THESIS

STORMWATER TREATMENT STRATEGY FOR THE DEGRADATION OF AIRCRAFT DEICING FLUID AT THE JOINT BASE ELMENDORF-RICHARDSON IN ANCHORAGE, ALASKA

Submitted by

Martha Liliana Nunez Hernandez

Department of Civil and Environmental Engineering

In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Spring 2017

Master's Committee:

Advisor: Kenneth Carlson

Sybil Sharvelle
Matthew Kipper

ABSTRACT

STORMWATER TREATMENT STRATEGY FOR THE DEGRADATION OF AIRCRAFT DEICING FLUID AT THE JOINT BASE ELMENDORF-RICHARDSON IN ANCHORAGE, ALASKA

Due to the large volumes of aircraft deicing fluids (ADF) applied by U.S. commercial airports during winter months, stricter pollution control by regulatory agencies has been implemented. Agencies such as the Environmental Protection Agency (EPA), have made several attempts to improve stormwater management practices in airports which has resulted in a decrease of the discharge volumes of ADF contaminated water. However, many U.S. airports continue to explore and develop new strategies to reduce contaminant concentrations to meet the benchmark concentrations required to comply with discharge permits.

One of the airports that has not complied with all EPA permits is the Air Force/Army military base Joint Base Elmendorf-Richardson (JBER) located in Anchorage, Alaska. The extremely low temperatures and high average yearly precipitation in Anchorage requires that JBER use a large volume of ADF solution to allow proper aircraft operations. The hundreds of thousand gallons of fluid that are applied during deicing season generates large volumes of contaminated stormwater runoff that is discharged into a nearby water body.

Joint Base Elmendorf-Richardson has made several attempts to manage ADF usage on site, but the chemical oxygen demand (COD) and biological oxygen demand (BOD) limits have not been reduced to the standards set by regulatory agencies. To address this issue, JBER contacted the Energy and Water Sustainability Laboratory at Colorado State University (CSU) to

determine possible stormwater treatment strategies to be applied on the military base. After considering all treatment technologies currently used at North America airports, the CSU team concluded that biological degradation by subsurface flow constructed wetlands (SFCW) was the most practical option for JBER. The final selection and recommendation was based on extensive literature review and analysis of design criteria, construction, O&M, and maintenance cost, as well as, information of various technologies used in cities with comparable climate conditions to Anchorage.

The CSU team developed a series of bench scale experiments that simulated biological degradation in batch SFCWs under ambient and operational conditions relevant to JBERs case. Degradation data was obtained by measuring daily COD concentrations over a 30-day period. A total of 14 experiments at different conditions were performed. Parameters including temperature (5°C vs. 20°C), aeration (aerated vs. non-aerated), ADF composition (all ADF types used by JBER vs. propylene glycol only), and nutrient addition (with nutrients vs. without nutrients) were varied to determine their effect on degradation rates (k), and lag phase in the system. All kinetic parameters were determined and calculated based on first order degradation kinetics in a biological system.

Numerical, graphical, and design of experiment (DOE) analyses suggested that the temperature in the system had the highest effect on degradation rates and lag-phases. Analysis of results suggested that the ADFs in stormwater can be treated with the SFCW technology under certain conditions. During winter months, sufficient aeration, nutrient addition and low propylene glycol content are necessary to achieve optimal degradation rates ($k=0.11\ day^{-1}$). However, during warmer months (May-August), it is possible to treat the stormwater under low oxygen, and low nutrient conditions reducing the energy costs of the system. If a stormwater strategy for treatment during warmer months is developed, the stormwater treatment can be optimized in the most economic manner.

TABLE OF CONTENTS

ABSTRACT ... ii
LIST OF TABLES ... vii
LIST OF FIGURES ... viii
LIST OF ACRONYMS ... x
1. INTRODUCTION ... 1
2. GENERAL BACKGROUND ON ADFs, STORMWATER MANAGEMENT, AND JBER'S CASE ... 3
2.1 Aircraft Deicing Fluids ... 3
2.1.1 ADF usage and contamination ... 3
2.1.2 Compounds in Deicing Fluids ... 4
2.1.3 Effect of ADF in surface waters ... 5
2.1.4 EPA regulations and attempts ... 6
2.2 Stormwater management practices ... 7
2.2.1 Optimization of ADF usage ... 8
2.2.2 Stormwater Treatment Options ... 8
2.3 JBERs case ... 13
2.4 The need for on-site biological treatment technologies at JBER ... 17
3. SELECTION OF ON-SITE TREATMENT TECHNOLOGY FOR JBER'S CASE: ... 21
3.1 Objectives: ... 22
3.2 Analysis of technology variables for application at JBER ... 24
3.2.1 Average Monthly Temperature comparison: ... 24
3.2.2 Important criteria for technology selection ... 27
3.2.3 Cost Considerations ... 31
3.4 Advantages of subsurface flow constructed wetlands to meet JBER's objectives ... 33
4. SUBSURFACE FLOW CONSTRUCTED WETLAND TECHNOLOGY ... 35
4.1 Airports around the world that use SFCWs on-site ... 36
4.2 Kinetics and flow equations for the design of a SFCW ... 40
4.3 Degradation Rates in a SFCW system ... 44
4.3.1 Variables that affect the degradation rates (k) of a SFCW ... 45
5. ADF DEGRADATION LABORATORY STUDY ... 50
5.1 Objectives ... 51
5.2 Methodology ... 52

5.2.1 Model water preparation 52
5.2.2 Experimental Design 53
5.2.3 Data Collection: 55
5.2.4 Experimental Nomenclature: 55
5.3 Results and Discussion: 57
5.3.1 Numerical and Graphical data: 57
5.3.2 Design Of Experiment (DOE) Analysis: 66
6. IMPLICATIONS FOR JBER, CONCLUSIONS, AND FUTURE WORK 76
6.1 Recommendations for JBER 77
6.2 Future Work and additional considerations: 78
APPENDIX A: Preparation of ADF model water 83
APPENDIX B: COD concentrations (mg/L) vs. time for all experiments. 84

LIST OF TABLES

Table 2.1 EPA standards from MSGS permit sector S. 7
Table 2.2 COD and BOD data from the 2013-2014 deicing /anti-icing season.......................... 16
Table 2.3 Biological Treatments in Airports worldwide.. 19
Table 3.1 Comparison of minimum and maximum monthly temperatures (in °F) from cities with airports that treat ADF on-site to temperatures in Anchorage, Alaska…………………………..25
Table 3.2 Important design criteria for biological treatment technology selection.. 28
Table 3.3 Average costs of construction and O&M of biological treatment systems................. 32
Table 4.1 Average SFCW design information from JBER and other airports…………………..38
Table 5.1 Bed nomenclature for all 14 experiments performed under different conditions…….56
Table 5.2 k values and half-lives parameters for all 14 experiments in increasing order. 63
Table 5.3 Lag phases for all 14 experiments in increasing order.. 65
Table A-1 JBER's ADF annual average use ………………………………………………83
Table A-2 COD values for each deicing fluid.. 83
Table A-3 Volume of ADF for a 10,000 mg/L mixture.. 83

LIST OF FIGURES

Figure 2.1 Options for ADF contaminated stormwater treatment 12
Figure 2.2 Aerial photo of the JBER airfield. 14
Figure 2.3 Airfield boundary and location of Cherry Hill outfall... 15
Figure 4.1 Phases of a typical microbial growth curve……………………………………….41
Figure 4.2 Graphical representation of a first order degradation natural log equation. 42
Figure 5.1 Gravel bed set-up…………………………………………………………………54
Figure 5.2 Aeration manifold.. 54
Figure 5.3 COD percent over time for all experiments with all ADFs. 59
Figure 5.4 COD percent over time for all experiments tested with propylene glycol (PG). 60
Figure 5.5 k values for all experiments in increasing order.. 63
Figure 5.6 Chart for lag phases for all experiments in increasing order. 65
Figure 5.7 Main effect plot of aeration and composition when nutrients are added................... 67
Figure 5.8 Main effect plot of nutrient and composition when experiments are aerated. 68
Figure 5.9 Main effect plot of aeration and nutrients when experiments have all ADFs added.. 69
Figure 5.10 Main effect plot of aeration and composition when nutrients are added................. 71
Figure 5.11 Main effect plot of nutrient and composition when they are aerated. 72
Figure 5.12 Main effect plot of aeration and nutrients when all ADFs are added. 73
Figure B-1a: COD data over time for AA1……………………………………………….84
Figure B-1b: Natural log plot vs. time for AA1 84
Figure B-2a COD data over time for PA1 85
Figure B-2b Natural log plot vs. time for PA1 85
Figure B-3a COD data over time for AA2 86
Figure B-3b Natural log plot vs. time for AA2... 86
Figure B-4a COD data over time for PA2 87
Figure B-4b COD Natural log plot vs. time for PA2.. 87
Figure B-5a COD data over time for AN1 88
Figure B-5b Natural log plot vs. time for AN1... 88
Figure B-6a COD data over time for PN1 89
Figure B-6b Natural log plot vs. time for PN1 89
Figure B-7a COD data over time for AN2 90
Figure B-7b Natural log plot vs. time for AN2... 90
Figure B-8a COD data over time for PN2 91
Figure B-8b Natural log plot vs. time for PN2 91
Figure B-9a COD data over time vs. time for AN1- 92
Figure B-9b Natural log plot vs. time for AN1- 92
Figure B-10a COD data over time for AN2- 93
Figure B-10b Natural log plot vs. time for AN2- 93
Figure B-11a COD data over time for AA1- 94
Figure B-11b Natural log plot vs. time for AA1- 94
Figure B-12a COD data over time for AA2- 95
Figure B-12b Natural log plot vs. time for AA2- 95
Figure B-13a COD data over time for PA1-... 96

Figure B-13b Natural log plot vs. time for PA1-.. 96
Figure B-14a COD data over time for PA2-.. 97
Figure B-14b Natural log plot vs. time for PA2-.. 97

LIST OF ACRONYMS

ADF: Aircraft deicing fluid and/or aircraft anti-icing fluid.

JBER: Joint Base Elmendorf-Richardson.

COD: Chemical oxygen demand.

BOD: Biological oxygen demand. (5 day standard).

PG: Propylene glycol.

PA: Potassium acetate.

SA: Sodium acetate.

EPA: Environmental Protection Agency

POTW: Publicly owned treatment works

MSGS: Multi sector general permit

SFCW: Subsurface flow constructed wetland

1. INTRODUCTION

The use of large volumes of aircraft deicing and anti-icing fluids (ADFs) in airports located in cold cities has brought attention to the need for increased stormwater management practices to prevent contamination in surface waters. The high concentrations of chemical oxygen demand (COD) and biological oxygen demand (BOD) in ADF compounds result in the impairment of water quality affecting aquatic life. To reduce contamination, regulatory agencies such as the EPA, require airports in the United States to comply with minimum COD and BOD discharge levels in their outfalls. As a result, airports have been making use of stormwater treatment technologies to degrade and/or separate the high concentration of organic compounds in their stormwater runoff.

To comply with EPA regulations, Joint Base Elmendorf-Richardson (JBER) is required to comply with the sector "S" of the Multi Sector General Permit (MSGP) which is specific to stormwater practices at airports where ADF is being utilized. Sector "S" of the MSGP specifies that concentrations of chemical oxygen demand (COD) and biological oxygen demand (BOD) in the discharge outfalls must not exceed the minimum benchmark concentrations (120 mg/L, and 30 mg/L respectively). To date, JBER has made several ADF management efforts to reduce the COD and BOD discharge concentrations in the outfall. However, due to the extremely high COD and BOD concentrations in ADF, the minimum discharge concentrations in JBER's main outfall have not been met.

To achieve their goal of complying with environmental regulations, JBER partnered with Colorado State University (CSU) to determine solutions for COD removal in their stormwater runoff. JBER requested that CSU provide laboratory data of ADF degradation rates (k), detailed protocols of the experiments, and recommendations for technology application on the military base. In response, the CSU team developed a study to analyze options for the most feasible procedure to be implemented by JBER based on weather conditions in Anchorage, costs of construction and operation, and minimum intervention with military operations. The subsurface flow constructed wetland technology was selected as the most feasible for JBER's conditions. The experimental part of the project conducted by CSU involved collecting COD degradation data and using subsurface flow constructed wetland design equations to obtain numerical values of first order degradation constants (k) under different operational conditions.

The purpose of this thesis is to document background information, experimental methods, and experimental results that led to CSU's conclusions about the stormwater treatment strategy recommended to JBER. Chapter 2 of this thesis contains the relevant literature review necessary to understand the importance and context of the project, the overall situation at JBER, and the need for biological treatments on-site. Chapter 3 explains the methodology for technology selection and decisions that led to biological degradation by SFCWs as the best choice for JBER's needs and conditions. Chapter 4 provides an overall summary of the SFCW technology, its applications, and relevant design and operation information used for the development of experimental procedures. Chapter 5 explains the experimental methods, assumptions made, and variables compared during the experimental phase. Also, this chapter includes all data analysis, calculations, tables and figures, and explanation of results for each one of the experiments. Finally, Chapter 6 contains experimental phase conclusions, which serve as basis for recommendations to JBER, and the optimal management strategy they should follow to achieve their goal.

2. GENERAL BACKGROUND ON ADFs, STORMWATER MANAGEMENT, AND JBER'S CASE

2.1 Aircraft Deicing Fluids

2.1.1 ADF usage and contamination

The use of aircraft deicing and anti-icing fluids (ADFs) at airports located in low temperature areas is necessary to allow optimal aerodynamic performance of the aircraft and to assure the safety of the passengers. When there is snow precipitation and/or low temperatures that create frost on the aircraft, the ability to have sufficient lift when departing is compromised. Similarly, airfield anti-icers must be applied to the pavement to prevent loss of traction from snow or frost build-up. To regulate aircraft safety, the Federal Aviation Administration (FAA) demands that aircraft may not take off if ice or snow is adhered to its wings, engines, and other important surfaces (FAA, 2015). Therefore, all airports located in cold weather locations are required to develop protocols for deicing procedures to guarantee that all airline operations are done in a safe manner.

More than 200 commercial airports in the United States located in cities in which winter temperatures allow frost formation on the aircraft. It is estimated that approximately 25 million gallons of ADF is used on average by U.S. airports per year and an additional of 35 thousand tons of airfield deicer per year (EPA, 2012). The type of fluid used by each airport varies by type (Type I to Type IV) and it is generally propylene glycol or ethylene glycol based. Currently in the United States, approximately 77.1% of ADFs usage is propylene glycol based. This is due to its less toxic properties when compared to ethylene glycol based fluids. Similarly, potassium acetate is the predominantly used airfield deicer and replaces the highly toxic urea based deicers. (EPA, 2000)

However, due to improper management of the stormwater runoff, several surface waters in the U.S. have been contaminated with the fluids from deicing operations. Before any strict regulations were made (pre-1990) approximately 28 million gallons of concentrated ADF were discharged to surface waters by U.S. airports on a yearly basis (EPA, 2000). The EPA realized the potential problems and addressed the adverse impacts on the environment by creating regulations to improve stormwater management by U.S. airports. As a result to these new regulations, the volume of ADF discharged reduced to 21 million gallons per year with an additional 2 million sent to publicly owned treatment works (POTWs). Nevertheless, U.S. airports have yet to comply with these regulations to minimize the effects that ADF compounds have in surface water ecosystems.

2.1.2 Compounds in Deicing Fluids

Aicraft Deicing Fluids are usually composed of a large percentage of carbon based freezing point depressants combined with smaller concentrations of surfactants, corrosion inhibitors, and flame retardants, among others. Around 50%-80% of an ADF mixture is propylene or ethylene glycol which when applied to aircraft increases the rate of snow melting (deicing) and/or prevent further ice build-up after deicing has taken place (anti-icing). Certain triazoles (mainly benzotriazole and methyl-substituted benzotriazole) and other toxic compounds are added to ADF mixtures to prevent corrosion, flammability, and to improve other ADF properties (EPA, 2000). These compounds are found in different concentrations that are unique to each ADF manufacturer and ADF type (Type I, II, III or IV) and their exact concentration values are usually unavailable to the public. In general, ADF mixtures are more toxic than pure propylene glycol (PG) and ethylene glycol (EG) due to the prevenient toxicity from additional chemicals that are present at lower concentrations (EPA, 2000).

In addition to PG and EG based ADFs, other pavement deicers and anti-icers are used in large quantities to prevent slippery conditions during take-off and landing. Pavement anti-icers are commonly acetate or formate based and are also successful in significantly reducing the freezing point of water. These compounds are more biodegradable than PG and EG, but these also contribute to the overall COD concentration in the runoff water (EPA, 2012). Urea has also been a common choice for pavement deicing. These deicers usually contain a small percentage of corrosion inhibitors but their actual composition is generally not available to the public.

2.1.3 Effect of ADF in surface waters

The main hazard related to the disposal of aircraft deicing fluids to surface waters is the high concentrations of organic compounds found in these fluids. As previously mentioned, PG and EG are the most commonly used freezing point depressants found in ADFs. These organic compounds have very high concentrations of chemical oxygen demand (COD) and biological oxygen demand (BOD) threaten to surface waters when snowmelt runoff is discharged in large quantities (Switzenbaum, 1999). Concentrated solutions of PG and EG based ADFs can have concentrations of COD of about 320,000 mg/L and 200,000 mg/L respectively. When the ADFs are diluted for aircraft application and snowmelt dilution, these values can reach up to 20,000 mg/L COD. (EPA, 2000).

When runoff with high COD and BOD concentrations is disposed in natural waters the result is a significant decrease of the dissolved oxygen (DO) in the water which allows anoxic conditions to take place. Reduction of DO occurs as a consequence of increased heterotrophic aerobic microorganisms in the surface waters that use the carbon compounds of the ADF as their food source. Since these microorganisms must use oxygen as the electron acceptor to breakdown the organic compounds, a higher production of these microorganisms in the water results in oxygen depletion over time. The overall quality of the surface water becomes impaired leading to die-off of aquatic aerobic organisms (e.g. fish) and giving rise to methane producing microorganisms. Additional detrimental factors include adverse health effects for humans and other mammals if the compounds are accidentally ingested (EPA, 2012).

2.1.4 EPA regulations and attempts

The EPA and other federal agencies continue to work on writing and enforcing proper regulations that require U.S. airports to improve their stormwater management in order to reduce environmental impacts from ADF contamination. Under the 1972 Clean Water Act, the EPA is required to set wastewater standards and monitor and control all polluted water discharge activities for different industrial sectors. Requirements for the Multi Sector General Permit (MSGP) was published by the EPA in 1993 and 1995 to comply with minimum water quality discharges by specific industries. The sector "S" of the MSGP addresses all requirements imposed by the EPA for stormwater management practices during deicing/anti-icing operations in U.S. airports. For instance, all airports that currently use 100,000 gallons of glycol based deicing/anti-icing fluids and/or 100 tons of urea must monitor and control ADF usage to minimize pollution (MSGS, 2015). Monitoring includes data collection in outfalls for overall water quality (pH, COD, BOD, ammonium, etc.) and overall quantification of ADF usage.

Control strategies may vary by case and include (but are not limited to) reducing total ADF quantities, switching to more biodegradable ADF mixtures, treating and/or recycling of stormwater runoff, sending stormwater runoff to a nearby POTW, etc. Successful strategies with optimal control procedures have been found to be a combination of previously mentioned strategies and on airports unique conditions define the proper choice (EPA, 2000).

Permit "S" (AKG060000) from the MSGP requires airports to monitor and control their ADF usage and stormwater runoff discharges in attempts to meet a minimum benchmark for COD, BOD, pH, and ammonium concentration in the outfalls. Minimum benchmarks are presented in the following Table 2.1:

Table 2.1 EPA standards from MSGS permit sector S.

Parameter	Benchmark Concentration
Biological oxygen demand (BOD)	30 mg/L
Chemical oxygen demand (COD)	120 mg/L
Ammonium	2.14 mg/L*
pH	6.5-8.5

*Ammonium data only if there is use of urea for deicing. (MSGS 2015)

The EPA estimates an overall reduction of ADF (at 50% dilution) discharge to surface waters from U.S. airports resulting in 17 million gallons if all permits are successfully implemented to meet regulatory requirements. Further management practices by all airports must occur to reduce overall ADF usage or, as an alternative, use treatment/recycling technologies to handle the ADF contaminated stormwater runoff to achieve the minimum required benchmarks (EPA, 2000).

2.2 Stormwater management practices

In an attempt to minimize the contamination from ADF in stormwater runoff in surface waters and comply with EPA regulations, airports have been applying several methods for better management. Operational procedures when applying the ADF to the aircraft and airfield have been developed to minimize the total ADF usage. Also, several stormwater treatment processes have been widely applied in most U.S. airports and have been highly effective in removing toxic compounds to the minimum EPA benchmarks. The following section summarizes current U.S.

airports' practices to optimize the ADF application and treatment alternatives for ADF contaminated stormwater runoff.

2.2.1 Optimization of ADF usage

Stricter regulations and the need to minimize pollution of water bodies for sustainable environment have led airports to find different alternatives for ADF application and stormwater management. Several methods for deicing have been applied as alternatives of common ADF applications. Mechanical means of deicing (use of blowers), infra-red deicing, and use of more environmentally friendly deicers have been successfully used by airports to meet their deicing standards (Switzenbaum, 2001). Switching to PG based deicers from EG based deicers, using acetate based pavement anti-icers from urea based, and choosing type III deicers over type I deicers are practices trending in U.S. airports (D'Avirro, J & Chaput 2011). Optimal methods of ADF application, which consider dilution, deicing/anti-icing time intervals, and weather prediction for application planning, have also helped reduce total ADF demand. Application practices have succeeded in reducing total carbon compounds in the runoff water. Yet, this reduction is still minimal and there is a need for more efficient technologies to meet the final benchmark limits set by the EPA.

2.2.2 Stormwater Treatment Options

The most efficient options for stormwater management have been chosen by U.S. commercial airports based on their needs and limitations for technology usage and/or water disposal. Options for stormwater management can be divided into three categories based on these needs and limitations. Management of contaminated stormwater may be done off-site (Option 1) by sending the collected water to an external treatment/recycling facility. When POTWs are not large enough to handle the COD and BOD loadings and nearby recycling facilities are not available airports must handle their stormwater runoff on-site. Airports must choose appropriate technologies to either recycle the PG for re-use and/or sell to local vendors (Option 2), or biologically treat the water on-site before it is discharged into a water body (Option 3) (ACRP, 2013). An overall evaluation must be done by each airport to determine the most energy efficient technology that best suits their environmental conditions while managing the water in an economic way.

Option 1: Off-site treatment

The most currently preferred option selected by airports is to send their stormwater runoff to an external treatment facility. Around 2 million gallons are disposed by airports to nearby POTWs that are large enough to handle the high COD and BOD loads during deicing periods (ACRP 2013). The contaminated stormwater is received by the POTW and mixed with municipal sewage water or other external industrial wastewaters. POTWs use aerobic biological processes like activated sludge in which oxygen is added by air compressors or mechanical aerators to enhance the degradation of organic pollutants. An assessment of the total volume and total COD and BOD loads must be done before the POTW agrees to receive contaminated water from an airport. Since the POTWs must also comply with minimum discharge benchmarks after treating the water it is important to determine if the facility can handle the total organic loads in the inflow. Stormwater waste can also be sent to an external facility that uses physical methods to recover the glycol for recycling purposes (Thermo Energy, 2012).

Option 2: On-site recycling by physical treatments

On-site recycling of the glycol compounds is a practice that allows airports to minimize the discharge COD and BOD concentrations by separating the glycol from the stormwater runoff with the use of physical treatment technologies (Thermo Energy, 2012). Mechanical vapor recompression (MVR) and distillation are usually used in conjunction to obtain an optimal separation of the ADF. The glycol recovered is subsequently sold to an external vendor and the effluent distillate sent to a local POTW for further treatment. Airports like the Denver International Airport (DIA) and Salt Lake City International Airport (SLC) have been making use of these technologies and successfully recovering the glycol with concentrations up to 99.5% (ACRP, 2013). Reverse osmosis is another type of physical treatment that, when used in conjunction with MVR or recompression, can achieve maximum separation of the glycol compounds. Salt Lake City International Airport is known to make use of both reverse osmosis and MVR technologies in conjunction to achieve optimal results (ACRP, 2013).

Option 3: On-site biological treatment

Stormwater treatment technologies that use biological degradation processes have been proven to be very effective in reducing COD and BOD concentrations down to the minimum required EPA benchmarks. In biological processes, the microorganisms present in a bioreactor or engineered wetland use the organic compounds in the wastewater as a food source. Therefore, the biological processes result in lower organic concentrations in the outflow. If the outflow water meets the minimum mandated regulatory benchmarks, the wastewater can be discharged into the water body after treatment. Aeration enhances the organic compound degradation by aerobic microorganisms.

Activated sludge process, subsurface flow constructed wetlands (SFCWs), and free water surface wetlands (FSWs) are common technologies used by U.S. airports on-site. For example, Cincinnati-Northern Kentucky Airport uses an activated sludge process in extended variation (longer aeration time) to manage their stormwater runoff. In Germany, Frankfurt International Airport (FRA) uses a sequencing batch reactor, which is another variation of the activated sludge technology (ACRP, 2013). In other U.S. airports, free water surface and subsurface flow constructed wetlands have also been successful, such as Buffalo Niagara International Airport and Nashville International Airport (Higgins et al., 2012). Conversely, anaerobic fluidized bed reactors (AFBR) are an alternative to aerated methods in which the lack of oxygen allows degradation of organic compounds by methanogenic microorganisms. The methane produced in the reactor is recycled and used to provide heat to the system, which increases the overall energy efficiency of the system. Albany Airport (ALB) and Akron-Canton Airport (CAK) use the AFBR systems to treat their stormwater on-site (Switzenbaum, 2001).

As another alternative, passive facultative treatments are low maintenance natural processes that degrade the organic compounds without the addition of oxygen, chemicals, and other engineered variables. These types of processes are slow, but fulfills the need for simple, low cost, operation that can produce efficient results when combined with other more rapidly reacting treatments. For example, Edmonton International Airport (EIA) discharges the contaminated stormwater in a facultative lagoon to allow partial degradation of organic compounds prior to degradation by aerobic processes (Higgins, 2012).

Chemical processes, such as advanced oxidation processes (AOPs), can also be very efficient in reducing the COD concentrations in the wastewater. Even though they have not been used for deicing fluid management, their effectiveness in degrading non-biodegradable organic compounds has made these technologies beneficial when used in conjunction with biological processes.

The following Figure 2.1 summarizes all stormwater treatment technologies currently used by airports to manage ADF contaminated water. As previously explained, approximately 2 million gallons of ADF discharge per year are sent to POTWs to treat off-site. Therefore, the technologies used to treat stormwater in Option 1 (off-site treatment) are the same technologies used to treat domestic sewage by the city where the airport is located. Technologies used on-site may be for the purpose of glycol reuse and recycling (Option 2), or degradation of organic compounds prior to disposal to surface waters (Option 3).

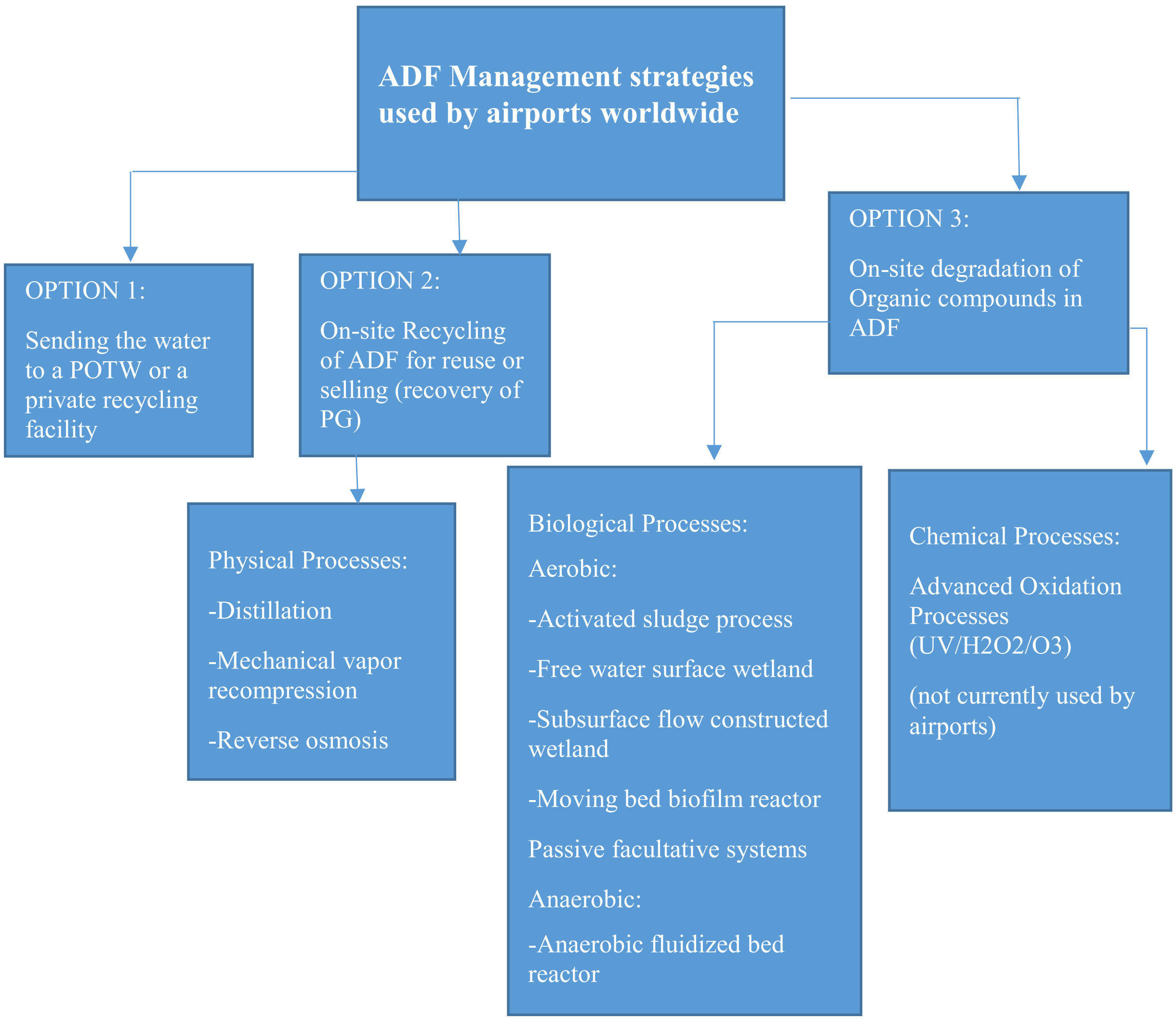


Figure 2.1 Options for ADF contaminated stormwater treatment

All the different options for stormwater management provided in Figure 2.1 have been successfully applied at airports in the United States and other parts of the world. In order to evaluate what the best option is for an airport, it is necessary to consider the goals, challenges, and limitations that are discussed in the technology selection. The challenge airports face is to select a technology that will be efficient in reducing the COD and BOD limits to the strict EPA defined benchmarks to comply with discharge regulations. Knowing and understanding the challenges and limitations an airport may face is key to determine the most feasible option to achieve that goal. These challenges and limitations are different for each airport and may depend on factors like location, weather, ADF usage, stormwater runoff quality, availability of POTWs, on-site operations, and other factors.

Gathering information about an airport's conditions is the first step to begin analyzing the context and possible options to achieve the primary goal of reducing discharge concentrations to the minimum benchmarks. The following section describes the situation at JBER and the stormwater management practices they currently utilize on-site. It also presents data about their water quality and explains the main challenges and limitations they have to further reduce the COD and BOD concentrations in the run-off water. The information obtained from JBER's team was crucial to evaluate the possible options previously described in this section.

2.3 JBERs case

Joint Base Elmendorf-Richardson (JBER) is a military base located in Anchorage, Alaska where year round temperatures and average precipitation require large use of aircraft deicing and anti-icing fluids (ADF) solutions to allow proper aircraft operations. The large quantities of fluids that are applied during deicing season generate large volumes of contaminated stormwater runoff that is discharged into a nearby water body. The contaminated water contains high COD and BOD concentrations that have exceeded the minimum benchmarks required by the EPA. JBER is required to meet these specifications to comply with the sector "S" permit of the MSGP described in the previous section.

Around 150,000 gallons of propylene glycol Type IV aircraft deicer (Safewing MP IV Launch) are used at JBER during deicing season. Additionally, JBER applies an average of 130,000 gallons of potassium acetate based liquid airfield deicer (Cryotech E36) and 150 tons of sodium acetate (Cryotech NAAC) solid airfield deicer to the runway. There are no centralized deicing pads at JBER and no centralized collections system. Approximately 60% to 70% of all aircraft deicing product is applied in the northern portion of the airfield and eventually drains its way into the JBER storm water system that discharges into Kink Inlet. Figure 2.2 displays an aerial picture of the Elmendorf Air Force base obtained from Google Maps. The majority of the aircraft deicing operations occur in the area highlighted in red where most of the aircraft is located.

Figure 2.2 Aerial photo of the JBER airfield.

The airfield deicing extends throughout the whole runway during take-off and landing. On the left side of the picture, the Kink Inlet is shown in a gray color adjacent to the Port of Anchorage (bottom left).

At JBER, there are a total of seven stormwater discharge points where stormwater leaves the installation from a pipe, ditch, or drainage feature. Approximately 70% of all the diverted stormwater is discharged from a single outfall point at Cherry Hill. Figure 2.3 displays the location of the Cherry Hill outfall (red star) in relation to the Elmendorf airfield boundary (area 1) and the Knik Arm water body in which the stormwater runoff is discharged.

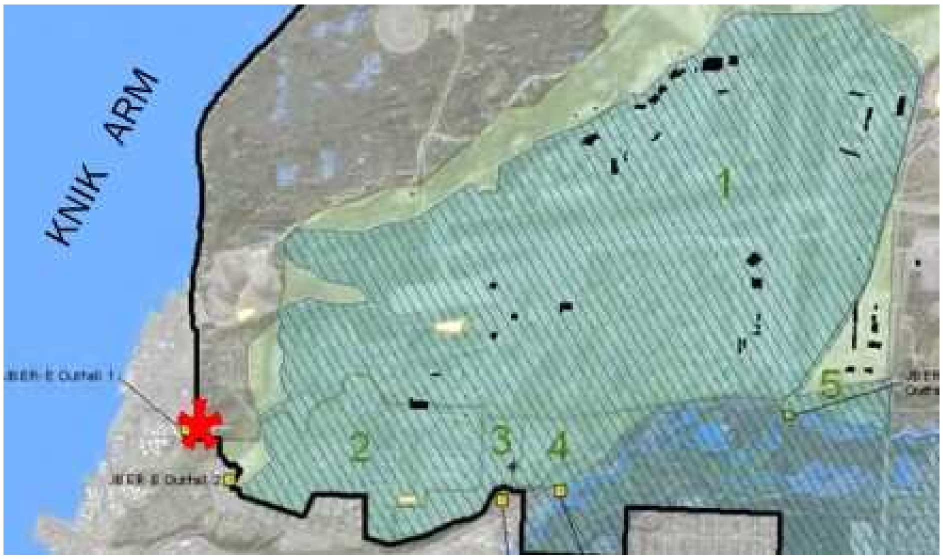


Figure 2.3 Airfield boundary and location of Cherry Hill outfall

The Cherry Hill outfall exits JBER's boundary and crosses the Port of Anchorage property through a belowground piping system. Given that the Port of Anchorage is part of the Municipality of Anchorage and a MS4 permittee, this borderline becomes the required sampling point. The current stormwater system configuration does not allow JBER to divert flows as climate changes from dry to wet season. The stormwater system also has several natural seeps along the northern portion of the runway that have been previously plumbed into the stormwater system numerous years ago. As a result, there is always a discharge at this sampling point even in extreme cold weather.

In order to lessen the total COD and BOD concentrations in the outfall, JBER has applied common management practices to reduce the potential impact to stormwater. To reduce the amount of ADF used during deicing practices, JBER switched 40 gpm nozzles in the application trucks to 6 gpm nozzles. The use of turbo blowers has also decreased the demand of ADF usage by aiding in bulk snow removal prior to deicing. Additionally, JBER began a training process to provide all deicing operators with the best application methods for optimal ADF usage. Ever since these practices took place at JBER, the total COD and BOD concentrations have decreased but the minimum benchmark concentrations are still not being met. The following Table 2.2 is a summary of four data points taken during the 2013-2014 deicing season:

Table 2.2 COD and BOD data from the 2013-2014 deicing /anti-icing season

	Jan 24, 2014 Rain Event	Feb 28,2014 Rain Event	Mar 31, 2014 Rain Event	April 4, 2014 Rapid Melt	Average	Benchmark
BOD (mg/L)	112.0	22.4	43.8	17.2	48.85	30.0
COD (mg/L)	211	43	48.9	244	136.7	120.0
Ammonia (mg/L)	0.88	0.35	0.379	0.147	0.439	2.14
pH	7.1	7.2	6.9	7.1	7.07	6.0-9.0

As presented in Table 2.2, the average COD and BOD concentrations for the 2014 deicing season are only a few digits above the maximum limits. Although there have been several attempts to reduce the COD and BOD concentrations in the outfall, JBER faces limitations that prevent further reduction. For example, JBER has no centralized deicing station and no market in Alaska for any recovered product. The local municipal wastewater treatment facility has also been contacted to determine if the untreated spent product and water could be diverted to their wastewater treatment plant. Unfortunately, they are currently having their own issues with the EPA as the Anchorage municipality operates only a primary treatment plant. There is currently no identified reuse on the installation for the mixed deicing product if it was able to be recovered. The wastewater treatment plant in Fairbanks (356 miles away) is significantly smaller than the facility in Anchorage, and is unlikely to accept several hundred thousand gallons of mixed deicer/water/snow. Even if there was available capacity to handle the additional wastewater, transporting such a large volume of liquid to Fairbanks would not be practical. Reusing this product in the oil and gas industry is not considered an option as it would again require pretreatment to remove excess water and then transportation to the North Slope. Sending the spent product back to the manufacturer in the lower contiguous United States would again require some type of dewatering facility, product storage, and then transport by barge.

To comply with the MSGS permit, JBER must develop different alternatives that will reduce the COD and BOD concentrations from ADF components. The limitations that JBER faces to meet the required benchmarks have exposed the necessity to consider treatment options prior to discharge through the Cherry Hill outfall. Stormwater management practices in cold region airports have been previously presented in section 2.2 as options for both off-site and on-site treatment. To select the best technology suited for JBER's conditions, it was necessary to analyze all possible options and evaluate their feasibility for JBER's case. However, based on the limitations explained in this section, some of the options presented in section 2.2 were eliminated.

2.4 The need for on-site biological treatment technologies at JBER

Joint Base Elmendorf-Richardson contacted the CSU team to determine the best stormwater management options to be applied at the military base. As summarized in section 2.2, airports choose between off-site treatments (Option 1) and on-site treatments (Options 2 and 3) to manage their wastewater. However, some of the limitations in JBER's case presented in section 2.3 imply that not all of these options are feasible.

As mentioned in JBER's background information in section 2.3, the lack of nearby POTWs that are able to handle the large loads of organic matters in JBER's stormwater and the unavailability of recycling treatment facilities in Anchorage have led to eliminate off-site treatment (Option 1) as a feasible alternative. Also, the lack of available vendors of recycled glycol make on-site physical treatments (Option 2) not feasible for JBER's case. Physical treatments are also relatively costly and require high energy demands to provide sufficient heat to the system. Therefore, on-site biological treatments (Option 3) has been considered the best stormwater treatment alternative that can be applied on the military base.

On-site biological processes are advantageous to reduce the concentrations of organic compounds in stormwater runoff at airports before reaching the outfall to surface waters. Microorganisms in a biological system consume the ADF based compounds as their carbon source and are subjected to enhanced conditions to benefit their growth. Different technologies have been applied on-site in airports around the world reducing the discharge concentrations of toxic compounds. A total of 22 airports that currently use biological on-site treatments are summarized in Table 2.3. Each airport is presented with its corresponding city and the technology they currently use on-site.

The technologies listed in Table 2.3 are subsurface flow constructed wetlands (SFCWs), free water surface wetlands (FSWs), activated sludge systems, anaerobic fluidized bed reactors (AFBRs), moving bed biofilm reactors (MBBR), and passive facultative systems. Some of the airports have used variations of these processes and are mentioned in the last column of the table. For instance, the activated sludge system at the Dane County Airport is operated as a sequencing batch reactor (SBR) with a preheater prior to digestion.

Each airport around the world has selected a different technology to treat their stormwater based on their feasibility on-site. Airports in Table 2.3 are commercial international airports located in cities with variable weather conditions and average temperatures during deicing season.

Table 2.3 Biological Treatments in Airports worldwide

AIRPORT	CITY	TECHNOLOGY	PROCESS VARIATION
Heathrow International Airport	London, England	Subsurface Flow Constructed Wetland	N/A
Buffalo-Niagara International Airport	Buffalo, New York	Subsurface Flow Constructed Wetland	N/A
Edmonton International Airport	Edmonton, Alberta, Canada	Subsurface Flow Constructed Wetland	N/A
Airborn Air Park	Wilmington, Ohio	Subsurface Flow Constructed Wetland	Reciprocating System
Long Island MacArthur Airport	Long Island, New York	Subsurface Flow Constructed Wetland	N/A
Frankfurt International Airport	Frankfurt, Germany	Activated Sludge	N/A
Dane County Airport	Madison, Wisconsin	Activated Sludge	Preheater and Sequencing Batch Reactor
Cincinnati-Northern Kentucky Airport	Hebron, Kentucky	Activated Sludge	N/A
Nashville International Airport	Nashville, Tennessee	Activated Sludge	N/A
Akron-Canton Airport	North Canton, Ohio	Anaerobic Fluidized Bed Reactor	N/A
Albany International Airport	Albany, New York	Anaerobic Fluidized Bed Reactor	N/A
Portland International Airport	Portland, Oregon	Anaerobic Fluidized Bed Reactor	N/A
T.F. Green Airport	Warwick, Rhode Island	Anaerobic Fluidized Bed Reactor	N/A
Toronto Pearson	Mississauga, Ontario, Canada	Passive Facultative	Treatment wetland
Washington Dulles Airport	Dulles, Virginia	Passive Facultative	Biological treatment unit
Westover Air Reserve Base	Springfield, Massachusetts	Passive Facultative	Treatment wetland
Zurich International Airport	Zurich, Switzerland	Passive Facultative	Irrigation system
Billings Logan International Airport	Billings, Montana	Passive Facultative	Series of detention ponds
Anchorage International Airport	Anchorage, Alaska	Passive Facultative	Open drainage swales
Baltimore/Washington International Airport	Washington	Passive Facultative	N/A
Oslo Gardermoen Airport	Gardermoen, Switzerland	Moving Bed Biofilm Reactor	N/A
Pittsburg International Airport	Pittsburg, Pennsylvania	Moving Bed Biofilm Reactor	N/A
Duluth Airport	Duluth, Minnesota	Free Water Surface Wetland	N/A
London Gatwick	London, England	Free Water Surface Wetland	N/A
Chicago Rockford International Airport	Rockford, Illinois	Free Water Surface Wetland	N/A

The decision of an airport to select one technology over the others was based on several considerations. Some technologies have advantages over others that can vary between maximum efficiency to maximum cost-effectiveness of a system. For example, the moving bed biofilm reactor (MBBR) can be very efficient in degrading the ADF compounds in a faster way.

However, the MBBR requires additional costs of operations and maintenance than when compared to a less efficient and simpler technology like a passive subsurface flow wetland. If operated in an optimal way, it is possible that more than one technology will be both efficient and economical as long as ambient conditions allow it. Therefore, it is also useful to consider external non-operational factors like weather conditions that may limit the efficiency of one technology over another in a specific case.

The first task completed by CSU's team was selecting a technology to be applied on-site based on general information about stormwater treatment options and JBER's goals, challenges and limitations. The technology selected was further tested at CSU's labs by simulating ambient conditions at JBER. Chapter 3 presents the selection process in a chronological manner in the same way the information was obtained and analyzed. The main influential factors that were considered in the selection process are also presented in the form of assumptions made on JBER's needs and limitations. Chapter 3 concludes with an explanation of technology advantages when applied at JBER and how it will meet JBER's needs by overcoming the major limitations on the military base. A more detailed background on the technology selected is presented in Chapter 4, followed by the experimental part of the study in Chapter 5.

3. SELECTION OF ON-SITE TREATMENT TECHNOLOGY FOR JBER'S CASE:

Selection of a treatment technology for a determined airport requires an in-depth analysis of the goals, challenges, and limitations that might affect the feasibility and effectiveness of a system. Even though all technologies have been successfully applied at numerous airports (Table 2.3), the results vary by case depending on each airport's objectives and site specific conditions. Chapter 2 presented information about JBER's case and some of the limitations that helped discard on-site recycling (Option 2), and POTW treatment (Option 1) as viable treatment options. In Chapter 3 the following points will be covered in detail:

- Describe in the form of assumptions the main limitations that a biological system must overcome and the main needs and goals it must meet to be a viable option for JBER.
- Describe the main goals and objectives established for the selection process
- Explain in chronological order how the technologies were evaluated to achieve the main objectives, and,
- Briefly explain why the technology selected it the most feasible for JBER over all other possible options.

One of the major external factors that must be considered when selecting the best technology is the average seasonal temperatures in the city the airport is located. Since degradation rates in a biological process are strongly dependent on the temperature of the system, it is necessary to evaluate how the low temperatures in a city impact the process efficiency. Temperatures in Anchorage fall well below the average temperature in most cities around the world. Therefore, temperature is an important factor that may be limiting in Anchorage for some of the technologies that are successfully used at other airports. JBER's main needs are to achieve COD and BOD concentration values below the benchmark limits in an economic manner that does not interfere with military operations. Therefore, considering economic advantages and process simplicity is crucial for the final decision. To simplify the selection process, assumptions were made based on available information about JBER's conditions on the military base. Four assumptions in JBER's selection process:

1. The average monthly temperatures in Anchorage are the biggest limitation that JBER faces compared to most U.S. cities. Since ambient temperature is a very important factor in the efficiency of biological processes, an evaluation of this limiting factor was the main focus of the selection process.
2. As other airports in the United States the goal at JBER is to reduce the COD and BOD concentrations in the outfall to 120 mg/L and 30 mg/L, respectively. Since the average concentrations in the 2014 deicing season are fairly close to the limits (136.7 mg/L for COD and 48.85 mg/L for BOD) it was assumed that moderately efficient technologies would achieve the desired goal.
3. Minimum interference with military operations is necessary when considering biological systems on-site.
4. The land available for construction at JBER is not a limitation.

3.1 Objectives:

The objective of this part of the study was to gather information about the currently used technologies for stormwater treatment in airports and analyze their feasibility for JBER's case. The primary goal was to select the best suited technology based on the assumptions made on JBER's needs and specific considerations for each technology. The following objectives outline the main steps taken to simplify the selection process and primary considerations taken for the analysis:

1. Determine if average monthly temperatures in cities around the world were a factor that strongly influenced the technology selection and determine if these technologies are only feasible for cities with warmer temperatures.
2. Analyze different factors for each technology and determine the challenges and limitations that JBER has for the application of each one when considering optimal process temperature, cost effectiveness, and minimum interference with military operations.
3. Select the best technology that meets JBER's needs and overcomes the main challenges and limitations made in assumptions 1-4.

This section presents all the information gathered on the biological systems used for ADF contaminated stormwater and main objectives were met to drive the final decision in the selection process. First, a comparison of average monthly temperatures in Anchorage to average monthly temperatures in commercial airports located in cold cities around the world is presented in Table 3.1. The monthly average temperatures for each city were obtained from several websites and summarized in an Excel spreadsheet by biological treatment type (see Table 2.3) for comparison with the corresponding technology used on-site. Information about these airports were obtained from the 2013 ACRP 99 report. Second, specific design criteria for technology selection obtained from the 2013 ACRP 99 report by the Federal Aviation Administration in 2013 is summarized in a Table 3.2. The information will be presented in the same order it was chronologically obtained and will be discussed in the same manner it was analyzed to lead to the final decision.

3.2 Analysis of technology variables for application at JBER

3.2.1 Average Monthly Temperature comparison:

Temperature conditions is an important factor to consider when dealing with biological processes. In cold temperatures, many microorganisms that are usually encountered in the environment are not able to grow or have very low growth rates. The year round colder weather in Anchorage compared to most cities in the U.S. was the main factor considered in the selection process. To evaluate how temperature conditions at an airport influenced technology selection, a summary of average monthly temperatures for the 22 airports presented in table 2.3 was developed and compared to those temperatures in Anchorage. The purpose of this comparison is to determine if there is a trend between technology selection by airports and average monthly temperatures, or if some technologies were not feasible in extremely cold weather. Table 3.1 is a color chart that displays the average monthly temperatures of Anchorage (left) and temperatures of each city previously summarized in table 2.3 (right).

The color chart ranges from blue to red depending on how cold or warm the temperature in each month is. This provides a good idea on how the technology selected varies with average monthly temperature. The rows are divided by each of the different technologies: subsurface flow constructed wetlands (SFCW), activated sludge systems, anaerobic fluidized bed reactors (AFBR), passive facultative systems, moving bed biofilm reactor, and free water surface wetlands (or aerated lagoons).

Based on the temperature information in Table 3.1, it can be observed by color variations that Anchorage is on average the coldest city when compared to others with airports that use biological processes on-site. Cities with the lowest average temperatures are considered to be

Table 3.1 Comparison of minimum and maximum monthly temperatures (in °F) from cities with airports that treat ADF on-site to temperatures in Anchorage, Alaska.

	SUBSURFACE FLOW CONSTRUCTED WETLANDS											
	ANCHORAGE		LONDON		LONG ISLAND		**EDMONTON**		**BUFFALO**		WILMINGTON	
MONTH	**MIN**	**MAX**	MIN	MAX	MIN	MAX	**MIN**	**MAX**	**MIN**	**MAX**	MIN	MAX
JAN	**8**	**22**	40	49	23	38	**7**	**23**	**16**	**32**	20	36
FEB	**11**	**26**	40	49	25	40	**10**	**30**	**17**	**34**	22	40
MAR	**17**	**34**	42	53	31	47	**16**	**36**	**24**	**43**	30	50
APR	**29**	**44**	45	58	41	58	**30**	**52**	**35**	**56**	40	63
OCT	**28**	**40**	50	60	46	63	**32**	**52**	**40**	**60**	42	66
NOV	**15**	**27**	45	53	37	53	**19**	**37**	**31**	**48**	34	52
DIC	**12**	**24**	40	48	28	43	**9**	**27**	**22**	**37**	24	39

			ACTIVATED SLUDGE SYSTEMS							
	ANCHORAGE		FRANKFURT		**MADISON**		HEBRON		NASHVILLE	
	MIN	**MAX**	MIN	MAX	**MIN**	**MAX**	MIN	MAX	MIN	MAX
JAN	**8**	**22**	26.6	39.2	**10**	**28**	23	39	28	47
FEB	**11**	**26**	26.6	39.2	**13**	**32**	26	43	32	52
MAR	**17**	**34**	33.8	48.2	**24**	**44**	34	53	39	61
APR	**29**	**44**	35.6	48.2	**35**	**58**	44	65	48	71
OCT	**28**	**40**	39.2	53.6	**37**	**61**	46	66	49	72
NOV	**15**	**27**	32	44.6	**28**	**46**	36	54	39	60
DIC	**12**	**24**	28.4	37.4	**15**	**32**	27	42	31	50

			ANAEROBIC FLUIDIZED BED REACTORS							
	ANCHORAGE		NORTH CANTON		**ALBANY**		PORTLAND		WARWICK	
	MIN	**MAX**	MIN	MAX	**MIN**	**MAX**	MIN	MAX	MIN	MAX
JAN	**8**	**22**	19	33	**15**	**31**	38	47	21	37
FEB	**11**	**26**	21	37	**17**	**35**	38	51	24	40
MAR	**17**	**34**	28	47	**26**	**44**	41	56	30	48
APR	**29**	**44**	39	60	**37**	**58**	44	61	40	59
OCT	**28**	**40**	43	61	**40**	**60**	48	63	44	63
NOV	**15**	**27**	34	49	**32**	**48**	41	52	36	53
DIC	**12**	**24**	24	37	**21**	**36**	36	45	26	42

			PASSIVE FACULTATIVE SYSTEMS									
	ANCHORAGE		MISSISSAUGA		DULLES		SPRINGFIELD		ZURICH		BILLINGS	
	MIN	**MAX**	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX		
JAN	**8**	**22**	19	32	24	42	18	36	28	39	16	41
FEB	**11**	**26**	21	34	26	47	21	39	28	43	19	45
MAR	**17**	**34**	28	41	33	56	29	49	34	52	26	54
APR	**29**	**44**	37	52	42	67	39	62	37	59	34	63
OCT	**28**	**40**	46	61	44	68	43	64	43	59	35	65
NOV	**15**	**27**	37	48	35	58	34	52	34	46	24	49
DIC	**12**	**24**	27	37	27	46	22	39	30	39	15	39

			MOVING BIOFILM BED				FREE WATER SURFACE WETLANDS			
	ANCHORAGE		GARDERMOEN		PITTSBURG		**DULUTH**		**ROCKFORD**	
	MIN	**MAX**	MIN	MAX	MIN	MAX	**MIN**	**MAX**	**MIN**	**MAX**
JAN	**8**	**22**	19.4	30.2	20	38	**2**	**21**	**13**	**29**
FEB	**11**	**26**	17.6	32	22	42	**6**	**26**	**18**	**34**
MAR	**17**	**34**	23	39.2	28	51	**17**	**35**	**28**	**47**
APR	**29**	**44**	32	48.2	38	64	**29**	**46**	**38**	**61**
OCT	**28**	**40**	35.6	46.4	41	65	**36**	**52**	**41**	**63**
NOV	**15**	**27**	26.6	28.4	33	53	**23**	**38**	**30**	**48**
DIC	**12**	**24**	19.4	30.2	24	41	**9**	**25**	**18**	**33**

Edmonton, Buffalo, Madison, Albany, Duluth, Gardermoen, and Rockford, all of which use different methods for deicing fluid management. These cities were considered to have average annual temperatures similar to those in Anchorage compared to all the other cities presented. The color chart provides a qualitative comparison for temperature differences.

A quantitative comparison of average annual temperatures was also done to provide more support on the selection of these cities. The difference in average minimum temperatures between the cities selected and the average minimum temperatures in Anchorage was of less than 10°F. For these same cities, the average maximum temperature over the whole deicing season was less than 13 °F the average maximum temperature in Anchorage. Note that this quantitative analysis was only done to provide more information about annual temperature conditions in each city and does not provide any statistically significant results.

The cities selected as having temperatures closest to those in Anchorage have used aerated gravel beds (Edmonton and Buffalo), activated sludge (Madison), AFBR (Albany), and free water surface wetlands (Duluth and Rockford). In general, temperature as the only factor does not seem to have a significant effect on treatment technology selection by airports. Most technologies have been effective even in the coldest cities. For example, the activated sludge technology is used by airports in colder cities, such as Madison, and also warmer cities such as Portland. The same trend is observed when comparing Buffalo and London both of which use SFCWs for treatment. Edmonton and Duluth are the cities that more closely resemble Anchorage's monthly temperature by an average difference of less than 10%. These cities use subsurface flow constructed wetlands and free water surface wetlands, respectively. Both are relatively slow processes, but efficient when properly designed. As shown in the comparative table, passive facultative systems are not used in extremely cold cities. However, the sample size is not large enough and this does not imply that these systems cannot be effective.

The comparative table implies that most technologies are successfully applied in the coldest cities. Comparing temperature conditions in other airports that manage their ADF contaminated water on- site provided good information about the success of the various technologies used in cold environments. However, a more detailed analysis of each technology was necessary to assess their feasibility under JBER's conditions. Since each technology has defined criteria limits for optimal performance, the CSU team evaluated the conditions at JBER to determine if a specific technology was superior to other technologies for the best outcome.

3.2.2 *Important criteria for technology selection*

The following section presents information of selection criteria compiled from the 2013 ACRP 99 report developed by the Federal Aviation Administration in 2013 which summarizes all technologies used on-site to degrade ADF stormwater. Important parameters that must be consider during the selection process are listed in Table 3.2 for each of the technologies. Minimum temperature of operation, inflow water quality, available land for construction, presence of open waters, and media availability are the main parameters discussed in this section. To determine which technology would be best for JBER, it was necessary to analyze the conditions on-site for each of the parameters listed. A primary focus was given to optimal temperature conditions, which is the biggest limiting factor at JBER. Additionally, cost considerations and minimum interference with military operations were important factors during the selection process.

Table 3.2 Important design criteria for biological treatment technology selection. (ACRP, 2013).

Parameter	Activated Sludge	Subsurface Flow Constructed Wetland (SFCW)	Free Water Surface Wetland (FWS)	Moving Bed Biofilm Reactor (MBBR)	Anaerobic Fluidized Bed Reactor (AFBR)	Facultative Processes
Temperature Considerations	Most critical condition when the water is below 41 F	Biological processes occur at environment temperatures. However they slow down during colder periods	Biological processes occur at environment temperatures. However they slow down during colder periods	Storm water temperature must be a factor to consider for the design of the reactor	Optimal growth at 85-90 F. Methane is used to help achieve this.	Biological processes occur at environment temperatures. However they slow down during colder periods
Influent streams and max COD	Dilute Streams. Approximately but not limited to 10,000 mg/L.	Dilute Streams Less than 10,000 mg/L	Dilute Streams Less than 0.5% (8000 mg/L COD)	Dilute Streams. (Low concentration/high volumes).	Concentrated Streams. Consistent concentrations above 2700 mg/L	Very Dilute
Minimum COD	No minimum	No minimum	No minimum	No minimum	2700 mg/L. At lower concentrations, methane production decreases.	No minimum
Area foot print	At least 1 acre. Sizing depends on mass flow loads. Majority of footprint is aeration basin and clarifier	At least 1 acre. Sizing depends on mass flow loads. Majority of footprint is gravel beds	At least 1 acre. Sizing depends on mass flow loads. Majority of footprint is water surface of lagoons.	Less than 1 acre. Majority of footprint is open aeration tank with media.	Less than 1 acre. Majority of footprint is processed tanks.	At least 1 acre.
Building Height	Less than 20 ft. House nutrient system and monitoring facilities.	Less than 20 ft. House nutrient system and monitoring facilities.	Less than 20 ft. House nutrient system and monitoring facilities.	Less than 20 ft. House nutrient and sludge handling make it around 10 ft.	At least 20 ft. Reactors are over 35 ft. in height.	Less than 20 ft. House nutrient system and monitoring facilities.
Open water	Open water aeration basins and clarifier	No open water. Water level below bed	Open water aeration basins and clarifier	Open water aeration basins and clarifier	No open water. All treatment in enclosed tanks.	Depends on technology used.
Media Availability	Activated sludge from municipal waste water plant	Local supply of clean, well-graded gravel material	N/A	Vendor must supply this	Activated carbon, sand or other material	N/A

As explained previously in Table 3.1, temperature conditions at JBER can be as low as 8°F during the coldest month (January), and reach up to 44°F during the warmest month of the deicing season (April). Precipitation during these months vary from high precipitation from October through December (wet months) to low precipitation from January through April

The runoff volumes and COD concentrations vary depending on the melting rate of accumulated snow and the amount of ADF used during that period of time. There is no specific data from runoff volumes and COD concentrations prior to discharge to Cherry Hill outfall; therefore the appropriate assumptions were made based on available information and consultation with the JBER team.

Firstly, it is important to note that concentrations in the outfall in Table 2.1 are extremely low compared to most stormwater runoff values prior to treatment (around 6,000-10,000 mg/L COD). This is due to the natural seeps that cause additional dilution of the runoff water to about 20 MGD of runoff constantly discharging at Cherry Hill. However, concentrations near aircraft deicing operations by the Elmendorf airport can reach much higher concentrated values. If a treatment system is built close to deicing operations, the concentrations of COD will be high enough to allow biological processes to function with enough carbon source for food.

Temperature Considerations:

Optimal temperature for biological growth was a crucial factor that disallowed some of the technologies available for biological degradation. Even though all technologies have been proved successful in other airports regardless of temperature conditions in the city they are located in, it is important to note that some of them require a minimum temperature that is well above the ambient conditions during the coldest months in Anchorage. For instance, an activated sludge system requires a minimum of 45°F to allow optimal microbial growth. Similarly, anaerobic fluidized bed reactors (AFBR) require a much higher temperature (85°F-90°F) to maintain the slow growing anaerobic bacteria in an optimal environment for growth. The performance of moving bed biofilm reactors is also known to be significantly dependent on warmer temperatures to allow attached bacteria to survive.

Also, free water surface wetlands, subsurface flow constructed wetlands (SFCW), and passive facultative processes are technologies that rely on natural microorganisms that survive during extremely cold temperatures. These technologies are designed to improve ambient conditions for microorganisms by adding aeration and sufficient nutrients. This allows the microorganisms already present in the water to enhance their growth and allow them to degrade the organic compounds at a higher rate. Although the degradation rates in these systems are much lower due to the lower temperature conditions, the microorganisms have been adapted to survive extremely cold weather. If designed and operated correctly, these simple biological systems can successfully treat the large loads of COD in the stormwater without the need for additional energy from heating systems.

Since temperatures at JBER are relatively low compared to most cities, the energy required to heat systems like activated sludge, AFBRs, and MBBRs can reach much higher levels than most of the cities that use these systems on-site. Higher energy requirements result in higher costs of operation during deicing season to maintain the efficiency of the treatment plant. One of the needs that JBER has is to efficiently reduce the COD in an economical way. Since process temperature is an important variable in process efficiency and energy demands, the selection of technology was mainly driven by this factor. However, other factors, such as the costs of construction and O&M, were taken into account when evaluating different technologies.

The following information presents additional information on costs that drove the final decision for selection.

COD, land available, media:

Most technologies have a minimum and/or maximum concentration of COD in which they operate efficiently. The size of a treatment facility is defined by the expected loading rates (volumetric or COD) of the influent to be treated. Since the runoff volumes and concentrations at JBER are variable and unpredictable, the water quality of the influent was not a primary factor to consider. However, it was assumed that land availability for system construction was at least one acre and there were no other limitations for construction. Additionally, it was assumed that necessary media were available in Anchorage and it would not be a limiting factor for technology selection.

3.2.3 Cost Considerations

One of the main goals for technology selection is to achieve maximum cost effectiveness from a system's implementation. As previously explained, the costs the heating systems are additional components of the total operational costs. Similarly, energy from aeration for most systems increase this cost during the treatment process. Additionally, construction costs of a facility must be evaluated. The following Table 3.3 was based on ACRP data from average costs in a 6000 lb COD/day system for each one of the technologies discussed. The costs of O&M are based on a 6 month operation period.

Table 3.3 Average costs of construction and O&M of biological treatment systems (ACRP 2013)

	Average Costs for a 6000 lb COD/day system	
Biological Process Technology	**Construction (Million Dollars)**	**O&M (Thousand Dollars)**
Activated Sludge	27.0	300
Subsurface Flow Constructed Wetland	15.0	170
Free Water Surface Wetland	4.5	290
AFBR	10.5	300
MBBR	4.9	450
Passive Systems	Data only available for less than 1000 lb COD/day	Data only available for less than 1000 lb COD/day

As previously explained, technologies like activated sludge, AFBRs, and MBBRs are generally expensive to operate due to the high energy demand required by these systems. Additionally, complex processes in the reactors require constant monitoring; therefore, they require additional costs for O&M throughout deicing season. AFBRs, and MBBRs have a relatively low economic construction cost with 10.5, and 4.9 million dollars, respectively. However, O&M costs are higher than when compared to SFCWs, FSWs, and passive facultative systems. Even though activated sludge systems are highly efficient, they are generally expensive for both construction and O&M due to the different equipment requirements for each procedure performed throughout various steps in the process (digesters, clarifiers, etc).

In contrast, free water surface wetlands, subsurface flow constructed wetlands (SFCW), and passive facultative processes are more economically viable processes. The simplicity of SFCWs and FSWs reduces the cost, respectively, to 4.5 and 15 million dollars for construction and to 290 and 170 million dollars for O&M. Since these systems require very little monitoring, they eliminate the need for multiple process operators and monitoring equipment. As previously explained, the elimination of heating systems is also an important factor that affects economic feasibility. Even though these types of systems may be slower than those that are done at higher temperatures, the total COD reduction required by JBER to meet the benchmark (approximately

20%-50% reduction based on data from Table 2.2 JBER data) can be met by the use of these technologies.

Based on temperature, cost considerations, and process simplicity and efficiency, the application of SFCWs, FSW, and passive facultative systems are more attractive for on-site application. However, to select the best technology, additional aspects were considered. One of the main concerns for technology implementation at JBER is the presence of open waters that might attract migrating birds or other wildlife to the biological system. In the case of free water surface wetlands, the system is designed to simulate natural wetlands with the addition of air and nutrients to enhance microbial growth. Since FSWs are open water systems, they can be harmful to birds if they consume the highly toxic water that is being treated. Additionally, a large number of migrating birds near the base will be detrimental during constant take-off and landing of aircraft on the military base. Environmental concerns to prevent harming birds and wildlife will highly impact military operations by limiting the number of aircraft landing/take-offs when migrating birds are abundant near the base.

3.4 Advantages of subsurface flow constructed wetlands to meet JBER's objectives

After a general evaluation of biological degradation technologies targeted to treat the ADF in stormwater runoff, it was concluded that the subsurface flow constructed wetland (SFCW) technology is most suited for JBER's case. They are able to overcome the temperature limitations in Anchorage while keeping the process simple and cost effective. As opposed to other heat sensitive processes like activated sludge systems, a SFCW relies on microorganisms in natural waters that have been adapted to extremely cold temperatures. This results in better degradation efficiencies without the need of additional energy costs during treatment. The process is very straightforward due to simplicity, and many O&M costs are reduced when compared to more sensitive and complex equipment. Even though the degradation rates in SFCWs are relatively slow during the coldest periods, it is expected that they will be sufficient to reduce the concentrations of COD and BOD in the Cherry Hill outfall. Additionally, SFCWs are not highly sensitive to volumetric flows and COD concentration variations, as opposed to highly sensitive technologies like activated sludge and AFBRs. Therefore, the system can be operated at different conditions to handle the high variation of COD loading rates in the influent.

After presenting the in-depth evaluation of technologies and final selection, JBER was satisfied with CSU's decision to proceed with SFCWs as the most feasible technology to study. Prior to the application of this technology on-site, determination of degradation parameters was the next step to evaluate feasibility of the technology on an experimental basis. To achieve this, it was useful to have a better understanding of the biological processes in SFCWs and the process variables that affect degradation efficiencies. Chapter 4 explains the process kinetics specific to SFCWs and the main design equations that aided the development of the experimental design and methods.

4. SUBSURFACE FLOW CONSTRUCTED WETLAND TECHNOLOGY

The subsurface flow constructed wetland technology has been used to treat different types of wastewaters for more than 30 years. When properly designed, SFCWs can be low-cost, and low-energy wastewater treatment alternatives (Castro, 2005). SFCWs also require minimal operation due to their reliance on enhanced natural processes to achieve biological degradation of different compounds. Due to their simplicity SFCWs have been used to treat wastewaters from municipal, agricultural, industrial, and non-point sources (Vymazal, J., & Kröpfelová, 2009). Treatment of stormwater runoff from airports has proved successful for degrading organic compounds in deicing fluids by the use of SFCWs. The SFCW design at these airports vary by case and has been adapted to achieve maximum compound removal based on their specific needs. Stormwater quality in the inflow, ambient conditions, and desired water quality in the outflow are important parameters that affect the best design (DuPoldt et al., 2000). Therefore to achieve the desired water quality from SFCW treatment the proper design must be used and biological processes in SFCW must be thoroughly understood.

Subsurface flow constructed wetlands are basically constructed wetlands that have been engineered to enhance the naturally occurring biological processes. To enhance microbial growth of carbon consuming microorganisms, oxygen from vegetation and/or aeration systems and necessary nutrients are usually provided to the system (Reed, 1993). The gravel or porous medium used in the system provides additional surface area for microorganisms to adhere to and to prevent washout. As wastewater enters the SFCW, the attached microorganisms make use of carbon (and sometimes nitrogen) as an electron donor to achieve the metabolic processes necessary for cell synthesis and cell function (Reed, 1993). If the SFCW design allows enough hydraulic retention time, the carbon concentrations will decrease significantly by the time the water reaches the outlet. The main advantage of SFCW is that microorganisms present in the water are naturally adapted to temperature conditions during deicing season, which eliminates the need for additional heating systems. However, biological degradation in these systems are relatively slow and variables in design parameters will determine the treatment efficiency in the system.

4.1 Airports around the world that use SFCWs on-site

The application of subsurface flow constructed wetlands (SFCWs) to treat aircraft deicing fluid (ADF) contaminated stormwater have been successful in airports located in Buffalo, Edmonton, and London. Each of these airports have taken different approaches in the design and operation of the SFCW. The ADF usage, ADF type and COD and BOD loadings also varies within these airports. Weather conditions in Edmonton and Buffalo are approximate to those in Anchorage, Alaska. Although, London has an average monthly temperature higher than these cities but has successfully implemented the SFCW system for handling their ADF contaminated stormwater.

The Buffalo Niagara International Airport (BNIA) has been successfully operating a vertical flow subsurface constructed wetland (VSSF) designed to treat 1150 m^3 PG/yr. Around 303,797 gallons of deicing fluids are reported to be used at BNIA during the 190 days of deicing season. The 1.9 ha wetland consists in four individual VSSF cells (51 m by 91 m each) that are located in an open space near the airport's main runway. The flow rates are approximately 3800 m3/d of total contaminated stormwater plus an additional 820 m^3/d of collected spent ADF. The VSSF is constantly aerated with four 250 hp blowers that provide airflow through a piping system below the gravel bed. The BNIA subsurface flow wetland system has resulted in a reduced COD and BOD to values below the 30 mg/L benchmark (Higgins et al., 2011) (Wallace, 2011).

The horizontal flow subsurface constructed wetland (HSSF) system in Edmonton International airport consists in twelve cells distributed evenly in a 2.4 ha area. The constructed wetland was designed for a maximum flow rate of 1,300 m^3/d glycol contamination level during cold months and a flow rate of 1,500 m^3/d during warmer months. It is capable of treating stormwater contaminated with up to 1,400 mg/L of ethylene glycol (EG) based ADF. The constructed wetland has been planted with 750 cattail clumps to provide additional oxygen to the system. The maximum BOD concentrations have been measured to be 25 mg/L well below the minimum benchmark desired (Higgins et al., 2002).

In addition, Heathrow Airport located in London has a constructed wetland system comprising of 12 beds planted with reeds as oxygen providers. The system was originally operated in a HSSF mode but it has recently been switching to a VSSF operation. Heathrow Airport uses a combination of propylene glycol (PG), ethylene glycol (EG), and diethylene glycol (DEG) based ADFs that provide more than 2,000 mg/L of BOD in the stormwater to be treated. The configuration of London Heathrow Airports' system is more complex than the systems at BNIA and EIA since photoremediation raft channels between the ponds are included. A total of 3.1 ha comprise the whole system and a total outlet concentration is reported to be around 40 mg/L of BOD (Murphy et al., 2015).

Table 4.1 summarizes the design parameters for each airport's SFCW, and additional information on their ADF usage. Each parameter is compared to the information available from JBERs conditions. The required design flow and concentrations in the influent at JBER are unknown and vary depending on the weather conditions and ADF usage. However, the proper size and design can be determined to fit the conditions on the military base. Information about the treatment capacity of other SFCWs is useful as a comparative basis for JBER's case. To allow a better understanding of treatment performance at airports with similar weather conditions and ADF usage as JBER.

Table 4.1 Average SFCW design information from JBER and other airports.

	Edmonton International Airport	Buffalo-Niagara International Airport	Heathrow Airport	Joint Base Elmendorf-Richardson
Design flow	1,300 m^3/d	4,620 m^3/d	3,456 m^3/d	Highly variable
Average BOD (mg/L) in inlet	1,350	2,400	>2000	Highly variable
Average BOD (mg/L) in outlet	25	30	40	Must be below 30 mg/L
Constructed Area	2.7 ha (6.67 acres)	Four 51m x 91m cells (4.5 acres)	2.1 ha (5.19 acres)	At least 1 acre
Average annual inches of Snow	48.6	91.8	18.4	70 (EPA app B-1)
ADF Usage	N/A	1150 m^3 (303,797.9 gal)	N/A	280,000 gal
Retention time (degradation rate k)	N/A	1.5 days (5.4 d^{-1})	13-21 days (5.6 to 8.3 d^{-1})	N/A

The different designs and operational variabilities between the SFCW systems in Edmonton, Buffalo, and London have been selected to handle the expected COD and BOD loadings for conditions at each airport. These international airports experience high traffic; therefore, require high demands of ADF application comparable to usage at JBER. For example, BNIA applies 1,150 m^3 (303,797.9 gallons) of ADF per year similar to the 280,000 gallons applied per season at the military base. ADF usage statistics for EIA and Heathrow were not available, but based on their size and weather conditions it can be implied that their usage is in the high range similar to BNIA.

However, the size of the SFCW is not only determined by the amount of ADF applied by the airport, but also the size depends on degradation efficiency of the system and the quality of the water to be treated under the environmental conditions at the airport. In the case of BNIA, the 4.5 acre SFCW was designed to handle loads of 4,620 m^3/d of 2,400 BOD mg/L stormwater runoff. This is partially due to the high average annual precipitation in Buffalo, NY that results in large volumes of high ADF concentration runoff. EIA is an airport of very similar size (per passenger traffic), but its 6.67 acre SFCW is designed to handle 1300 m^3/d of 1350 BOD mg/L. The higher efficiency of BNIA's wetland might be due to faster degradation rates in the system from operational upgrades (mechanical aeration) and also the warmer average temperatures in Buffalo compared to those in Edmonton.

Heathrow's 5.19 acre SFCW is also designed to handle a quantity similar to BNIA's system. London's average temperature and precipitation is relatively higher that those at Buffalo; therefore Heathrow's yearly ADF demand per single aircraft is lower than at BNIA. However, Heathrow airport's quantity of aircraft traffic (474,087 aircraft movements per year) requires a large total ADF demand which results in highly concentrated stormwater runoff after deicing. Therefore, Heathrow's runoff volume is comparable to an airport with less traffic in a city with high yearly precipitation such as Buffalo.

This comparison between BNIA and Heathrow shows how airports of different sizes and weather conditions can handle similar volumetric and BOD concentration loads with successful results. Additionally, all airports, including EIA, use of different kinds of ADFs that degrade at different rates. Operational variables such as the use of vegetation vs. mechanical aeration or horizontal vs. vertical flow, also affect the efficiency of ADF degradation. These different variables must be considered when designing a SFCW on a case-by-case basis. A proper design and size can be determined with knowledge of the expected degradation efficiency due to conditions at each airport. To determine the size of a SFCW, applicable design equations have been generated to describe the biological processes inside the system, and the water flow through the packed bed system. The following section explains the basic knowledge necessary to understand the SFCW design and performance.

4.2 Kinetics and flow equations for the design of a SFCW

When compared to heated systems like activated sludge reactors and anaerobic fluidized bed reactors (AFBRs), SCFWs are slow and result in lower degradation percentages. Selection of important design parameters must be done by considering the quality of the water to be treated and the average volumes during the deicing season. Design equations are based on first order kinetics that describe the degradation of COD and BOD by microorganisms in SCFW and Darcy's Law that describes flow regime in porous media (DuPoldt et al 2000) (Reed, 1993).

The quality of the water in the inflow and the desired outflow quality define the hydraulic retention time (HRT) by the first order kinetics equation (Reed, 1993) (Bergdolt et al. 2013)

$$\frac{C_t}{C_o} = e^{(-k*t)} \quad \text{(Equation 4.2)}$$

C_t = concentration of the compound at time t
C_o = initial concentration
k = first order degradation constant
t = hydraulic retention time

When rearranged, the equation can be used to determine the required treatment time in order to achieve a target concentration in a specific system:

$$t\ (HRT) = \frac{-\ln\left(\frac{C_t}{C_o}\right)}{k} \qquad \text{(Equation 4.3)}$$

The initial and final concentrations in this equation are variables determined by the water quality before treatment and the desired target concentrations (i.e., benchmarks required by regulatory agencies). The k value, is an important parameter determined by experimental procedures and data acquisition, and it varies based on the environmental conditions of the system.

A larger k value corresponds to faster degradation rates and lower HRTs required to achieve a desired concentration. Therefore, these parameters must be taken into consideration when sizing and designing a SFCW treatment process. Degradation rates can be easily determined by mathematical procedures and basic knowledge of microbial kinetics. The following figure is a representation of a typical first order kinetic growth curve and compound degradation over time:

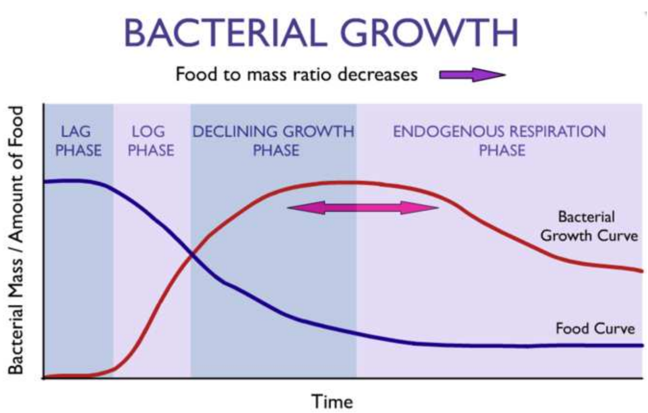


Figure 4.1 Phases of a typical microbial growth curve. Retrieved from http://www.ebsbiowizard.com/2010/11/biological-growth-curve-in-aerated-stabilization-basins/

In Figure 4.1, the purple curve describes degradation of food source (i.e. organic compounds) over time. The red curve describes microbial growth as the bacteria consumes the food source. The process begins with a lag phase in which organisms must adapt to the new conditions. Therefore, the “food” concentration and biomass (from microorganisms) remain constant for a period of time. As microorganisms adapt and begin to grow, the microbial density increases as the “food” concentration declines with time. Eventually, the microorganisms exhaust all their food sources and begin to die.

In a first order kinetics process, the rate of degradation (k) is determined during the declining growth phase when microorganisms grow at a rate that is proportional to the concentration in the system. To obtain a numerical k value, it is useful to obtain reliable degradation data reported as food concentration over time. From the first order degradation Equation 4.2, the following equation of a line can be obtained:

$$\ln[C_t] = \ln[C_o] - kt \qquad \text{(Equation 4.4)}$$

This equation corresponds to a line with a negative slope of k. When plotting the natural log of the concentration vs time, the k value of a microbial process can be easily obtained.

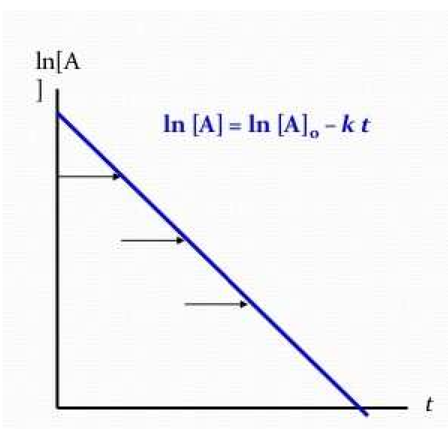


Figure 4.2 Graphical representation of a first order degradation natural log equation.

The equation of a line (y=mx+b) shows that the negative slope k defines the degradation rate of the biological system. The hydraulic properties of a SFCW are defined by Darcy’s Law which describes hydraulic flow on a porous medium. This equation defines other design parameters that closely depend on wastewater volumetric flows. Darcy's Law is described with the following equation:

$$Q = K_s * A * S \qquad \text{(Equation 4.5)}$$

Q = volumetric flow rate
K_s= hydraulic conductivity
A = cross sectional area perpendicular to flow
S = hydraulic gradient

Although the flow in a SFCW is highly variable in volumetric flows and initial toxic compounds concentration, Darcy's model has been successfully used in large scale design and operation of SFCWs (DupPoldt et al., 2000) (Reed, 1993). When combined with a first order kinetics model (Equation 4.3), the equations provide useful information to determine the size and configuration of a wetland that will treat the expected flows to a desired minimum concentration.

The EPA provided a step-by-step tentative process for SFCW sizing based on the previously described formulas. In summary, determining the final design of a SFCW is an iterative process in which optimal parameters must be carefully selected to guarantee that the system can handle the expected volumetric flows. Therefore, the size of the bed must be determined based on the expected volumetric storm water runoff (Q) during extreme weather conditions to prevent flooding in the system. The parameters hydraulic gradient (S) and hydraulic conductivity (K_s) also affect the size and hydraulic performance of the wetland and may be chosen based on optimal ranges provided by the EPA. Published guidelines are stated as optimal aspect ratio (L:W, no larger than 3:1), hydraulic gradient (less than 10%), and hydraulic conductivity, (less than 1/3 of the "effective" value) (Reed, 1993).

The initial concentration in the system (C_o) and the degradation rate constant (k) are also important variables considered when designing a SFCW. As previously described, if a final effluent concentration (C_T) value is specified the required time of degradation (t=HRT) can be determined using equation 4.3. In extremely cold environments, degradation rates can fall below optimal values and therefore require longer HRTs to achieve the desired concentration in the effluent. Based on volumetric flow equations, it is implied that longer HRTs can be achieved with larger wetlands that can retain larger volumes. However, the constructed wetland manual by EPA 1993 states that after a certain HRT has been reached, the extent of degradation in the system does not improve significantly. As a result it is implied that the parameter k is the determining factor that determines if optimal degradation in the system can be achieved. Overall, the challenge in a SFCW is to optimize the k value so that minimum HRT is necessary to degrade the organic compounds in a bed sized to handle the expected volumetric flows.

4.3 Degradation Rates in a SFCW system

The degradation rates (k) in a SFCW system strongly define the overall treatment performance and extent of degradation. Therefore, optimal conditions for microbial growth must be achieved to reduce the COD and BOD of the wastewater. Ambient conditions are an important factor to consider. In a biological treatment process the temperature of the system can be a limiting factor for degradation rates (Lorion, 2001).

If the wastewater is very high in carbon content, additional oxygen may be required to sufficiently allow metabolic processes to take place. Therefore an oxygen source must therefore be considered in the final design of the SFCW. An economic approach incorporates vegetation planted on the surface of the SFCW (Akratos & Tsihrintzis, 2007). An efficient method is the addition of oxygen from blowers that provide aeration through pipelines in the bottom of the SFCW. Necessary nutrients must be added to aid in cell synthesis and function (Wallace & Liner, 2010). Degradation rates are strongly dependent on water temperatures. Lower temperatures generally result in longer adaptation, slower microbial growth, and slower carbon removal (Nedwell, 1999). Another important consideration is the carbon composition in the feed water. Some carbon sources tend to have a lower biodegradability than others depending on their molecular formula (Corsi et al., 2012). These are important variables that significantly affect degradation rates in a system. Different studies have been done to determine how these variables affect degradation rates and to what extent. The following section provides information about the effects these variables have in the overall condition of the system and their importance.

4.3.1 Variables that affect the degradation rates (k) of a SFCW

Temperature:

Ambient temperature is a parameter that is known to have an effect on microbial growth and degradation rates in the environment. Optimal temperature for microbial growth varies by microbial population. There is evidence of bacterial populations that can exist in the coldest (psychrophilic) and warmest (thermophilic) environments. However, in most biological treatment systems, bacteria that survive at intermediate temperatures (mesophilic) is predominant. In general higher temperatures are beneficial to microbial growth unless the optimal temperature is exceeded and denaturing of proteins takes place. In activated sludge systems a decreased performance has been seen for temperatures under 41°F whereas the optimal temperatures for anaerobic processes are 85°F-90°F (ACRP, 2013).

In SFCWs, microbial populations exist at ambient temperatures. However, biological processes slow down during colder periods. Some studies show that COD degradation rates in SFCWs during colder conditions are slower than during warmer conditions. Degradation of propylene glycol (PG) has also been severely inhibited under low temperature (5°C) conditions. Whereas, PG degradation at 20°C was a lot more rapid (Stein & Hook, 2005). In some cases

COD removal was not significantly affected by temperature conditions while nitrogen removal required a higher HRT for temperatures under 15°C (Akratos & Tsihrintzis, 2007). In a SFCW, higher loads of BOD can be handled during summer months compared to those during winter months.

Aeration:

The effect of aeration in a biological degradation process is an important one that must be considered in the design of most biological treatment plants. Oxygen is the strongest electron acceptor for heterotrophic bacteria resulting in higher microbial yields when present. In conditions where there is oxygen depletion, heterotrophs make use of other electron acceptors (NO_3^-, SO_2^{-4}, and CO_2) to survive. The energy provided by anoxic oxidation reactions is lower than the energy released when oxygen is the electron acceptor. As a consequence, there is lower microbial yield, and therefore slower degradation rates.

Complete glycol degradation is known to be successful during both aerobic and anaerobic conditions. The PG degradation process generally follows the same oxidation path in both cases. Initially, PG degradation follows a redox process in which PG is separated into its oxidized fatty acid (propionate) and its reduced alcohol form (n-propanol). The alcohol form is further oxidized to a fatty acid with release of hydrogen atoms. Propionate is converted to acetate, which is subsequently converted to methane if anaerobic conditions exist (Zitomer & Tonuk, 2003).

In SFCWs, both aerobic and anaerobic degradation processes may take place depending on the wetland design and operation. Oxygen transfer methods may also vary by case. Aeration can be provided by mechanical means and/or blowers, or use certain type of plants that provide oxygen through diffusion in the system (Reed, 1993).

Horizontal flow wetlands that are planted for the purpose of oxygen addition usually undergo aerobic degradation near the zones adjacent to the roots and rhizomes. Anaerobic degradation takes place below the wetland where oxygen concentrations tend to be low due to the limited oxygen transfer in horizontal flow systems. In hybrid wetland designs that use mechanical aeration, the aeration rates and dissolved oxygen concentrations are adjusted to achieve the degradation process desired (Vymazal, 2005). Nutrient removal by nitrification (aerated) and denitrification (anoxic) processes is used in certain cases where minimum nitrogen and phosphorous concentrations in the outlet are desired. Hybrid systems that interchange vertical and horizontal flow to allow oxygen transfer capacities have been found to be useful as an oxygen addition method with low energy requirements.

Nutrient Addition:

For microorganisms to grow, reproduce, and perform functions for survival, they need a minimum amount of nutrients available in the environment they exist. The chemical composition of most microorganisms includes carbon (45%-55%), oxygen (22%-28%), nitrogen (8%-13%), hydrogen (5%-7%) and other inorganic chemicals in lower concentrations (phosphorous, sulfur, etc). In natural environments, these chemicals are found in sufficient amount to allow microbial populations to thrive in biological equilibrium. However, for enhanced growth in a biological treatment system, the addition of nutrients may be necessary to achieve desired microbial growth.

Two of the most important nutrients for microbial synthesis are nitrogen and phosphorous. Nitrogen is an important element that is present in proteins and nucleic acids, which represent about three quarters of the organic matter in the cell. Phosphorous is also present in nucleic acids and composes part of important enzymes that aid in essential chemical reactions for cell function and synthesis. Insufficient concentrations of these compounds in the water can result in slower microbial growth and increased lipid production by the cells. This can affect the efficiency and performance of a SFCW system. At some airports, the degradation rates have been found to be slow due to nutrient limitations (e.g. Buffalo and Heathrow). Slime and foaming due to polysaccharide production also affected the hydraulic conductivity of the wetland (Wallace & Liner, 2010). Further addition of nutrients was implemented and COD removals were found to increase and foaming was eliminated.

Composition:

Several types of ADFs are applied by airports and each type serves a different purpose depending on its composition. Type I and II are propylene glycol based deicing fluid and anti-icing fluid, respectively. Type III and IV are ethylene glycol based fluids (Ramakrishna & Viraraghavan, 2005). These fluids contain additional compounds (e.g. corrosives, surfactants, etc.) that are largely unknown in composition and concentration (EPA, 2012). Additionally, airports apply large quantities of acetate, formate, or urea based deicers to the airfield. All these ADFs are usually combined as the water is washed out and discharged in the form of runoff.

The degradation rates in a biological system are important kinetic parameters that define the speed and efficiency of the system under certain conditions. In SFCWs used for stormwater treatment, the degradation rates tend to be relatively low compared to systems with added energy from heat like activated sludge and anaerobic fluidized bed reactors (ACRP, 2013). Nevertheless, SFCWs have proved to be successful in degrading the organic compounds in ADF from airports around the world even under very cold temperatures and high precipitation rates. Several parameters of SFCW design must be considered including land availability, operational procedures, aeration source, and gravel size. Therefore, additional knowledge of the operational and process variables of the system must be known for a particular case.

To obtain additional knowledge about the unknown variables of the process, it is necessary to collect data from experimental procedures that represent conditions in which the SFCW will operate. The first step of this process is to analyze the microbial activity by obtaining degradation data over time so that a first order equation is obtained and the degradation rate of the system can be determined. The experimental study described in Chapter 5 aimed to determine the degradation rates (k) of a system that simulated a SFCW under conditions that will simulate those at the JBER base. The equations of first order degradation in this chapter were used to determine the k value for each experiment. Conditions for each experiment were based on the variables temperature, aeration, nutrient addition, and composition as explained in this chapter. The analysis of the experimental results was used as evidence to make the proper recommendations to JBER’s on-site system and the future work that must take place prior to implementation (Chapter 6).

5. ADF DEGRADATION LABORATORY STUDY

To obtain data for microbial kinetics in a SFCW relevant to JBER, it was necessary to simulate conditions at JBER as accurately as possible. Several process variables affect the performance of a SFCW, but for simplicity purposes this experimental process was mainly based on degradation rates (k) to evaluate performance of the system. As discussed in Chapter 3, economy and simplicity were important factors for technology selection. Therefore, variables that add to the costs of the system, such as aeration and nutrient addition, were studied. Additionally, as explained in Chapter 4, the composition of ADF present in the water might have a significant effect on the degradation rates of the system. The following variables were tested and their importance to JBER's case are discussed below:

Temperature:

Temperatures in Anchorage, Alaska are relatively low all year long. However, during the summer temperatures can reach up to 65°F on the warmer days. Therefore, two temperatures were tested that simulate colder temperatures during deicing season (winter, at 5°C) and warmer temperatures for periods when deicing is not necessary (summer, at 20°C).

Aeration:

Although aerobic systems provide faster removal rates than anaerobic reactors it is useful to compare both cases to consider a more economic design for SFCWs. Since JBER's total COD and BOD removal fractions that are needed to meet the benchmark are not very high, a system without aeration might be a feasible alternative.

Composition:

Since propylene glycol (PG), potassium acetate (PA), and sodium acetate (SA) have different degradation rates, the study was useful to determine if the composition of ADF has a significant effect in the overall efficacy of the system. PG is known to have a slower degradation rate than acetate based deicing fluids. As expected, large concentrations of PG based ADF in the stormwater would result in slower degradation rates.

Nutrients:

Nutrient addition has been proven to be necessary to achieve optimal BOD and COD removal rates. Since the addition of nutrients would result in increased operating costs, this variable was studied. Also, nutrients can be detrimental to water surfaces if they are not removed from the treated water prior to discharge. Therefore, various scenarios were examined for reactors with necessary nutrients compared to those where nutrients were absent.

5.1 Objectives

The general objective of this part of the thesis was to experimentally evaluate the performance of SFCWs under different conditions relevant to JBER's case. The following variables considered in this evaluation as previously mentioned: temperature, aeration, nutrient addition, and composition. A total of 14 batch experiments for different case scenarios were performed. The COD concentration data was collected over a 30-35 day time frame. The main objectives that this experimental study aims to achieve are:

1. Obtain data of COD degradation over time in batch SFCWs to generate first order degradation curves and determine the degradation rates, lag phases, and half-lives of the system when tested under different conditions.

2. Determine the effect of each testing variable on degradation rates with the help of graphical and numerical data, and of design of experiment (DOE) analysis.
3. Evaluate and compare results found during summer and winter conditions, and determine the implications of other variables for optimal performance at JBER.

5.2 Methodology

5.2.1 Model water preparation

Bench scale experiments that simulate SFCWs were designed with consideration to JBER's ADF usage during deicing season and expected COD concentrations on the base. JBER reported that during deicing season an average of 130,000 gallons of propylene glycol (PG) based type IV aircraft deicer fluid is applied on the military base. Additionally, JBER applies around 120,000 gallons of potassium acetate (PA) liquid airfield deicer, and 150 tons of sodium acetate (SA) based solid airfield deicer. As previously mentioned 70% of the ADF contaminated stormwater runoff is discharged at the outfall where COD data is collected. The average value of COD concentration in the outfall point is 136.7 mg/L which is very low compared to the large COD concentrations in ADF. This is due to the dilution caused by the large amount of water coming from natural seeps located in the north part of the runway and by stormwater runoff. It is expected that the stormwater runoff near the runway has much higher COD concentration values and that water volumes are lower than those reaching the discharge point year-round.

Utilizing previous information, the model water used during testing was made to simulate stormwater runoff to be treated near the runway where most deicing operations occur. Water from Horsetooth Reservoir in Fort Collins, CO was mixed with the ADFs provided by JBER to achieve COD concentrations between 9,000 mg/L and 10,000 mg/L. These concentrations were achieved under different ADF compositions for the model water.

The first set of experiments evaluated the different parameters for a model water with a mixture of the PG, PA, and SA based ADFs. The volumetric ratios used were based on the average volumes applied by JBER during deicing season (Appendix A). Based on applied fractions at JBER, model ADF was composed of 47.45% PG based ADF, 43.8% PA based ADF, and 8.74% SA based ADF. The second set of experiments was done with model water compared of 100% PG based ADF. A mixture of all ADFs is likely to be seen near JBERs runway based on the information given. However, the application rates/volumes for each ADF may vary depending on JBER's needs. Since PG is less biodegradable compared to PA and SA, it is valuable to obtain degradation rates of PG only and understand how its concentration in the stormwater affects overall treatment. A yield ratio of 0.3 biomass produced per mass of influent BOD for nutrient addition was used-similar to that determined by BNIA. (Higgins et al., 2011)

5.2.2 Experimental Design

Gravel Beds

Subsurface flow constructed wetlands were simulated by bench scale gravel beds in a batch configuration. Model water was prepared at a specified COD concentration and poured into 16.25 in. x 13 in. x 6.125 in. boxes filled with 3.5 inches of pea gravel. The pea gravel used had an average diameter of 3/8 inches and was obtained from Pioneer Sand Company in Fort Collins, CO. The boxes tested were then sealed with parafilm around their borders to minimize evaporation of water. To prevent algae formation and to avoid errors in COD removal data, the beds were covered with aluminum foil to prevent light exposure.

Figures 5.1 and 5.2 show the typical set-up of each gravel bed. For experiments done under anaerobic conditions, the boxes were sealed to prevent any oxygen diffusion into the gravel. A total of 3.6 liters of ADF solution was added to the bed to ensure the gravel and water were at equal heights.

Figure 5.1 Gravel bed set-up

For aerated experiments, an air distribution manifold shown in Figure 5.2 was placed at the bottom of the beds to allow for even distribution of air.

Figure 5.2 Aeration manifold.

As seen in figure 5.2 the manifold was connected to an air flow port and the flow rate was adjusted to allow a minimum of 2 mg/L of dissolved oxygen (DO) throughout the box.

5.2.3 Data Collection:

COD data was collected daily and COD degradation percent per day was calculated for each bed. The COD was analyzed with HACH HR+ COD vials. Approximately 1 milliliter of water was pipetted out from a middle point inside the bed for analysis. The water samples collected for analysis were filtered through a 0.2 micron filter to prevent microbial COD from affecting the measurements. 200 microliters of sample was added to each COD vial and the vials were incubated for 2 hours to allow for a complete oxidation reaction. The COD was measured with a HACH COD analyzer at a wavelength of 620 nm. Triplicate data points were collected each day and the average COD was calculated for each point

5.2.4 Experimental Nomenclature:

Different conditions for gravel bed experiments have been tested to determine first order reaction rates and total degradation percentage as a function of hydraulic retention time. A total of 14 cases have been considered and the most relevant scenarios have been tested using bench scale experiments. Variables that differ from each case scenario are ambient temperature (summer vs. winter), composition of ADF (all ADFs combined vs PG only), oxygen addition (aerated vs. non-aerated), and nutrient addition (nutrient addition vs. nutrient deficiency). Bed nomenclature consists of two letters, a digit (1 or 2), and a minus (-) sign. This nomenclature is described below.

A or P: The model water is a mixture of propylene glycol, potassium acetate, and sodium acetate decicers (A); or the mixture contains propylene glycol only (P)

A or N: Aeration is added to the gravel bed (A), or the bed is non-aerated (N)

1 or 2: The bed is placed in a cold temperature room at 5°C simulating winter conditions **(1)** or the bed is placed on the lab bench at 20°C simulating summer conditions **(2)**

Minus (-) sign: If a minus sign is added following the first three terms, it means nutrients were not added to the model water and the system is nutrient deficient.

For instance, conditions of bed PA2- are: only propylene glycol based deicer was added, the bed was subjected to aeration, placed at a 20°C laboratory bench, and nutrients were not added. Table 5.1 is a summary of all case scenarios that were tested with their corresponding ID.

Table 5.1 Bed nomenclature for all 14 experiments performed under different conditions.

				BED ID
AERATED	WINTER	All De-icers	NUTRIENTS	AA1
			NO NUTRIENTS	AA1-
		Propylene Glycol ONLY	NUTRIENTS	PA1
			NO NUTRIENTS	PA1-
	SUMMER	All De-icers	NUTRIENTS	AA2
			NO NUTRIENTS	AA2-
		Propylene Glycol ONLY	NUTRIENTS	PA2
			NO NUTRIENTS	PA2-
NON AERATED	WINTER	All De-icers	NUTRIENTS	AN1
			NO NUTRIENTS	AN1-
		Propylene Glycol ONLY	NUTRIENTS	PN1
			NO NUTRIENTS	
	SUMMER	All De-icers	NUTRIENTS	AN2
			NO NUTRIENTS	AN2-
		Propylene Glycol ONLY	NUTRIENTS	PN2
			NO NUTRIENTS	

The first column indicates if the experiment was done under aerated or non-aerated conditions. For each aeration conditions the temperature was varied between summer (20°C), and winter (5°C). The third column shows different compositions in the model water: either all ADFs or PG only. Most experiments were tested with and without nutrient addition under the same conditions except for PN1 and PN2 which were expected to have very low degradations if nutrients were lacking (based on results from the PN1 and PN2 experiments).

All experiments were conducted over a 30 day timeline and COD samples were taken on a daily basis to determine total degradation as a function of time and obtain a numerical value for the first order degradation constant (k). The data was added to an Excel spreadsheet and plotted against time (days) to obtain microbial growth curves. Individual degradation curves for each experiment is presented in Appendix B with their corresponding ln(COD) vs time curve that was used to determine k values. All results are presented in the following section in a convenient manner to compare the different parameters and their effect on COD degradation. Numerical values of k values, lag phases, and half-lives determined are also presented in the next section. A design of experiment (DOE) analysis was used as additional evidence to make the appropriate conclusions based on the observations made in the numerical and graphical data.

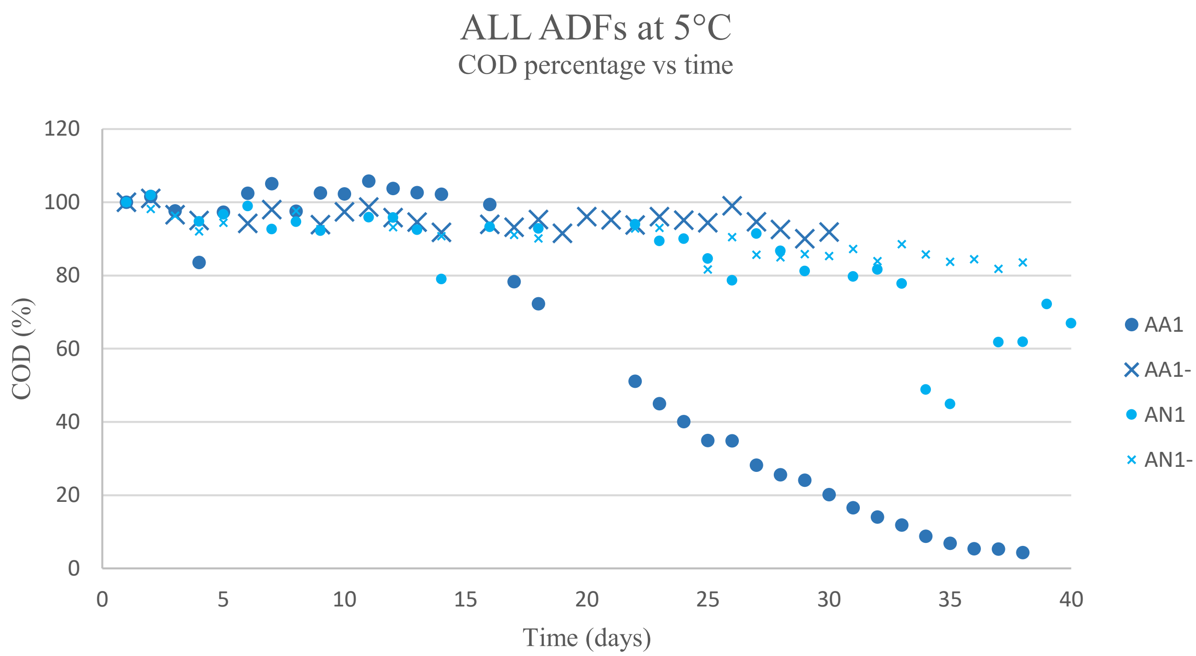
5.3 Results and Discussion:

5.3.1 Numerical and Graphical data:

Figures 5.1 and 5.2 represent the degradation of COD over time for all experiments performed during winter and summer conditions. Figure 5.1 shows experiments where all ADFs were added to the model water (PG, PA, and SA based fluids), and Figure 5.2 shows experiments where only PG based fluid was added. A total of 14 experiments with varied conditions were performed (8 for all ADFs, and 6 for PG only). Temperature conditions are identified by the color red (summer) and blue (winter). Aerated experiments are identified by large dark markers while non-aerated experiments are identified by small lighter colored markers. Finally, nutrient conditions are identified by circles (nutrients added) or crosses (no nutrients added).

All plots are presented as COD percent over time. This means the initial COD measured in day 1 corresponds to 100% of the COD in the system. The COD after each day of treatment is therefore, the percentage of COD not degraded in the system since day 1. This was done to account for small discrepancies in initial COD between all experiments. In some instances, the COD during the first few days of adaptation increases above the initial COD taken on day 1 (above 100%). This may be attributed to either an increase of soluble microbial byproducts from non-adapting microorganisms that have died during the adaptation period or to measurement error.

Most experiments were tested in a time frame of 30 days minimum with only a few exceptions. If most of the COD was degraded or if a k value was determined before day 30, the experiment was terminated. During the first days of treatment, there was no degradation (or very slow) for all experiments. This time period corresponds to the adaptation lag phase in which microorganisms must adjust to the new conditions in the system. After the lag phase, most experiments showed a decline of COD that followed a first order degradation curve when plotted. Appendix B shows the first order degradation plots used to determine the k value. The natural logarithm of COD values during the steady growth phase was plotted against time fitted with a linear equation to determine the k value (negative slope) of first order degradation rate.



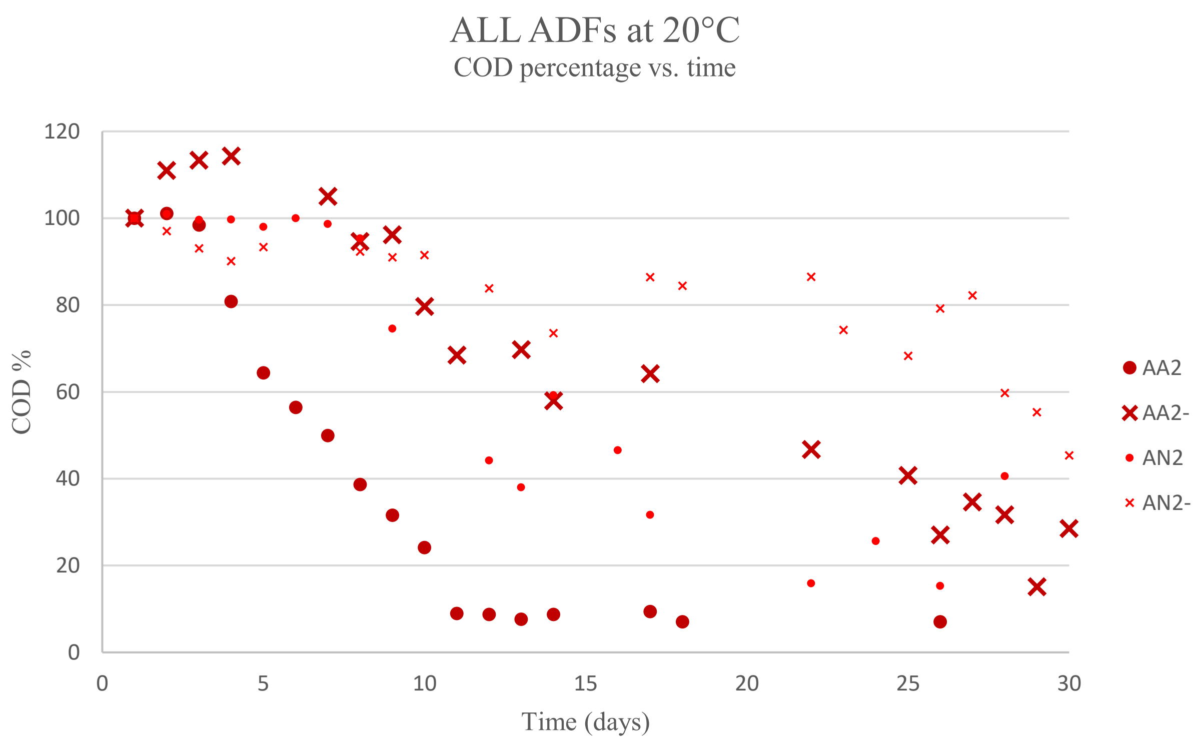
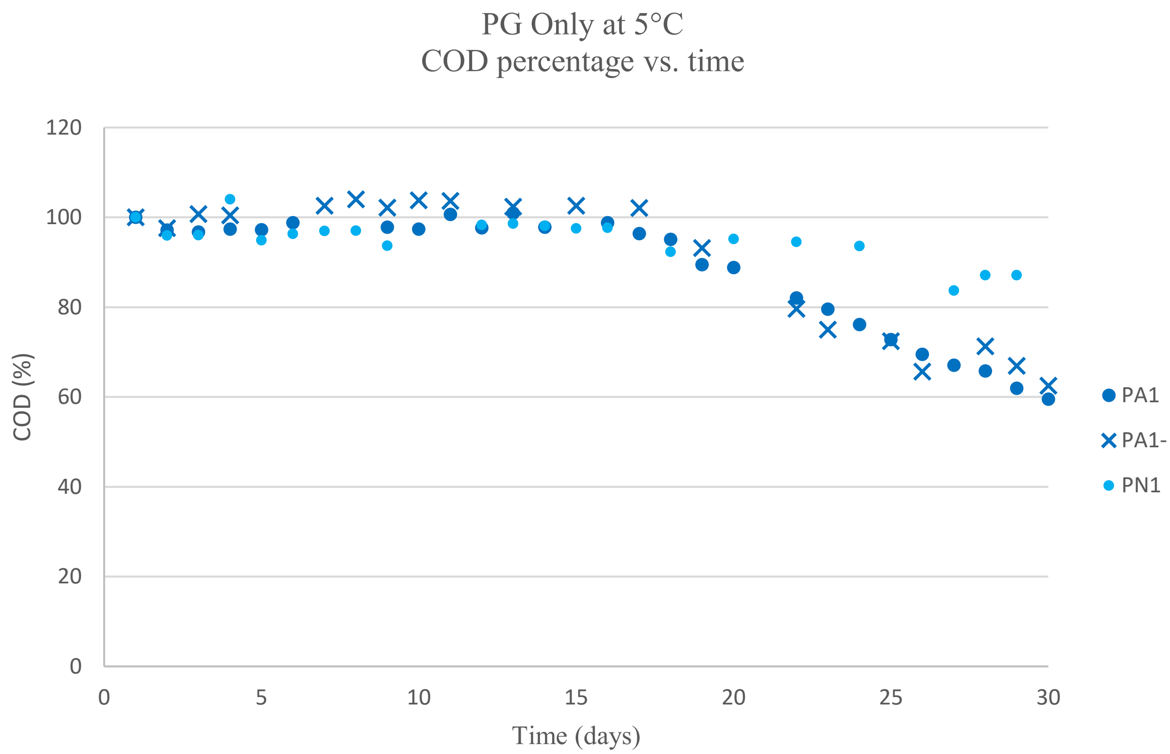


Figure 5.3 COD percent over time for all experiments with all ADFs during winter conditions (top), and summer conditions (bottom).



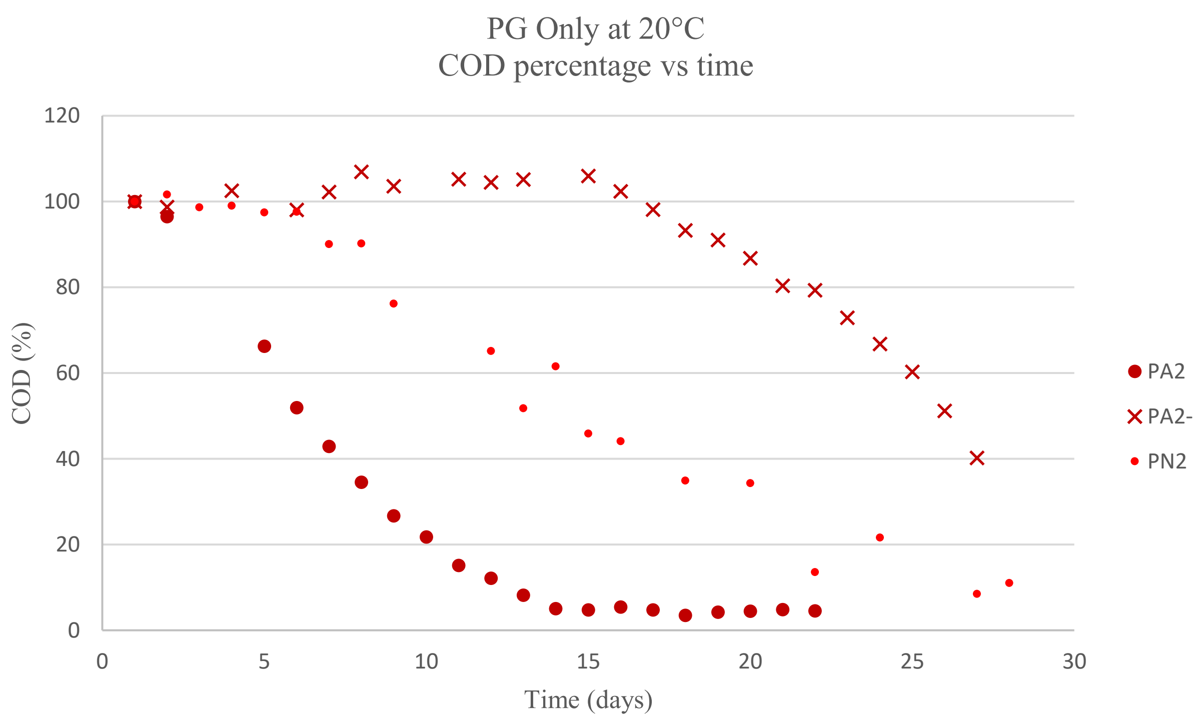


Figure 5.4 COD percent over time for all experiments tested with propylene glycol (PG) based ADF during winter conditions (top), and summer conditions (bottom).

In general, degradation curves in both Figures 5.3, and 5.4 follow a similar pattern when comparing winter vs summer conditions. Regardless of the composition in the model water, the experiments conducted in 20°C (summer) show steeper degradation curves with lower COD percent values after the 30 day period than experiments conducted under 5°C (winter). Most summer degradation curves show short lag phases followed by first order degradation curves showing steady consumption of ADF in the wastewater until complete degradation. Conversely, winter curves show longer lag phases with larger COD percent values at the end of the 30 day period showing lower total COD degradation. Some winter curves in both figures do not show any significant degradation after 30 days and no steady first order degradation curves cannot be determined. Only experiment AA1 in Figure 5.3 (winter) showed a steep degradation curve and a total degradation of COD before the end of the 30-day period.

In all plots, the largest degradations were seen for experiments tested under aerated conditions with nutrients added (large circles; AA1, AA2, PA1, and PA2). These experiments showed steeper slopes and lower final COD percent values. For most plots, it can be seen that curves of experiments with nutrients (circles) are steeper and correspond to faster degradations than when nutrients are not added (crosses). In Figure 5.4, the experiments tested under winter conditions with nutrients (PA1) and without nutrients (PA1-) show very similar degradation curves and total degradation after 30 days.

Numerical data

Additional numerical data of k values, lag phases, and half-lives provided more information about the extent of degradation under different conditions. Tables 5.2 and 5.3 provide a summary of the kinetic parameters obtained from the first-order COD degradation curves.

In three instances (AA1-, AN1-, and PN1), the COD measurements did not show a steady COD decrease of more than 5% during the 30-day period. This could mean that either the system has an adaptation phase of longer than 30 days or the conditions of the system are largely unfavorable for bacterial growth to show first order degradation behavior. For analysis purposes, the lag phase value for these conditions was assumed to be larger than 30 days. While a first order degradation could not be identified for these values, a first order degradation line was fitted and the k value and half-lives were determined the in same manner as the other experiments so that they could be included in the analysis.

Numerical values in Tables 5.2 and 5.3 are presented in increasing order of half-life (decreasing degradation rates) and lag phases, respectively. Figures 5.5 and 5.7 provide a graphical representation of the magnitude of these values when compared to each other. All COD degradation plots and their corresponding first order natural logarithm curves can be found in Appendix B with their corresponding equation and r-squared values. All r-squared values were recorded and summarized in Table 5.2 next to the corresponding k values.

Table 5.2 summarizes the first order degradation rates or “k values” with their corresponding half-life values in days. The k values in the third column were determined by plotting a ln(COD) vs. time curve and fitting a linear in the form of y= -mx+b in which the negative slope (-m) corresponds to the first order degradation rate constant during. This was done by excluding the COD values during the lag phase. The half-lives of the system were obtain with Equation 4.3 by fixing the value $Ct/Co = 0.5$ for a 50% total removal from the starting concentration, and using the corresponding k value for each condition.

Table 5.2 k values and half-lives parameters for all 14 experiments in increasing order.

BED ID	**Conditions**	**First order rate constants (k day^{-1}) (R^2 value)**	**Half-Life (days)**
AA2	All ADFs/aerated/summer/nutrients	0.283 (0.908)	2.5
PA2	PG only/aerated/summer/nutrients	0.273 (0.982)	2.5
PN2	PG only/nonaerated/summer/nutrients	0.121 (0.908)	5.7
AN2	All ADFs/nonaerated/summer/nutrients	0.118 (0.77)	5.9
AA1	all ADFs/aerated/winter/nutrients	0.116 (0.98)	6.0
AA2-	All ADFs/aerated/summer/no nutrients	0.08 (0.912)	8.7
PA2-	PG only/aerated/summer/no nutrients	0.058 (0.964)	11.9
PA1	PG only/aerated/winter/nutrients	0.04 (0.995)	17.5
PA1-	PG only/aerated/winter/no nutrients	0.031 (0.81)	22.4
AN1	All ADFs/nonaerated/winter/nutrients	0.024 (0.7571)	28.5
AN2-	All ADFs/nonaerated/summer/no nutrients	0.018 (0.6484)	38.5
AN1-	All ADFs/nonaerated/winter/no nutrients	0.005 (N/A)	> 100
AA1-	All ADFs/aerated/winter/no nutrients	0.004 (N/A)	> 100
PN1	PG only/nonaerated/winter/nutrients	0.003 (N/A)	> 100

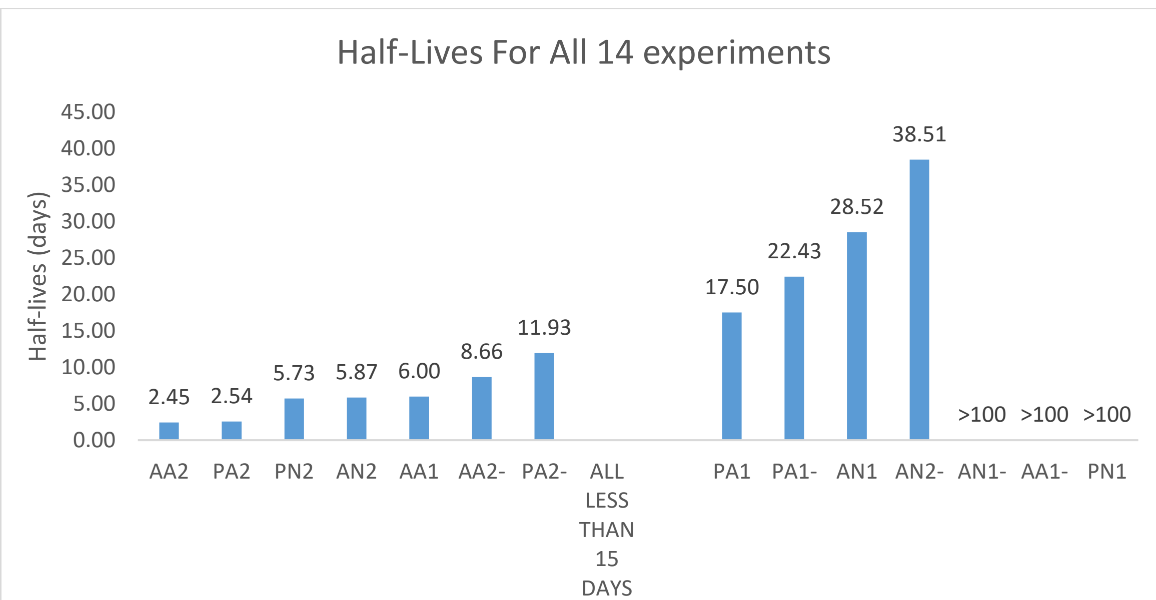


Figure 5.5 k values for all experiments in increasing order

Organizing the numerical data in Table 5.2 allows the separation of the acceptable conditions for a SFCW system from those conditions that may not be feasible due to very slow degradation rates. Figure 5.5 presents the numerical values of half-lives in increasing order separating those values that reached higher than 15 days on the right.

The figure shows a clear trend in which most experiments done at 20°C (recall nomenclature 2 = summer; 1 = winter) show half-lives shorter than 15 days and most experiments tested at 5°C show half-lives larger than 15 days. The three experiments that did not follow a first order decay relationship (AN1-, AA1-, and PN1) were all tested at 5°C and all resulted in a half-lives longer than 100 days. The only experiment tested at 5°C that showed a half-life less than 15 days was AA1 which was tested with aeration and nutrient addition for all ADFs combined. The only experiment tested at 20°C that showed a half-life longer than 15 days was experiment AN2-, which lacked both nutrients and aeration for all ADFs combined. The best conditions that showed shorter half-lives of less than 3 days were AA2 and PA2, both tested at 20°C, with aeration and nutrient addition for all ADFs and PG only, respectively.

Table 5.3 and Figure 5.6 summarizes the values of lag phase in days. As discussed in section 4.2, the lag phase is the time (days) that microorganisms take to adapt to the system's conditions before they begin to steadily grow. The numerical values in the first column were obtained by calculating the percent difference between COD measurements within two consecutive days. If the difference was lower than 5%, it was assumed that there was no degradation in the system and that microorganisms were still adapting. Once the concentration of COD decreased to at least a 5% difference from the previous day, it was assumed that microorganisms began to grow and the day was recorded as the end of the lag phase.

Table 5.3 Lag phases for all 14 experiments in increasing order

BED ID	Conditions	Lag Phase (days)
AA2	All ADFs/aerated/summer/nutrients	2
PA2	PG only/aerated/summer/nutrients	2
AA2-	All ADFs/aerated/summer/no nutrients	6
AN2	All ADFs/nonaerated/summer/nutrients	8
PN2	PG only/nonaerated/summer/nutrients	8
AN2-	All ADFs/nonaerated/summer/no nutrients	9
PA2-	PG only/aerated/summer/no nutrients	15
AA1	all ADFs/aerated/winter/nutrients	16
AN1	All ADFs/nonaerated/winter/nutrients	18
PA1	PG only/aerated/winter/nutrients	18
PA1-	PG only/aerated/winter/no nutrients	18
AA1-	All ADFs/aerated/winter/no nutrients	> 30
AN1-	All ADFs/nonaerated/winter/no nutrients	> 30
PN1	PG only/nonaerated/winter/nutrients	> 30

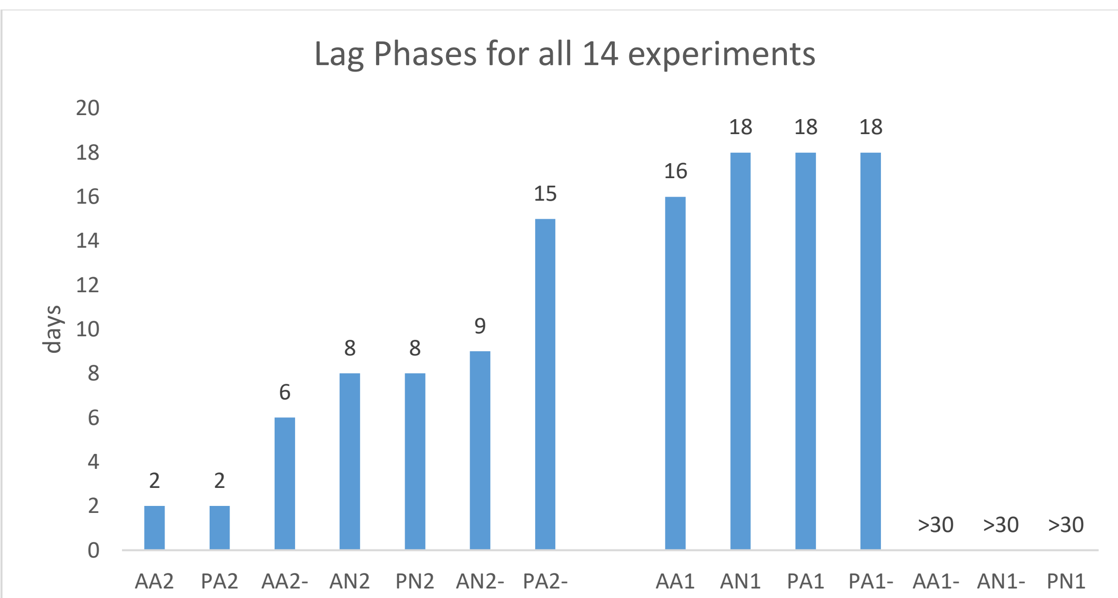


Figure 5.6 Chart for lag phases for all experiments in increasing order.

Similarly to the k values and half-lives in Table 5.2, the trend shows shorter lag phases for favorable temperature conditions. In this case, all experiments tested under 20°C resulted in lag phases of at least 15 days. Experiment PA2- had a lag phase of 15 days and all other experiments tested under 20°C resulted in lag phases ranging from 9 days to only 2 days for AA2 and PA2. The longest lag phases corresponded to experiments that did not show a first order degradation due to extremely low degradation during the 30 day period (AA1-, AN1-, PN1). For comparison purposes, the lag phases in these experiments were defined to greater than 30 days (>30). Lag phases of all other experiments tested under 5°C were 16 days for AA1, and 18 days for AN1, PA1, and PA1-.

5.3.2 Design Of Experiment (DOE) Analysis:

A clear effect of temperature on overall degradation rates and lag phases was seen. However, the effect of nutrient addition, aeration, and composition parameters were not apparent. Rather than looking at the numerical data for each parameter independently to compare favorable vs. non-favorable bacterial growth conditions, a design of experiment analysis (DOE) was performed to evaluate the effects of each parameter on degradation rates of the system. To evaluate all parameters and their effect, it was useful to consider aeration, nutrient addition, and composition parameters for both summer and winter conditions separately.

A DOE analysis with Minitab 17 was performed by using a 2 by 2 factorial regression and comparing two parameters at a time while keeping the other parameter constant. The following plots aim to show the main effect that each parameter has when under favorable conditions (1) and non-favorable conditions (-1). A larger slopw in the main effect plot corresponds to a greater effect the parameter is to the k value. Values for main effect are summarized in the figure description below each plot.

Main effect plots for conditions done at 5°C (winter):

To evaluate the main effects of aeration and composition relative to each other when nutrients are added to the system, experiments AA1, PA1, AN1, and PN1 were compared. Figure 5.7 shows the results of the DOE analysis conducted.

The DOE numerical results show that aeration has a mean effect of 0.0638 day^{-1} on the k value and composition has a mean effect of 0.0485 day^{-1} on the k value. These numbers represent the magnitude of the improvement on the degradation rate when each parameter goes from non-favorable (-1) to favorable (1) conditions.

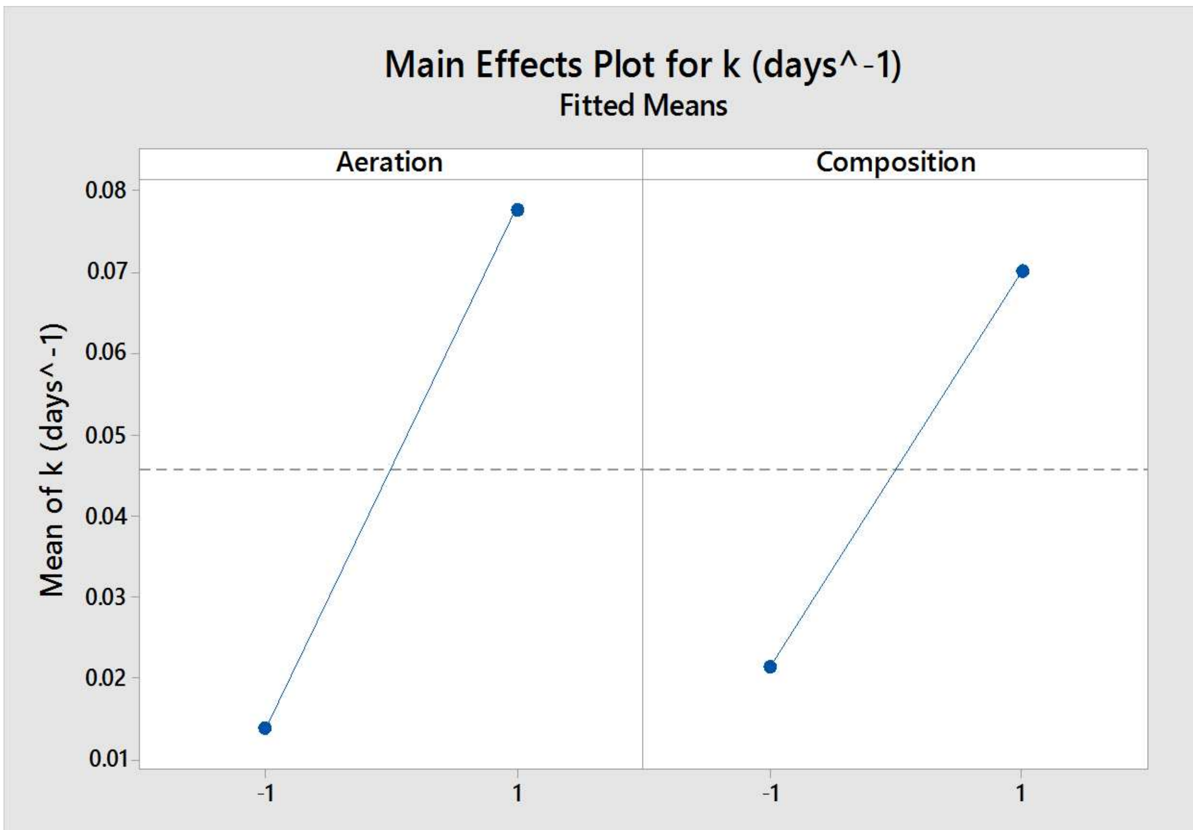


Figure 5.7 Main effect plot of aeration and composition when nutrients are added

As expected, k values show improvements when both parameters are favorable. Aeration shows to only have a slightly greater effect on the k values than composition. Therefore, the importance of effect of composition must be considered in certain conditions. For instance, from the numerical data in Table 5.2 the degradation of rate of AA1 (0.116 day^{-1}) was greater than PA1 (0.04 day^{-1}) which implies that composition is also favorable when a lower amount of PG is present at winter conditions.

Subsequently, to evaluate the effect of nutrient addition and composition, a DOE analysis was made for all experiments in which aeration was added to the system. This includes experiments AA1, AA1-, PA1, and PA1-. The graphical results are displayed in Figure 5.8.

Numerical results of the DOE indicate that nutrient addition has a mean effect of 0.0603 day^{-1} on the k value, whereas composition has a mean effect of 0.0244 day^{-1} on the k value. The addition of nutrients had a greater effect than composition.

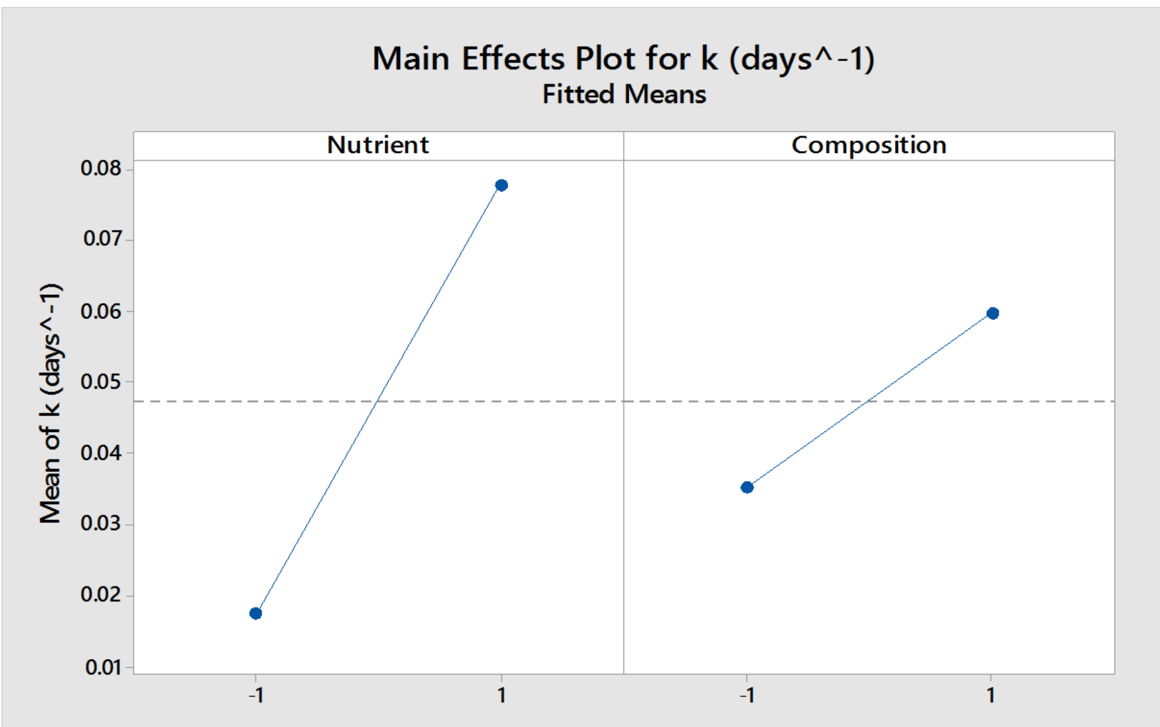


Figure 5.8 Main effect plot of nutrient and composition when experiments are aerated.

The effect of nutrient addition when compared to composition is also larger than the effect of aeration over composition in Figure 5.7.

Although the effect of composition is positive with lower concentration of propylene glycol in the system, the effect of aeration and nutrient addition was greater in both comparisons.

To determine the effect of aeration and nutrient addition when compared to each other, a DOE analysis was done with all experiments where all ADFs were added to the system. Experiments AA1, AA1-, AN1, and AN1- were compared in this DOE analysis. The main effects plot is displayed in Figure 5.9. Aeration had an effect of 0.04505 day^{-1} on the k value, while nutrient addition has a mean effect of 0.06565 day^{-1} on the k value.

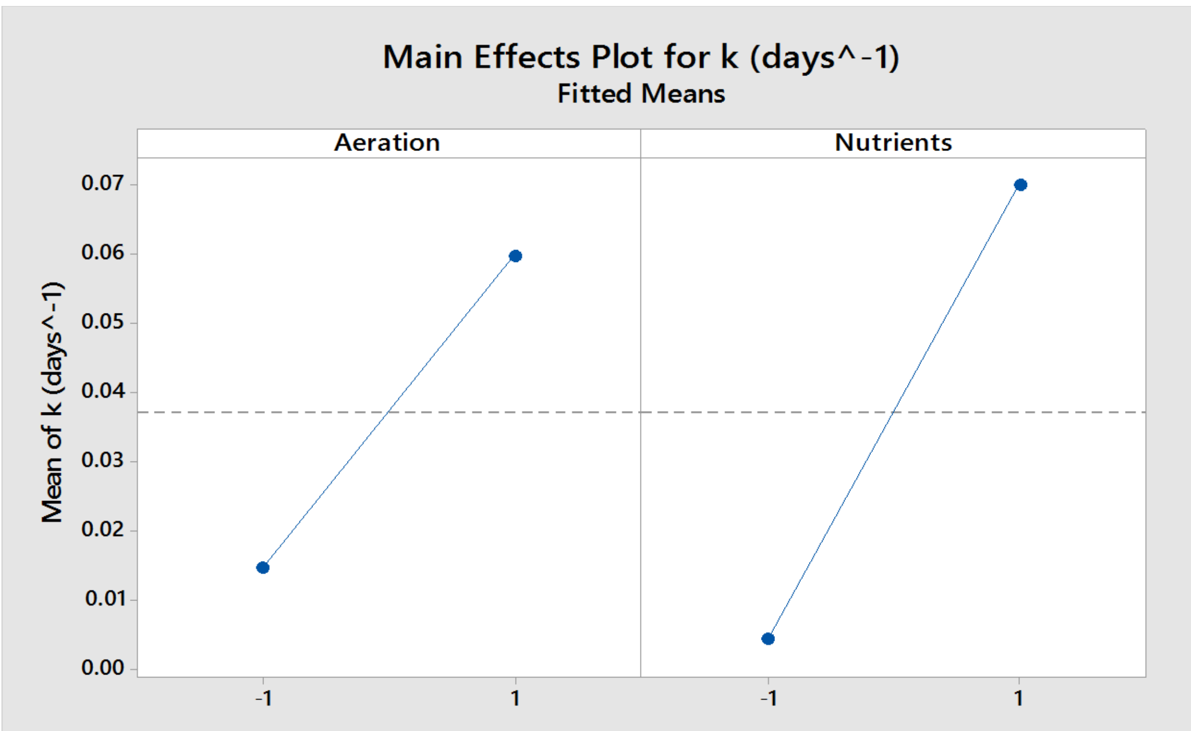


Figure 5.9 Main effect plot of aeration and nutrients when experiments have all ADFs added.

Again, nutrient addition resulted in a greater effect. The larger effect of nutrient presence compared to composition and aeration may explain why all winter experiments done without nutrients (PA1-, AN1-, and AA1-) had half-lives larger than 15 days (Table 5.2). This implies that nutrient addition is essential in the system under favorable temperature.

It is important to note that the effect of nutrient addition is slightly larger than the effect of aeration. This can be explained by looking at the numerical data of degradation rates in Table 5.2. For example, Table 5.2 and Fig 5.5 demonstrate that if nutrients are lacking, the system will not perform well even if aeration has been added as in the case of AA1- and PA1- with k values of 0.004 $days^{-1}$ and 0.03 $days^{-1}$, respectively. In contrast, if the system is not aerated when nutrients are added, it will not result in optimal degradation rates as in the case of AN1 (0.024 $days^{-1}$) and PN1 (0.003 $days^{-1}$).

Overall the DOE analysis in Figures 5.7-5.9 highlights the importance of nutrient addition, aeration, and low PG concentrations if a higher degradation rate is desired. All parameters showed a positive effect on the k values when in favorable conditions. However, no significant effect was seen for any specific parameter over the other parameters. This may be attributed to the overall low degradation under cold temperatures. Since temperature poses the biggest challenge to achieve fast degradation rates, there may not be a positive impact on the k value if only one of these variables are under favorable conditions. Experiment AA1 (0.116 $days^{-1}$) shows that when nutrient addition, aeration, and concentration are favorable in the system will result in degradation rates that are feasible even under very cold temperatures.

To evaluate the effects on the variables during summer temperatures, the same DOE analysis was conducted for all experiments done at 20°C. Figures 5.10 to 5.12 display the results of this analysis.

Main effect plots for conditions done at 20°C (summer)

To compare the effect of aeration and composition when nutrients are added to the system, experiments AN2, PN2, AA2, and PA2 were analyzed. Figure 5.10 shows the results of the DOE analysis for this set of experiments. Aeration has a mean effect of 0.1583 day^{-1} on the k value, whereas composition has a mean effect of 0.0036 day^{-1} on the k value.

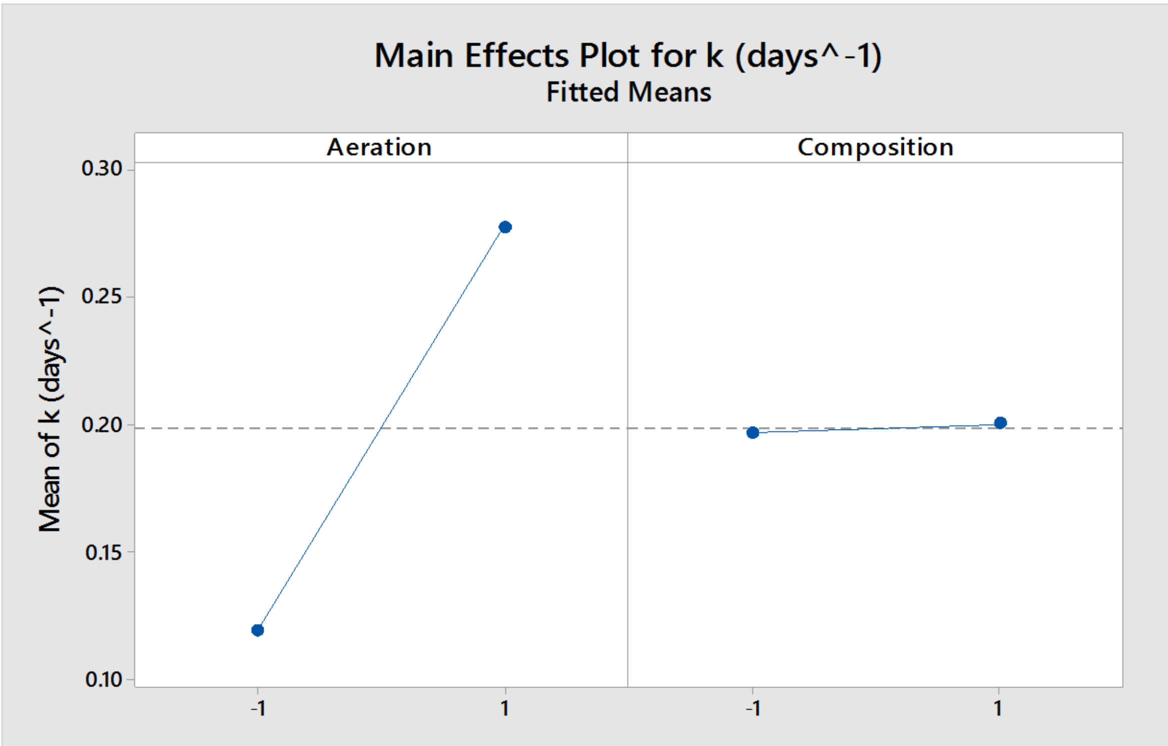


Figure 5.10 Main effect plot of aeration and composition when nutrients are added.

The effect of aeration during warmer conditions is much greater than the effect of composition, which explains why both PA2 and AA2 (0.273 day^{-1} and 0.283 day^{-1}, respectively) and PN2, and AN2 (0.121 day^{-1} and 0.118 day^{-1}, respectively) had similar degradation rates. This highlights the importance that aeration has in the system at warm temperatures, which results in better degradation rates regardless of the composition in the water.

The main effect plot of nutrient addition and composition is displayed in Figure 5.11. Experiments compared in the analysis corresponding to PA2, PA2-, AA2, and AA2- are all conducted under aerated conditions.

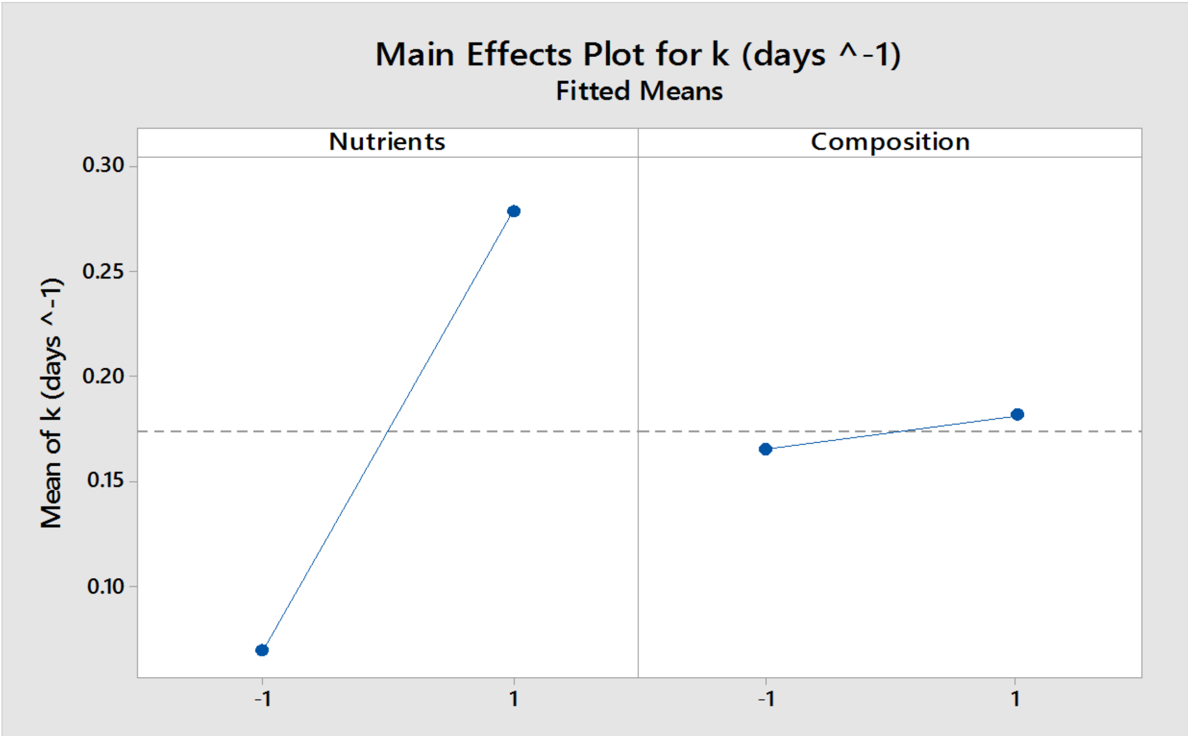


Figure 5.11 Main effect plot of nutrient and composition when they are aerated.

The results of the DOE analysis indicated that nutrient addition has a mean effect of 0.2087 day^{-1} on the k value and composition has a mean effect of 0.016 day^{-1} on the k value. As previously noted, this indicates that the effect of composition is very low during summer temperatures and the system experiences fast degradation rates even with high PG concentrations. Just like PA2 and AA2, (0.273 days^{-1} and 0.283 days^{-1}, respectively), experiments PA2- and AA2- (0.058 days^{-1} and 0.08 days^{-1}, respectively) also resulted in similar degradation rates.

The main effect plots in Figure 5.10 to 5.11 showed a significantly greater effect for aeration and nutrient addition over composition. This explains why the values of k during summer conditions for all ADFs were very similar to the k values during summer conditions when only PG was used. Therefore, it can be concluded that composition in the system does not have a great effect on the degradation rates of the system compared to aeration and nutrient addition when the system operates at 20°C.

To evaluate the effects of aeration and nutrient addition relative to each other, experiments AA2, AA2-, PA2, and PA2- were compared in the DOE analysis. Figure 5.12 displays the main effects of these parameters on degradation rates when all ADFs were added to the system.

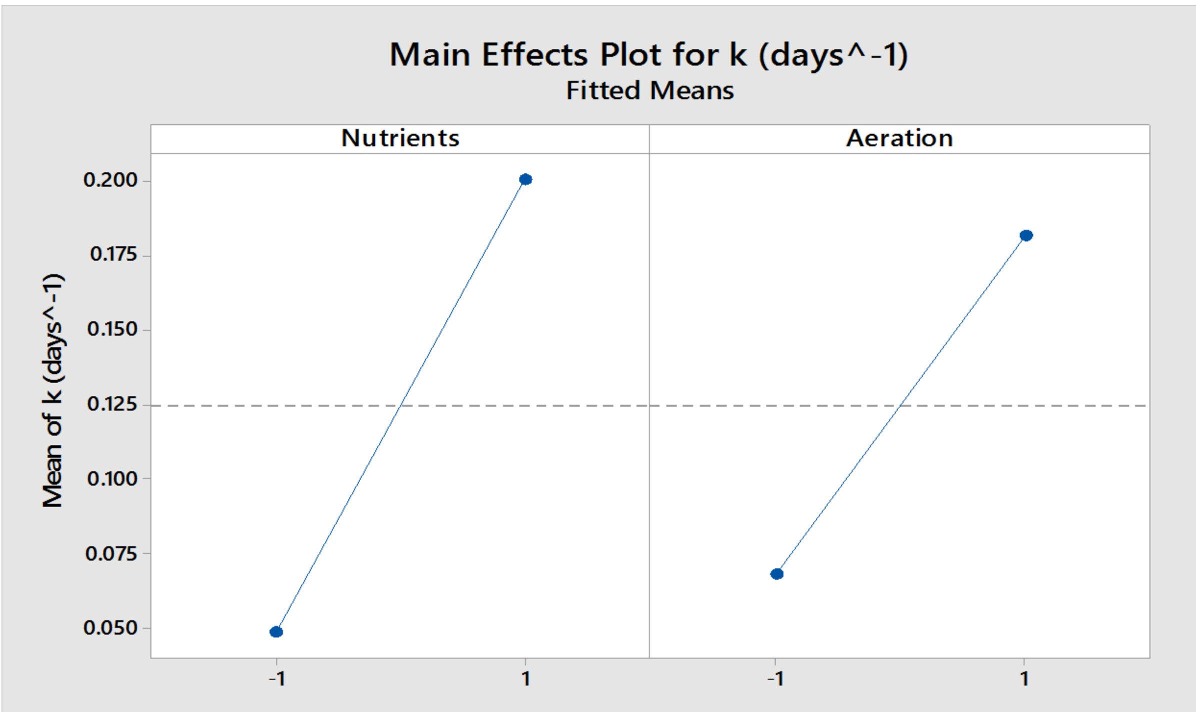


Figure 5.12 Main effect plot of aeration and nutrients when all ADFs are added.

Nutrient addition has a mean effect of 0.1514 day^{-1} on the k value. Aeration has a mean effect of 0.1134 day^{-1} on the k value. When comparing the effects of nutrient addition with aeration, neither showed a much larger effect than the other. This may be due to high k values obtained even when nutrients were lacking as in AA2- (0.08 day^{-1}) and PA2- (0.058 day^{-1}), which indicates that only using aeration can result in effective degradation rates. Similarly, when aeration is lacking like in AN2 (0.118 day^{-1}) and PN2 (0.121 day^{-1}), the sole use of nutrients can be effective and result in half-lives below 15 days.

In this analysis, the effect of nutrient addition is also higher when compared to both aeration and composition effect. In this particular case, the effect of composition is the lowest. The only summer condition that did not show a half-life below 15 days was AN2- (0.018 day^{-1}), which lacked both nutrients and aeration. This result confirms that both parameters are important in the system during summer conditions and the degradation rates are low if they are not favored. From this analysis, it can be concluded that at summer temperatures nutrient addition, composition, and aeration parameters can be under non-favorable conditions. When at least two of these parameters are not favored, it will result in degradation rates that are not feasible for a system (AN2-).

The borderline of this experimental analysis is that the degradation rates, lag phases, and overall degradation efficiency will depend strongly on weather conditions and average temperatures in Anchorage. Therefore, operational variables in the system (nutrient addition, aeration, and composition) must be adjusted differently to optimize the process during winter temperatures (5°C), and summer temperatures (20°C).

In assessing feasibility, it should be noted that half-lives longer than 15 days may not be economically or spatially viable. Therefore, only experiment AA1 showed feasible degradation rates for winter temperature applications. Since temperatures in Anchorage year-round are generally cold, the design and operation of a SFCW at JBER must be planned to provide sufficient aeration and nutrients during deicing season without reaching high loadings of PG based ADF. With additional stormwater management considerations, it is possible that during warmer months the system can be operated with minimal aeration, nutrients, and high PG content while meeting appropriate COD limits and minimizing costs.

6. IMPLICATIONS FOR JBER, CONCLUSIONS, AND FUTURE WORK

After evaluating all stormwater treatment technologies, it was decided that the biological degradation of ADF by a subsurface flow constructed wetland (SFCW) is the most feasible option for JBER. Due to the operational simplicity and efficiency in the coldest weather without the need for heating systems, the SFCW technology has economic advantages over more complex systems.

Experimental results showed that under cold temperatures the biological degradation of ADF is extremely challenging if the microorganisms in the water are not exposed to favorable conditions. The low degradation rates in experiments when aeration and nutrients are lacking showed that when these parameters are limited, the operation of a SFCW is not practical. These results confirm that at JBER the relatively low temperatures are the biggest challenge for COD removal; and therefore, the operating conditions of a SFCW must be optimized to overcome that limitation.

As opposed to the other variables considered in the experimental analysis, temperature is the only variable that cannot be manipulated in a cost-effective manner. Nutrient addition, aeration, and composition in the stormwater runoff can be adapted to optimize the degradation rates in the system. Experimental results indicate that during winter conditions it is only practical to operate with both aeration and nutrients added to the system. If these parameters are not sufficient, the system could take at least 15 days (and up to more than 30 days) to degrade the ADF to a concentration of 50% COD. Although, during warmer months the nutrient addition and aeration can be reduced to minimize costs of the system from energy demand and purchase of nutrients. Nutrient reduction is also beneficial to prevent high concentrations of nutrient discharge to surface waters. Composition of ADFs in the water can also be manipulated by minimizing usage of large concentrations of propylene glycol based ADFs during the coldest months.

With the appropriate design and operation, the treatment system can degrade more than 50% of the COD in only 6 days of retention time during winter months (AA1) and summer months (AN2). If at least 50% of the COD in the system is degraded, the targeted COD benchmark can be achieved.

6.1 Recommendations for JBER

It is recommended that JBER implement a subsurface flow constructed wetland (SFCW) with an aeration system that can be to be adjusted as desired. This can be done by designing the wetland with a certain number of cells or stages that can be monitored and controlled separately to optimize the process.

During winter months when deicing is occurring, the aeration rates in the system must be sufficient to achieve the highest degradation possible. Nutrient addition must be added during this time to increase the metabolic growth of microorganisms. To prevent slow degradation rates due to high propylene glycol concentrations, it is recommended that JBER closely monitors the ADF usage to prevent high loadings of PG based ADF during aircraft deicing.

Summer temperatures at JBER can reach up to 65°F. Although no deicing is occurring during these months, it is beneficial to consider taking advantage of faster degradation during warmer months. To achieve this, it is recommended that JBER constructs a storage system for stormwater runoff storage at the end of the deicing season for water to be treated later under warmer temperatures. By taking advantage of the higher degradation rates during the summer, the large volumetric loads at JBER can be treated under low energy conditions and have the same results while reducing operational costs. Since nutrient depletion during summer months did not seem to negatively affect the degradation rates in the system, it is suggested that additional nutrients not be added to the system during warm months. This can result in cost savings and less chance of contaminating the surface waters with additional nutrients. Composition in the water during summer temperatures did not affect degradation rates, which adds one more advantage to degrading the remaining stormwater during the summer.

6.2 Future Work and additional considerations:

Determining the degradation rates in a SFCW for JBER's case is one of the first steps to technology implementation. To construct a treatment plant on site, it is necessary to create the best design that will handle the COD and BOD loadings produced at JBER. To make this possible, necessary information must be collected and Chapter 4 design equations used. Since the area of operation depends on the expected COD and BOD volumetric loadings, accurate information about average precipitation and ADF usage is necessary to make approximate estimates for inlet flow rates and concentrations. Since the residence time is an important consideration, appropriate wetland size that will allow sufficient degradation of the water as it flows through the gravel cells is necessary. Hydraulic considerations must also be taken since the flow of water through a gravel bed follows Darcy's Law which requires numerical data of hydraulic conductivity constants (Ks).

Another factor to consider is that the location of the SFCW must be near the runway where deicing operations are occurring. As previously stated, the low COD concentrations in the outfall are a result of recurring water discharges from natural seeps that dilute the ADF contaminated runoff as it makes its way to the Cherry Hill outfall. Therefore, to achieve high COD and low volumetric rates in the inflow of the wetland, it must be placed near the runway.

This is also convenient in a management perspective since it will reduce the costs and complications of transferring the water to a different location.

This research provides JBER an educated decision approach for controlling discharge of ADF to receiving water bodies adjacent to the military base. If an appropriate design is developed and control strategies are implemented during operation, it is possible to create optimal conditions for biological growth during deicing season even during the coldest months. Experiences of SFCW applied in airports like Buffalo-Niagara International Airport and Edmonton International Airport have proved them highly effective even under extreme weather conditions. Therefore, it is expected that the implementation at JBER will have results that satisfy the needs of ADF degradation and lower the contamination to the Knik Arm.

REFERENCES

Environmental Protection Agency. (1993). Subsurface flow Constructed wetlands for Wastewater treatment (EPA-832-R-93-008). Environmental Protection Agency.

Environmental Protection Agency. (1999). Stormwater Technology Fact Sheet: Storm Water Wetlands (EPA-832-F-99_025). Washington, DC: U.S. Environmental Protection Agency.

Environmental Protection Agency. (2000). Preliminary Data Summary: Airport Deicing Operations (EPA-821-R-00-016). Washington, DC: U.S. Environmental Protection Agency.

Environmental Protection Agency. (2012). Environmental Impact and Benefit Assessment for the Final Effluent Limitation Guidelines and Standards for the Airport Deicing Category (EPA-821-R-12-003). Washington, DC: U.S. Environmental Protection Agency.

Adeola, S., Revitt, M., Shutes, B., Garelick, H., Jones, H., & Jones, C. (2009). Constructed wetland control of BOD levels in airport runoff. *International Journal of Phytoremediation*, *11*(1), 1-10.

Airport Cooperative Research Program, United States. Federal Aviation Administration, CH2M HILL (Firm), CH2M Hill, inc, (2013). *Deicing Treatment Technologies* (Vol. 99). Transportation Research Board

Akratos, C. S., & Tsihrintzis, V. A. (2007). Effect of temperature, HRT, vegetation and porous media on removal efficiency of pilot-scale horizontal subsurface flow constructed wetlands. *Ecological engineering*, *29*(2), 173-191.

Bergdolt, J., Sharvelle, S., & Roesner, L. (2012). Estimation of graywater constituent removal rates in outdoor free-water-surface wetland in temperate climate. *Journal of Environmental Engineering*, *139*(5), 766-771.

Castro, S., Davis, L. C., & Erickson, L. E. (2005). Natural, cost-effective, and sustainable alternatives for treatment of aircraft deicing fluid waste. *Environmental progress*, *24*(1), 26-33.

Corsi, S. R., Mericas, D., & Bowman, G. T. (2012). Oxygen demand of aircraft and airfield pavement deicers and alternative freezing point depressants. *Water, Air, & Soil Pollution*, *223*(5), 2447-2461.

D'Avirro, J., & Chaput, M. D. (2011). *Optimizing the use of aircraft deicing and anti-icing fluids* (Vol. 45). Transportation Research Board.

DuPoldt, C., Edwards, R., Garber, L., Isaacs, B., Lapp, J., & Murphy, T. (2000). A Handbook of constructed wetlands. *A guide to creating wetlands for: Agricultural Wastewater, Domestic Wastwater, Coal Mine Drainage, Stormwater*, *1*.

Federal Aviation Administration. (2016, Nov 1). Electronic Code of Federal Regulations. Retrieved From the U.S. Government Publishing Office website: http:// http://www.ecfr.gov

Higgins, J., & MacLean, M. (2002). Technical note. The use of a very large constructed sub-surface flow wetland to treat glycol-contaminated stormwater from aircraft de-icing operations. *Water Quality Research Journal of Canada*, *37*(4), 785-792.

Higgins, J., Dechaine, L., Minkel, K., Liner, M., & Wallace, S. (2007). Sub-surface flow wetlands to treat glycol-contaminated stormwater from aircraft de-icing operations, BATEA. *Proceedings of the Water Environment Federation*, *2007*(13), 5577-5593.

Higgins, J., Wallace, S., Minkel, K., Wagner, R., Liner, M., & Meal, G. (2011). The design & operation of a very large vertical sub-surface flow engineered wetland to treat spent deicing fluids and glycol-contaminated stormwater at Buffalo Niagara International Airport. *Water Practice and Technology*, *6*(3), wpt2011044.

Lorion, R. (2001). *Constructed wetlands: Passive systems for wastewater treatment*. US EPA Technology Innovation Office.

Multi-Sector General Permit for Storm Water Discharges Associated with Industrial Activity (MSGP), 2015, p. 188

Murphy, C., Wallace, S., Knight, R., Cooper, D., & Sellers, T. (2015). Treatment performance of an aerated constructed wetland treating glycol from de-icing operations at a UK airport. *Ecological Engineering*, *80*, 117-124.

Nedwell, D. B. (1999). Effect of low temperature on microbial growth: lowered affinity for substrates limits growth at low temperature. *FEMS Microbiology Ecology*, *30*(2), 101-111.

Ramakrishna, D. M., & Viraraghavan, T. (2005). Environmental impact of chemical deicers–a review. *Water, Air, and Soil Pollution*, *166*(1-4), 49-63.

Reed, S. C. (1993). Subsurface flow constructed wetlands for wastewater treatment: a technology assessment.

Rousseau, D. P., Vanrolleghem, P. A., & De Pauw, N. (2004). Model-based design of horizontal subsurface flow constructed treatment wetlands: a review. *Water research*, *38*(6), 1484-1493.

Schoenberg, T., Veltman, S., & Switzenbaum, M. (2001). Kinetics of anaerobic degradation of glycol-based Type I aircraft deicing fluids. *Biodegradation*, *12*(1), 59-67.

Stein, O. R., & Hook, P. B. (2005). Temperature, plants, and oxygen: how does season affect constructed wetland performance? *Journal of Environmental Science and Health*, *40*(6-7), 1331-1342.

Switzenbaum, M. S., Veltman, S., Mericas, D., Wagoner, B., & Schoenberg, T. (2001). Best management practices for airport deicing stormwater. *Chemosphere*, *43*(8), 1051-1062.

Verhoeven, J. T., & Meuleman, A. F. (1999). Wetlands for wastewater treatment: opportunities and limitations. *Ecological engineering*, *12*(1), 5-12.

Vymazal, J. (2005). Horizontal sub-surface flow and hybrid constructed wetlands systems for wastewater treatment. *Ecological Engineering*, *25*(5), 478-490.

Vymazal, J., & Kröpfelová, L. (2009). Removal of organics in constructed wetlands with horizontal sub-surface flow: a review of the field experience. *Science of the total environment*, *407*(13), 3911-3922.

Wallace, S., & Liner, M. (2010, October). Nutrient limitations in industrial treatment wetlands. *In the IWA International Conference on Wetland Systems for Water Pollution Control, held in Venice, Italy* (pp. 1071-1074).

Wallace, S., & Liner, M. (2011). Design and performance of the wetland treatment system at the Buffalo Niagara International Airport. *Specialist Group on Use of Macrophytes in Water Pollution Control*, *36*.

Zitomer, D. H., & Tonuk, G. U. (2003). Propylene glycol deicer biodegradation kinetics: Anaerobic complete-mix stirred tank reactors, filter, and fluidized bed. *Journal of environmental engineering*, *129*(2), 123-129.

APPENDIX A: Preparation of ADF model water

JBER uses an annual volume of 150,000 gallons of propylene glycol (PG) based ADF, 130,000 gallons of potassium acetate (PA) based liquid airfield deicer, and 150 tons of sodium acetate (SA) solid airfield deicer. Based on these average values, a mixture of natural water with all three ADFs was prepared at a COD concentration of 10,000 mg/L. Natural water was obtained from Horsetooth Reservoir located in Fort Collins, CO. Although the water at Horsetooth Reservoir does not accurately simulate stormwater runoff at JBER, it is expected that the microorganisms present in this habitat are adapted to cold weather environments. The model water was prepared with the same volumetric proportions of the average annual values that JBER uses during deicing season.

Table A-1 JBER's ADF annual average use

Aircraft/Airfield deicing fluid	Main organic compound	Total average volume (gal)	Volumetric percentage (%)
Safewing MP IV Launch	Propylene glycol	150,000.00	51.02
Cryotech E36	Potassium acetate	120,000.00	40.82
Cryotech NAAC	Sodium acetate	23965.48	8.15
Total	All ADFs	293,965.48	100.00

Table A-2 COD values for each deicing fluid

Aircraft/Airfield deicing fluid	Main Organic Compound	COD (mg O_2/L of deicer)
Safewing MP IV Launch	Propylene glycol	863,200
Cryotech E36	Potassium acetate	409,600
Cryotech NAAC	Sodium acetate	1,110,000

Table A-3 Volume of ADF for a 10,000 mg/L mixture

Aircraft/Airfield deicing fluid	Main Organic Compound	Volume for a 10,000 mg/L COD mixture (mL)	Mass for a 10,000 mg/L COD mixture (g)
Safewing MP IV Launch	Propylene glycol	26.311	N/A
Cryotech E36	Potassium acetate	21.049	N/A
Cryotech NAAC	Sodium acetate	4.204	2.80

APPENDIX B: COD concentrations (mg/L) vs. time for all experiments.

Experiment AA1: Aerated, all ADFs, at 5°C, with nutrients added.

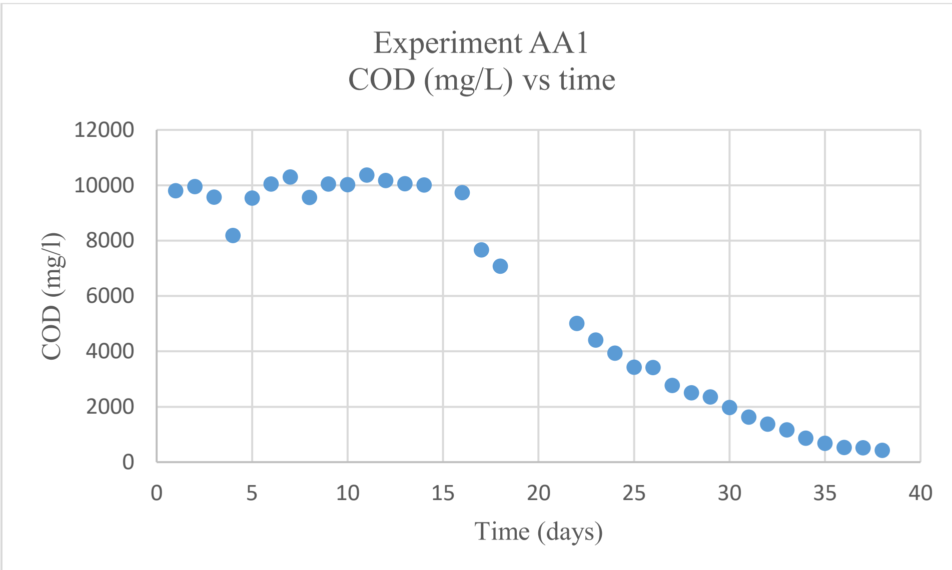


Figure B-1a COD data over time for AA1

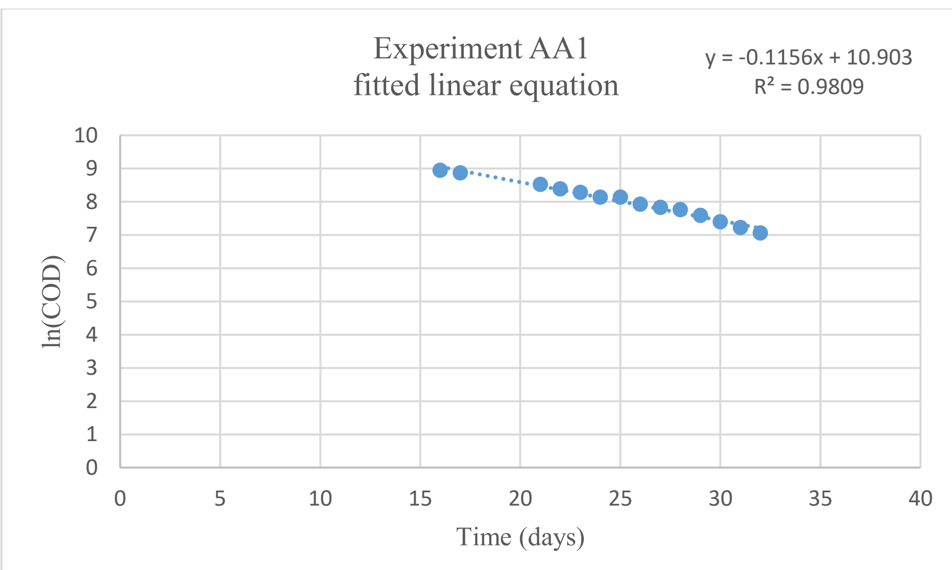


Figure B-2b Natural log plot vs. time for AA1

Experiment PA1: Aerated, all PG only, at 5°C, with nutrients added.

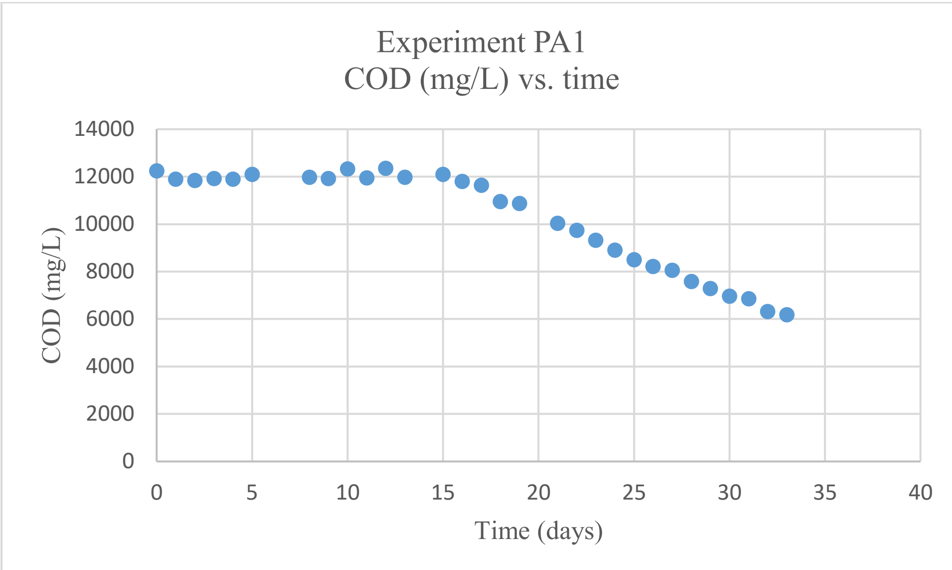


Figure B-3a COD data over time for PA1

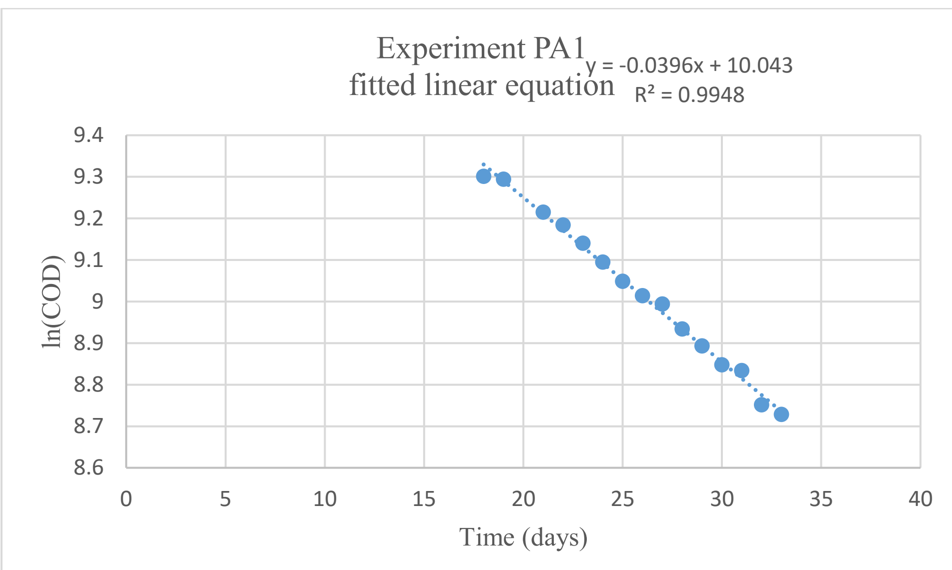


Figure B-4b Natural log plot vs. time for PA1

Experiment AA2: Aerated, all ADFs, at 20°C, with nutrients added.

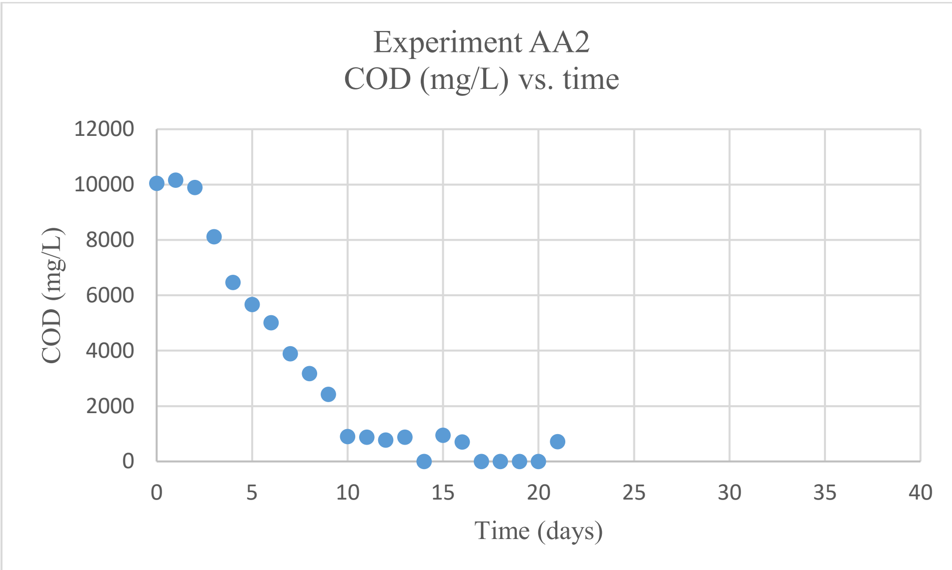


Figure B-5a COD data over time for AA2

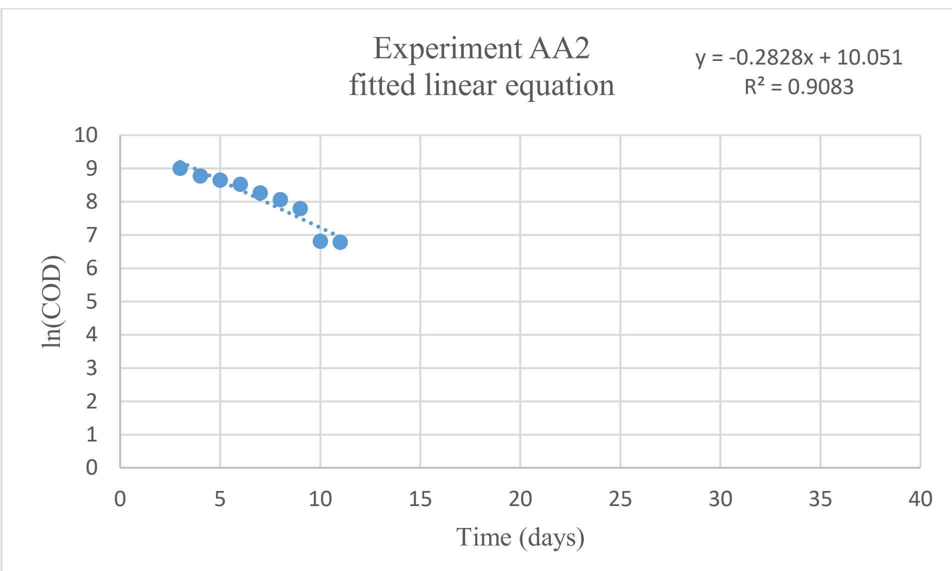


Figure B-6b Natural log plot vs. time for AA2

Experiment PA2: Aerated, PG only, at 20°C, with nutrients added.

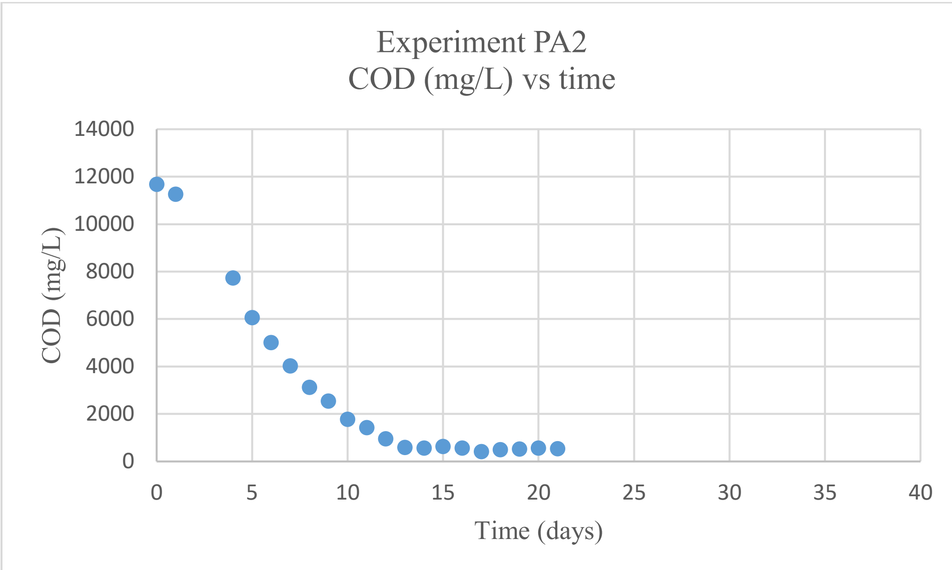


Figure B-7a COD data over time for PA2

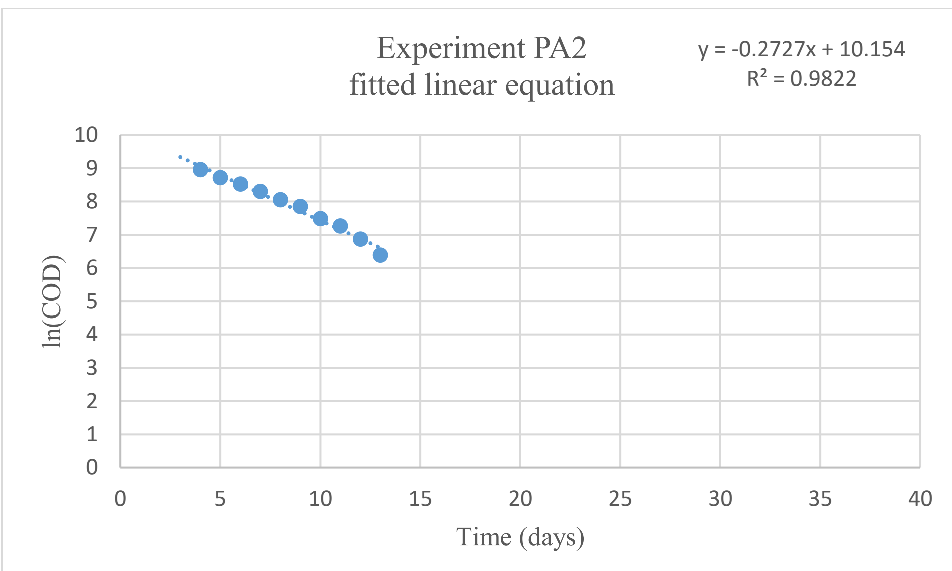


Figure B-8b COD Natural log plot vs. time for PA2

Experiment AN1: Non-aerated, all ADFs, at 5°C, with nutrients added.

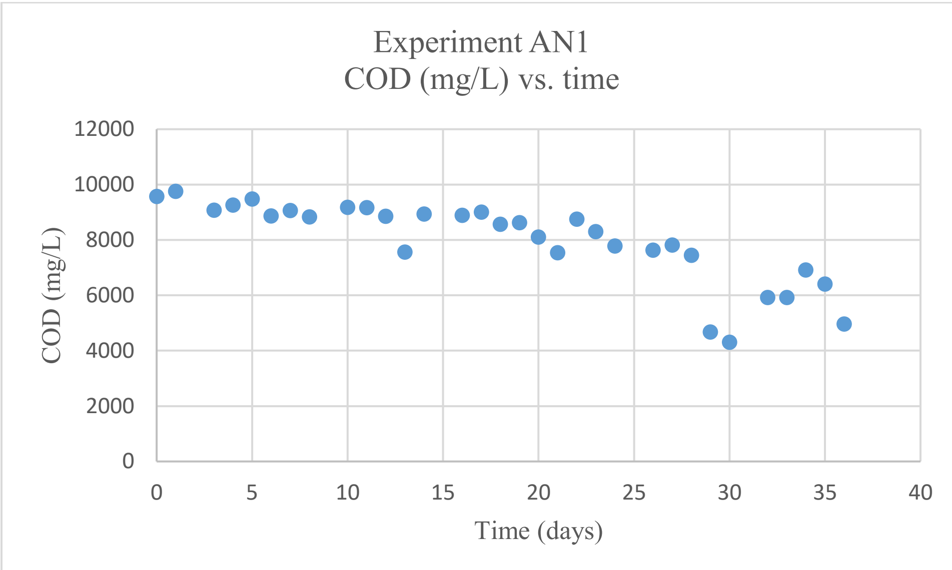


Figure B-9a COD data over time for AN1

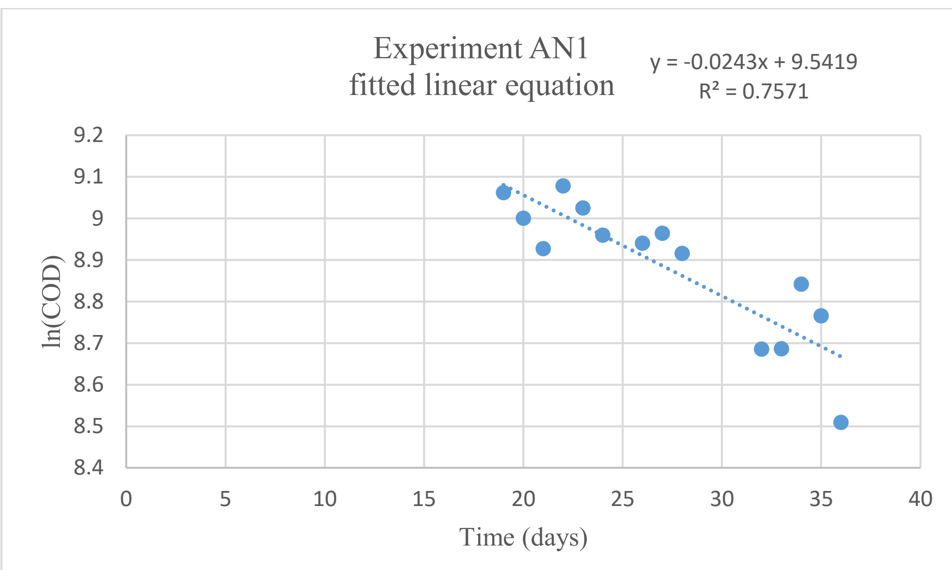


Figure B-10b Natural log plot vs. time for AN1

Experiment PN1: Non-aerated, PG only, at 5°C, with nutrients added.

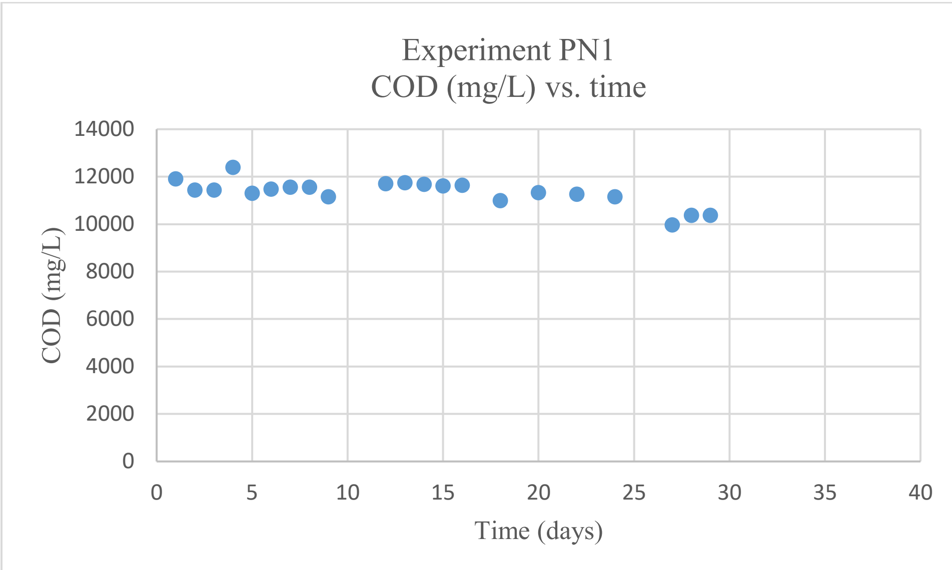


Figure B-11a COD data over time for PN1

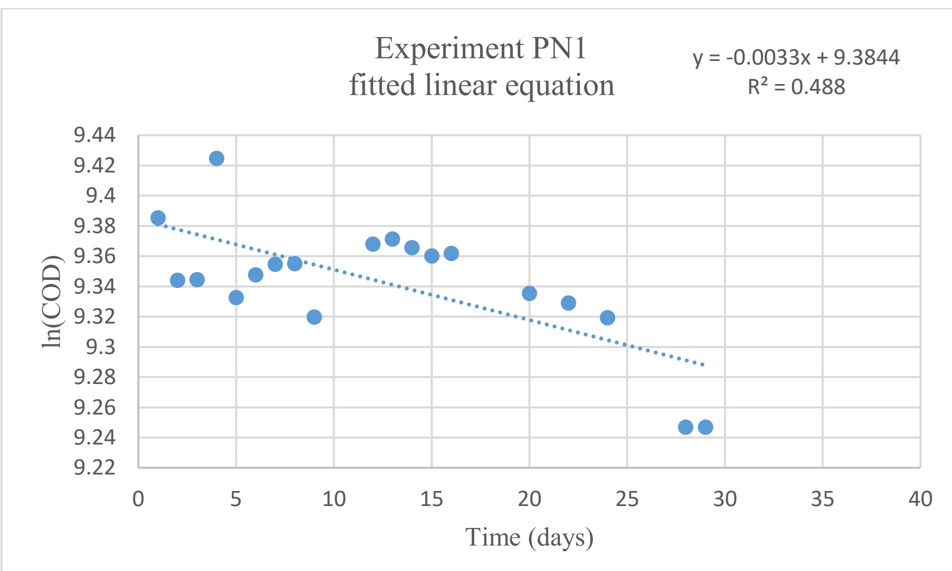


Figure B-12b Natural log plot vs. time for PN1

Experiment AN2: Non-aerated, all ADFs, at 20°C, with nutrients added.

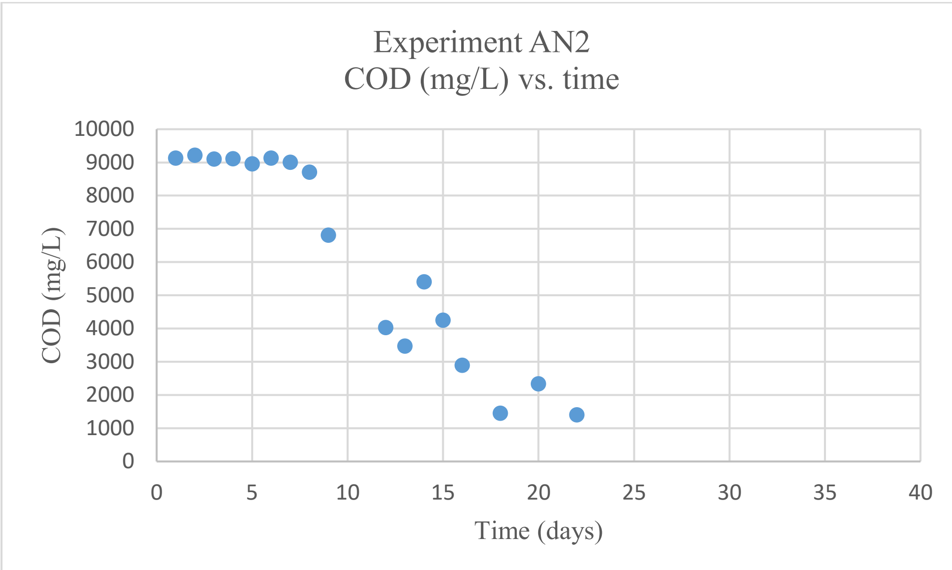


Figure B-13a COD data over time for AN2

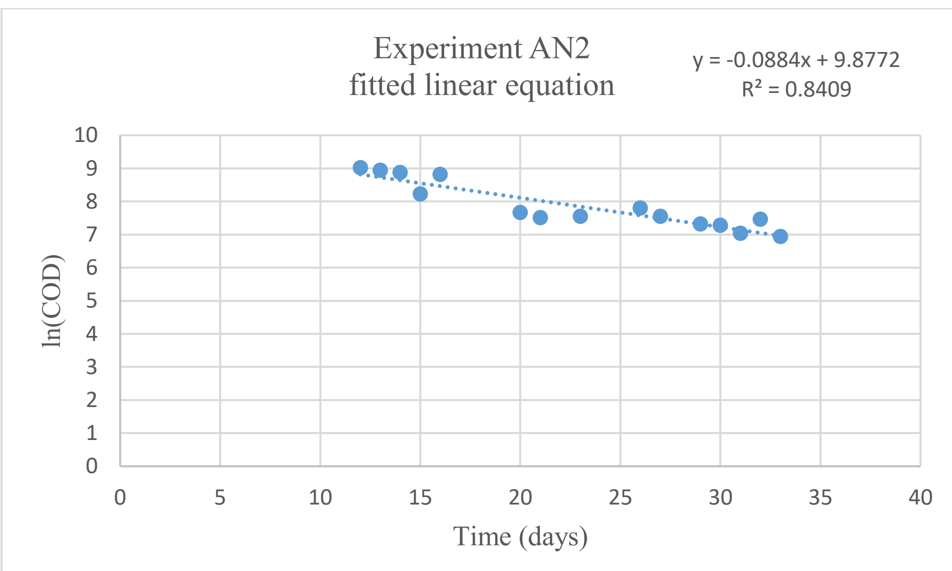


Figure B-14b Natural log plot vs. time for AN2

Experiment PN2: Non-aerated, PG only, at 20°C, with nutrients added.

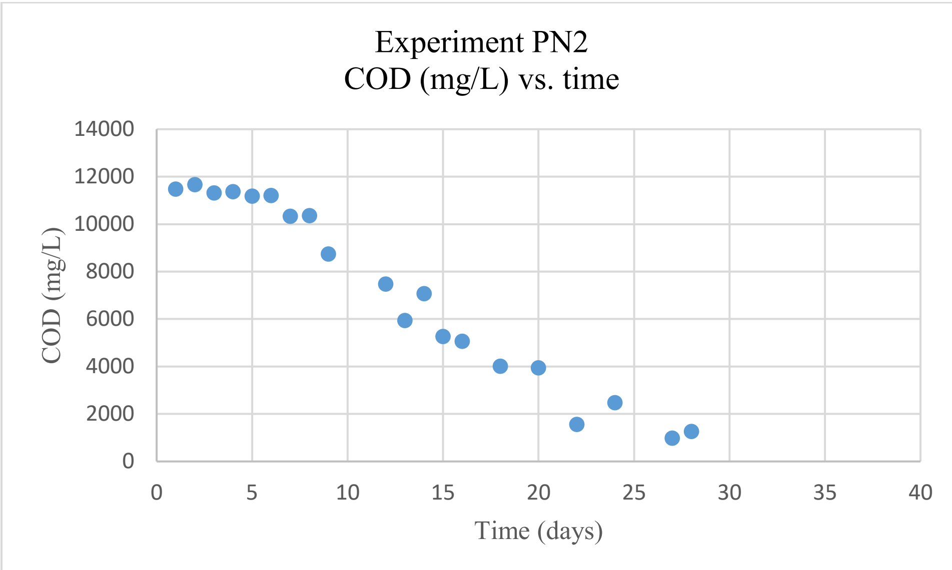


Figure B-15a COD data over time for PN2

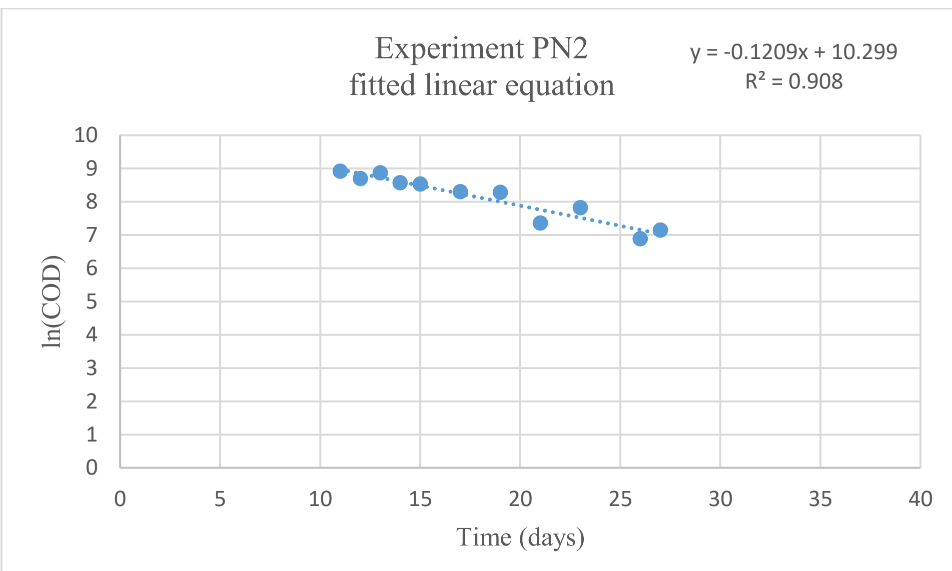


Figure B-16b Natural log plot vs. time for PN2

Experiment AN1-: Non-aerated, all ADFs, at 5°C, without nutrients.

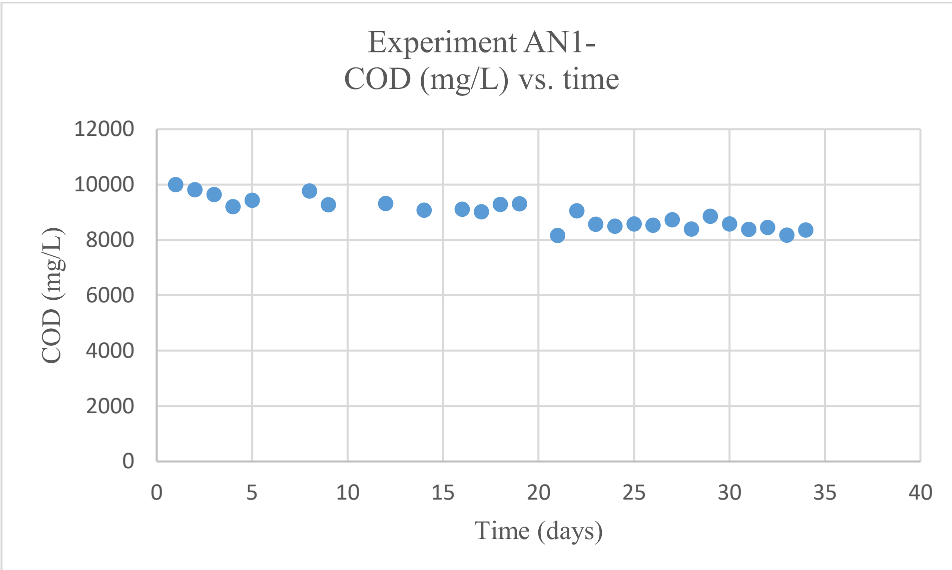


Figure B-17a COD data over time vs. time for AN1-

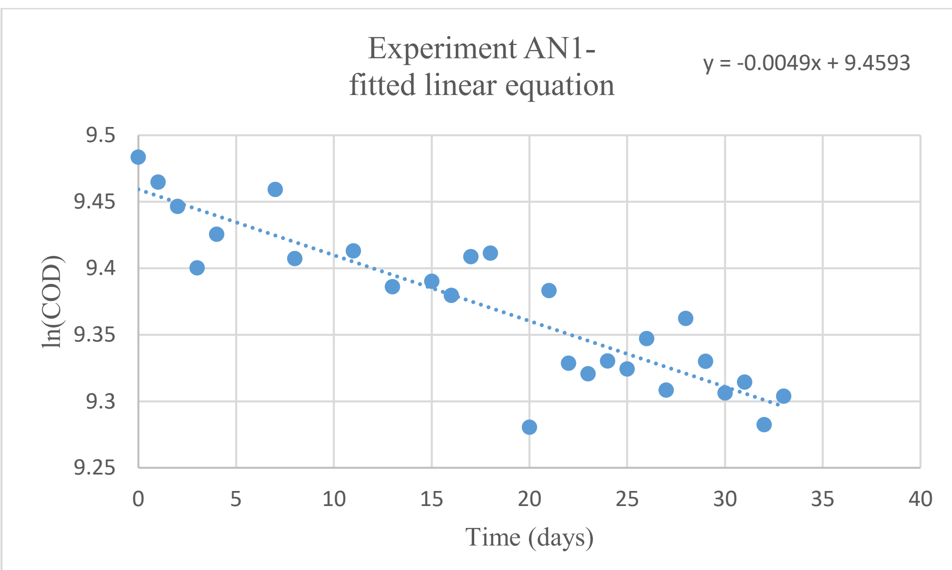


Figure B-18b Natural log plot vs. time for AN1-

Experiment AN2-: Non-aerated, all ADFs, at 20°C, without nutrients.

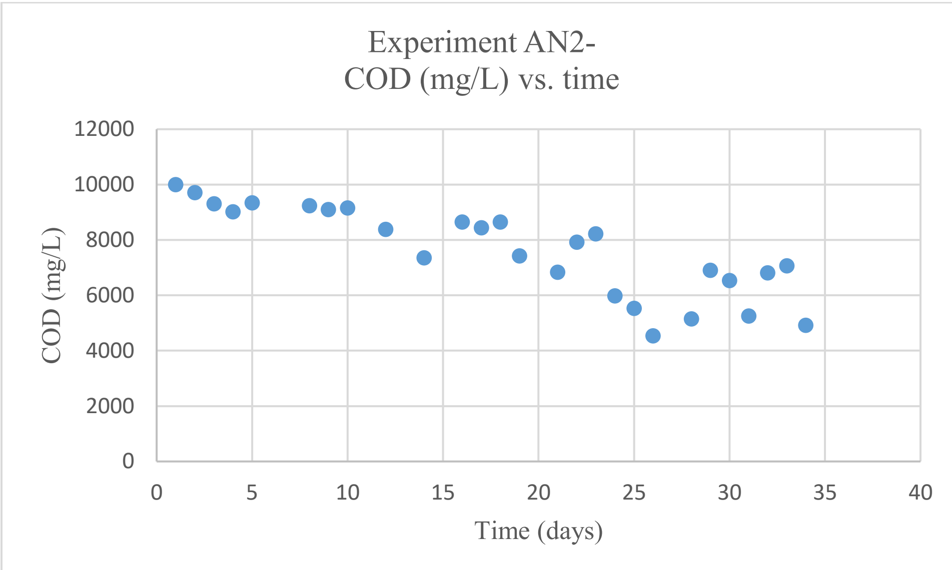


Figure B-19a COD data over time for AN2-

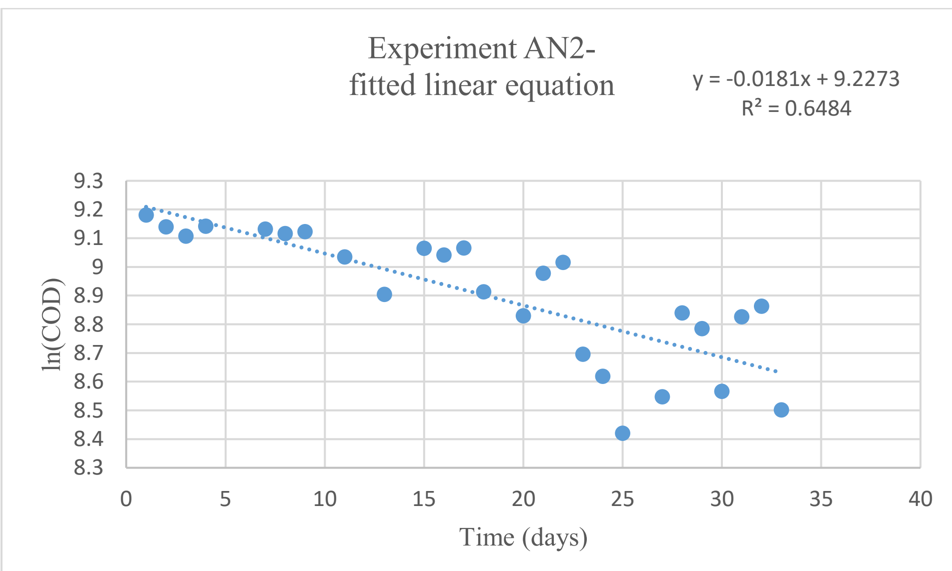


Figure B-20b Natural log plot vs. time for AN2-

Experiment AA1-: Non-aerated, all ADFs, at 20°C, without nutrients.

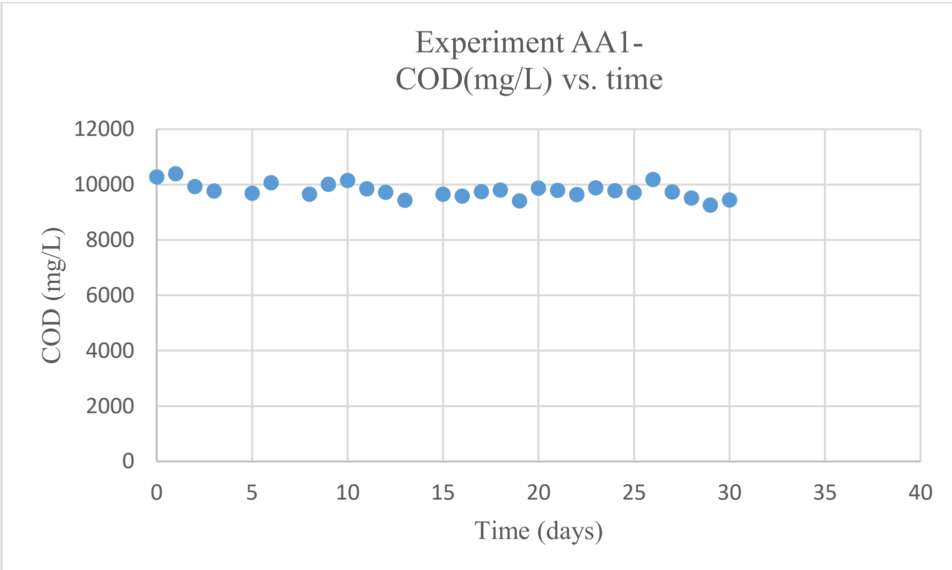


Figure B-21a COD data over time for AA1-

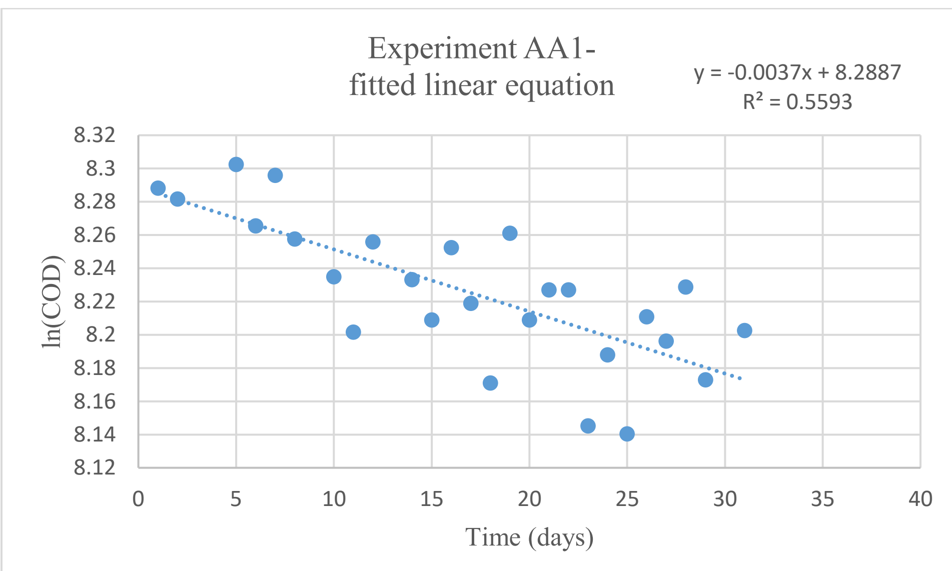


Figure B-22b Natural log plot vs. time for AA1-

Experiment AA2-: Aerated, all ADFs, at 20°C, without nutrients.

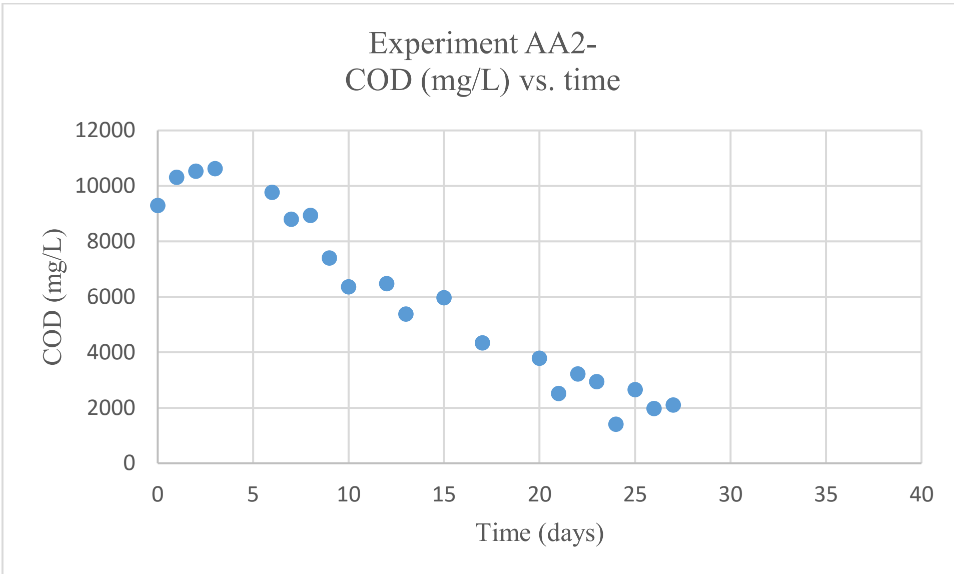


Figure B-23a COD data over time for AA2-

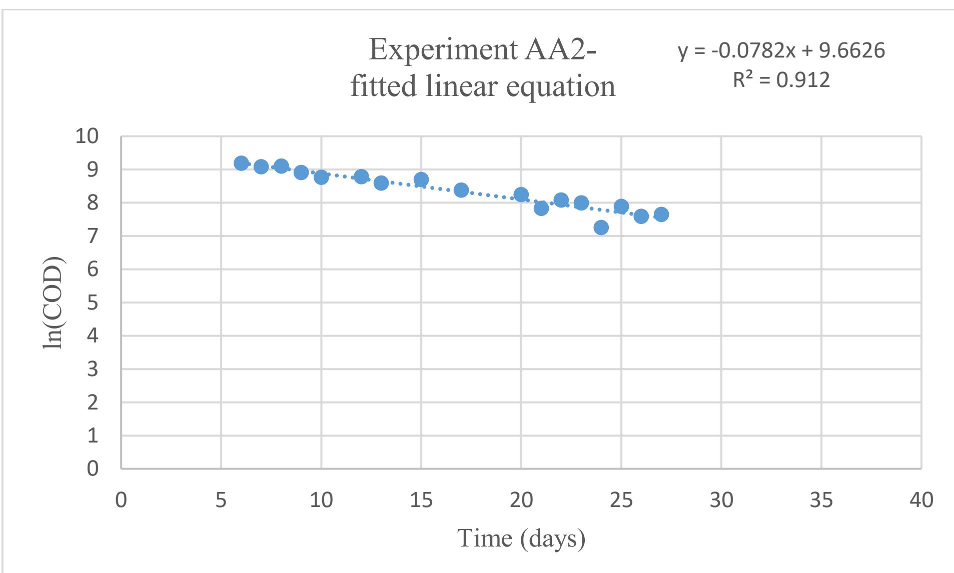


Figure B-24b Natural log plot vs. time for AA2-

Experiment PA1-: Aerated, PG only, at 5°C, without nutrients.

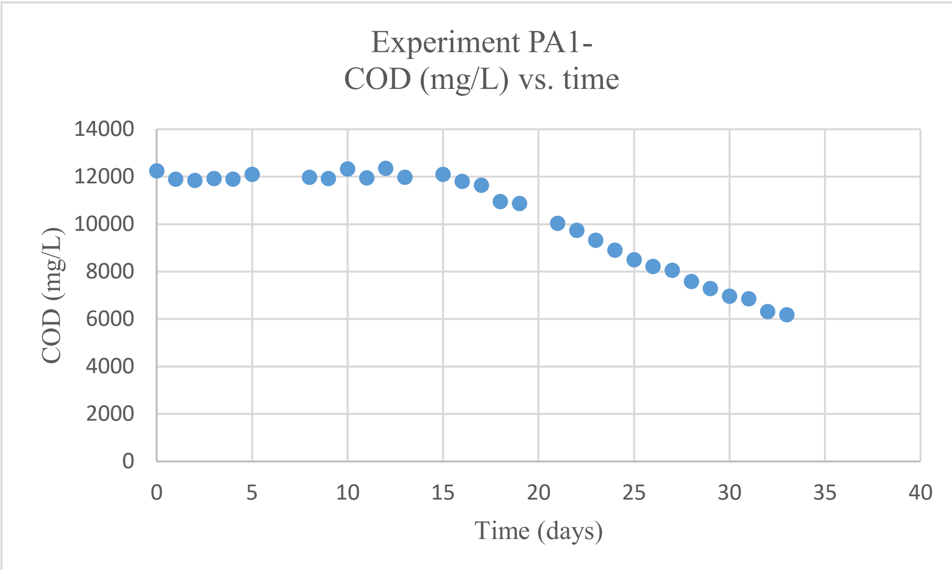


Figure B-25a COD data over time for PA1-

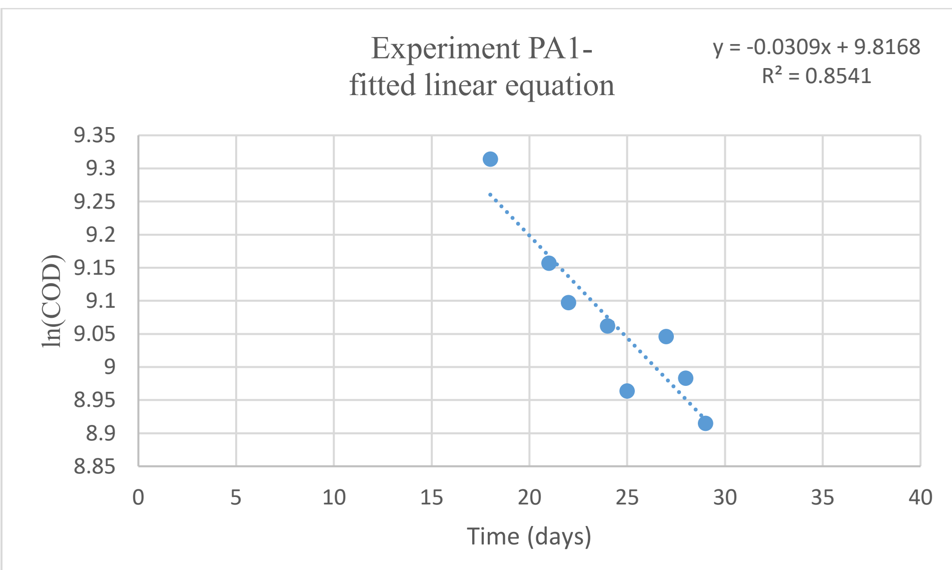


Figure B-26b Natural log plot vs. time for PA1-

Experiment PA2-: Aerated, PG only, at 20°C, without nutrients.

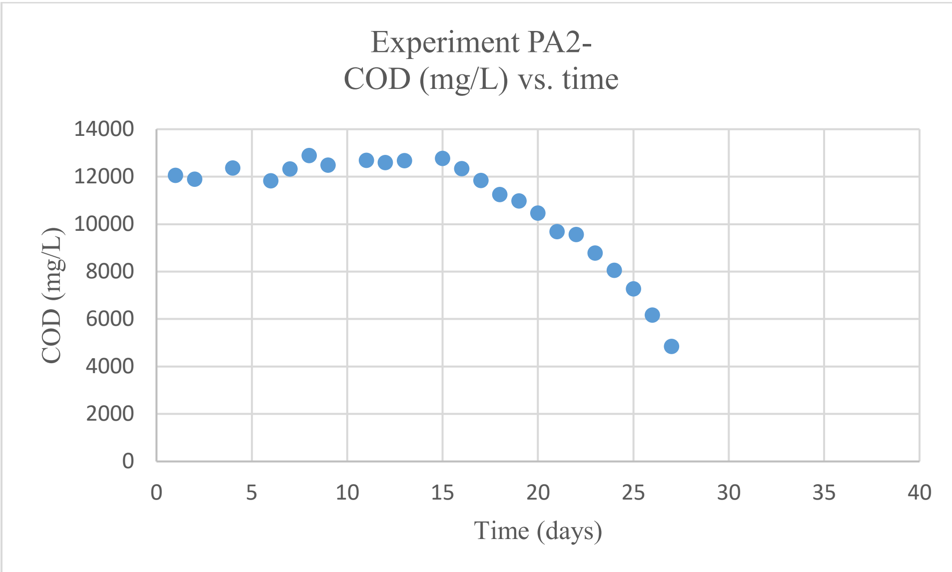


Figure B-27a COD data over time for PA2-

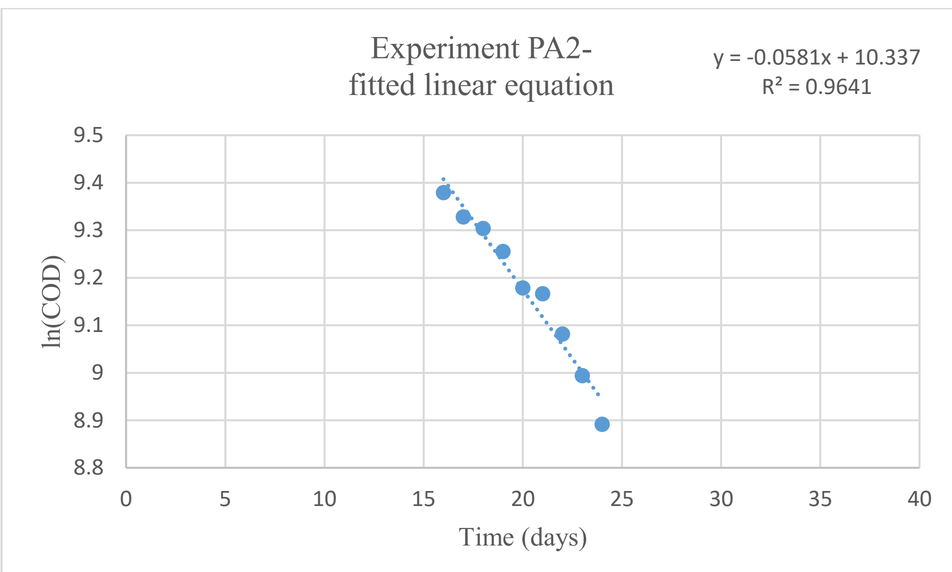


Figure B-28b Natural log plot vs. time for PA2-