Improving the Removal of Emulsified Oil from Wastewater with a Membrane Bioreactor using Powdered Activated Carbon

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Abstract

This project analyzed the effectiveness of powdered activated carbon (PAC) in removing oil from wastewater. To test this, a membrane bioreactor was run with mineral oil (30 ppm), sludge, and various PACs (463 ppm). Based on COD and turbidity results, WPH, WPH-1000, and WP260-90 were the most effective for improving water quality. WP260-90 was the ideal choice as it had the lowest respective transmembrane pressure and was used to design an on-site water reuse system for a car wash.

Professional Licensure Statement

To protect the health, safety, and welfare of the public, professionals in a variety of fields are required to receive licensure (The Office of Consumer Affairs & Business Regulation, 2016). Licensure provides credentials and a set of guidelines to the professional. Specific to engineering, receiving your professional engineer (PE) license gives you the authority to approve and seal engineering work for clients, and it conveys that your engineering skills are reputable (National Society of Professional Engineers, 2016).

The first step in receiving your PE license is to complete the Fundamentals of Engineering (FE) exam and become an engineer-in-training (EIT). EITs must then complete four years of "qualifying engineering experience," (National Society of Professional Engineers, 2016). This is often performed under the guidance of a professional engineer. The final step is to complete and pass the PE exam. The exam varies by state in terms of required qualifications (National Society of Professional Engineers, 2016). To maintain licensure, PEs must work to improve and retain their skills as they further their careers.

As a PE, you are required to follow a set of ethics and guidelines, known as the NSPE Code of Ethics for Engineers. Engineers must take in consideration the safety, health, and welfare of the public, avoid deception, be faithful to employers and clients, and only provide services in areas where they are competent. For engineering plans, it is a legal requirement for a PE to sign off on the plans. PEs must also consider the safety of the lives affected by their designs (National Society of Professional Engineers, 2016).

Executive Summary

Oil and grease are found in domestic and industrial waste, including sewage and discharge from food processing, textile factories, metal fabrication, petroleum refining and from other common industries. Oil and grease cause not only environmental problems, but also problems in the wastewater treatment process (Alade et al., 2011). They can be toxic to wildlife, especially to fish that inhabit the water where the wastewater is released. Oil and grease also prevent the transfer of oxygen into the water and negatively impact the aesthetics of the water. In treatment plants, oil and grease can clog pipes and restrict the flow of water, leading to dangerous situations and costly repairs. Current methods to treat oil in wastewater are inefficient and have high operating costs (Zhou et al., 2008).

To prevent equipment failures and environmental problems, this project researched the effectiveness of removing emulsified oils with powdered activated carbon (PAC) in a membrane bioreactor (MBR) provided by Koch Membrane Systems, Inc. Our main objective was to run the MBR with seven different PACs to determine the amount of oil that can be removed by the PACs in the MBRs. The effluent from the MBRs was collected, and chemical oxygen demand (COD) and turbidity were used as indicators of the quality of water and level of treatment attained.

MBRs are an activated sludge process, in which microorganisms are suspended in the wastewater using aeration (a process that is used in a variety of wastewater treatment systems). MBRs have increased in popularity due to their minimal size requirements when compared with conventional activated sludge systems. A conventional system needs two units, an aeration basin and a clarifier, to separate the microorganisms causing a large physical size requirement for an activated system (Droste, 1997). However, MBRs can accomplish the tasks of an activated sludge process in a smaller space because the clarifier is not needed. MBRs are placed within the aeration tank and the membranes become a physical barrier to separate the biomass and solids from the effluent by only allowing water to pass through (Faisal et al., 2014).

The integrity of a membrane is vital to the MBR's ability to function; small amounts of damage to its integrity can largely impact its effectiveness. With oil being the main pollutant tested, fouling of the membrane was of concern. Membrane fouling occurs when substances create deposits that accumulate on the surface of a membrane, internally or externally, during operation (Song, 1998). When larger particles accumulate on the external surface of the membrane, it is referred to as cake fouling because the larger particles create a layer that blocks anything else from reaching the surface of the membrane. Fouling on the internal surface of the membrane is referred to as pore blocking because the smaller particles accumulate within the pores of the membrane. Both types of fouling reduce the flow of water through the membrane, resulting in a higher transmembrane pressure when operating the MBR at a constant flux. Fouling contributes to the high cost of operating and maintaining an MBR, along with the initial high capital investment for equipment (EPA, 2008). When a membrane becomes fouled, the membrane must be cleaned or replaced, adding to the overall cost of the system (Judd, 2008). The high cost is also influenced by the need for a higher aeration rate to minimize the risk of fouling; which demands a higher energy input (EPA, 2008).

With the addition of PAC to the MBR, the degree of potential fouling could decrease because of the carbon's characteristics. Activated carbon has pores that create a large surface area, allowing it to adsorb organic compounds. The range of adsorption is mainly dependent on the activated carbon properties; one characteristic is the iodine number. The project tested multiple repurposed granular activated carbons, as well as charcoal- and wood-based carbons, each with varying iodine numbers. The seven PAC types manufactured by Calgon that were available were WPX, WPX-Z, Pulsorb WP260-90, WPH, WPH-1000, WPH-W, and WPC.

Each test was run in a benchtop MBR as a continuous operation with the permeate return directed to the feed tank. The tank contained 30 parts per million (ppm) of emulsified oil, secondary sludge at a concentration between 6 and 8 g/L, and 2.5 g (463 ppm) of PAC. The MLSS, initial COD, and initial turbidity were measured using samples taken from the tank prior to adding PAC and starting the apparatus. The apparatus was run for 4 hours, with measurements taken every 5 minutes to calculate transmembrane pressure, which can be used to indicate potential fouling. Effluent was collected to measure final COD, turbidity, and the amount of mineral oil remaining. The hexane extraction method was used to measure the amount of oil in the samples. A run was performed with no PAC to provide a baseline. The MBR was cleaned after each test by rinsing the system three times with clean water and then backwashing and soaking with chlorine to disinfect the apparatus. This was repeated with each PAC.

Six PAC types were tested in the MBR after WPC was eliminated due to its excessive hardness. Our first attempt used a high concentration of PAC, at 27g (5,000 ppm), and one of the MBRs clogged and ceased function. This led to a beaker test for all six PACs in which each PAC was mixed with primary effluent, mineral oil and surfactant, to observe their interaction. It was determined that all the PACs could still be tested in the MBR if the concentration was significantly lower.

The six PACs and the baseline were all tested for COD and turbidity. The highest change in COD was with the WPH-1000 PAC, a coal-based carbon, which resulted in

79.54% COD removal. The lowest change in COD was in the no carbon baseline, at 11.29% removal. PACs with an MLSS concentration between 7 g/L and 7.6 g/L resulted in the higher COD removal, and MLSS concentrations above this range resulted in the lowest removal. Percent removal of turbidity for all of the runs, besides the baseline, were 93% and above. The highest change in turbidity was in the WPH-W, at 99.66% removal. The lowest change in turbidity was in the no carbon baseline, at 86.31% removal. Although WPH-W has the highest percent removal of turbidity, it had the second lowest percent removal of COD at 13.79%. MLSS concentration had no apparent effect on turbidity.

After analyzing all the data, it was determined that the coal-based PACs, WPH-1000, WPH, Pulsorb WP260-90, were the most effective in cleaning the water. The transmembrane pressures of these PACs were higher than the baseline, with the exception of Pulsorb WP260-90. Since a high TMP may indicate potential fouling problems, Pulsorb WP260-90 was determined to be the ideal PAC.

There were various aspects of the experiments that created limitations and caused possible errors in the data collected. The oil often adhered to various containers and apparatus used for each test. This made it difficult to accurately measure oil removal. Another issue occurred in taking effluent samples in that different runs took various amounts of time to fill the sample container. This means that the effluent was exposed to the membrane and PACs for different lengths of time. The varying MLSS for each run may have also skewed results. Improvements to this experiment to gather more representable and reproducible data would include implementing an effective measurement method for the oil used in these experiments because the hexane extraction method proved to be ineffective and unreliable for our research. Another improvement would be to perform multiple runs for each PAC, as well as longer runs to more accurately represent an MBR system. This would provide more data for the effectiveness of the carbon and demonstrate whether or not the process would work with an MBR that has biological growth.

To satisfy the design portion of the MQP, an on-site treatment process was designed for a typical car washing facility using PAC and a membrane filtration system in order to allow for the reuse of water at the facility. The design eliminated the use of biology to treat the water because the contaminants in car wash effluent do not include domestic waste, meaning the biological treatment is unnecessary and likely ineffective.

The final portion of this project was dedicated to studying the social and environmental impacts of oily wastewater, along with potential environmental justice issues. Environmental justice is the uneven distribution of environmental hazards within and between communities (Cutter, 1995). Environmental justice groups can be defined based on race, income, and language barriers. These groups often experience a closer proximity to environmental hazards, and as a result are more vulnerable to their impacts (Goldstone, 2015). In order to identify potential environmental justice issues involving oily wastewater, a main contributor of oily waste in many locations was identified as car washing facilities. A map of Massachusetts towns was then analyzed with data on the locations of environmental justice groups and car washes as well as data on land elevations, water bodies, and wetlands. The different data layers were studied in an attempt to determine which groups were most likely to encounter the impacts of oily waste discharged by car washes.

Design Statement

According to the Clean Water Act, professional car wash facilities are required to dispose of car wash wastewater either through a water treatment facility or state-approved drainage facility (Illinois Environmental Protection Agency, 2015). Before the wastewater from a car wash is sent to a facility or drainage system, it should be filtered to reduce the amount of solids in the water. Filters, as well as oil-water separators, are beneficial to capture and recycle car wash wastewater and prevent soil and groundwater contamination. A car wash water-reuse system was designed using the combination of a membrane system and PAC to produce what may be a more effective oil-water separator compared to a conventional oil-water separator. This design includes an initial and clean water storage tank, a settling tank, and a membrane filter with amended PAC. There are also two lines of settling tanks and membrane filters for maintenance and overflow reasons.

The design in this project was to treat wastewater from a car wash facility handling 110 cars per day. Using data from various car washes in three major U.S. cities, it is assumed that each car uses an average of 37 gal of water. From this information, the design flow rate was determined to be 4,477 gpd with 10% leakage accounted for. The storage tank was designed to collect all the water from the day to then be sent through the treatment system at night when the frequency of car washes will be low. This allows energy to be saved since the system will not be operational all day.

The initial storage tank will require volume of 4,500 gal with a depth, width, and length of each 8.44 ft. For construction purposes, the actual tank will be 9 ft. wide, 9 ft. long, and 8 ft. deep.

The objective of the settling tank is to have larger suspended solids settle to the bottom prior to entering the membrane process. Removal of suspended solids will reduce the potential for abrasions on the membrane surfaces and reduce potential fouling. A flow rate of 4,477 gpd and a hydraulic loading rate of 150 gpd/ft.^{2} were used to design the settling tank. The settling tank will be 6.5 ft deep, 10 ft long, and 3 ft wide; these were rounded up to standard numbers to allow for easier ordering for construction while still meeting the minimum requirements.

The membrane treatment step will have both the membrane filters in hollow fiber configuration, and PAC will be amended to the tank containing the membranes. To properly fit the membrane unit, the tank will be 8 ft deep and 3 ft wide. The Koch Membrane Systems, Inc. PSH 31HD model was used in the design of this system. The model has a length of 3.62 in., a width of 32.6 in. and a height of 71.7 in. Only one membrane unit is necessary for the design flow rate and the size of the tank. The permeate flux will be 25 LMH, giving a flow of 4,853 gpd. PSH 31HD has nine columns, each assumed to have 100 fibers for a total of 900 fibers. An important part of the membrane system operation is the air scour to prevent solids from settling at the foot of the membrane. An airflow rate of 1369 scfh will be needed based on the surface area of the membrane. The PAC chosen based on lab results was Calgon's Pulsorb WP260-90 as it produced effective COD removal and turbidity decrease in the bench-scale membrane reactor experiments. Out of the three best PACs, this one produced the lowest TMP, meaning the pressure buildup was not as substantial as when using the other PACs. This indicated a lower risk for fouling. For a dosage of 463 ppm and a flow rate of 4,477 gpd, the total PAC amount needed will be 7,847 g/day.

A clean water storage tank will receive all the clean water that is treated overnight, and will be ready to supply water once the workday starts. No treatment process is conducted in this tank. The storage tank will be a 4,500 gal tank made of coated steel. All piping material will be coated low-carbon or low-alloy steel as steel is durable and the coating will prevent corrosion. Using the 4,477 gpd design flow rate and a velocity of 1.5 ft/sec, the cross-sectional pipe area would be 1.6 in^2. This gives an inside diameter of 1.4 in., but for construction purposes a nominal pipe size of 1-½ with a schedule of 80 will be used. This will provide an internal diameter of 1.50 in.

There are two pumps in this system: one after the initial storage tank and one after the membrane tank. Assuming a pump efficiency of 0.6, a minimum power required of 0.008 kW, or 0.011 HP was found. Using this, the overall flow rate, and the diameter of our pipes, the Berkeley 7SLP42-03 was determined to be the best fit for the system. The design of this system requires four valves total. All of them will be brass 1-½ in ball valves to allow one train to be shut down completely when not in use. It is also important that the valve can flow both ways, as a backflush will be necessary to clean the membrane.

Based on our experiments, we determined that using PAC in combination with a membrane system would be an efficient oil-water separator for a car wash water reuse system.

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1.0 Introduction

Oil and grease are found in the industrial wastewater from sewage, food processing, textile factories, metal fabrication, petroleum refining and other common industries. Oil and grease cause not only environmental problems, but also problems in wastewater treatment processes (Alade et al., 2011). They are toxic to wildlife, especially to the fish that inhabit the water where the wastewater is released. Oil and grease also prevent the transfer of oxygen into the water and negatively impact the aesthetics of the water. In treatment plants, oil and grease can clog pipes and restrict the flow of water, leading to dangerous situations and costly effects. Current methods to treat oil in wastewater are inefficient and have high operating costs (Zhou et al., 2008).

Membrane Bioreactor (MBR) technology is used to treat water and wastewater through filtration. MBRs efficiently remove biochemical oxygen demand (BOD) and chemical oxygen demand (COD), requires less space than traditional treatment systems, and can run at longer retention times, yielding less activated sludge (Faisal et al., 2014). Data indicates that compared to a conventional activated sludge system, MBRs can effectively remove oils (Li et al., 2006 and Scholz et al., 2000).

This project aimed to research the effectiveness of removing emulsified oils with powdered activated carbon (PAC) in addition to using a membrane bioreactor (MBR). We pursued the following objectives:

1. Operate an MBR to treat domestic wastewater spiked with mineral oil,
2. Augment the wastewater with PAC,
3. Analyze the effectiveness of the removal of the mineral oil using the hexane extraction method,
4. Analyze the effectiveness of the MBR and PAC in combination by measuring the COD and turbidity in the effluent, and
5. Conduct an analysis of potential environmental justice issues surrounding oil in wastewater, with a specific focus car washes.

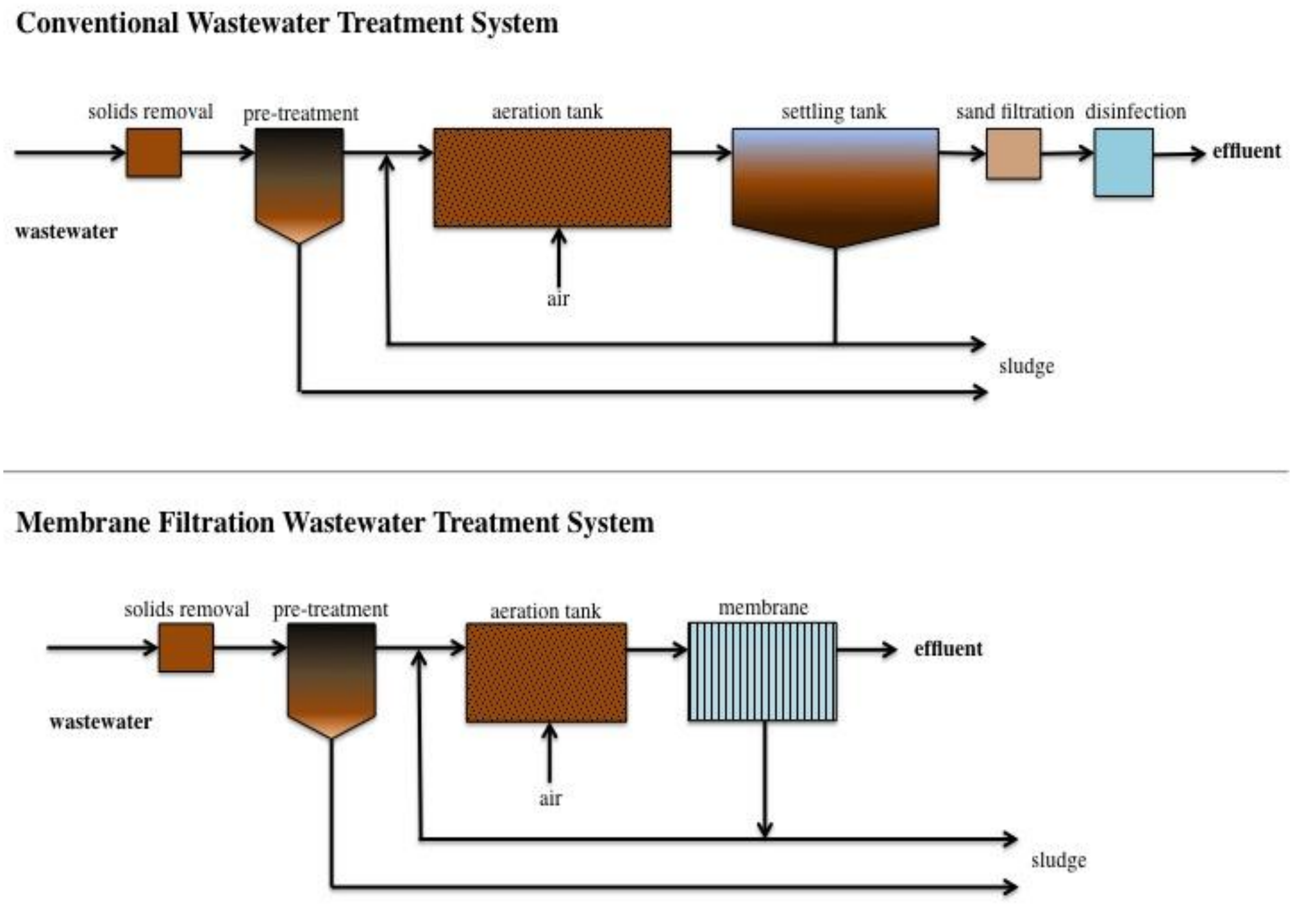
2.0 Background

2.1 Membrane Bioreactors

Membrane Bioreactors (MBRs) are designed according to the principles of an activated sludge, suspension of microorganisms through aeration that is used in a variety of wastewater treatment systems. Activated sludge treats water that is high in organics and biodegradables such as oil; the organics provide carbon and energy needed for the microorganisms, typically bacteria, to grow and reproduce (Sustarsic, 2009). This happens in an aeration basin with adequate mixing to prevent sedimentation of the microorganisms and to mix the nutrients and oxygen. The combined organic matter and wastewater is known as mixed liquor. The mixed liquor passes to a second basin known as a clarifier, where the separation of the biomass and suspended solids occur. The effluent of the clarifier is relatively free of suspended solids and a portion of the sludge is returned to the aeration basin to maintain a specific concentration of organisms (Droste, 1997).

2.1.2 Process

While this system works well, there is a physical size requirement that is addressed in an MBR process, allowing it to increase in popularity over the last 10 years (EPA, 2008). A conventional system needs two units, an aeration basin and a clarifier, to separate the microorganisms causing a physical size requirement for an activated system (Droste, 1997). However, MBRs can accomplish the tasks of an activated sludge process in a smaller space because the clarifier is not needed. MBRs are placed within the aeration tank and the membranes become a physical barrier to separate the biomass and solids, only allowing water to pass through, as seen in Figure 1 (Faisal et al., 2014). This retention is done by microfiltration (MF) or ultrafiltration (UF); microfiltration can retain compounds with the molecular weight of 200,000 g/mol and ultrafiltration can retain 20,000 g/mol (Cecen, 2012).



Adapted from, U.S. Environmental Protection Agency

Figure 1. Conventional Wastewater Treatment vs. Wastewater Treatment using Membrane Filtration (U.S. EPA, 2015)

2.1.3 Membrane Material

The membranes themselves can be manufactured with various forms of polymer materials including cellulose (EPA, 2008). Ceramic membranes may also be used. They have the benefit of being fouling-resistant but at the highest cost (Judd, 2008). The pore size is adjusted to about 1 micron to prevent the microorganisms from passing through the membrane (EPA, 2008). Membranes can be arranged as a flat sheet or hollow fibers if placed inside the bioreactor or, if placed outside, can be multitube (Judd, 2008). Hollow fibers grouped in bundles or flat sheets are the most popular configurations (EPA, 2008).

2.1.4 Solids

The MBR can run at a longer solids retention time with higher mixed liquor suspended solids (MLSS) concentrations. In an activated sludge wastewater treatment process MLSS concentrations are typically kept between 1,500 mg/L and 5,000 mg/L due to the limitations of the clarifier. With an MBR, however, the MLSS concentrations can be 10,000 mg/L to 12,000 mg/L. This is because the membrane process does not rely on gravity. The higher MLSS concentration provides better and faster treatment of the water, allowing for increased loading rates (Bernal et al., 2012). A higher MLSS concentration also lowers the sludge production associated with an MBR; its yield is less than that of an activated sludge system. While this is an advantage, it also introduces a disadvantage to MBRs. The inefficient mixing would raise the aeration demand and the membrane cleaning, increasing the cost and offsetting the economic advantage of less sludge. If the MBR is not run at longer retention times, the sludge production would be slightly higher compared to an activated sludge system because of the particles and colloids separation by the membrane (Faisal et al., 2014).

2.1.5 Effluent

Effluent from an MBR process is better compared to a conventional activated sludge system. The membrane prevents colloidal and some soluble compounds to pass; therefore allowing them to be further biodegraded (Faisal et al., 2014). This allows the effluent to contain a lower concentration of bacteria, total suspended solids, biochemical oxygen demand, and phosphorus (EPA, 2008). An MBR can provide 96-99% COD removal while a conventional system achieves about 95% (Faisal et al., 2014). Additionally, some chlorine resistant pathogens, like *Cryptosporidium* and *Giardia*, are filtered depending on the pore size of the membrane (Escobar, 2010). The effluent quality is suitable for surface stream discharge and reuse applications such as irrigation (EPA, 2008).

2.1.6 Membrane Integrity

The integrity of a membrane is vital to its ability to function as designed; small amounts of damage to its integrity can largely impact its effectiveness. Integrity issues can be categorized into two categories: manufacturing defects and operational problems. Manufacturing defects occur during the creation process of the membranes and are not controllable by the operator other than purchasing from a reliable company. These defects can occur many different ways, such as voids in the membrane creating a weakness and leading to breakage, slits created from the membrane being crushed during the manufacturing process, and epoxy issues creating weakness near the tube sheets.

Operational problems stem from improper use and treatment of the membranes. This includes scratching and piercing from debris that were not removed before the MBR, contact of large particles due to improper pretreatment, exposure to strong chemicals, and creation of slits caused by over pressurization of the MBR (Hai et al., 2014).

2.1.7 Abrasion

One process that negatively impacts the membrane's efficiency is abrasion. Abrasion occurs when rough materials or particles hit or rub against a surface, deteriorating it over time. It is a common problem for waters with high turbidity and particulate matter, such as seawater pretreatment, agricultural treatment, storm water, industrial water, and processes using powdered activated carbons (Lai et al., 2015 a). The presence of abrasive materials in an MBR can drastically shorten its lifespan by wearing away the surface of the membrane. When UF and MF membranes with a life expectancy of 7-10 years were used in salt-water desalination plants, the life expectancy was decreased to 3-5 years (Lai et al., 2015 b). As the abrasive particles collide with the membrane they slowly break apart the surface, creating relatively large holes, ruining the effectiveness of the membrane. As these holes are formed, undesired contaminants will be able to get through the membrane, lowering the quality of the water as time goes on. This damage caused by abrasion is irreparable.

2.1.8 Fouling

Fouling is often used as a general term for any loss in membrane effectiveness or productivity. More specifically, membrane fouling occurs when substances create deposits that accumulate on the surface of a membrane, internally or externally, during operation (Song, 1998). When larger particles accumulate on the external surface of the membrane, it is referred to as cake fouling because it creates a layer that blocks anything else from reaching the surface of the membrane. Fouling on the internal surface of the membrane is referred to as pore blocking because the smaller particles accumulate within the pores on the membrane. Both of these prevent the flow of water through the membrane, resulting in a high pressure required to operate the MBR at a constant flux. Fouling can also be classified by its ability to be removed through three different processes. The first, physically reversible fouling, is the result of foulants that are loosely attached to the membrane's surface. These foulants are easily removed through physical means such as backwashing or scouring. The second, chemically reversible fouling, is caused by stronger foulants that can only be removed by chemically cleaning the membrane. The final, irreversible fouling, occurs over a longer period of time and is a permanent loss in efficiency or permeability (Hai et al., 2014).

Fouling is a driving force to the high cost of operating and maintaining an MBR, alongside with the initial high capital equipment (EPA, 2008). When a membrane fouls, the membrane must be cleaned or replaced, adding to the overall cost of the system (Judd, 2008). The high cost is also influenced by the need for a higher aeration rate to minimize the risk of fouling; which needs a higher energy input (EPA, 2008). The energy required for an activated sludge system is about 0.25-0.3 kWhr/m^3 water treated compared to 1.2-1.5 kWhr/m^3 water treated for smaller MBR facilities and 1.0 kWhr/m^3 water treated for larger MBR facilities in 2011. However, there have been energy improvements in the design as it has decreased from 2.5 kWhr/m^3 water treated in 1999 (Faisal et al., 2014).

2.2 Damage Caused by Oil & Grease

Oil and grease may be deleterious to public health and the discharge of oil and grease is becoming more environmentally concerning in industrial wastewater pollution. Oil and grease can contaminate drinking water and groundwater resources, endanger human and wildlife health, and damage natural aesthetics. Often, depending on the industry, oily wastewater contains phenols, petroleum hydrocarbons, and polyaromatic hydrocarbons, toxic substances that are carcinogenic to humans and can inhibit the growth of plants and animals (Alade et al., 2011). Specifically, oil is dangerous to aquatic environments because it is hydrophobic and has low solubility in water. This causes a layer of oil to form on the top of contaminated water bodies, preventing light penetration and photosynthesis as well as the transfer of oxygen, decreasing the amount of dissolved oxygen in the bottom layer of the water. A decrease in dissolved oxygen directly affects the reproduction and growth ability of aquatic species such as fish.

Physically, oil and grease cause damages in wastewater treatment plants and sewers, increasing maintenance costs and potential for dangerous outcomes. Oil gets stuck in pipes and screens throughout the plant and in the sewers, leading to blockages that decrease flow efficiency or burst pipes (Alade et al., 2011).

2.3 Conventional Treatment Methods for Emulsified Oil

Emulsified oil is a stable mixture that has oil droplets dispersed throughout water. Emulsified oil is more problematic than free oil (oil not dispersed throughout the water) since free oil stays in a layer separate from the water, allowing it to be easily removed. Emulsified oil, on the other hand, may pass through filtration systems, contaminating the effluent. Emulsions are most commonly found in effluents from petroleum refineries, chemical processing plants, and manufacturing plants (Ibrahim et al., 2010).

Some conventional treatments for removing emulsified oil in wastewater include flotation, coagulation, and membrane filtration. Flotation injects tiny air bubbles into the water that adhere to the oil particles. Because oil's density is less than that of water, the bubbles float to the top of the water and form a separate layer (Yu et al., 2013). There are several varieties of flotation, including electro flotation, dissolved air flotation, induced air flotation, and nozzle air flotation. Flotation can efficiently remove emulsions with a chemical addition, however this then requires chemical sludge handling (Bennett et al., 2010).

Coagulation produces precipitates through the use of coagulating agents, such as aluminum sulfate. These precipitates have a positive surface charge, which attracts the negatively charged oil surfaces and destabilizing them. This allows for the precipitates, with the oil attached, to be filtered out of the water (Welz et al., 2010). Coagulation has a high removal of suspended solids and emulsified oil, but is costly and produces chemical sludge (Bennett et al., 2010).

Membrane filtration can remove emulsions as well. The membrane allows for water to filter through its pores while trapping the oil in the membrane. The disadvantage to membranes filtering oil is that the membranes are easily fouled by elevated concentrations of oil (Kong et al., 1999).

2.4 Activated Carbon

Carbon is activated through physical or chemical processes, allowing the creation of pores and an increased surface area. Physical activation is usually performed through carbonization, oxidation, or a combination of both. During carbonization, organic material goes through pyrolysis within a temperature range of 600-900°C. Pyrolysis decomposes organic material thermochemically at high temperatures in the absence of oxygen. The process is irreversible and changes the chemical composition of the organic material and the physical phase (CPEO, n.d.). During carbonization, some oxidation occurs because it is impossible to create an oxygen-free environment. Oxidation exposes raw organic material or carbonized material to oxygen or steam within a temperature range of 600-1200°C. During the chemical activation process, acids, strong bases, or salts are infused with the raw organic material. The material is then carbonized within a temperature range of 450-900°C. Chemical activation is often preferred over physical activation because it requires a shorter activation time and lower temperatures (OMRI, 2002).

Activation allows for the effective adsorption of contaminants. Activated carbon is most commonly used in water treatment to adsorb volatile organic chemicals (VOCs), pesticides, taste and odor compounds, chlorine and other man-made chemicals. The two most commonly used forms of activated carbon are granular activated carbon (GAC) and powdered activated carbon (PAC). The main difference between the two forms is PAC has a smaller particle size than GAC. Advantages of PAC include a low initial cost and flexibility of dosage, allowing for concentration adjustment. Disadvantages include large quantities of sludge and PAC's inability to regenerate. GAC is a better option in a treatment process where taste and odor needs to be controlled continuously; however, there is a high initial cost to operate GAC and a tendency for them to grow bacteria (U.S. Environmental Protection Agency, 2015).

PAC has various attributes that affect their adsorption of different molecules. It is defined as having a diameter of 0.177 mm or smaller with a density ranging from 23 – 46 lb/ft^3 (U.S. Environmental Protection Agency, 2015). PAC is also characterized by its pore size and quantity using its Iodine and Molasses numbers. The Iodine number measures the milligrams of iodine adsorbed by one gram of activated carbon. This indicates the potential pore volume that is available within the activated carbon (ASTM International, 2015). Similarly, the Molasses number measures the amount of molasses adsorbed by carbon, which indicates the potential pore volume available for large molecules. Wood, bituminous coal, lignite coal, and coconut shells have high carbon contents and are the primary organic materials that PAC is made from. These different types of materials create different adsorption properties within the PAC. The material PAC is made from also affects the hardness, a measurement of the carbon's ability to withstand frictional forces (U.S. Environmental Protection Agency, 2015).

2.4.1 Tested Powdered Activated Carbons

Seven PACs were collected from Calgon Carbon to be tested: WPX, WPX-Z, Pulsorb WP260-90, WPH, WPH-1000, WPH-W, and WPC. The characteristics of the PACs depend on the type of carbon used to create the PAC. Important characteristics, such as iodine number, maximum moisture percent weight, and percent weight for various meshes, make specific PACs more ideal for certain situations of removal than others. The iodine number is the amount, in milligrams, of 0.02N iodine adsorbed by one gram of carbon. It is a significant characteristic because it demonstrates the adsorption capacity of the carbon. (Calgon Carbon, 2011). See Table 1 for specific characteristic values of the PACs evaluated in this work.

Table 1. Summary of PAC Properties (Calgon Carbon, 2011).

PAC Name	Iodine Number (mg/g)	Maximum Moisture % Weight	% Weight for a 0.045 mm US Mesh
WPX	800	4	60-80
WPX-Z	800	2	60-70
Pulsorb WP260-90	1000	10	90
WPH	800	8	90
WPH-1000	1000	8	90
WPH-W	500	8	80
WPC	800	8	90

WPX

This PAC is created from reactivated granular carbon. It has a high iodine number of 800 mg/g, allowing for a wide adsorption range of organic chemicals found in industrial wastewater. The moisture percent weight is a maximum of 4 and for a US Mesh less than 325 it has a percent weight ranging from 60-80. It also has been successful in stabilizing soil and sludge. WPX can be used in a variety of markets including municipal and industrial wastewater, sludge stabilization, soil remediation and agricultural and industrial spill sites. It is best used to remove toxic compounds, dyes, and refractory organic chemicals. This PAC should not be used for Food Grade or potable water applications as it is made from previously used, regenerated carbon. This is an economical alternative to virgin PACs (Calgon Carbon, 2011).

WPX-Z

WPX Z is similar to WPX as it is also created from reactivated granular carbon. The iodine number is 800 mg/g, meaning that it will also have a wide adsorption range of organic chemicals. The moisture content is a maximum of 2% by weight and for a US Mesh less than 325 it has a percent weight ranging from 60-70. The market for this PAC is similar to that of WPX and should not be used for Food Grade or potable water applications. It is also an economical alternative to virgin PACs (Calgon Carbon, 2011).

Pulsorb WP260-90

This is a virgin coal based PAC. It has an iodine number of 1000 mg/g, a maximum 10% moisture content, and percent weight of 90 for a US Mesh less than 325. It is specifically designed for potable water treatment and removes taste and odor compounds, pesticides and herbicides. Additionally, it can be used to remove endocrine disruptors and organic compounds in some applications (Calgon Carbon, 2015).

WPH

This is a virgin PAC that is bituminous coal based. It has an iodine number of 800 mg/g, maximum 8% moisture content, and percent weight of 90 for a US Mesh less than 325. It is specifically designed to treat potable water. WPH best removes taste and odor-causing compounds like geosmin and methylisoborneol and can also remove herbicides and pesticides. Additionally, it can be used for industrial wastewater treatment to remove refractory organic chemicals (Calgon Carbon, 2011).

WPH-1000

WPH-1000 is similar to WPH as it is also a virgin PAC that is bituminous coal based that is specifically designed to treat potable water. It has an iodine number of 1000 mg/g, a maximum moisture percent of 8, and percent weight of 90 for a US Mesh less than 325. Like WPH, it best removes taste and odor-causing compounds, herbicides and pesticides. It can also be used in industrial treatment to remove refractory organic chemicals (Calgon Carbon, 2011).

WPH-W

This PAC is wood based. It has an iodine number of 500 mg/g, a maximum moisture percent of 8, and percent weight of 80 for a US Mesh less than 325. It is used for drinking water systems (Calgon Carbon, 2011).

WPC

WPC is a virgin coconut based PAC. It has an iodine number of 800 mg/g, a maximum moisture percent of 8, and percent weight of 90 for a US Mesh less than 325. It is specifically designed to treat potable water and is used to remove taste and odor-causing compounds, herbicides and pesticides. WPC can also be used in industrial treatment to remove refractory organic chemicals (Calgon Carbon, 2011). Coconut based PAC is one of the hardest forms of PAC. With a hardness of over 99%, the durability is increased, but the hardness would have negative impacts on the membrane. Koch Membrane Systems, Inc. advised not pursuing the WPC because of this potential for membrane damage.

2.4.2 Case Studies: Activated Carbon Removal of Emulsified Oils

Wastewater treatment of a vegetable oil factory by a hybrid ultrafiltration-activated carbon process. Mohammadi, T., & Esmaeelifar, A. (2005).

The operating conditions for an ultrafiltration membrane system were tested in combination with a charcoal-based PAC in the wastewater treatment of a vegetable oil factory. Conditions such as pressure difference, temperature, pH, and fouling resistance were studied. The findings included that the PAC improved the solids separation performance of the membrane. It was found that the optimum concentration found of PAC to prevent membrane fouling was about 0.1%.

Residual oil and suspended solid removal using natural adsorbents chitosan, bentonite and activated carbon: A comparative study. Ahmad, A. L., Sumathi, S., & Hameed, B. H. (2005).

This case study investigated the removal of residual palm oil and suspended solids using jar tests of several adsorbents: chitosan, activated carbon, and bentonite. Chitosan performed the best to adsorb residual oil with a 99% removal rate. Chitosan is a natural adsorbent similar to activated carbon. Chitosan is a "natural, modified carbohydrate biopolymer." Activated carbon was shown to not effectively remove the residual oils and required a larger concentration to remove a smaller amount than the chitosan. The activated carbon would be a poor choice economically to remove residual oil.

3.0 Methodology

The goal of this project was to explore the interaction of PAC with mineral oil in an MBR. To accomplish this goal, the wastewater collected was spiked with mineral oil and run in bench-scale MBRs with various PACs. The first section of this chapter describes the MBR apparatus that was used to run the tests. The second section describes the beaker tests run with each of the PAC types to ensure that equipment failure did not occur. The following two sections describe how to run the MBR and the process of cleaning the MBR. The fifth section describes how to determine the MLSS concentration. The sixth, seventh, and eighth sections explain our methods for determining COD, turbidity, and mineral oil concentration, respectively.

3.1 MBR Apparatus

Koch Membrane Systems, Inc. supplied the bench top membrane bioreactors used in this experiment. They each consisted of a black 9-liter tank with an opening in the top for manual feed. In the bottom of the 9-liter tank, there was a pump that is powered via a power strip connected to a voltage regulator. The pump drew the water down from the tank where it could leave the system via the drain valve, follow the bleed connection (½ in. tubing) back into the tank (bleed connection has a valve allowing pressure to be adjusted), or follow the feed connection (¼ in. tubing). The feed connection led to the feed rotameter, which then connected to the feed pressure, via ¼ in. tubing, and the membrane cartridge, via ½ in. tubing. The membrane cartridge was a PURON® MP Hollow Fiber Demo Cartridge, a product of Koch Membrane Systems, Inc. This membrane cartridge has a nominal pore size of 30 nanometers. Water that entered the cartridge but was not filtered returned to the tank via the Mixed Liquor Return tube (½ in. tubing). The remainder of the water in the cartridge was drawn into the membrane fibers, which filter the water. The filtered water was then carried through the center of the membrane fibers and out the top of the membrane cartridge into the permeate line (1/2 in. tubing). The permeate line splits with ¼ in. tubing going to the permeate pressure gauge and the ½ in. tubing continuing to the peristaltic pump. The peristaltic pump created the negative pressure that drew the water from the membrane fibers and through the permeate line, while the permeate pressure gauge allowed the operator to monitor that pressure. After passing through the peristaltic pump, the water passed through ¼ in. tubing to the permeate rotameter, which is used to adjust the permeate flow rate. More ¼ in. tubing then led to a split in the line with a valve that allowed the operator to either sample the filtered water or allowed it to return to the initial tank.

In addition to the water lines, there was an air connection line. This line of ¼ in. tubing connected to the air at the laboratory bench, and the air then passed through an inlet valve, an air regulator, followed immediately by an air relief valve, an air pressure gauge, and an air flow rotameter, allowing for the air flow to be adjusted. From the air flow rotameter, the air line then passed through another valve that prevented water from entering the rotameter to ½ in. tubing that connects to the base of the membrane cartridge. The purpose of this air connection was to provide bursts of aeration that loosen the filtered debris from the membrane fiber, allowing the debris to be carried into the Mixed Liquor return and the membrane fibers to remain clean. See Figure 2 and Figure 3 for pictures of the apparatus. Figure 4 shows the flow of water through the apparatus.

Figure 2. Benchtop Membrane Bioreactor, Labeled, Front Right View (Koch Membrane Systems, Inc., 2015).

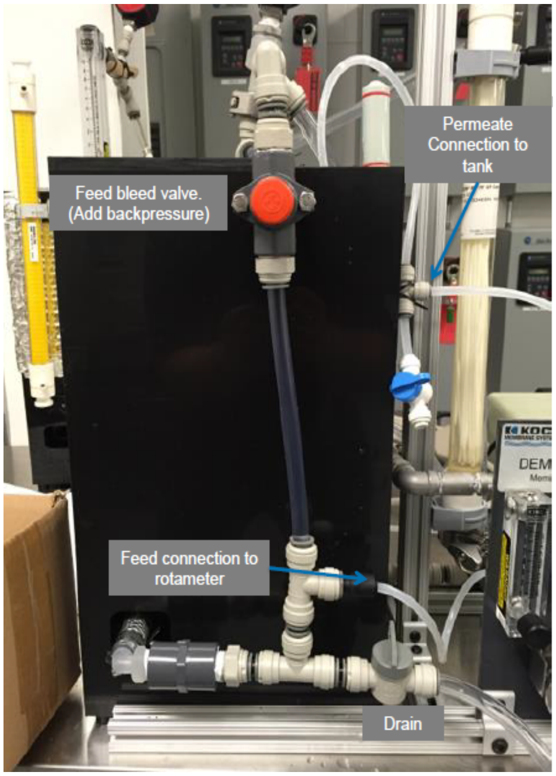


Figure 3. Benchtop Membrane Bioreactor, Labeled, Front Left View (Koch Membrane Systems, Inc., 2015).

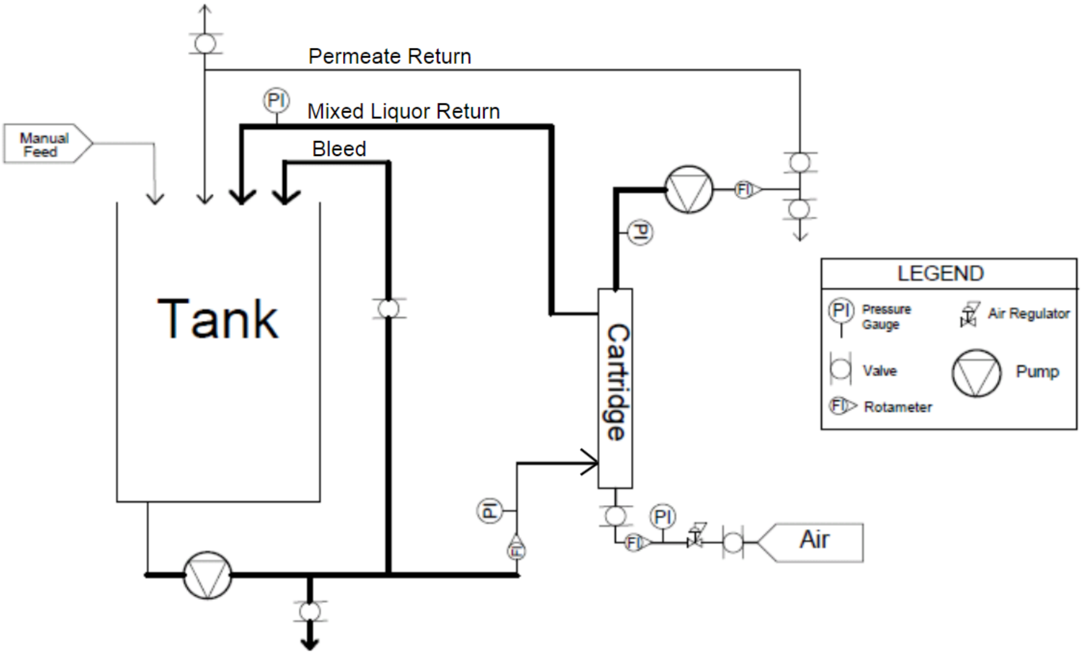


Figure 4. Schematic of Benchtop MBR

3.2 PAC/Oil Beaker Testing

In the first attempt at running the MBR with the PAC, primary effluent, sludge, oil and surfactant, WPX and WPH-W, a wood-based PAC, were used. The WPH-W caused a clog in various parts of the equipment (see Results and Data). To prevent further equipment failure, each of the six PACs was tested in a 500 mL beaker with the correct proportions of primary effluent, oil and surfactant with a total of 1.5 g of PAC. The beaker was placed on a stir plate with a stir bar in the beaker to thoroughly mix the solution, as it would be in the MBR. The 1.5 g of PAC were added to each beaker in increments (1 g, and later 0.5 g), and observations were noted on the thickness of the solutions and any solids that formed that could increase the chances of equipment failure.

The test was run again with distilled water. The oil (17.5 uL), surfactant (1 uL), and water (500 mL) were first mixed together in a blender to ensure that the oil was emulsified. The 6 beakers (with the same solution in each) were placed on a stir plate with a stir bar in the beaker to allow for thorough mixing. A PAC (1 g) was slowly added to each beaker while the solution was simultaneously agitated with a stirring rod to break up any clumps of carbon. Observations were taken on the thickness of the solutions and any solids that formed that could increase the chances of equipment failure.

3.3 MBR Operational Procedure

In order for the MBRs to run in continuous operation, the permeate return tube was run to the feed tanks. A permeate pump was connected to each system with the suction pulling from the base of the fiber at the top of the membrane cartridge. The air line was connected to the closed air inlet valve. The regulator and the air flow rotameter were both closed. The 2 MBR tanks were each filled with 6 L of secondary sludge from the Upper Blackstone Wastewater Treatment Facility, and aeration stones were used to ensure that the sludge was well mixed.

Two 5 mL samples were taken from each of the tanks to determine the MLSS concentration. A mixture of 10 mL of water, 0.212 mL (30 ppm) of mineral oil, and 9 uL of Titron X-100 (surfactant) was made in a beaker to ensure that the mineral oil was emulsified. The contents were then added to the bioreactor. Three 300 mL samples were taken from the tank, one was saved for initial COD (Section 3.5) and turbidity measurements (Section 3.6) and one was dumped since it was only removed so that the tank reached a volume of 5.4 L. The standard batch size for this apparatus was 5.4 L. The third 300 mL sample was mixed with 2.5 g (approximately 463 ppm) of PAC.

The feed bleed valve and the feed bleed rotameter were both set to the half open position. The pump voltage regulator was set to 30% and turned on in order to start the feed pumps. As water began to fill the cartridges and flow through the bleed, the feed flow was set to approximately 2 gph using the feed rotameter valve and the feed bleed valve. The air regulator and valve were then opened enough to allow airflow. The air inlet valve was opened, and the air was turned on. The air regulator and air flow rotameter were then adjusted to give an air pressure of 5.5 psig on the air pressure gauge. The permeate rotameter was then opened slightly, and the permeate pumps were turned on and set to 28 mL/min (25 LMH). The permeate rotameter was set to a flow of approximately 28 mL/min as well. After allowing the MBRs to run for 4 hours, a sample of at least 500 mL was taken for COD, turbidity, and mineral oil concentration (using the hexane extraction method in Section 3.7) measurements, and the MBRs were shut down using the reverse of the startup procedure.

After the MBR was thoroughly cleaned using the procedure in Section 3.4, the experiment was conducted with a different PAC. This was done until all PACs were tested.

3.4 Cleaning the MBR

After each run with the MBR, the entire system was cleaned. The system was drained and rinsed with clean water by adding clean water to the tank, circulating it through all lines (feed and permeate), draining. This process was repeated two more times. The tank was filled with 6 L of warm water and 240 mL of NaOCl. The system was then back flushed with a water and chlorine mixture by setting the permeate pump to take suction from the feed tank and discharge to the top port of the membrane cartridge. The permeate pump was started at a speed of 28 mL/min (25 LMH). The system operated in this mode for 60 minutes, with the permeate pressure being monitored to ensure that it does not exceed 10 psig. The machine was then shut down, allowed to soak overnight, and drained the following day. The system was then rinsed with clean water again 3 times, and the third rinse was used as a clean water permeability test to check pressure and temperature at 25 LMH.

3.5 MLSS Concentration

To determine the mixed liquor suspended solids (MLSS) concentration, glass fiber filters were prepared by rinsing three times with 20 mL of reagent grade water and using the filtration apparatus to suction off all traces of water. The filters were then placed in small porcelain dishes, dried for approximately 1 hour at 103 to 105°C, cooled for 30 minutes in a desiccator, and weighed. A sample size of 5 mL (it is desired to have 2.5 to 200 mg dried residue) was taken from the well-stirred mixed liquor. The sample was filtered through the prewashed glass fiber filter in the filtration apparatus and rinsed with 10 mL of reagent grade water. Suction was applied for about 3 minutes after the filtration was complete. The filter and the collected solids were then transferred to a porcelain dish, placed in the oven to dry at 103 to 105°C, and cooled in the desiccator for 30 minutes. The dish, filter, and solids were weighed, and the MLSS was calculated using Equation 1, where A is the combined mass of the porcelain dish, the filter, and the solids and B is the mass of the dish and the filter alone.

$$\frac{mg\ of\ total\ suspended\ solids}{L} = \frac{(A-B)\times 1000}{sample\ volume\ (mL)} \qquad \text{Equation 1.}$$

3.6 Chemical Oxygen Demand (COD)

In order to measure COD, a standard curve was created. To do this, a stock solution of known COD (1000 mg/L) was made by adding 425 mg of potassium hydrogen phthalate (KHP) to 500 mL of pure water. The stock was then diluted to get four samples of known COD (800, 600, 400, and 200 mg/L). These four samples and a blank were placed in the COD heating apparatus for 2 hours at 150°C, pipetted into plastic spectrophotometer vials, and analyzed with the Varian Cary 50 Scan UV-Visible Spectrometer (using the blank first to zero the spectrometer). The absorbance for each sample was recorded and plotted versus the COD concentration (absorbance on the y-axis).

To measure COD, two testing vials were obtained. In one vial, 2.5 mL of well-stirred sample was added, and in the other, 2.5 mL of pure water was added to serve as a blank. Both vials were placed in the COD heating apparatus for 2 hours at 150°C. After the 2 hours, the blank and the sample were pipetted into spec cells. The blank was placed in the spectrometer first to zero the machine. After zeroing, the blank was removed, the sample was placed in the spectrometer. The absorbance of light was recorded for the sample. Using this measurement, the COD was calculated based on the standard curve using Equation 2.

$$Concentration = \frac{Absorbance}{Slope} \qquad \text{Equation 2.}$$

3.7 Turbidity

In order to measure turbidity before and after treatment in the MBR, the samples were well mixed to ensure uniformity. Sample waste was then carefully poured into the turbidity vials to prevent the formation of bubbles. The turbidity vial was then capped and inverted twice to disperse any particulate matter. The outside of the vial was rinsed with reagent water and wiped with a Kimwipe to remove dirt and fingerprints. The vial was then placed into the turbidimeter with the arrow on the vial facing the arrow on the turbidimeter. After the cover of the turbidimeter was closed, the number on the screen was allowed to stabilize and the reading (in Nephelometric Turbidity Unit, NTU) was recorded. NTU measures the scattering of light from the organics in the water.

3.8 Hexane Extractable Gravimetric Method for Oil Analysis

The Hexane Extractable Gravimetric Method was used to measure the amount of mineral oil in the effluent. This procedure is modified from USEPA Hexane Extractable Gravimetric Method (U.S. Environmental Protection Agency 2015). The following procedure was used:

A 350 mL sample of effluent was collected into a 500 mL beaker. Next, 4 mL of 1:1 Hydrochloric Acid was added into the beaker and thoroughly mixed. The mixture was then transferred into a 1000 mL separatory funnel. Hexane has a tendency to attract mineral oil, so 20 mL of hexane was added into the 500 mL beaker and stirred to attract additional mineral oil beads remaining. This was then added to the separatory funnel. The funnel was stoppered and inverted. Once inverted, the funnel was shaken and the stopcock was opened to release the gases that formed. This process was repeated until no more gas was being released. After closing the stopcock, the funnel was vigorously shaken for approximately 1 minute then set on the stand for 10 minutes. During the 10 minutes, the funnel was not moved to allow a separation to occur, with the bottom layer being water and the top layer being the hexane and oil mixture. After the two layers formed, the stopper was removed and the stopcock was opened slowly to collect the water layer into the initial 500 mL beaker. It typically took 3 to 4 minutes for the water layer to drain to prevent water interference. Once the solvent layer reached the bottom, a pre-weighed 100 mL beaker was used to collect the solution. This beaker was then put in a RapidVap evaporator. This process was repeated two more times for a total of three beakers in the RapidVap.

The RapidVap was set to 60 ºC with an N_2 purge for 12 hours in order to allow the hexane to evaporate, leaving only the mineral oil in the beaker. The beakers were then weighed, placed back in the RapidVap for another 2 hours, and reweighed. This process was repeated until the mass of the beakers remained constant, indicating that all of the hexane had evaporated. Once the hexane was completely evaporated, the final weight was recorded. The following equation provided from the USEPA Hexane Extractable Gravimetric Methodology was used to determine the amount of mineral oil (hexane extractable materials) that was collected (U.S. Environmental Protection Agency, 2015):

$$\frac{(W_{f1}-W_{i1}) \times (W_{f2}-W_{i2}) \times (W_{f3}-W_{i3})(g) \times 1000 \left(\frac{mg}{g}\right)}{Sample\ Volume\ (L)} = \frac{mg}{L} HEM \qquad \text{Equation 3.}$$

$$W_f = final\ weight$$

$$W_i = initial\ weight$$

4.0 Sources of Error

There were various aspects of the experiments that could have caused possible errors within the data collected. One problem was the oil being used was adhering to beakers, surfaces within the MBR, and other instruments used for each test. Because of this, any final effluent oil measurements would be skewed. The concentration of oil in the effluents would be lower than they should be, making the MBR and PACs appearing to be more effective than they actually were. Because there was already small amounts of oil to begin with, any oil lost this way would create a large difference from the accurate results. To see where the oil was being lost, the oil sample was first dyed red before being put into the MBR. This test showed the oil sticking to various tubes and surfaces within the MBR unit, see Figure 5. A similar test was also performed, but using the dyed oil to run a hexane extraction test. During this test the oil was seen adhering to the various beakers that were used to transport the water and oil mixture, see Figure 6 and Figure 7. The oil was also sticking to the separatory funnel used in the final steps of the hexane extraction, see Figure 8. These tests showed that oil was lost throughout the experiment.

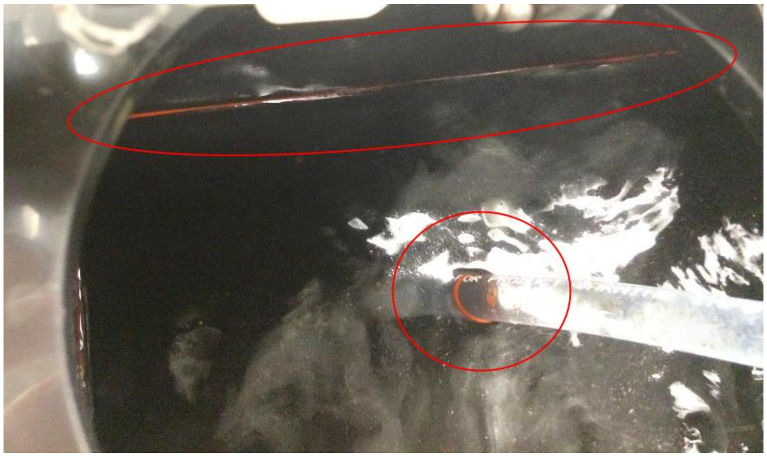


Figure 5. Dyed Oil Sticking to the Inside of the MBR

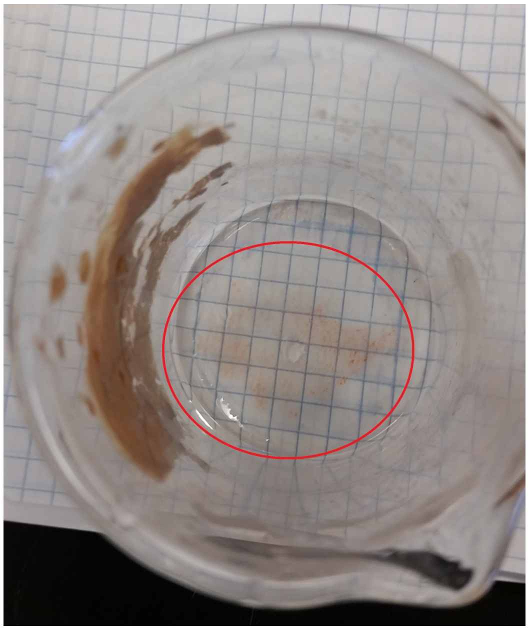


Figure 6. Dyed Oil Sticking to the Bottom of the Beaker

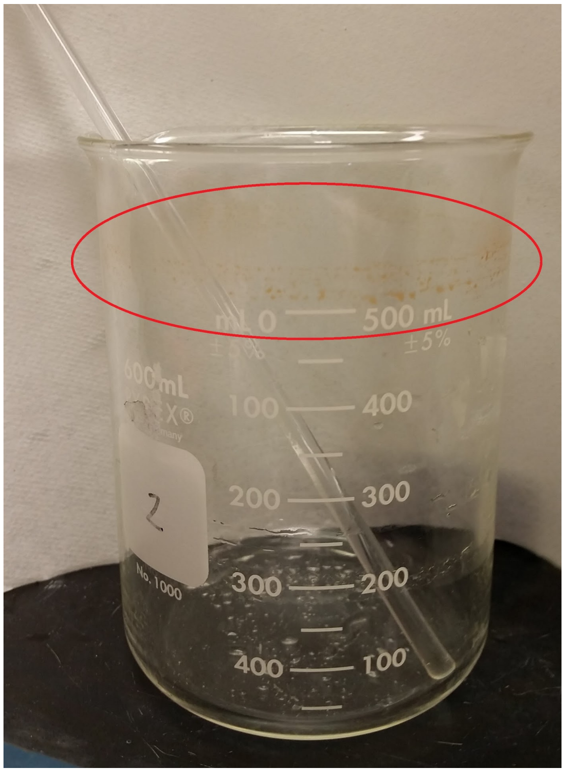


Figure 7. Dyed Oil Sticking to the Sides of a Beaker

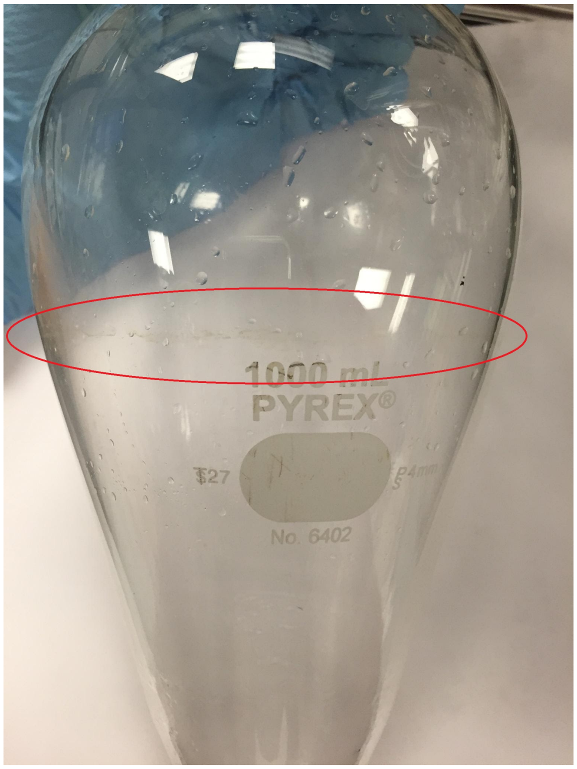


Figure 8. Dyed Oil Sticking to the Separatory Funnel

Another possible source of error occurred during the COD and turbidity measurements. For these measurements, samples of the water before and after the MBR process were tested. Because the MBR required an MLSS between 6 and 8 mg/L, the influent had a large amount of microorganisms and sludge. This meant when measuring the COD and turbidity, there was a chance the sludge would greatly skew the results. In an attempt to prevent this, samples were allowed to settle before water was drawn from the upper portion of each. Although this reduced the chances of the sludge affecting the results, it was still possible for the microorganisms to be drawn out with the water tested. If this occurred, the values obtained for the COD and turbidity measurements would be higher than they should have been.

Each run of the MBR lasted four hours so the oil would be exposed to each PAC for the same length of time to prevent any time-based variables. One issue that arose, however, was when taking the effluent samples, it took different lengths of time to fill the sample container. While some filled with relative ease, it took other samples a couple hours to fill one container. Because of this the water and oil was exposed to the PACs for different lengths of time. It was determined that the cause of this was the membrane becoming blocked by various entities within the water. In an attempt to prevent this, the air scour rate was turned higher when collecting samples, but it was not always effective in reducing the time needed.

As mentioned above, the MLSS varied between each run. This variation may have produced errors when comparing the data. A higher MLSS could result in a higher initial COD and turbidity, causing one PAC to appear superior to others. Because of this, the removal percentage for COD and turbidity for each PAC was calculated. Although this should have accounted for any fluctuations in MLSS, there could have been other issues this created that went unaccounted for.

4.1 Suggestions for Improvement

There are other ways the experiment could be improved to gather more precise and in depth data. The lack of these methods do not produce any errors, using them would only increase the data available. Throughout the course of the experiment, the hexane extraction method proved to be ineffective and unreliable. As previously mentioned, this was due to oil being lost to various surfaces throughout the process. In order to determine the amount of oil in two selected effluent samples, the samples were sent to Industrial Analytical Services, Inc. for fats, oils, and grease (FOG) testing. To determine the oil concentration for each effluent, all samples could be tested if the equipment was available, or they could be sent to a lab for FOG testing.

Another way to improve the accuracy of the experiment would be to perform multiple runs for each desired PAC. This would allow any deviations to be noticed and would show whether or not the results can be replicated.

Along with multiple runs, longer runs could be done. Shorter runs similar to the ones performed in this experiment could be used to eliminate the less successful PACs. From there the remaining PACs should be put through a longer run lasting a few weeks or more. This would more accurately represent real MBR systems because the sludge would be able to acclimate, grow, and aid in the removal of contaminants. Doing this would provide other issues such as keeping the microorganisms alive, but would be beneficial to gather more accurate data.

5.0 Results and Data

All raw data for MBR runs is located in Appendix I.

5.1 Initial Elimination

From research and discussion with Koch Membrane Systems, Inc., WPC was eliminated prior to testing due to its high abrasiveness. As previously mentioned, PAC created from coconut shells is one of hardest PACs. This was not an ideal characteristic for operation of the membrane, as it would cause fouling, and therefore was not tested.

5.2 Preliminary Tests

In the first attempt at running the MBR with 27g (5,000 ppm) of PAC, primary effluent, sludge, oil and surfactant, WPX and WPH-W, a wood-based PAC, were used. The WPH-W was the cause of clogging in various parts of the equipment. The feed rotameter accumulated carbon buildup, preventing water from being fed into the membrane. See Figure 9. Additionally, the feed pump clogged causing there to be no fluid traveling through the bleed or the feed connections.

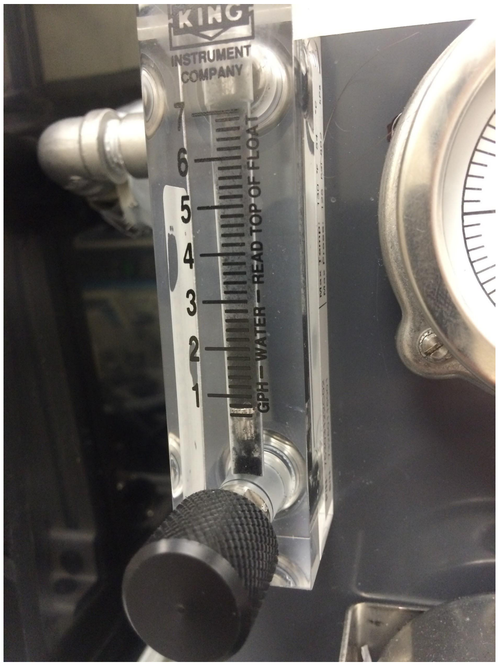


Figure 9. Clogged Feed Rotameter

From this attempt, we deducted that 5,000 ppm was too high of a concentration. We altered our PAC amount to be 2.5g (approximately 463 ppm) to prevent further equipment failure. Additionally, we tested each PAC individually in a beaker to water and oil to see if they would form any sort of thick layer that may cause equipment failure. This was called the Beaker Test.

5.3 Beaker Test for PAC

The six PACs were tested in primary effluent, oil and surfactant and observations were collected to learn how the components would interact.

5.3.1 Observations

A summary of observations for the carbon beaker tests is shown in Table 2.

Table 2. Observations of PAC Beaker Tests

Time (min)	**WPH**	**WPH-W**	**WPH-1000**	**Pulsorb WP260-90**	**WPX**	**WPX-Z**
0 (1 g PAC added)	Watery, Black	Thick, Metallic appearance	Watery, Black	Watery, Black	Watery, Black	Watery, Black
5	No change	No change	No change	No change	Some clumping on surface	No change
15	Thin layer forming on surface	Thick layer on surface	Small clumps on surface	Thin layer forming on surface	Small clumps on surface	Small clumps on surface
30	No change	No change	No change	No change	No change	No change
35 (0.5 g PAC added)	Appears to have a thick consistency towards the center	Thick layer on surface, mixing slower than others	Broken-up layer on surface	Appears to have a thick consistency towards the center	Watery, Black	Appears to have a thick consistency towards the center
60	Similar to WPX-Z but with thicker layer	Surface layer becoming more widespread	No change	No change	No change	Thin layer on surface, more widespread

5.3.2 Discussion

WPH

WPH had some mild clumping form. A solid piece of carbon formed, as seen in Figure 10, while smaller clumps stuck to the side of the beaker, as seen in Figure 11. The carbon settled to the bottom when the mixer was stopped. There was no visible oil.

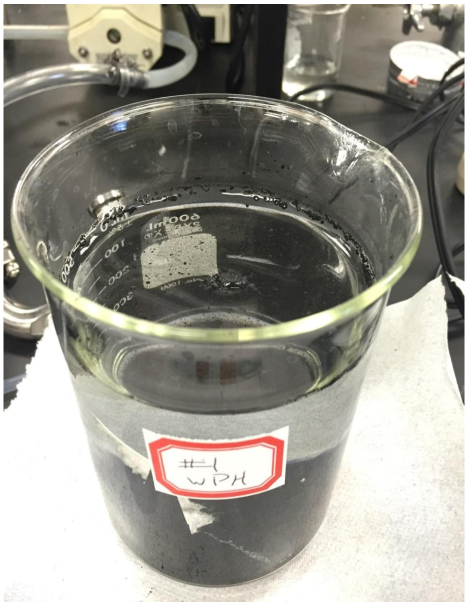


Figure 10. WPH, Top View

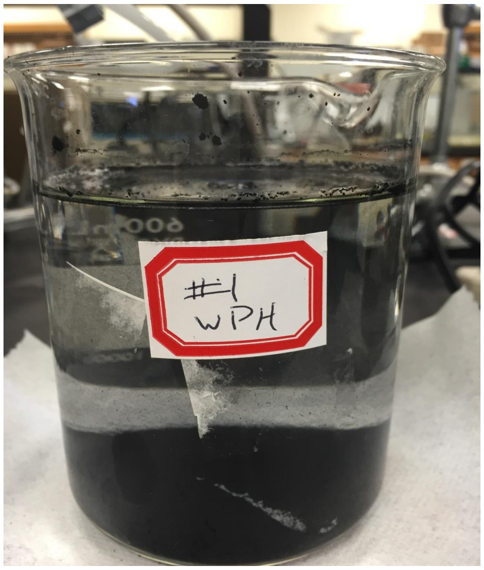


Figure 11. WPH, Side View

WPH-W

WPH-W created a thick carbon layer at the top of the solution as seen in Figure 12 and Figure 13. It did not settle once the mixer was turned off. There was a visible oil layer that was combined with carbon on top of the thick carbon layer.

Figure 12. WPH-W Top View

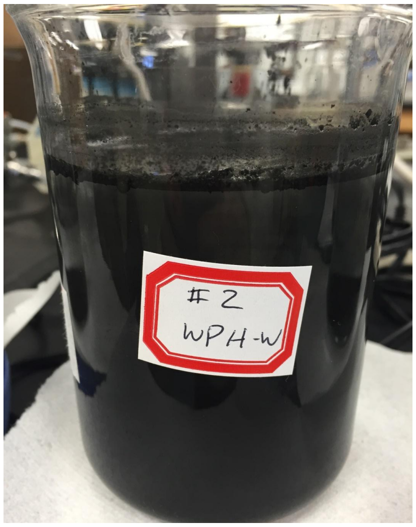


Figure 13. WPH-W Side View, Carbon Layer

WPH-1000

WPH-1000 created carbon beads, but the beads were not as solid and thick as the solid carbon formed in WPH. The beads were scattered throughout the top layer and along the edge of the beaker as seen in Figure 14 and Figure 15. The carbon settled to the bottom once agitation stopped. Additionally, there was a visible oil layer combined with carbon where the beads were embedded.

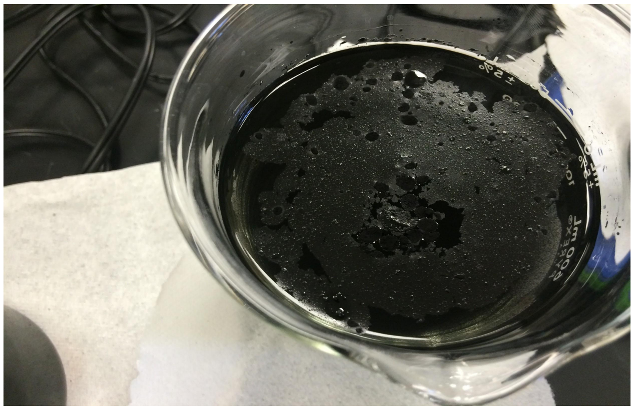


Figure 14. WPH-1000 Top View

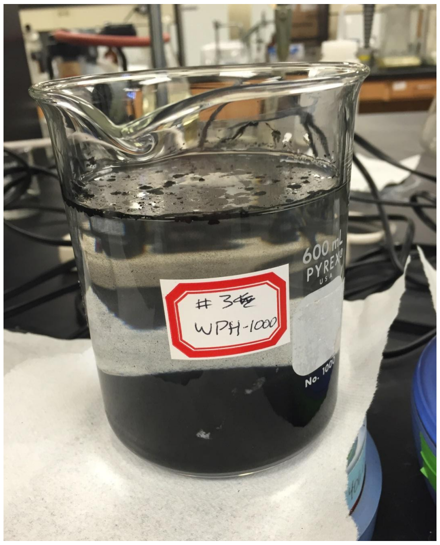


Figure 15. WPH-1000 Side View

Pulsorb WP260-90

Pulsorb WP260-90 created a large, solid carbon clump, see Figure 16, and minor clumps along the edge of the beaker, see Figure 17. The carbon settled to the bottom once the mixer was turned off. There was a visible oil layer combined with carbon.

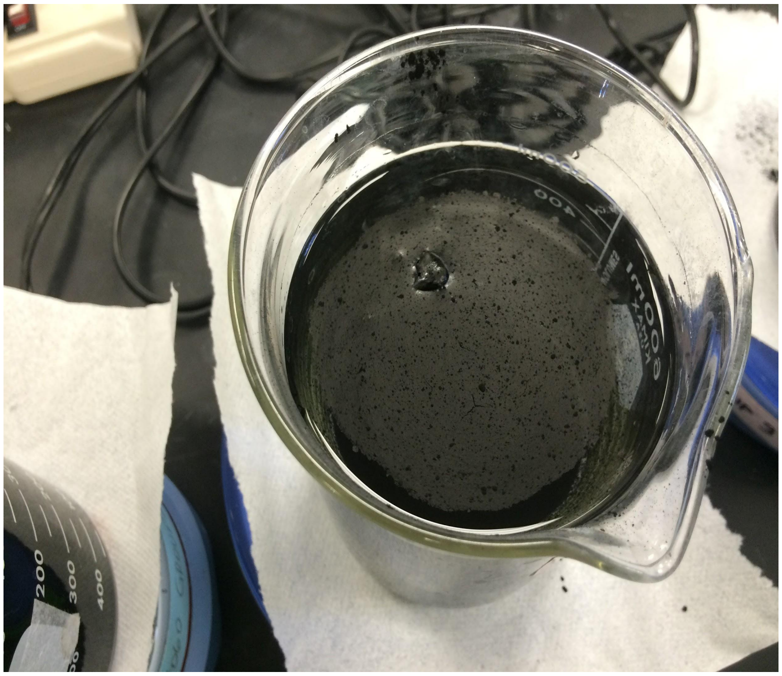


Figure 16. Pulsorb WP260-90, Top View

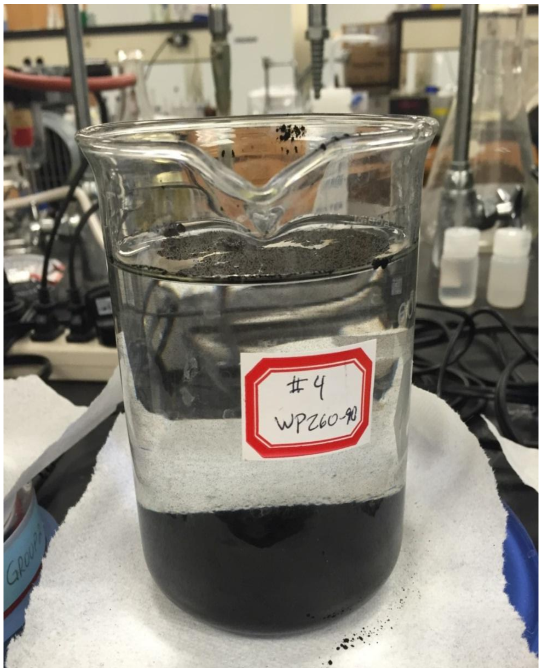


Figure 17. Pulsorb WP260-90, Side View

WPX

WPX had little to no clumps or carbon formations of any kind as shown in Figure 18. The carbon settled to the bottom once agitation stopped. Unlike most of the carbons, the oil was clearly separate from the set of the solution, similar to how it would look if it was in regular water, shown in Figure 19.

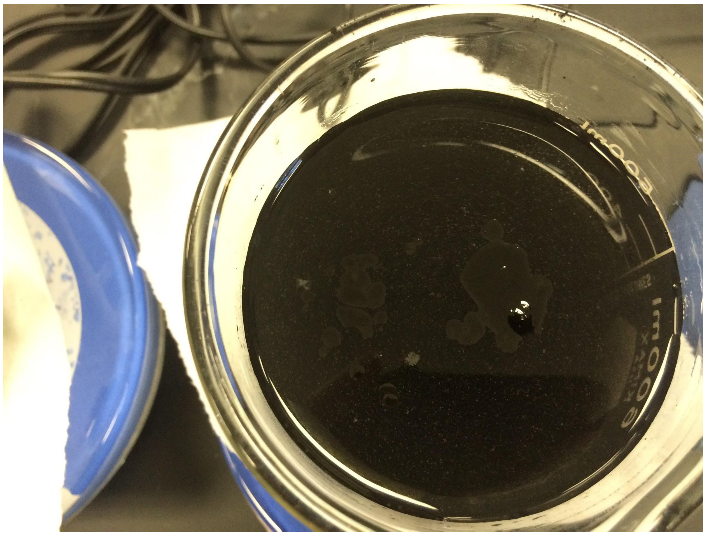


Figure 18. WPX, Top View

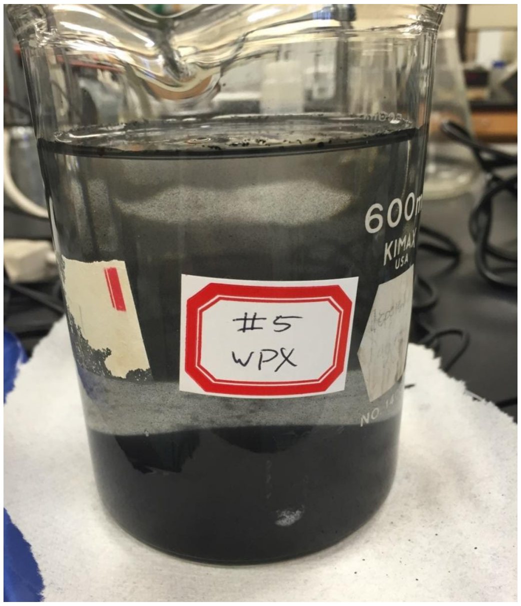


Figure 19. WPX, Side View

WPX-Z

WPX-Z formed some smaller clumps and some residue on the side of the beaker as shown in Figure 20 and Figure 21. The carbon settled to the bottom once the mixer was stopped. There was very faint traces of oil that could be later distinguished.

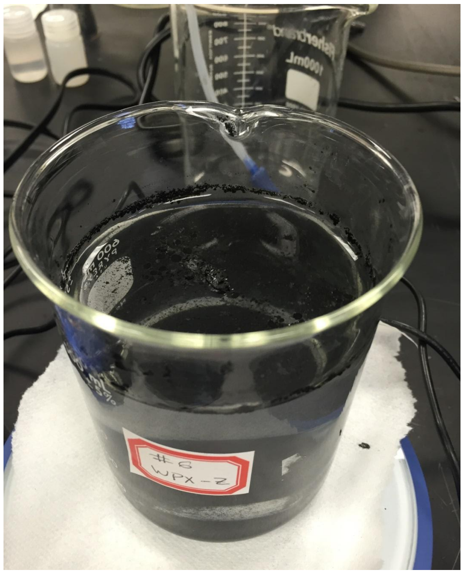


Figure 20. WPX-Z, Top View

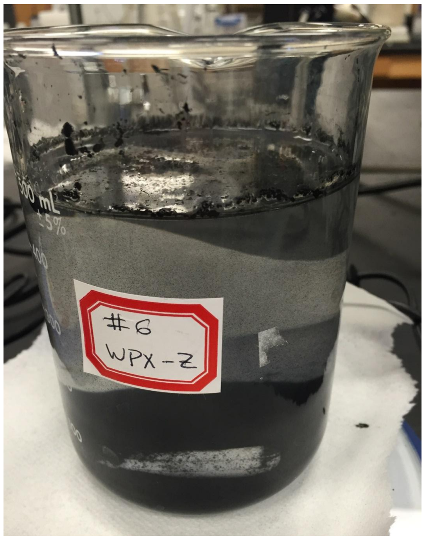


Figure 21. WPX-Z, Side View

5.3.3 Beaker Test Conclusions

It was concluded from this test that despite some clump formation or thick layers, all the PACs could still be tested. The clumps were not substantial enough to eliminate the PAC. This test was qualitative and allowed us to observe how the carbons interacted with the oil in a simpler setting.

5.4 Data Summary

There were seven runs executed in the MBRs with 30 ppm mineral oil added, each with a different PAC at a concentration of 463 ppm. The results can be seen in Table 3.

Table 3. Data Summary of PAC Runs

Carbon	MLSS (g/L)	COD (Initial) (mg/L)	Effluent COD (Final) (mg/L)	Change in COD (%)	Turbidity (Initial) (ntu)	Effluent Turbidity (Final) (ntu)	Change in Turbidity (%)
No Carbon	8.60	362.63	321.70	-11.29	2.52	0.345	-86.31
WPH-W	8.56	116.74	100.64	-13.79	42.6	0.145	-99.66
WP260-90	7.72	157.33	57.36	-63.54	6.06	0.369	-93.91
WPX	8.74	157.67	91.92	-41.70	27.4	0.11	-99.60
WPH	7.00	767.53	235.49	-69.32	11.4	0.45	-96.05
WPX-Z	6.22	486.75	302.25	-37.90	18.8	0.17	-99.10
WPH-1000	6.94	585.37	119.76	-79.54	21.6	0.307	-98.58

5.4.1 COD

COD is an indicator of the overall amount of organics in the water, making it a good measurement for water quality. It is measured by the amount of strong oxidant consumed by the organics in the water. The addition of WPH-1000 to the MBRs resulted in the greatest decrease in COD, 79.54%. This means that WPH-1000 removed the greatest amount of organics from the water, improving the overall water quality. However, the solution that the WPH-W was added to had the lowest initial COD, 116.74mg/L, and the smallest decrease, 13.79%. It was not as successful in removing organics from the water; only slightly more effective than the performance of the MBR without any PAC. We can infer that the WPH-W was not a very effective PAC for this application.

5.4.2 MBR MLSS Concentration vs. Effluent COD Trends

As shown in Figure 22, it was found that the greatest COD removal occurred in the range of 7.00 g/L and 7.60 g/L MLSS concentrations. Concentrations outside of this range had a lower COD removal, with MLSS concentrations about 8.50 g/L having the lowest removal.

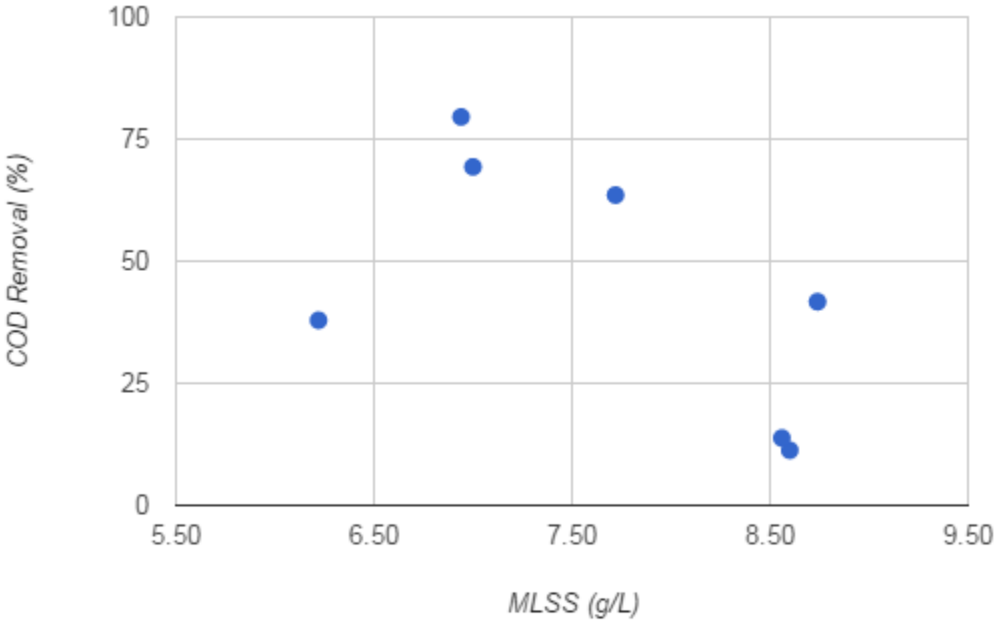


Figure 22. Plot of COD Removal versus MLSS Concentration

5.4.3 Effluent Turbidity

Turbidity is a measure of the scattering of light passing through a solution, and it provides a quantitative indication of the number of small (colloidal) particles present in the water. The addition of WPH-W to the MBRs provided the greatest decrease in turbidity, 99.66%, which indicated that the water was clear. Pulsorb WP260-90 provided the smallest decrease in turbidity, 93.91%, which indicated the water was still clear but not as clear as the effluent from the other PACs tested. Overall, the additional of all PACs to the MBR test platform resulted in successful turbidity removal, and a significant improvement over operating the MBRs without any PAC.

5.4.4 Trend of Effluent Turbidity versus MBR MLSS

Shown in Figure 23, the MLSS concentration did not affect the results of turbidity. All effluent MLSS concentrations in the MBR test provided successful turbidity removal.

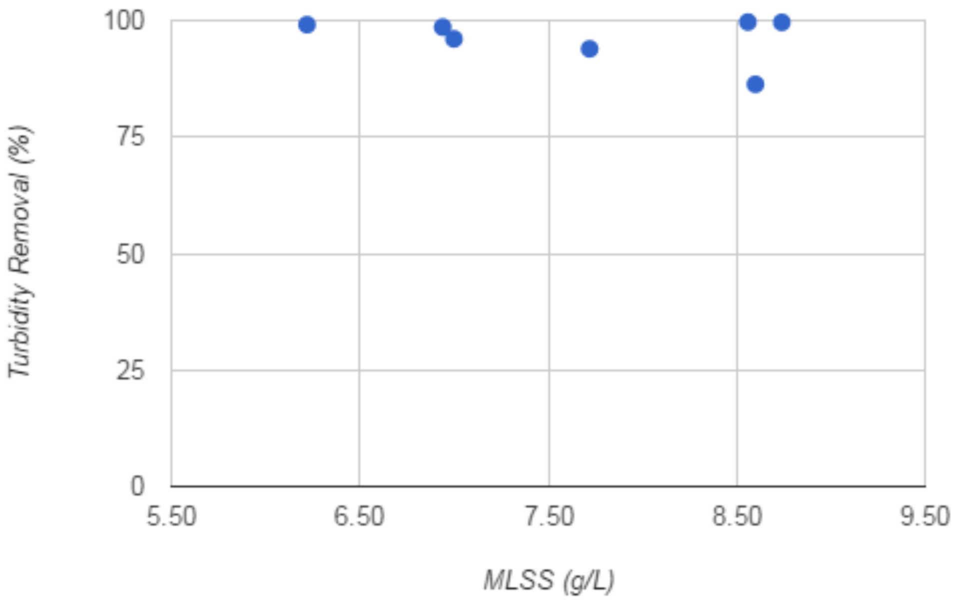


Figure 23. Effluent Turbidity Removal versus MBR MLSS Concentration

5.4.5 Transmembrane Pressure Fluctuations

While the experiment was being conducted, some trials with different PACs resulted in inconsistent feed flows at the beginning of the experiments, perhaps due to the high MLSS concentration. The experiment using WPX produced little fluid in the membrane cartridge until after approximately 20 min. run time. For the WPX experiment, after running between 90 and 100 minutes, the needle of the feed pressure gauge started to rapidly move up and down preventing us from getting an accurate reading. The values for those ten minutes were immeasurable so no measurements were taken while attempting to resolve the issue. The experiment using Pulsorb WP260-90 also resulted in similar behavior until 15 min. into the run. All transmembrane pressures can be found in Figure 24 and the average pressures can be found in Table 4.

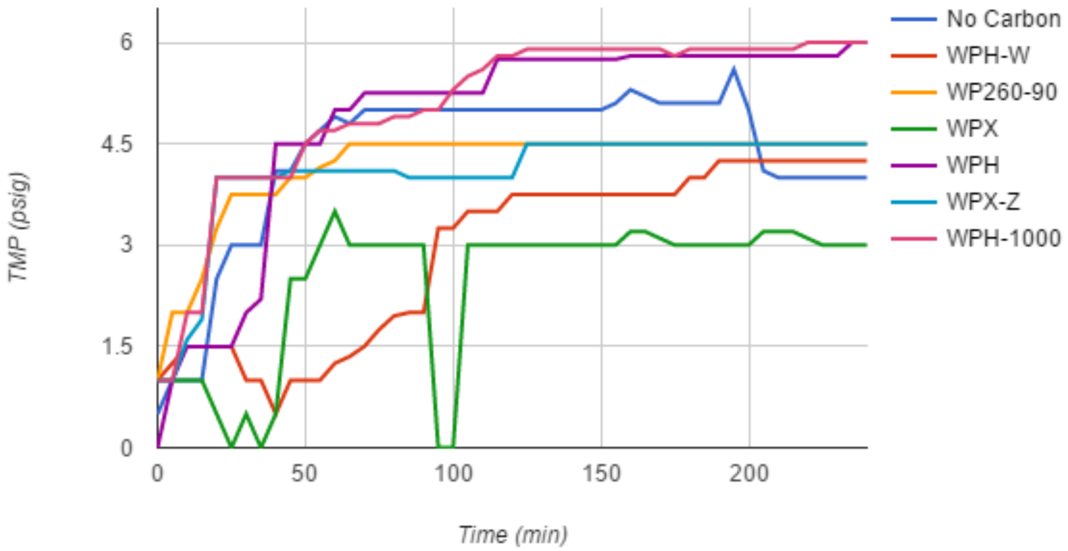


Figure 24. Transmembrane Pressure Over Time for Each PAC

Table 4. Average Transmembrane Pressure of Each PAC

Carbon	Avg. Transmembrane Pressure (TMP) (psig)	Peak Pressure (TMP) (psig)
No Carbon	4.3	5.6
WPH-W	2.9	4.25
WP260-90	4.17	4.5
WPX	2.45	3.2
WPH	4.84	6.0
WPX-Z	4.05	4.5
WPH-1000	5.06	6.0

Transmembrane pressure (TMP) is the difference in pressure across the membrane. As water passed through the MBR, sludge and PAC collected on the outside of the membrane, causing a higher outer pressure with a lower inner pressure (a higher

TMP). Though the relationship between transmembrane pressure and fouling is complicated and not always consistent, a high TMP can be used to indicate a higher chance of irreversible fouling (Crozes, 1997). Even without the potential for increased fouling, it was noted that a higher TMP resulted in a lower effluent flow. As seen in Figure 24 and Table 4, the use of WPX in the MBR resulted in the lowest average TMP (2.45 psig) and the lowest peak TMP (3.2 psig).The run with WPX had little fluid in the membrane cartridge until about 20 minutes into the run, which resulted in multiple drops in pressure. Additionally, for the experiments using WPX, between 90 and 100 minutes in the run, the needle of the feed pressure gauge started to rapidly move up and down preventing us from getting an accurate reading. Therefore, no pressure measurements were able to be taken. However, according to Figure 24, the use of WPX still seems to provide the lowest TMP even if the drop in TMP is excluded. Using WPH-W produced the next lowest average TMP at 2.9 psig, and it remained below the TMP of the "no carbon" baseline after the first 15 minutes of the run. Using Pulsorb WP260-90 also resulted in a low amount of water in the membrane cartridge until 15 minutes into the run, but otherwise WPX-Z and Pulsorb WP260-90 remain around the same TMP, with an average of 4.05 and 4.17 psig, respectively, which is still below the "no carbon" average TMP of 4.3. WPH and WPH-1000 both reach a maximum TMP of 6.0 and maintain a TMP higher than the baseline for most, if not all, of the run time with an average of 4.84 and 5.06 psig, respectively. As mentioned in Chapter 4, there were variations in MLSS, which may have also had an impact on the TMP. However, Figure 25 shows little relationship between the two. Additionally, variations in feed flow rate may also influence TMP.

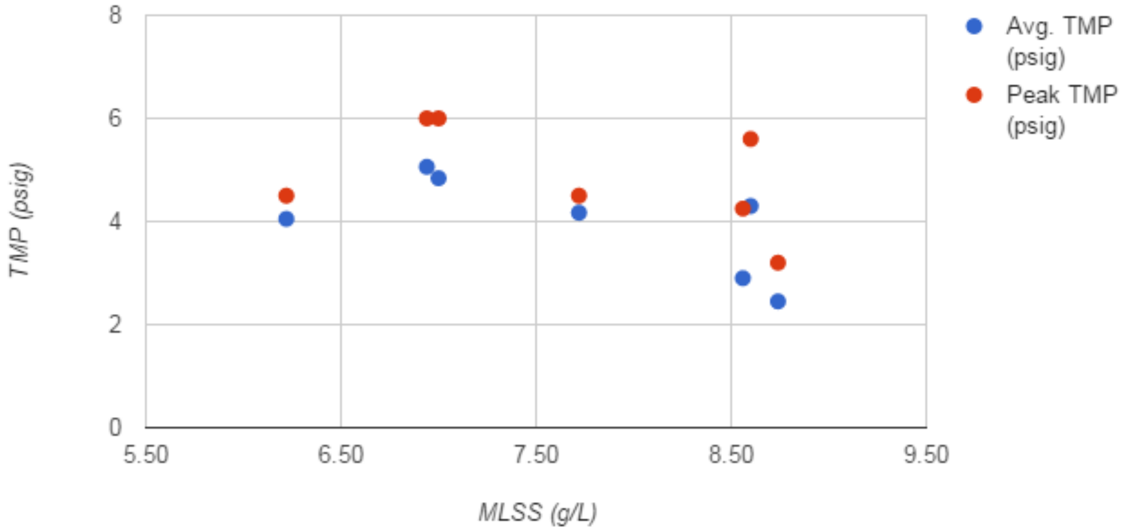


Figure 25. Correlation between MLSS and TMP

5.4.6 Oil Removal Measurements

With the inaccuracies of determining the oil concentration using the hexane extraction method, two samples were sent to an outside lab for testing. We were limited to two samples because of experimental cost. The inaccuracies of the hexane extraction method are shown in Appendix II. The detection limit for the lab's test was noted to be 0.10 ppm, far below our desired minimum of 10 ppm. The results from the test are shown as the "Oil Amount Detected in Effluent" on Table 5.

Table 5. Oil Concentration Removal

Carbon	MLSS Conc. (g/L)	Amount of PAC Used (g)	Initial Oil Amount Added (ppm)	Oil Amount Detected in Effluent (ppm)	Percent Decrease in Oil Conc. (%)
None (baseline)	-	None	30	27.0	10
WPX	2.62	27	30	2.0	93

5.5 Final Analysis

From the data gathered, Pulsorb WP260-90, WPH and WPH-1000, all coal based PACs, had the most effective results in terms of cleaning the water with WPH-1000 having the greatest percent decrease for both COD and turbidity and Pulsorb WP260-90 having the lowest overall final COD and turbidity. When comparing the transmembrane pressure to the baseline pressure with no carbon, two bring up concerns of possible fouling of the membrane. The transmembrane pressure with no carbon was about 4.30 psig whereas WPH was 4.84 psig and WPH-1000 was 5.06 psig. Pulsorb WP260-90 had a transmembrane pressure less than that of the baseline, 4.17 psig. This could indicate that the carbon was able to adsorb oil and other contaminates in the water prior to reaching the membrane. The lower pressure could also be a result of lower fluid volume in the membrane cartridge at the beginning of the run, indicating the potential creation of equipment malfunctions in the system. The 93% oil removal in the WPX sample compared to the 10% oil removal in the baseline showed that the PAC did have some positive impact on oil removal.

6.0 Project Design

Using our results involving the effectiveness of the PAC and membrane technology, an on-site water reuse system was designed for a car wash, a common generator of oily wastewater. Figure 26 outlines the design.

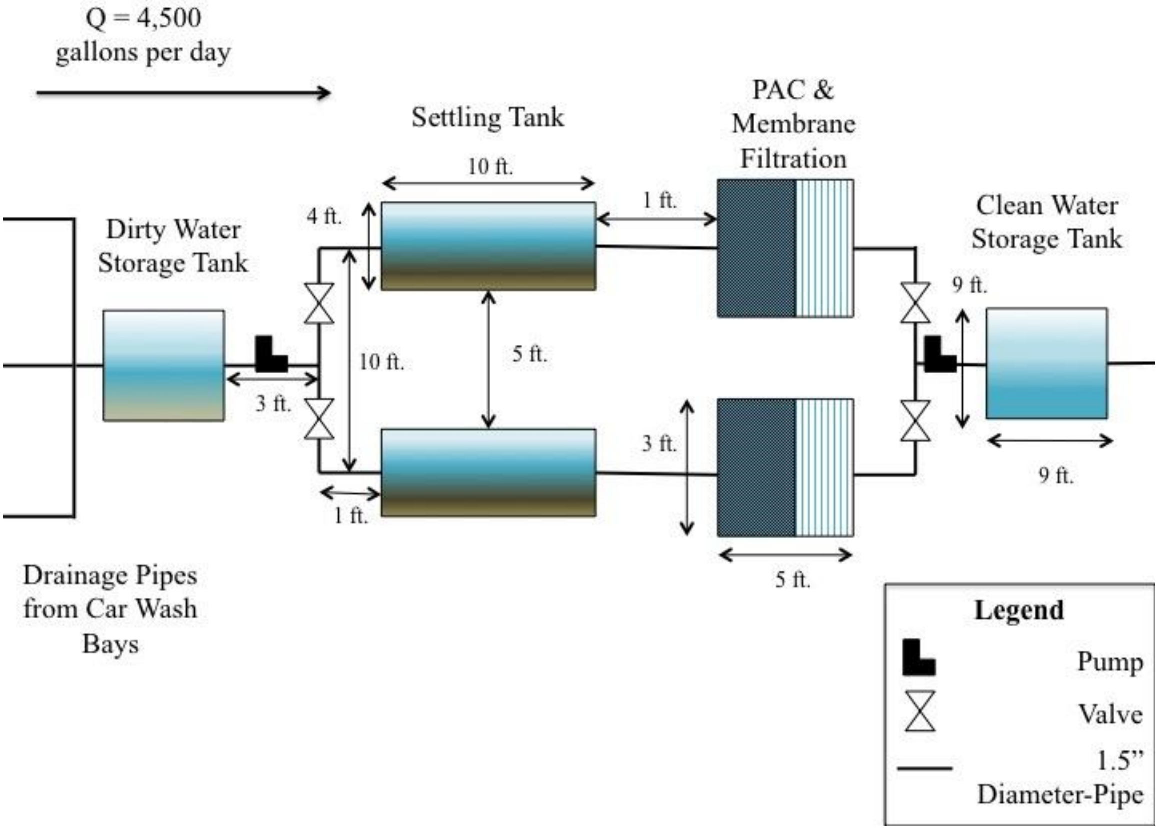


Figure 26. Underground Car Wash Schematic, Top View

6.1 Flow Rate

This design is for a treatment system that will handle 110 cars per day with an expected flow rate of 37 gal per vehicle. A 10% loss was assumed, giving an average daily demand of 4,477 gal/day. The system was designed with two parallel treatment trains, each capable of handling this flow rate. Only one train would be functioning at a time, the second train is a backup for maintenance and repairs, and for treating occasional high flows. The calculations for the flow rate can be found in Appendix IV.

6.2 Initial Storage Tank

This storage tank was designed to collect all the water from the day to then be sent through the treatment system at night when the frequency of car washes will be low. This allows energy to be saved since the system will not be operational all day.

The tank will require volume of 4,500 gal with a depth, width, and length of each 8.44 ft. Calculations for the storage tank capacity can be found in Appendix VI. For construction the actual tank will be 9 ft wide, 9 ft long, and 8 ft deep. The material of the tank will be steel, particularly low-carbon or low-alloy steel. These are ideal for oil pipelines for their toughness and strength, which is also necessary for an underground storage tank. To prevent corrosion, the steel should be coated with epoxy.

6.3 Settling Tank

The objective of the settling tank is to have suspended solids settle to the bottom prior to entering the membrane tank. Removal of suspended solids will reduce the potential for abrasions on the membrane surfaces. A flow rate of 4,477 gal/day and a hydraulic loading rate of 150 GPD/ft^2 was used, giving the tank an area of 29.8 ft^2. Using a 3:1 length to width ratio, the tank was calculated to have a length of 9.46 ft and a width of 3.15 ft. The length needs to be substantial in order to provide enough time for water to flow through and settle out. The depth was calculated to be 6.25 ft to provide a volume of 1,395.33 gal. The actual tank will be 6.5 ft deep, 10 ft long, and 3 ft wide to allow for easier construction while still meeting the minimum requirements. Appendix V has the calculations for the settling tank. An access hatch will be installed on the top of the tanks to allow for the solids to be pumped out, similar to a typical septic tank. Coated steel will also be the material used for the settling tank.

6.4 Membrane Tank

The flow rate of the wastewater in the tank is 4,477 gal/day and will have a retention time of 4 hours. This gives the tank a volume of 746 gal. The membrane tank will have both the membrane fibers as well as the PAC. The retention time is so long to ensure the PAC has enough time to interact with the oil to prevent fouling. To properly fit the membrane unit, the tank will be 8 ft deep and 3 ft wide. This gave a calculated length of 4.16 ft, but for construction purposes this value will be rounded up to 4.5 ft. Coated steel will also be the material used for this tank. Calculations for all aspects of this phase can be found in Appendix VII.

6.5 Membrane

The Koch Membrane Systems, Inc. PSH 31HD model was used in the design of this system. The model has a length of 3.62 in., a width of 32.6 in. and a height of 71.7 in. The area of the unit is 330 ft^2. A ratio of the surface area used in the benchtop experiment was used to determine the surface area needed for the full scale system. Only one membrane unit is necessary for the design flow rate and the size of the tank. The permeate flux will be 25 LMH, giving a flow of 4,853 gal/day. PSH 31HD has nine columns, each has 280 fibers for a total of 2,520 fibers. An important part of the membrane system operation is the air scour to prevent solids from settling at the foot of the membrane. An air flow rate of 1,369 scfh will be needed based on the surface area of the membrane.

6.6 PAC

The PAC chosen based on lab results was Pulsorb WP260-90 as it produced effective COD removal and turbidity decrease in the membrane reactor. Out of the three best PAC results, this one had the lowest TMP meaning the pressure buildup was not as substantial. This indicated a lower risk for fouling which is ideal for a system that is underground. For a dosage of 463 ppm and a flow rate of 4,477 gal/day, the total PAC amount needed will be 7,847 g/day.

6.7 Clean Water Storage Tank

The purpose of this tank is to collect all the clean water that was treated overnight and will be ready to use once the workday starts. No treatment process is conducted in this tank. It will be a 4,500 gal tank made of coated steel. It has the same dimensions as the initial storage tank with a length and width of 9 ft and a depth of 8 ft. Calculations can be found in Appendix VI.

6.8 System Piping

All pipes will be coated low-carbon or low-alloy steel as steel is durable and the coating will prevent corrosion. Using the 4,477 gal/day flow rate and a velocity of 1.5 ft/sec, the cross-sectional pipe area would be 1.6 in^2. This gives an inside diameter of 1.4 in., but for construction purposes a nominal pipe size of 1-½ with a schedule of 80 will be used. This will provide an internal diameter of 1.50 in.

The total length of the pipes from the storage tank to the settling tank will be 18.5 ft. It would go down 1 ft, over 3 ft, 5 ft over after being split into two trains, up 8.5 ft, and over 1 ft to go into the settling tank at the top. The next pipe would leave the top of the settling tank and enter the top of the membrane tank, it is a foot long pipe. For the pipe that moves from the membrane to the end water storage tank will be a total of 18.5 ft. It would go down 1 ft, over 5 ft, straight for 3 ft towards the pump that will push the water up 8.5 ft and over 1 foot to enter at the top of the storage tank. Calculations can be found in Appendix VIII.

6.9 Pumps

There are two pumps in this system: one after the initial storage tank and one after the membrane tank. To determine the pumps needed, the total head that the pump would have to achieve was found using the static head of 8.5 ft and the friction head. The friction head was found using the Hazen-Williams equation with a roughness coefficient of 100 (Engineering Toolbox) and dividing this value by 100 to get 0.0024 ft/ft of pipe. This was then multiplied by the length of the pipes to get the friction head loss. Head loss from the fittings, such as valves, was assumed to be 30% of the friction loss from the pipe. The total head for each pump was 8.56 ft. This and the flow rate of the system were used to determine the theoretical minimum power required would be 0.005 kW. Assuming a pump efficiency of 0.6, a minimum power required of 0.008 kW, or 0.011 HP was found. Using this, the overall flow, and the diameter of our pipes, the Berkeley 7SLP42-03 was determined to be the best fit for the system. Allowing the system a run time of 10 hours, these pumps produce an energy demand of 5.6 kWh each. Calculations can be found in Appendix IX.

6.10 Valves

The design of this system requires four valves total. All of them will be a brass 1-½ in. ball valve to allow one train to be shut down completely when not in use. It is also important that the valve can flow both ways, as a backflush will be necessary to clean the membrane.

7.0 Could the Application of Membrane Filtration and PACs Address Environmental Injustice?

It was previously mentioned that oil and grease can have a number of negative impacts on the environment, human health, and wastewater treatment processes (Alade et al., 201). It was also shown that PACs and membrane technology can be successful in the removal of oil from wastewater.

This chapter will look deeper into these impacts of oily wastewater, with a focus on car washes, a common generator of wastewater contaminated with oil, proving the significance of using this cleaning technology (Illinois Environmental Protection Agency, 2015). In addition, this chapter will look how these impacts are distributed in order to determine if car washes are creating an “environmental injustice”, or a disproportionate negative impact on poor communities and/or communities of color (Cutter, 1995). Wastewater from washing cars can run off of impervious surfaces and contaminate, not only the sanitary system, but also nearby surface waters as well as groundwater (Illinois Environmental Protection Agency, 2015). If the proximity of car washes to environmental justice groups causes an unequal distribution of pollution, then there is an environmental injustice.

The goal of this chapter was to consider the social and environmental impacts of oily wastewater. More specifically, it evaluated oily wastewater from car washes and considered potential environmental justice issues. The following objectives were established in order to accomplish these goals:

1. Determine the environmental, health, and social impacts of oily wastewater produced by car washes.
2. Investigate the geographic and socioeconomic distribution of car washes in Massachusetts.

7.1 The Impacts of Washing Cars

There are typically 3 different types of car washes. In-bay car automatic washes, conveyor car washes, and self-service facilities. For in-bay automatic car washes, the driver pulls into a bay and parks the vehicle, and the cleaning machinery moves back and forth over the vehicle. This type is found mainly at gas stations and coin-operated car washes. Conveyor car washes can be full-service, where the exterior and interior are both cleaned while the customer waits outside of the car, or exterior only, where the customer sits in the car while it is being cleaned and no interior cleaning is performed. In both cases, the car is carried through a tunnel by a conveyor belt. A self-service carwash allows customers to pay for an initial amount of wash time at a minimum price, and they are then able to wash the car themselves (Brown, 2002). These different types of car washes can have different impacts. Additionally, commercial car washes can have different impacts than washing your car at home or going to a charity car wash. This section will evaluate potential impacts of the three types of commercial car washes from a number of perspectives.

7.1.1 Contaminants

Water used in washing cars can contain a number of different contaminants. One of the major contaminants, part of the main focus of this project, is oil. Oil and grease can also contain a number of toxic materials, as previously mentioned, in addition to hazardous materials such as benzene, lead, zinc and other metals. Detergents used to wash the cars, which can be poisonous to aquatic life, are also present in the wastewater. Chemicals and oils used to maintain the cleaning machinery may be present. Other harmful chemicals and phosphates may be contaminating the water as well. Additionally, debris from cleaning vehicles may clog drains, rerouting the flow of water (Illinois Environmental Protection Agency, 2015).

7.1.2 Treatment of Water

After the water is used to clean the vehicles, it can either be discharged to the sanitary system or recycled on site (Brown, 2002). Before discharging to the sanitary system, car washes are often required to perform some form of filtration before discharging to the sanitary system. However, oil emulsions that are distributed throughout wastewater can sometimes pass through filters. Oil-water separators may also be used on site to manage this issue, but the remainder of the treatment typically occurs at the wastewater treatment facility (Illinois Environmental Protection Agency, 2015). Some commercial car washes also perform treatment on-site allowing them to recycle the water. This treatment often involves settling, oil-water separation, and filtration. In this sense, commercial carwashes have a significantly smaller impact than charity or at-home car washes. Noncommercial car washes do not have a controlled drainage system. Instead, wastewater runs off of impervious surfaces into stormwater drains, where it can pollute receiving bodies, or onto soil where it can pollute groundwater (Peirce, 2016; Illinois Environmental Protection Agency, 2015). However, there is no current way to track noncommercial car washing, and as a result, it was not accounted for in this analysis.

7.1.3 Environmental Impacts

Oily wastewater can have a significant impact on the environment, particularly aquatic environments. Being hydrophobic in nature, oil can create a layer on the surface of water bodies. This oil layer hinders the ability of light to penetrate the surface, making photosynthetic processes difficult, if not impossible, for aquatic organisms. In addition to blocking light, an oil layer also prevents the exchange of air between the water and the atmosphere, resulting in a drop in dissolved oxygen in the water. Such a drop in dissolved oxygen is detrimental to the survival of aerobic aquatic organisms (Alade et al., 2011). Toxic compounds that exist in oil can also have adverse health impacts on wildlife that use the contaminated water as a drinking source (Showstack, 2002). In addition to these direct impacts, oil, as well as grease can reduce the efficiency of wastewater treatment processes, causing blockages, pump failures, and reduced oxygen for biological treatment. Ineffective treatment can then result in a discharge of effluent that does not meet standards, resulting in increased concentration of contaminants in receiving streams and local ecosystems (Alade et al., 2011).

In addition to the potential pollution issues resulting from oily discharges, car washes also consume significant amounts of water. Depending on the type of facility, the amount of water used per vehicle can vary. In-bay car automatic washes tend to consume the most water, followed by conveyor car washes, and self-service facilities, but the average water usage for commercial carwashes is 37 gallons per vehicle (Brown, 2002). The average water usage for a charity or at-home car wash is significantly more, at approximately 116 gallons of water per vehicle (Peirce, 2016). High water consumption contributes to the increasing scarcity of a limited resource. Additionally, increased water usage can result in accelerated degradation of aquatic environments, leading to habitat loss (Burke, et al., 2009). This consumption can be significantly reduced through an on-site water treatment and reuse system at commercial car washes.

7.1.4 Human Health Impacts

Oil contamination in water, specifically from crude oils (used in cars) or those used in industrial processes, can also have adverse impacts on human health. When oil seeps into groundwater, it can make the soil less fertile, destroying crops. A poor harvest not only affects the economy, but it can also lead to malnutrition in some communities. Oily water can also result in the bioaccumulation of toxic substances in aquatic life, plants (including crops), and animals. Based on their placement in the food chain, this could result in human consumption of these contaminants, which can have acute or long-term effects. For example, polycyclic aromatic hydrocarbon is often found in oily wastewater and, being a known carcinogen, human exposure can cause significant long-term effects. Extreme cases of exposure have also been noted to result in hepatoxicity and/or hemotoxicity (Ordinioha and Brisibe, 2013). There is potential for humans to consume some contaminants directly as well. With treatment processes being affected by oil and grease, drinking water can be contaminated. More than two-dozen major utilities supplying cities in the United States draw water from rivers with a flow that consists of more than 50% treated wastewater in dry conditions (Loraine, 2006). This can have major health impacts since the wastewater may contain phenols, petroleum hydrocarbons, and polyaromatic hydrocarbons, toxic substances that are carcinogenic to humans (Alade et al., 2011). Additionally, if emulsified oil is able to pass through treatment processes such as filtration, it could end up in drinking water. Considering these health impacts, the proximity of facilities that generate oily wastewater (like car washes) to residential areas and drinking water sources can increase health risks for local residents.

7.2 Environmental Justice Analysis

Environmental justice is defined by the United States Environmental Protection Agency as "the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies". The overarching goal of environmental justice is to provide each person with the same protection from environmental and health hazards, as well as allowing them equal access to the decision-making process (US EPA, 2016). The definition and goals embody a normative position on the way things "should be", but there is also "analytical" side to environmental justice, which uses facts and recognized the way that things are currently. Analyses that focus on environmental justice show that, despite what "should be," the impacts of environmental hazards are often not experienced equally among society. Environmental justice populations, or those who experience environmental injustice, are often identified as minority populations or low-income groups (Cutter, 1995).

Environmental justice may seem like an abstract concept, but there are communities in the United States facing very clear environmental injustice. One highly publicized example, though perhaps not discussed on the media in terms of environmental justice, is Flint, Michigan. Flint is a relatively poor, minority community (Mooney, 2016). After the governor nullified free election and appointed someone to run the city, they switched the city's water supply from Lake Huron to the highly toxic Flint River in order to save money. Children were getting lead poisoning for over a year, while the General Motors facility was given a hookup to clean water. Property value has also significantly dropped, so the citizens of Flint cannot afford to leave (Moore, n.d.). The lack of an elected official in Flint resulted in a clear political disadvantage. Additionally, the favor shown to General Motors by allowing them clean water over the general population shows discrimination against a poor minority population, while the low income of the population left people without the option to leave the contaminated area. Another example is clear in San Diego County, California, where two very different communities face very different amounts of pollution. In Barrio Logan, 97 percent of the population is people of color and 35 percent of families live in poverty. In La Jolla, on the other hand, 14 percent of the population is colored, and 3 percent of families live in poverty. In Barrio Logan there are 127,908,799 pounds of toxic substances, while in La Jolla there are only 3,203,992 pounds (Environmental Health Coalition, 2011). There is clear discrimination against Barrio Logan for the race and economic status of the citizens, and those citizens are likely to face significant negative impacts as a result. Many places, however, are moving to resolve their environmental justice issues.

In 2001, Daniel Faber released a report showing that communities of color in Massachusetts, one of the nation's most progressive states in terms of environmental policy, bear an environmental burden 20 times greater than that of predominantly white communities. In 2005, he found that the disparities were getting worse (Goldstone, 2015). With the government recognizing that there is an issue in 2014, an Executive Order was signed requiring Secretariats to actively promote environmental justice. This order required that a Governor's Advisory Council be established to advise on environmental justice issues, a Secretariat Environmental Justice Coordinator be appointed by each Secretariat, environmental justice policies and strategies be updated, and periodic meetings of the Interagency Environmental Justice Coordinating Group be held. As part of the updates to the policies, the state defined environmental justice communities as groups with an annual median household income at or below 65 percent of the statewide median, with 25 percent of residents, or more, identifying as minority, or with 25 percent of households having no person over the age of 14 that speaks English only or very well (Simpson, 2016). The following images were generated using MassGIS data to give a better idea of the distribution of different environmental justice communities across Massachusetts. In the color key, "M" represents groups that fulfill minority population criteria, "I" represents groups that fulfill the low-income criteria, and "E" represents groups with Limited English Proficiency (MassGIS, 2012).

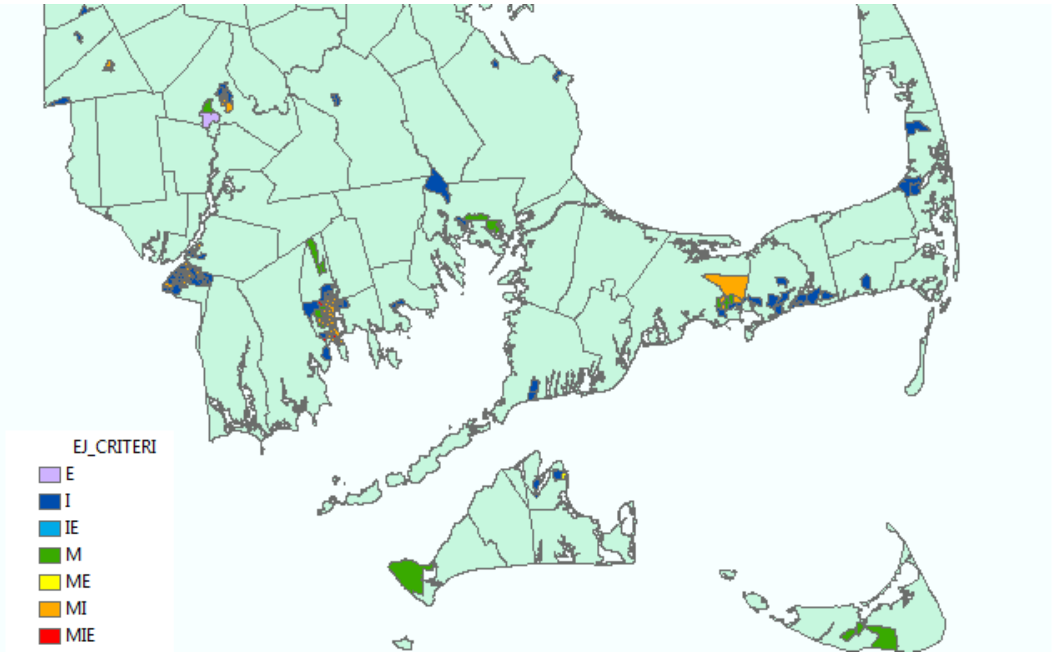


Figure 27. MA Environmental Justice Groups - Cape Cod

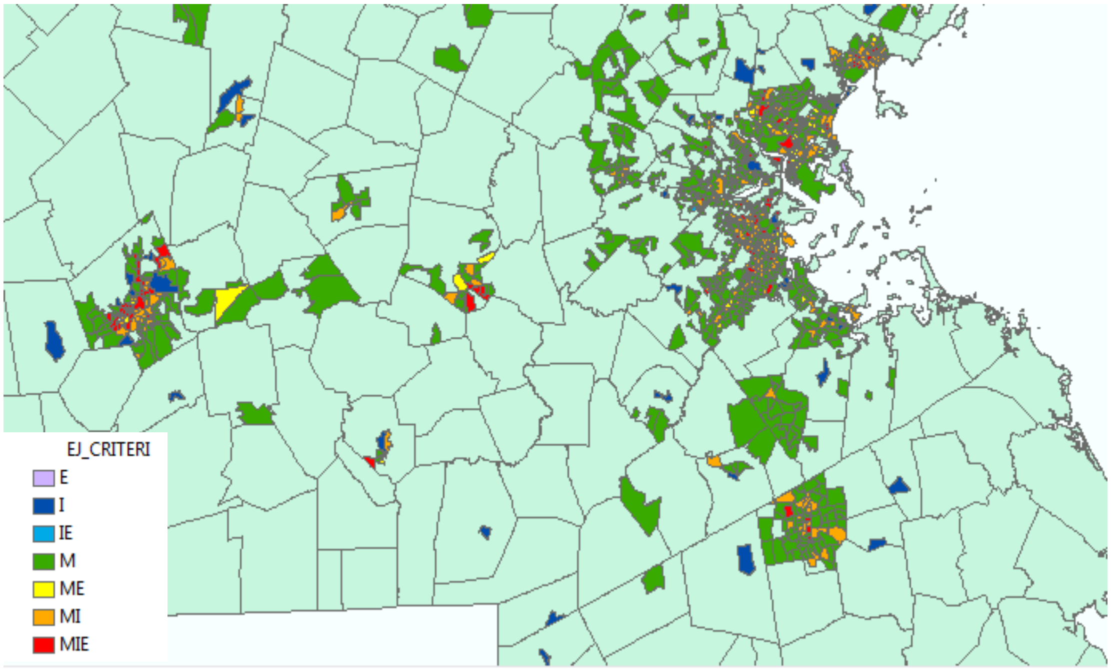


Figure 28. MA Environmental Justice Groups - Greater Boston Area

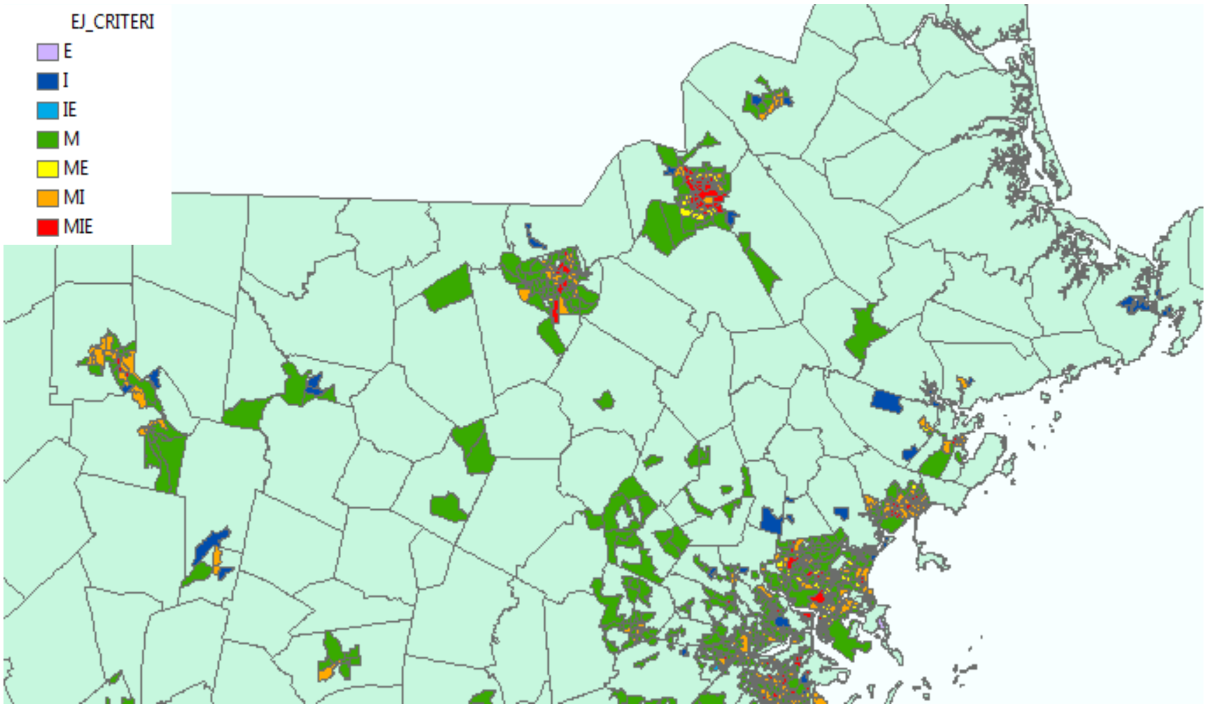


Figure 29. MA Environmental Justice Groups - Northeast

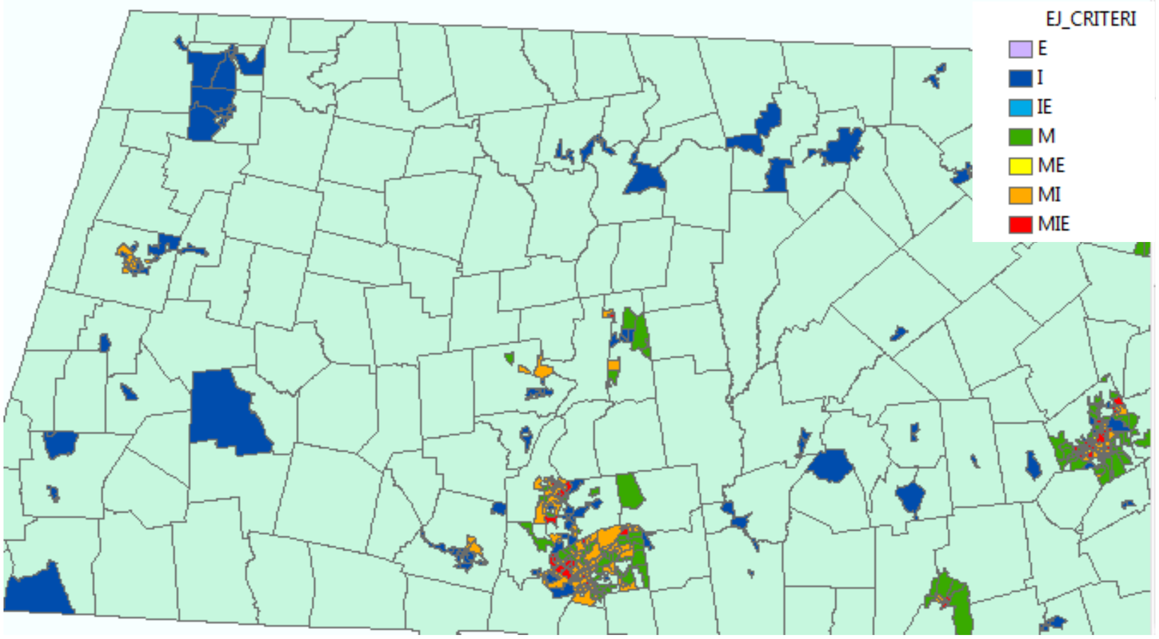


Figure 30. MA Environmental Justice Groups - Western Massachusetts

Figures 27 through 30 show that the main two defining factors for environmental justice communities in Massachusetts are minority population (eastern MA) and income (western MA). These groups face discrimination that is not always intentional. Companies often seek locations where the land is cheap and labor is readily available, and this often happens to be in area where marginalized groups already live. After a hazard is created, these communities typically lack the resources to move. Environmental justice communities also often lack a strong voice in governmental matters, making them less resistant to the addition of a hazardous facility. Environmental racism also exists. There have been situations where minority groups themselves were viewed as a form of pollution, making it morally easier to pollute the community with industrial waste (Brehm, 2013). Despite the state's attempts to support environmental justice groups and eliminate potential injustice, there is a high chance that it is still prevalent. Car washes are one example of a potential hazard that is not often considered. The remainder of this chapter will try to determine if such an injustice exists.

7.2.1 Methodology

In order to analyze the potential for environmental justice issues surrounding car washes, ArcGIS software was used to compare the siting of carwashes with the location of EJ communities. Since the focus of this study was on the state of Massachusetts, the state's polygon shapefile from the Massachusetts 2010 Census Data was added to provide an outline of the state and individual town boundaries. The shapefile for statewide environmental justice populations derived from the 2010 Census Data was also added. These populations were determined using three criteria: percent minority population, income, and English language isolation. For data on car washes, the website for the New England Carwash Association was searched. The addresses of most of the car washes in Massachusetts were pulled off of the member directory, and corresponding websites, and entered into an excel sheet. The latitudinal and longitudinal coordinates for each of these addresses was found using a free geocoding website. After entering the coordinates into the spreadsheet, it was uploaded into ArcMap as a .crv file, with an adjustment to the coordinates system to account for both sets of data. The map was analyzed for any correlation between car wash locations and environmental justice populations (specifically looking at car washes that were within or touching the border of environmental justice communities). Additionally, information on land elevation was added to allow for assumptions to be made on the movement of groundwater, and water bodies and wetlands were added to evaluate other potential environmental impacts. In order to further analyze potential contamination from car wash runoff, drinking water reports for areas with a high number of environmental justice groups and car washes were searched for signs of oil/hydrocarbons or other car wash contaminants.

7.2.2 Results and Discussion

Using the ArcGIS software, a number of maps were generated. The first set of figures display the map of Massachusetts towns/cities (light green) with environmental justice groups (purple) and car washes (blue dots). Figure 31 shows the distribution of all car washes registered with the New England Carwash Association (114 total) and environmental justice populations across the state.

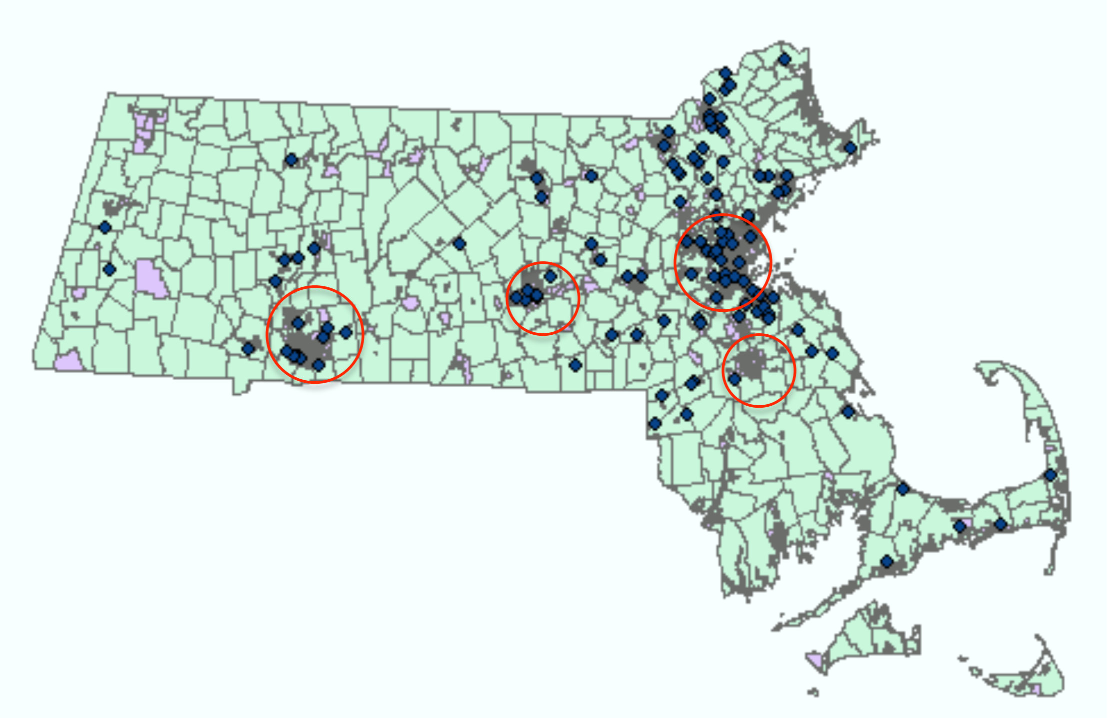


Figure 31. Distribution of Car Washes and Environmental Justice Population in MA

Though the individual features in the statewide view of the map are not clearly distinguishable, it can be noted that most car washes, and environmental justice populations, are located towards the east coast in the Boston area. However, this finding, at this state level, seems intuitive because of the far greater population in the Boston area compared to the rest of the state. Most environmental justice populations appear to be in urban areas, such as Boston, Worcester, Springfield, and Brockton (circled in red). There seems to be an overall trend in which car washes are within or touching the border of environmental justice populations, but there are also some car washes that seem to go against this trend. Figures 32 through 36 show a closer look at various regions of Massachusetts.

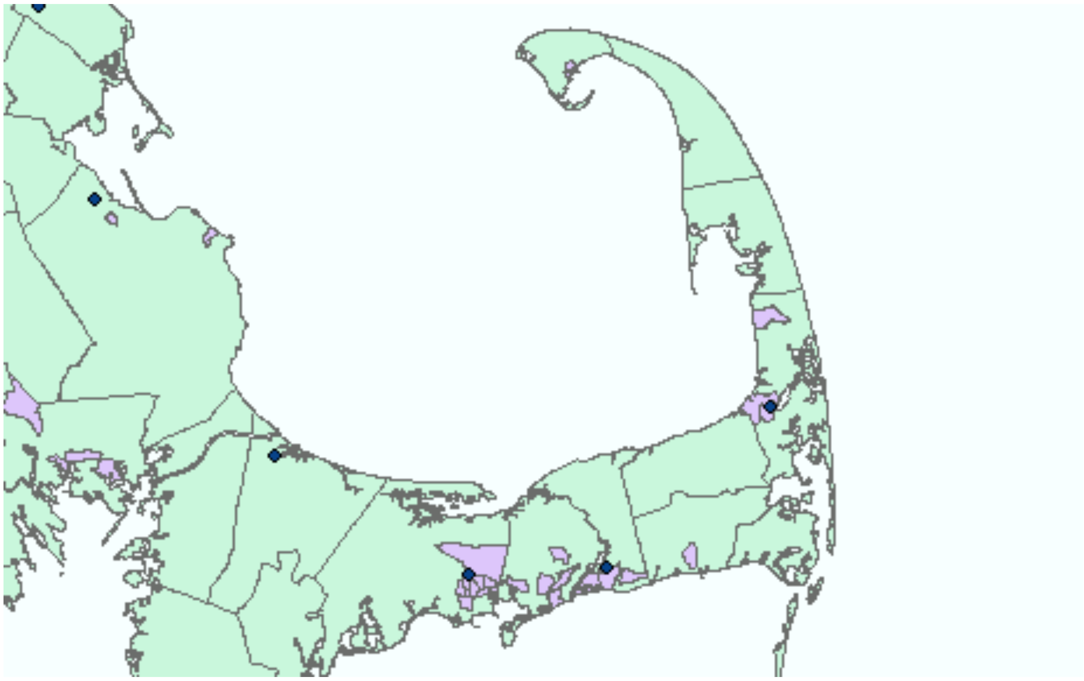


Figure 32. Car Washes and Environmental Justice Populations along Cape Cod

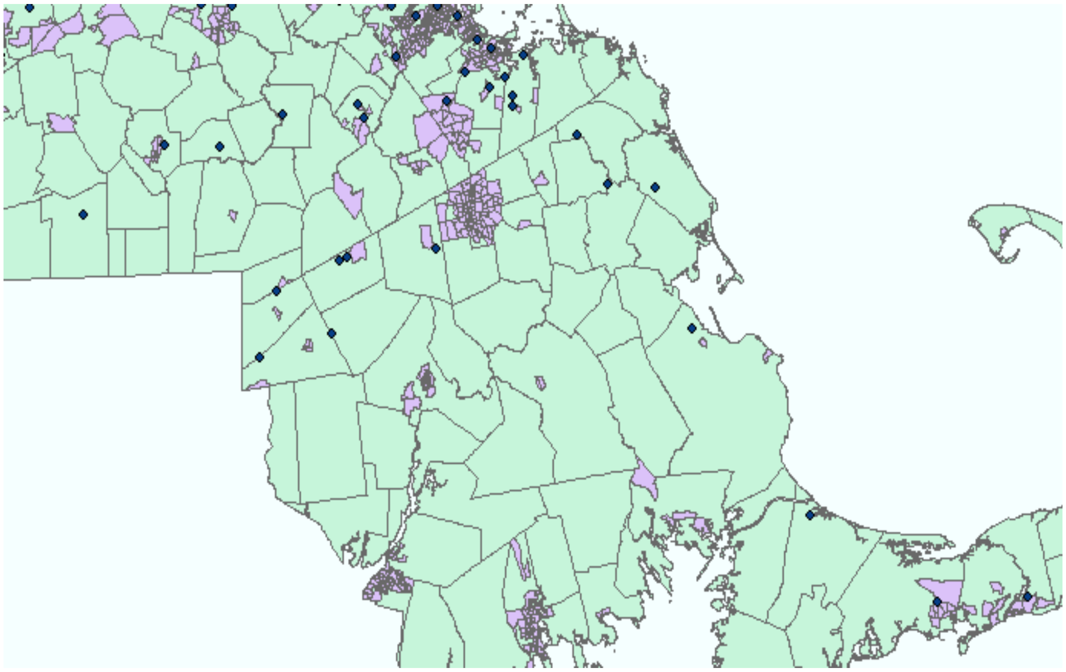


Figure 33. Car Washes and Environmental Justice Populations in Southern MA

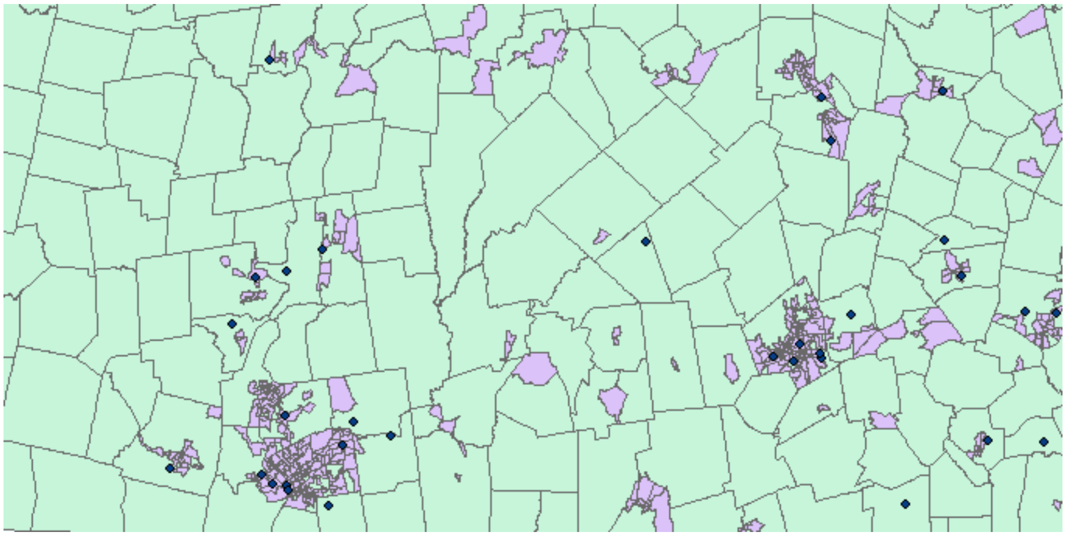


Figure 34. Car Washes and Environmental Justice Population Mid-State

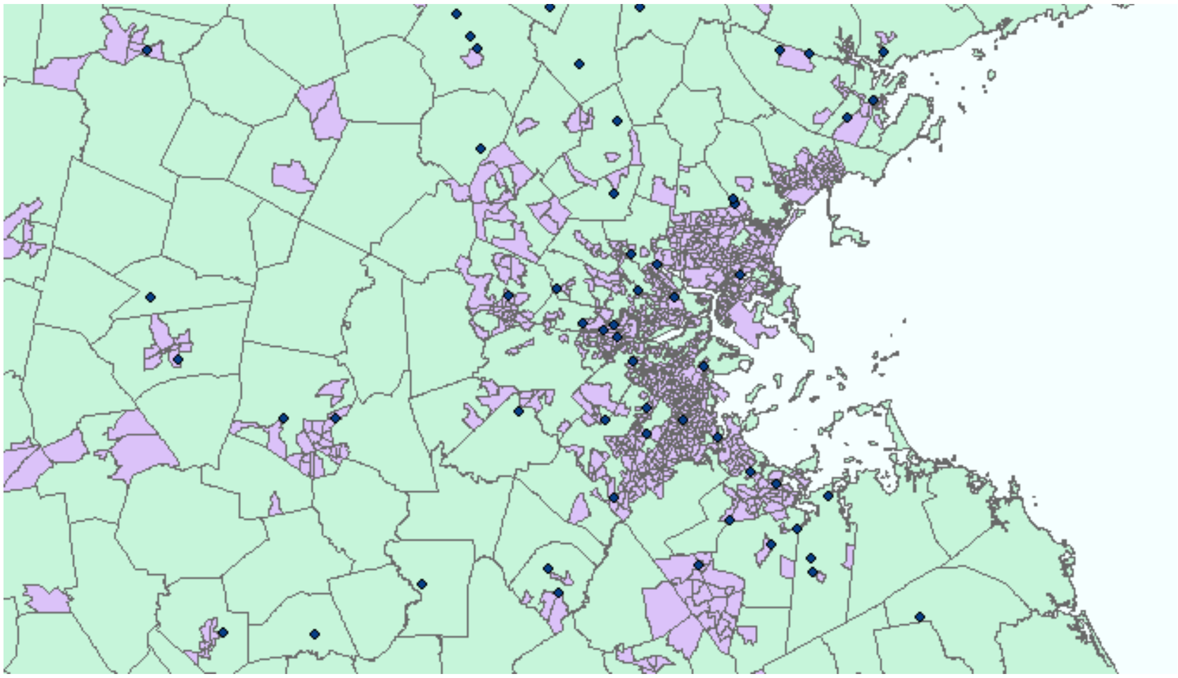


Figure 35. Car Washes and Environmental Justice Population in Greater Boston Area

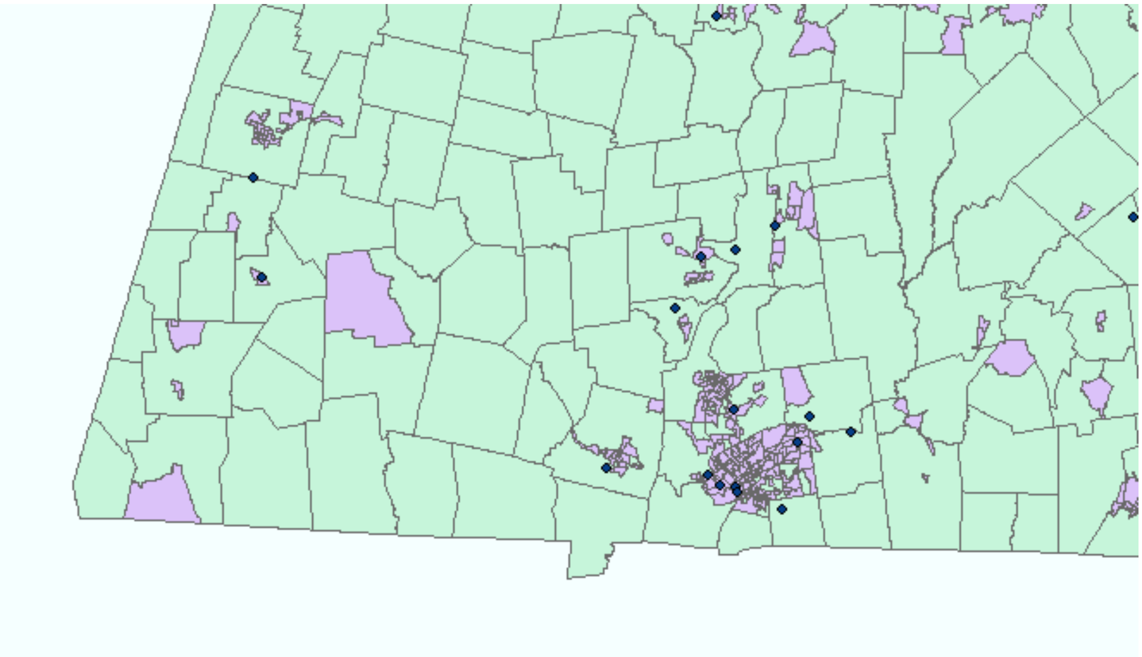


Figure 36. Car Washes and Environmental Justice Populations in Western MA

With these figures, it is easier to see that many car washes are located around the border of environmental justice populations. This could be a result of the higher throughput of traffic in those mainly urban areas. Figures 37 through 42 were taken from a map showing elevation (lighter green indicating a higher elevation) in addition to the environmental justice groups (purple outline) and car washes (blue dots). The purpose of this analysis was to determine if car washes were at a higher elevation relative to the environmental justice populations, as water and any associated contaminants travel down slope.

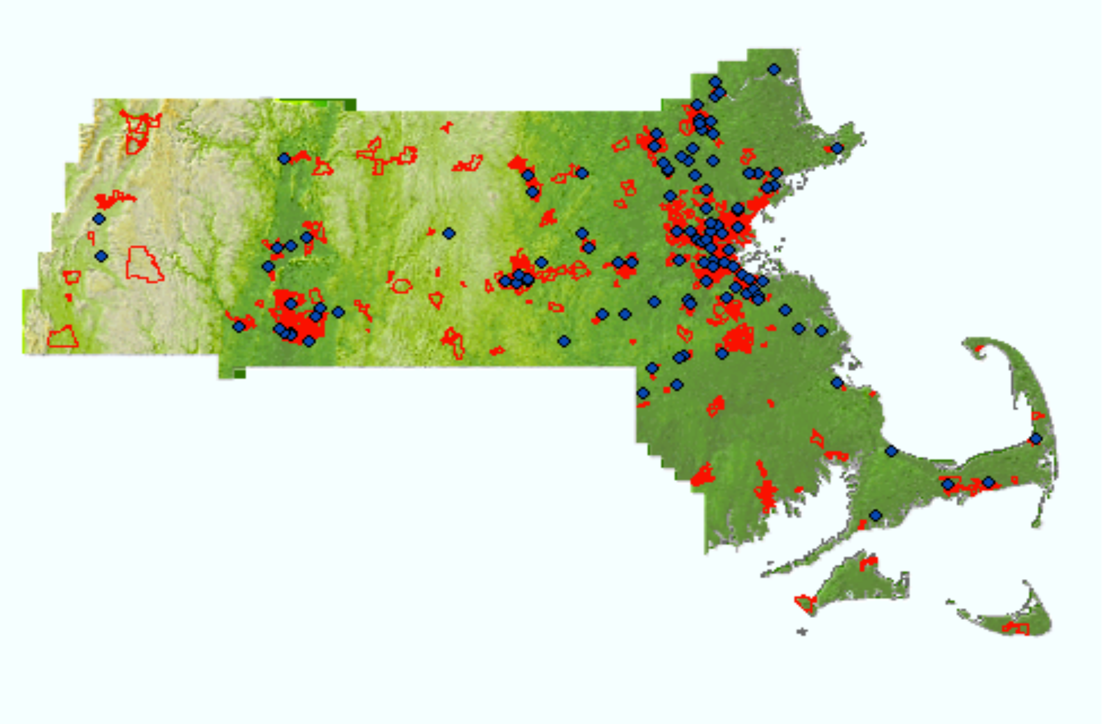


Figure 37. Elevation Analysis for Entire State of MA

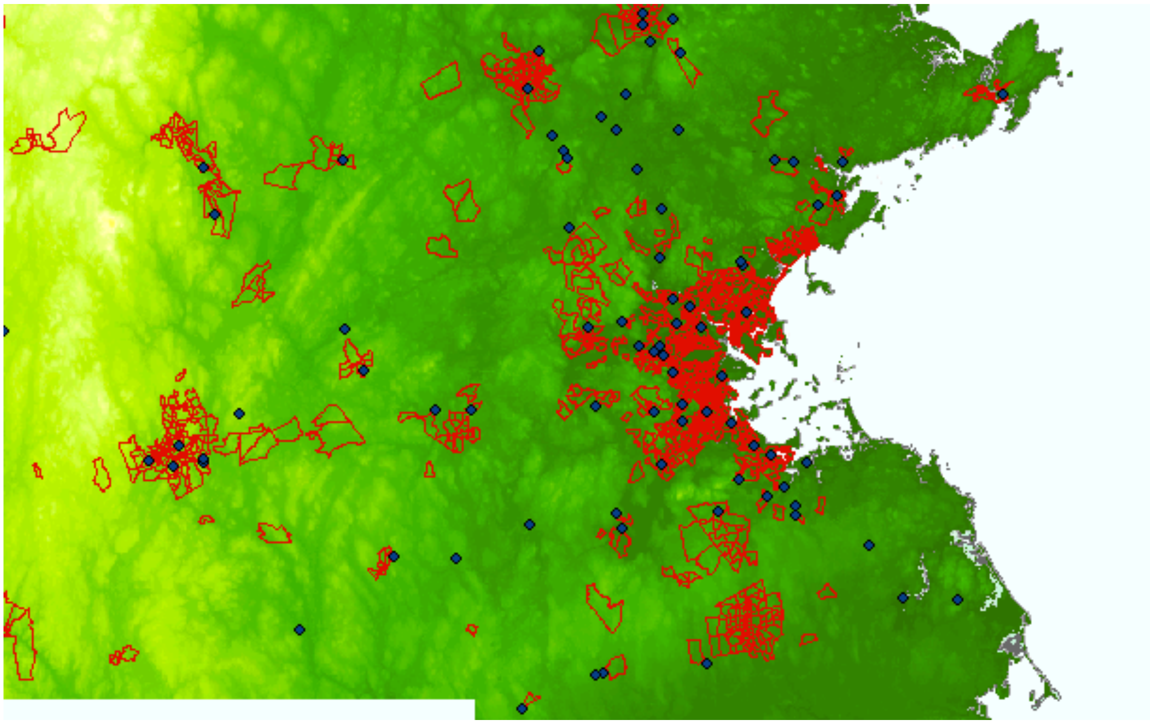


Figure 38. Elevation Analysis for Greater Boston Area

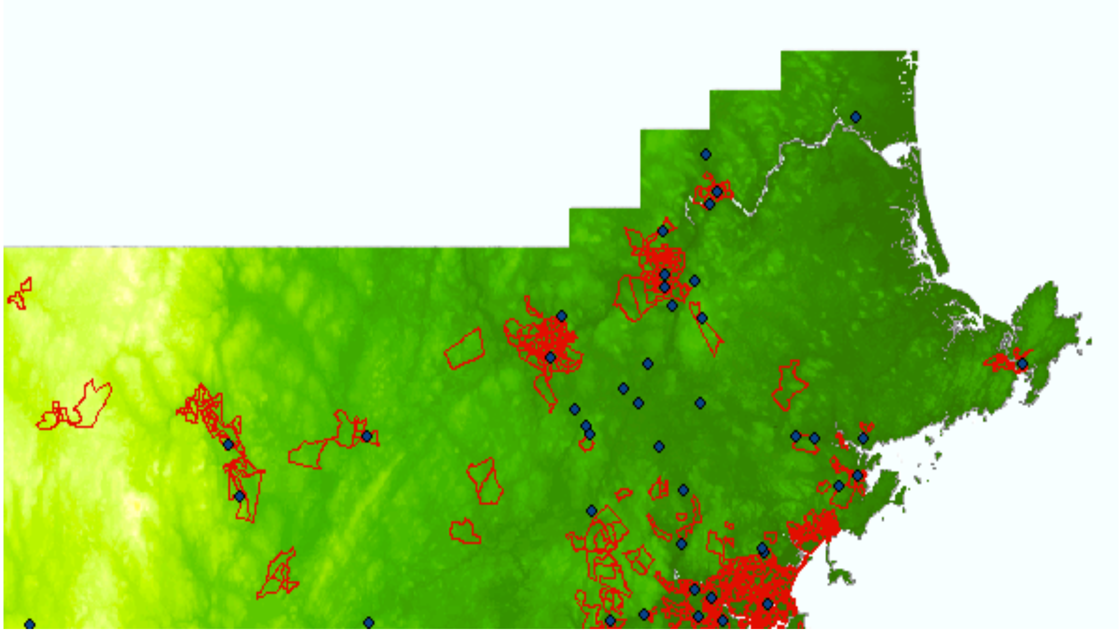


Figure 39. Elevation Analysis for Northeastern MA

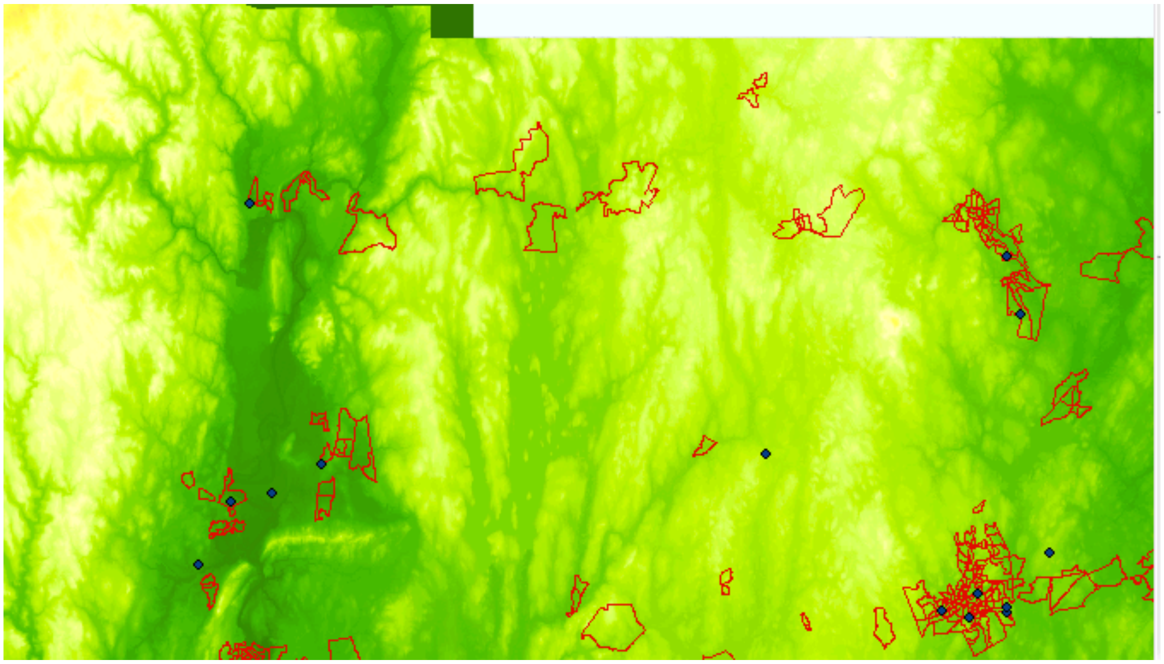


Figure 40. Elevation Analysis for Mid-Northern MA

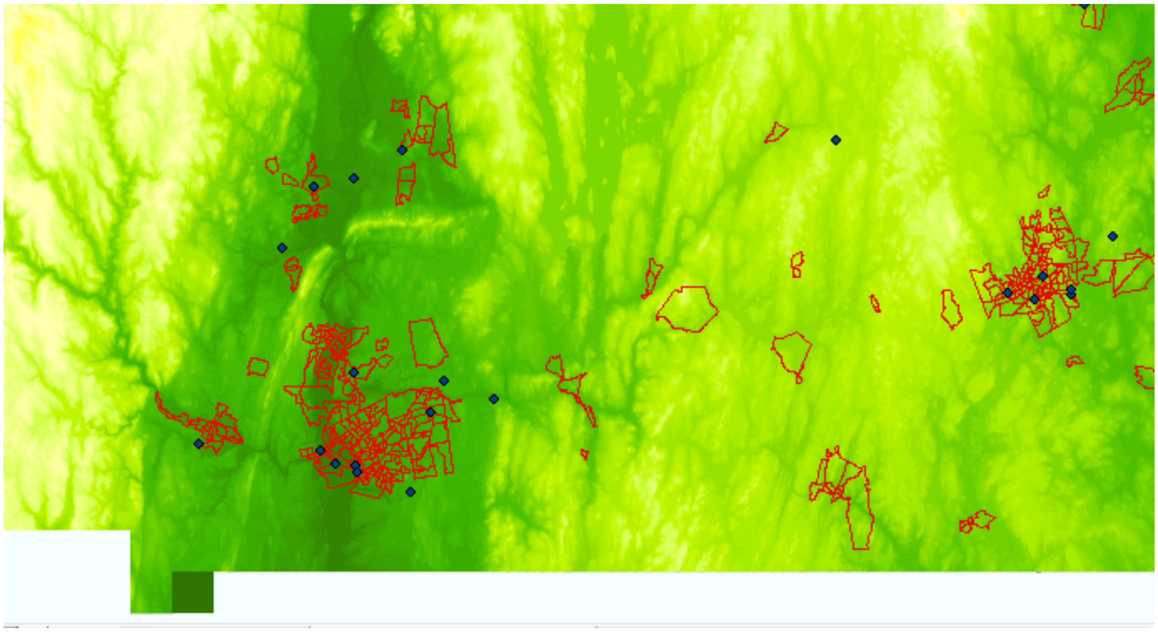


Figure 41. Elevation Analysis for Southern MA

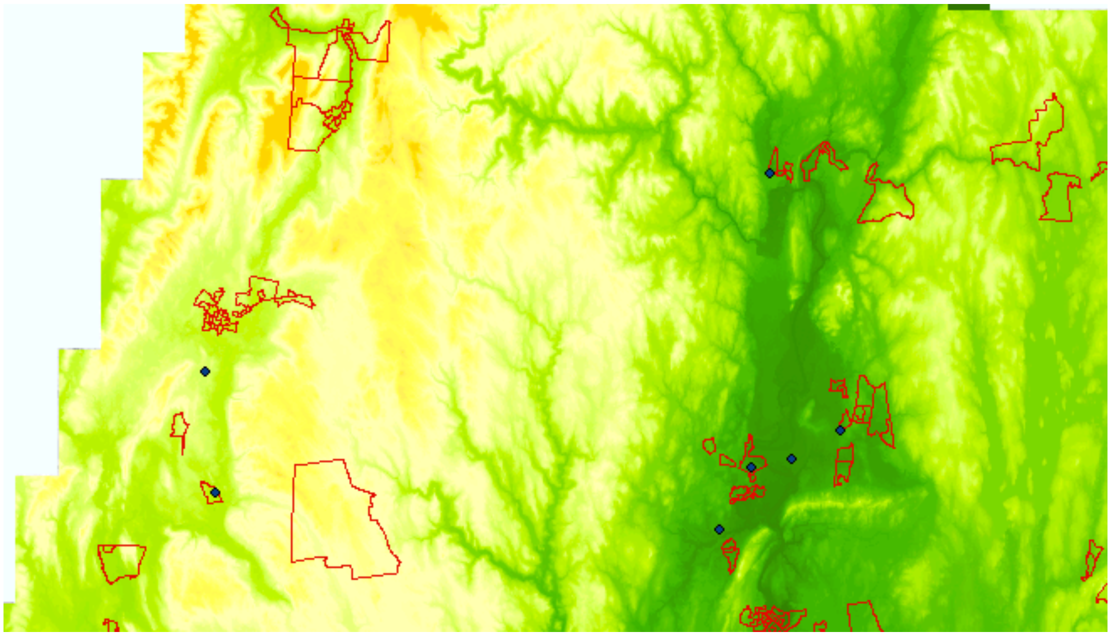


Figure 42. Elevation Analysis for Western MA

Based on the map (seen in the figures above), there does not seem to be any distinct pattern in the elevations surrounding the EJ groups and car washes. Often both are on a similar, if not the same, elevation since they are located relatively close together. In fact both environmental justice populations and car washes seem to be located most frequently at low elevations. However, there are also locations where the car washes are on a higher elevation than the environmental justice populations and vice versa.

Figures 43 through 47 are portions of a map that displays elevations of land in Massachusetts (lighter green indicates higher elevations), environmental justice populations (outlined in red), car washes (yellow dots), and hydrography (blue lines and polygons), which includes aqueducts, reservoirs, wetlands, lakes, ponds, bogs, swamps, rivers, streams, and others (MassGIS, 2013).

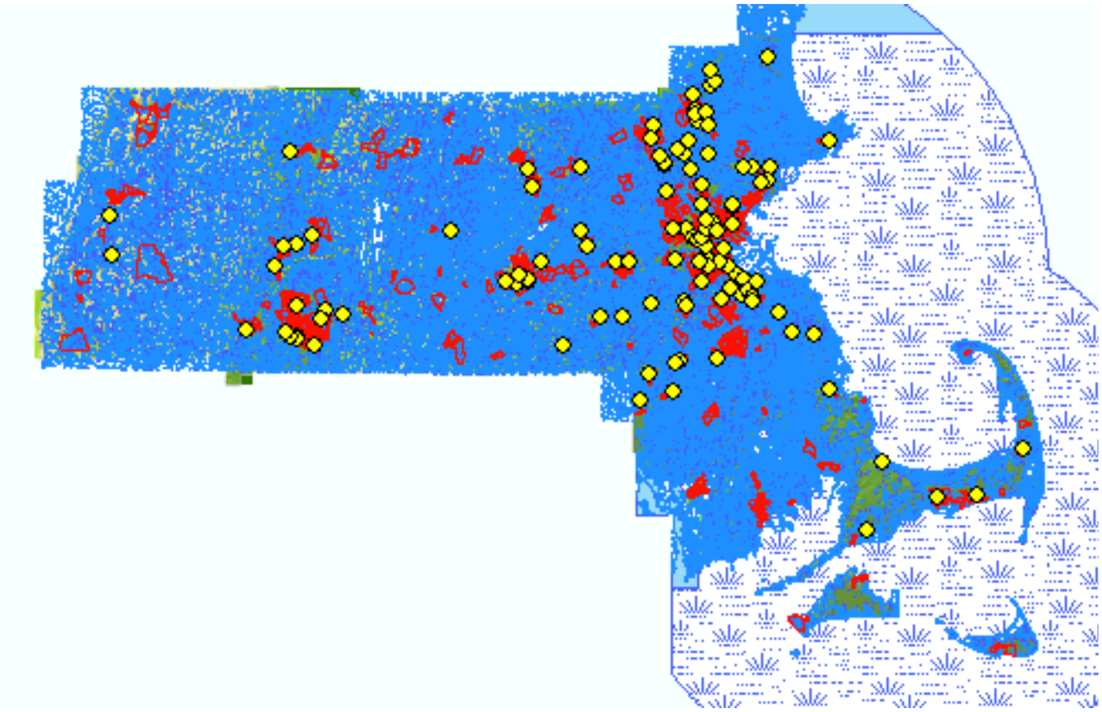


Figure 43. Water Bodies Analysis for Entire State of MA

Figure 43 shows the entire state. While there details are not clear from the statewide view, it can be easily seen that there are a large number of water bodies that could be affected by car wash runoff. Areas with a lower density of water bodies (west and northwest) seem to have fewer car washes. This observation could actually be positive because wastewater from commercial car washes is much more likely to be treated than water from charity or at-home car washing. If areas with a higher density of water bodies have more car washes, people are more likely to use car washes than they are to wash their cars at home, and the numerous water bodies are less likely to be contaminated. With fewer commercial car washes, more people will wash cars at home, and more water bodies will likely be contaminated. As a result, it is better to have more commercial car washes where there are more water bodies since they will properly treat the wastewater or discharge it to the appropriate facilities.

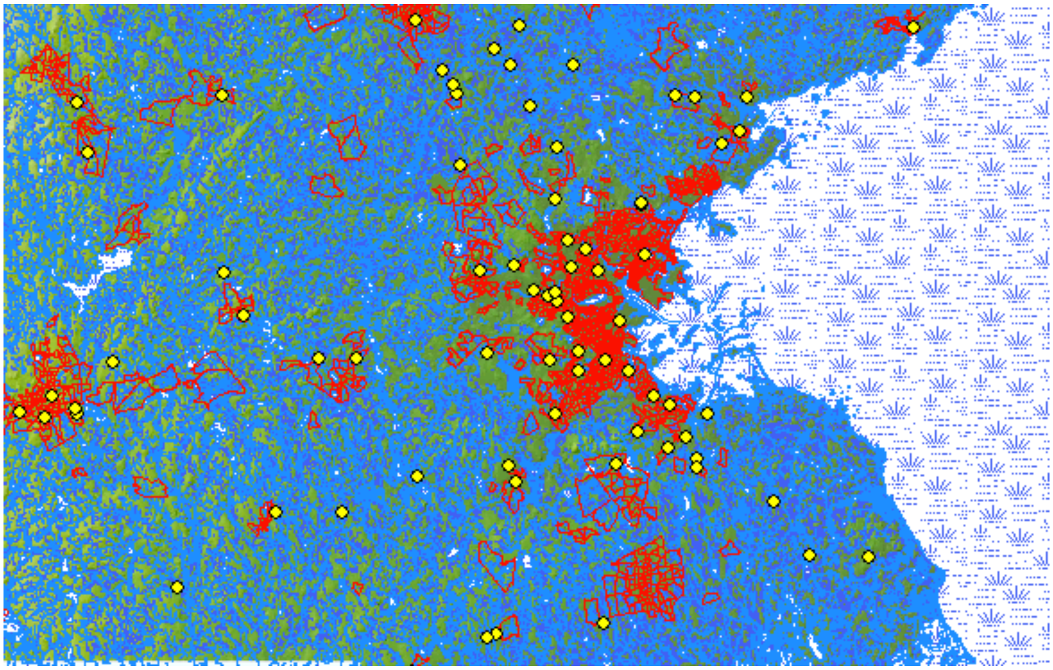


Figure 44. Hydrography Analysis for Greater Boston Area

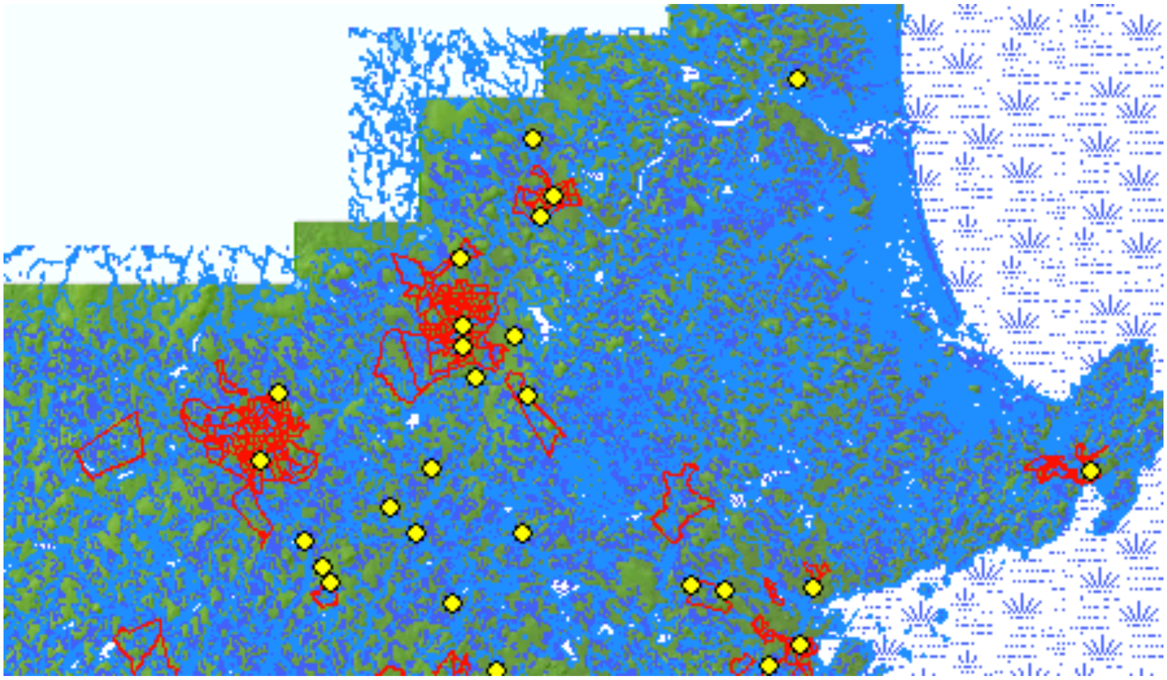


Figure 45. Hydrography Analysis for Northeastern MA

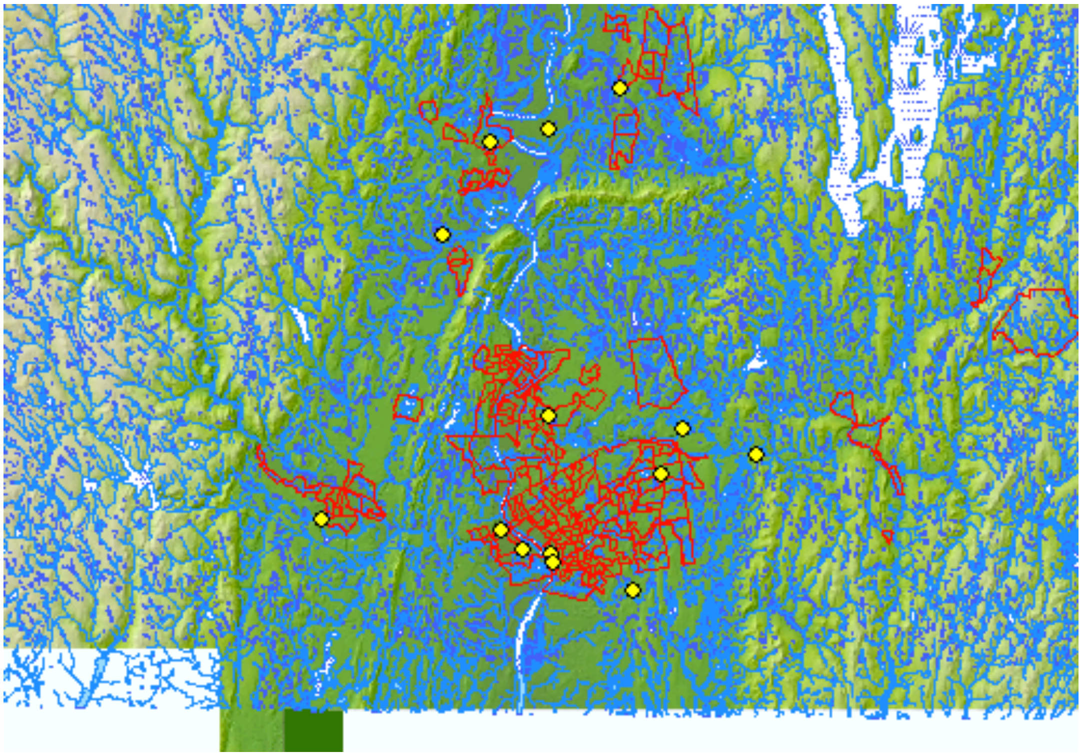


Figure 46. Hydrography Analysis for Mid-Southern MA

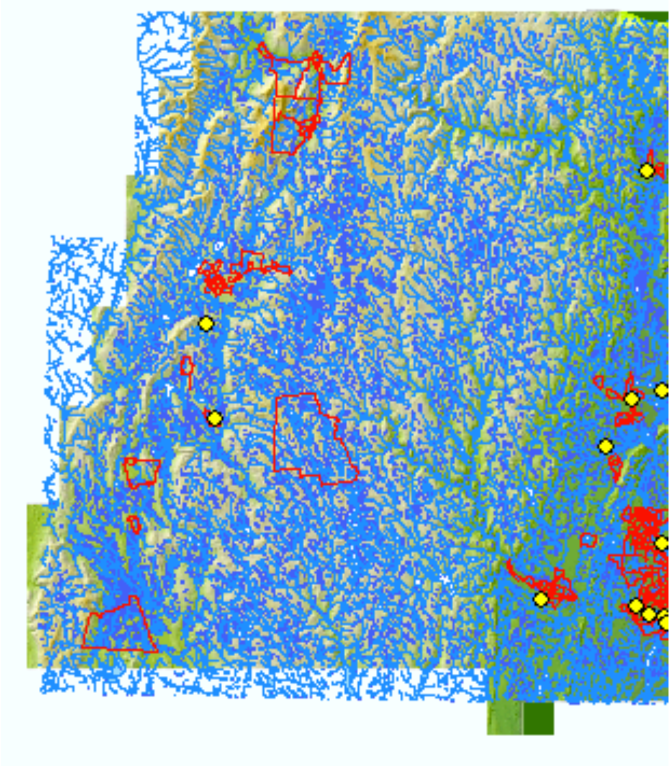


Figure 47. Hydrography Analysis for Western MA

Figures 44 through 47 show a more detailed view of the water bodies throughout the state. Figures 44 and 45 display the eastern side of the state, which has a higher concentration of water bodies, and Figure 45 shows a portion of the mid-western part of the state (Springfield), which has a much lower concentration of water bodies. It can also be seen in Figures 45 and 46 that the density of water bodies lessens as the distance from the car washes and environmental justice groups increases. This decrease in density is also likely due to the increase in elevation since water tends to collect at lower elevations.

Finally, drinking reports for notable communities (Springfield, Boston, Worcester, and Brockton) were studied in an attempt to see any specific impacts. However, when looking at the water quality reports for Worcester and Brockton, no notable pollutants were listed in violation (Wu, 2014; City of Brockton, 2014). Looking through the EPA's list of regulated and monitored contaminants, it was found that oil and grease (also searched for hydrocarbons) were not listed (Environmental Protection Agency, 2016).

The following results were considered:

- Many car washes tend to be located within or on the border of environmental justice communities,
- Environmental justice communities are not at a disadvantage in terms of elevation since they are at similar, if not the same, elevations as car washes,
- The high density of water bodies across the state makes it likely that some will be contaminated, and
- Oil and grease are not listed as regulated or monitored contaminants.

It is unclear whether the locations of car washes are creating an environmental justice issue. There is certainly potential for water contamination due to the sheer amount of water bodies that exist across the state. The wastewater from commercial car washes is more likely to be properly treated than non-commercial car cleaning. However if commercial facilities do not properly manage their wastewater, the nearby environmental justice groups could be facing the impacts of the contaminated runoff. Due to the lack of information in reports and the large number of factors that play a role, the potential for environmental justice issues surrounding carwashes was found to be inconclusive, but the results indicate that there is still a possibility for issues.

7.3 Future Considerations

This research has raised questions on a number of other potential factors or additional issues. In order to better understand the potential for environmental justice issues surrounding car washes, a deeper analysis needs to be conducted. One of the potential factors that should be considered is traffic in the area. Are there more car washes because there is more traffic in urban areas? What role does public transport play? It is possible that people living in environmental justice groups are more likely to use public transport. If this is the case, and they are in fact using fewer cars, the car washes are mainly for the use of non-residents. Another factor that should be considered is runoff from at-home or charity car washes. Since the water from these sources is untreated, it could generate more pollution. Considering this, commercial car washes could actually be eliminating an issue instead of creating one. If this is the case, an environmental justice issue could be generated by the lack of commercial car washes, as opposed to their presence. Customers should also be considered upon further analysis. Who is using the car wash? Is it located within a community where the residents will be likely to use it? What role does cost play? If lower income populations are less likely to pay for a commercial car wash but car washes are bordering these communities, the placement of the car washes is less likely to be determined by where the customers living. Finally, it would be beneficial to conduct further research on zoning regulations for car washes. Zoning laws vary from town to town, but they dictate which areas are suitable for residential use and commercial use. Zoning information would help determine the allowable proximity of car washes to homes and water sources. Finally, a cost-benefit analysis for implementing the membrane/PAC technology for oil removal should be conducted. This analysis would help to gauge the possibility of implementing the technology at a number of car washes in order to reduce potential hazards.

8.0 Conclusions

The goal of this project was to investigate the effectiveness of adsorbing mineral oil onto PACs to reduce the potential risk of equipment failure in a wastewater treatment plant from membrane fouling due to oil. To accomplish this goal, this project operated an MBR to treat domestic wastewater spiked with mineral oil and PACs and analyzed the effectiveness of this system in terms of oil removal, COD, and turbidity.

A benchtop MBR was run in a continuous system to execute the experiments. An MLSS between 6 g/L and 8 g/L was desired for the 5.4 L of sludge and water in the tank. The additional contents in the tank included 30 ppm of mineral oil, 9 uL of Titron X-100 (surfactant), and 2.5 g of PAC. The tank was aerated with laboratory compressed air using an aeration stone to ensure mixing throughout the solution. Initial turbidity and COD measurements were taken prior to starting the 4 hour run. The wastewater was pumped from the tank to the membrane where the PAC and mineral oil were separated by the membrane. The water that passed through the membrane left the MBR as effluent. An effluent sample was taken to measure mineral oil removal, COD, and turbidity. This was done for a no carbon baseline and all six types of PAC: WPX, WPX-Z, Pulsorb WP260-90, WPH-W, WPH-1000, and WPH.

Results from the laboratory experiments indicated that PAC was compatible with the MBR and produced positive performance when removing mineral oil. The Pulsorb WP260-90 showed high COD removal and turbidity improvement. Additionally, the experiments with Pulsorb WP260-90 operated with better average transmembrane pressure than the baseline. This suggests that it has less risk of fouling than a system with no PAC. WPH and WPH-1000 also resulted in acceptable COD and turbidity removal but a resulted in higher TMP than the baseline, indicating a greater risk of fouling. The effluent from a baseline experiment and the effluent from the experiment employing WPX were both sent to an outside lab to measure oil removal. The results of this fats, oils, and grease (FOG) test showed that the baseline run effluent contained 27 ppm of mineral oil, and the experiment with WPX produced effluent that contained 2 ppm of mineral oil. From this FOG measurement, we can infer that the addition of PAC to a membrane process could increase oil removal.

There were several limitations that may have affected our results. Oil often adhered to containers and instruments, resulting in a loss of oil that prevented accurate measurements. When measuring turbidity and COD, the presence of sludge in the samples may have negatively impacted initial measurements. This could have led to inaccurate removal percentages. Another limitation was that the final effluent from different runs were exposed to the membrane and PAC for varying amounts of time, due to the fact that some runs took a longer time than others to fill the sample container. Also, the variation in MLSS concentration for each run may have affected the transmembrane pressure and/or the percent removal of COD and turbidity. Based on the data collected, it was found that PACs have promise for oil removal when coupled with MBRs for industrial wastewater treatment. Using the PAC results, a car wash water reuse system was designed.

An environmental justice analysis was conducted to determine whether pollution from car washes was resulting in an environmental injustice. Based on the location of a number car washes near the border of environmental justice communities and the high density of water bodies throughout the state, it was determined that environmental justice issues are a possibility. However, due to the lack of reporting on oil contamination in drinking water treatment facilities and the appearance of new uncertainties, the results were found to be indefinite.

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Appendix I: Membrane Bioreactor Runs

Table 6. MBR Run with No Carbon (1)

Time (min)	Temp	Permeate Pressure	Air Pressure	Feed Pressure	TMP
0 min	20.8	0	5.5	0	0
5	21	0	5.4	0	0
10	21.3	0	5.4	0	0
15	21.5	0	5.1	0	0
20	21.7	0	5.1	0	0
25	22	0	5.5	0	0
30	22.1	0	5.5	0	0
35	22.3	0	5.5	0	0
40	22.4	0	5.4	0	0
45	22.5	0	5.4	0	0
50	22.6	0	5.3	0	0
55	22.7	0	5.2	0	0
60	22.8	0	5.1	0	0
65	22.9	0	5.1	0	0
70	23	0	5.1	0	0
75	23.1	0	5	0	0
80	23.2	0	5	0	0
85	23.4	0	5	0	0
90	23.4	0	5	0	0
95	23.5	0	4.9	0	0
100	23.6	0	5.5	0	0
105	23.7	0	5.8	0	0
110	23.7	0	5.8	0	0
115	23.8	0	5.8	0	0
120	23.8	0	5.6	0	0
125	23.9	0	5.6	0	0

130	24	0	5.6	0	0
135	24.1	0	5.5	0	0
140	24.1	0	5.5	0	0
145	24.2	0	5.45	0	0
150	24.3	0	5.4	0	0
155	24.3	0	5.4	0	0
160	24.4	0	5.4	0	0
165	24.4	0	5.3	0	0
170	24.5	0	5.2	0	0
175	24.6	0	5.2	0	0
180	24.6	0	5.1	0	0
185	24.6	0	5.1	0	0
190	24.6	0	5.1	0	0
195	24.7	0	5.1	0	0
200	24.7	0	5.1	0	0
205	24.7	0	5.1	0	0
210	24.7	0	5	0	0
215	24.7	0	5	0	0
220	24.7	-0.5	5	0	0.5
225	24.7	-1	5	0	1
230	24.7	-1	5	0	1
235	24.6	-1	5	0	1
240	24.6	-1	5	0	1

Table 7. MBR Run with No Carbon (2)

Time (min)	Temp	Permeate Pressure	Air Pressure	Feed Pressure	TMP
0	12.9	-0.5	5.25	0	0.5
5	13.8	-1	5.75	0	1

10	14.3	-1	5.25	0	1
15	14.9	-1	5.1	0	1
20	15.4	-2.5	5.25	0	2.5
25	16	-3	5.2	0	3
30	16.5	-3	5.9	0	3
35	16.9	-3	5.9	0	3
40	17.3	-4.1	5.6	0	4.1
45	17.7	-4.1	5.5	0	4.1
50	18.1	-4.5	5.5	0	4.5
55	18.1	-4.7	5.5	0	4.7
60	18.4	-4.9	5.4	0	4.9
65	18.6	-4.8	5.8	0	4.8
70	18.9	-5	5.7	0	5
75	19.2	-5	5.5	0	5
80	19.4	-5	5.5	0	5
85	19.6	-5	5.4	0	5
90	19.8	-5	5.4	0	5
95	20.1	-5	5.4	0	5
100	20.2	-5	5.4	0	5
105	20.4	-5	5.3	0	5
110	20.6	-5	5.2	0	5
115	20.8	-5	5.1	0	5
120	21	-5	5.1	0	5
125	21.2	-5	5.1	0	5
130	21.3	-5	5.1	0	5
135	21.5	-5	5	0	5
140	21.7	-5	5	0	5
145	21.8	-5	5	0	5
150	21.9	-5	5	0	5
155	22.1	-5.1	5	0	5.1

160	22.2	-5.3	5.8	0	5.3
165	22.3	-5.2	5.3	0	5.2
170	22.4	-5.1	5.3	0	5.1
175	22.7	-5.1	5.1	0	5.1
180	22.8	-5.1	5.1	0	5.1
185	22.8	-5.1	5.1	0	5.1
190	22.9	-5.1	5.1	0	5.1
195	22.9	-5.6	5.1	0	5.6
200	23.1	-5	5	0	5
205	23.1	-4.1	5	0	4.1
210	23.3	-4	5	0	4
215	23.3	-4	5	0	4
220	23.4	-4	5.8	0	4
225	23.5	-4	5.8	0	4
230	23.6	-4	5.7	0	4
235	23.6	-4	5.7	0	4
240	23.7	-4	5.7	0	4

Table 8. MBR Run with WPX Carbon *Run with 27g of carbon

Time (min)	Temp	Permeate Pressure	Air Pressure	Feed Pressure	TMP
0	22.6	0	5.5	0	0
5	-	-	-	-	0
10	-	-	-	-	0
15	-	-	-	-	0
20	22.6	-2	5.5	0	2
25	22.7	-2	5.5	0	2
30	22.8	-2	5.5	0	2
35	22.9	-2	5.5	0	2

40	23	-2	5.5	0	2
45	23.1	-2	5.4	0	2
50	23.2	-2	5.2	0	2
55	23.3	-2	5.1	0	2
60	23.4	-2	5.1	0	2
65	23.5	-2	5.1	0	2
70	23.5	-2	5.1	0	2
75	23.6	-2	5	0	2
80	23.7	-2	5	0	2
85	23.8	-2	5.3	0	2
90	23.8	-2	5.2	0	2
95	24	-2	5.1	0	2
100	24	-2	5.1	0	2
105	24.1	-2	5.1	0	2
110	24.1	-2	5.1	0	2
115	24.2	-2	5.1	0	2
120	24.2	-2	5	0	2
125	24.2	-2	5	0	2
130	24.3	-2	5	0	2
135	24.4	-2	5	0	2
140	24.4	-2	5.8	0	2
145	24.4	-2	5.8	0	2
150	24.5	-2	5.8	0	2
155	24.6	-2	5.7	0	2
160	24.6	-2	5.7	0	2
165	24.6	-2	5.7	0	2
170	24.7	-2	5.7	0	2
175	24.7	-2	5.7	0	2
180	24.7	-2	5.7	0	2
185	24.8	-2	5.6	0	2

190	24.8	-2	5.6	0	2
195	24.8	-2	5.5	0	2
200	24.8	-2	5.5	0	2
205	24.8	-2	5.5	0	2
210	24.9	-2	5.6	0	2
215	24.9	-2	5.6	0	2
220	24.9	-2	5.6	0	2
225	24.9	-2	5.6	0	2
230	24.9	-2	5.6	0	2
235	24.9	-2	5.6	0	2
240	24.9	-2	5.5	0	2

Table 9. MBR Run with WPX Carbon

Time (min)	Temp	Permeate Pressure	Air Pressure	Feed Pressure	TMP
0	13.6	-1	5.5	0	1
5	14.7	-1	5.1	0	1
10	15.4	-1	4.8	0	1
15	15.9	-1	5.7	0	1
20	16.6	-0.5	5.5	0	0.5
25	17	0	5.5	0	0
30	17.5	-0.5	5.4	0	0.5
35	17.8	0	5.4	0	0
40	18	-0.5	5.25	0	0.5
45	18.3	-2.5	5.75	0	2.5
50	18.6	-2.5	5.75	0	2.5
55	18.9	-3	5.75	0	3
60	19.1	-3.5	5.5	0	3.5
65	19.3	-3	5.5	0	3

70	19.6	-3	5.5	0	3
75	19.8	-3	5.5	0	3
80	20	-3	5.5	0	3
85	20.2	-3	5.5	0	3
90	20.4	-3	5.4	0	3
95	FEED PRESSURE VIOLENTLY SHAKING, TRIED TO ADJUST TO CREATE LESS PRESSURE FOR PUMP				0
100					0
105	21	-3	5		3
110	21.1	-3	5.9		3
115	21.4	-3	5.8	0	3
120	21.5	-3	5.8	0	3
125	21.7	-3	6	0	3
130	21.8	-3	6	0	3
135	22	-3	5.9	0	3
140	22.1	-3	6	0	3
145	22.3	-3	6	0	3
150	22.4	-3	6	0	3
155	22.5	-3	5.9	0	3
160	22.7	-3.2	5.9	0	3.2
165	22.8	-3.2	5.9	0	3.2
170	22.9	-3.1	5.9	0	3.1
175	23	-3	6	0	3
180	23.1	-3	5.9	0	3
185	23.3	-3	6	0	3
190	23.3	-3	5.9	0	3
195	23.5	-3	6	0	3
200	23.6	-3	5.8	0	3
205	23.7	-3.2	5.9	0	3.2
210	23.7	-3.2	5.9	0	3.2

215	38.8	-3.2	5.9	0	3.2
220	23.9	-3.1	6	0	3.1
225	24	-3	6	0	3
230	24.1	-3	6	0	3
235	24.2	-3	5.9	0	3
240	24.2	-3	6	0	3

Table 10. MBR Run with WPH-1000 Carbon

Time (min)	Temp	Permeate Pressure	Air Pressure	Feed Pressure	TMP
0	13.9	-1	5.5	0	1
5	14.4	-1	5.1	0	1
10	15.2	-2	5.2	0	2
15	15.6	-2	5.7	0	2
20	16.1	-4	5.7	0	4
25	16.5	-4	5.6	0	4
30	17.1	-4	5.6	0	4
35	17.5	-4	5.5	0	4
40	17.8	-4	5.5	0	4
45	18.1	-4	5.4	0	4
50	18.3	-4.5	5.4	0	4.5
55	18.6	-4.7	5.3	0	4.7
60	18.8	-4.7	5.2	0	4.7
65	19	-4.8	5.1	0	4.8
70	19.2	-4.8	6	0	4.8
75	19.4	-4.8	5	0	4.8
80	19.6	-4.9	5.5	0	4.9
85	19.8	-4.9	5.4	0	4.9
90	20	-5	5.3	0	5

95	20.2	-5	5.4	0	5
100	20.4	-5.3	5.3	0	5.3
105	20.6	-5.5	5.3	0	5.5
110	20.8	-5.6	5.2	0	5.6
115	21	-5.8	5.1	0	5.8
120	21.2	-5.8	5.6	0	5.8
125	21.3	-5.9	5.6	0	5.9
130	21.4	-5.9	5.7	0	5.9
135	21.6	-5.9	5.7	0	5.9
140	21.7	-5.9	5.7	0	5.9
145	21.9	-5.9	5.7	0	5.9
150	22	-5.9	5.7	0	5.9
155	22.1	-5.9	5.7	0	5.9
160	22.3	-5.9	5.6	0	5.9
165	22.3	-5.9	5.6	0	5.9
170	22.5	-5.9	5.6	0	5.9
175	22.6	-5.8	5.6	0	5.8
180	22.7	-5.9	5.6	0	5.9
185	22.8	-5.9	5.6	0	5.9
190	22.9	-5.9	5.5	0	5.9
195	23	-5.9	5.6	0	5.9
200	23.1	-5.9	5.6	0	5.9
205	23.2	-5.9	5.6	0	5.9
210	23.3	-5.9	5.5	0	5.9
215	23.5	-5.9	5.6	0	5.9
220	23.6	-6	5.6	0	6
225	23.6	-6	5.6	0	6
230	23.8	-6	5.6	0	6
235	23.9	-6	5.6	0	6
240	24	-6	5.6	0	6

Table 11. MBR Run with WPX-Z Carbon

Time (min)	Temp	Permeate Pressure	Air Pressure	Feed Pressure	TMP
0	13.6	-1	5.5	0	1
5	14.3	-1	5.75	0	1
10	14.3	-1.6	5.4	0	1.6
15	14.7	-1.9	5	0	1.9
20	15.3	-4	5	0	4
25	15.9	-4	6	0	4
30	16.5	-4	5.8	0	4
35	17.2	-4	5.5	0	4
40	17.5	-4	5.6	0	4
45	17.8	-4.1	5.4	0	4.1
50	18.1	-4.1	5.5	0	4.1
55	18.4	-4.1	5.1	0	4.1
60	18.6	-4.1	6	0	4.1
65	18.8	-4.1	6	0	4.1
70	19.1	-4.1	6	0	4.1
75	19.3	-4.1	5.5	0	4.1
80	19.5	-4.1	5.6	0	4.1
85	19.7	-4	5.4	0	4
90	20	-4	5.4	0	4
95	20.2	-4	5.5	0	4
100	20.3	-4	5.1	0	4
105	20.5	-4	6	0	4
110	20.7	-4	5.9	0	4
115	20.8	-4	6	0	4

120	21	-4	6.1	0	4
125	21.1	-4.5	5.2	0	4.5
130	21.3	-4.5	5.2	0	4.5
135	21.5	-4.5	5.1	0	4.5
140	21.7	-4.5	5.2	0	4.5
145	21.8	-4.5	5.1	0	4.5
150	21.9	-4.5	5.1	0	4.5
155	22	-4.5	5.1	0	4.5
160	22.2	-4.5	4.9	0	4.5
165	22.2	-4.5	5.9	0	4.5
170	22.3	-4.5	5.7	0	4.5
175	22.5	-4.5	6	0	4.5
180	22.5	-4.5	5.8	0	4.5
185	22.6	-4.5	5.8	0	4.5
190	22.7	-4.5	6	0	4.5
195	22.8	-4.5	5.6	0	4.5
200	22.9	-4.5	5.7	0	4.5
205	23	-4.5	6	0	4.5
210	23	-4.5	5.5	0	4.5
215	23.1	-4.5	5.9	0	4.5
220	23.2	-4.5	5.5	0	4.5
225	23.3	-4.5	5.4	0	4.5
230	23.3	-4.5	5.5	0	4.5
235	23.4	-4.5	5.7	0	4.5
240	23.4	-4.5	5.4		4.5

Table 12. MBR Run with WPH Carbon

Time (min)	Temp	Permeate Pressure	Air Pressure	Feed Pressure	TMP

0	12.9	0	5.5	0	0
5	13.7	-1	5.6	0	1
10	14.4	-1	5.5	0.5	1.5
15	14.8	-1	5	0.5	1.5
20	15.3	-1	5.6	0.5	1.5
25	15.7	-1	5.5	0.5	1.5
30	16.1	-1.5	5.5	0.5	2
35	16.3	-1.7	5.5	0.5	2.2
40	17	-4.5	5.5	0	4.5
45	17.5	-4.5	5.4	0	4.5
50	17.8	-4.5	5.4	0	4.5
55	18.1	-4.5	5.4	0	4.5
60	18.4	-4.5	5.3	0.5	5
65	18.6	-4.5	5.3	0.5	5
70	18.8	-4.5	5.8	0.75	5.25
75	19	-4.5	6	0.75	5.25
80	19.2	-4.5	5.8	0.75	5.25
85	19.3	-4.5	5.8	0.75	5.25
90	19.5	-4.5	5.8	0.75	5.25
95	19.6	-4.5	5.8	0.75	5.25
100	19.7	-4.5	5.8	0.75	5.25
105	19.9	-4.5	5.75	0.75	5.25
110	20	-4.5	5.75	0.75	5.25
115	20.1	-5	5.6	0.75	5.75
120	20.2	-5	5.75	0.75	5.75
125	20.4	-5	5.6	0.75	5.75
130	20.5	-5	5.6	0.75	5.75
135	20.6	-5	5.6	0.75	5.75
140	20.7	-5	5.6	0.75	5.75
145	20.7	-5	5.5	0.75	5.75

150	20.9	-5	5.5	0.75	5.75
155	20.9	-5	5.5	0.75	5.75
160	21	-5	5.5	0.8	5.8
165	21.1	-5	5.5	0.8	5.8
170	21.1	-5	5.5	0.8	5.8
175	21.2	-5	5.5	0.8	5.8
180	21.3	-5	5.4	0.8	5.8
185	21.4	-5	5.4	0.8	5.8
190	21.4	-5	5.4	0.8	5.8
195	21.5	-5	5.6	0.8	5.8
200	21.5	-5	5.1	0.8	5.8
205	21.6	-5	5.4	0.8	5.8
210	21.6	-5	5.4	0.8	5.8
215	21.7	-5	5.5	0.8	5.8
220	21.7	-5	5.5	0.8	5.8
225	21.7	-5	5.9	0.8	5.8
230	21.7	-5	5.7	0.8	5.8
235	21.8	-5	6	1	6
240	21.8	-5	5	1	6

Table 13. MBR Run with Pulsorb WP260-90 Carbon

Time (min)	Temp	Permeate Pressure	Air Pressure	Feed Pressure	TMP
0	17	-1	5.5	0	1
5	20.8	-2	5.6	0	2
10	18.3	-2	5.6	0	2
15	17.9	-2.5	5.5	0	2.5
20	18.5	-3	5.5	0.25	3.25
25	18.7	-3.5	5.3	0.25	3.75

30	19	-3.5	5.1	0.25	3.75
35	19.3	-3.5	5.1	0.25	3.75
40	19.5	-3.5	5	0.25	3.75
45	19.8	-3.75	5.6	0.25	4
50	20.1	-3.75	5.7	0.25	4
55	20.4	-3.9	5.6	0.25	4.15
60	20.6	-4	5.6	0.25	4.25
65	20.9	-4	5.5	0.5	4.5
70	21.1	-4	5.6	0.5	4.5
75	21.4	-4	5.5	0.5	4.5
80	21.5	-4	5.5	0.5	4.5
85	21.7	-4	5.3	0.5	4.5
90	21.9	-4	5.5	0.5	4.5
95	22.1	-4	5.3	0.5	4.5
100	22.3	-4	5.4	0.5	4.5
105	22.4	-4	5.2	0.5	4.5
110	22.6	-4	5.8	0.5	4.5
115	22.7	-4	5.8	0.5	4.5
120	22.8	-4	5.7	0.5	4.5
125	22.9	-4	4.8	0.5	4.5
130	23.1	-4	5.7	0.5	4.5
135	23.1	-4	5.6	0.5	4.5
140	23	-4	5.6	0.5	4.5
145	23.2	-4	5.5	0.5	4.5
150	23.3	-4	5.6	0.5	4.5
155	23.4	-4	5.6	0.5	4.5
160	23.5	-4	5.5	0.5	4.5
165	23.5	-4	5.6	0.5	4.5
170	23.7	-4	5.6	0.5	4.5
175	23.7	-4	5.5	0.5	4.5

180	23.8	-4	5.5	0.5	4.5
185	23.9	-4	5.5	0.5	4.5
190	24	-4	5.5	0.5	4.5
195	24.1	-4	5.4	0.5	4.5
200	24.1	-4	5.4	0.5	4.5
205	24.2	-4	5.4	0.5	4.5
210	24.2	-4	5.5	0.5	4.5
215	24.3	-4	5.4	0.5	4.5
220	24.4	-4	5.3	0.5	4.5
225	24.5	-4	5.3	0.5	4.5
230	24.5	-4	5.3	0.5	4.5
235	24.6	-4	5.4	0.5	4.5
240	24.7	-4	5.2	0.5	4.5

Table 14. MBR Run with WPH Carbon

Time (min)	Temp	Permeate Pressure	Air Pressure	Feed Pressure	TMP
0	14.8	-1	5.5	0	1
5	14.8	-1	5.5	0.25	1.25
10	15.5	-1	5.7	0.5	1.5
15	16.1	-1	6	0.5	1.5
20	16.5	-1	5.6	0.5	1.5
25	17.2	-1	5.7	0.5	1.5
30	17.6	-1	5.9	0	1
35	17.9	-1	5.9	0	1
40	18.3	-0.5	5.5	0	0.5
45	18.5	-1	6	0	1
50	19	-1	5.6	0	1
55	19.1	-1	5.7	0	1

60	19.4	-1	5.5	0.25	1.25
65	19.7	-1.1	5.6	0.25	1.35
70	20	-1.5	5.5	0	1.5
75	20.3	-1.5	5.1	0.25	1.75
80	20.5	-1.7	5.4	0.25	1.95
85	20.8	-2	5	0	2
90	21	-2	6	0	2
95	21.3	-3	5.5	0.25	3.25
100	21.5	-3	5.7	0.25	3.25
105	21.8	-3.25	5.6	0.25	3.5
110	21.9	-3.25	5.5	0.25	3.5
115	22.1	-3.25	5.1	0.25	3.5
120	22.3	-3.5	5.2	0.25	3.75
125	22.5	-3.5	5.1	0.25	3.75
130	22.6	-3.5	5.4	0.25	3.75
135	22.8	-3.5	5	0.25	3.75
140	22.9	-3.5	5.4	0.25	3.75
145	23.1	-3.5	5.9	0.25	3.75
150	23.2	-3.5	5.1	0.25	3.75
155	23.4	-3.5	5	0.25	3.75
160	23.6	-3.5	5.4	0.25	3.75
165	23.7	-3.5	5.2	0.25	3.75
170	23.8	-3.5	5	0.25	3.75
175	24	-3.5	5.1	0.25	3.75
180	24.1	-3.75	5.3	0.25	4
185	24.2	-3.75	4.9	0.25	4
190	24.3	-4	6	0.25	4.25
195	24.4	-4	5.6	0.25	4.25
200	24.6	-4	5.6	0.25	4.25
205	24.6	-4	6	0.25	4.25

210	24.7	-4	5.6	0.25	4.25
215	24.8	-4	5.9	0.25	4.25
220	24.9	-4	5.9	0.25	4.25
225	25	-4	5.8	0.25	4.25
230	25.1	-4	5.5	0.25	4.25
235	25.1	-4	5.9	0.25	4.25
240	25.2	-4	5.5	0.25	4.25

Appendix II: Hexane Extraction Method Measurements/Calculations

$$Density\ of\ mineral\ oil\ = 850\frac{mg}{L}$$

$$20\ ppm = 20\frac{mg}{L}\times 0.35L = 7\ mg$$

$$\frac{7\ mg}{850\frac{mg}{L}} = 8.235\ \mu L\ of\ mineral\ oil$$

$$10\ ppm = 10\frac{mg}{L}\times 0.35L = 3.5\ mg$$

$$\frac{3.5mg}{850\frac{mg}{L}} = 4.117\ \mu L\ of\ mineral\ oil$$

$$5\ ppm = 5\frac{mg}{L}\times 0.35L = 1.75\ mg$$

$$\frac{1.75\ mg}{850\frac{mg}{L}} = 2.059\ \mu L\ of\ mineral\ oil$$

$$Oil\ Remaining = \frac{Sum\ of\ Differences}{850\frac{mg}{L}}\times\frac{1000\ mg}{1\ g}$$

Table 15. Hexane Extraction Method Data

Dish Number	Ppm (mg/L)	Initial Mass (g)	Final Mass (g)	Mass Difference	Sum of Differences	Oil Remaining
1	10.00	111.10	111.10	0.00	0.00	0.00
2	10.00	111.00	111.00	0.00		
3	10.00	109.90	109.90	0.00		
1	10.00	111.13	111.16	0.03	0.06	0.07
2	10.00	111.08	111.10	0.02		
3	10.00	109.98	109.99	0.01		
1	10.00	21.68	21.69	0.01	0.01	0.01
2	10.00	25.94	25.94	0.00		
3	10.00	21.45	21.46	0.00		
1	10.00	21.65	21.67	0.02	0.02	0.02
2	10.00	25.62	25.62	0.00		

3	10.00	21.45	21.45	0.00		
1	10.00	21.41	21.42	0.01	0.01	0.01
2	10.00	21.57	21.57	0.00		
3	10.00	21.32	21.32	0.00		
1	10.00	59.89	59.91	0.02	0.02	0.02
2	10.00	57.29	57.29	0.00		
3	10.00	61.37	61.37	0.00		
1	20.00	51.54	51.55	0.02	0.07	0.08
2	20.00	54.73	54.74	0.05		
3	20.00	50.28	50.28	0.00		
1	20.00	54.77	54.78	0.01	0.02	0.02
2	20.00	48.49	48.49	0.01		
3	20.00	49.63	49.64	0.00		
1	20.00	2.35	2.35	0.00	0.00	0.01
2	20.00	2.36	2.36	0.00		
3	20.00	2.37	2.37	0.00		
1	20.00	2.34	2.35	0.02	0.03	0.03
2	20.00	2.34	2.34	0.00		
3	20.00	2.35	2.36	0.01		
1	20.00	2.36	2.37	0.01	0.01	0.02
2	20.00	2.34	2.35	0.01		
3	20.00	2.35	2.34	-0.01		
1	20.00	2.34	2.34	0.00	0.00	0.00
2	20.00	2.32	2.32	0.00		
3	20.00	2.36	2.36	0.00		

Appendix III: MLSS Concentration Calculations

$$MLSS\ Concentration = \frac{Final\ Mass - Initial\ Mass}{Volume\ of\ Sludge}$$

Table 16. MLSS Concentration Data

Carbon	Dish Number	Initial Mass(g)	Volume of Sludge (mL)	Final Mass (g)	Mass Difference	MLSS Conc. (g/L)	Avg. MLSS Conc. (g/L)
WPX-Z	1	2.4829	5	2.5138	0.0309	6.18	6.22
	2	2.4275	5	2.4588	0.0313	6.26	
WPH	1	2.4511	5	2.4864	0.0353	7.06	7
	2	2.4386	5	2.4733	0.0347	6.94	
WP260-90	1	2.451	5	2.4885	0.0375	7.5	7.72
	2	2.4365	5	2.4762	0.0397	7.94	
WPX	1	2.4366	5	2.4805	0.0439	8.78	8.74
	2	2.4504	5	2.4939	0.0435	8.7	
WPH-W	1	2.4393	5	2.4819	0.0426	8.52	8.56
	2	2.4616	5	2.5046	0.043	8.6	
WPH-1000	1	2.445	5	2.4612	0.0162	3.24	6.94
	2	2.445	5	2.4982	0.0532	10.64	
Baseline	1	2.4376	5	2.4809	0.0433	8.66	8.6
	2	2.4519	5	2.4946	0.0427	8.54	

Appendix IV: Carwash Flow Rate

Water use =	37	gal/car
Average amount of cars =	110	cars/day
Assumed Leakage =	10	%
Average Daily Demand (ADD) =	4477.0	gal/day
2 trains, one active at a time		

$$\text{Number of Cars} \times \text{Usage per Car} = \text{demand}$$

$$37\ \frac{\text{gal}}{\text{car}} \times 110\frac{\text{cars}}{\text{day}} = \text{Q} = 4{,}070\ \text{gpd}$$

Assumed Daily Demand (ADD)

$$\text{Q} \times 1.1\ \text{leakage} = \text{ADD}$$

$$4{,}070\ \text{gpd} \times 1.1\ \text{leakage} = \mathbf{4,477\ gpd}$$

Appendix V: Settling Tank

Flow rate (per train) =	4477.0	gal/day
HLR =	150.0	GPD/ft^2
Area =	29.8	ft^2
Time =	1	hr
Volume =	1395.33	gal
Volume =	186.54	ft^3
Depth =	6.25	ft
Length =	9.46	ft
Width =	3.15	ft
Material =	Steel	

$$\text{Q} \times \text{Loading Rate} = \text{Tank Area}$$

$$4{,}447\ \text{gpd} \times 150\ \frac{\text{gpd}}{\text{ft}^2} = 29.8\ \text{ft}^2$$

$$\frac{\text{Area} \times \text{Depth}}{\text{Q}} = \text{Detention Time}$$

$$\frac{29.8\ \text{ft}^2 \times \text{Depth}}{\left(4477.0\ \frac{\text{gal}}{\text{day}} \div 24\,\frac{\text{day}}{\text{hrs}}\right)} = 1\ \text{hrs}$$

$$\mathbf{Depth = 6.25\ ft}$$

$$3\text{x}^2 = 29.8\ \text{ft}^2$$

$$\text{x} = \mathbf{3.15\ ft = width}$$

$$3\text{x} = \text{length}$$

$$3 \times 3.15 = \mathbf{9.46\ ft = length}$$

$$\text{Surface Area} \times \text{Depth} = \text{Volume}$$

$$29.8\ \text{ft}^2 \times 6.25\ \text{ft} = 186.25\ \text{ft}^3 = \mathbf{1,395.33\ gal}$$

Appendix VI: Initial and Final Storage Tank

Volume =	4500.0	gal
Volume =	601.60	ft^3
Depth =	8.44	ft
Length =	8.44	ft
Width =	8.44	ft
Material =	Steel	

$$\sqrt[3]{\mathrm{Volume}} = \mathrm{Depth, Length, Width}$$

$$\sqrt[3]{601.60\mathrm{ft}^3} = \mathrm{Depth, Length, Width} = \mathbf{8.44\ ft}$$

Appendix VII: Membrane Tank

Tank:

Flow rate (per train) =	4477.0	gal/day
Time =	4	hr
Volume =	746.17	gal
Volume =	99.75	ft^3
Depth =	8.00	ft
Length =	4.16	ft
Width =	3.00	ft
Material =	Steel	

$$\text{Q} \times \text{Detention Time} = \text{Volume}$$

$$4477 \text{ gpd} \times 4 \text{ hr} \times \frac{\text{day}}{24 \text{ hr}} = \text{Volume} = 746.17 \text{ gal} = \mathbf{99.75\ ft^3}$$

Depth and width were chosen based on the membrane model's dimensions, Length was calculated

$$\text{Volume} \div (\text{Depth} \times \text{Width}) = \text{Length}$$

$$99.75 \text{ ft}^3 \div (8 \text{ ft} \times 3 \text{ ft}) = \mathbf{4.16\ ft}$$

Membrane:

Model =	PSH 31HD	
Length =	3.62	in
Width =	32.6	in
Height =	71.69	in
Area/unit =	330.00	ft^2
Area/unit =	30.66	m^2
Number of units =	1	
Permeate Flux =	25	LMH
Permeate Flux =	14.7	gfd
Permeate Flow =	4852.94	gpd
Fibers (280/column) =	2520	
Air Scour Rate per Area =	44.67	$scfh/m^2$
Air Scour Rate =	1369	scfh

$$\text{Permeate Flux} \times \text{Membrane Area} = \text{Permeate Flow}$$

$$25\ \text{lmh} \times 330\ \text{ft}^2 \times \frac{\text{gpd}}{1.7\ \text{lmh}} = \text{Permeate Flow} = \mathbf{4852.94\ gpd}$$

$$\text{Air Scour Rate per Area} \times \text{Membrane Area} = \text{Air Scour Rate}$$

$$44.67 \frac{\text{scfh}}{\text{m}^2} \times 30.66\ \text{m}^2 = \text{Air Scour Rate} = \mathbf{1369\ scfh}$$

PAC:

Flow rate (per train) =	16947.28	L/day
PAC Dose =	463	ppm
PAC Amount =	7846.59	g/day

$$\text{PAC Dosage} \div \text{Flow Rate} = \text{PAC amount}$$

$$463\ \text{ppm} = \frac{463\ \text{g}_{\text{PAC}}}{1{,}000{,}000\ \text{g}_{\text{H2O}}} \times 4477\text{gpd} \times \frac{3.79\ \text{L}}{\text{gal}} \times \frac{1{,}000\ \text{g}_{\text{H2O}}}{\text{L}} = \text{PAC amount}$$
$$= \mathbf{7846.59\ g/day}$$

Appendix VIII: Pipes

Pipes to Trains		
Velocity =	1.5	ft/s
Area =	1.6	in^2
Diameter =	1.4	in
Nominal Pipe Size =	1-1/2	
Schedule =	80	
Actual internal diameter =	1.50	in
Length =	18.5	ft
Material =	Steel	

Pipes from Settling to Membrane		
Velocity =	1.5	ft/s
Area =	1.6	in^2
Diameter =	1.4	in
Nominal Pipe Size =	1-1/2	
Schedule =	80	
Actual internal diameter =	1.50	in
Length =	1.0	ft
Material =	Steel	

Pipes from Membrane to Water storage		
Velocity =	1.5	ft/s
Area =	1.6	in^2
Diameter =	1.4	in
Nominal Pipe Size =	1-1/2	
Schedule =	80	
Actual internal diameter =	1.50	in
Length =	18.5	ft
Material =	Steel	

$$\mathrm{Q} \div \mathrm{Velocity} = \mathrm{Area}$$

$$\left(4477\frac{\mathrm{gal}}{10\ \mathrm{hr}} \times \frac{\mathrm{ft}^3}{7.48\ \mathrm{gal}}\right) \div \left(1.5\ \frac{\mathrm{ft}}{\mathrm{s}} \times \frac{3600\ \mathrm{s}}{\mathrm{hr}}\right) \times \frac{144\ \mathrm{in}^2}{\mathrm{ft}^2} = \mathrm{Area} = 1.6\ \mathrm{in}^2$$

Appendix IX: Pumps

The same type of pump was used from the initial storage tank to the settling tank and the membrane tank to the final storage tank as they had the same static head and the friction heads were similar.

Pumps:

Static head =	8.5	ft
Hazen-Williams roughness constant (c) =	100	
Friction head loss per 100 ft of pipe =	0.24	ft/100 ft
Friction loss from pipe =	0.0024	ft/ ft
Friction loss from pipe =	0.044	ft
Friction of fittings vs friction of pipe =	30	%
Friction loss from fittings =	0.013	ft
Friction head =	0.057	ft
Total head =	8.56	ft
Total head =	2.61	m
Flow capacity =	0.71	m^3/hr
Density of water =	1000	kg/m^3
Gravity =	9.81	m/s^2
Theoretical minimum power required =	0.005	kW
Pump efficiency =	0.6	
Minimum power required =	0.008	kW
Minimum power required =	0.011	HP
Power of pump =	0.75	HP
Power =	0.56	kW
Operation time =	10	hours
Energy demand =	5.60	kWh

$$\frac{0.2083\left(\frac{100}{\mathrm{c}}\right)^{1.852}\mathrm{Q}^{1.852}}{\text{Pipe Diameter}^{4.8655}}=\text{Friction head loss per 100 ft of pipe}$$

$$\frac{0.2083\left(\frac{100}{100}\right)^{1.852}\left(4477\text{ gpd}\times\frac{\text{day}}{1440\text{ min}}\right)^{1.852}}{1.5^{4.8655}\text{ in}}=\text{Friction head loss}$$

$$=\mathbf{0.24\ ft\ per\ 100\ ft\ pipe}$$

$$\text{Friction head loss per 100 ft of pipe }\div 100\times\text{Length of pipe}=\text{Friction loss from pipe}$$

$$0.24\text{ ft per 100 ft pipe }\div 100\times 18.5\text{ ft}=\text{Friction loss from pipe}=\mathbf{0.044\ ft}$$

$$\text{Friction loss from pipe} \times 30\% = \text{Friction loss from fittings}$$

$$0.044\ \text{ft} \times 30\% = \text{Friction loss from fittings} = \mathbf{0.013\ ft}$$

$$\text{Friction loss from pipe} + \text{friction loss from fittings} = \text{Friction head}$$

$$0.044\ \text{ft} + 0.013\ \text{ft} = \text{Friction head} = \mathbf{0.057\ ft}$$

$$\text{Static Head} + \text{Friction Head} = \text{Total Head}$$

$$8.50\ \text{ft} + 0.057\ \text{ft} = \text{Total Head} = \mathbf{8.56\ ft}$$

$$\frac{\text{Flow capacity} \times \text{Water density} \times \text{Gravity} \times \text{Total Head}}{3.6 \times 10^6} = \text{Power}_{\text{theoretical}}$$

$$\frac{0.71\ \left(\frac{\text{m}^3}{\text{hr}}\right) \times 1000\ \left(\frac{\text{kg}}{\text{m}^3}\right) \times 9.81\ \left(\frac{\text{m}}{\text{s}^2}\right) \times 8.56\ \text{ft} \times \left(\frac{1\text{m}}{3.28\ \text{ft}}\right)}{3.6 \times 10^6} = \text{Power}_{\text{theoretical}}$$

$$= \mathbf{0.005 kW}$$

$$\frac{\text{Power}_{\text{theoretical}}}{\text{Pump}_{\text{efficiency}}} = \text{Power}_{\text{required}}$$

$$\frac{0.005\ \text{kW}}{0.6} = \text{Power}_{\text{required}} = \mathbf{0.008\ kW}$$

$$\text{Power} \times \text{Operation time} = \text{Energy demand}$$

$$0.75\ \text{HP} \times \frac{0.746\ \text{kW}}{\text{HP}} \times 10\ \text{hr} = \text{Energy demand} = \mathbf{5.60\ kWh}$$