.38	0.44	220.81	0.10	3.44	0.07	151.20	1.40	3.63	0.05	97.2	0.12	3.37	0.03	107.2	0.09	3.47	0.10	0.0			

MASS (mg)

	Feed				Reactor				Theoretical Reactor (Cumulative)				Total Permeate				Waste				Permeate 1				Permeate 2				Permeate 3			
Day	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN
2	81.33	6.72	69.22	5.39	102.27	3.21	94.89	4.16	88.05	7.57	75.26	5.22	54.64	1.09	50.89	2.66	40.91	1.29	37.96	1.66	16.39	0.00	16.39	0.00	18.56	0.71	15.82	2.03	19.69	0.38	18.68	0.63
6	161.57	2.66	83.03	75.88	101.71	6.27	88.83	6.61	132.32	6.84	48.28	77.20	76.62	0.87	74.48	1.26	40.68	2.51	35.53	2.65	23.53	0.58	22.95	0.00	25.45	0.00	24.18	1.26	27.64	0.29	27.35	0.00
11	198.99	8.03	190.95	0.00	110.01	3.14	80.79	26.07	120.38	4.31	66.94	49.13	155.92	8.99	131.90	15.03	55.00	1.57	40.40	13.04	29.55	0.59	28.96	0.00	48.15	5.07	41.66	1.42	78.23	3.33	61.29	13.61
16	345.02	8.56	336.47	0.00	120.49	7.38	113.12	0.00	237.74	9.18	181.20	47.37	167.41	0.00	165.65	1.76	60.25	3.69	56.56	0.00	86.93	0.00	86.93	0.00	80.48	0.00	78.72	1.76	0.00	0.00	0.00	0.00
20	128.60	5.24	109.49	13.88	93.26	4.57	88.69	0.00	240.76	11.26	179.65	49.86	88.28	1.33	75.56	11.38	37.30	1.83	35.48	0.00	30.99	0.00	30.99	0.00	57.29	1.33	44.57	11.38	0.00	0.00	0.00	0.00
24	99.52	2.81	93.96	2.75	82.45	0.00	82.25	0.19	251.32	13.85	186.68	50.79	55.98	0.21	54.03	1.75	32.98	0.00	32.90	0.08	29.24	0.21	27.29	1.75	26.74	0.00	26.74	0.00	0.00	0.00	0.00	0.00
30	124.62	12.58	110.40	1.64	74.82	2.45	67.65	4.72	259.00	23.79	187.98	47.23	72.05	1.18	68.51	2.36	44.89	1.47	40.59	2.83	28.53	0.76	27.77	0.00	43.52	0.42	40.74	2.36	0.00	0.00	0.00	0.00
35	90.04	11.57	77.57	0.91	73.28	2.84	68.25	2.19	293.71	33.49	214.27	45.95	18.69	0.45	17.15	1.09	36.64	1.42	34.12	1.10	13.11	0.22	11.80	1.09	5.58	0.23	5.35	0.00	0.00	0.00	0.00	0.00
41	144.90	18.66	123.87	2.37	91.88	6.93	84.95	0.00	324.08	47.23	229.18	47.66	59.40	0.76	57.99	0.65	55.13	4.16	50.97	0.00	27.35	0.35	26.79	0.22	32.05	0.41	31.20	0.43	0.00	0.00	0.00	0.00
47	161.46	37.41	121.64	2.41	98.40	9.59	70.59	18.22	386.34	78.72	268.84	38.79	40.16	0.17	39.64	0.35	59.04	5.75	42.35	10.93	17.93	0.00	17.93	0.00	22.22	0.17	21.70	0.35	0.00	0.00	0.00	0.00
62	295.03	0.00	289.89	5.14	108.76	16.61	66.79	25.36	459.08	53.53	405.55	0.00	61.59	0.28	52.98	8.32	163.14	24.91	100.19	38.04	24.66	0.16	24.50	0.00	36.93	0.12	28.49	8.32	0.00	0.00	0.00	0.00
66	72.58	0.00	72.58	0.00	198.50	30.31	121.91	46.28	448.48	41.29	407.20	0.00	26.00	0.12	22.18	3.71	79.40	12.13	48.76	18.51	9.54	0.06	9.48	0.00	16.46	0.05	12.70	3.71	0.00	0.00	0.00	0.00
74	124.90	32.62	88.78	3.51	164.39	43.96	119.17	1.26	384.12	36.85	347.27	0.00	64.61	1.89	53.37	9.35	131.51	35.17	95.33	1.01	27.85	1.50	18.38	7.96	36.77	0.39	34.99	1.39	0.00	0.00	0.00	0.00
80	100.13	20.22	70.47	9.44	95.99	26.42	68.69	0.88	395.92	40.33	347.29	8.30	30.73	0.88	29.24	0.62	57.60	15.85	41.21	0.53	11.40	0.39	10.90	0.11	19.33	0.49	18.33	0.51	0.00	0.00	0.00	0.00



Comparison between Measured and Theoretical NOM Constituents in System Reactor for HMW, HS and LMN over Time for Passive Membrane Filtration under 4 hours off-5 Minutes On Aeration Cycles and Daily Wasting

Appendix O: Mass Balance of NOM in a Wasting Passive Membrane System under No Aeration

CONCENTRATION (ppm)

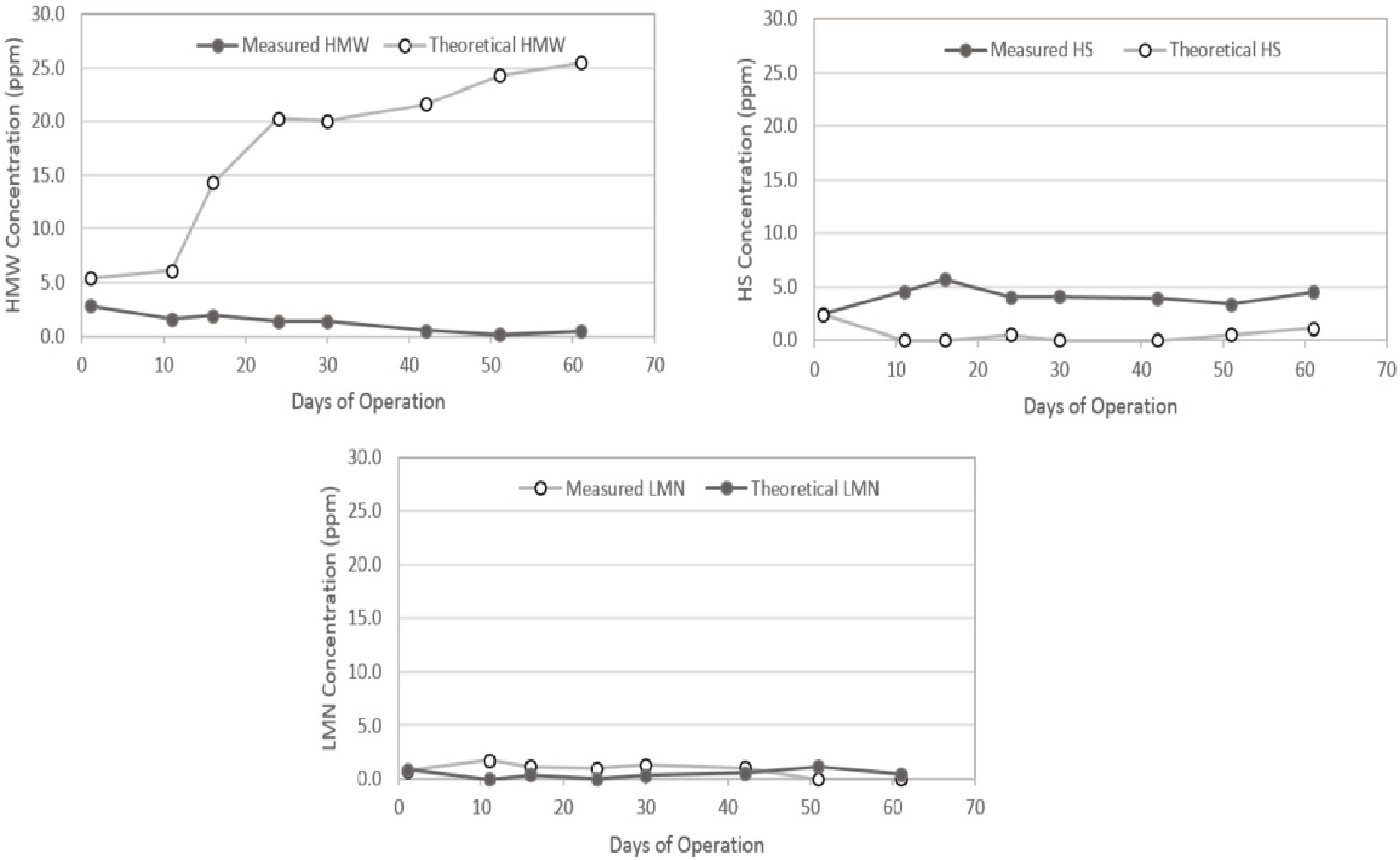
Day	Feed				Reactor				Theoretical Reactor				Total Permeate			
	Cum. Vol (L)	HMW	HS	LMN	Volume (L)	HMW	HS	LMN	Volume (L)	HMW	HS	LMN	Cum. Vol (L)	HMW	HS	LMN
1	4.7	1.67	5.02	0.59	18.90	2.85	2.50	0.85	18.90	3.0	2.4	0.8	3	0.00	1.16	0.00
11	76.3	1.44	3.92	0.40	18.90	1.62	4.59	0.00	18.90	6.1	0.0	1.8	55	0.27	5.15	0.19
16	143.8	2.63	3.92	0.02	18.90	1.94	5.72	0.39	18.90	14.3	0.0	1.2	114	0.06	3.73	0.16
24	210.2	1.86	4.27	0.25	18.90	1.35	4.01	0.01	18.90	19.7	0.6	1.0	165	0.02	4.15	0.39
30	231.8	1.12	3.53	0.54	18.90	1.39	4.08	0.32	18.90	20.0	0.0	1.3	175	0.19	4.20	0.10
42	269.3	1.20	3.55	0.30	18.90	0.53	3.94	0.57	18.90	21.6	0.0	1.0	190	0.23	3.70	0.27
51	296.2	1.66	3.79	0.00	18.90	0.15	3.43	1.18	18.90	23.8	0.5	0.0	200	0.13	3.39	0.13
61	325.4	0.76	4.92	0.43	18.90	0.46	4.51	0.48	18.90	24.4	1.1	0.0	210	0.18	4.56	0.51

Day	Waste				Permeate 1				Permeate 2				Permeate 3			
	Cum. Vol (L)	HMW	HS	LMN	Cum. Vol (L)	HMW	HS	LMN	Cum Vol (L)	HMW	HS	LMN	Cum Vol (L)	HMW	HS	LMN
1	1.89	2.85	2.50	0.85	1.3	0.00	1.16	0.00	0.2	0.01	1.41	0.03	1.3	0.00	1.11	0.00
11	20.79	1.62	4.59	0.00	18.0	0.20	5.25	0.08	19.2	0.45	5.10	0.26	18.3	0.14	5.12	0.23
16	30.24	1.94	5.72	0.39	38.1	0.06	3.89	0.14	36.9	0.04	3.55	0.12	38.6	0.09	3.73	0.22
24	45.36	1.35	4.01	0.01	55.8	0.04	5.33	1.14	52.6	0.00	3.72	0.00	56.5	0.01	3.35	0.00
30	56.70	1.39	4.08	0.32	59.1	0.18	4.71	0.17	56.1	0.16	3.67	0.06	59.9	0.22	4.24	0.06
42	79.38	0.53	3.94	0.57	63.9	0.13	3.80	0.32	61.0	0.19	3.69	0.29	65.0	0.36	3.61	0.20
51	96.39	0.15	3.43	1.18	67.2	0.06	3.34	0.24	64.2	0.20	3.43	0.03	68.4	0.13	3.39	0.13
61	115.29	0.46	4.51	0.48	70.6	0.01	3.97	0.15	67.6	0.39	6.02	0.94	72.0	0.15	3.74	0.45

MASS (mg)

Day	Total Organics	BioPolymers	HS + LMA	Humic Subs.	Reactor				Theoretical Reactor (Cumulative)				Total Permeate			
					Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN
1	15.09	7.84	6.48	0.77	117.23	53.86	47.29	16.08	117.35	56	46	15	3.25	0.00	3.24	0.01
11	412.45	103.35	280.72	28.38	117.23	30.57	86.66	0.00	148.28	115	0	33	295.75	14.17	271.33	10.25
16	443.71	177.37	264.69	1.66	152.16	36.70	108.07	7.39	292.08	270	0	22	229.72	3.71	216.53	9.48
24	423.76	123.34	283.69	16.73	101.36	25.45	75.80	0.11	401.05	372	10	18	233.70	0.85	212.64	20.22
30	111.93	24.10	76.16	11.67	109.48	26.31	77.10	6.07	404.06	379	0	25	45.82	1.92	42.90	1.00
42	189.36	45.01	133.19	11.16	95.25	10.02	74.44	10.78	427.92	408	0	20	62.28	3.36	54.95	3.97
51	146.84	44.75	102.09	0.00	90.06	2.92	64.78	22.35	459.39	449	10	0	36.21	1.31	33.59	1.31
61	178.18	22.08	143.65	12.45	103.05	8.75	85.31	8.98	482.12	461	21	0	54.18	1.88	47.05	5.25

Day	Waste				Permeate 1				Permeate 2				Permeate 3			
	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN
1	11.72	5.39	4.73	1.61	1.50	0.00	1.50	0.00	0.30	0.00	0.29	0.01	1.46	0.00	1.46	0.00
11	117.23	30.57	86.66	0.00	92.50	3.31	87.81	1.38	110.27	8.49	96.80	4.98	92.98	2.37	86.72	3.89
16	76.08	18.35	54.03	3.69	82.03	1.15	78.04	2.84	65.54	0.74	62.69	2.11	82.15	1.81	75.80	4.54
24	81.08	20.36	60.64	0.09	115.18	0.75	94.21	20.22	58.56	0.00	58.56	0.00	59.97	0.10	59.87	0.00
30	65.69	15.79	46.26	3.64	16.80	0.61	15.63	0.56	13.35	0.54	12.59	0.22	15.67	0.78	14.68	0.22
42	114.30	12.03	89.33	12.94	20.62	0.62	18.46	1.53	20.50	0.92	18.14	1.43	21.17	1.81	18.35	1.00
51	81.05	2.63	58.30	20.12	11.83	0.19	10.86	0.77	11.91	0.65	11.16	0.09	12.47	0.46	11.57	0.45
61	103.05	8.75	85.31	8.98	13.93	0.02	13.42	0.49	24.83	1.32	20.34	3.17	15.43	0.54	13.29	1.59



Comparison between Measured and Theoretical NOM Constituents in System Reactor for HMW, HS and LMN over Time for Passive Membrane Filtration without Aeration and with Daily Wasting

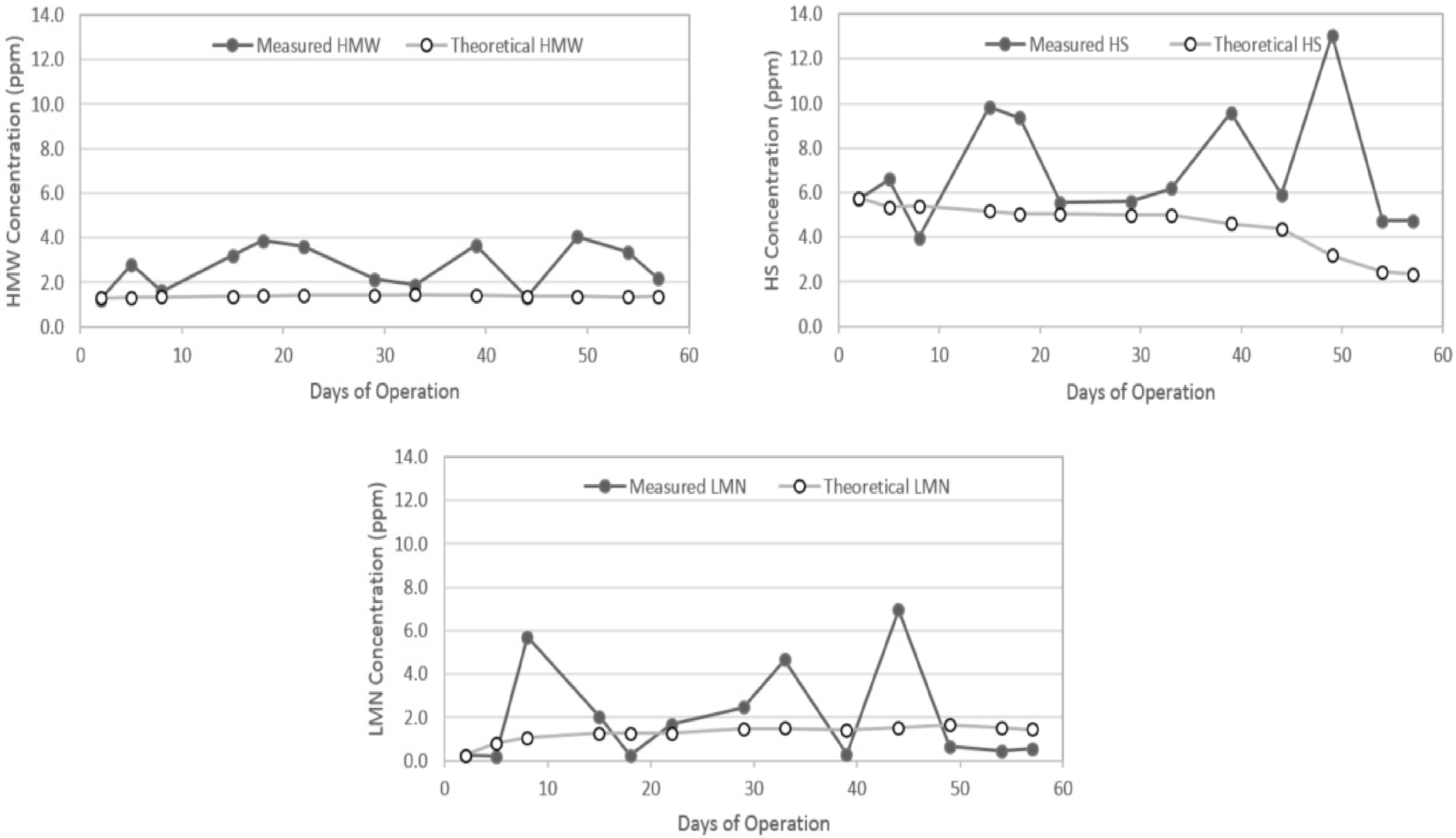
Appendix P: Mass Balance of NOM in a Non-Wasting Passive Membrane System without Backwash

CONCENTRATION (ppm)

	Feed				Reactor				Theoretical Reactor				Total Permeate				Waste				Permeate 1				Permeate 2				Permeate 3			
Day	Cum. Vol (L)	HMW	HS	LMN	Volume (L)	HMW	HS	LMN	Volume (L)	HMW	HS	LMN	Cum. Vol (L)	HMW	HS	LMN	Cum. Vol (L)	HMW	HS	LMN	Cum. Vol (L)	HMW	HS	LMN	Cum. Vol (L)	HMW	HS	LMN	Cum. Vol (L)	HMW	HS	LMN
2	1.91	0.86	4.03	0.25	18.90	1.22	5.70	0.23	18.90	1.30	5.78	0.25	1.91	0.05	3.30	0.13	0.00	1.22	5.70	0.23	0.30	0.00	0.00	0.00	0.53	0.04	4.67	0.23	1.08	0.07	3.55	0.12
5	2.30	0.47	2.58	5.11	18.90	2.79	6.60	0.20	18.90	1.32	5.37	0.80	2.30	0.30	5.92	0.53	0.00	2.79	6.60	0.20	0.80	0.28	4.14	0.08	1.51	0.31	6.86	0.76	0.00	0.32	3.64	0.21
8	1.32	0.71	3.59	3.79	18.90	1.61	3.99	5.72	18.90	1.35	5.39	1.06	1.32	0.27	3.25	0.13	0.00	1.61	3.99	5.72	0.46	0.28	4.14	0.08	0.86	0.27	2.77	0.16				
15	1.64	0.78	3.36	2.47	18.90	3.20	9.83	2.05	18.90	1.39	5.17	1.26	1.64	0.32	5.89	0.17	0.00	3.20	9.83	2.05	0.60	0.55	8.27	0.17	1.04	0.19	4.51	0.18				
18	0.61	1.49	4.71	0.16	18.90	3.88	9.35	0.25	18.90	1.41	5.06	1.26	0.61	0.98	8.36	0.18	0.00	3.88	9.35	0.25	0.61	0.98	8.36	0.18								
22	0.62	0.94	3.72	0.72	18.90	3.61	5.56	1.67	18.90	1.42	5.05	1.28	0.62	0.51	3.99	0.18	0.00	3.61	5.56	1.67	0.62	0.51	3.99	0.18								
29	0.75	0.69	3.33	5.73	18.90	2.13	5.63	2.47	18.90	1.43	5.01	1.49	0.75	0.40	4.42	0.30	0.00	2.13	5.63	2.47	0.75	0.40	4.42	0.30								
33	0.40	1.56	4.98	0.57	18.90	1.87	6.20	4.66	18.90	1.46	5.00	1.49	0.40	0.39	5.22	0.43	0.00	1.87	6.20	4.66	0.40	0.39	5.22	0.43								
39	0.53	1.56	4.98	0.57	18.90	3.68	9.59	0.28	19.90	1.41	4.62	1.41	0.53	0.38	9.64	0.84	0.00	3.68	9.59	0.28	0.53	0.38	9.64	0.84								
44	0.79	0.91	4.51	5.10	18.90	1.33	5.93	6.96	20.90	1.37	4.38	1.52	0.79	0.21	5.25	0.37	0.00	1.33	5.93	6.96	0.79	0.21	5.25	0.37								
49	3.63	0.97	6.39	2.10	18.90	4.06	13.05	0.66	21.90	1.38	3.18	1.65	3.63	0.58	12.38	0.95	0.00	4.06	13.05	0.66	3.63	0.58	12.38	0.95								
54	2.24	0.75	2.19	0.07	18.90	3.35	4.75	0.45	22.90	1.35	2.46	1.51	2.24	0.42	8.19	0.68	0.00	3.35	4.75	0.45	2.24	0.42	8.19	0.68								
57	1.70	1.20	3.84	0.48	18.90	2.16	4.76	0.56	23.90	1.36	2.34	1.46	1.70	0.26	3.99	0.42	0.00	2.16	4.76	0.56	1.70	0.26	3.99	0.42								

MASS (mg)

	Feed				Reactor				Theoretical Reactor (Cumulative)				Total Permeate				Waste				Permeate 1				Permeate 2				Permeate 3			
Day	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN	Total Organics	HMW	HS	LMN
2	9.82	1.65	7.69	0.48	135.20	22.99	107.81	4.40	138.36	24.54	109.19	4.63	6.67	0.10	6.31	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.10	0.02	2.48	0.12	7.88	0.08	3.84	0.13
5	18.80	1.08	5.95	11.77	181.34	52.74	124.80	3.79	141.62	24.93	101.50	15.19	15.54	0.69	13.64	1.21	0.00	0.00	0.00	0.00	6.87	0.22	3.29	0.07	22.31	0.47	10.35	1.15	0.00	0.00	0.00	0.00
8	10.68	0.94	4.74	5.01	213.95	30.41	75.43	108.10	147.48	25.50	101.96	20.02	4.82	0.36	4.28	0.18	0.00	0.00	0.00	0.00	3.96	0.13	1.90	0.04	5.15	0.23	2.39	0.14	0.00	0.00	0.00	0.00
15	10.87	1.29	5.52	4.06	285.01	60.49	185.83	38.69	147.84	26.26	97.79	23.79	10.50	0.53	9.69	0.28	0.00	0.00	0.00	0.00	10.42	0.33	5.00	0.10	9.77	0.20	4.69	0.18	0.00	0.00	0.00	0.00
18	3.86	0.90	2.86	0.10	254.94	73.42	176.81	4.71	145.93	26.57	95.58	23.78	5.77	0.60	5.07	0.11	0.00	0.00	0.00	0.00	10.84	0.60	5.07	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
22	3.34	0.58	2.31	0.45	204.94	68.21	105.14	31.59	146.37	26.83	95.42	24.12	2.90	0.32	2.47	0.11	0.00	0.00	0.00	0.00	5.38	0.32	2.47	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
29	7.32	0.52	2.50	4.30	193.40	40.35	106.33	46.73	149.84	27.05	94.60	28.20	3.85	0.30	3.32	0.22	0.00	0.00	0.00	0.00	7.16	0.30	3.32	0.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
33	2.82	0.62	1.97	0.23	240.63	35.31	117.21	88.11	150.27	27.51	94.51	28.25	2.39	0.15	2.07	0.17	0.00	0.00	0.00	0.00	4.46	0.15	2.07	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
39	3.78	0.83	2.65	0.30	256.16	69.47	181.33	5.36	148.27	28.14	92.03	28.11	5.78	0.20	5.13	0.45	0.00	0.00	0.00	0.00	10.90	0.20	5.13	0.45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
44	8.33	0.72	3.57	4.04	268.76	25.12	112.12	131.52	151.99	28.69	91.44	31.85	4.61	0.17	4.15	0.29	0.00	0.00	0.00	0.00	8.77	0.17	4.15	0.29	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
49	34.35	3.53	23.18	7.63	335.74	76.66	246.61	12.46	135.90	30.13	69.72	36.05	50.44	2.10	44.91	3.43	0.00	0.00	0.00	0.00	95.34	2.10	44.91	3.43	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
54	6.74	1.68	4.91	0.15	161.66	63.38	89.81	8.47	121.79	30.86	56.26	34.67	20.85	0.95	18.37	1.53	0.00	0.00	0.00	0.00	39.22	0.95	18.37	1.53	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
57	9.42	2.05	6.55	0.83	141.33	40.82	89.90	10.60	123.24	32.46	56.00	34.78	7.97	0.45	6.81	0.72	0.00	0.00	0.00	0.00	14.78	0.45	6.81	0.72	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00



Comparison between Measured and Theoretical NOM Constituents in System Reactor for HMW, HS and LMN over Time for Constant Low-Flux without Backwash and without Wasting

Appendix Q: Mass Balance of NOM in a Non-Wasting Passive Membrane System with Backwash

CONCENTRATION (ppm)

Day	Feed HMW	Feed HS	Feed LMN	Reactor Volume (L)	Reactor HMW	Reactor HS	Reactor LMN	Theoretical Reactor Volume (L)	Theoretical Reactor HMW	Theoretical Reactor HS	Theoretical Reactor Humic Subs.	Theoretical Reactor Low Mol.	Theoretical Reactor LMN
1	0.86	4.03	0.25	18.90	1.18	5.86	0.28	18.90	1.26	5.81	5.30	0.52	0.29
5	0.47	2.58	5.11	18.90	1.38	4.57	3.90	18.90	1.35	5.49	5.01	0.48	1.22
8	0.71	3.59	3.79	18.90	2.54	4.57	5.97	18.90	1.41	5.50	5.03	0.47	1.73
15	0.78	3.36	2.47	18.90	2.85	5.77	10.70	18.90	1.45	5.38	4.93	0.45	1.93
18	1.49	4.71	0.16	18.90	8.91	12.37	0.83	18.90	1.51	5.05	4.66	0.39	1.91
22	0.94	3.72	0.72	18.90	2.16	5.67	8.85	18.90	1.57	5.04	4.67	0.36	1.96
29	0.69	3.33	5.73	18.90	5.65	8.14	0.57	18.90	1.59	4.72	4.43	0.29	2.54
33	1.56	4.98	0.57	18.90	4.43	8.74	0.73	18.90	1.64	4.57	4.33	0.24	2.54
39	1.56	4.98	0.57	18.90	1.49	5.65	10.12	19.90	1.67	4.40	4.21	0.19	2.43
44	0.91	4.51	5.10	18.90	3.51	12.04	0.56	20.90	1.64	3.70	3.69	0.01	2.74
49	0.83	3.35	2.58	18.90	3.26	9.48	17.25	21.90	1.51	1.82	2.27	0.00	3.10
54	0.75	2.19	0.07	18.90	4.10	5.43	0.57	22.90	1.47	1.36	1.89	0.00	2.92
57	1.20	3.84	0.48	18.90	2.06	5.10	0.56	23.90	1.48	1.25	1.80	0.00	2.79

Day	Total Permeate Cum. Vol (L)	Total Permeate HMW	Total Permeate HS	Total Permeate Humic Subs.	Total Permeate Low Mol.	Total Permeate LMN	Waste Cum. Vol (L)	Waste HMW	Waste HS	Waste LMN
1	2.03	0.08	4.43	3.83	0.60	0.16	0.00	1.18	5.86	0.28
5	4.83	0.14	3.85	3.43	0.43	1.48	0.00	1.38	4.57	3.90
8	2.65	0.22	3.49	3.12	0.36	0.14	0.00	2.54	4.57	5.97
15	1.61	0.33	4.80	4.34	0.46	0.14	0.00	2.85	5.77	10.70
18	1.35	0.65	9.35	8.22	1.13	0.40	0.00	8.91	12.37	0.83
22	1.68	0.31	3.85	3.39	0.45	0.21	0.00	2.16	5.67	8.85
29	2.05	0.50	6.28	5.38	0.90	0.41	0.00	5.65	8.14	0.57
33	1.18	0.75	7.38	6.36	1.02	0.51	0.00	4.43	8.74	0.73
39	1.61	0.21	4.23	3.50	0.73	0.29	0.00	1.49	5.65	10.12
44	2.01	0.39	9.57	7.44	2.14	0.75	0.00	3.51	12.04	0.56
49	6.12	1.01	9.48	7.54	1.94	0.84	0.00	3.26	9.48	17.25
54	1.67	0.37	7.39	5.80	1.59	0.69	0.00	4.10	5.43	0.57
57	1.67	0.17	4.58	3.30	1.28	0.51	0.00	2.06	5.10	0.56

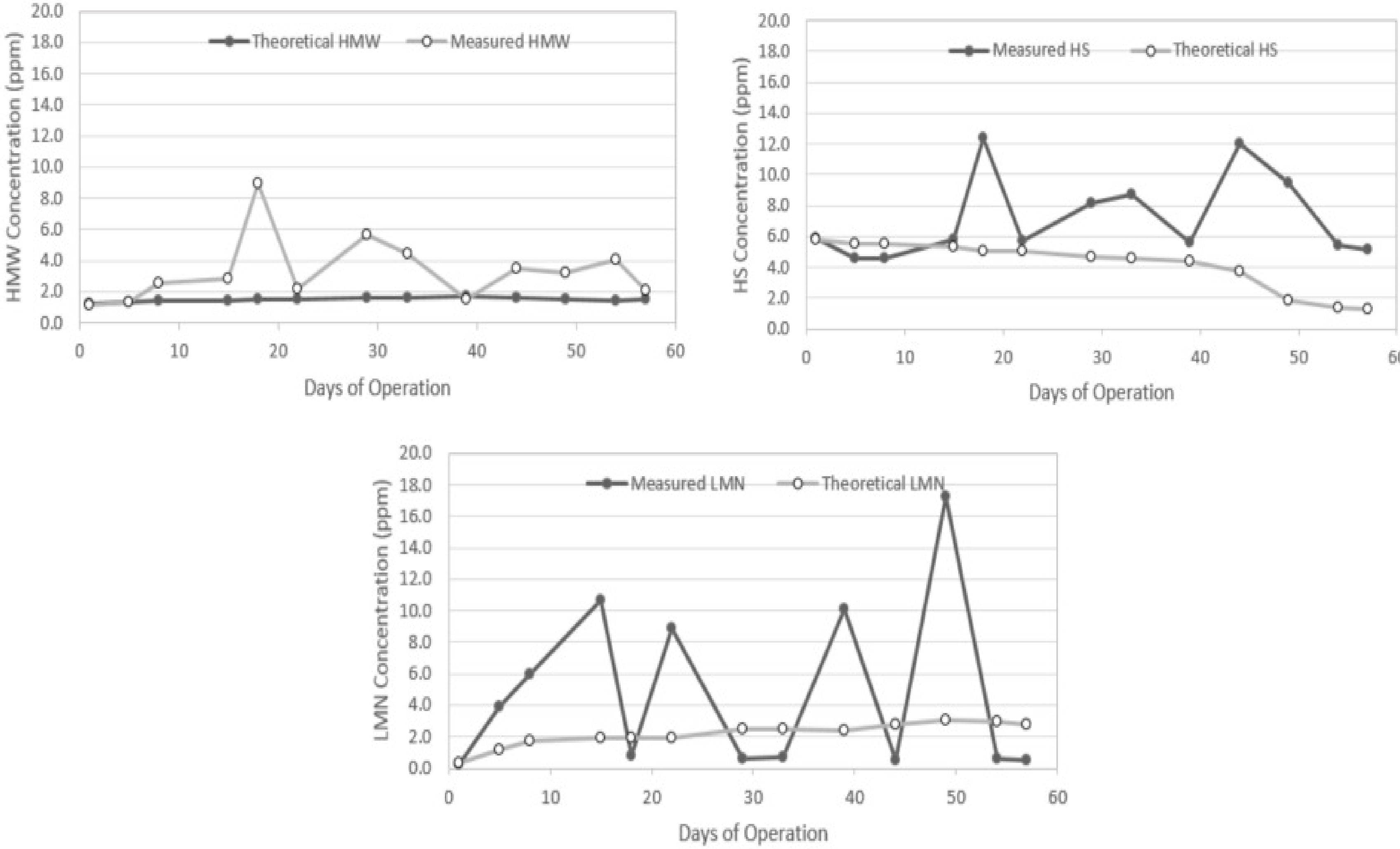
Day	Permeate 1 Cum. Vol (L)	Permeate 1 HMW	Permeate 1 HS	Permeate 1 LMN	Permeate 2 Cum. Vol (L)	Permeate 2 HMW	Permeate 2 HS	Permeate 2 LMN	Permeate 3 Cum. Vol (L)	Permeate 3 HMW	Permeate 3 HS	Permeate 3 LMN
1	0.35	0.05	4.77	0.14	0.58	0.04	4.64	0.09	1.10	0.11	4.21	0.20
5	0.83	0.25	4.89	0.10	1.42	0.14	3.27	4.81	2.59	0.11	3.84	0.11
8	0.47	0.25	4.89	0.10	0.80	0.24	3.88	0.17	1.38	0.20	2.78	0.14
15	0.60	0.46	5.02	0.06	1.01	0.26	4.67	0.19				
18	0.51	0.60	10.03	0.37	0.84	0.68	8.93	0.42				
22	0.64	0.27	4.14	0.21	1.03	0.33	3.66	0.21				
29	0.79	0.67	6.44	0.32	1.27	0.39	6.18	0.47				
33	0.44	0.71	7.66	0.43	0.74	0.78	7.21	0.56				
39	0.56	0.24	4.86	0.23	1.05	0.19	3.89	0.32				
44	0.76	0.65	11.62	0.89	1.25	0.23	8.34	0.67				
49	3.54	0.56	10.21	0.87	2.58	1.64	8.47	0.79				
54	1.67	0.37	7.39	0.69								
57	1.67	0.17	4.58	0.51								

MASS (mg)

Day	Feed HMW	Feed HS	Feed LMN	Reactor Total Organics	Reactor HMW	Reactor HS	Reactor LMN	Theoretical Reactor (Cumulative) Total Organics	Theoretical Reactor (Cumulative) HMW	Theoretical Reactor (Cumulative) HS	Theoretical Reactor (Cumulative) Humic Subs.	Theoretical Reactor (Cumulative) Low Mol.	Theoretical Reactor (Cumulative) LMN
1	1.75	8.16	0.51	138.33	22.29	110.71	5.33	139.30	23.88	109.90	100.14	9.76	5.52
5	2.26	12.49	24.69	186.06	26.15	86.29	73.62	152.24	25.44	103.76	94.75	9.02	23.03
8	1.88	9.51	10.05	247.34	48.10	86.34	112.90	163.48	26.74	104.04	95.11	8.93	32.70
15	1.27	5.41	3.98	365.14	53.91	109.07	202.17	165.63	27.47	101.71	93.16	8.55	36.45
18	2.02	6.38	0.22	417.83	168.38	233.82	15.63	160.19	28.61	95.44	88.11	7.32	36.13
22	1.57	6.24	1.21	315.30	40.83	107.16	167.31	161.89	29.67	95.23	88.33	6.90	36.99
29	1.42	6.85	11.78	271.37	106.75	153.87	10.75	167.16	30.06	89.18	83.70	5.48	47.92
33	1.85	5.89	0.67	262.75	83.81	165.17	13.78	165.35	31.02	86.34	81.81	4.53	47.99
39	2.51	8.01	0.91	326.26	28.19	106.75	191.31	169.19	33.19	87.55	83.84	3.71	48.44
44	1.83	9.07	10.25	304.38	66.29	227.51	10.57	168.80	34.25	77.37	77.21	0.15	57.18
49	5.08	20.50	15.81	566.72	61.66	179.11	325.95	140.86	33.13	39.85	49.65	0.00	67.88
54	1.25	3.66	0.11	190.96	77.53	102.69	10.75	131.76	33.77	31.15	43.17	0.00	66.83
57	2.01	6.42	0.81	146.10	39.00	96.44	10.66	132.19	35.49	29.92	43.10	0.00	66.78

Day	Total Permeate Total Organics	Total Permeate HMW	Total Permeate HS	Total Permeate Humic Subs.	Total Permeate Low Mol.	Total Permeate LMN	Waste Total Organics	Waste HMW	Waste HS	Waste LMN
1	9.44	0.16	8.97	7.76	1.21	0.32	0.00	0.00	0.00	0.00
5	26.50	0.70	18.62	16.56	2.06	7.17	0.00	0.00	0.00	0.00
8	10.20	0.58	9.24	8.27	0.96	0.38	0.00	0.00	0.00	0.00
15	8.50	0.53	7.74	7.00	0.74	0.23	0.00	0.00	0.00	0.00
18	14.07	0.88	12.65	11.13	1.52	0.54	0.00	0.00	0.00	0.00
22	7.31	0.51	6.45	5.69	0.76	0.35	0.00	0.00	0.00	0.00
29	14.77	1.03	12.90	11.05	1.85	0.85	0.00	0.00	0.00	0.00
33	10.22	0.89	8.72	7.52	1.20	0.61	0.00	0.00	0.00	0.00
39	7.59	0.34	6.80	5.63	1.17	0.46	0.00	0.00	0.00	0.00
44	21.54	0.78	19.25	14.96	4.29	1.51	0.00	0.00	0.00	0.00
49	69.33	6.20	58.02	46.13	11.89	5.12	0.00	0.00	0.00	0.00
54	14.13	0.61	12.36	9.69	2.67	1.16	0.00	0.00	0.00	0.00
57	8.81	0.29	7.66	5.51	2.14	0.86	0.00	0.00	0.00	0.00

Day	Permeate 1 Total Organics	Permeate 1 HMW	Permeate 1 HS	Permeate 1 LMN	Permeate 2 Total Organics	Permeate 2 HMW	Permeate 2 HS	Permeate 2 LMN	Permeate 3 Total Organic	Permeate 3 HMW	Permeate 3 HS	Permeate 3 LMN
1	3.38	0.02	1.66	0.05	5.47	0.02	2.70	0.05	9.57	0.12	4.62	0.22
5	8.42	0.21	4.07	0.08	16.28	0.20	4.63	6.81	20.42	0.28	9.93	0.28
8	4.80	0.12	2.32	0.05	6.50	0.19	3.08	0.14	8.13	0.27	3.83	0.19
15	6.37	0.28	3.03	0.03	9.88	0.26	4.71	0.19	0.00	0.00	0.00	0.00
18	10.81	0.31	5.16	0.19	15.91	0.57	7.49	0.35	0.00	0.00	0.00	0.00
22	5.62	0.17	2.65	0.13	8.14	0.34	3.79	0.22	0.00	0.00	0.00	0.00
29	10.94	0.53	5.08	0.25	16.73	0.50	7.82	0.59	0.00	0.00	0.00	0.00
33	7.23	0.31	3.36	0.19	11.71	0.58	5.36	0.42	0.00	0.00	0.00	0.00
39	5.71	0.14	2.72	0.13	8.68	0.20	4.08	0.33	0.00	0.00	0.00	0.00
44	18.75	0.49	8.79	0.68	22.05	0.29	10.46	0.84	0.00	0.00	0.00	0.00
49	77.41	1.97	36.18	3.08	49.93	4.22	21.84	2.03	0.00	0.00	0.00	0.00
54	26.49	0.61	12.36	1.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
57	16.46	0.29	7.66	0.86	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00



Comparison between Measured and Theoretical NOM Constituents in System Reactor for HMW, HS and LMN over Time for Constant Low-Flux with Backwash and without Wasting