Salinity Impacts on Coastal Wastewater Treatment Facilities

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By

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Abstract

Global warming is an ever-present problem resulting in increasing sea level rise and surge flooding. This water misplacement can infiltrate coastal wastewater treatment collection systems and interfere with treatment processes. Many coastal facilities have already experienced problems relating to higher concentrations of seawater in their wastewater influent. The specific effects of salinity on the sedimentation and aeration activated sludge processes were analyzed to determine what mitigation techniques could be employed. Bench-scale experimental results suggested that at concentrations of salinity between 2.63 and 5.24 percent by weight, the traditional sedimentation and aeration processes could no longer operate effectively. A salinity monitoring system, which includes isolated reseeding and reverse sedimentation tanks, was designed to trigger a process control response during high salinity events.

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PE Licensure

There is a process every engineer must undergo to obtain his or her Professional Engineering (PE) Licensure. The first step in the process is to pass the Fundamentals of Engineering (FE) Exam and become an Engineer in Training (EIT). After this, the engineer must complete a minimum of four years of qualifying engineering experience, under the supervision of a PE. After an EIT has completed the minimum qualifying period, he or she must submit an application for registration to become a PE. The Board of Registration will then review the applicant's education, work experience, character and experience references. Once the board has determined that the applicant has met all requirements, he or she will be scheduled to sit for the Principles and Practice of Engineering (PE) Exam. Upon completion of these requirements, the applicant will be issued a license to practice as a PE. The licensure is state specific, therefore, engineers wishing to practice in multiple states must register their license with each state’s board and gain approval before being permitted to practice.

Procurement of a PE illustrates that an engineer has not only obtained an engineering degree, but has also gained valuable experience in the work force. PE’s are seen to have a full understanding of the components of their profession and are the only people certified to sign, seal, and submit engineering plans and drawings on behalf of their clients. This ability makes them more desirable as employees, especially in the consulting industry. Licensure is also essential for moving up in responsibility and authority in many companies and PEs generally earn higher wages as compared to non-licensed engineers.

Due to the high level of responsibility, PEs must also adhere to a stringent code of ethics. PE’s must act morally and ethically in all professional situations, always keeping in mind the well-being of the public before making decisions. The prestige that comes with the PE title is an advantage that opens many doors for engineers who obtain it.

Design Statement

This project incorporates design by including experimental design and a full-scale process modification, and fulfills ABET's requirement for capstone design experience.

The goal of the project was to determine how increased salinity levels affected biological and chemical wastewater treatment processes, such as activated sludge, aeration and sedimentation. Experimental procedures were researched and designed to test how increased salinity levels affect sedimentation, oxygen solubility, and aeration. To mitigate the effects of salinity on the aeration and sedimentation processes, new treatment processes and protocols were designed. These included an evaluation system to measure salinity with a control that is to be activated once salinity has reached a critical level, a reseeding tank to culture activated sludge in the case of a high salinity disturbance event, and a system to remove flocs from the top of a sedimentation basin as opposed to the bottom.

Chapter 1: Introduction

Wastewater is defined as the water supply of a community after it has been used in domestic, institutional, commercial or industrial applications. It is typically composed of microorganisms, biodegradable organic materials, non-biodegradable organic materials – such as detergents, pesticides, fats, oils, and grease – nutrients, metals, and other inorganic materials. Table 2.1 shows the typical composition of domestic wastewater before treatment.

Table 1.1: Typical Composition of Untreated Domestic Wastewater

Adapted from: Crittenden, 2012

Contaminants	Unit	Concentration[a]
Solids, total (TS)	mg/L	390-1230
Dissolved solids, total (TDS)	mg/L	270-860
Suspended solids, total (TSS)	mg/L	120-400
5-day Biochemical Oxygen Demand (BOD_5,	mg/L	110-350
Total Organic Carbon (TOC)	mg/L	80-260
Chemical Oxygen Demand (COD)	mg/L	250-800
Nitrogen	mg/L	20-70
Phosphorus	mg/L	4-12
Chlorides	mg/L	30-90
Sulfate	mg/L	20-50
Oil and grease	mg/L	50-100
Volatile Organic Compounds (VOCs)	mg/L	<100 - >400
Coliform, total	No./100 mL	10^6-10^{10}
Fecal coliform	No./100 mL	10^3-10^8
Cryptosporidium oocysts	No./100 mL	10^1-10^2
Giardia lamblia cysts	No./100 mL	10^1-10^3

[a] *Low range is based on an approximate wastewater flowrate of 200 gal/capita*day. High range is based on wastewater flowrate of 60 gal/capita*day*

Proper wastewater treatment is important for protecting public health. If untreated, fecal coliform, cryptosporidium, and giardia can cause disease outbreaks and contaminate drinking water sources. In addition, nutrients, such as nitrogen and phosphorus, can damage the discharging bodies of water, as well as any organisms living within them.

Wastewater treatment dates back to the Romans, who used stone channels to send wastewater to the Tiber River (Nathanson, 2016). Throughout most of the 1800's there was no running water or modern toilets in homes. Instead, both industry and local residents dumped their waste directly into cesspools, privy vaults, and surface waters, which leached into groundwater. Water companies often utilized source water directly from these surface waters and the groundwater was tapped for drinking water. Due to the high concentration of microorganisms in raw wastewater, epidemic outbreaks of cholera, typhoid, and giardia were common. Between 1831 and 1854, tens of thousands of people in England died of cholera (Tuthill, 2003). One British scientist, John Snow, tracked down cases of cholera throughout his neighborhood and was able to prove that the outbreak was stemming from the consumption of water at a single infected pump on Broad Street. This breakthrough discovery lead to the construction of specific facilities for wastewater treatment and the establishment of stringent water treatment regulations, many of which are still intact today.

By 1948, the United States government implemented the Water Pollution Control Act to restore the nation's water to conditions that were suitable for public use. This was later expanded and renamed the Clean Water Act (CWA) of 1972, which set the first regulations on pollutants discharged from wastewater treatment facilities (WWTFs) into nearby waters. The law requires a permit for discharging and sets maximum contaminant levels for various pollutants. WWTFs must comply with the Environmental Protection Agency's CWA Monitoring Program, including annual quality reporting and on-site compliance evaluations (EPA, 2016).

According to the census, there were 16,024 WWTFs operating in the United States by the middle of the 1990's. These facilities combine to provide an overall design capacity of 42,225 million gallons per day (mgd) of wastewater treatment, which serves over 180 million Americans (US Census, 2006). WWTFs must be equipped to handle water from both domestic and industrial sources, as well as inflow and infiltration (I/I). Infiltration occurs when groundwater enters the collection system through defective or broken pipes. Groundwater gains access when a system lies beneath a water table or the soil above has become overly saturated. Inflow refers to water entering a system at connection or access points, and tends to spike during precipitation events. Both inflow and infiltration add water to the system, which alters the composition of the wastewater and causes volumes to exceed capacity, affecting treatment efficiency. Coastal communities are at an especially high risk for I/I as high tides, rising sea levels, and oceanic flooding can cause saltwater to enter the system on a regular basis.

Globally, eight out of ten of the world's largest cities are near a coast and approximately 40 percent of the United States' population lives in relatively high-density coastal areas (National Oceanic and Atmospheric Association, 2016). This means a vast majority of wastewater treatment occurs near the ocean and is susceptible to saltwater intrusion. As sea levels increase and extreme weather events occur more frequently every year due to global climate change, the threat of saltwater inflow becomes more imminent.

Global climate change refers to the ongoing increase in the temperature near the Earth's surface. It is a result of high concentrations of greenhouse gases in the atmosphere. Greenhouse gases (GHGs) – such as water vapor, carbon dioxide, and methane – absorb energy released by the Earth, which slows or prevents the release of heat to space, effectively warming the Earth. This process is often called the “greenhouse effect”, as a greenhouse traps heat inside a structure to warm the air. Some of these GHGs are released by natural processes, however much of it is a direct result of human activities that burn fossil fuels. The main GHGs emitted by humans include carbon dioxide, methane, and nitrous oxide. For example, the graph below shows atmospheric carbon dioxide concentrations over time.

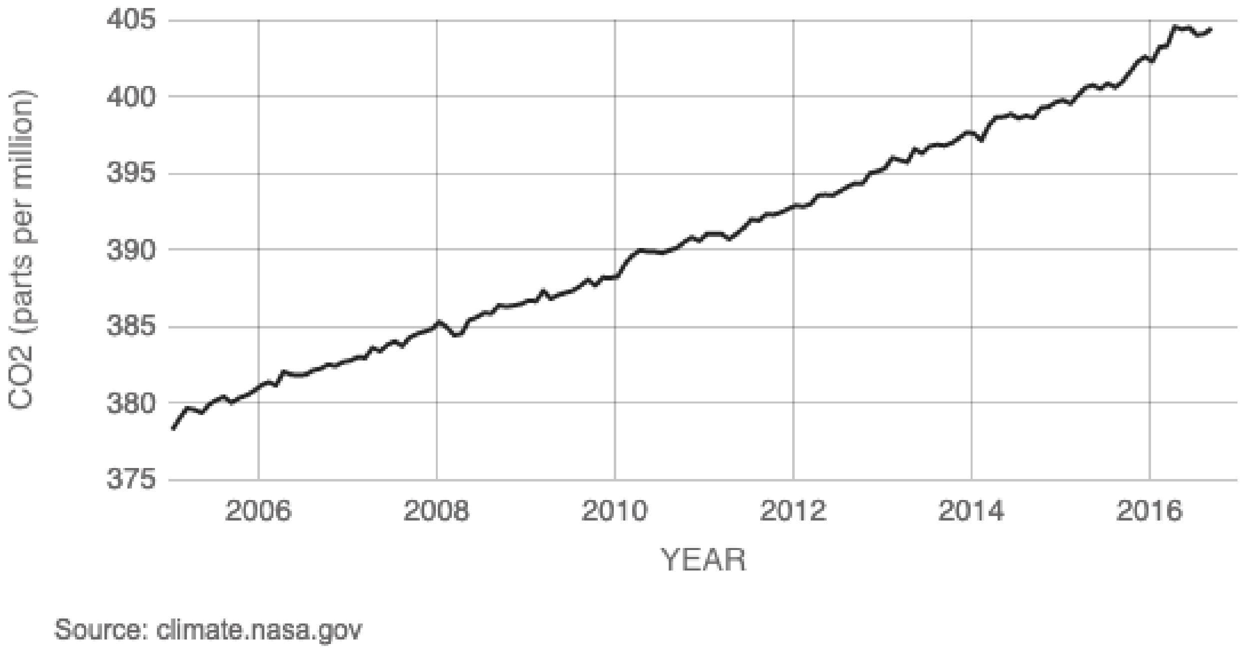


Figure 1.1: Atmospheric Carbon Concentrations 2005-Present

Source: NASA, 2016

Over the last ten years alone, carbon dioxide has increased by over 100 parts per million (ppm) and does not seem to be subsiding any time soon. This has been a substantial escalation since the 1950 concentration level, which was considered a peak in the history of carbon dioxide concentrations over the last three glacial cycles, as shown in the graph below.

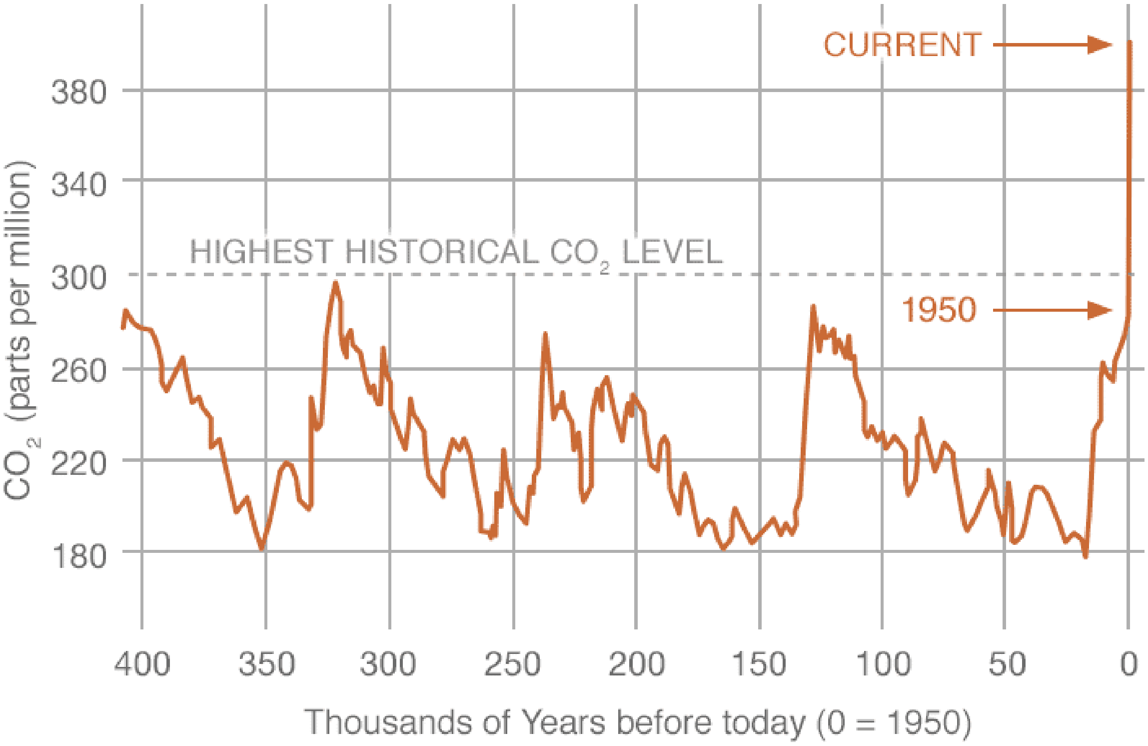


Figure 1.2: Atmospheric Carbon Dioxide Concentrations Over Three Glacial Cycles

Source: NASA, 2016

Both carbon dioxide concentrations and temperature have risen in approximately the same time frame. In a similar trend to the graph above, as depicted in Figure 1.3 below, the average global temperature has increased approximately 1.4 degrees Fahrenheit since 1880, of which two-thirds has occurred since 1975 (Carlowicz, 2014).

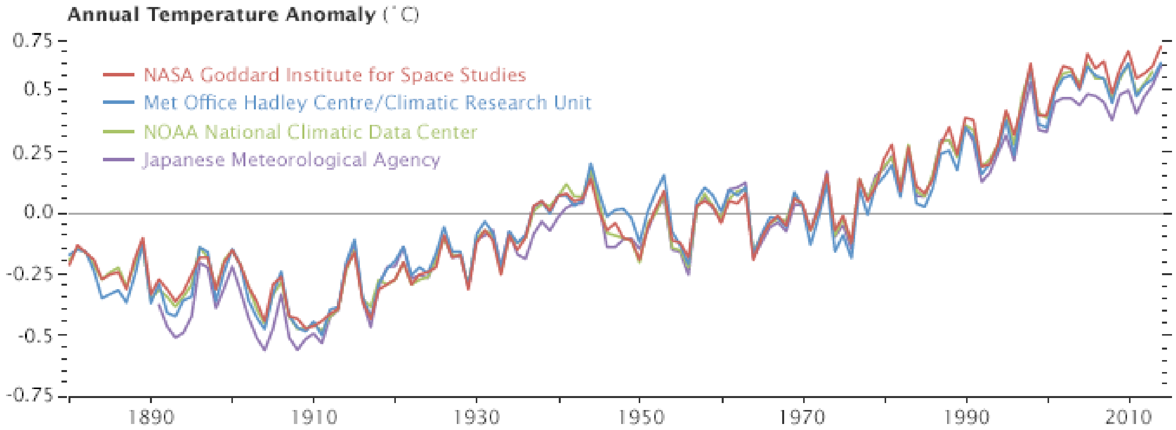


Figure 1.3: Global Average Annual Temperature Change

Source: Carlowicz, 2014

Although this 1.4 degree Celsius change may seem insignificant, the ice age was caused by a mere two-to-three degree drop (Carlowicz, 2014). As seen in the Figure 1.4, sea-levels have also risen proportionally with temperature change, an average of 3.4 millimeters per year (mm/year) over the past 20 years.

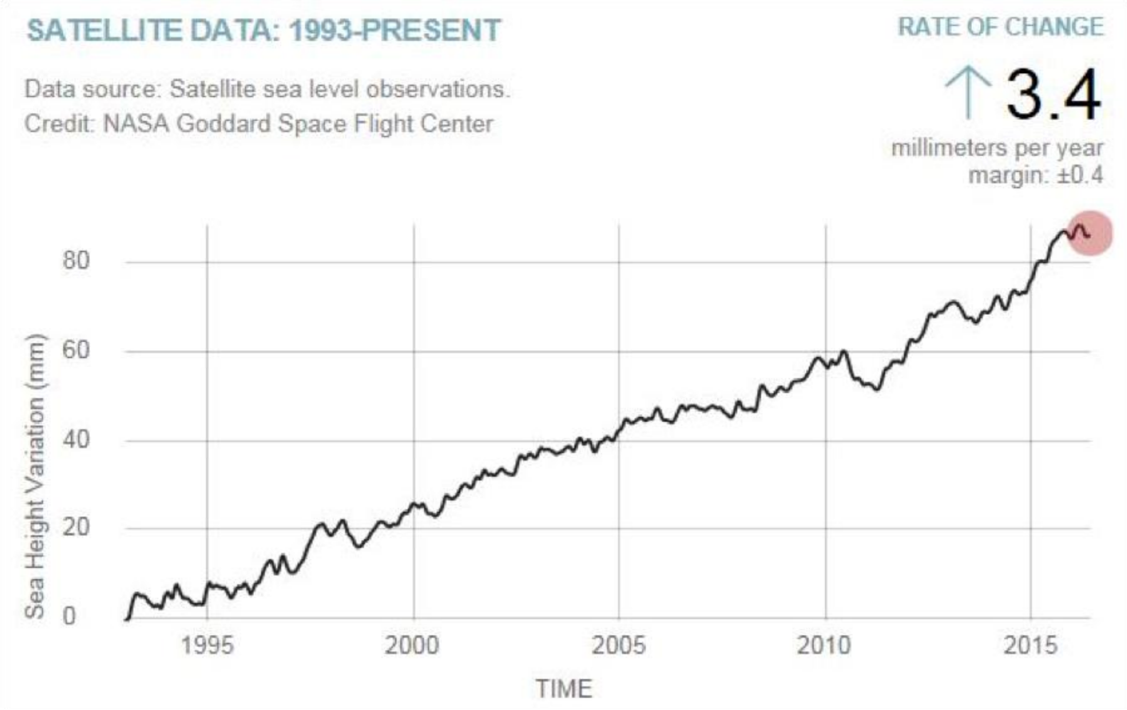


Figure 1.4: Sea Level Changes 1993-Present

Source: NASA, 2016

This is double the average increase that occurred throughout the twentieth century. In Boston alone, sea levels have risen 0.92 feet over the past 100 years (National Oceanic and Atmospheric Association, 2016).

Scientists attribute both of the major causes of sea-level rise (SLR) to global climate change. The first is thermal expansion, when the ocean expands as the temperature rises due to global climate change. Oceans are absorbing approximately 90 percent of the increased atmospheric heat, and expanding rapidly as a result (National Oceanic and Atmospheric Administration, 2016). A 2010 study on the impact of SLR on coastal areas estimated that thermal expansion has contributed between 25-50 percent to global mean SLR since 1960 (Nicholls, 2010). The second major cause is the loss of land-based ice, when glaciers and ice sheets melt due to elevated temperatures. Atlantic ice loss has quadrupled since 1992 and the

Greenland ice sheets have decreased in mass six-fold (Carlowicz, 2014). Land-based water storage changes are suspected to contribute approximately 30 percent to SLR (Nicholls, 2010).

The primary way, however, that most people experience global climate change is through changes in extreme weather events. Additional water from thermal expansion and ice melt has caused more periodic nuisance flooding. Storm surges inland are 300 to 900 percent more frequent within United States coastal communities than 50 years ago (National Oceanic and Atmospheric Association, 2016). North Atlantic hurricanes have also increased substantially in intensity, frequency, and duration since the early 1980s. Increases in activity are linked to higher average oceanic temperatures (USGCRP, 2014). A study on the risk of climate change to coastal wastewater collection systems found that Hurricane Ophelia in 2005 and El Niño-associated rain events during 2006 had "impressive effects" on total flow. For example, Ophelia caused influent flow at a WWTF in Wilmington, North Carolina to be as high as 17.0 mgd at a facility that typically experiences a mean flow rate of 8.18 mgd and is only designed for a capacity of 12.0 mgd (Flood, 2011). Not only does saltwater intrusion exhibit problems in terms of a high saline content, but the excess water consumes system capacity needed during critical overflow periods.

Overloaded systems are at risk for inefficient treatment, as well as sanitary and combined sewer overflows (Flood, 2011). A sanitary sewer overflow spills raw sewage into basements or out of manholes into the streets before it can reach the WWTF due to excess I/I. A combined sewer overflow discharges surplus wastewater directly into surface waters during heavy rainfall or snowmelt. Both overflow events can ensue as a direct result of global climate change, causing more frequent rainfall and other extreme weather events, as well as higher mean sea levels.

Manchester-by-the-Sea (MBTS) is one of many coastal communities already noticing the effects of climate change associated SLR. Large amounts of seawater are entering the system through manholes, contributing approximately 10 percent of the flow for the entire community. A report completed by CDR Maguire showed 273,000 gpd enters the system at peak infiltration. This report also estimated approximately 1,473,000 gallons of inflow during a typical storm event (CDR Maguire, 2016). The high salinity concentration has become enough of a problem that the Massachusetts Department of Public Works issued the town an Administrative Consent Order, mandating them to address I/I problems within their wastewater collection system.

King County in Seattle, Washington has also experienced similar I/I complications. Since 2003, the county’s Wastewater Treatment Division has been monitoring locations in the combined sewer and found that between three and six million gallons of saltwater enter the system each day. This amounts to be between one and two billion gallons per year (Phillips, 2011). During periods of high tide, seawater enters through gates, overflow weirs, and groundwater infiltration. Operators noticed spikes in conductivity, a measure of salinity, during or after tides greater than 10 feet, which occurs approximately 250 times per year in that area. Typical wastewater has a conductivity of 0.65 milli-Siemens per centimeter (mS/cm) and readings over 2 mS/cm indicate saltwater intrusion. In some areas of the collection system, King County wastewater averages 3.2 mS/cm, indicating that the flow is about 10 percent saltwater (Phillips, 2011). This prompted the county to raise the level of its waterfront weirs by six inches as a short-term solution and undertake a more comprehensive study in order to develop strategies to stop the sources of intrusion.

Elevated levels of salinity within the wastewater process present a number of challenges to the treatment plant. Increased salinity negatively affect the organisms responsible for removing pollutants, such as colloids, and elemental nutrients, like nitrogen, sulfur, and phosphorus. Population size and diversity of these organisms decrease with increasing salinity.

The amounts of dissolved oxygen, required by these organisms to grow, within the process stream also decreases as salinity within the system increases. This leaves the activated sludge less effective at removing pollutants from the wastewater. Aside from the impact of salinity on activated sludge, research shows that increased salt contents in wastewater may also reduce the effectiveness of the sedimentation process.

The purpose of this project was to determine the impact of increased salinity on the biological and chemical treatment processes used for wastewater treatment. To do so, laboratory experiments were conducted to determine a ‘critical salinity level’ at which point treatment processes would need to be modified in order to continue to operate appropriately, as well as recommendations on how these issues can be mitigated. The results produced from this study will be increasingly pertinent as more coastal WWTFs face problems related to global climate change and SLR.

Chapter 2: Background

Section 2.1: Pre-Treatment

Large debris can potentially damage or clog pumps, pipes, and channels, therefore raw sewage must undergo pre-treatment to ensure these are removed upon reaching the WWTF. In order to do so, screens and bar racks are utilized. Spacing of bars ranges from coarse (50-150 mm openings) to fine (10 mm opening), and screens are typically arranged from largest (in opening size) to smallest to act as a sieve. Particles must be maintained at a velocity of at least 0.6 meters per second (m/s) in order to prevent settling before water enters the primary treatment.

Section 2.2: Sedimentation

Sedimentation is the use of gravity to physically separate suspended material from water. When water enters the sedimentation basin, it contains small, negatively charged particles. Particles with the same charge repel each other, which hinders combination of these particles into a settled form. To combine them, the velocity in the sedimentation basins is decreased to a calm, quiescent flow so that particle suspension is no longer supported.

There are four types of sedimentation commonly used in WWTFs. Type I sedimentation is referred to as discrete particle settling. As such, the particle’s size, shape, and specific gravity do not change with time — these particles settle independently of each other. Type II sedimentation is called flocculant settling. Particles in this type aggregate as they settle meaning that they change in size, shape, and specific gravity with each contact. Type III settling is known as zone settling. There is a concentration of particles in this type, but not enough to cause substantial displacement of water. Lastly, Type IV sedimentation is compression settling, in which particles are in such high concentration that they constantly touch each other. Settling, therefore, can only occur by compression of the mass.

Sedimentation is typically separated into two stages: primary and secondary. The goal of primary sedimentation is to remove settleable solids and a portion of the BOD. Approximately 35 percent BOD and 60 percent-suspended solids are removed during this step in the treatment process (Henze, 2011). Colloidal and dissolved constituents, however, are not affected at this stage. Primary settling basins are either circular or rectangular, typically three to five meters in depth, with a hydraulic retention time of about two hours. Settled solids, also known as primary sludge, are removed from the bottom of the basin via scrapers and sent to further sludge processing. Solids that float to the top, also known as scum, are removed by water jets or mechanical arms and sent to further sludge processing as well.

The goal of secondary sedimentation is to remove the residual organics and suspended solids not removed in primary treatment. Wastewater enters the secondary sedimentation basin after going through the aeration and activated sludge process. Suspended solids will either settle to the bottom of the basin and be recycled into the activated sludge process, or be sent for further sludge treatment processes further downstream. BOD is typically reduced to 80 percent of influent levels at this stage (Henze, 2011).

Section 2.2.1: Effect of Salinity on Sedimentation

Previous studies on the effects of salinity on the sedimentation process have produced mixed results. Some research suggests that higher salinity makes it more difficult for suspended solids to settle. One such study, published in the *Journal of Environmental Progress*, attributed this to salinity's effect on water density (Smythe, 1997). The more salt present in a given amount of water, the more mass per unit volume the solution will contain. The volume of the water does not increase as the salt dissolves into solution, thus the density of the mixture increases with salinity (Moussa, 2006). Higher density wastewater could pose problems during sedimentation as the difference in density between the water and flocs decreases, which inhibits settling. This results in a large number of suspended solids and bacteria remaining in the effluent wastewater stream (Smythe, 1997).

Not all research, however, supports these conclusions. The sludge volume index (SVI), a measurement of the settled sludge volume over the mixed liquor suspended solids, can loosely reflect the performance of sedimentation:

$$SVI\left(\frac{mL}{g}\right) = (Settled\ Sludge\ Volume/Mixed\ Liquor\ Suspended\ Solids) * 1000$$

High SVI values can be attributed to sludge bulking. A study published in *Water, Science, and Technology* compared the activity and settling of microbes in the activated sludge process at various levels of salinity. The study found that wastewater with increased levels of salinity showed reduced SVIs, and settlement occurred more quickly. Reductions in SVI, however, as the Smythe study concluded, have also been attributed with increased amounts of suspended solids in effluent (Zhao, 2014). It appears that the supernatant of certain sludge becomes rather turbid at salinity above five percent (Tan, 2016). Increased turbidity, however, can result in quicker settling and SVI decrease. Low SVI values are characteristic of poor sludge activity due to a lack of nutrition for the microorganisms. Debate on whether increased salinity improves or degrades SVI is ongoing.

Section 2.3: Biological Wastewater Treatment

Activated sludge is defined as an aerobic process utilizing increased concentrations of microorganisms, both living and dead, that are suspended in wastewater that break down contaminants. These microorganisms require oxygen to grow cell mass. Aeration is the primary process used to supply the activated sludge with oxygen. The ideal range of dissolved oxygen (DO) content for microbial survival ranges between two to five mg/L (Michigan Water Resources Division; Wilén 2010). If DO levels drop below 2 mg/L, not only will the desired microorganisms die, but filamentous microorganisms, those that adversely affect the settleability of sludge, will increase (Wilén, 2010).

When microorganisms are mixed with raw sewage and oxygen, the organics are metabolized into new biomass. Thorough mixing is required to combine the sewage, microorganisms, oxygen and nutrients before clarification can take place. Contents in the aeration basin are commonly referred to as mixed liquor. After aeration, the biomass and suspended solids must be separated from the wastewater. To do so, a clarifying tank is used. Sludge is discharged from the bottom of the clarifying tank, while particles that float to the surface of the water, known as scum, are collected in a trough. Excess sludge is either returned to the aeration basin, discarded as waste, or sent for further processing. Aeration is a resource intensive process because oxygen needs to be constantly supplied to the aeration basin. Sludge processing and disposal are also major operational expenses.

Aeration is also useful for other important tasks, such as carbon dioxide (CO_2) removal. High levels of carbon dioxide can cause operational issues, such as increases in the acidity of water, increases in the amounts of lime needed to soften water, and more difficulty removing iron. Aeration is used to lower CO_2 values if concentrations are higher than 10 mg/L. When oxygen is added to the wastewater, it forces CO_2 out of solution, as it is more readily soluble. Aeration is also useful for iron (Fe) and manganese (Mn) precipitation. Aeration reduces Fe and Mn into less soluble forms, which in turn allows them to precipitate out of solution to be removed later in the treatment process.

Section 2.3.1: Effect of Salinity on the Activated Sludge Process

Increased levels of salinity in wastewater inhibit the effectiveness of the activated sludge process. In particular, population size and diversity of the microbes vital to the process are hindered. A study conducted by the United Nations Educational, Scientific, and Cultural Organization-Institute for Water Education (UNESCO) found that at salt contents of one percent, populations of key organisms responsible for the removal of nitrogen, phosphorus, and organic compounds are affected. The nitrification process, which is carried out by ammonium and nitrite oxidizing bacteria, was decreased by 20 to 30 percent. In addition, phosphate accumulating organism populations, responsible for the removal of phosphorus, were found to decrease 70 percent at salinity of one percent (Welles, 2012).

This data is in agreement with an older study from 1966, published in the *Water Pollution Control Federation Journal*, which examined the effects of salinity on activated sludge. The study compared volatile solid production and average oxygen demand in samples of wastewater at various levels of salinity. Results showed significant reduction in solid production and oxygen demand at levels of 45 g/L of NaCl, as shown in Figure 2.1 below (Kincannon, 1966).

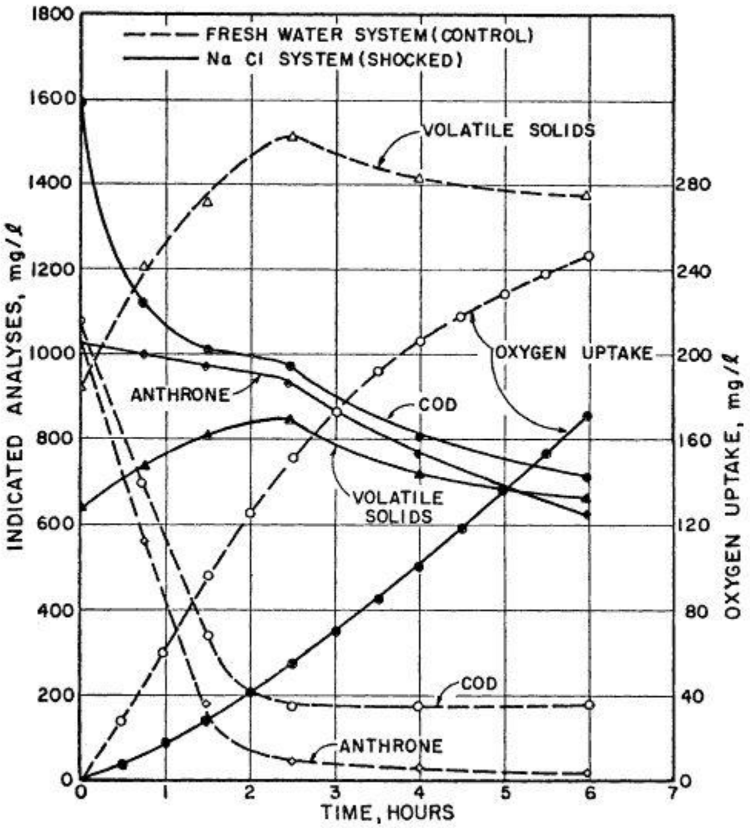


Figure 2.1: Solid Production and Oxygen Demand of Wastewater at 45 g/L NaCl

Source: Kincannon, 1966

These results, along with the findings of UNESCO, support the conclusion that microbe populations and diversity within activated sludge decrease as salinity increases.

Several studies have been completed to determine if activated sludge made with halophilic bacteria were able to withstand higher salt concentrations. High salinity results in loss of cell activity in activated sludge. Bacteria can thrive in water with up to two percent salinity before serious degradation of cell ability occurs (Zhang, 2014). To increase the cellular activity of activated sludge, halophilic bacteria are utilized. Halophilic bacteria thrive in high salt concentrations, unlike regular bacteria found in activated sludge. Studies have shown the use of salt tolerant bacteria that are able to yield high COD removal rates. One study done by the Pathology Department at Harbin Medical University in China found a bacterium called NY6 that can withstand salinity up to six percent, with optimal conditions being at two percent salinity (Zhang, 2014). NY6 is characterized as slightly halophilic. It was utilized because of its strong ability to be salt-resistant and its high rate of COD removal. A study done by Harbin Engineering University yielded similar results from observations on the microorganisms in a sequencing batch reactor (SBR) for 300 days with salinity varying from zero to three weight percent. The results of the study determined the SBR could maintain good performance below two percent salinity with a COD and BOD removal rate of 95 percent (Zhao, 2016).

Harbin Institute of Technology tested the effects of varying levels of salinity on three modified types of activated sludge. Type I activated sludge, called Marine Activated Sludge (MAS), was cultivated in a reactor for 60 days using seawater and sea mud. The strains of bacteria that reside in the sea ecosystem need certain levels of salinity to grow. The optimal range for MAS was between two and four percent (Tan, 2016). A second type of sludge, Domesticated Activated Sludge (DAS), was cultivated for 60 days using activated sludge from a treatment plant and continuously mixing it with seawater. This sludge performed best in the range of three to ten percent salinity. Although DAS showed similar trends to MAS, MAS performed better in terms of maintaining biodiversity of the microorganisms (Tan, 2016). The third type of activated sludge was cultured similarly to DAS, but saline water was used instead of seawater. This was called Conventional Activated Sludge (CAS). CAS performed best at a salinity of one percent. Above two percent, there was a severe loss of biodiversity and a reduction in the ability to treat (Tan, 2016). Although MAS and DAS performed well in increased salinity, neither could withstand salinity over ten percent.

Salt-resistant bacteria, as well as reverse osmosis through membrane bioreactors (MBRs), are both proven solutions to address salinity issues in wastewater, however, given their constraints, were deemed unfeasible as solutions for this project. Halophilic bacteria used to treat wastewater containing between three and five percent salinity by weight, resulted in higher COD removal efficiency and lower COD concentrations. Unfortunately, these bacteria are not available widespread, the organisms require a minimum 10 day cultivation period, and the cultivation media must be replaced every three days (Kargi, 2000). This is simply impractical and too costly for wastewater treatment plants that only experience occasional spikes in salinity. There is also evidence that MBRs are capable of removing salt from wastewater and can produce high quality effluent. However there are some negative considerations that may deem them a poor choice for some applications. MBRs are expensive, unsuitable for large-scale facilities, and high maintenance. Furthermore, coastal WWTFs that experience saltwater intrusion may need an emergency solution, whereas recommending a MBR is practically equivalent to asking these communities to build new WWTFs.

Section 2.4: Effect of Salinity on Oxygen Solubility

In addition to the effect of salt concentration on the organisms within sludge, higher levels of salinity cause oxygen’s solubility in wastewater to decrease. The Virginia Institute of

Marine Science studied the effects of increased salinity on oxygen solubility, particularly in estuaries, and found that as salinity increases in a body of water, oxygen solubility decreases. According to data published by the Fondriest Environmental Group, oxygen solubility in seawater is 20 percent less than that of fresh water at the same temperature and pressure (FEG, 2014). On a molecular level, this is due to the fact that water is made up of polar molecules. When salt ions are added, they attract the water molecules better than the non-polar oxygen molecules, leading to less oxygen being able to remain dissolved in the solution.

Furthermore, the diffusivity of oxygen through water may also be affected by increased salinity. A study published in the *Journal of Experimental Marine Biology and Ecology* found that the diffusivity of oxygen in water decreases as salinity levels are increased. The authors attributed this to salt's effect on the activity coefficient, a measure of how much a solution deviates from thermodynamically expected behavior (Cao, 2015).

The effects of salinity on oxygen solubility and diffusion are of importance to wastewater treatment because of the impacts to the activated sludge process. The bacteria and protozoa in activated sludge are aerobic, meaning that they require oxygen to grow and reproduce. Decreases in soluble oxygen available in the wastewater spurs competition amongst the organisms, hindering overall population size and growth rate. Fewer organisms decrease the effectiveness of the sludge to remove soluble organics from the wastewater process stream.

Chapter 3: Methodology

The main objective of this project was to gain a better understanding of the impacts of increased salinity on the biological and chemical processes within WWTFs. The goal was to determine a critical salinity threshold, at which the amount of salt would no longer allow a facility to operate normally. Salinity management and mitigation techniques were then developed from this threshold. In order to do so, the following experimentation was performed as outlined in the sections below.

Section 3.1: Artificial Seawater

Components were added to wastewater samples in order to artificially reproduce saltwater intrusion on a WWTF in accordance with ASTM D1141 - 98 (2013): Standard Practice for the Preparation of Substitute Ocean Water. The procedure, as shown in Appendix A, gives quantities to create a one-liter, 3.5 percent salinity by weight solution. Quantities were manipulated using these standard ratios to create solutions of lower and higher salinity and scaled to provide the required amount of seawater.

Section 3.2: Respirometry

Respirometry tests were run on wastewater to determine BOD removal at varying levels of salinity. The wastewater was diluted with artificial seawater, as well as deionized water, to produce 500 mL of solution at a desired salinity level. Each sample was then placed in a respirometer reaction vessel along with a headspace vial containing 5 mL of 30 percent potassium hydroxide by weight to absorb any carbon dioxide produced. The sample was mixed at 700 rotations per minute (rpm) for the duration of the test. Each vessel was tightly sealed and connected via a tube and needle to the respirometer flow-cell base. The base, which sourced oxygen from a tank, added oxygen to the sample in order to maintain a constant oxygen content in the reaction vessel. A computer attached to the base measured and recorded the amount of oxygen added over time. Each sample was tested for a period of 48 hours. The full experimental procedure can be found in Appendix B.

Section 3.3: Sedimentation

Sedimentation tests were run to determine the impact of varying levels of salinity on the sedimentation process. To achieve differing salinity levels, wastewater samples were diluted with an artificial seawater solution and deionized water to a total of 500 mL. Initial turbidity readings were taken for each sample using the Hach 2100N Turbidimeter. Samples were placed on a paddle mixer and set at a rapid mix rate between 150 and 200 rpm for approximately two minutes. After this time, paddle speed was reduced to approximately 30 rpm for 20 minutes to allow for the formation of flocs. Next, the paddles were turned off and the flocs were left to settle for another 20 minutes. After settling, approximately 3 mL of supernatant were pipetted from each solution and diluted to a factor of 3/28 using deionized water before measuring the final turbidity. A full experimental procedure can be found in Appendix C.

Section 3.4: Oxygen Solubility

Oxygen solubility experiments were run on samples of wastewater to determine how salinity affects the amount of soluble oxygen in wastewater. To do so, samples of wastewater were diluted using artificial seawater and deionized water to make 250 mL of solution at a desired salt concentration. Each sample was placed into a flat bottom flask connected to an oxygen source. Oxygen was bubbled through until the system reached steady state. A dissolved oxygen probe was used to measure the amount of oxygen dissolved in the wastewater sample. A full experimental procedure can be found in Appendix D.

Chapter 4: Results and Analysis

Section 4.1: Salinity and Sedimentation

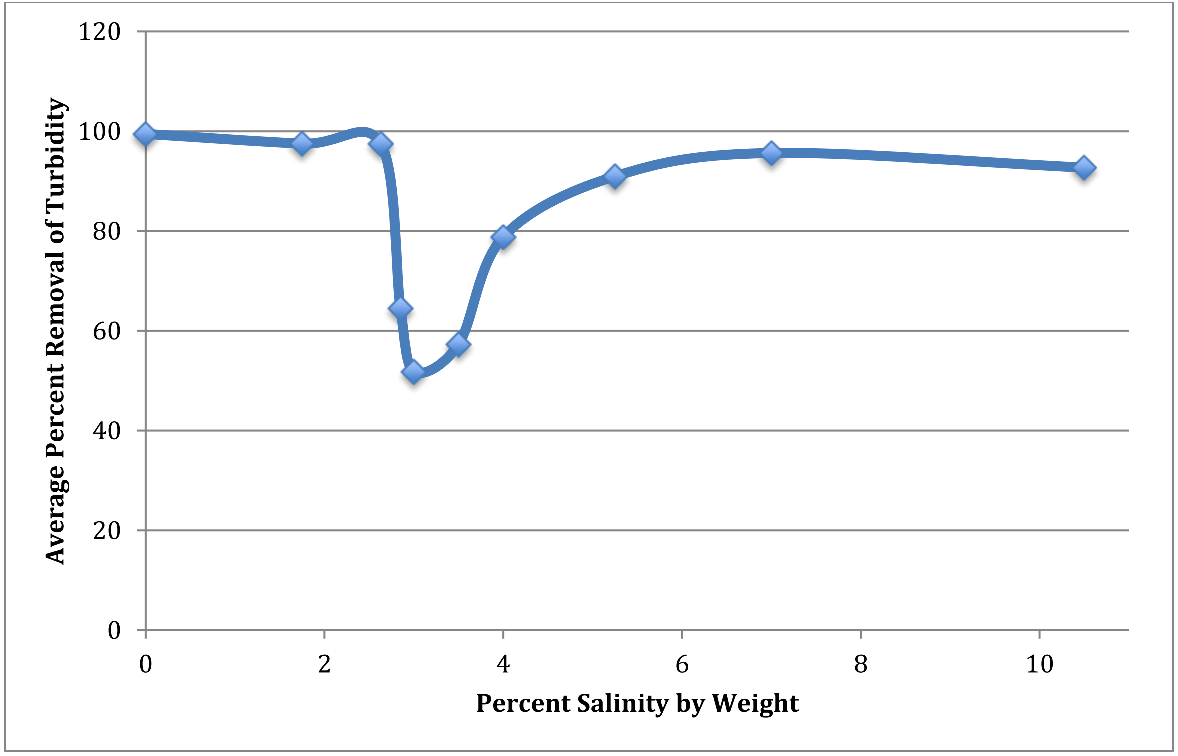


Figure 4.1: Average Percent Turbidity Reduction

The data presented above represents the average removal of turbidity found during sedimentation experimentation. During the tests, saline solutions were added prior to taking initial turbidity values. For this reason, the data is shown as percent changes from initial to final turbidity levels in the samples after sedimentation occurred. Trends in the data show that turbidity removal decreased as the salinity levels in the samples increased. However, once the salinity within the sample reached four percent, turbidity removal increased. Although the 10.5 percent sample does not follow this trend, it is attributed to the fact that excess salt particles contributed to a more turbid solution. Seven percent salinity by weight represents a sample that is entirely composed of seawater; therefore 10.5 percent salinity represents an extremely salty solution, in which the particles have trouble dissolving entirely. This is in accordance with research published on the *Fresenius Environmental Bulletin*, which stated that the supernatant of certain sludge becomes rather turbid at salinity above five percent (Tan, 2016).

While high salinity solutions exhibited almost as much turbidity removal as the baseline samples, the suspended solids in these samples floated to the top as opposed to settling to the bottom, as shown in Figure 4.2 below.

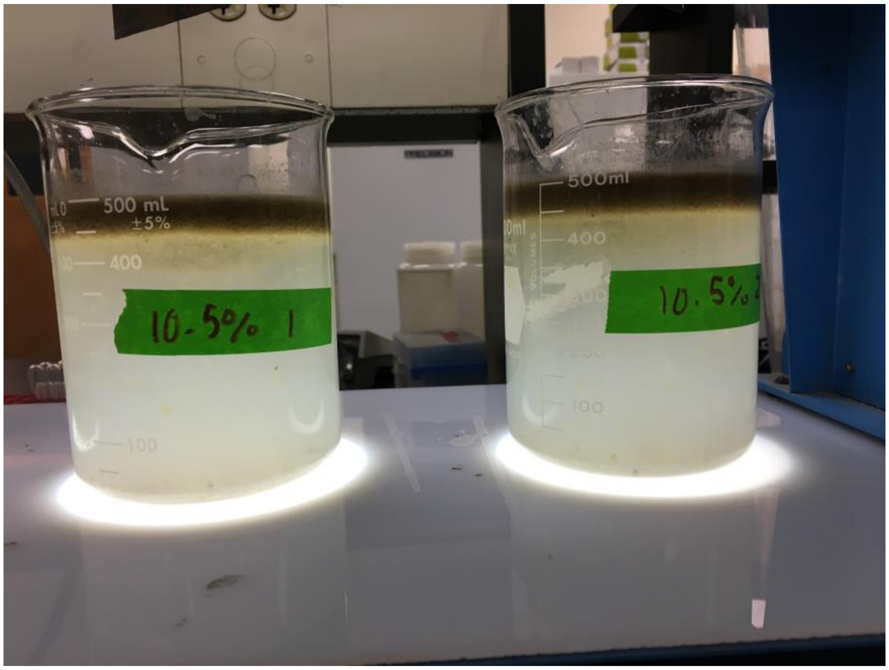


Figure 4.2: High Salinity Sedimentation

This phenomenon is due to the fact that the added salt in these samples increased the density of the water above that of the suspended solids, causing them to float. This may prove ineffective in commercial and industrial settings where equipment is typically designed to remove sludge from the bottom of a tank rather than the top.

The critical salinity threshold is then twofold: at salinity percentages above 2.63, there is a significant decrease in turbidity removal and at salinity percentages above three, flocs begin floating to the top.

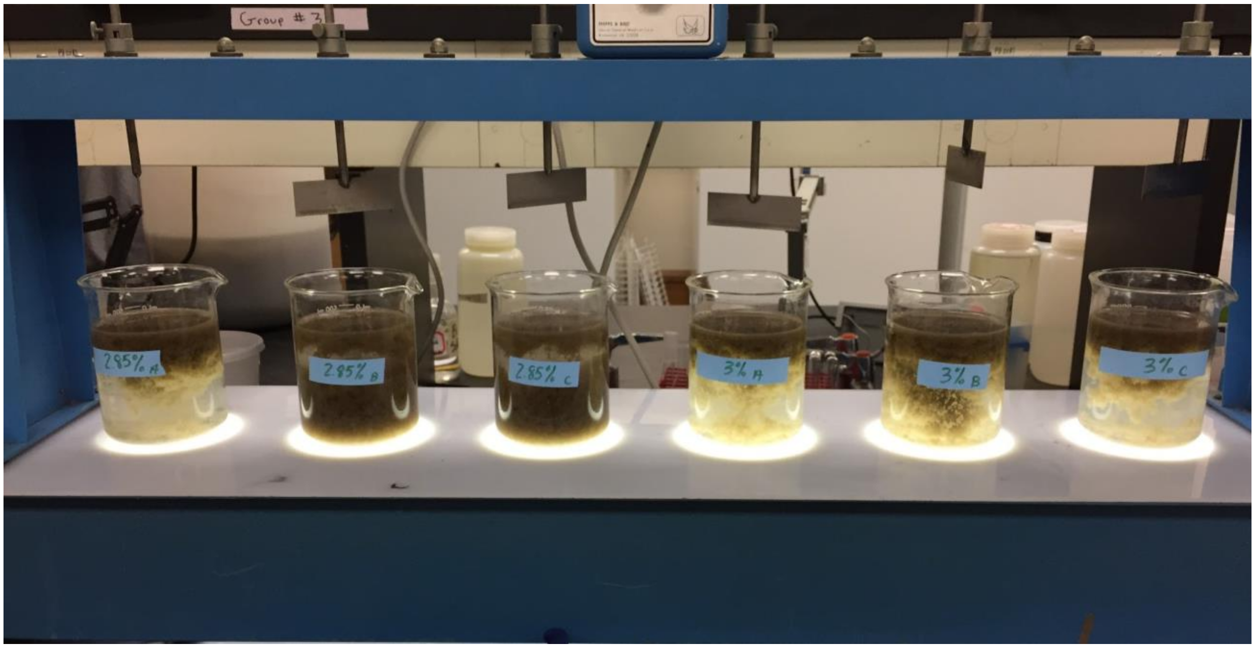


Figure 4.3: Sedimentation Experimentation Results

As shown in Figure 4.3 above, at 2.85 percent salinity by weight, separation is weak and flocs both settle to the bottom and float to the top. Furthermore, the results are inconsistent, which would make treatment difficult for a facility. This means typical sedimentation processes would no longer be effective with influent composed of 40 percent seawater. At salinity levels above three percent, separation is still weak, however flocs float entirely to the top rather than settle to the bottom, indicating that I/I resulting in 43 percent seawater would require skimming sludge from the top of the tank rather than the bottom.

These results confirm previous studies of salinity's effect on sedimentation. The 1997 study by Smythe published in the *Journal of Environmental Progress* attributed salinity with decreased efficacy of sedimentation due to changes in water density. Smythe argued that his data showed that as water density became closer to that of the suspended solids, the separation of the two was hindered. These findings confirm this as turbidity removal was found to decrease around 2.85 percent salinity, but increase above levels of 3.5 percent salinity by weight.

Also confirmed by these results is the theory that high levels of salinity cause quicker separation of water and suspended solids. Separation in samples greater than or equal to seven percent salinity was observed to occur significantly quicker than samples with lower salinity. For example, samples containing 10.5 percent salinity were observed to separate within a few minutes of the saline solution being placed in the wastewater, and would require mixing prior to taking the initial turbidity measurement. These high salinity samples would again separate almost to completion within 30 seconds of the settling period after flocculation. Given, however, that the suspended solids in these samples floated to the surface, the more rapid rate of separation may not be beneficial for commercial and industrial uses.

Section 4.2: Salinity and Dissolved Oxygen

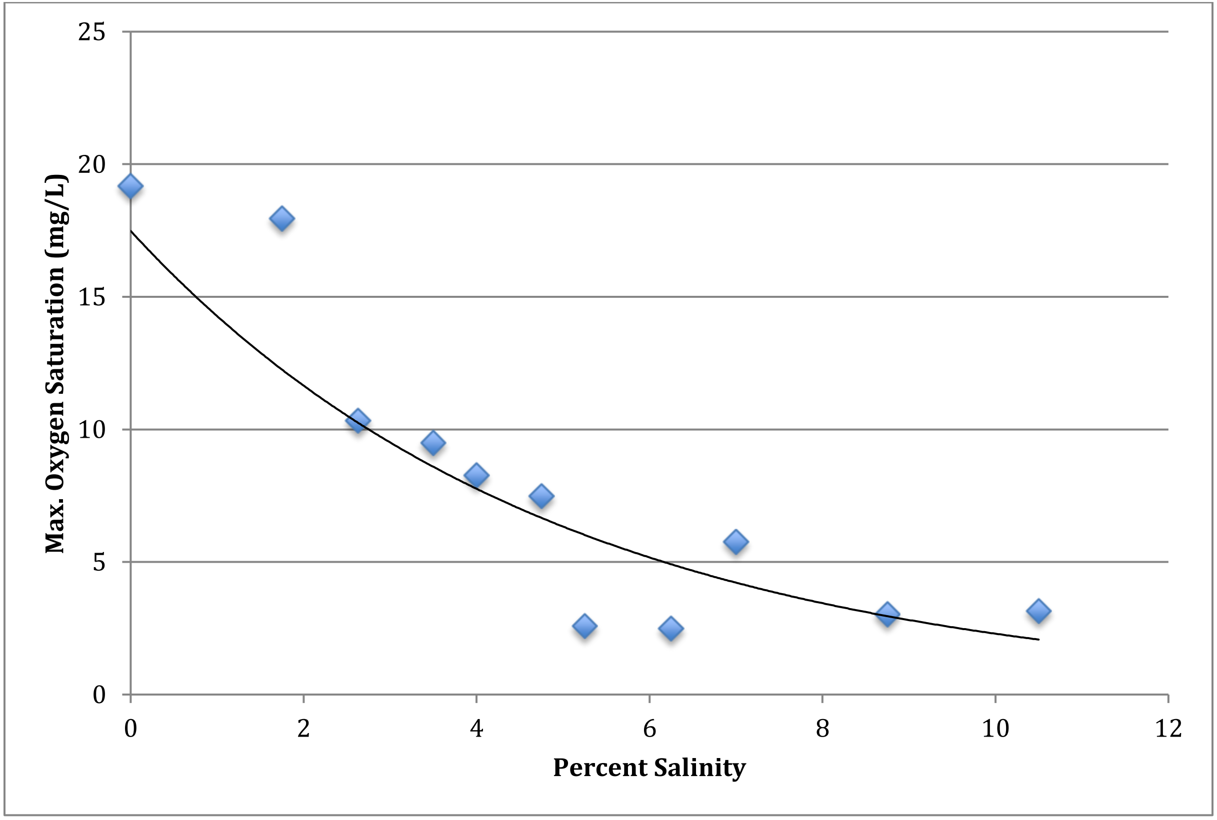


Figure 4.4: Maximum Oxygen Saturation vs. Percent Salinity

The graph above shows the maximum oxygen saturation of wastewater between 15 and 17°C at varying salinity levels. Factors had to be closely monitored as the solubility of oxygen varies greatly based on temperature, pressure, and salinity. Only data within a specific temperature range is presented in Figure 4.4, as the dissolution of oxygen in water is an exothermal process, therefore, colder temperatures shift the equilibrium towards the dissolved form.

The maximum dissolved oxygen concentration of water between 15 and 17°C is between 9.65 and 10.07 mg/L (EPA, 2012). It is clear, therefore, that the wastewater solutions used in this experiment were supersaturated most likely due to rapid aeration and the excess of organic material in the water. This is not surprising as organic materials retain more soluble oxygen in solution, and the oxygen was bubbled directly into the samples minimizing mass diffusion limitations. The baseline sample was approximately 194 percent saturated, whereas the sample with 4.75 percent salinity by weight was only about 78 percent saturated, indicating that the ability of the microorganisms to intake oxygen decreases as salinity increases.

Trends in the data align with previous studies, such as that of the Virginia Institute of Marine Science, in that dissolved oxygen decreases as salinity increases. The average DO of a baseline sample of wastewater containing no salinity was measured to be 19.18 mg/L. Once salinity was increased to just 2.63 percent by weight, the average DO decreased to 10.33 mg/L – a 46 percent drop in DO within a salinity change of less than 3 percent. Furthermore, the data also reaffirms a study published in 2014 by the Fondriest Environmental Group, which claimed that oxygen solubility in seawater is 20 percent less than that of fresh water. DO at seven percent salinity by weight, the concentration of seawater, was 5.77 mg/L, which is 30 percent of the baseline DO of 19.18 mg/L. The excess organic material in wastewater can account for the 10 percent difference in oxygen solubility.

Oxygen solubility less than 2 mg/L has been shown to have significant effects on water quality. Below 2 mg/L, the wastewater is at risk of dead zones, which will promote anaerobic conditions (Wilén, 2010). It is typical to design between 25 and 75 percent of the minimum operating values; therefore WWTFs require a maximum oxygen saturation of at least 8 mg/L (Turton, 2008). At four percent salinity by weight, the average DO was measured to be 8.28 mg/L, but at 4.75 percent salinity by weight, the average DO was 7.49 mg/L, below the critical threshold. Using the trend line equation, $y = 17.484e^{-0.232x}$, it was calculated that the critical salinity threshold sits at 3.85 percent salinity by weight, meaning that wastewater containing more than 55 percent seawater will not meet DO requirements, potentially rendering the aeration process insufficient. Although 55 percent seawater would indicate a larger I/I event, respirometry data provides evidence of microbial inhibition at lower salinity levels, which also greatly affect the aeration process. For a more detailed discussion regarding respirometry, refer to Section 4.3 below.

It is interesting to note that for both DO and sedimentation experimentation, the critical salinity threshold lies between two and four percent salinity by weight. Additionally, in both, 3.5 percent salinity by weight represents a turning point in the data. For oxygen solubility, salinity around 3.5 percent marks the beginning of the downfall of DO towards a dangerous level, whereas, in sedimentation, it marks the beginning of increasing average percent removal of turbidity. Clearly, when wastewater is comprised of 50 percent seawater, it substantially alters the chemical and biological composition of the solution wherein it no longer behaves as anticipated.

Section 4.3: Salinity and Respirometry

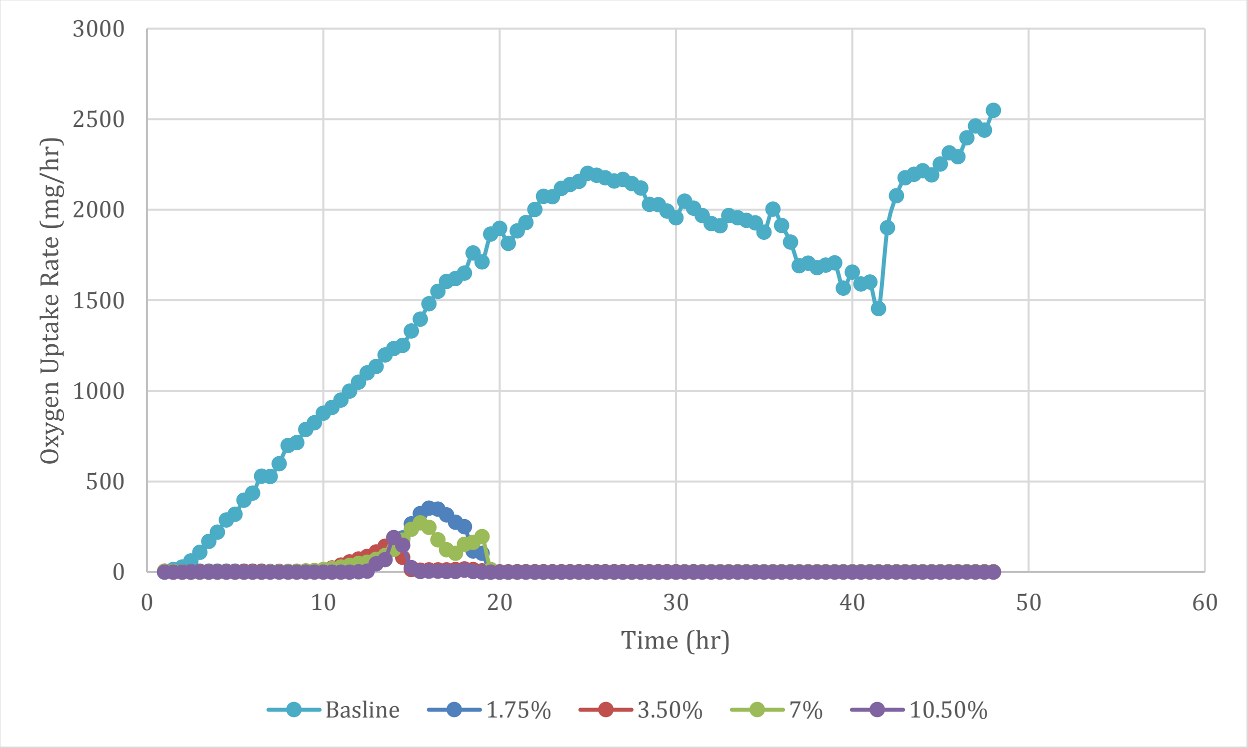


Figure 4.5: Oxygen Uptake Rates vs. Time

The data shown in the graph above represents the Oxygen Uptake Rate (OUR) found during the respirometry experimentation over a period of 48 hours at various levels of salinity. For each level of salinity, the respirometry experiment was run on three duplicate samples and the resulting data was averaged to create the trends shown above. Baseline samples containing no added salt exhibited the largest OUR, far exceeding the rates produced by samples at higher salinity concentrations. As discussed previously, the microorganism populations within samples require oxygen to consume soluble organics, therefore OUR is a direct indicator of cell growth and BOD removal.

As expected, in the samples in which no salt was added, the OUR was highest but as the salinity level increased, the OUR dropped considerably. The significant decrease in OUR between the baseline samples and those at salinity levels of 1.75 percent confirms the finding of the Tan study conducted at the Harbin Institute of Technology, which found that Conventional Activated Sludge exhibited a severe loss of bioactivity and diversity at concentrations around two percent.

Also supported by this data are Tan's findings that organisms could be cultured in solutions with elevated salt concentrations in an effort to adapt them to higher salinity. Figure 4.6 below shows a subset of the OUR graph in Figure 4.5 above.

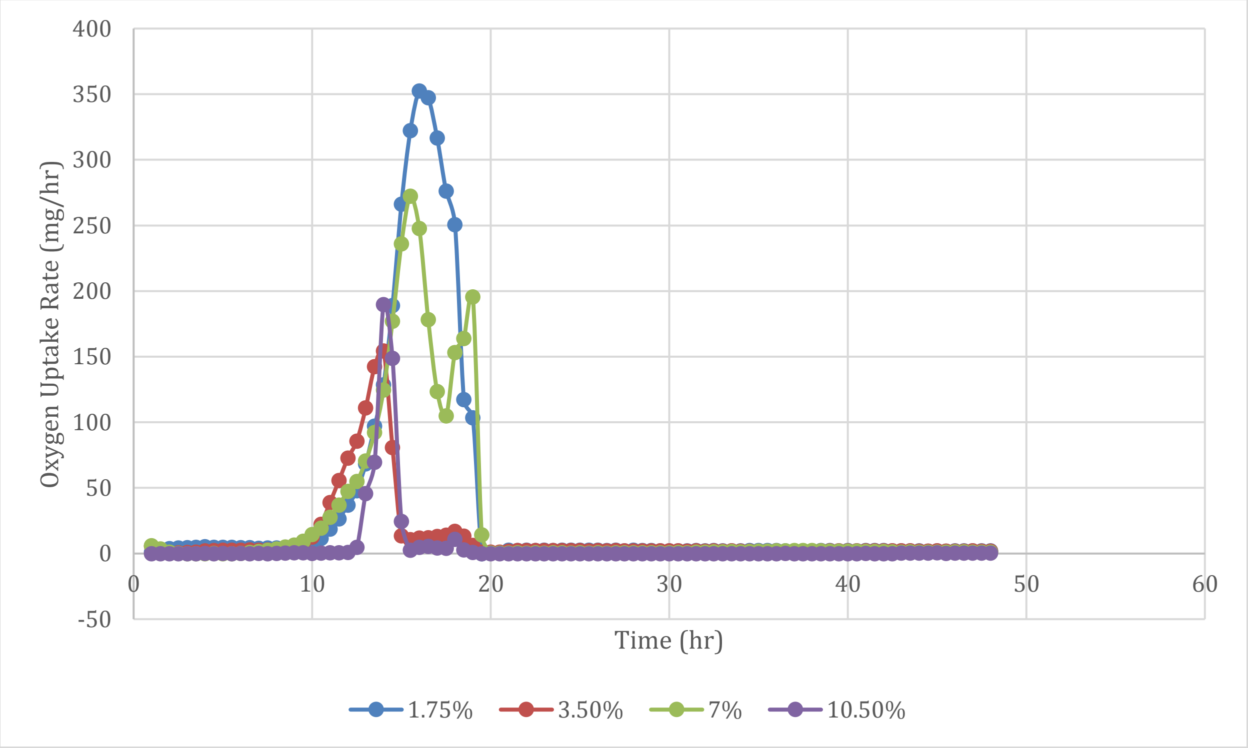


Figure 4.6: Enlarged Oxygen Uptake Rate vs. Time

In the samples with added salt, OUR did not begin to increase until 10 to 13 hours into the experimentation. This phenomenon, known as lag time, is indicative that the microbes within the sample required time to adapt to their saline shocked environment. Following the lag phase, the microbes began to consume oxygen, indicating adaption to the additional salinity. OURs within these samples, however, recovered only to a small fraction of the baseline OUR.

Trends in the data show that samples with higher salinity will experience a significant decrease in OUR and increase in lag time, illustrating that salinity negatively effects the microorganism populations within activated sludge crucial to BOD removal. At salinity levels as low as 1.75 percent by weight, the aeration processes of wastewater treatment are expected to be greatly hindered. While some level of aeration will continue to occur at any salinity level, the ‘critical threshold’ is anything above zero percent salinity by weight, as the extreme reduction in BOD removal will disrupt downstream treatment processing and overall water effluent quality. These findings were used to develop and design methods by which WWTFs can respond to disturbances in salinity within wastewater to minimize the effects on aeration processes.

Chapter 5: Design

Through bench-scale experimentation, it was identified that increased levels of salinity greatly affect the sedimentation and activated sludge processes in WWTFs. Salinity ranging between 2.63 to 5.24 percent by weight exhibited poor floc separation and, therefore, the sedimentation processes cannot be sufficiently completed. At 5.25 percent salinity by weight and above, flocs aggregate and float to the top of the water. When activated sludge comes into contact with wastewater containing salinity over 2.63 percent by weight, there is a longer acclimation period for microorganisms and BOD removal is diminished. To mitigate both of these issues, a salinity monitoring system was designed to be put into place before primary settling. During salinity disturbance events, the evaluation system will trigger newly-designed technologies that address the issues salt imposes on the activated sludge and sedimentation processes. The details of each design are discussed below, and derivatives and example calculations can be found in Appendix F-J.

Section 5.1: Activated Sludge Reseeding System Design

In order to address the negative effects of salinity on the microorganism populations within the activated sludge used in the activated sludge process, it is recommended that a sample of activated sludge be maintained in a reseeding tank separate from the processing stream. This sample, which can be isolated from the system in the event of a spike in salinity, would be used to reseed the activated sludge process in an effort to restore the system following salinity levels returning to normal operating conditions.

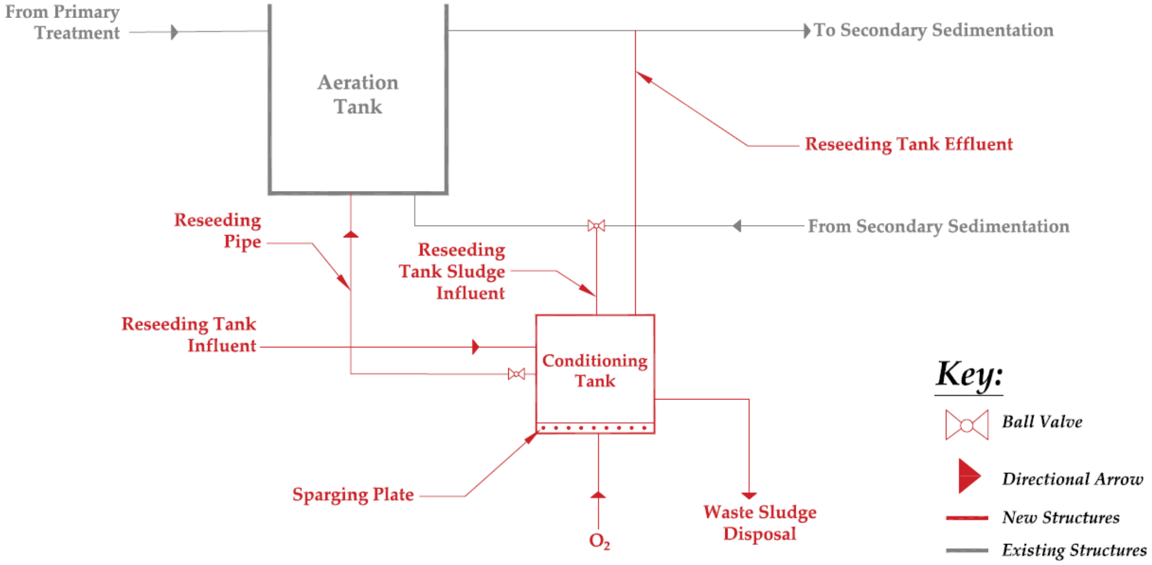


Figure 5.1: Activated Sludge Reseeding System Schematic

As shown in Figure 5.1 above, the reseeding tank is placed in parallel to the aeration tank. Sludge for the reseeding tank is pumped from the secondary sedimentation tank via the reseeding sludge influent pipe on the sludge recycle stream. Wastewater is taken from the influent stream into the plant to provide the necessary organic matter for microbial growth within the reseeding tank. Oxygen, a requisite nutrient, is sparged at the bottom of the tank. This not only maintains required DO levels, but also provides the system with low shear mixing. Once wastewater is stripped of its organic materials within the reseeding tank, it is pumped via the reseeding effluent pipe into the secondary sedimentation tank. The concentration of activated sludge within the reseeding tank should be equivalent to the concentration within the main aeration tank. For details on sizing of the pipes and reseeding tank, refer to Section 5.3 below.

Section 5.2: Sedimentation Process Design

Findings show that wastewater containing salinity concentrations between 2.64 and 5.24 percent salinity by weight does not flocculate, and therefore the clarification process will not be effective. To address this issue, it is recommended to redesign the secondary sedimentation system to input ocean water to increase the salinity to a level where flocs will float and, in essence, flip the tank to skim sludge from the top and dispel clean water from the bottom.

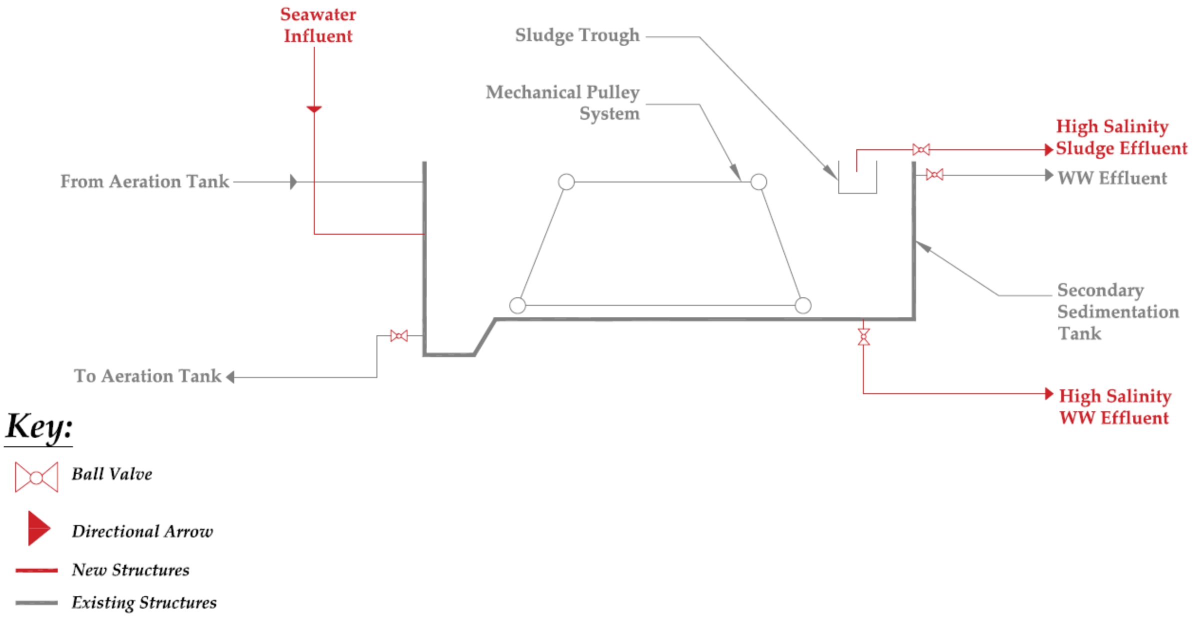


Figure 5.2: Sedimentation System Schematic

In order to flip the tank, as shown in the Figure 5.2 above, both sludge and effluent pipes are placed on both exits of the tank. Clean water is piped from the bottom of the tank directly to the next stage of the treatment process via a chlorinated polyvinyl chloride (CPVC) pipe and continues on normally. CPVC is recommended as it is a cheaper, lighter weight, and easier to install alternative to metallic piping. Additionally, the extra chlorination of the polyvinyl chloride resin makes it resistant to degradation and bacteria formation, which is especially advantageous in the handling of ocean water and sludge.

Sludge is collected in the trough typically designated for skimmings and floated debris, and piped out via a CPVC pipe. The new sludge pipe is larger than the existing to account for the high flow rate needed to ensure that flocs to do not overflow from the trough. For sizing specifications, refer to Section 5.3 below. Due to the fact that the trough is traditionally intended for small amounts of organic material, it may be beneficial to also resize it to be larger if the WWTF experiences frequent disturbances. In addition, the mechanical sludge scraper system must be turned off during a disturbance to keep flocs afloat and ensure proper flow. Ball valves are placed on all existing and new effluent and sludge pipes to control the flow of sludge and clean water as needed.

A pump transfers seawater into the sedimentation tank via a CPVC pipe. The pump contains a screen to ensure aquatic plants and animals do not enter the system. For pump specifications, refer to Section 5.3 below. Seawater is added to the tank according to the following equation:

$$Q_s = 3Q_w - \left(\frac{x_w}{0.0175}\right) Q_w$$

where Q_s is the volumetric flow rate of seawater to be added, Q_w is the volumetric flow rate of wastewater present, and x_w is the concentration of salinity present in the wastewater. For detailed calculations, refer to Appendix E. The flow rate of wastewater from the existing influent must be slowed to account for the additional volume of seawater to the tank.

Considering that seawater contains approximately seven percent salinity by weight, depending on the frequency of disturbances, the sedimentation tank may degrade as a result of the salt. It is recommended that operators inspect tanks post-disturbance to evaluate the degree of rehabilitation required. If necessary, a polyurethane or polyurea resin spray coating can be applied to the concrete.

Section 5.3: Sizing Calculations

Section 5.3.1: High Salinity WW Effluent and Seawater Influent Pipe Sizing

The following equations may be used to calculate the proper pipe diameter for the Salinity Effluent Pipe and Seawater Influent Pipe (schematic 5.3):

$$D_{we} = 656.98 \times Q_{we}$$

$$D_{si} = 166.7 \times Q_{si}$$

Where:

$D_{we} = Diameter\ of\ Disturbance\ WW\ Effluent\ Pipe$ (m)

$D_{si} = Diameter\ of\ Seawater\ Influent\ Pipe$ (m)

$Q_{we} = flowrate\ through\ Disturbance\ WW\ Effluent\ Pipe$ (m^3/s)

$Q_{si} = flowrate\ through\ Seawater\ Influent\ Pipe$ (m^3/s)

These values are based on a laminar flow profile for the wastewater (Re = 1900) and turbulent flow (Re = 7500). They are a function of volumetric flow rate, Q (m^3/s), through each pipe. Derivations and physical fluid properties used to develop these equations can be found in Appendix F.

Section 5.3.2: High Salinity WW Effluent and Seawater Influent Pump Sizing

In order to calculate the pump power, U (kW), required per unit length (m) for the High Salinity WW Effluent and Seawater Influent Pipes (schematic 5.3), the following equations may be used:

$$U_{we} = \frac{7.97 \times 10^{-17}}{Q_{we}^{2}}$$

$$U_{si} = \frac{9.53 \times 10^{-17}}{Q_{si}^{2}}$$

Where:

$$U_{we} = \frac{Disturbance\ WW\ Effluent\ Pump\ Energy}{Meter\ of\ Pipe} \left(\frac{kW}{m}\right)$$

$$U_{si} = \frac{Seawater\ Influent\ Pump\ Energy}{Meter\ of\ Pipe} \left(\frac{kW}{m}\right)$$

These equations rely on pressure drop calculations based on a laminar flow profile (Re=1900). Pump energy efficiency is assumed to be 70 percent and the equations are presented as a function of the anticipated flow rate, Q (m^3/s), through each pipe. Derivations of the pump power equations, pressure drop values, and physical fluid properties used can be found in Appendix G.

Section 5.3.3: High Salinity Sludge Effluent Pipe Sizing

The following equation may be used to calculate the required pipe diameter of the Salinity Sludge Removal Pipe (Schematic 5.3) based on the flowrate through the pipe (Q_{sr}):

$$D_{se} = \frac{12.85 \times Q_{se}}{Z}$$

Where:

$D_{se} = Diameter\ of\ Disturbance\ Sludge\ Effluent\ Pipe$ (m)

$Q_{se} = flowrate\ through\ Disturbance\ Sludge\ Effluent\ Pipe$ (m^3/s)

$Z = \frac{V_T}{V_S} = Sludge\ collection\ ratio$

$V_T = Volume\ of\ Sludge\ Trough$

$V_S = Volume\ of\ Sedimentation\ Tank$

And

$Q_{se} \geq 0.0856$ (m^3/s)

The values were calculated based on a semi-turbulent flow profile (Re=3500). Based on specifications outlined in the 2014 edition of *Recommended Standards for Wastewater Facilities* published by the Great Lakes-Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers, a minimum flow rate of Q = 0.0856 m^3/s is required to prevent blockage of sludge removal piping.

In most WWTFs, the volume of the sludge collection trough situated at the top of the sedimentation tank is significantly smaller than the volume of the sedimentation tank. In order to ensure the diameter of the pipe is sufficient to prevent overflow of the trough, a sizing factor, Z, relating the two volumes, is utilized. Derivations and physical fluid properties used to develop this equation can be found in Appendix H.

Section 5.3.4: High Salinity Sludge Effluent Pump Sizing

In order to calculate the pump power, U (kW), required per unit length (m) for the High Salinity Sludge Effluent Pipe, the following equation may be used:

$$U_{se} = \lambda \frac{3.5 \times 10^{-6}}{Q_{se}^2}$$

Where:

$$U_{se} = \frac{Disturbance\ Sludge\ Effluent\ Pump\ Energy}{Meter\ of\ Pipe} \left(\frac{kW}{m}\right)$$

$$\lambda = Darcy - Weisbach\ Friction\ Coefficient$$

This equation relies on pressure drop calculations based on a turbulent flow profile (Re=3500). Pump energy efficiency is assumed to be 70 percent and the equations are presented as a function of the anticipated flow rate, Q (m^3/s), and the Darcy-Weisbach friction coefficient, λ.

The friction coefficient is a function of the Reynolds number (Re), as well as the relative roughness of the piping, defined as the ratio of the absolute roughness to the diameter of the pipe (ε/D). For the recommended CPVC pipe material, the absolute roughness is $\varepsilon = 1.5 \times 10^{-6}$ (m). Once the desired diameter of the High Salinity Sludge Effluent Pipe is determined, the relative roughness can be calculated. This value can be used along with the design Reynolds number (Re=3500) to determine the Darcy-Weisbach friction coefficient using a Moody Chart. The derivation of this equation and physical fluid properties used can be found in Appendix I.

Section 5.3.5: Sizing of Reseeding Tank

The amount of sludge required to reseed the aeration tank following a salinity disturbance is the main determining factor in the sizing of the reseeding tank. According to the EPA's 1973 published guide *Start-Up of Municipal Wastewater Treatment Facilities*, the maximum effective reseeding size for an activated sludge process is ten percent of the total sludge population. Accordingly, the amount of reseeding activated sludge recommended to be retained in the reseeding tank is ten percent of the overall sludge volume in the aeration tank. As such, the volume of the reseeding tank (V_c) must be one-tenth the volume of the aeration tank (V_{aer}).

$$V_c = \frac{V_{aer}}{10}$$

Furthermore, it is assumed that all flows entering and exiting the reseeding tank are ten percent of their analogous flows entering and leaving the aeration tank. As such, the diameter of the pipes connected to the reseeding tank should be designed with diameters ten percent of their existing counterparts. The table below correlates the pipes leading to and from the reseeding tank to their existing system counterparts as labeled in Figure 5.3.

Table 5.1: Pipe Correlation Table

Reseeding System	Existing System
Reseeding Tank Influent	Aeration Influent
Reseeding Pipe	Sludge Recycle Pipe
Reseeding Tank Sludge Influent	Sludge Recycle Pipe
Reseeding Tank Effluent	Aeration Effluent

Section 5.4: System Controls and Process Response

A salinity monitoring system must be installed to measure the salinity of wastewater before and primary settling and trigger the control system response. Conductivity is measured to evaluate the salinity concentration. Conductivity is the measurement of water's ability to pass an electrical flow. This is directly related to the concentration of ions in the water -- the more ions present in the water, the higher the conductivity. Waters containing high levels of salinity will, therefore, have high conductivity. The meter uses a probe to measure the conductivity. An electrical current flows between two electrodes within the probe that are set at various distances from each other. The strength of the electrical current measured is directly related to the concentration of ions present, which is a measure of salinity. Readings should be continually taken before primary settling to determine salinity before the next step of the treatment process. If the salinity of the wastewater is above 2.63 percent by weight, systematic changes to both the activated sludge and secondary sedimentation processes will be triggered as shown in Figure 5.3 below.

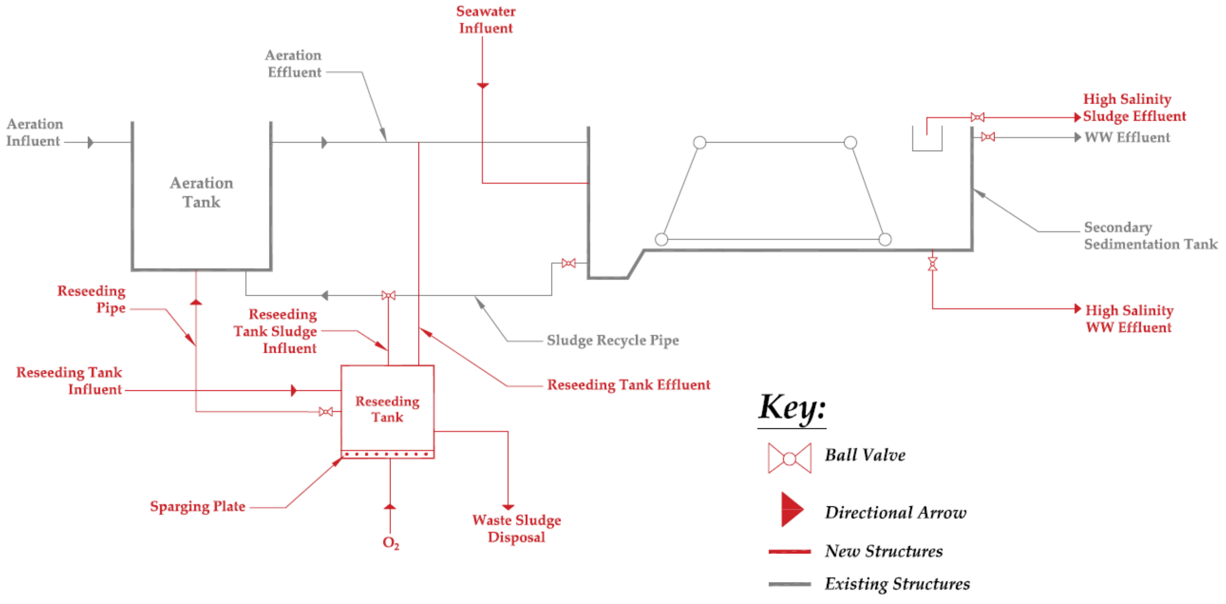


Figure 5.3: Overall System Schematic

Following a measured disturbance in the level of salinity above 2.63 percent, the process response will be triggered by the control system in the following order:

1. Wastewater entering the reseeding tank via the WW Influent Pipe will be stopped.
2. Sludge entering the reseeding tank via the Reseeding Tank Influent Pipe will be stopped.
3. Existing WW Effluent Pipe and Sludge Recycle Pipe will be closed.
4. High Salinity Sludge Effluent and High Salinity WW Effluent Pipes will be opened.
5. The sludge scraper will be turned off.
6. Seawater will be pumped into the sedimentation tank via the Seawater Influent Pipe.
7. Once the disturbance is observed to have ended and salinity levels return to normal operating conditions, the process response will occur in the following order:
8. All piping will return to its pre-disturbance state.
9. The sludge scraper will be turned on.
10. Reseeding sludge from the reseeding tank will be pumped into the aeration tank.

Conclusion

Through bench scale experimentation which replicated the chemical and biological processes related to wastewater treatment, the impacts of salinity on WWTF was successfully studied. Critical salinity thresholds for activated sludge aeration, sedimentation, and dissolved oxygen levels were determined. Above these thresholds, the treatment processes would need to be modified in order to effectively continue to treat the wastewater. Additionally, design recommendations, which detail how a coastal WWTF could address salinity issues was included.

Prior to this study, little research had been conducted as to the effect salinity has on wastewater treatment. With global warming continuing to raise sea levels and adverse storm events and flooding becomes more common and frequent, the results of this study will become increasingly relevant. The knowledge and data collected over the course of this study can be used to further design salinity mitigation techniques to be used by coastal WWTFs.

Appendix A: Artificial Seawater Generation Procedure

The procedure to create one liter (L) of 3.5 percent salinity by weight artificial seawater as adapted from ASTM D1141 - 98 (2013) is as follows:

1. Label a container *Stock Solution No. 1*
2. Add 555.6 grams (g) $MgCl_2 \cdot 6H_2O$, 57.9 g $CaCl_2$ (anhydrous), and 2.1 g $SrCl_2 \cdot 6H_2O$
3. Dilute to a total volume of 1 L. Store in a well-stoppered glass container.
4. Label a second container *Stock Solution No. 2*
5. Add 69.5 g KCl, 20.1 g $NaHCO_3$, 10.0 g KBr, 2.7 g H_3BO_3, and 0.3 g NaF
6. Dilute to a total volume of 1 L. Store in a well stoppered amber glass container.
7. Pour approximately 0.75 L of wastewater into a separate container.
8. Dissolve 24.53 g sodium chloride (NaCl) and 4.09 g anhydrous sodium sulfate (Na_2SO_4) in the wastewater.
9. Slowly add 20 mL of Stock Solution No. 1 while stirring vigorously.
10. Next add 10 mL of Stock Solution No. 2
11. Dilute to a total volume of 1 L.

Appendix B: Respirometry Testing Procedure

1. Using the Challenge Technology Respirometer, insert a Teflon-coated magnetic stirring bar in each reactor vessel.
2. Connect the clear tubing to the large luer of the manifold on the flow-cell base. Connect the other end to the oxygen cylinder. The open end of the yellow tubing should be attached to the connectors on the top of the manifold, while the end with the luer fitting should be inserted into the matching fitting on the inlet side of the flow-cell. One end of the long pieces (~0.5m) of yellow tubing should be attached to the outside fitting of the flow cells. The other end of the tubing will be attached to a 20-gage needle for connection to each respirometer reaction vessel. Open the oxygen tank and adjust the airflow so that an air bubble is observed in the regulator bottle but not in the manifold cells.
3. Add test waste, or desired volume of test solution to each 500 mL vessel.
4. The volume of the vessel should be at 500 mL. If necessary, add dilution water to make this volume. *Note: the temperature of the water should be around room temperature.*
5. Add 5 mL of 30 percent potassium hydroxide solution to the carbon dioxide absorption tube.
6. Place a KOH absorption tube into each reactor vessel. Add screw cap with inserted butyl rubber septum to each reactor vessel. Tighten to seal.
7. Place reactor vessels on the Challenge MS-304 magnetic stirrer and adjust the stirring to at least 700 rpm.
8. Vent the reactor vessel by momentarily inserting a clean 20-gage needle through the septum. This action equalizes the pressure, prior to the beginning of the test.
9. Attach the flow-cell base to the reactor vessel by inserting the 20 gauge needle in the septum of the vessel. For best results, insert the needle at a 45 degree angle.
10. Start the flow of oxygen into the reactor vessel using a 20 mL syringe and 20-gage needle. Withdraw the headspace gas from each reactor vessel, until one or two counts occur in the flow-cell base. Visual confirmation of gas bubbling through the flow-cell manifold should be made. Check to make sure the counts are registered on the computer.

Appendix C: Sedimentation Testing Procedure

The procedure to measure the turbidity of a sample is as follows:

1. Pour 500 mL of sample at the desired salinity contents in the six beakers.
2. Pipette 3mL of the sample into a turbidity vial. Fill the vial the rest of the way (25mL) with reagent grade water.
3. Gently invert the vial to mix the sample evenly. Be careful not to create air bubbles.
4. Clean the vial with a Kimwipe to ensure there are no scratches or marks. Rinse with reagent grade water if necessary.
5. Place the vial in the turbidimeter with the arrow on the vial facing the line on the inside of the turbidimeter.
6. After 10 seconds has passed, watch the reading closely for another 10-20 seconds. Wait until the results begin to hover over a central value and record that value as initial turbidity.

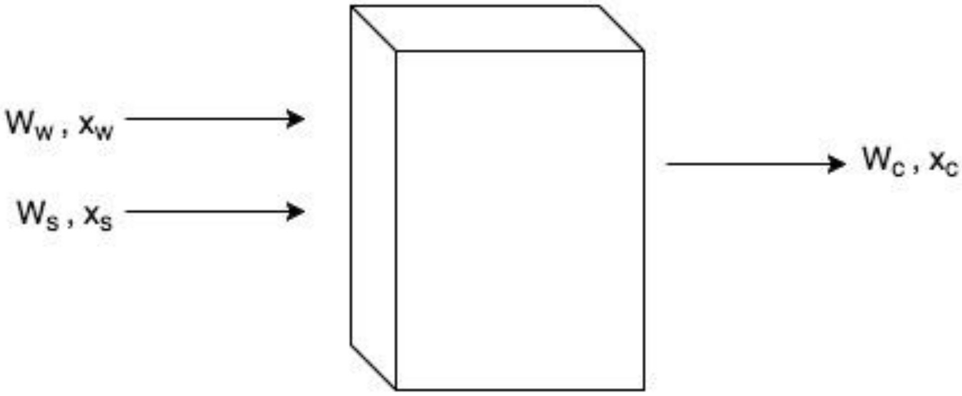
The procedure to test sedimentation and flocculation is as follows;

1. Place beakers onto the Phipps & Bird stirrer and lower paddles into each beaker.
2. Take an initial turbidity measurement from each sample as outlined in the procedure above.
3. Set the paddle speed between 150-200 rpm and mix for two minutes.
4. After two minutes, reduce the speed to 30 rpm and flocculate for 20 minutes. Turn the paddles off and allow the floc to settle for 20 minutes.
5. After the samples have been allowed to settle, take a final turbidity measurement. The samples should be pipetted out of the beaker at a distance of 2/3 of the height of the beaker.

Appendix D: Oxygen Solubility Testing Procedure

1. Charge the beaker with 250 mL of the wastewater sample at the desired salinity level.
2. Place the dissolved oxygen probe into the beaker, ensuring adequate space for effluent gas.
3. Place open tubing connected to an oxygen tank into the wastewater sample and bubble oxygen into the beaker.
4. Allow the system to run until the oxygen level in the sample converges to a steady value.

Appendix E: Seawater Addition Calculation



where W_W = volume of wastewater

x_w = concentration of salinity in the wastewater

W_s = amount of seawater

x_s = concentration of salinity in the sweater = 7 percent

W_c = amount of combined (waste and sea) water

x_c = concentration of salinity in the combined water = 5.25 percent

$$W_c = W_W + W_s$$

$$x_w W_W + x_s W_s = x_c W_s$$

$$x_w W_W + x_s W_s = x_c (W_W + W_s)$$

$$x_w W_W + 0.07 W_s = 0.0525 (W_W + W_s)$$

$$W_s = 3W_W - \left(\frac{x_w}{0.0175}\right) W_W$$

Appendix F: Equations and Physical Properties for Pipe Sizing: High Salinity WW Effluent and Seawater Influent Pipe

$$D = \frac{Re \times \mu}{\rho \times v}$$

$$v = \frac{Q}{A_c}$$

$$A_c = \frac{\pi \times D^2}{4}$$

Where:

D = Diameter of the pipe

Re = Reynolds Number

μ = Fluid Kinematic Viscosity

ρ = Fluid Density

v = Fluid Kinematic Velocity

Q = Volumetric Flowrate

A_c = Pipe cross-sectional area

Fluid Physical Properties:

Wastewater	
Kinematic Viscosity (μ)	1.02×10^{-3} (Pa s)
Density (ρ)	1000 (Kg/m^3)
Reynold's Number* (Re)	1900
Seawater	
Kinematic Viscosity (μ)	1.08×10^{-3} (Pa s)
Density (ρ)	1027 (Kg/m^3)
Reynold's Number* (Re)	7500

** Reynold's number was selected based on desired laminar flow profile*

Appendix G: Equations and Physical Properties for Pump Sizing: High Salinity WW Effluent and Seawater Influent Pipe

$$P_h = \frac{Q \times \Delta p}{700}$$

$$\Delta p = \frac{\lambda \rho L v^2}{2D}$$

$$v = \frac{Q}{A_c}$$

$$A_c = \frac{\pi \times D^2}{4}$$

Where:

Δp = pressure drop along pipe

ρ = Fluid Density

λ = Darcy-Weisbach Friction Coefficient

D = Pipe Diameter

L = length of pipe

v = Fluid Kinematic Velocity

Q = Volumetric Flowrate

A_c = Pipe cross-sectional area

Fluid Physical Properties:

Wastewater	
Friction Factor* (λ)	8.42 x 10^{-3}
Density (ρ)	1000 (Kg/m^3)
Reynold's Number** (Re)	1900
Seawater	
Friction Factor* (λ)	8.42 x 10^{-3}
Density (ρ)	1027 (Kg/m^3)
Reynold's Number** (Re)	1900

**Friction factor found using moody chart relating relative roughness of piping and Re*

*** Reynold's number was selected based on desired laminar flow profile*

Appendix H: Equations and Physical Properties for Pipe Sizing: Sludge Effluent Pipe

$$D = \frac{Re \times \mu}{\rho \times v}$$

$$v = \frac{Q}{A_c}$$

$$A_c = \frac{\pi \times D^2}{4}$$

Where:

D = Diameter of the pipe

Re = Reynolds Number

μ = Fluid Kinematic Viscosity

ρ = Fluid Density

v = Fluid Kinematic Velocity

Q = Volumetric Flowrate

A_c = Pipe cross-sectional area

Fluid Physical Properties:

Activated Sludge	
Kinematic Viscosity (μ)	3 x 10^{-2} (Pa s)
Density (ρ)	1060 (Kg/m^3)
Reynold’s Number* (Re)	3500

** Reynold’s number was selected based on desired turbulent flow profile*

Appendix I: Equations and Physical Properties for Pump Sizing: High Salinity Sludge Effluent Pipe

$$P_h = \frac{Q \times \Delta p}{700}$$

$$\Delta p = \frac{\lambda \rho L v^2}{2D}$$

$$v = \frac{Q}{A_c}$$

$$A_c = \frac{\pi \times D^2}{4}$$

Where:

Δp = pressure drop along pipe

ρ = Fluid Density

λ = Darcy-Weisbach Friction Coefficient

D = Pipe Diameter

L = length of pipe

v = Fluid Kinematic Velocity

Q = Volumetric Flowrate

A_c = Pipe cross-sectional area

Fluid Physical Properties:

Activated Sludge	
Density (ρ)	1060 (Kg/m^3)
Reynold's Number* (Re)	3500

** Reynold's number was selected based on desired turbulent flow profile*

Appendix J: Example Pipe Sizing

Assumptions:

- The total flow to the plant is 1MGD
- The salinity in the wastewater was measured at 3 percent by weight
- 20 percent of the total flow into the plant passes through the piping at any given time
- Sludge travels through the piping at 0.0856 cubic meters per second
- The sludge collection ratio is 0.5
- The aeration tank is 350 cubic meters

Calculations:

Seawater addition:

$$Q_s = 3Q_w - \left(\frac{x_w}{0.0175}\right) Q_w = 3(0.05) - \frac{0.03}{0.0175} \times 0.05 = 0.64 \left(\frac{m^3}{s}\right)$$

High Salinity WW Effluent and Seawater Influent Pipe Sizing:

$$D_{we} = 656.98 \times Q_{we} = 656.98 \times 0.01 = 6.57\ (m)$$

$$D_{si} = 166.7 \times Q_{si} = 166.7 \times 0.06 = 10(m)$$

High Salinity WW Effluent and Seawater Influent Pump Sizing:

$$U_{we} = \frac{7.97 \times 10^{-17}}{Q_{we}^2} = \frac{7.97 \times 10^{-17}}{0.01^2} = 7.97 \times 10^{-13} \left(\frac{Kw}{m}\right)$$

$$U_{si} = \frac{9.53 \times 10^{-17}}{Q_{si}^2} = \frac{9.53 \times 10^{-17}}{0.06^2} = 2.65 \times 10^{-14} \left(\frac{Kw}{m}\right)$$

High Salinity Sludge Effluent Pipe Sizing:

$$D_{se} = \frac{12.85 \times Q_{se}}{Z} = \frac{12.85 \times 0.0856}{0.5} = 2.19\ (m)$$

Reseeding Tank Sizing:

$$V_c = \frac{V_{aer}}{10} = \frac{350}{10} = 35\ (m^3)$$

Appendix K: list of abbreviations

PE	Professional Engineering
FE	Fundamentals of Engineering
EIT	Engineer in Training
CWA	Clean Water Act
WWTF	Wastewater Treatment Facility
EPA	Environmental Protection Agency
MGD	million gallons per day
I/I	inflow and infiltration
GHGs	greenhouse gases
ppm	parts per million
SLR	sea level rise
MBTS	Manchester by the Sea
SVI	sludge volume index
DO	dissolved oxygen
SBR	sequencing batch reactor
MAS	marine activated sludge
DAS	domesticated activated sludge
CAS	conventional activated sludge
MBR	membrane bioreactor
RPM	rotations per minute
OUR	oxygen uptake rate
CPVC	chlorinated polyvinyl chloride

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