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Assessment and Modeling of Three Decentralized Resource Recovery Systems in the Cayes of the Belize Barrier Reef

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Assessment and Modeling of Three Decentralized Resource Recovery Systems in the Cayes of the Belize Barrier Reef

by

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A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Environmental Engineering
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Biodigester, Onsite Wastewater, Coastal Contamination

DEDICATION

To my loving family, I would never have been able to cross over this hill without your constant and unwavering support you have given me through all of my life decisions. To Jackie. I'm looking forward to finishing this part of my life and starting a new one in another country with you. And lastly, to the endless support of my friends and peers. May we always work together to realize the future we want to see on this earth.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Three wastewater treatment systems (WWTS) situated on Cayes in the Belize Barrier Reef System were assessed in terms of the unique public health and environmental circumstances of being a tourist destination surrounded by fragile coral reef. Laughing Bird Caye, Silk Caye, and Little Water Caye are three small cayes that are the staging points for local diving, fishing, and other recreational tourism. All three systems are based upon pour-flush toilets, semi-anaerobic biodigesters and drainage fields. Limitations in cost, available resources, useable area, high infiltration rates of the sand, and salinity of the water have played a major factor in the construction and performance of the WWTS on the Cayes. This thesis aims to form an understanding of treatment efficiency of the WWTS, investigate the effectiveness of decentralized saltwater-based WWTS in comparison to freshwater-based WWTS, and provide recommendations to improve the performance and resource recovery in a manner appropriate for the context in which the systems are deployed.

A mathematical model was developed to predict the performance of the WWTS based on available operational and water-quality input data. The model is based on the mass balances of six species: inert solids, fecal solids, bacterial biomass, soluble substrate (i.e. dissolved organic carbon), ammonium and nitrate. Effects of salinity were estimated for the two saltwater-based WWTS. The model predicted the effluent concentrations of fecal solids, soluble biological oxygen demand (BOD), ammonium, and nitrate. A sensitivity analysis was also performed on the predicted effluent treatment efficiency based upon influent load, oxygen concentration and system salinity.

Results from Silk Caye and Laughing Bird Caye indicate that varying the number of visitors from seasonal lows to highs has a moderate impact on the effluent fecal solids and soluble BOD in the effluent. Due to the relatively large volume of the WWTS at Little Water Caye, and thus high HRT, varying the

number of visitors did not have a significant effect. The model predicted a reduction of nitrogen from the effluent due to settled solids and the assimilation of the nitrogen into bacteria. However the model consistently projected an effluent nitrate concentration (as mg/L as N) between 60 and 63 across the three WWTS. The oxygen concentration within the WWTS had the greatest effect on effluent BOD of the three parameters tested in the sensitivity analysis. Results from the sensitivity analysis indicate that a minimum concentration of 0.95 mg/L of oxygen is required before the model can accurately predict the effluent BOD concentration. The concentration of effluent fecal solids did not significantly change with changes in oxygen concentration. Salinity had a significant effect on the predicted fecal solids and soluble BOD in the effluent. Predicted fecal solids in the effluent wastewater increased approximately 60 percent from freshwater conditions to 4 percent salinity. Similarly, effluent BOD concentration increased strongly with increasing salinity. The increase in concentration is due to the major reduction of substrate-consuming bacteria by cell-die-off. The model predicts that a significant increase in cell die-off begins to occur at 2.4 percent salinity.

The predicted effluent of the freshwater-based WWTS on Little Water Caye was compared to 166 wastewater treatment plants operating in Brazil. Comparison between the WWTS on the Caye and the decentralized WWTS in Brazil indicate that the predicted removal efficiencies of total suspended solids and soluble BOD are higher than the measured efficiencies of the WWTS. However, the total nitrogen removal efficiency for the WWTS on the Caye was the least effective; most-likely because the model does not account for denitrification within the biodigester. The comparison between the WWTS illustrates that the predicted removal efficiency of BOD and TSS solids is most likely less in the actual measurement than predicted value from the model.

The WWTS on the Cayes were constructed to mitigate the impacts of the wastewater produced by visitors on the general health of the pubic and the environment. Considering the reports of the eutrophication affecting the coral reefs surrounding the Cayes, the WWTS have largely failed in at least one aspect of their purpose. The effluent water quality predicted by the model also suggests that significant concentrations of nitrogen are entering the surrounding ocean habitat as ammonia and nitrate.

Recommendations to improve the effluent wastewater quality were separated into three categories based upon the required level of input to realize the recommendation. The input includes the capital cost and labor of the change, the level of buy-in from the users of the system, and the resulting maintenance requirements. The implementation of a urine separation toilet system was proposed as a method to reduce effluent nitrogen entering the environment and to create a resource recovery system (RR) from the already constructed WWTS.

CHAPTER 1: INTRODUCTION

The treatment and elimination of wastewater poses a challenge around the world. Plagued by budget shortages, lack of local expertise, and inadequate maintenance and management practices, the majority of low- and middle-income countries do not adequately treat municipal wastewater (Flores *et al.*, 2009; Massoud *et al.*, 2009; Singhirunnusorn and Stenstrom, 2009). As Target 7.C of the Millinium Development Goals, all 189 United Nations (UN) member states agreed to "halve, by 2015, the proportion of the population without sustainable access to safe drinking water and basic sanitation" (Watkins *et al.*, 2006). Although significant progress has been made to reduce the number of people worldwide without access, the World Health Organization (WHO) and the United Nations Children's Fund (UNICEF) estimates that over 2.4 billion people worldwide do not have adequate access to safe sanitation (WHO/UNICEF, 2015). Due to these factors, the majority of sewage produced in the low- and middle-income countries is not adequately treated before being discharged into local water bodies (Gutterer *et al.* 2009). These challenges are even more apparent and important when the receiving water bodies host some of the most fragile organisms in the ocean, coral. Coral reefs are widely considered the most complex and diverse of all marine ecosystems (Lapointe, 1997). Nutrient fluxes caused by anthropogenic sources have lain waste to these ecosystems around the world (Bruno *et al.* 2003; Rasher *et al.* 2012; D'Angelo & Wiedenmann 2014). The Great Barrier Reef off the coast of Australia has experienced a reduction of more than 70% of its hard cover coral, largely attributed to a chronic state of eutrophication as well as other compounding factors linked to increasing temperatures and ocean acidifications (Bell *et al.* 2014). Target 6.3 of the MDG aims to improve water quality by reducing pollution and halving the proportion of untreated wastewater that enters the environment globally (Zhang *et al.*, 2016).

Situated in and around the Belize Barrier Reef System, a world heritage site, Little Water Caye, Laughing Bird Caye, and Silk Caye play a major role in the local tourism and fishing economy of Belize, hosting as many as 50 visitors per day at each caye (SEA Belize, 2010a, 2010b). Many of the tourists visit the cayes to scuba dive and snorkel around the coral reefs that surround the cayes. This raises two challenges: first, how to provide adequate sanitation services to the daily visitors; and second, how to protect the general public health and the local coral ecosystem from the wastewater generated by human visits? SEA Belize has sought to answer this challenge by employing Eco-Friendly Solutions, a local company in Belize, to construct a wastewater treatment system on each of the three Cayes.

Through a series of advanced treatment processes, Eco-Friendly Solutions has sought to mitigate the effects that the generated wastewater can have on the local environment and human health. Each of the three Cayes has presented a unique situation with respect to the design and construction of the wastewater treatment systems. All three systems are based upon pour-flush toilets, septic tank and drainage field; but cost, available resources, spatial limitations, and erosion have played a major factor in the actual construction of the wastewater treatment facilities. Freshwater sources on Little Water Caye have proven adequate for implementation of a fresh-water-based wastewater treatment system. No such fresh water source is available on Silk or Laughing Bird Caye; thus both systems rely upon seawater for operation. Although the three treatment systems were designed for the treatment and removal of wastewater constituents, up until now, no scientific study nor monitoring has been performed on these onsite wastewater treatment systems.

This raises two important needs for the constructed wastewater treatment systems. The first need is to assess the performance of the systems being constructed by Eco-Friendly Solutions in terms of the unique public health and environmental circumstances associated with Laughing Bird, Silk, and Little Water Cayes. Performance comprises system reliability, system efficiency, ability of the system to treat wastewater to comply with regulatory standards, ability to work in given land requirements, system affordability, social acceptability, and overall sustainability. The second need is a comparison between the performance of the saltwater septic systems at Laughing Bird Caye and Silk Caye with the fresh water system at Little Water Caye. A detailed search through peer-reviewed literature suggest that no studies have yet been conducted in the assessment of decentralized saltwater-flush WWTS in a developing-world setting.

Therefore the objectives of this thesis are:

1) Predict the performance of three decentralized on-site wastewater treatment systems in Belize based on available operational and water-quality input data.
2) Compare the performance predictions to gathered performance data.
3) Compare the measured and/or predicted performance of the freshwater system to the performance of the two saltwater systems.
4) Compare the measured and/or predicted performance of the three systems in Belize to analogous, existing treatment systems in other locations.
5) Recommend possible changes to the existing systems to improve performance and resource recovery in a manner appropriate to the context in which the systems are deployed.

Taken together, these five objectives will help to (1) form an understanding of the environmental and public health services provided and risks posed by these wastewater treatment systems constructed by Eco-Friendly Solutions, and (2) investigate the effectiveness of decentralized saltwater-based treatment systems in comparison to the freshwater-based system and larger centralized saltwater systems. Ultimately, this research aims to protect the health and environmental concerns of the three Cayes and the surrounding coral reef.

To achieve these objectives, Dr. Jeffrey Cunningham and Christine Prouty developed a mathematical model that predicted the effluent parameters of biochemical oxygen demand, fecal solids, ammonium and nitrate for the WWTS that reside on the Cayes. This thesis sought to utilize the developed equations to understand the significant input and operating parameters and how the variations of these affected the effluent wastewater quality. With an understanding of the significant parameters, recommendations were made to improve the treatment efficiency of the WWTS.

CHAPTER 2: LITERATURE REVIEW

2.1 Types of Wastewater

The proper treatment of wastewater from municipal and household sources is an issue all over the globe. Studies show that 80% of the wastewater generated around the globe is not properly collected or treated (Corcoran *et al.*, 2010); approximately 2 million cubic meters are directly discharged into local waterbodies each year (WWAP 2012). These discharges contribute to contamination of inland and coastal waters due to the increased inputs of phosphorus and nitrogen from wastewater, and have been detrimental to aquatic systems by initiating algal blooms and eutrophic conditions (Gill *et al.*, 2009). The unchecked discharge of wastewater in aquatic environments is also the main cause for diarrheal illness around the globe (Lens *et al.*, 2005). Although a critical environmental and public health issue when released into the local environment, wastewater can provide benefit if properly treated, collected, and used as fertilizer (Xinzhong, 2010).

Wastewater from household sources can be classified with four categories. Each type varies in the original source, contaminants present, and the concentration of organic matter. Table 1 is a general characterization of the different categories of wastewater, as used in this thesis.

Table 1: Types of Municipal Wastewater (Brandes, 1978; Nelson and Murray, 2008; Collivignarelli, 2012; Tilley et al., 2014)

Type of Wastewater	**Source**
Black	Liquid and solid human bodily waste, most commonly produced through toilet flushing.
Grey	The waste discharged through the kitchen sink and dishwasher, tub and shower, and the clothes washing machine.
Yellow	Urine when separated from other wastes (with or without flushing water). Does not contain fecal matter.
Brown	Black water with the exclusion of Yellow wastewater. Does not contain fecal matter.

Of the four types of wastewater, black and grey forms are most commonly referenced for generation by households, and subsequent flows into a wastewater treatment system (WWTS). The relative strength, contamination, and overall characteristics of the wastewaters depend upon several factors, including dilution from flushing, local conditions, time of day, or season (Halabi and Hamed, 2005). However, a general expectation of the strength and the composition of the wastewaters is presented in Table 2. In this table, the grey water and black water are separated into the categories of developed countries and low- and middle-income countries. The difference is presented because Oliveira & von Sperling (2011) found that concentrations from influent wastewaters in Brazil were significantly higher than previously reported in the literature for developed countries. The general reasoning behind the difference in concentrations is that the lower consumption of water in low- and middle-income countries and the lower amount of water used for flushing leads to less dilution (Nelson and Murray, 2008). In the US, the majority of toilets use 5 gallon tanks to remove the waste, while in most low- and middle-income countries much less water is used, meaning all the contaminants are more concentrated. Considering the wastewater treatment plants assessed in the study of Oliveira & von Sperling (2011) are located in Southern Brazil, a developing country featuring a tropical climate with average temperatures between 20 and 25 °C, the black water values reported in Table 2 are likely to be a representation of the wastewater found in Laughing Bird Caye, Silk Caye, and Little Water Caye.

Table 2: Typical Waste Parameters of Black and Grey Wastewater from Developed and Developing Countries (USEPA 1980; Oliveira & von Sperling 2011; Peters 2003)

Contaminant	Black Water (Developed Countries)	Black Water (Developing Countries)	Grey Water (Developed Countries)	Grey Water (Developing Countries)
BOD_5 (mg L^{-1})	280	670	260	37
TSS (mg L^{-1})	450	480	160	290
Total Nitrogen (mg L^{-1})	1403	78	17	43
Total Phosphorus (mg L^{-1})	13	9	26	7
Fecal Coliforms (MPN per 100 L)	2.4×10^7	2.6×10^7	2.3×10^6	1.2×10^8

Within Table 2 several water quality parameters are presented to describe the organic, nutrient, and pathogenic pollution contained within wastewater.

- BOD (Biochemical Oxygen Demand) describes what can be oxidized biologically, by bacteria, within the wastewater. It is usually measured as BOD_5, the oxygen consumed over a five day period. It is a measurement of the total oxygen consumed by the organisms metabolizing the organic matter in the wastewater (Madigan *et al.*, 2009). Thus, higher concentrations of BOD indicate the presence of more organic matter in the wastewater.
- The Total Suspended Solids (TSS) are usually the main source of turbidity in a water body. The amount of solids in water affects treatment of other parameters, and high concentrations of solids can cause clogging of treatment systems or leach fields (Payment *et al.*, 1997).
- Total nitrogen and phosphorus are indicators for the overall nutrient concentration in a wastewater. In raw wastewater, nitrogen is usually present in a complex organic molecular form of the proteinaceous matter in feces and urea in urine (Montangero and Belevi, 2007b). The phosphorus concentration in urine is almost entirely inorganic, upwards of 95%, and excreted as phosphate ions, while the phosphorus in feces is primarily found as calcium phosphate (Natural England, 2015). In most bodies of water, either nitrogen or phosphorus is the limiting nutrient in the system. The addition of that nutrient would cause eutrophication within the water body (Rabalais, 2002). In saltwater conditions, nitrogen is usually considered the limiting nutrient for biomass accumulation, and ultimately, eutrophication (Rabalais, 2002).
- Fecal coliforms are microbiological indicator species that suggest the relative presence of fecal pathogens in the wastewater (Ashbolt *et al.*, 2001).

2.2 The Treatment of Wastewater in the High-Income Countries

Within the last century the developed world has experienced widespread adoption of centralized wastewater treatment plants (WWTP) (USEPA 2002). With this expansion of centralized treatment came a wave of better public health as the proper disposal of wastewater separated fecal pathogens from the general population. Over time, WWTPs have grown and become more complex, and overall treatment standards have become more stringent. No longer are centralized treatment systems simply removing pathogenic organisms, or nutrients, from the wastewater stream. Now the treatment plants are also looked upon to be the primary barrier between aquatic ecosystems and emerging micropollutants, such as pharmaceuticals and hormones (Joss *et al.*, 2006). Whole effluent toxicity methodologies are now often incorporated in evaluations of the effluent quality from centralized WWTPs (Garcia *et al.*, 2013).

While centralized treatment systems are the paradigm for treatment of contaminants and the overall water quality of the effluent, many aspects of the plants make them impractical in rural settings. Centralized WWTPs are expensive to build and maintain, consume large amounts of energy, produce massive quantities of secondary waste (particularly sludge), and require a high level of expertise to manage (Von Sperling, 1996; Zeeman and Lettinga, 1999; Muga and Mihelcic, 2008; Garcia *et al.*, 2013). Also, the treatment systems depend upon the conveyance of the wastewater from the point of generation to the centralized WWTP, which is practical in high density urban areas, but not in low housing density. These characteristics make many of the centralized system designs impractical for rural settings, and therefore impractical for many areas throughout the low- and middle-income countries.

2.3 The Treatment of Wastewater with Septic Tanks and Soil Adsorption Systems (SAS)

Although centralized treatment is prevalent in the developed world, more than 60 million people in the United States of America, about 20% of the population, rely upon decentralized wastewater treatment systems. This includes as many as one-third of the new homes being built and more than half of the mobile homes in the country (USEPA 2002). Historically the most common type of decentralized on-site wastewater treatment has been the septic tank with a soil absorption system (SAS) leach field (Garcia *et al.*, 2013). The use of septic tanks for principal treatment of wastewater started appearing in the US in the late 1800s. By the middle of the 20th century discharge of the tank effluent into gravel-lined leach fields had become commonplace. Over the last 30 years states have gradually increased the required tank and leach field size, while also putting more stringent requirements on where septic tanks can be constructed (USEPA 2002). The requirements have been instituted to reduce the environmental impact that septic tank effluent has on the surrounding area. Currently upwards of 15% of the United States public relies upon a septic tank to treat the wastewater from their homes and workplaces (Du *et al.*, 2014).

Typical onsite wastewater treatment systems are comprised of 4 distinct components: the wastewater source, a pretreatment unit, an effluent delivery system, and a component that releases the effluent into the surrounding environment (McCray *et al.*, 2005). The septic tank primarily serves as the pretreatment unit of the system. Figure 1 is a representation of the normal configuration of a septic tank-leach field wastewater treatment system. In these systems, the septic tank provides the principal treatment, while the leach field serves as the secondary treatment component.

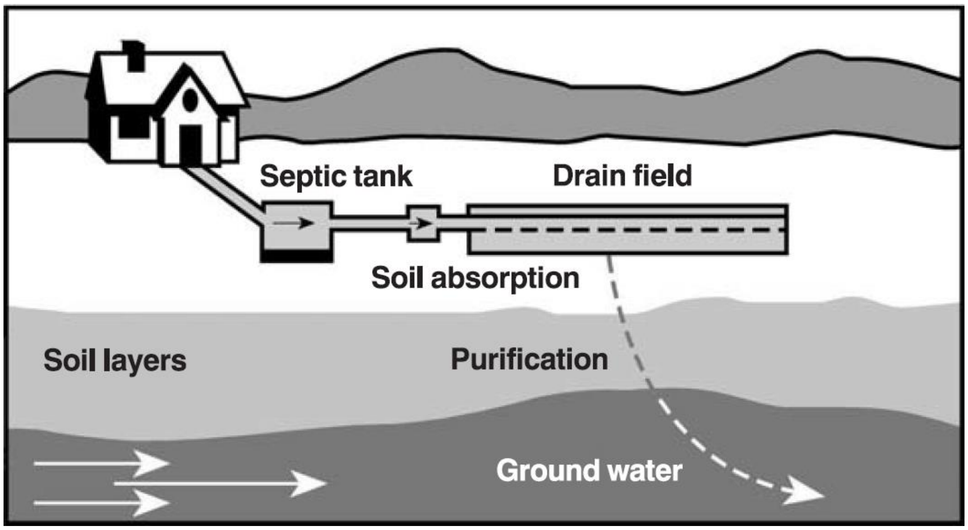

Figure 1: Typical On-Site Wastewater Treatment System (Reprinted from USEPA 2002, open domain)

The primary goal of a septic tank is to act as a settlement chamber to separate the solid and liquid effluent through a passive process. As the influent enters the septic tank, the denser solids sink to the bottom of the tank and become the sludge layer through the process of sedimentation. The scum layer is comprised of oils and greases that have floated to the surface of the wastewater. By allowing only the liquid effluent to pass through to the leach field, the septic tank removes 60-80% of solids, oils and greases from the wastewater (USEPA 2002). The tank also provides anaerobic conditions to facilitate the reduction of suspended solids and organic matter within the wastewater (Canter and Knox, 1985). Table 3 summarizes typical influent into the septic tank and the reductions of the contaminants in the black and grey wastewater.

Table 3: Common Constituents from the Effluent of a Septic Tank in a Developed Country (Gardner et al., 1997)

Contaminant	Black Water (Developed Countries)
BOD (mg L^{-1})	120-180
TSS (mg L^{-1})	40-190
Total Nitrogen (mg L^{-1}) NO_3^--N (%TN)	40-50 (0%)
Total Phosphorus (mg L^{-1}) Orthophosphates (%TP)	10-15 (90%)
Fecal Coliforms (MPN per 100 L)	10^5 - 10^7

In many centralized WWTPs, the treatment processes cycle between anaerobic and aerobic conditions to remove the nutrients. Since the environment of the septic tank is anaerobic, neither total nitrogen nor phosphorus is removed from the wastewater, but rather both are changed to other forms. The organic nitrogen that enters the septic tank can only be converted to ammonium (NH_4^+) through the process of hydrolysis, breaking the complex organic compounds into simpler compounds (Gardner *et al.*, 1997). The phosphorus that enters the system is converted from the forms of organic and condensed phosphate (polyphosphate) to inorganic phosphate to one of the orthophosphates (PO_4^{3-}, HPO_4^{2-}, $H_2PO_4^-$) (Gill *et al.*, 2009). Figure 2 depicts a typical septic tank with the associated reactions of nitrogen and phosphorus.

Sludge that settled down to the bottom of the septic tank also undergoes hydrolysis through the breaking apart of the proteins and the conversion of volatile fatty acids (VFA), which are in turn dissolved into the soluble phase. The VFAs still release much of the BOD that was originally in the organic suspended solids. Because these acids are in the soluble form, they pass from the septic tank in the effluent stream, limiting the BOD removal efficiency of septic tanks (USEPA 2002). Pathogenic bacteria are also reduced through the system by changes in chemical composition of the wastewater, and through the predation of the pathogens by other microorganisms (USEPA 2002). The liquid effluent then travels into the leach field, also referred to as a Soil Adsorption System (SAS), where it percolates through the vadose zones of the soil and into the groundwater (McCray *et al.*, 2005).

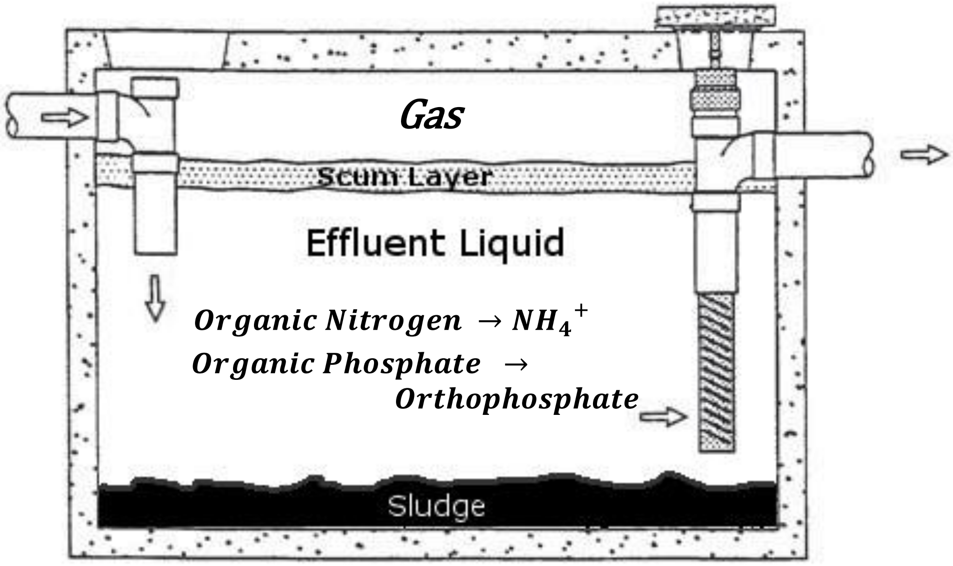

Figure 2: Typical Septic Tank and Nutrient Chemistry that Occurs (Adapted from USEPA 2002, open domain)

In contrast to other treatment systems, a Soil Adsorption System is constructed totally underground. The benefit of being constructed underground is that humans and animals have no direct contact with the wastewater under normal operations. This also eliminates the threat of odor from the secondary treatment system (Hu *et al.*, 2007). The SAS works by dispersing the septic tank effluent into the soil. SAS utilizes the natural biochemical processes in the soil to assimilate and treat the various contaminants (Beal *et al.*, 2005). As the septic tank effluent flows through the soil pores, it becomes treated by means of filtration, sedimentation, chemical absorption, and biological reactions (Hu *et al.*, 2007). Figure 3 shows the various zones of a typical SAS system. The critical zone of the SAS is the biomat zone, located directly beneath the septic tank effluent pipe. Formed by biological growth on the soil media as the effluent passes through, the biomat zone is characterized by a clogging of the pores within the natural soil. This accumulation of microorganisms takes several months to develop within the soil. All treatment processes that occur in the SAS are highly influenced by the performance of the biomat zone (Gardner *et al.*, 1997). The vast majority of the removal of contaminants occurs within the first few centimeters of this biologically active zone, including the removal of TSS, BOD, and pathogens (Beal *et* *al.*, 2006). The biomat also slows down the infiltration so that nutrients can be taken up by the microorganisms and plants (Hu *et al.*, 2007).

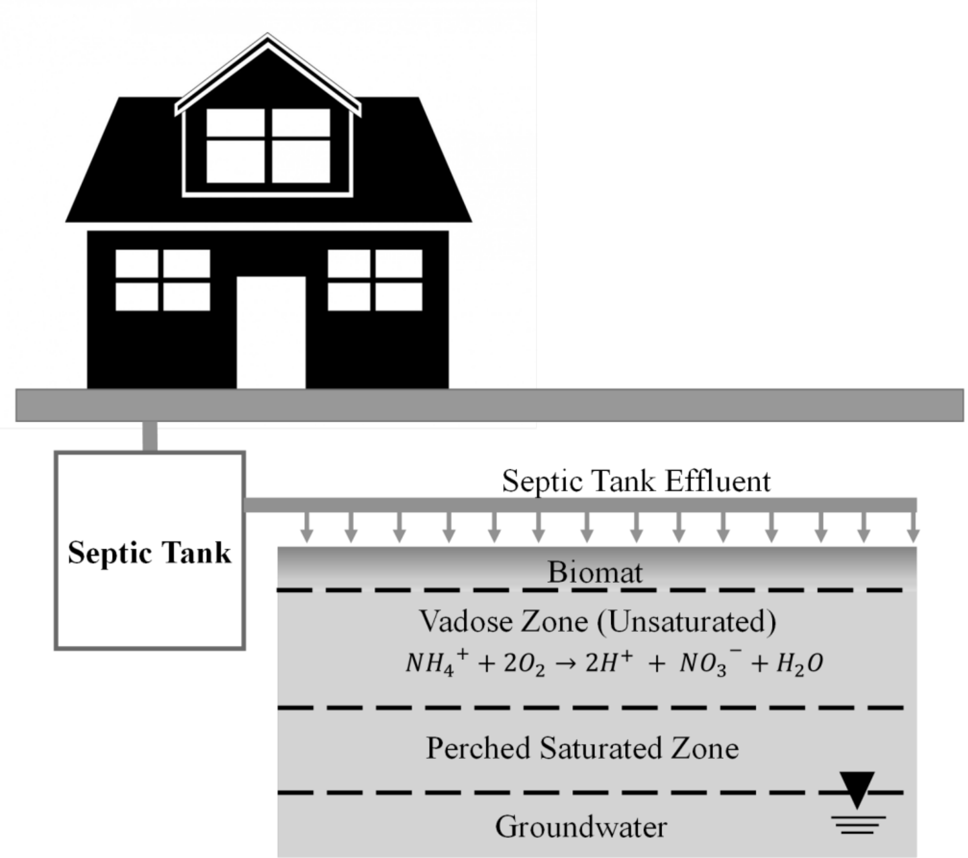

Figure 3: Leach Field of a Soil Adsorption System (adapted image from Open Domain, Appendix G*)*

After passing through the biomat zone, the effluent water trickles down to the vadose zone, characterized as the unsaturated zone directly beneath the biomat. Using oxygen that has diffused in through the porous soil, the vadose zone promotes degradation of pathogens and physical filtration of solids that were not collected in the septic tank (Beal *et al.*, 2005). The purification processes that occur when the septic tank effluent passes through the vadose zone are critical to the overall treatment of the contaminants. It is within the vadose zone that ammonia from the wastewater quickly undergoes nitrification into nitrite and nitrate, as seen in equations 1 and 2:

$$NH_4{}^+ + \frac{3}{2}O_2 \rightarrow NO_2{}^- + 2H^+ + H_2O \qquad [1]$$

$$NO_2{}^- + \frac{1}{2}O_2 \rightarrow NO_3{}^- \qquad [2]$$

Microbial denitrification requires anoxic conditions, the presence of organic substrates, and NO_3^- as the electron acceptor (Cannavo *et al.*, 2004). Although most studies concur that there is some denitrification that occurs in the septic system, studies suggests that most of the denitrification that occurs in the system occurs in the vadose zone (Cannavo *et al.*, 2004; McCray *et al.*, 2005; Gill *et al.*, 2009). Denitrification is the stepwise reduction of nitrate into nitrogen gas by bacteria, depicted in Equations 3 and 4. Since the denitrifying bacteria are part of the heterotrophic community, an organic substrate is needed to serve as an electron donor (Cannavo *et al.*, 2004). In the equations methanol, CH_3OH, is used as the electron donor; however any readily assimilable organic substrate can serve as the donor.

$$NO_3{}^- + \frac{1}{3}CH_3OH \rightarrow NO_2{}^- + \frac{1}{3}CO_2 + \frac{2}{3}H_2O \qquad [3]$$

$$NO_2{}^- + \frac{1}{2}CH_3OH \rightarrow \frac{1}{2}N_2(gas) + \frac{1}{2}CO_2 + \frac{1}{2}H_2O + OH^- \qquad [4]$$

Cannavo *et al.* (2004) noted that the vadose zone features several benefits that aid in the denitrification process. First, oxygen concentrations tend to decrease with depth, which favors the denitrification process. Secondly, the carbon dioxide concentration, largely controlled by microbiological activities, affects soil pH to a more basic level. Denitrification of NO_2^- to nitrogen gas occurs more readily under basic conditions. Thirdly, dissolved organic carbon is generally present due to the septic tank effluent. Lastly, residence times of water and the solutes within the effluent are long. The type of soil media thus has an impact on the denitrification process. A study by Tucholke *et al.* (2007) showed that the denitrification of nitrite tends to occur more readily in fine-textured soils (i.e. clays and silt/clays) compared to coarse-textured soils (silts and sands) due to the longer residence times.

The principal removal mechanisms of phosphate also occur in the vadose zone. The orthophosphate undergoes adsorption or mineral precipitation, depending on the pH and the chemical makeup of the soil. Phosphorus precipitation is controlled by iron and aluminum under acid conditions, and by calcium content under alkaline conditions as is typical of domestic sewage (Arias *et al.*, 2001). Therefore the attenuation of phosphorus depends on the presence of aluminum, manganese, or iron in acidic soils and the presence of calcium in alkaline soils (Gill *et al.*, 2009).

An important aspect of the SAS is drainage. Without sufficient drainage or ventilation for oxygen in the vadose zone, a clog can occur as a result of soil particles bonding together, creating an anaerobic environment that reduces the ability to treat the contaminants (Hu *et al.*, 2007).

Although septic tanks are commonly used in the developed world, there are major shortcomings in their abilities. Septic tank treatment systems rely upon technology and treatment practices that are now over 100 years old. Septic tanks were never designed to treat nutrients (nitrogen and phosphorus) that cause eutrophication; these nutrients can cause significant impact on the ecosystems receiving the effluent (Lapointe *et al.*, 1990; Withers *et al.*, 2011). There are newer septic tank systems available that are better at treating nutrients in the wastewater. However, these new systems are not installed in most areas (Nasr and Mikhaeil, 2014; Natural England, 2015). The US Census Bureau estimated that over half of the onsite WWTS in use in the US are more than 30 years old (USEPA 2002). These problems have culminated in the USEPA reporting that 10%-20% of all decentralized WWTS are failing in their ability to effectively treat nutrients to the required EPA limits (USEPA 2000). The problem is that nitrate is soluble and is easily transported to ground water after being discharged from the WWTS (Glass and Silverstein, 1999). One study performed in 1991 found that 74% of nitrogen from wastewater effluent that entered a septic tank-leach field treatment system was discharged into the groundwater (USEPA 1991). In another study only about 15% of phosphorus was removed by the treatment system (Gill *et al.*, 2009). More recent studies have shown that septic systems have little or no treatment impact upon micropollutants (DeJong *et al.*, 2004; Stanford *et al.*, 2010). Hormones, such as estrogen, are of particular concern. These hormones may affect the reproductive abilities of aquatic vertebrates if wastewater-impacted groundwater reaches a surface water body (Swartz *et al.*, 2006).

2.4 The Challenges of Treating Wastewater in the Low- and Middle-Income Country

While large centralized wastewater treatment systems are commonly used and applicable in the developed world, their hindrances make them impractical in the low- and middle-income countries. Previous wastewater treatment plants constructed in the low- and middle-income countries have used conventional wastewater treatment techniques that were practical in a developed-world setting, yet widely ignored the contextual differences of economics and culture between the two settings (Singhirunnusorn and Stenstrom, 2009). As a result, many treatment plants in low- and middle-income countries have been abandoned due to the inability to deliver adequate operation and maintenance, find spare parts, function during frequent power supply cuts, and/or find staff with necessary skill levels (Gutterer *et al.*, 2009). A study conducted in Mexico found that of all the centralized wastewater treatment systems that were constructed in the country, 90% of the plants are non-functional (Flores *et al.*, 2009). Similarly, a recent survey in Thailand found that only 20% of the municipal-scale wastewater treatment plants were in working condition (Singhirunnusorn and Stenstrom, 2009). To cope with the problems of centralized WWTS, decentralized WWTS, in coordination with local governments, are increasingly looked upon to provide sanitation to the low- and middle-income countries (Libralato *et al.*, 2012). In general, decentralized WWTS are usually more flexible and can adapt easily to local conditions as well as grow with the community as its population increases (Bdour *et al.*, 2009).

The major factor that impairs conventional WWTP from performing correctly is the contextual differences that exist between developed and low- and middle-income countries. Aside from the technical aspects that engineers often analyze, there are many other factors that determine the suitability and sustainability of wastewater treatment plants in the low- and middle-income countries (Tilley *et al.*, 2014). An ideal WWTP should not only produce the best quality effluent at the most affordable price, but should meet local needs, such as: socio-cultural acceptability, technological feasibility, resource reuse and conservation, economical affordability, and environmental acceptability (Muga and Mihelcic, 2008; Flores *et al.*, 2009; Singhirunnusorn and Stenstrom, 2009; Libralato *et al.*, 2012).

2.5 Decentralized Treatment of Wastewater in the Low- and Middle-Income Country

While there are many challenges associated with wastewater treatment in the low- and middle-income countries, there are also many opportunities for alternative systems that are not commonly employed in developed countries. In the developed world, many of the wastewater treatment options are limited due to the stringent effluent quality standards that are enforced. However, this is not the case in most low- and middle-income countries. There is a wide range of water quality standards in low- and middle-income countries where the vast majority of the required effluent quality is more lenient than in the developed world (Massoud *et al.*, 2009). Due to the weighted importance of other factors and the leniency of effluent quality standards, many types of decentralized WWTS are employed, other than just a septic tank-leach field system. Table 4 is a list of some of the most common decentralized WWTS that have been used in the low- and middle-income countries. As noted in Table 4, each WWTS is advantageous for certain situations, while impractical in others.

Table 4: Types of WWTS Used in the Low- and Middle-Income Country (Von Sperling, 1996; Flores et al., 2009; Gutterer et al., 2009; Massoud et al., 2009; Oliveira and von Sperling, 2011; Starkl et al., 2013)

Technology	**Benefits**	**Disadvantages**
Septic Tank + Anaerobic filter	• Can receive higher loads of wastewater than other WWTS. • Relatively little maintenance required.	• Drain fields are prone to clogging. • Unable to remove nutrients from the effluent efficiently.
Facultative pond	• Good treatment of pathogens • Able to absorb and sequester nutrients. • Cost effective where land is inexpensive.	• Problems with sludge accumulation. • Mosquitos, insects and odor • Require more land than other WWTS.
Upflow Anaerobic Sludge Blanket Reactor (UASB)	• Very low land requirements. • Simple construction, operation and maintenance. • Low energy requirements.	• Effluent not aesthetically pleasing. • Unable to remove nutrients from the effluent efficiently. • Sensitive to variations in influent loads.
Anaerobic pond	• Simple and robust. • Ability to handle large fluctuations in influent load.	• Problems with sludge accumulation. • Mosquitos, insects and odor. • Require more land than other WWTS.
Anaerobic Filter	• Good adaptation to different influent types and concentrations. • Sludge stabilization is in the reactor itself. • Resistant to changes in influent load.	• Restricted to influents with low concentrations of suspended solids. • Effluent not aesthetically pleasing. • Risk of clogging the filter.
Activated Sludge	• High efficiency BOD removal. • Achieve greater nitrification and phosphorus removal. • Operational flexibility.	• High construction and operation costs. • Need of sophisticated operational skillsets. • Possible environmental problems due to noise and aerosols.
Dehydration (Ecosan) toilets	• Little to no additional water is required. • Waste able to be converted to renewable resource.	• Requires greater responsibilities to the user than other WWTS. • Must be cleaned out every 6 months.
Constructed Wetland	• Minimal operation is required. • Inexpensive to construct and operate. • Able to handle variable wastewater loading condition.	• Require more land than other WWTS. • More complicated than waste stabilization ponds, requiring more management skills. • May take a year or two to achieve the optimum treatment efficiency.

2.6 Components of Eco-Friendly Solutions Wastewater Treatment

In Laughing Bird Caye, Little Water Caye, and Silk Caye the situation includes five important aspects that control the selection of a WWTS:

- Little land area to place a WWTS
- Surrounded by fragile coral that is susceptible to excess nutrient loading

- Fine sands create high infiltration rates in the soil
- Tourists visit and swim in the water directly off of the Cayes
- Anywhere from 5 to 200 tourists visit each Caye daily, depending on the season

Because of these limitations Eco-Friendly Solutions, a small company in Belize, was tasked with creating WWTS in these Cayes. The WWTS ability to remove nutrients from the effluent before they seep into the sandy soil, and ultimately, leach out into the aquatic ecosystem is important for the health of the surrounding coral reefs. Multiple studies have shown that excess nutrients from anthropogenic sources have led to a steep decline in coral species (Hallock and Schlager, 1986; Lapointe, 1997). In the Caribbean, coral populations have been reduced steadily over the past 30 years. The combination of decreased fish populations that eat algae and increased coral mortality have led to a Caribbean-wide ecosystem shift from coral-dominated to microalgae-dominated ecosystems (Scheffer *et al.*, 2001; Bruno *et al.*, 2003).

2.7 Effects of Saltwater on Wastewater Treatment

In two of the Cayes, Laughing Bird and Silk, the entire WWTS uses salt water to flush the toilets. The pour-flush toilet operates nearly the same as toilets in developed countries, where water is used to move the effluent to an area away from direct contact with the user. In the case of the WWTS in the Cayes, the wastewater (effluent plus water used to flush the toilet) flows into a partially anaerobic biodigester. Salt water is used because there is no fresh water readily available on the Cayes. Although the use of salt water for flushing is common in coastal communities of the low- and middle-income countries, there is little literature of the performance of decentralized WWTS with saline wastewater. Instead, studies have looked at specific areas of treatment in salt water conditions; namely, the removal of pathogens, the stabilization of organic compounds, and the treatment of nutrients (Hanes and Fragala, 1967; Omil *et al.*, 1995; Dinçer and Kargi, 1999; Uygur and Kargi, 2004; Anderson *et al.*, 2005; Gross and Bounds, 2007; Wu *et al.*, 2008). No studies were found that have looked at all three of these objectives in one study for salt water. In the absence of literature on the performance of decentralized saltwater-based WWTS, an inference of the treatment abilities must be made using the information available about salt-water-based centralized WWTS and salt-water-based anaerobic digesters.

Few functioning centralized saltwater WWTS were identified within published literature that was found, namely: Hong Kong; Avalon, CA; the Marshall Cayes, located between Hawaii and Papua New Guinea in the Pacific Ocean; and South Tarawa, in the Republic of Kiribati (Yang *et al.*, 2015). Of these systems, Hong Kong's WWTS is the only one that functions extensively on salt water flushing (Li *et al.*, 2005). In Hong Kong, the use of salt water for flush is necessary to conserve the limited fresh water available in the area. Due to the extremely high population density in Hong Kong, the annual per capita supply of fresh renewable water is constrained to 125 m^3, well below the World Bank's classification of minimum renewable water "scarcity" of 1000 m^3 (Leung *et al.*, 2012). The dual system of fresh water-salt water flushing was constructed in 1958 to combat the severe shortage of fresh water that plagues Hong Kong. Currently the WWTS provides sanitation for over 80% of the city's 7 million people, supplying an average of 750,000 m^3 of seawater per day to fill toilets (Leung *et al.*, 2012). In most regards, the WWTS of Hong Kong functions like one of fresh water, containing screening processes, sedimentation, and sections specifically for aerobic and anaerobic digestion (Tang *et al.*, 2007).

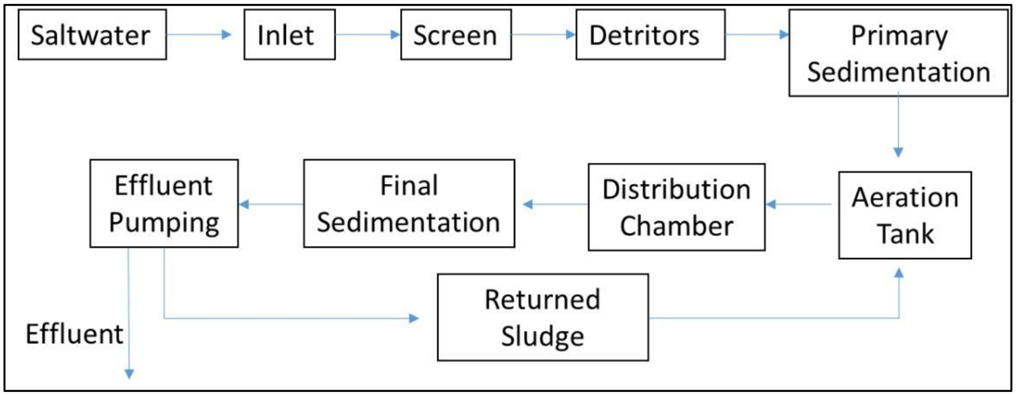

Figure 4: Diagram of the Saltwater-based WWTS in Hong Kong (Source: Tang *et al.*, 2007, created image)

Although the WWTS at Hong Kong does have issues due to the characteristics of saltwater, most notably corrosion of pipes, severe disinfection by-products from chlorination, sudden deterioration of influent water quality, and ecological problems of effluent discharge in freshwater rivers (Tang *et al.*, 2007), the plant has functioned well at producing high-quality effluent. Using internal data from the Municipality of Hong Kong, Lueng *et al.* (2012) determined that the effluent from the WWTS of Hong Kong would meet the effluent standards of the US Environmental Protection Agency and the Ministry of the Environment of Japan. Thus, the example of Hong Kong shows that wastewater treatment of salty black water, at least in centralized WWTS, is possible.

To estimate the likely performance of a saltwater-based decentralized WWTS, the system must be looked at in its ability to treat pathogens, stabilize organic compounds, and removal of nutrients from the waste stream. The survival of pathogenic bacteria has been a topic of discussion in scientific literature for years. Aside from the obvious public health implications of fecal bacteria living in recreational seawater, high concentrations of NaCl provide a unique environmental stress that scientists use to measure the bacterial response. In general a high salt concentration in wastewaters induces osmotic stress to the microbiological species, resulting in the inhibition of many enzymes, decrease in cell activity, and eventually plasmolysis (Rene *et al.*, 2008). The crippling effects of seawater environments affect the fecal pathogenic bacteria in much the same way. Multiple studies have found that neither *E. coli* nor enterococci, two common indicator bacteria used to detect the presence of fecal contamination, are able to reproduce in the open, saltwater environment (Dawe and Penrose, 1978; Rozen and Belkin, 2005). Although the bacteria are unable to reproduce, the cells do survive and remain viable in saltwater. The total time needed for fecal bacteria cells to lyse is difficult to accurately determine and relies on several factors. These factors include: nutrient availability, salinity, temperature, pH, microbial predation, and solar radiation (Davies-Colley *et al.*, 1994; Rozen and Belkin, 2005). The exact amount of time required for cell death is hard to determine, but the maximum time that the bacteria can survive in open seawater has been found to be around 5 days (Moss and Smith, 1981). Sinton *et al.* (1994) mixed sewage into seawater and found that the inactivation of one log of pathogenic bacteria required no more than 115 hours. Considering that the pathogenic bacteria entering a saltwater-based decentralized WWTS would first pass through an anaerobic biodigester, and then a leach field, where other stresses and predation occur, it is unlikely that pathogenic organisms from the WWTS would contaminate the water around the

Cayes. There are multiple studies that have found that pathogenic organisms survive, and even reproduce, in saltwater sediments (Shiaris *et al.*, 1987; Anderson *et al.*, 2005; Rozen and Belkin, 2005). However, all of these articles report that raw sewage was deposited directly into the seawater, which would not be the case for a saltwater-based WWTS.

Two other critical aspects in the treatment of wastewater are nutrient removal and organic compound stabilization. As described in the previous paragraph, the stress of salinity causes a decrease in cell activity and even plasmolysis. Due to this stress, the performance of biological treatment in saline wastewaters is poor, leading to poor-quality effluent in terms of nutrient removal (Yang *et al.*, 2013). Under aerobic conditions, salinity was shown to affect the metabolic activity of nitrifying bacteria, reducing microbial growth and ammonium oxidation rates (Bassin *et al.*, 2012). In the case of anaerobic digestion, studies indicate that the saltwater inhibits the production of biofilms, and renders the biofilm unstable in the formation of an anaerobic filter (Yang *et al.*, 2013). In addition to the salinity of the wastewater, the density of salt in comparison to fresh water has been found to alter or inhibit the sludge settleability characteristics, sludge flocs and biofilms architecture (João P. Bassin *et al.*, 2011). These results together have combined to reduce the effectiveness of WWTS. In a study performed by Panswad & Anan (1999), unacclimated bacteria functioning in an anaerobic-anoxic-aerobic treatment train were exposed to 30 g NaCl/kg for four weeks. The bacteria experienced reductions in performance by at least 30% for the removal of COD, nitrogen, and phosphorus in comparison to the freshwater-based WWTS. However, these results also come with a silver lining. During that same study, acclimated bacteria were 10% better at removing the contaminants than the unacclimated bacteria. Similarly, in another study on the treatment of fishmeal waste, acclimated bacteria were able to hydrolyze suspended organic solids, mainly proteins, and remove COD sufficiently (Guerrero *et al.*, 1997). Furthermore, Bassin *et al.* (2011) showed that acclimated bacteria are able to convert 90% of ammonia to nitrate in nitrification, well past the saline concentration of wastewater.

Judging from the descriptions above in the ability of salt water systems to remove bacteria, reduce organic compounds, and remove nutrients from the waste stream, a few general assumptions are made and presented in Table 5. In general, the elimination of pathogenic organisms is most likely greater in salt water conditions than in fresh water WWTS. However, the ability of salt water WWTS to settle organic material and remove nutrients is also likely reduced.

Table 5: Relative Comparison of Fresh Water and Salt Water WWTS in Terms of the General Wastewater Treatment Objectives

Treatment Objective	**Fresh Water WWTS**	**Salt Water WWTS**
Removal of Pathogenic Bacteria	-	+
Organic Compound Settleability	+	-
Nutrient Removal	+	-

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CHAPTER 3: SITE DESCRIPTION

3.1 Background of the Mesoamerican Barrier Reef

The Mesoamerican Barrier Reef in the coastal waters of Belize is part of the largest fringing barrier reef in both the Northern and Western hemispheres (World Conservation Monitoring Centre, 2008). Stretching over 1,000 kilometers from the Yucatán of Mexico to the coast of Belize, the Mesoamerican Reef is second in areal extent only to the Great Barrier Reef of Australia. Though smaller than the Great Barrier Reef, the Mesoamerican Reef has a wider range of geologic features that make many areas of the region unique. Unlike the Great Barrier Reef of Australia, it has benefited from relatively low human utilization in the past centuries (Kramer and Kramer, 2002). Due to the low historical Usage and the preservative actions taken by the government of Belize, this area contains some of the most pristine habitats of coral in the world (World Conservation Monitoring Centre, 2008). The region possesses essential resources that have important ecological, economic, and cultural significance, and that help to sustain an estimated 2 million people that live in the local coastal communities (Kramer and Kramer, 2002).

The largest components of the Mesoamerican Barrier Reef is the Belize Barrier Reef. Representing a sub-set of the Belize Barrier Reef, the Belize Barrier Reef System is the most well-known and economically important area of the region. Recognized as a World Heritage Site in 1996, 7 marine reserve areas, as seen in Table 6, adding up to 96,300 hectares of the reef system make up an estimated 12% of the total Mesoamerican Barrier Reef complex (World Conservation Monitoring Centre, 2008). The Reserve System has been cited as having "universal natural heritage value representative of unique biological reef formations" (Cho, 2005). This was historically noted in 1846 when Charles Darwin described it as "the most remarkable reef of the West Indies" (Darwin, 1987). This section of the Mesoamerican Barrier Reef is the central portion of many interconnected coastal habitats and currents that propagate throughout the Caribbean basin. A unique collection of fish, invertebrates, birds, sea turtles, plants, corals, and other animals inhabit the Barrier Reef. The region contains the greatest concentration of coral in the Caribbean basin, an estimated 90% of some of the rarest types of coral for the entire Caribbean (World Conservation Monitoring Centre, 2008). In addition to the reef ecosystems, the region encompasses beaches, coastal rivers and lagoons, mangroves, seagrasses, and coastal wetlands that grant essential breeding, nesting, and foraging habitat for numerous species (Kramer and Kramer, 2002). An estimated 260 (or 66%) of the 320 resident bird species of Belize visit the cayes and wetlands throughout the year, including thousands of birds that use the area as a staging area during seasonal migrations. The parks are also home to several endangered species, including the manatee, the scalloped hammerhead shark, the Nassau and goliath grouper, the hawksbill, leatherback and green marine turtles, and several coral species (Kramer and Kramer, 2002; World Conservation Monitoring Centre, 2008; SEA Belize, 2010a, 2010b).

Table 6: World Heritage Sites Incorporated into the National Parks of the Belize Barrier Reef System

Name of National Park	Hectares
Glover's Reef Marine Reserve	30,800
South Water Caye Marine Reserve	29,800
Sapodilla Cayes Marine Reserve	12,700
Bacalar Chico National Park and Marine Reserve	10,700
Laughing Bird Caye National Park	4,300
Half Moon Caye Natural Monument	3,900
Blue Hole Natural Monument	4,100

Source: World Conservation Monitoring Centre (2008)

This ecologically and economically interconnected region provides local communities with abundant resources. Originally used by local villagers for small-scale fishing and recreation, the Belize Barrier Reef System has steadily grown in economic importance with the growth of the local coastal population (World Conservation Monitoring Centre, 2008). Cho (2005) estimated that the Barrier Reef in Belize contributed about 30% of the gross domestic product for the entire country of Belize through fisheries, eco-tourism, and a relatively new boom of cruise tourism. Currently the main economic service of the region is tourism, which is the country’s largest source of foreign exchange (Ministry of

Agriculture and Fisheries of Belize, 1995). An estimated 390,000 tourists visited the Reserve System in 2006, generating more than $75 million in income for the local inhabitants (World Conservation Monitoring Centre, 2008). In addition to the tourism industry, fishing maintains a small group of people. Spalding et al. (2001) reported that approximately 2,000 fishers exported $10.5 million in seafood from the area.

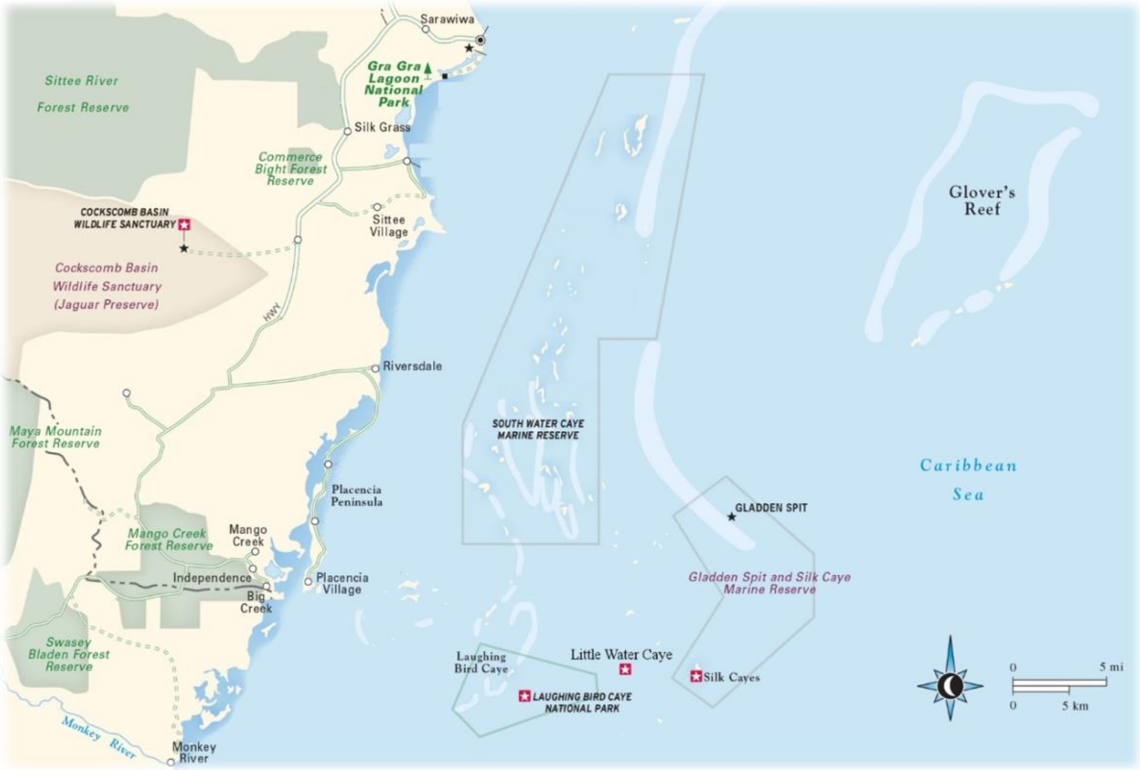

Figure 5: Map of Little Water, Laughing Bird, and Silk Caye in the Belize Barrier Reef
(Reprinted with permission of Girma, 2016; Appendix G)

Situated within and directly adjacent to the Belize Barrier Reserve System are the 3 Cayes that are the focus of this thesis. Laughing Bird Caye, Silk Caye, and Little Water Caye are three small cayes managed by the non-governmental organization (NGO) Southern Environmental Association Belize (SEA Belize). Together these three cayes are the staging points for local diving, fishing, and other recreational tourism. Laughing Bird Caye and Little Water Caye house a ranger station that carries out marine enforcement and aquatic research. SEA Belize has purchased three waste water treatment systems (WWTS) from Eco-Friendly Solutions to treat wastewater generated on the cayes. Eco-Friendly Solutions is a company that builds WWTS in Belize. The approach of Eco-Friendly solutions is the construction of semi-anaerobic biodigesters, sometimes multiple in series, followed by small leach fields.

3.2 Descriptions of WWTS on the Cayes

As Little Water, Laughing Bird, and Silk Cayes became a more popular tourist destination, SEA Belize reached out to a local sanitation company to build WWTS to provide sanitation services on the Cayes. Eco-Friendly Solutions is a small company based out of Belize City that designs and installs decentralized WWTS on both the residential and commercial scale. Contacted in 2009 by SEA Belize, Eco-Friendly Solutions built 3 pour-flush bathrooms with the WWTS that rely upon semi-anaerobic biodigesters and drain fields. Each system was uniquely designed for the number of daily visitors and the amount of money that SEA Belize could pay for the systems. A general description of each Caye and the WWTS installed are provided in the sections below.

3.2.1 Little Water Caye

Little Water Caye is strategically located between Laughing Bird Caye and Silk Caye (GPS Coordinates: N $16^0$26.921, W $88^0$5.759). Historically used by local fishermen to receive fresh water, the caye was partially purchased by SEA Belize as a base of operations in managing the other cayes. SEA Belize has constructed a ranger station, watchman's quarters, educational facility, and 300-foot pier on the caye. In addition to its function as a hub for researchers and enforcement officials, Little Water Caye is also the home of the Placencia Producers Cooperative's seaweed project. On the banks of Little Water Caye, local fishermen and tour guides have planted seaweed which they harvest to sell in local markets and restaurants for nutritional supplements (Sniffin, 2013). This provides an alternative livelihood for those fishermen during the low tourism seasons or when fish stocks are not abundant.

Built in the summer of 2015, the wastewater treatment system at Little Water Caye (LWC) is the newest, and largest, of the three WWTS. This is the only system of the three cayes that has a freshwater treatment system connected to the toilets of the caye. LWC uses a rainwater catchment system that provides the residents fresh water year-round. Thus, unlike Laughing Bird Caye and Silk Caye, the wastewater treatment is freshwater-based.

The wastewater treatment system consists of two semi-anaerobic biodigesters working in series and a leach field. Figure 1 is a schematic of the wastewater system, while Appendix A contains photographs of the system. Eco-Friendly Solutions designed the WWTS to handle approximately 3,000 liters of black or grey water per day. The semi-anaerobic biodigesters are two Rotoplast plastic water tanks with capacities of 3,500 liters and 1,200 liters. The goal of the two biodigesters in series is to separate the solids from the effluent wastewater, while providing extra residence time for wastewater in the digesters. While the solids are settling to the bottom of the tank, anaerobic redox zones in the bottom and through the middle of the tank nitrify the influent ammonium into nitrate and consume the influent BOD. At the top of each semi-anaerobic biodigester is a biofilm contact chamber. The cone-shaped filter has been packed with broken plastic crates and PVC pipes to provide extra surface area for the growth of organisms required to reduce the BOD and convert the organic nutrients within the system. The upped cavity of the tank does not fill with wastewater, leaving a semi-aerobic zone where the wastewater BOD is further consumed and the nitrate undergoes a small amount of denitrification. The sizing of the anaerobic biodigesters and designed load of the system produce a hydraulic retention time (HRT) of 1.5 days.

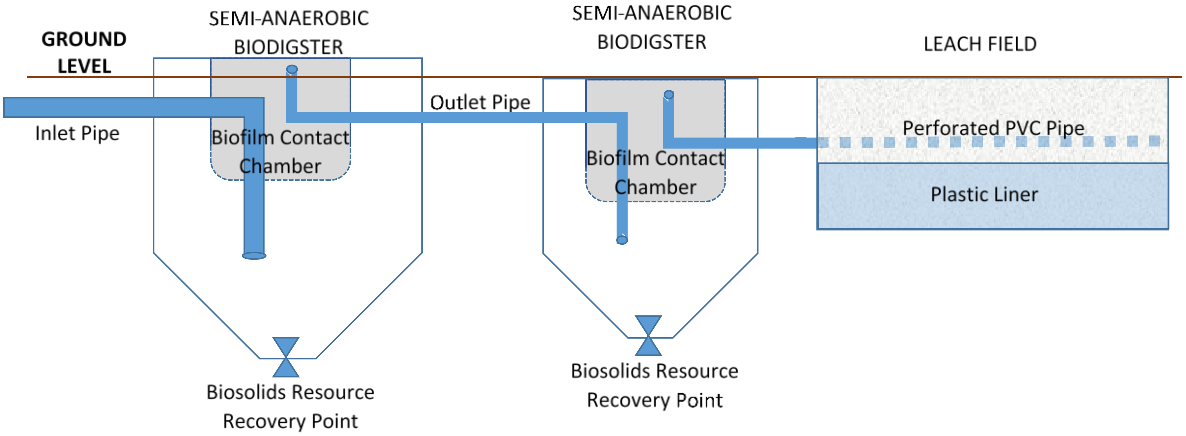

Figure 6: Diagram of the Wastewater Treatment System at Little Water Caye
*Used with permission of Christine Prouty

The leach field consists of a perforated 2-inch polyvinyl chloride (PVC) pipe running down the leach field trench, with a combination of crushed conch shells, rocks and coral surrounding the pipe. The trench has the dimensions of 30 feet long by 3 feet wide by 3 feet deep, and is located over 100 yards away from the nearest coastline to the west. The trench itself was constructed with a construction-grade plastic tarp at the bottom so that the treated effluent does not filter into the sandy soil of the Caye, but rather stays within the trench. The trench was then backfilled with rocks with smaller diameter sizes being placed at the bottom. As the trench fills with wastewater, it flows over the top of the liner into the local sand. Lily pads, a native plant that have the ability to take up ortho-phosphates and nitrate from the surrounding soil, have been planted in the sand next to the liner to reduce the amount of nutrients that are discharged into the sand. Additionally, the nitrate in the wastewater undergoes denitrification as more oxygen is available to the microbes.

By far the largest wastewater treatment system on the Cayes, it is also the least utilized system. The regular population of Little Water Caye is a research team, visiting Department of Fisheries enforcement officers, volunteers from Projects Abroad, and the rangers that are employed by SEA Belize. The research team may consist of 5-6 Belizean or international students and professors. In addition to the 4 rangers that occupy the caye year-round, high season usually consists of 10 visitors per day using the wastewater treatment system for toilet utilization. During the low season months, only the 4 rangers use the wastewater treatment systems with regularity.

3.2.2 Laughing Bird Caye

Laughing Bird Caye is the most well-known of the three Cayes. Classified as part of the World Heritage Site of the Belize Barrier Reserve System, Laughing Bird Caye is the central area of Laughing Bird Caye National Park (LBCNP). Covering approximately 41 km^2, the national park is located 18 km offshore on the shallow reef platform of the Atlantic Coast of the Mesoamerican Barrier Reef (SEA Belize, 2010b). The park supports a nursery and feeding habitat for at least 23 species of “international concern, recognized under the International Union for Conservation of Nature (IUCN) Redlist as Critically Endangered, Endangered or Vulnerable” (SEA Belize, 2010b). The caye itself, while only 4,000 m^2 in size, provides a wide mixture of habitats that host several endemic species. Laughing Bird Caye is a short 40-minute boat ride from Placencia, a popular tourist town and the launching point for most tours in the area, and is the closest Caye to the Central Belize Coastline that has beaches instead of mangroves (SEA Belize, 2010b). This location makes Laughing Bird Caye a critical tourist site for those interested in visiting a part of the Belize Barrier Reserve System but without SCUBA training or interest in boating to the next popular tourist site (Silk Caye) approximately an hour away. Annually, LBCNP hosts between 6,500 and 10,000 tourists, of which 90% are foreigners and 10% are Belizean (SEA Belize, 2010b). The Caye is divided into two sections: the highly trafficked tourists' section and the restricted access (SEA Rangers only) birds' nesting ground. The tourism section includes barbeque pits, a palapa with picnic tables, a public use toilet with a salt-water based treatment system, and the rangers' station. The rangers' station is the largest structure on the caye and was constructed in 2001 to provide housing for enforcement officials to improve their ability to carry out conservation practices in and around 2Laughing Bird Caye National Park.

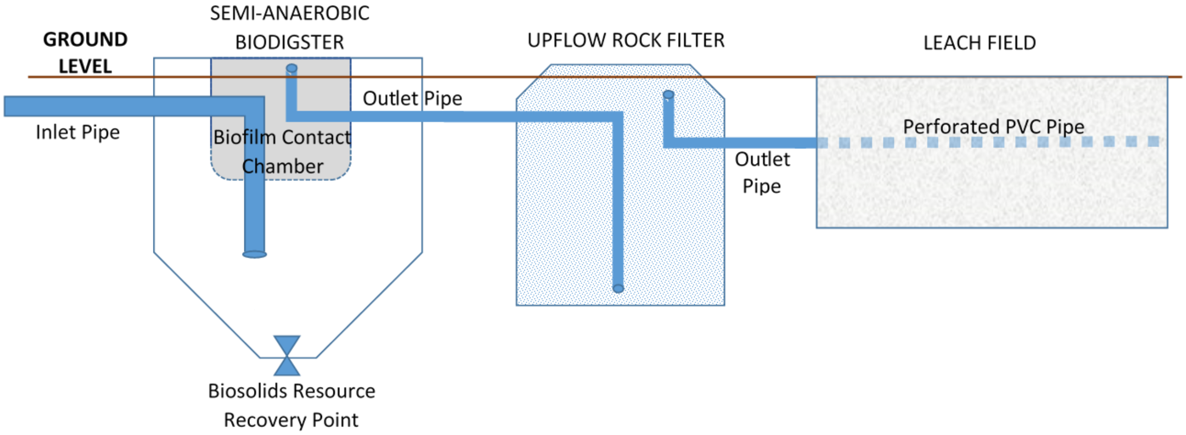

Figure 7: Diagram of the Wastewater Treatment System at Laughing Bird Caye
*Used with permission of Christine Prouty

The wastewater treatment system consists of a semi-anaerobic biodigester, a rock filter, and a small leach field. A schematic is drawn in Figure 7. Since there is no fresh-water collection system on the Caye, the wastewater treatment system is operated entirely from saltwater collected along the shoreline.

The biodigester is a 1,500 liter Rotoplas water tank, and the rock filter is a 500 liter Rotoplas water tank with a rock bed incrementally decreasing in size as the water flows upward. Principally used following the facultative pond or maturation pond WWTS, studies indicate that the effluent BOD and solids are further removed in a functioning rock filter, but have little effect in the denitrification process

(Middlebrooks, 1988; Katukiza *et al.*, 2014). The leach field was constructed like the leach field in Little Water Caye, in that an impermeable plastic sheet was installed in the base of the trench. A 2” perforated PVC pipe discharges the effluent into the leach field, which is filled with rocks and coral, and sand covers the entire leach field. However, there are several key differences between the two leach fields. In Laughing Bird Caye, the leach field is much smaller, measuring 3 meters long, by 0.6 meters wide, by 1 meter deep. In addition, the leach field is located less than 5 meters from the nearest shoreline. Appendix A contains photos that depict how near the shoreline is to the leach field. To combat the proximity of the leach field to the shoreline, native vegetation, water lilies, was planted along the leach field. The idea is that the water lilies absorb the excess nutrients in the effluent before those nutrients come into contact with the seawater.

3.2.3 Silk Caye

Silk Caye is part of the Gladden Spit and Silk Caye Marine Reserve (GSSCMR). The Caye is located 35 km offshore, due east of Placencia. The GSSCMR network was created in 2001 as a means to “preserve unique and important marine habitats” (Cho, 2005). The concept of a Marine Reserve or Marine Protected Area (MPA) is not only for environmental protection, but also to improve the conditions of fisheries and enhance the area for tourism. As a mating area of the cubera, dog, and mutton snappers (the last of which is the most common harvested fin-fish in Belize), the area is known for attracting whale sharks in a distinctive fashion that occurs in no other place in the world (SEA Belize, 2010a). In addition to the snapper and whale sharks, the MPA hosts five species of coral, three species of turtle, and over 25 different species of reef fish that amass to spawn annually (SEA Belize, 2010a). The sandy beaches and clear water of the Silk Caye region are important features of the area, attracting substantial tourism from Placencia. Tourism in Silk and Gladden Caye brings an average of 25 people to the caye per day, the majority coming between the months of March and April, tying in with the occurrence of the whale-sharks during those months. In 2009 an estimated 8,580 tourists visited Silk Caye, generating over Bz$136,100, about US$68,000, in ticket revenue for SEA Belize (Bravo, 2010). Most of the tourists are daytime travelers that go snorkeling off of the Caye, but several kayaking tours and sailing charters use the caye as an overnight stop (SEA Belize, 2010). The smallest of the three Cayes, less than 2,000 m^2 in size, Silk Caye itself is comprised of a barbeque grill, a picnic area with tables, and two toilets with a salt-water based treatment system. There are no permanent settlements on the Caye.

The water treatment system consists of a semi-anaerobic biodigester, a chlorine contact chamber, and a leach field (Figure 8). As with Laughing Bird Caye, the wastewater treatment system on Silk Case uses salt water from the surrounding shoreline exclusively. The semi-anaerobic biodigester is a 1,500 liter Rotoplas drinking water tank, which is filled with plastic material to provide more surface area for the digestion. The chlorine contact chamber is tablet based, a system most commonly used in the chlorination of pools in developed countries, and in water treatment systems in low- and middle-income countries (Orner *et al.*, 2017). However, it has been reported that the chlorine contact chamber is not currently functioning within the system (Prouty, 2016). Unlike the WWTS at Little Water and Laughing Bird Caye, a leachfield was not constructed for Silk Caye. Instead a pipe (listed as a soak away) feeds the treated wastewater directly into the ground without additional treatment. In addition, the soak away itself is less than 3 meters away from the nearest shoreline. No vegetation has been planted near or on top of the area.

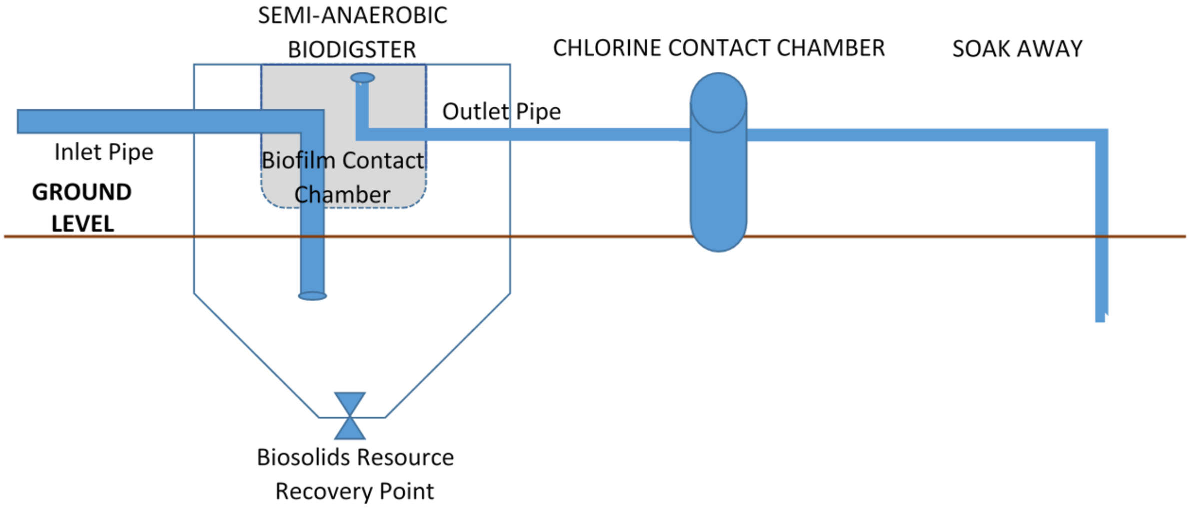

Figure 8: Diagram of the Wastewater Treatment System at Silk Caye
**Used with permission of Christine Prouty.*

3.2.4 Maintenance of the Three Systems

SEA Belize is responsible for the day-to-day management of the three Cayes. The responsibility includes collecting fees from the visiting tourists, patrolling the Cayes and the surrounding water, and working with the local government to improve the environmental management and local science research that occurs on the Cayes. The responsibilities also include regular maintenance of the three wastewater treatment systems. However, recent conversations with Luis Garcia, project manager for Eco-Friendly Solutions, indicated that little maintenance is performed (Garcia, 2016). In the last six years, the anaerobic biodigesters in Laughing Bird Caye and Silk Caye have been purged by Eco-Friendly Solutions only twice, meaning excess buildup of biosolids within the systems is probably occurring. Construction of the wastewater system on Little Water Caye was completed in the summer of 2015. Once every two years the rangers of SEA Belize purchase a Septic Aid liquid to help in the digestion of waste by the bacteria (Garcia, 2016).

There is a supply train to purchase replacements for broken or expended materials and parts from Eco-Friendly Solutions on the mainland. However, these maintenance calls are made only after the system has failed and stopped functioning correctly. In essence, the maintenance of the systems stops at the toilets. Thus is the reason for this Thesis, to determine if the three WWTS are treating the wastewater produced at the Cayes to limits that do not impact the local environment or visitors. Furthermore, if not being treated correctly, what changes could be made to ensure better treatment of the wastewater?

CHAPTER 4: METHODS

4.1 Tests Performed at Laughing Bird, Little Water and Silk Caye

In December of 2015, Christy Prouty visited the Silk, Little Water and Laughing Bird Cayes for one month to collect data on the performance of the three systems. The specific variables that were investigated and quantified were water quality parameters influencing treatment efficiency (BOD and pH), levels of public health exposure to pathogens (E. coli and total coliforms), and concentrations of nutrients (both nitrogen and phosphorus) remaining in the recovered resources at Laughing Bird, Little Water, and Silk Cayes. A specific list of activities and individual tests that were performed are provided in Appendix B.

4.2 Modeling the Performance

4.2.1 Model Description and Assumptions

A mathematical model was developed by Christy Prouty and Jeffrey Cunningham to estimate the treatment efficiency of the systems, removal of biological oxygen demand, fecal solids, and nutrients—particularly nitrogenous species. The model is based on the mass balances of six species: inert solids, fecal solids, bacterial biomass, soluble substrate (i.e. dissolved organic carbon), ammonium and nitrate. From these mass balances, the model predicts or estimates the effluent concentrations of these same six species. A list of the six chemical and solid species that were tracked by the model is presented in Table 7. Furthermore, an illustrated description of the modeled mass balance of the WWTS is presented in Figure 9.

To develop a tractable model, several assumptions were made based on observed conditions at the WWTS. For the sake of model simplicity, the WWTS was assumed to behave like a continuously stirred tank reactor (CSTR), in which all chemical and solid species are uniformly distributed within the system. The pH of the system was assumed below 8, making the conversion of aqueous ammonium to gaseous ammonia, and thus the gaseous effluent, negligible within the model. Dissolved oxygen was assumed to be present in small concentrations, making the WWTS a semi-anaerobic environment. The WWTS was assumed to be in steady state, meaning the chemical, physical, and biological parameters within the system are not changing over time.

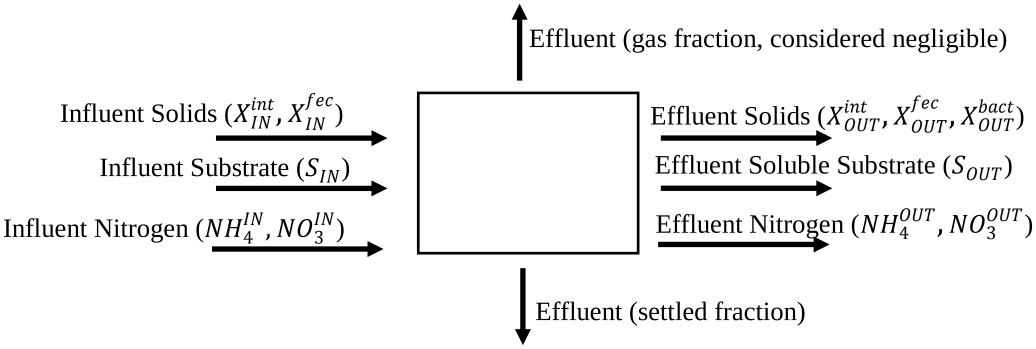

Figure 9: Mass Balance for the Modeled WWTS

Table 7: Chemical and Solid Species that were Tracked in the Model

Tracked Parameter	**Parameter Description**
X_{OUT}^{int}	Inert Solids Effluent Concentration
X_{OUT}^{fec}	Fecal Solids Effluent Concentration
X_{OUT}^{bact}	Bacterial Solids Effluent Concentration
S_{OUT}	Effluent Soluble Substrate (BOD) Concentration
NH_4^{OUT}	Effluent Ammonium Concentration (as N)
NO_3^{OUT}	Effluent Nitrate Concentration (as N)

As described in Chapter 3, inspections at Little Water, Laughing Bird, and Silk Caye found that the treatment processes following the semi-anaerobic biodigester (upflow clarifier, chlorine contact chamber, and drain fields) were in various conditions of operation; including disrepair (upflow clarifier) and/or unused (chlorine contact chamber). Additionally, as discussed in Section 3.2.2, the upflow rock filter does not affect the nitrification/denitrification process. In regard to the drain fields installed on Little Water and Laughing Bird Caye, neither system was constructed in the typical mold described in Chapter 2, making an accurate model of this treatment process difficult. Since the treatment efficiency of the additional treatment methods were inconclusive, the model system boundaries, and thus the predicted wastewater treatment, were based solely upon the treatment that occurs within the semi-anaerobic biodigesters.

The microbiology of a semi-anaerobic digestion process, the removal of soluble BOD from the waste stream through waste stabilization, is complex and includes thousands of different bacterial species operating under variable chemical and physical conditions through several step-wise processes occurring in concert with one another (Husain, 1998; Amani *et al.*, 2010; Chen *et al.*, 2012). In general, the number of identifiable bacterial populations involved in the process is directly linked to the model complexity (Bernard *et al.*, 2001). As one of our goals is to obtain a model that would be able to represent the semi-anaerobic degradation process, while also being simple enough to be identifiable, the model assumes a homogenous bacterial population that has three functions: hydrolysis of the fecal matter, degradation of the soluble substrate, and nitrification. The bacterial population is therefore characterized by a single value of growth rate, death rate, and yield, but the rate coefficients for nitrification, fecal hydrolysis, and substrate utilization are different.

The modeling of biological kinetics is a difficult task for which systematic methodology is still imprecise (Bernard *et al.*, 2001). For model simplicity, and in accordance with other studies on aerobic digestion modeling (Henze *et al.*, 2000; Dinçer and Kargi, 2001; Schroeder and Wuertz, 2003; Ergas and Aponte-Morales, 2014), dual Monod kinetics were assumed for the rates of both substrate utilization and nitrification. Additionally, bacterial growth is assumed to be directly linked to the concentration of the primary substrate of carbon, the concentration of which is expressed as BOD.

4.2.2 Presentation of the Model

The mass balance equations developed for this model are presented in Equations 5 through 10. For the sake of brevity, the mathematical developments are not detailed. A short description of the processes that occur in the mass balance equations is presented before each equation as an extension of the explanations given in Chapter 3. A table with the definition of the parameters used in the model is presented in Table 8.

Some of the solids entering the WWTS are inert. That might include sand and inorganic solids materials and also recalcitrant organic solids. The inert solids enter the WWTS, settle at the bottom of WWTS as settled solids, or exit the WWTS in the wastewater (X_{OUT}^{int}).

$$X_{OUT}^{int} = \frac{X_{in}^{int}}{(1+ k_{sett}^{int}\theta)} \qquad [5]$$

The fecal solids that enter the WWTS are composed of the portion that is able to be hydrolyzed by bacteria and the recalcitrant portion, inert solids, that is not hydrolyzed. The fecal solids that are able to be hydrolyzed enter the WWTS, settle at the bottom of WWTS as settled solids, undergo hydrolysis, or exit the WWTS in the wastewater (X_{OUT}^{fec}). The fecal solids release ammonium and soluble substrate during the hydrolysis process.

$$X_{OUT}^{fec} = \frac{X_{in}^{fec}}{\left(1+ k_{sett}^{fec}\theta\right)+ \left(k_{hydro}^{\prime fec} X_{out}^{bact}\theta\right)} \qquad [6]$$

The homogeneous bacteria within the WWTS grow by aerobically degrading the soluble BOD that enters the system (S_{IN}) and is released during the hydrolysis process. The bacteria settle at the bottom of the WWTS as settled solids, die, or exit the WWTS in the wastewater (X_{OUT}^{bact}).

$$X_{OUT}^{bact} = \frac{S_{in}- S_{out}}{\left(\theta\left(\frac{1}{Y}\right)\mu_{max}^{bact}\left(\frac{O_2}{O_2+k_s^{O_2}}\right)\left(\frac{S_{out}}{S_{out}+ k_{sat}^{sub}}\right)\right)- \left(\gamma k_{hydro}^{\prime fec} X_{out}^{fec}\theta\right)} \qquad [7]$$

The soluble substrate, BOD, enters the WWTS, is released by the fecal solids during the hydrolysis process, and is consumed by the bacteria within the system. The portion of soluble BOD that is not utilized and consumed by the bacteria exits the wastewater system as effluent soluble substrate (S_{OUT}).

$$S_{out} = \frac{\left[\left(k_{sat}^{sub}\right)\left(\theta b+ \theta k_{sett}^{bact}+1\right)\right]}{\left[\theta\mu_{max}^{bact}\left(\frac{O_2}{O_2+k_s^{O_2}}\right)- \theta b- \theta k_{sett}^{bact}-1\right]} \qquad [8]$$

The ammonium enters the WWTS through the urine and feces. The ammonium that enters through the feces is released during hydrolysis process. Ammonium is assimilated by the bacteria within the WWTS during cellular growth. Additionally, ammonium is converted to nitrate during the nitrification process. The portion of ammonium that is not assimilated by the bacteria, or converted to nitrate, exits in the wastewater stream (NH_4^{OUT}).

$$NH_4^{OUT} = \frac{1}{2}\left[\left(NH_4^{+in} - k_{sat}^{NH_4^+} + \theta k'^{fec}_{hydro} X_{out}^{fec} X_{out}^{bact}\alpha - \theta\mu_{max}^{bact}\left(\frac{S}{S+k_{sat}^{sub}}\right)\left(\frac{O_2}{O_2+k_{sat}^{O_2}}\right)X_{out}^{bact}\beta - \theta\left(\frac{1}{Y}\right)\mu_{max}^{nit}\left(\frac{O_2}{O_2+k_{sat}^{O_2}}\right)X_{out}^{bact}\right) + \sqrt{\left[\begin{array}{c}\left(-NH_4^{+in} + k_{sat}^{NH_4^+} - \theta k'^{fec}_{hydro} X_{out}^{fec} X_{out}^{bact}\alpha + \theta\mu_{max}^{bact}\left(\frac{S}{S+k_{sat}^{sub}}\right)\left(\frac{O_2}{O_2+k_{sat}^{O_2}}\right)X_{out}^{bact}\beta + \theta\left(\frac{1}{Y}\right)\mu_{max}^{nit}\left(\frac{O_2}{O_2+k_{sat}^{O_2}}\right)X_{out}^{bact}\right)^2 \\ +4\left(NH_4^{+in}k_{sat}^{NH_4^+} + \theta k'^{fec}_{hydro} X_{out}^{fec} X_{out}^{bact}\alpha k_{sat}^{NH_4^+} - \theta\mu_{max}^{bact}\left(\frac{S}{S+k_{sat}^{sub}}\right)\left(\frac{O_2}{O_2+k_{sat}^{O_2}}\right)X_{out}^{bact}\beta k_{sat}^{NH_4^+}\right)\end{array}\right]}\,\right] \qquad [9]$$

A small amount of nitrate enters the WWTS through the urine and feces. However, the majority of the nitrate produced is through the conversion of ammonium during the nitrification process. The nitrate in the influent, and produced in the denitrification process, exits in the wastewater stream (NH_4^{OUT}).

$$NO_3^{OUT} = NO_3^{IN} + \theta\mu_{max}^{nit}\left(\frac{NH_4^+}{NH_4^+ + k_{sat}^{NH_4^+}}\right)\left(\frac{O_2}{O_2+k_{sat}^{O_2}}\right)X_{out}^{bact}\left(\frac{1}{Y}\right) \qquad [10]$$

Table 8: Parameter Name, Symbol, and Unit Used in Modeling Equations

Influent Parameters		
Variable Name	***Variable***	***Units***
Flow Rate	Q	L/day
Hydraulic retention time	θ	day
Influent inert solids concentration	X_{IN}^{int}	mg/L
Influent fecal solids concentration	X_{IN}^{fec}	mg VSS/L
Influent substrate concentration	S_{IN}	mg BOD/L
Influent ammonium concentration	NH_4^{IN}	mg/L as N
Influent nitrate concentration	NO_3^{IN}	mg/L as N

Biological Parameters		
Variable Name	***Variable***	***Units***
Maximum bacterial growth rate	μ_{max}^{bact}	1/day
Degradation rate coefficient (for BOD)	μ_{max}^{bact}/Y	1/day
Rate coefficient for the nitrification process	μ_{max}^{nit}/Y	1/day
Death rate	b	1/day
Yield	Y	mg VSS / mg BOD
Fecal hydrolysis rate coefficient	k'^{fec}_{hydro}	L/mg*day
Mass fraction of nitrogen in fecal solids	α	unitless

Table 8 (Continued)

Oxygen concentration	O_2	mg/L

Settling Constants		
Variable Name	***Variable***	***Units***
Fecal solids settling constant	k_{sett}^{fec}	1/day
Inert solids settling constant	k_{sett}^{int}	1/day
Bacterial solids settling constant	k_{sett}^{bact}	1/day

Mass fraction of nitrogen in bacteria	β	unitless
Stoichiometric coefficient of mg/L BOD released per mg/L bacterial solids hydrolyzed	γ	unitless

Half-Saturation Rates		
Variable Name	***Variable***	***Units***
Monod half-saturation coefficient for substrate utilization	k_{sat}^{sub}	mg/L
Monod half-saturation coefficient for oxygen utilization	$k_{sat}^{O_2}$	mg/L
Monod half-saturation coefficient for nitrification of ammonium	$k_{sat}^{NH_4}$	mg/L

4.2.3 Parameter Estimation

Default values for most of the parameters identified in Table 8 were obtained from the literature. The default values are the standard values that are used during the model calculations to obtain the effluent species through the mass balance equations. A complete list of the values used and the resources from which they were obtained is provided in Appendix C. However, several of the values were unable to be obtained through a thorough literature review and had to be estimated. These parameters included oxygen concentration and gamma.

Gamma is defined as the mg/L of BOD released per mg/L fecal solids hydrolyzed. Using the stoichiometric equation for municipal solid waste $C_{10}H_{19}O_3N$ (Rittmann and McCarty, 2001), if all the COD within the feces were hydrolyzed to soluble substrate, the upper limit of gamma would be around 2 mg BOD/mg fecal solids. However, as described in the previous section, influent fecal solids are divided into portions that are able hydrolyzed by bacteria and recalcitrant portions that are not hydrolyzed. The inert solids contribute to the overall COD, but do not contribute to the BOD. Furthermore, as described in Chapter 2, BOD measures only that portion of the biodegradable COD that is oxidized in 5 days.

Therefore, the practical value of gamma is considerably lower than 2. Since a standard number could not be found, the gamma default value was set to 1.0 mg BOD/mg fecal solids.

The solids that settled to the bottom of the tank, and therefore removed from the effluent waste stream, was calculated as an equivalent concentration of nitrogen. Calculations were based upon stoichiometric equations for municipal solid waste ($C_{10}H_{19}O_3N$, 7% nitrogen by mass) and bacterial cells ($C_5H_7O_2N$, 12% nitrogen by mass) (Rittmann and McCarty, 2001). Fecal and bacterial solids within the WWTS were multiplied by the settling constants and the referenced percent nitrogen by mass to obtain the equivalent concentration of nitrogen.

The extent of the anaerobic or anoxic environment within the biodigesters has been identified as an uncertain parameter, and will be discussed in greater detail within Section 4.3. However, the default value for the concentration of oxygen was set at 0.5 mg/L for the model equations.

Due to the variation of the number of daily visitors and total system volume, each Caye had specific default values for the flow rate and hydraulic retention time. The number of visitors was based upon SEA Belize Reports and interviews for Luis Garcia from Eco-Friendly Solutions (SEA Belize, 2010a, 2010b; Garcia, 2016). The site-specific default values are presented in Table 9. In general, the flow rate per visitor was based upon each visitor using the toilet once and flushing one gallon (3.78 L) of water into the WWTS.

Table 9: Default Parameters Used for Little Water, Laughing Bird, and Silk Caye

	Little Water Caye	**Laughing Bird Caye**	**Silk Caye**
Number of Visitors per Day	25	50	20
Flow Rate per Visitor (L/day)	3.78	3.78	3.78
Flow Rate (L/day)	95	189	76
Hydraulic Retention Time (days)	31	7	16

4.2.4 Corrections for Saline-Based WWTS

The WWTS at Laughing Bird and Little Water Caye function on saltwater, as previously discussed in Chapter 3. However, the extent of saline concentration of the WWTS on the Cayes is unknown. The salinity of seawater is estimated as 3.5 percent by mass (Rozen and Belkin, 2005). An assumption was made that the overall concentration within the WWTS was 2 percent salinity since the data found in the literature was between fresh water (zero) and 4 percent salinity; making 2 percent salinity the median salinity of the data. The 2 percent salinity was used as the default salinity for the WWTS at Laughing Bird and Little Water Caye. With the use of 2 percent salinity, the default values identified in Appendix C also needed to be modified.

Nitrifying bacteria and the overall process of anaerobic biodegradation are sensitive to environmental factors, including the concentration of salinity (Moussa *et al.*, 2006). The model equations presented above do not directly account for the change in performance due to the use of seawater. Instead multiple parameters used in the equations are changed due to salt concentrations. These parameters that are sensitive to the concentration of salinity include: k_{sett}^{int}, μ_{max}^{bact}, μ_{max}^{nit}, b, k_{sett}^{fec}, $k_{sat}^{NH_4}$, Y, $k_{hydro}^{\prime fec}$, $k_{sat}^{NO_3}$, k_{sat}^{sub}, $k_{sat}^{O_2}$, and k_{sett}^{bact}.

A sensitivity analysis was performed on the parameters to determine which had the most significant impact to the overall model output, and thus needed to be changed for Laughing Bird and Little Water Caye. The overall procedure of a sensitivity analysis is presented in Section 4.3. For this particular analysis, parameters were varied from 50 percent to 150 percent of their default value. The mass balance equations were run on the changed values to determine the variation of the four output parameters X_{OUT}^{fec}, S_{OUT}, NH_4^{OUT}, and NO_3^{OUT}. The analysis indicated that the six parameters that had the greatest effect on predicted effluent were:

- Maximum bacterial growth rate (μ_{max}^{bact})
- Maximum degradation rate for nitrification process (μ_{max}^{nit})
- Death Rate (b)
- Yield (Y)
- Fecal hydrolysis rate coefficient ($k_{hydro}^{\prime fec}$)
- Bacterial settling constant (k_{sett}^{bact})

Calculations and results of the saline sensitivity analysis are presented in Appendix D. Of the six parameters identified as having a significant impact to the overall model output, four were identified from the literature as changing with increasing salinity. A list of the parameters and their interpreted values is presented in Table 10.

Wu et al. (2008) indicated that the glucose utilization rate decreased by approximately 30% when increasing salinity from zero to 4 percent. Uygur and Kargi (2004) came to analogous conclusions. Interpreting these studies, the values used from the maximum BOD utilization rate (μ_{max}^{bact}) for Laughing Bird and Little Water Caye were decreased by 30% from the default value in Appendix C when increasing salinity from zero to 4 percent. Similarly, Wu et al. (2008) and Dinçer and Kargi (2001) indicated that the overall rate of nitrification is reduced with increasing salinity. Therefore, the maximum nitrification rate (μ_{max}^{nit}) was also decreased by 30 percent from the default value in Appendix C when increasing salinity from zero to 4 percent.

Dinçer and Kargi (2001) found that increasing salinity from zero to 3 percent increased the death rate constant 220 percent in an activated sludge unit. Therefore the death rate constant was linearly increased by 220 percent from the default value at zero percent salinity to 3 percent, and the slope of the linear increase was extended to 4 percent salinity.

Wu et al. (2008) found that the sludge volume index (SVI) increased by 55% when the salinity was increased from zero to 3 percent. Similarly Moussa et al. (2006) found that increased salt concentrations resulted in better settling characteristics of the nitrifying sludge. Therefore the bacterial settling constant (k_{sett}^{bact}) was linearly increased by 55 percent from the default value in Appendix C when increasing salinity from zero to 3 percent, and the slope of the settling constant was extended to 4 percent salinity.

The dependence of bacterial yield and the fecal hydrolysis rate coefficient on salinity is inconclusive in the literature review and these parameters were left at their default values. Table 10 indicates the default value of a 2 percent saline wastewater, and the corresponding changes to the default values for Laughing Bird and Silk Caye, and are highlighted in bold. These modified values were used during the sensitivity analysis discussed in Section 4.3. The effects of the salinity to the treatment efficiency of the WWTS are also further discussed in Section 4.3.2.

Table 10: Parameters that Change with Salinity in Model for Laughing Bird and Silk Caye (Dinçer and Kargi, 2001; Wu et al., 2008; Abou-Elela et al., 2010; Ye and Zhang, 2010; J. P. Bassin et al., 2011)

	Low				**DEF**				High
Salinity (%)	0.00	0.40	0.80	1.20	1.60	**2.00**	2.40	2.80	3.20	4.00
Maximum bacterial growth rate	10.8	10.21	9.63	9.04	8.46	**7.87**	6.75	5.63	4.51	3.39
Maximum growth rate (nitrification)	0.9	0.73	0.67	0.62	0.57	**0.52**	0.53	0.48	0.43	0.37
Death Rate	0.021	0.024	0.027	0.029	0.032	**0.035**	0.038	0.040	0.046	0.067
Bacterial settling constant	0.96	1.03	1.09	1.16	1.22	**1.29**	1.36	1.42	1.49	1.56

4.3 Sensitivity Analysis

4.3.1 Principles of Sensitivity Analysis

Several parameters of the model have been identified as having unknown or varying values in the WWTS; in particular, parameters of the salinity concentration, oxygen concentration, and the number of visitors using the WWTS per day. A sensitivity analysis was performed on the parameters to determine which of the parameters caused significant impact to the output parameters within the model.

The concentration of oxygen, and thus the extent of the anaerobic or anoxic environment, within the biodigesters has been identified as a parameter that is unknown in the system. Likewise, the number of daily visitors, and thus the system flow rate, was identified as variable during the high and low tourist seasons. Lastly, as previously discussed, Little Water and Laughing Bird Caye use sea water exclusively for toilet flushing. However, the extent of the salinity within the WWTS was uncertain. Therefore the parameters of salinity, oxygen, and number of visitors using the WWTS per day were explored in the sensitivity analysis.

4.3.2 Process of the Sensitivity Analysis

Cho et al. (2004) designed the process for the sensitivity analysis employed in this study. The sensitivity analysis was performed to understand how the changes in real-world parameters would affect the simulation results and to evaluate the different scenarios identified within the three Cayes. The salinity, oxygen concentration, and number of visitors were selected for the sensitivity analysis because these parameters either are known to vary or are difficult to estimate. With all other parameters held at their default values, the target parameters were changed to the minimum and maximum expected values. The values for each parameter are indicated in Table 11. The model results were calculated using the mass balance equations presented in Section 4.2.2. The sensitivity analysis coefficient was determined using Equation 11.

$$SA\ (i) = \frac{|R(i^{max}) - R(i^{min})|}{R(i^{DEF})} \qquad [11]$$

In Equation 11 *i* represents the target parameter, and $SA\ (i, n)$ is the sensitivity analysis coefficient for the model result to the target parameter *i*. $R(i^{max})$ is the predicted model result of the maximum anticipated value of the target parameter, $R(i^{min})$ is the predicted model result of the minimum anticipated value of the target parameter, and $R(i^{DEF})$ the output of the parameters for the default value.

Table 11: Parameters Used in the Sensitivity Analysis with the Minimum, Maximum and Default Values for Little Water, Silk, and Laughing Bird Caye

	Little Water Caye			Laughing Bird Caye			Silk Caye		
Parameters	MIN	DEF	MAX	MIN	DEF	MAX	MIN	DEF	MAX
Number of Visitors per Day (#)	5	25	50	20	50	200	10	20	110
Oxygen with the System (mg/L O_2)	0.1	2.0	3.0	0.1	2.0	3.0	0.1	2.0	3.0
Salinity of System (% by mass in water)	0	2	4	0	2	4	0	2	4

4.4 Use of the Model and Sensitivity Analysis to Fulfill Thesis Objectives

The mass-balance-based model was constructed to accomplish the first objective of this thesis, to predict the performance of the three WWTS based on available operational and water-quality input data. The sensitivity analysis accounts for the variations found in the behavioral data (number of visitors per day), operational (oxygen concentration), and water-quality input data (salinity concentration); and how they may affect the overall removal efficiencies of the WWTS. The effluent parameters of fecal solids, soluble BOD, ammonium, and nitrate generated by the model were used to indicate key removal efficiencies of the WWTS. The predicted model outputs were compared to the gathered performance data (Objective 2) from the December 2015 sampling event. Similarly, the third objective of this thesis was accomplished by comparing the model outputs of the freshwater-based Little Water Caye to the saltwater-based Laughing Bird and Silk Cayes. Objective 3 was further assessed by comparing the results of the salinity sensitivity analysis to the model predictions if Laughing Bird and Silk Caye used freshwater. The sensitivity analysis was utilized to further understand the model-predicted values of the output parameters under the varying conditions that may be occurring in the WWTS.

To fulfill Object 4 of the thesis, the predicted effluent removal efficiencies of Little Water Caye were compared to both the existing treatment systems in other locations and to the regulatory standards of the Florida Department of Environmental Protection (FDEP), Belize Department of Environment (DoE), and the World Health Organization (WHO) recommended guidelines for municipal wastewater. The predicted removal efficiencies of Laughing Bird and Silk Caye were not compared to existing treatment systems in other locations because no saltwater-based decentralized WWTS could be found in a literature review.

CHAPTER 5: MODELING RESULTS AND DISCUSSION

5.1 Predictions from the Model

Variations of effluent fecal solids, soluble BOD, ammonium and nitrate that were predicted through the sensitivity analysis are presented in Table 12. The calculations for the presented results are located in Appendix E.

Table 12: Predicted Model Results of Effluent Parameters from the Sensitivity Analysis

Default Values of the Effluent Wastewater		X_{OUT}^{fec} **(mg/L)**	S_{out} **(mg BOD/L)**	NH_4^{OUT} **((mg/L as N)**	NO_3^{OUT} **((mg/L as N)**
Laughing Bird Caye		2.52	7.12	0.75	62
Little Water Caye		0.05	3.48	0.23	63
Silk Caye		1.98	6.58	0.71	62
Number of Visitors					
Laughing Bird Caye	High	3.61	10.1	1.2	62
	Low	1.98	6.6	0.7	62
	SA	65%	50%	65%	0%
Little Water Caye	High	0.10	3.56	0.23	63
	Low	0.01	3.41	0.25	62
	SA	190%	4%	6%	2%
Silk Caye	High	3.05	8.33	0.9	62
	Low	1.53	6.41	0.7	62
	SA	23%	29%	28%	0%
Oxygen Concentration					
Laughing Bird Caye	High	2.52	182	0.7	62
	Low	3.61	7	46	26
	SA	43%	2465%	5970%	59%
Little Water Caye	High	0.05	24	0.3	63
	Low	0.05	3.28	2.6	61
	SA	3%	581%	1002%	2%
Silk Caye	High	1.98	6.15	0.6	62
	Low	2.37	119	37	31
	SA	20%	1714%	5161%	50%

Table 12 (Continued)

Salinity					
Laughing Bird Caye	High	2.63	9.27	0.8	62
	Low	2.00	3.54	0.2	63
	SA	25%	81%	72%	1%
Silk Caye	High	2.06	8.56	0.7	62
	Low	1.60	3.22	0.2	62
	SA	23%	81%	73%	1%

The second tank in series at Little Water Caye was removed from the final WWTS model. The change is discussed in greater detail in the following sections.

5.1.1 Effect of Number of Visitors

Results from Silk Caye and Laughing Bird Caye indicate that varying the number of visitors from seasonal lows to highs has a moderate impact on the effluent fecal solids and soluble BOD in the effluent. The sensitivity analysis output indicated an approximate 23 to 65 percent variation of effluent fecal solids for Laughing Bird and Silk Caye from the default output results, and a 29 to 50 percent variation of soluble BOD in the effluent. Little Water Caye experienced a 190% increase in the effluent fecal solids and 4 percent increase in the soluble BOD. However, the effluent at the seasonal high was 0.10 mg/L fecal solids and 3.56 mg BOD/L. Results suggest several key differences between Little Water Caye and Laughing Bird/Silk Caye.

The HRT for Silk and Laughing Bird Caye at high visitor rates ranged from 3 to 7 days, respectively. However, the HRT for the WWTS at Little Water Caye remained at over 31 days even during the seasonal high loads. Due to the high HRT within the first partially nitrifying tank in the Little Water Caye WWTS, the soluble BOD in the effluent was removed to the extent that the microbial population in the second tank-in-series was unable to be sustained, negating any additional biological treatment the second tank could provide to the effluent. Interpreting the variance in HRT, the WWTS at Silk and Laughing Bird Caye are underdesigned in terms of treatment efficiency required to meet effluent standards, discussed in Section 5.4.2, for the influent load per day experienced during seasonal high periods of the year. Likewise, considering the second tank is not used during high load periods, the WWTS at Little Water Caye is overdesigned.

As discussed in previous sections, the water used to flush the toilets at Laughing Bird and Silk Cayes is retrieved from the nearby coast. To account for this practice in the model, a salinity of 2 percent was assumed for the water within the WWTS. Results of the model indicate that the WWTS was still able to reduce the BOD and fecal solids in the effluent wastewater but the biological hydrolysis and nitrification rates were reduced relative to the freshwater rates. As a result of the reduced rates, the fecal solids were unable to be hydrolyzed and converted into substrate to the same extent before exiting the WWTS in the effluent. Similarly, the soluble BOD was unable to be consumed to the same extent as a freshwater-based WWTS with a similar HRT. The shorter HRT and reduced biological rates contributed to the lower overall quality of the effluent of Silk and Laughing Bird Cays in comparison to Little Water Caye.

Effluent ammonia concentration of Laughing Bird and Silk Caye increased by upwards of 65 percent with the reduction of HRT. However, the ammonia concentration contributed less than 2 percent of the total nitrogen effluent concentration, making the change negligible to the overall reduction of nitrogen. The model showed a 17 to 25 mg/L reduction of nitrogen from the effluent due to settled solids and the assimilation of the nitrogen into bacteria. However the model consistently predicts across the three WWTS an effluent nitrate concentration between 60 and 63 (mg/L as N, except at oxygen concentrations lower than

5.1.2 Effect of Oxygen Concentration

Graphical results of the predicted effluent fecal solids and BOD as a function of varying oxygen concentration are presented in Figure 10. Results from the sensitivity analysis indicate that a minimum concentration of oxygen is required before the model can predict the effluent BOD concentration. Under the minimum oxygen concentration the predicted soluble BOD within the WWTS (S_{out}) becomes a negative number, indicating the aerobic bacteria are unable to survive under the simulated conditions. The minimum concentration was determined to be between 0.05 and 0.095 mg/L of oxygen. Therefore the minimum oxygen concentration was taken as 0.1 mg/L.

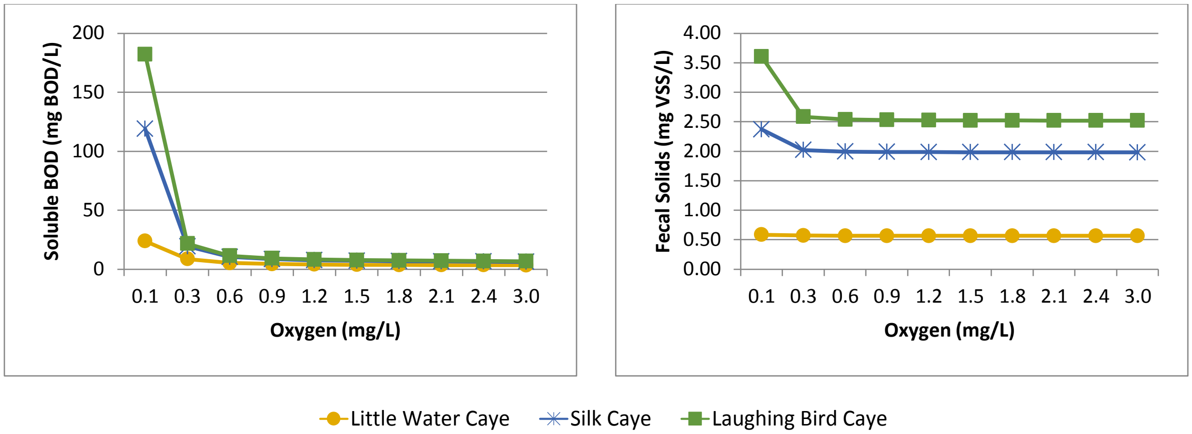

Figure 10: Comparison of Effluent BOD and Fecal Solids between Cayes by Varying Oxygen in the Model

The oxygen concentration within the WWTS had the greatest effect on effluent BOD of the three parameters tested in the sensitivity analysis. Effluent BOD concentrations were reduced from upwards of 182 mg BOD/L to less than 7 mg BOD/L by increasing oxygen concentrations from 0.1 mg/L to 3.0 mg/L of O_2. The concentration of effluent fecal solids did not significantly change with the variance of oxygen concentration. Results indicate that the reduction of effluent BOD could be achieved with a constant flow of oxygen into the WWTS. However graphical results indicate a horizontal asymptote where the increase in oxygen does not reduce effluent BOD to the same degree, signifying a diminishing rate of effluent BOD removal as oxygen concentrations increase.

Figure 11 shows the effluent concentrations of ammonia, nitrate, fecal solids, and bacteria compared to the influent nitrogen removed by solids settling and the total nitrogen entering the system for Laughing Bird Caye by varying oxygen concentration. The presented results are indicative of the overall results observed across the WWTS in all variations of the sensitivity analysis. Model predictions indicate that upwards of 70 percent of incoming nitrogen leaves the WWTS in the wastewater as the nitrate form. The nitrogen removed through the settled solids account for 25 percent of the total nitrogen. The remaining 5 percent is split between the effluent fecal and bacterial solids, and the nitrogen absorbed during bacterial growth in the WWTS.

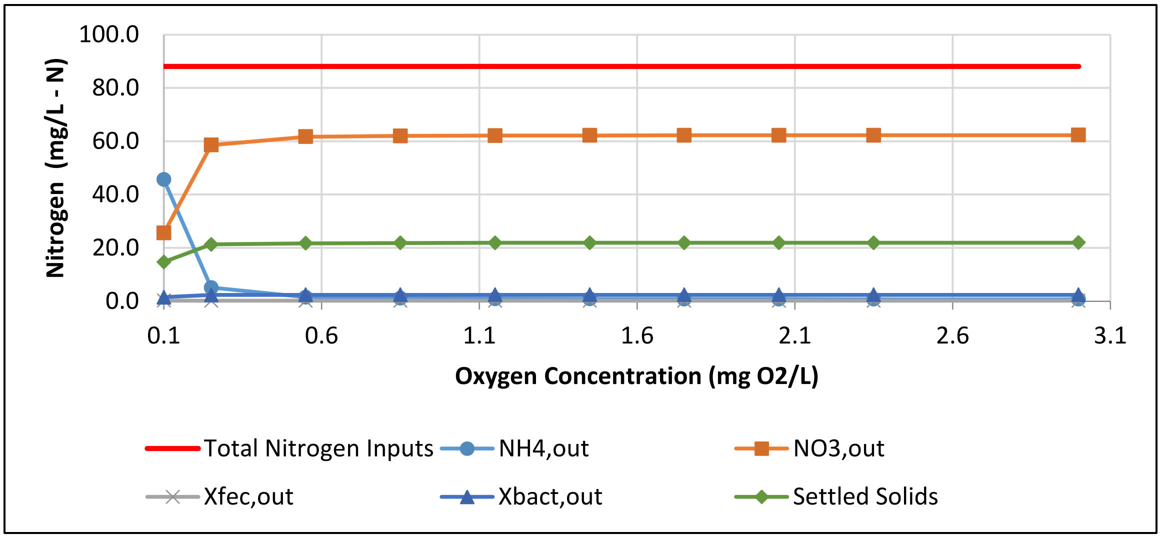

Figure 11: Total Nitrogen Output in Little Water Caye by Varying Oxygen in the Model

5.2 Comparison of Data from the Model to Collected Field Data

The results from the field tests conducted in December of 2015 were inconclusive in most of the parameters predicted in the model. However, the field measurements did indicate that the ammonium in the WWTS was almost fully converted to nitrate in the effluent wastewater, between 85 and 95 percent conversion. These results concur with the effluent data predicted by the model where upwards of 99 percent of the total effluent nitrogen is in the form of nitrate; include the denitrification was not included in the predicted model. These results confirm that the WWTS are operating as a partially nitrifying environment. Table 13 presents a comparison between the field data and the model predictions for the partition between ammonium and nitrate in the effluent wastewater.

Table 13: Partition of Ammonia and Nitrate Concentrations in the Effluent Wastewater for Field Measurements and Model Predictions

		NH_4-N (%)	**NO_3-N (%)**
Silk Caye	Measured	15	85
	Predicted	1	99
Little Water Caye	Measured	8	92
	Predicted	0	100
Laughing Bird Caye	Measured	5	95
	Predicted	1	99

5.3 Comparison of the Performance of Freshwater Based WWTS to Saltwater-based WWTS

During the sensitivity analysis the saline concentration of Laughing Bird and Silk Caye was incrementally changed from freshwater (zero percent salinity) to 4 percent salinity. The predicted model results are depicted in Figure 12. Due to the significant difference of HRT between the Cayes, a comparison between the freshwater-based Little Water Caye and the salt-water-based Cayes was not considered the optimal process to highlight the effects that salinity has on the effluent water quality.

Results of the sensitivity analysis indicate that salinity had a significant effect on the predicted fecal solids and soluble BOD in the effluent. Predicted fecal solids in the effluent increased approximately 60 percent from freshwater conditions to 4 percent salinity in Laughing Bird and Silk Caye. The elevated fecal solid concentration in the effluent lead to seemingly contradictory results; the settling constant was increased with salinity and the effluent concentration of fecal solids increased. Elevated salinity in the wastewater led to an increased water density, which would further cause the effluent fecal solids to float instead of settle. Furthermore, as discussed in Section 2.7 of this thesis, high salt concentrations cause unstable flocs that reduce the settleability (João P. Bassin *et al.*, 2011). However multiple studies have reported similar results as the ones predicted in the model (Dahl *et al.*, 1997; Dinçer and Kargi, 2001; Uygur and Kargi, 2004; Moussa *et al.*, 2006; Cortés-Lorenzo *et al.*, 2015).

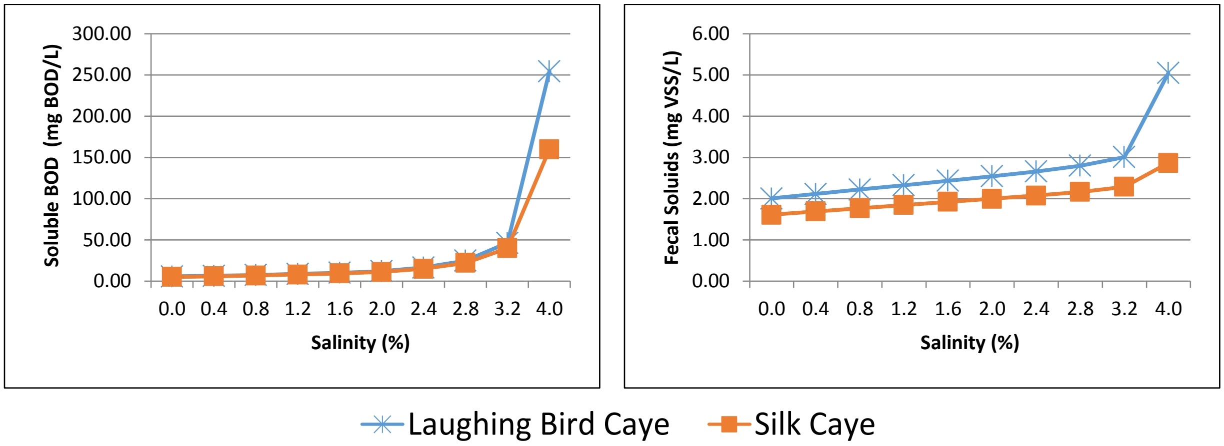

Figure 12: Comparison of Effluent BOD and Fecal Solids between Cayes by Varying Salinity in the Model

Moussa *et al.*(2006) proposed two mechanisms to explain why the settling rate may be greater under saline conditions. Increased water density leads to washout of lighter solids, leaving only the larger flocs in the WWTS. This process would lead to the selection of larger solids that have greater settling characteristics within the WWTS but also lead to higher solids concentrations in the effluent. Secondly, the increased solid size may also be caused by the electrostatic and hydrophobic interactions occurring between the flocs. Increased salinity in the wastewater could reduce the electric double layers surrounding the individual particles, and thereby reduce the overall repulsive force between them. The microbial aggregates would then be able to come close enough to form larger floc sizes.

Effluent BOD concentration increased strongly with increasing salinity. The increase in concentration is due to the major reduction of substrate-consuming-bacteria by cell-die-off. The model predicts that a significant increase in the cell die-off begins to occur at 2.4 percent salinity. This prediction concurs with the results reported by Wu *et al.* (2008), who observed a similar die-off occurring at 3 percent salinity. This die-off could have significant effects on the effluent water quality. The water salinity within the WWTS of Laughing Bird and Silk Caye was assumed to be 2 percent, a dilution from the urine combined with the 3.5 percent saline concentration of seawater. However, small variances in the saline concentration above the assumed 2 percent saline concentration could significantly reduce the BOD treatment within the WWTS.

5.4 Compare Performance of Freshwater Based WWTS to WWTS in the Literature

5.4.1 Comparison of Results to Decentralized WWTS in Brazil

The predicted effluent of the Little Water Caye WWTS was compared to 166 wastewater treatment plants operating in Brazil. Oliveira and von Sperling (2011) compared decentralized WWTS comprising of six different treatment processes: septic tank and anaerobic filter, facultative pond, anaerobic pond and facultative pond, activated sludge, UASB reactors alone, and UASB reactors followed by post-treatment. A comparison between the results of the predicted effluent of Little Water Caye and the other WWTS is presented in Table 14. For comparison to the WWTS, the effluent total suspended solids (TSS) was calculated as the sum of the three calculate effluent solid fractions (inert, fecal, and bacterial) tracked in the model.

Table 14: Comparison Between the Removal Efficiency of the Predicted Effluent of Little Water Caye and Field Tests Conducted on Six Different Type of Decentralized WWTS in Brazil (Oliveira and von Sperling, 2011)

	Little Water Caye	**Septic Tank and Anaerobic Filter**	**Facultative Pond**	**Anaerobic Pond and Facultative Pond**	**Activated Sludge**	**UASB Reactors Alone**	**USB and Post Treatment**
BOD Removal Efficiency (%)	99	59	75	82	85	72	88
TSS Removal Efficiency (%)	91	66	48	62	76	67	82
TN Removal Efficiency (%)	22	24	44	39	50	-13	-

Comparison between Little Water Caye and the decentralized WWTS in Brazil indicate that the predicted removal efficiencies of total suspended solids and soluble BOD at Little Water Caye are higher than the measured efficiencies of the WWTS. However, the total nitrogen removal efficiency for Little Water Caye is the lowest of the WWTS at only 22 percent removal. A possible explanation for the low removal of nitrogen could be that the model did not account for the denitrification that occurs in the semi-anaerobic biodigester, and thus have over-estimated the effluent nitrogen. However, the reduction of nitrogen from the denitrification would probably not significantly affect the overall results.

The comparison between the WWTS illustrates that the predicted removal efficiency of BOD and TSS solids is most likely less in the actual measurement than predicted value from the model. The nitrogen removal in the WWTS at Little Water Caye appears to be on par with the other WWTS. Considering the configuration of the WWTS at Little Water Caye most closely resembles a septic tank, the difference of 2 percent in the removal efficiency is reasonable.

5.4.2 Comparison of Results to Regulatory Standards

Predicted effluent water quality parameters of Little Water Caye were compared to the regulatory standards of the Florida Department of Environmental Protection (FDEP), Belize Department of Environment (DoE), and the recommended guidelines World Health Organization (WHO) for municipal wastewater. The results of the comparison are presented in Table 15.

Predicted effluent BOD was found to be below regulatory standards for all three organizations. The TSS was similarly below standards for the Belize DoE and the WHO. However, standards for the nitrogen species and total nitrogen were significantly above regulatory levels. Total nitrogen levels in the Little Water Caye are 20 times the standard set by the FDEP

Table 15: Comparison of Predicted Effluent of Little Water Caye to Regulatory Effluent Standards of the FDEP and BoE, and Guidelines of the WHO

	Little Water Caye	FDEP	Belize DoE (Schedule II and II)	WHO (Class I)
BOD (mg/L)	3.5	5	30	2
TSS (mg/L)	15	5	30	25
Nitrate (as NO_3^-)	62.6	-	3	-
Ammonia (as NH_4^+)	0.3	-	1	-
Total Nitrogen (mg/L as N)	66.3	3	-	0.3

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CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

The decentralized WWTS constructed on Laughing Bird Caye (LBC), Silk Caye (SC), and Little Water Caye (LWC) by Eco-Friendly Solutions were evaluated based on operational and water-quality input data to understand the environmental and public health impacts of the systems. A model of the predicted outputs was composed and analyzed in Chapter 5 of this thesis. Results of the model were compared to the saltwater-based systems of Laughing Bird and Silk Caye and compared against the decentralized WWTS found in the literature.

Results indicate that the removal efficiency for three of the four predicted effluents were lower in the freshwater-based WWTS at LBC than the saltwater-based WWTS at SC and LBC. Oxygen was the most important parameter for the effluent concentrations of soluble BOD, ammonium, and nitrate. The number of visitors was the most significant parameter for the effluent concentration of fecal solids.

The overall goal of this thesis is to provide recommendations to the currently installed WWTS in the Cayes to improve the environmental and public health impacts of the systems.

6.1 Recommendations for the Modeling of the WWTS

The objective of the constructed model for the WWTS in the Cayes of Belize was to estimate the treatment efficiency of the biological oxygen demand, effluent fecal solids, and nutrients—particularly nitrogenous species. The analysis performed in this thesis was an initial iteration of the evaluation of the WWTS. However, several additional steps should be done to further develop a more accurate model of the WWTS. Below are the major recommendations to promote the model accuracy.

6.1.1 Include Effluent Treatment by the Soil Adsorption System (SAS)

As stated in Chapter 2, the SAS is an important treatment component that utilizes the natural biochemical processes in the soil to assimilate and treat the various contaminants. As the wastewater effluent flows through the soil pores, it becomes treated by means of filtration, sedimentation, chemical absorption, and biological reactions. In particular is the additional treatment of the nutrients where the vadose zone features several benefits that aid in the denitrification process and where the principal removal mechanisms of phosphate occurs. The WWTS at LBC and LWC were constructed with a form of a SAS that would further treat the wastewater before entering the surrounding ocean waters.

Research has found that modeling the effluent treatment by the SAS and soil infiltration yield varying results that are difficult to predict (Beal *et al.*, 2006). The treatment systems constructed on the Cayes would be particularly difficult to test due to the original design of Eco-Friendly Solutions and the high infiltration rates of the sands that compose the soils on the Cayes. Due to these constraints, a valid set of equations for modeling were unable to be included in the confines of this Thesis. However, an individual study of the SAS on the Cayes would provide a more accurate indication of the treatment efficiencies of the WWTS.

6.1.2 Produce Better Site-Specific Data

Several important parameters were assumed from other decentralized WWTS in the rural areas of Brazil due to the incomplete water quality data obtained for the Cayes (Peters, 2003; Oliveira and von Sperling, 2011). Although the data was considered sufficient for the initial evaluation of the model, the use of data that is not site specific leads to inherent inaccuracies in the predicted effluent quality. A system of calibration and validation steps should be included in the further development of a model.

A model calibration is defined as the adaptation of the model to fit a certain set of information obtained from the WWTP under study (Petersen and Vanrolleghem, 2002). With a calibration procedure, all parameters of the model which can be based upon analytical measurements, and have significant influence to the simulation results, can be adjusted. The goal of which is to fit the effluent water quality results with the observed WWTS characteristics within a defined accuracy (Langergraber *et al.*, 2004). Similarly, validation is the process of demonstrating that the WWTS model can make sufficiently accurate predictions (Refsgaard, 1997). Through the sensitivity analysis performed on in this thesis, the parameters that had significant impacts on the predicted effluent were determined for both the freshwater and saltwater systems. Table 16 presents a list of the suggested calibration and validation parameters for the site specific data.

Table 16: Suggested Calibration and Validation Parameters for Modeling Little Water, Laughing Bird, and Silk Caye

Little Water Caye (Freshwater WWTS)		**Laughing Bird and Silk Caye (Saltwater WWTS)**	
Suggested Calibration Parameters	***Suggested Validation Parameters***	***Suggested Calibration Parameters***	***Suggested Validation Parameters***
• Oxygen Concentration • Influent Total Nitrogen	• Effluent Ammonia and Nitrate Concentration	• Number of Visitors • Salinity	• Bacterial Settling Constant • Effluent

Utilizing the listed parameters during the calibration and validation process would allow the site-specific data obtained to be used and create a more accurate model. Langergraber *et al*. (2004) presented a 9-phase guideline to performing a study with calibration and validation checks that could be used to create the procedures.

6.1.3 Install Sampling Ports at Specific Locations on the WWTS

As stated in the previous section, several important parameters were assumed due to the incomplete water quality data obtained. Additionally, samples were not collected in the optimal locations within the WWTS to obtain the relevant site-specific data that would lead to more accurate predictions of the developed model. The SEA Operation and Maintenance Recommendations Report details the data collection sample points (Prouty, 2015). The installation of ‘sampling ports’ at strategic locations of the WWTS is recommended to obtain the necessary site-specific data. At a minimum sampling port should be installed at the influent pipe, effluent pipe, and active zone of the semi-anaerobic biodigester. The active zone for this recommendation is the treatment zone above the settleable solids and below the aerobic filter.

6.2 Recommendations for Improving Effluent Water Quality of the WWTS

The WWTS on the Cayes were constructed to mitigate the impacts of the wastewater produced by visitors on the general health of the pubic and the environment. Considering the reports of the eutrophication affecting the coral reefs surrounding the Cayes, the WWTS have largely failed in at least one aspect of their purpose. The effluent water quality from the model confirms that high concentrations of nitrogen are entering the surrounding ocean habitat as ammonia and nitrate.

In light of the failings of the WWTS, changes must be made to further protect the surrounding coral reef habitat from the excess nutrients of the wastewater. As stated in Chapter 3, significant constraints are placed on the WWTS constructed on the Cayes that affect the feasibility of the recommendations. The Southern Environmental Association (SEA Belize) has repeatedly indicated that capital investment costs are a significant impediment to changes in the current WWTS. Rangers from SEA Belize are responsible for the regular maintenance of the three wastewater treatment systems, representing a limited expertise in the maintenance of the systems. Additionally, environmental characteristics affect the type of system that is implemented. Erosion of the shoreline continuously occurs within the Cayes; meaning that a leachfield reconstructed in the center of the Caye will in time be next to the shoreline again. With the exception of Little Water Caye, the average size of the Caye is less than 4,000 m^2; leaving little room for the WWTS and magnifying the affect any insects or odor would have on the general experience of the public. Lastly, the soils of the Cayes are comprised of poorly graded sand, as with most beaches and coastlines, which can have horizontal infiltration rates of more than 100 meters per day (Houston *et al.*, 1999). The high infiltration rates indicate that the leachfield and SAS treatment may not have sufficient residence time to effectively treat the effluent wastewater before it is flushed out into the surrounding ocean environment.

The challenge is to develop recommendations that are effective at minimizing the effect of the wastewater treatment systems as well as remaining feasible options in reference to the constraints. To achieve these two objectives, the recommendations have been separated into three input categories: Low, Medium, and High. Table 17 present the recommendations in their specific category. The label of low, medium, and high indicate the required level of input to realize the recommendation. The input includes the capital cost and labor of the change, the level of buy-in from the users of the system, and the resulting maintenance requirements.

Table 17: Recommendations for Laughing Bird, Little Water, and Silk Caye Based upon the Required Low, Medium, and High Input Parameters

Low Input Requirements	***Medium Input Requirements***	***High Input Requirements***
• Repair rock clarifier at LBC • Install drainfield at SC near the center of the Caye • Purge solids from the WWTS at least once a year • Provide training to the rangers on proper WWTS maintenance	• Install Urine Separation Toilets	• Replace WWTS for new, more efficient design

6.2.1 Low Input Requirements

The low input requirement recommendations are characterized by small changes that can be made to the WWTS that would improve the current treatment efficiency. The improvements will help the systems to perform more efficiently, but will not be able to mitigate the main issues of nutrient eutrophication surrounding the WWTS. However, the recommendations are easily obtainable with little capital costs (estimated at less than $2000) and a minimal amount of buy-in from the users of the WWTS.

6.2.2 Medium Input Requirements

The installation of urine separation toilets is a relatively simple solution to mitigate the effluent nutrient problem. Approximately 90 percent of nitrogen, and 50 percent of phosphorus, in black wastewater is from urine (Montangero and Belevi, 2007a). A significant reduction of nutrients could be achieved by separating the urine at the source instead of all urine remaining diluted in the wastewater. Studies on urine separation in centralized and decentralized WWTS have shown a reduction of nutrient loads in the effluent and increased treatment efficiencies for BOD (Wilsenach and Van Loosdrecht, 2003; Halabi and Hamed, 2005; Guest *et al.*, 2009).

Additionally, urine separation is a method to create a resource recovery system (RR) from the already constructed WWTS. Urine has been proven to be a low cost and effective fertilizer for crop production around the globe (Etter *et al.*, 2011; Andersson, 2015; Ranasinghe *et al.*, 2016). Through the implementation of urine separation toilets, upwards of 1,700 gallons of liquid fertilizer could be produced per year at no additional cost.

The required capital cost of implementing a urine separation toilet system in the each Caye is minimal (an estimated cost of under $300 for the toilet and the required buckets). However, the medium input requirement stems from the buy-in required by the users of the Cayes. Boat Captains that visit the Cayes daily use small boats that are unable to transport large quantities of urine back to the mainland. Additionally rangers visit the caye approximately once a week, meaning there exist significant constraints on the two users that would need to participate in a urine separation program.

To understand the required buy-in and scale of a urine separation system. Initial calculations of the urine production levels and means of removing the urine were created, and are presented in Appendix E. The average human produces 30 – 80 ml of urine per hour (A.D.A.M. Medical Encyclopedia, 2017). Assuming that the average visitor stays at one of the Cayes for 3 hours, produces an average of 60 ml of urine per hour, and number of estimated visitors introduced in Chapter 4, Table 18 presents the accumulation of urine at the Cayes with 100 percent urine collection.

Table 18: Accumulation of Urine (Gallons) by Implementing a Urine-Separation Toilets

	Laughing Bird Caye			**Little Water Caye**			**Silk Caye**		
	Low	***Def***	***High***	***Low***	***Def***	***High***	***Low***	***Def***	***High***
Number of Visitors	20	50	200	5	25	50	10	20	110
Accumulation Per Hour	0.31	0.77	3.09	0.08	0.39	0.77	0.15	0.31	1.70
Accumulation Per Day	0.9	2.3	9.3	0.2	1.2	2.3	0.5	0.9	5.1
Accumulation Per Week	6	16	65	2	8	16	3	6	36

During peak usage of the cayes, and using a 2.5 gallon container, boat captains would be required to transport a total of four, one, and two containers per day from Laughing Bird, Little Water, and Silk Caye, respectively. This method seems to be the most feasible. If rangers were required to remove the urine once a week, upwards of fifteen 5-gallon buckets would need to be collected at Laughing Bird Caye alone during peak seasons. However, it should be noted that when performed correctly, little to no insect or odor issues arise from the collection and storage of urine (Flores *et al.*, 2009), meaning the accumulation of containers could occur during peak times without negative impacts to the experience of the general public on the Cayes.

6.2.3 High Input Requirements

The highest input requirement would be the construction of a new WWTS at each Caye. To effectively remediate the effluent nitrogen concentration, the new WWTS would require a combination of biological nitrification and denitrification. Both nitrification and denitrification can be mediated by suspended-growth or attached-growth processes, which have been achieved in decentralized WWTS through the use of a sequencing batch reactor (SBR) (Oakley *et al.*, 2010).

Several alternative WWTS were considered for the implementation at the Cayes, many of the alternatives are described in Chapter 2. However, the limited space constraints in conjunction with minimal expertise in maintenance reduced the viable options, and eventually lead to the SBR being considered the optimal choice for a new WWTS. SBRs have gained interest in the treatment of wastewater due to the simple configuration and flexibility as a treatment process (U.S. Environmental Protection Agency (USEPA), 1999). Multiple studies have proven the success of SBRs in low- and medium-income countries to consistently treat wastewater to high effluent qualities (Al-Rekabi *et al.*, 2007; Nelson and Murray, 2008; Kalbar *et al.*, 2012; Avery *et al.*, 2014). Run as a batch or continuous operation, SBR use aeration and mixing to achieve high effluent qualities. Under HRTs of 12 to 24 hours, studies have shown total kjeldahl nitrogen removal efficiencies of 50 to 85 percent (Mahvi *et al.*, 2004; Al-Rekabi *et al.*, 2007; Fernandes *et al.*, 2013). A list of advantages and disadvantages are provided in Table 19.

Table 19: Advantages and Disadvantages of an Sequencing Batch Reactor (U.S. Environmental Protection Agency (USEPA), 1999)

Advantages	***Disadvantages***
• Minimal footprint requirement, requiring only one reactor • Low HRT time • Operating flexibility and control to help in maximum removal of nutrients	• Higher level of sophistication is required for the initial implementation compared to conventional systems • Higher level of maintenance • Potential plugging of aeration devices

Although an SBR WWTS would be capable of treating the high nitrogen concentrations in the effluent wastewater, the capital cost would be significant for the implementation. Additionally, high user buy-in would be required by the rangers to learn how to properly maintain the WWTS. Electricity for the aeration pumps could come from a solar cell.

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APPENDIX A: PHOTOGRAPHS OF THE WWTS AND GENERAL CONDITIONS OF THE THREE CAYES

A-1. Laughing Bird Caye

Figure A-1: Semi-Anaerobic Biodigester (Black) and Upflow Rock Clarifier (White) at Laughing Bird Caye (Photo taken by Christine Prouty)

Figure A-2: Upflow Rock Clarifier at Laughing Bird Caye (Photo taken by Christine Prouty)

Figure A-3: Inside of Upflow Rock Clarifier at Laughing Bird Caye (Photo taken by Christine Prouty)

Figure A-4: Leach Field with Native Plants at Laughing Bird Caye (Photo taken by Christine Prouty)

A-2. Little Water Caye

Figure A-5: Semi-Anaerobic Biodigesters in Series at Little Water Caye (Photos taken by Christine Prouty)

Figure A-6: Leach Field with Crushed Conch Shells at Little Water Caye (Photos taken by Christine Prouty)

Figure A-7: Distribution System from Ranger Facility to WWTS at Little Water Caye (Photo taken by Christine Prouty)

A-3. Silk Caye

Figure A-8: Wastewater Treatment System at Silk Caye (Photo taken by Christine Prouty)

Figure A-9: Inside of Semi-Anaerobic Biodigester at Silk Caye (Photo taken by Christine Prouty)

Figure A-10: PVC Pipe of Soak Away Close to Shoreline at Silk Caye (Photo taken by Christine Prouty)

Figure A-11: Chlorine Contact Chamber (Without Tablets) at Silk Caye (Photos taken by Christine Prouty)

Figure A-12: Picture of Silk Caye (Photo taken by Christine Prouty)

APPENDIX B: LIST OF ACTIVITIES AND INDIVIDUAL TESTS PERFORMED AT LAUGHING BIRD, LITTLE WATER, AND SILK CAYE

The information in this Appendix was taken from SEA Operation and Maintenance Recommendations Report by Christine Prouty (September 2015). The writer does not claim any of the information in this Appendix is his original work. Permission to republish the relevant information was given by Christine Prouty on June 4, 2016.

B-1. Water Quality Parameters Tested

- BOD_5
- *Enterococci*
- *E. coli*
- Total Coliforms
- Nitrates (NO_3^-)
- Phosphates (PO_4^{3-})

B-2. Wastewater Sampling Methods

Separate grab samples were collected at the same time but in various locations along the wastewater treatment chain. The justification for this protocol was to give a step-wise picture of the change in water quality parameters throughout the treatment process. Consequently, the order of the sampling locations should be tested in such a way that the materials are used to sample the cleanest location first, continuing through to the dirtiest (closest to the influent) last.

Wastewater samples were collected in a few different ways. First, if there was access to the top of the biodigester and/or filter, the ladle was used to dip out wastewater samples and pour the contents into sterilized 500 mL plastic water bottles. Afterwards, the samples were stored in an ice chest.

In the instance when the volume of wastewater in the biodigester was too low, and could not be accessed from the top of the tank, a plastic bag with a sliding lock was secured over the evacuation valve.

This is the valve on the side of the tank that is responsible for emptying the digested sludge. The valve was slowly turned to the “open” position to evacuate the sludge until the gallon sized bag was filled approximately halfway full. The valve was then returned to the off position and the digested sludge was poured into the sterilized 500 mL plastic water bottles and stored on ice.

Finally, given the situation when a leachfield pipe was exposed and provided the opportunity to directly collect the effluent, the sample bottle held under the exposed pipe without making contact. If space was a limiting factor, a sterilized bottle was cut in half and maneuvered under the exposed pipe to collect small amounts of the effluent to pour into another sterilized container. In a consistent manner as the other scenarios, the sample was then stored on ice.

B-3. Sampling Limitations

During the execution of the study, there were multiple factors that influenced the location, method, number, and volume of samples that were taken from each field site including (1) restricted access to parts of the systems, (2) limited resources at the laboratory to conduct the tests, and (3) recent sludge harvesting resulting in sample volumes too small for testing.

B-4. Processing Samples

When possible, the researcher requested that, for each sampling point, all of the water quality parameters listed be systematically tested using consistent procedures. However, occasional limitations were encountered resulting in alterations to the sampling protocol or laboratory tests that were conducted. Consequently, these changes were noted in the field log for each site.

B-5. Data Collected

Table B-1: Ammonia, Nitrate, and Total Nitrogen Collected at the Three Cayes in December 2015

			Considering Dilutions		Considering Dilutions		Considering Dilutions
Sample Type	Sample Location	NH$_3$-N (mg/L)	NH3-N (mg/L)	N0$_3$-N (mg/L)	N03-N (mg/L)	**TN**	**TN**
				Silk Caye			
surface water	SC 1A	-0.07	-0.7	85.2	852	**0.731**	7.31
	SC 1B	-0.06	-0.6	76.6	766	**2.25**	22.5

Table B-1 (Continued)

	SC 2A	-0.05	-0.5	68.2	682	**0.609**	6.09
	SC 2B	-0.01	-0.1	81.6	816	**0.826**	8.26
	SC 3A	-0.05	-0.5	82.4	824	**0.874**	8.74
	SC 3B	-0.01	-0.1	95.4	954	**0.585**	5.85
	SC 4A	-0.05	-0.5	75.8	758	**0.487**	4.87
	SC 4B	-0.03	-0.3	84.8	848	**0.707**	7.07
	SC 5A	-0.01	-0.1	71.2	712	**0.567**	5.67
	SC 5B	-0.04	-0.4	78.2	782	**8.85**	88.5
	SC 6A	0.01	0.1	80.2	802	**1.42**	14.2
	SC 6B	-0.03	-0.3	70.8	708	**0.854**	8.54
wastewater	SC 7A	911.31	9113.1	192.3	1923	**6.44**	64.4
	SC 7B	361.07	3610.7	203.2	2032	**8.04**	80.4
				Little Water Caye			
brackish well	LW 1A	n/a	n/a	77.9	779	**2.21**	22.1
	LW 1B	n/a	n/a	75.9	759	**1.34**	13.4
wastewater	LW 3A	912.8	9128	99.6	996	**3.94**	39.4
	LW 3B	996.43	9964.3	93.3	933	**2.92**	29.2
				Laughing Bird Caye			
surface water	LB 1A	0	0	91.0	910	**1.43**	14.3
	LB 1B	0.04	0.4	83.2	832	**1.6**	16
	LB 2A	-0.05	-0.5	92.8	928	**1.49**	14.9
	LB 2B	-0.02	-0.2	77.9	779	**-1.34, and -0.654**	13.4
	LB 3A	-0.02	-0.2	76.8	768	**1.00**	10
	LB 3B	0.02	0.2	82.1	821	**3.46**	34.6
	LB 4A	-0.01	-0.1	84.8	848	**1.1**	11
	LB 4B	-0.03	-0.3	83.5	835	**1.37**	13.7
wastewater	LB 8A	651.67	6516.7	1016.2	10162	**1.15**	1150
	LB 8B	381.83	3818.3	974.3	9743	**0.299**	299
	LB 9A	626.39	6263.9	1209.6	12096	**0.211**	211
	LB 9B	464.02	4640.2	1247.6	12476	**0.275**	275

APPENDIX C: PARAMETER NAME, SYMBOL, UNIT, VALUE AND RESOURCE USED IN MODELING EQUATIONS FOR THE SENSITIVITY ANALYSIS

Table C-1: Parameter Name, Symbol, Unit, Value and Resource Used in Modeling Equations for the Sensitivity Analysis

Variable Name	Variable	Value	Units	Source
Influent inert concentration	X_{IN}^{int}	60	mg/L	(Rittmann and McCarty, 2001)
Inert settling constant	k_{sett}^{int}	0.1	1/day	(Woo, 2012)
Hydraulic retention time	θ	Variable	day	Calculated from model
Influent fecal concentration	X_{IN}^{fec}	100	mg VSS/L	(Rittmann and McCarty, 2001)
Fecal settling constant	k_{sett}^{fec}	0.96	1/day	(Struck et al., 2008)
Yield	Y	0.4	mg VSS / mg BOD	(Rittmann and McCarty, 2001)
Fecal hydrolysis rate coefficient	$k_{hydro}^{\prime fec}$	0.82	L/mg*day	(Bhunia and Stenstrom, 1986)
Influent substrate concentration	S_{IN}	420	mg BOD/L	(Rittmann and McCarty, 2001;WERF, 2009)
Substrate half saturation	$K_{half\ sat}^{sub}$	25	mg/L	(Ergas and Aponte-Morales, 2014)
Bacterial settling constant	k_{sett}^{bact}	0.96	1/day	(Struck et al., 2008)
Flow Rate	Q	variable	L/day	Calculated from model
Maximum bacterial growth rate	$\mu_{max}^{bact\ gro}$	10.8	1/day	(Rittmann and McCarty, 2001)
Portion of the Rate coefficient for the nitrification process	μ_{max}^{N}	0.9	1/day	(Ergas and Aponte-Morales, 2014)
Death rate	b	0.13	1/day	(Ergas and Aponte-Morales, 2014)
Influent ammonia concentration	NH_4^{in}	78	mg/L	(Oliveira & von Sperling 2011)
Monod half-saturation coefficient for nitrification of ammonium	$k_{sat}^{NH_4}$	1.1	mg/L	(Ghimire, 2012)
Influent nitrate concentration	NO_3^{in}	3	mg/L	(Henze and Comeau, 2008)
Monod half-saturation coefficient for nitrification of ammonium	$k_{sat}^{NO_3}$	0.26	mg/L	(Ghimire, 2012)
Oxygen concentration	O_2	2	mg/L	ASSUMED

.

Table C-1 (Continued)

Monod half-saturation coefficient for oxygen utilization	$k_{sat}^{O_2}$	0.37	mg/L	(Ghimire, 2012)
Stoichiometric coefficient	α	0.07	unitless	(Rittmann and McCarty, 2001)
Mass fraction of nitrogen in fecal solids	β	0.12	unitless	(Rittmann and McCarty, 2001)
Stoichiometric coefficient of mg/L BOD released per mg/L bacterial solids hydrolyzed	ɣ	1	unitless	ASSUMED

APPENDIX D: CALCULATIONS AND RESULTS OF THE SALINE SENSITIVITY ANALYSIS

Table D-1: Calculations of the Saline Sensitivity Analysis

Variable:	k_{sett}^{int}	
	Low (50%)	High (150%)
	0.05	**0.15**

Effluent inert Solids concentration

Variable X_{OUT}^{int}

Equation $\frac{X_{IN}^{int}}{(1+k_{sett}^{int}\theta)}$

	Low (50%)	High (150%)	
X_OUT^int	49.0	35.8	mg/L

Effluent Fecal Solids Concentration

Variable X_{OUT}^{fec}

Equation $\frac{X_{IN}^{fec}}{\left(1+k_{sett}^{fec}\theta\right)+\left(k'^{fec}_{hydro}X_{OUT}^{bact}\theta\right)}$

	Low (50%)	High (150%)	
X_OUT^fec	2.76	2.76	mg/L
	2.76	2.76	Solver equation

Effluent substrate concentration

Variable S_{OUT}

Equation $\frac{\left[\left(k_{sat}^{sub}\right)\left(\theta b+\theta k_{sett}^{bact}+1\right)\right]}{\left[\theta\mu_{max}^{bact}\left(\frac{O_2}{O_2+k_s^{O_2}}\right)-\theta b-\theta k_{sett}^{bact}-1\right]}$

	Low (50%)	High (150%)	
S_OUT	4.20	4.20	mg BOD/L

Effluent bacterial Solids Concentration

Variable X_{OUT}^{bact}

Equation $\frac{S_{in}-S_{out}}{\left(\theta\left(\frac{1}{Y}\right)\mu_{max}^{bact}\left(\frac{O_2}{O_2+k_s^{O_2}}\right)\left(\frac{S_{out}}{S_{out}+k_{sat}^{sub}}\right)\right)-\left(\gamma k'^{fec}_{hydro}X_{out}^{fec}\theta\right)}$

	Low (50%)	High (150%)	
X_OUT^bact	28.65	28.65	mg VSS/L

Equations for Nitrogen

Cunningham: Dual monad kinetics

Effluent ammonia concentration

Variable NH_4^{out}

Equation [illegible]

	Low (50%)	High (150%)	
NH4_OUT	132.027	132.027	mg/L

Effluent nitrate concentration

Variable NO_3^{out}

Equation $NO_3^{in}+\theta\mu_{max}^{bact}\left[\frac{NH_4}{NH_4+k_{sat}^{NH_4}}\right]\left[\frac{O_2}{O_2+k_{sat}^{O_2}}\right]X^{bact}\left(\frac{1}{Y}\right)$

	Low (50%)	High (150%)	
NO3_OUT	242	242	mg/L

Table D-1 (Continued)

Variable:	μ_{max}^{N}	
	Low (50%)	High (150%)
	0.45	**1.35**

Effluent inert Solids Concentration

Variable X_{OUT}^{int}

Equation $$\frac{X_{IN}^{int}}{\left(1+k_{sett}^{int}\theta\right)}$$

	Low (50%)	High (150%)	
X_OUT^int	41.4	41.4	mg/L

Effluent Fecal Solids Concentration

Variable X_{OUT}^{fec}

Equation $$\frac{X_{IN}^{fec}}{\left(1+k_{sett}^{fec}\theta\right)+\left(k_{hydro}^{\prime fec}X_{OUT}^{bact}\theta\right)}$$

	Low (50%)	High (150%)	
X_OUT^fec	2.76	2.76	mg/L
	2.76	2.76	Solver equation

Effluent substrate concentration

Variable S_{OUT}

Equation $$\frac{\left[\left(k_{sat}^{sub}\right)\left(\theta b+\theta k_{sett}^{bact}+1\right)\right]}{\left[\theta\mu_{max}^{bact}\left(\frac{O_2}{O_2+k_s^{O_2}}\right)-\theta b-\theta k_{sett}^{bact}-1\right]}$$

	Low (50%)	High (150%)	
S_OUT	4.20	4.20	mg BOD/L

Effluent bacterial Solids Concentration

Variable X_{OUT}^{bact}

Equation $$\frac{S_{in}-S_{out}}{\left(\theta\left(\frac{1}{Y}\right)\mu_{max}^{bact}\left(\frac{O_2}{O_2+k_s^{O_2}}\right)\left(\frac{S_{out}}{S_{out}+k_{sat}^{sub}}\right)\right)-\left(\gamma k_{hydro}^{\prime fec}X_{out}^{fec}\theta\right)}$$

	Low (50%)	High (150%)	
X_OUT^bact	28.65	28.65	mg VSS/L

Equations for Nitrogen

CB33ningham: Dual monad kinetics

Effluent ammonia concentration

Variable NH_4^{out}

Equation [illegible]

	Low (50%)	High (150%)	
NH4_OUT	73.9	190.8	mg/L

Effluent nitrate concentration

Variable NO_3^{out}

Equation $$NO_3^{in}+\theta\mu_{max}^{bact}\left[\frac{NH_4}{NH_4+k_{sat}^{NH_4}}\right]\left[\frac{O_2}{O_2+k_{sat}^{O_2}}\right]X^{bact}\left(\frac{1}{Y}\right)$$

	Low (50%)	High (150%)	
NO3_OUT	120.6	365.0	mg/L

Table D-1 (Continued)

Variable: k_{sett}^{fec}

Low (50%)	High (150%)
0.48	**1.44**

Effluent inert Solids Concentration

Variable X_{OUT}^{int}

Equation $\dfrac{X_{IN}^{int}}{(1 + k_{sett}^{int}\theta)}$

	Low (50%)	High (150%)	
X_OUT^int	41.4	41.4	mg/L

Effluent Fecal Solids Concentration

Variable X_{OUT}^{fec}

Equation $\dfrac{X_{IN}^{fec}}{(1 + k_{sett}^{fec}\theta) + (k'^{fec}_{hydro}X_{OUT}^{bact}\theta)}$

	Low (50%)	High (150%)	
X_OUT^fec	2.90	2.62	mg/L
	2.90	2.62	Solver equation

Effluent substrate concentration

Variable S_{OUT}

Equation $\dfrac{\left[(k_{sat}^{sub})(\theta b + \theta k_{sett}^{bact} + 1)\right]}{\left[\theta\mu_{max}^{bact}\left(\dfrac{O_2}{O_2 + k_s^{O_2}}\right) - \theta b - \theta k_{sett}^{bact} - 1\right]}$

	Low (50%)	High (150%)	
S_OUT	4.20	4.20	mg BOD/L

Effluent bacterial Solids Concentration

Variable X_{OUT}^{bact}

Equation $\dfrac{S_{in} - S_{out}}{\left(\theta\left(\frac{1}{Y}\right)\mu_{max}^{bact}\left(\dfrac{O_2}{O_2 + k_s^{O_2}}\right)\left(\dfrac{S_{out}}{S_{out} + k_{sat}^{sub}}\right)\right) - \left(\gamma k'^{fec}_{hydro}X_{out}^{fec}\theta\right)}$

	Low (50%)	High (150%)	
X_OUT^bact	28.96	28.36	mg VSS/L

Equations for Nitrogen

Cunningham: Dual monad kinetics

Effluent ammonia concentration

Variable NH_4^{out}

Equation [illegible]

	Low (50%)	High (150%)	
NH4_OUT	133.4	130.8	mg/L

Effluent nitrate concentration

Variable NO_3^{out}

Equation $NO_3^{in} + \theta\mu_{max}^{bact}\left[\dfrac{NH_4}{NH_4 + k_{sat}^{NH_4}}\right]\left[\dfrac{O_2}{O_2 + k_{sat}^{O_2}}\right]X^{bact}\left(\dfrac{1}{Y}\right)$

	Low (50%)	High (150%)	
NO3_OUT	245	240	mg/L

Table D-1 (Continued)

Variable:	k'^{fec}_{hydro}	
	Low (50%)	High (150%)
	0.12	**0.36**

Effluent inert Solids Concentration

Variable X_{OUT}^{int}

Equation $$\frac{X_{IN}^{int}}{(1+k_{sett}^{int}\theta)}$$

	Low (50%)	High (150%)	
X_OUT^int	41.4	41.4	mg/L

Effluent Fecal Solids Concentration

Variable X_{OUT}^{fec}

Equation $$\frac{X_{IN}^{fec}}{(1+k_{sett}^{fec}\theta)+(k'^{fec}_{hydro}X_{OUT}^{bact}\theta)}$$

	Low (50%)	High (150%)	
X_OUT^fec	4.89	1.92	mg/L
	4.89	1.92	Solver equation

Effluent substrate concentration

Variable S_{OUT}

Equation $$\frac{\left[(k_{sat}^{sub})(\theta b+\theta k_{sett}^{bact}+1)\right]}{\left[\theta\mu_{max}^{bact}\left(\frac{O_2}{O_2+k_s^{O_2}}\right)-\theta b-\theta k_{sett}^{bact}-1\right]}$$

	Low (50%)	High (150%)	
S_OUT	4.20	4.20	mg BOD/L

Effluent bacterial Solids Concentration

Variable X_{OUT}^{bact}

Equation $$\frac{S_{in}-S_{out}}{\left(\theta\left(\frac{1}{Y}\right)\mu_{max}^{bact}\left(\frac{O_2}{O_2+k_s^{O_2}}\right)\left(\frac{S_{out}}{S_{out}+k_{sat}^{sub}}\right)\right)-\left(\gamma k'^{fec}_{hydro}X_{out}^{fec}\theta\right)}$$

	Low (50%)	High (150%)	
X_OUT^bact	28.00	28.90	mg VSS/L

Equations for Nitrogen

Cunningham: Dual monad kinetics

Effluent ammonia concentration

Variable NH_4^{out}

Equation [illegible]

	Low (50%)	High (150%)	
NH4_OUT	129.2	133.1	mg/L

Effluent nitrate concentration

Variable NO_3^{out}

Equation $$NO_3^{in}+\theta\mu_{max}^{bact}\left[\frac{NH_4}{NH_4+k_{sat}^{NH_4}}\right]\left[\frac{O_2}{O_2+k_{sat}^{O_2}}\right]X^{bact}\left(\frac{1}{Y}\right)$$

	Low (50%)	High (150%)	
NO3_OUT	237	245	mg/L

Table D-1 (Continued)

Variable:	$k_{sat}^{O_2}$
	Low (50%)	High (150%)
	0.185	**0.555**

Effluent inert Solids Concentration

Variable X_{OUT}^{int}

Equation $\frac{X_{IN}^{int}}{(1+k_{sett}^{int}\theta)}$

	Low (50%)	High (150%)	
X_OUT^int	41.4	41.4	mg/L

Effluent Fecal Solids Concentration

Variable X_{OUT}^{fec}

Equation $\frac{X_{IN}^{fec}}{(1+k_{sett}^{fec}\theta)+(k'^{fec}_{hydro}X_{OUT}^{bact}\theta)}$

	Low (50%)	High (150%)	
X_OUT^fec	2.57	2.95	mg/L
	2.57	2.95	Solver equation

Effluent substrate concentration

Variable S_{OUT}

Equation $\frac{\left[\left(k_{sat}^{sub}\right)\left(\theta b+\theta k_{sett}^{bact}+1\right)\right]}{\left[\theta\mu_{max}^{bact}\left(\frac{O_2}{O_2+k_s^{O_2}}\right)-\theta b-\theta k_{sett}^{bact}-1\right]}$

	Low (50%)	High (150%)	
S_OUT	3.83	4.59	mg BOD/L

Effluent bacterial Solids Concentration

Variable X_{OUT}^{bact}

Equation $\frac{S_{IN}-S_{OUT}}{\left(\theta\left(\frac{1}{Y}\right)\mu_{max}^{bact\ gro}\left(\frac{S_{out}}{S_{out}+K_s^{sub}}\right)\right)-\left(k'^{fec}_{hydro}X_{OUT}^{fec}\theta\right)}$

	Low (50%)	High (150%)	
X_OUT^bact	31.16	26.50	mg VSS/L

Equations for Nitrogen

Cunningham: Dual monad kinetics

Effluent ammonia concentration

Variable NH_4^{out}

Equation $\frac{\left(-k_{sat}^{NH_4}-\theta\mu_{max}^{bact}\left[\frac{O_2}{O_2+k_{sat}^{O_2}}\right]X^{bact}+NH_4^{in}+\theta k'^{fec}_{hydro}X^{fec}X^{bact}\alpha\right)+\sqrt{\left[\left(k_{sat}^{NH_4}+\theta\mu_{max}^{bact}\left[\frac{O_2}{O_2+k_{sat}^{O_2}}\right]X^{bact}-NH_4^{in}-\theta k'^{fec}_{hyd}}}{2}$

	Low (50%)	High (150%)	
NH4_OUT	153.5	115.1	mg/L

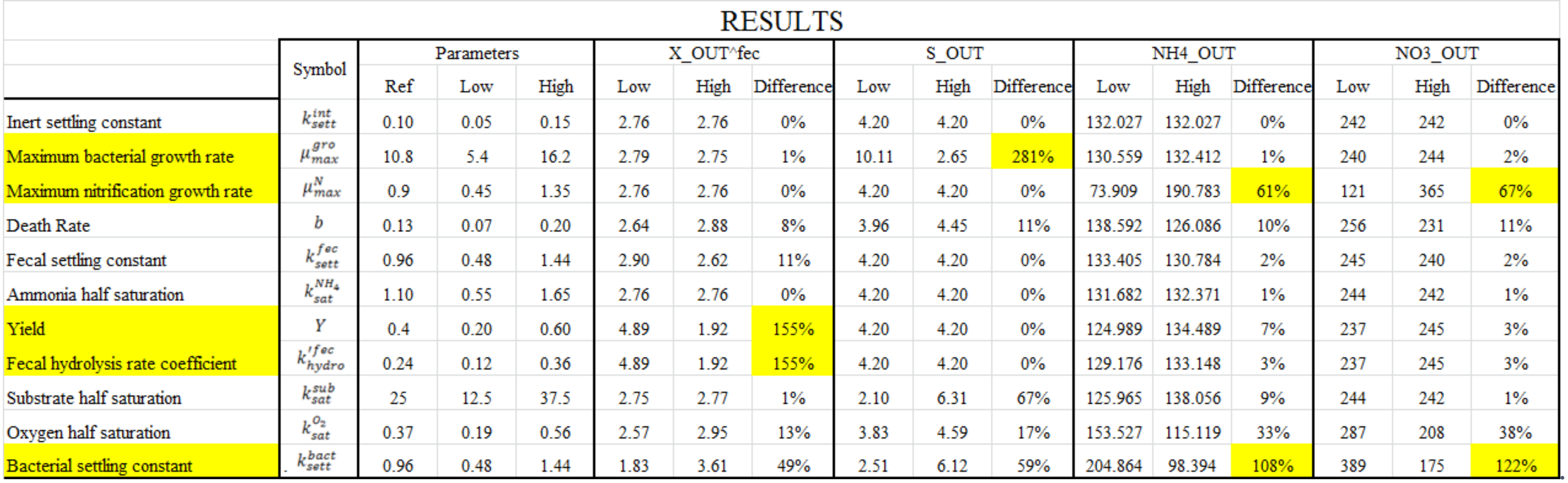
Effluent nitrate concentration

Variable NO_3^{out}

Equation $NO_3^{in}+\theta\mu_{max}^{bact}\left[\frac{NH_4}{NH_4+k_{sat}^{NH_4}}\right]\left[\frac{O_2}{O_2+k_{sat}^{O_2}}\right]X^{bact}\left(\frac{1}{Y}\right)$

	Low (50%)	High (150%)	
NO3_OUT	287	208	mg/L

Table D-2: Results from Saline Sensitivity Analysis



RESULTS

	Symbol	Parameters			X_OUT^fec			S_OUT			NH4_OUT			NO3_OUT		
		Ref	Low	High	Low	High	Difference	Low	High	Difference	Low	High	Difference	Low	High	Difference
Inert settling constant	k_{sett}^{int}	0.10	0.05	0.15	2.76	2.76	0%	4.20	4.20	0%	132.027	132.027	0%	242	242	0%
Maximum bacterial growth rate	μ_{max}^{gro}	10.8	5.4	16.2	2.79	2.75	1%	10.11	2.65	281%	130.559	132.412	1%	240	244	2%
Maximum nitrification growth rate	μ_{max}^{N}	0.9	0.45	1.35	2.76	2.76	0%	4.20	4.20	0%	73.909	190.783	61%	121	365	67%
Death Rate	b	0.13	0.07	0.20	2.64	2.88	8%	3.96	4.45	11%	138.592	126.086	10%	256	231	11%
Fecal settling constant	k_{sett}^{fec}	0.96	0.48	1.44	2.90	2.62	11%	4.20	4.20	0%	133.405	130.784	2%	245	240	2%
Ammonia half saturation	$k_{sat}^{NH_4}$	1.10	0.55	1.65	2.76	2.76	0%	4.20	4.20	0%	131.682	132.371	1%	244	242	1%
Yield	Y	0.4	0.20	0.60	4.89	1.92	155%	4.20	4.20	0%	124.989	134.489	7%	237	245	3%
Fecal hydrolysis rate coefficient	$k_{hydro}^{\prime fec}$	0.24	0.12	0.36	4.89	1.92	155%	4.20	4.20	0%	129.176	133.148	3%	237	245	3%
Substrate half saturation	k_{sat}^{sub}	25	12.5	37.5	2.75	2.77	1%	2.10	6.31	67%	125.965	138.056	9%	244	242	1%
Oxygen half saturation	$k_{sat}^{O_2}$	0.37	0.19	0.56	2.57	2.95	13%	3.83	4.59	17%	153.527	115.119	33%	287	208	38%
Bacterial settling constant	k_{sett}^{bact}	0.96	0.48	1.44	1.83	3.61	49%	2.51	6.12	59%	204.864	98.394	108%	389	175	122%

APPENDIX E: CALCULATIONS OF THE SENSITIVITY ANALYSIS

Table E-1: Calculations of the Sensitivity Analysis

Laughing Bird Caye

Variable: Number of Visitors per Day **Reference** **50**

	Low									High		
	20	40	60	80	100	120	140	160	180	200		

Influent to Anaerobic Biodigestor

∀Blackwater/Flush = 1 gal/flush = 3.78 L/flush

Flush/visitor = 1

											Reference	
Qinfluent =	75.6	151.2	226.8	302.4	378	453.6	529.2	604.8	680.4	756	**189**	L/day
Qeffluent =	75.6	151.2	226.8	302.4	378	453.6	529.2	604.8	680.4	756	**189**	L/day

$$HRT = \forall_{Tank} \times f_L \times (Q_{influent})^{-1}$$

∀Tank = 1500 L

$$f_L = \frac{\forall_{Liquid}}{\forall_{Tank}} = 1 - f_s - f_G$$

	0	0
	0	0
fL =	0.85	0
	0	0

											Reference	
HRT =	17	8	6	4	3	3	2	2	2	2	**7**	**days**
	405	202	135	101	81	67	58	51	45	40	**162**	**hours**

Effluent Inert Solids concentration

Variable X_{OUT}^{int}

Equation $\frac{X_{IN}^{int}}{(1 + k_{sett}^{int}\theta)}$

	Low									High	**Reference**	
X_OUT^int	22.3	32.6	38.4	42.2	44.9	46.8	48.4	49.6	50.5	51.3	**35.8**	**mg/L**

Effluent fecal Solids concentration

Variable X_{OUT}^{fec}

Equation $\frac{X_{IN}^{fec}}{(1 + k_{sett}^{fec}\theta) + (k'^{fec}_{hydro} X_{OUT}^{bact}\theta)}$

	Low									High	**Reference**	
X_OUT^fec	1.98	2.39	2.63	2.80	2.96	3.10	3.23	3.36	3.49	3.61	**2.52**	mg/L
	1.98	2.39	2.63	2.80	2.96	3.10	3.23	3.36	3.49	3.61	**2.52**	Solver equ

Effluent substrate concentration

Variable S_{OUT}

Equation $\frac{[(k_{sat}^{sub})(\theta b + \theta k_{sett}^{bact} + 1)]}{\left[\theta\mu_{max}^{bact}\left(\frac{O_2}{O_2 + k_s^{O_2}}\right) - \theta b - \theta k_{sett}^{bact} - 1\right]}$

	Low									High	**Reference**	
S_OUT	6.58	6.94	7.31	7.68	8.07	8.46	8.87	9.28	9.71	10.14	7.12	mg BOD/L

Effluent bacterial Solids concentration

Variable X_{OUT}^{bact}

Equation $\frac{S_{in} - S_{out}}{\left(\theta\left(\frac{1}{Y}\right)\mu_{max}^{bact}\left(\frac{O_2}{O_2 + k_s^{O_2}}\right)\left(\frac{S_{out}}{S_{out} + k_{sat}^{sub}}\right)\right) - \left(\gamma k'^{fec}_{hydro} X_{out}^{fec}\theta\right)}$

	Low									High	**Reference**	
X_OUT^bact	8.21	16.14	23.48	30.26	36.53	42.34	47.75	52.79	57.49	61.88	19.89	mg VSS/L

Equations for Nitrogen

Effluent ammonia concentration

Variable NH_4^{out}

Equation [illegible]

	Low									High	**Reference**	
NH4_OUT	0.7	0.7	0.8	0.8	0.9	0.9	1.0	1.1	1.1	1.2	0.8	mg/L

Effluent nitrate concentration

Variable NO_3^{out}

Equation $\theta\mu_{max}^{nit}\left(\frac{NH_4^+}{NH_4^+ + k_{sat}^{NH_4^+}}\right)\left(\frac{O_2}{O_2 + k_{sat}^{O_2}}\right)X_{out}^{bact}\left(\frac{1}{Y}\right)$

	Low									High	**Reference**	
NO3_OUT	62	62	62	62	62	62	62	62	62	62	62	mg/L

Settled Solids												
SS	23.7	22.4	21.4	20.5	19.7	19.0	18.3	17.7	17.1	16.6	21.9	mg/L

Bacterial Death												
Death	0.58	0.57	0.55	0.53	0.52	0.50	0.48	0.47	0.45	0.44	0.56	mg/L

Table E-1 (Continued)

Laughing Bird Caye

Variable: Salinity

	Low					Reference				High
Salinity	0.005	0.405	0.805	1.205	1.605	**2.01**	2.405	2.805	3.205	4
Maximum growth rate	10.8	10.21	9.63	9.04	8.46	**7.87**	6.75	5.63	4.51	3.39
Yield	0.4	0.40	0.40	0.40	0.40	**0.40**	0.40	0.40	0.40	0.4
Maxium Growth Rate (nitrogen)	0.9	0.73	0.67	0.62	0.57	**0.52**	0.53	0.48	0.43	0.37
Death Rate	0.021	0.024	0.027	0.029	0.032	**0.03**	0.038	0.040	0.0460	0.0670
Fecal hydrolysis rate coefficient	0.24	0.240	0.240	0.240	0.240	**0.24**	0.240	0.240	0.240	0.24
Bacterial settling constant	0.96	1.03	1.09	1.16	1.22	**1.29**	1.36	1.42	1.49	1.56

Influent to Anaerobic Biodigestor 1

∀Blackwater/Flush = 1 gal/flush = 3.78 L/flush

Flush/visitor = 1

Qinfluent = 189 L/day
Qeffluent = 189 L/day

$$HRT = \forall_{Tank} \times f_L \times (Q_{influent})^{-1}$$

0 0

∀Tank = 1500 L

$$f_L = \frac{\forall_{Liquid}}{\forall_{Tank}} = 1 - f_s - f_G$$

fL = 0.85

HRT = 7 **days**
162 **hours**

Effluent Inert Solids concentration

Variable X_{OUT}^{int}

Equation $\dfrac{X_{IN}^{int}}{(1 + k_{sett}^{int}\theta)}$

	Low					Reference				High	
X_OUT^int	35.8	35.8	35.8	35.8	35.8	**35.8**	35.8	35.8	35.8	35.8	**mg/L**

Effluent fecal Solids concentration

Variable X_{OUT}^{fec}

Equation $\dfrac{X_{IN}^{fec}}{(1 + k_{sett}^{fec}\theta) + (k'^{fec}_{hydro} X_{OUT}^{bact}\theta)}$

	Low					Reference				High	
X_OUT^fec	2.00	2.10	2.21	2.31	2.42	**2.52**	2.63	2.74	2.87	3.11	mg/L
	2.00	2.10	2.21	2.31	2.42	**2.52**	2.63	2.74	2.87	3.11	Solver equ

Effluent substrate concentration

Variable S_{OUT}

Equation $\dfrac{[(k_{sat}^{sub})(\theta b + \theta k_{sett}^{bact} + 1)]}{\left[\theta\mu_{max}^{bact}\left(\frac{O_2}{O_2 + k_s^{O_2}}\right) - \theta b - \theta k_{sett}^{bact} - 1\right]}$

	Low					Reference				High	
S_OUT	3.54	4.04	4.62	5.30	6.12	7.12	9.27	12.82	19.80	40.80	mg BOD/L

Effluent bacterial Solids concentration

Variable X_{OUT}^{bact}

Equation $\dfrac{S_{in} - S_{out}}{\left(\theta\left(\frac{1}{Y}\right)\mu_{max}^{bact}\left(\frac{O_2}{O_2 + k_s^{O_2}}\right)\left(\frac{S_{out}}{S_{out} + k_{sat}^{sub}}\right)\right) - \left(\gamma k'^{fec}_{hydro} X_{out}^{fec}\theta\right)}$

	Low					Reference				High	
X_OUT^bact	26.34	24.76	23.35	22.08	20.93	19.89	18.88	17.92	16.87	15.25	mg VSS/L

Equations for Nitrogen

Effluent ammonia concentration

Variable NH_4^{out}

Equation $\dfrac{\left(NH_4^{in} - k_{sat}^{NH_4^+} + \theta k'^{fec}_{hydro} X_{out}^{fec} X_{out}^{bact}\alpha - \theta\mu_{max}^{bact}\left(\frac{S}{S + k_{sat}^{sub}}\right)\left(\frac{O_2}{O_2 + k_{sat}^{O_2}}\right) X_{out}^{bact}\beta - \theta\left(\frac{1}{Y}\right)\mu_{max}^{nit}\left(\frac{O_2}{O_2 + k_{sat}^{O_2}}\right) X_{out}^{bact}\right) + \sqrt{\left(-NH_4^{in} + k_{sat}^{NH_4^+} - \theta k'^{fec}_{hydro} X_{out}^{fec} X_{out}^{bact}\alpha + \theta\mu_{max}^{bact}\left(\frac{S}{S + k_{sat}^{sub}}\right)\left(\frac{O_2}{O_2 + k_{sat}^{O_2}}\right) X_{out}^{bact}\beta + \theta\left(\frac{1}{Y}\right)\mu_{max}^{nit}\left(\frac{O_2}{O_2 + k_{sat}^{O_2}}\right) X_{out}^{bact}\right)^2 + 4\left(NH_4^{in} k_{sat}^{NH_4^+} + \theta k'^{fec}_{hydro} X}}{2}$

	Low					Reference				High	
NH4_OUT	0.24	0.33	0.40	0.48	0.59	0.75	0.78	1.03	1.50	2.87	mg/L

Effluent nitrate concentration

Variable NO_3^{out}

Equation $\theta\mu_{max}^{nit}\left(\dfrac{NH_4^+}{NH_4^+ + k_{sat}^{NH_4^+}}\right)\left(\dfrac{O_2}{O_2 + k_{sat}^{O_2}}\right) X_{out}^{bact}\left(\dfrac{1}{Y}\right)$

	Low					Reference				High	
NO3_OUT	63	63	62	62	62	62	62	62	62	62	mg/L

Settled Solids

SS	21.4	21.5	21.6	21.7	21.8	21.9	21.9	21.9	21.6	20.6	mg/L

Bacterial Death

Death	2.77	2.61	2.46	2.32	2.20	2.09	1.99	1.89	1.78	1.60	mg/L

Table E-1 (Continued)

Little Water Caye												
Variable:	Number of Visitors per Day				**Reference**	**25**						
	Low									High		
	5	7	12	17	22	27	32	37	42	50		
Influent to Anaerobic Biodigestor 1												
∀Blackwater/Flush =	1	gal/flush		=	3.78	L/flush						
Flush/visitor =	1											
											Reference	
Qinfluent =	18.9	26.46	45.36	64.26	83.16	102.06	120.96	139.86	158.76	189	**94.5**	L/day
Qeffluent =	18.9	26.46	45.36	64.26	83.16	102.06	120.96	139.86	158.76	189	**94.5**	L/day
	$HRT = \forall_{Tank} \times f_L \times (Q_{influent})^{-1}$											
∀Tank_1 =	3500	L										
∀Tank_2 =	1200	L										
	$f_L = \frac{\forall_{Liquid}}{\forall_{Tank}} = 1 - f_s - f_G$											
fL =	0.85											
HRT_1 =	157	112	66	46	36	29	25	21	19	16	**31**	**days**
	3778	2698	1574	1111	859	700	590	511	450	378	**756**	**hours**
HRT_2 =	54	39	22	16	12	10	8	7	6	5	**11**	**days**
	1295	925	540	381	294	240	202	175	154	130	**259**	**hours**
Effluent Inert Solids concentration												
	Variable	X_{OUT}^{int}										
	Equation	$\frac{X_{IN}^{int}}{(1+k_{sett}^{int}\theta)}$										
Biodigestor 1												
	Low									High		
X_OUT^int	3.6	4.9	7.9	10.7	13.1	15.3	17.3	19.2	20.9	23.3	**14.5**	**mg/L**
Biodigestor 2												
	Low									High		
X_OUT^int	0.6	1.0	2.4	4.1	5.9	7.7	9.4	11.1	12.7	15.1	**7.0**	**1/day**
Effluent fecal Solids concentration												
	Variable	X_{OUT}^{fec}										
	Equation	$\frac{X_{IN}^{fec}}{(1+k_{sett}^{fec}\theta)+(k_{hydro}^{\prime fec}X_{OUT}^{bact}\theta)}$										
Biodigestor 1												
	Low									High		
X_OUT^fec	0.34	0.40	0.48	0.52	0.55	0.57	0.59	0.60	0.61	0.62	**0.56**	mg/L
	0.34	0.40	0.48	0.52	0.55	0.57	0.59	0.60	0.61	0.62	**0.56**	Solver equ
Biodigestor 2												
	Low									High		
X_OUT^fec	0.0065	0.0105	0.0213	0.032	0.043	0.054	0.065	0.076	0.086	0.103	**0.050**	1/day
	0.0065	0.0105	0.0213	0.032	0.043	0.054	0.065	0.076	0.086	0.103	**0.050**	Solver equ
Effluent substrate concentration												
	Variable	S_{OUT}										
	Equation	$\frac{[(k_{sat}^{sub})(\theta b+\theta k_{sett}^{bact}+1)]}{\theta\mu_{max}^{bact}\left(\frac{O_2}{O_2+k_s^{O_2}}\right)-\theta b-\theta k_{sett}^{bact}-1}$										
Biodigestor 1												
	Low									High		
S_OUT	3.42	3.43	3.45	3.47	3.50	3.52	3.54	3.56	3.59	3.62	3.51	mg BOD/L
Biodigestor 2												
	Low									High		
S_OUT	3.46	3.49	3.55	3.62	3.69	3.75	3.82	3.89	3.96	4.07	3.73	1/day
Effluent bacterial Solids concentration												
	Variable	X_{OUT}^{bact}										
	Equation	$\frac{S_{in}-S_{out}}{\left(\theta\left(\frac{1}{Y}\right)\mu_{max}^{bact}\left(\frac{O_2}{O_2+k_s^{O_2}}\right)\left(\frac{S_{out}}{S_{out}+k_{sat}^{sub}}\right)\right)-\left(\gamma k_{hydro}^{\prime fec}X_{out}^{fec}\theta\right)}$										
Biodigestor 1												
	Low									High		
X_OUT^bact	1.08	1.53	2.68	3.83	4.97	6.10	7.22	8.33	9.42	11.15	5.65	mg VSS/L
Biodigestor 2												
	Low									High		
X_OUT^bact	0.00	0.00	0.00	0.00	-0.01	-0.01	-0.01	-0.01	-0.02	-0.03	-0.01	mg BOD/I
Equations for Nitrogen												
Effluent ammonia concentration												
	Variable	NH_4^{out}										
	Equation	[illegible]										
Biodigestor 1												
	Low									High		
NH4_OUT	0.25	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	mg/L
Biodigestor 2												
	Low									High		
NH4_OUT	0.25	0.25	0.26	0.26	0.27	0.28	0.29	0.30	0.31	0.32	0.27	mg/L
Effluent nitrate concentration												
	Variable	NO_3^{out}										
	Equation	$\theta\mu_{max}^{nit}\left(\frac{NH_4^+}{NH_4^+ + k_{sat}^{NH_4^+}}\right)\left(\frac{O_2}{O_2+k_{sat}^{O_2}}\right)X_{out}^{bact}\left(\frac{1}{Y}\right)$										
Biodigestor 1												
	Low									High		
NO3_OUT	62	62	62	62	63	63	63	63	63	63	63	mg/L
Biodigestor 2												
	Low									High		
NO3_OUT	62	62	62	62	63	63	63	63	63	63	63	mg/L
Settled Solids												
Biodigestor 1												
SS	23.1	22.9	22.4	22.1	21.8	21.6	21.4	21.3	21.1	20.9	21.7	mg/L
Biodigestor 2												
SS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	mg/L
Total												
SS	23.2	22.9	22.4	22.1	21.8	21.6	21.5	21.3	21.1	20.9	21.7	mg/L
Bacterial Death												
Death_Tank 1	0.00	2.69	2.74	2.77	2.77	2.77	2.77	2.76	2.76	2.74	2.77	mg/L
Death_Tank 2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	mg/L

Table E-1 (Continued)

Little Water Caye

Variable: O_2

	Low									High	
	0.1	0.4	0.7	1	1.3	1.6	1.9	2.2	2.5	3	

Influent to Anaerobic Biodigestor 1

∀Blackwater/Flush = 1 gal/flush = 3.78 L/flush

Flush/visitor = 1

Qinfluent = 94.5 L/day
Qeffluent = 94.5 L/day

$$HRT = \forall_{Tank} \times f_L \times (Q_{influent})^{-1}$$

∀Tank_1 = 3500 L
∀Tank_2 = 1200 L

$$f_L = \frac{\forall_{Liquid}}{\forall_{Tank}} = 1 - f_s - f_G$$

	0	0
fL =	0.85	0

HRT_1 = 31 **days**
756 **hours**

HRT_2 = 11 **days**
259 **hours**

Effluent Inert Solids concentration

Variable X_{OUT}^{int}

Equation $\frac{X_{IN}^{int}}{(1 + k_{sett}^{int}\theta)}$

Biodigestor 1	Low									High	
X_OUT^int	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	**mg/L**

Biodigestor 2	Low									High	
X_OUT^int	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	**1/day**

Effluent fecal Solids concentration

Variable X_{OUT}^{fec}

Equation $\frac{X_{IN}^{fec}}{(1 + k_{sett}^{fec}\theta) + (k_{hydro}^{\prime fec} X_{OUT}^{bact}\theta)}$

Biodigestor 1	Low									High	
X_OUT^fec	0.54	0.57	0.57	0.57	0.57	0.56	0.56	0.56	0.56	0.56	mg/L
	0.59	0.57	0.57	0.57	0.57	0.56	0.56	0.56	0.56	0.56	Solver equ

Biodigestor 2	Low									High	
X_OUT^fec	0.0472	0.0503	0.0500	0.0499	0.0498	0.0498	0.0498	0.0498	0.0498	0.0000	1/day
	0.0482	0.0502	0.0500	0.0499	0.0498	0.0498	0.0498	0.0498	0.0498	0.0498	Solver equ

Effluent substrate concentration

Variable S_{OUT}

Equation $\frac{[(k_{sat}^{sub})(\theta b + \theta k_{sett}^{bact} + 1)]}{\left[\theta\mu_{max}^{bact}\left(\frac{O_2}{O_2 + k_s^{O_2}}\right) - \theta b - \theta k_{sett}^{bact} - 1\right]}$

Biodigestor 1	Low									High	
S_OUT	23.84	6.25	4.72	4.15	3.85	3.67	3.54	3.45	3.38	3.30	mg BOD/L

Biodigestor 2	Low									High	
S_OUT	26.51	6.68	5.03	4.41	4.09	3.90	3.76	3.67	3.59	3.51	mg BOD/L

Effluent bacterial Solids concentration

Variable X_{OUT}^{bact}

Equation $\frac{S_{in} - S_{out}}{\left(\theta\left(\frac{1}{Y}\right)\mu_{max}^{bact}\left(\frac{O_2}{O_2 + k_s^{O_2}}\right)\left(\frac{S_{out}}{S_{out} + k_{sat}^{sub}}\right)\right) - (\gamma k_{hydro}^{\prime fec} X_{out}^{fec}\theta)}$

Biodigestor 1	Low									High	
X_OUT^bact	5.32	5.62	5.64	5.64	5.65	5.65	5.65	5.65	5.65	5.65	mg VSS/L

Biodigestor 2	Low									High	
X_OUT^bact	-0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	mg BOD/L

Equations for Nitrogen

Effluent ammonia concentration

Variable NH_4^{out}

Equation [illegible]

Biodigestor 1	Low									High	
NH4_OUT	2.8	0.4	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	mg/L

Biodigestor 2	Low									High	
NH4_OUT	2.8	0.6	0.5	0.4	0.4	0.4	0.4	0.3	0.3	0.3	mg/L

.

Variable NO_3^{out}

Equation $\theta\mu_{max}^{nit}\left(\frac{NH_4^+}{NH_4^+ + k_{sat}^{NH_4^+}}\right)\left(\frac{O_2}{O_2 + k_{sat}^{O_2}}\right)X_{out}^{bact}\left(\frac{1}{Y}\right)$

Biodigestor 1	Low									High	
NO3_OUT	60.8	62.5	62.6	62.6	62.6	62.6	62.6	62.6	62.6	62.6	mg/L

Biodigestor 2	Low									High	
NO3_OUT	60.7	62.5	62.5	62.6	62.6	62.6	62.6	62.6	62.6	62.6	mg/L

Settled Solids

Biodigestor 1											
SS	20.4	21.6	21.6	21.7	21.7	21.7	21.7	21.7	21.7	21.7	mg/L
Biodigestor 2											
SS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	mg/L
Total											
SS	20.4	21.6	21.7	21.7	21.7	21.7	21.7	21.7	21.7	21.7	mg/L

Bacterial Death

Death_Tank 1	2.61	2.76	2.77	2.77	2.77	2.77	2.77	2.78	2.78	2.78	mg/L
Death_Tank 2	-0.004888	-0.0007883	-0.000564205	-0.0004858	-0.00045	-0.000421855	-0.00041	-0.00039	-0.00039	-0.00037	mg/L

Table E-1 (Continued)

Silk Caye

Variable:	θ					Reference	20					
	Low									High		
	10	21	32	43	54	65	76	87	98	110		

Influent to Anaerobic Biodigestor 1

∀Blackwater/Flush = 1 gal/flush = 3.78 L/flush

Flush/visitor = 1

											Reference	
Qinfluent =	37.8	79.38	120.96	162.54	204.12	245.7	287.28	328.86	370.44	415.8	**75.6**	L/day
Qeffluent =	37.8	79.38	120.96	162.54	204.12	245.7	287.28	328.86	370.44	415.8	**75.6**	L/day

$$HRT = \forall_{Tank} \times f_L \times (Q_{influent})^{-1}$$

∀Tank = 1500 L

$$f_L = \frac{\forall_{Liquid}}{\forall_{Tank}} = 1 - f_s - f_G$$

fL =	0.8271813		0									
		0	0								**Reference**	
HRT =	33	16	10	8	6	5	4	4	3	3	**16**	**days**
	788	375	246	183	146	121	104	91	80	72	**394**	**hours**

Effluent Inert Solids concentration

Variable X_{OUT}^{int}

Equation $\frac{X_{IN}^{int}}{(1 + k_{sett}^{int}\theta)}$

	Low									High	Reference	
X_OUT^int	14.0	23.4	29.6	34.0	37.3	39.9	41.9	43.6	44.9	46.2	**22.7**	**mg/L**

Effluent fecal Solids concentration

Variable X_{OUT}^{fec}

Equation $\frac{X_{IN}^{fec}}{(1 + k_{sett}^{fec}\theta) + (k'^{fec}_{hydro} X_{OUT}^{bact}\theta)}$

	Low									High	Reference	
X_OUT^fec	1.53	2.03	2.28	2.45	2.58	2.69	2.79	2.88	2.96	3.05	**2.00**	mg/L
	1.53	2.03	2.28	2.45	2.58	2.69	2.79	2.88	2.96	3.05	**2.00**	Solver equ

Effluent substrate concentration

Variable S_{OUT}

Equation $\frac{[(k_{sat}^{sub})(\theta b + \theta k_{sett}^{bact} + 1)]}{\left[\theta\mu_{max}^{bact}\left(\frac{O_2}{O_2 + k_s^{O_2}}\right) - \theta b - \theta k_{sett}^{bact} - 1\right]}$

	Low									High	Reference	
S_OUT	6.41	6.61	6.81	7.02	7.22	7.43	7.65	7.86	8.08	8.33	6.59	mg BOD/L

Effluent bacterial Solids concentration

Variable X_{OUT}^{bact}

Equation $\frac{S_{in} - S_{out}}{\left(\theta\left(\frac{1}{Y}\right)\mu_{max}^{bact}\left(\frac{O_2}{O_2 + k_s^{O_2}}\right)\left(\frac{S_{out}}{S_{out} + k_{sat}^{sub}}\right)\right) - \left(\gamma k'^{fec}_{hydro} X_{out}^{fec}\theta\right)}$

	Low									High	Reference	
X_OUT^bact	4.17	8.86	13.39	17.73	21.88	25.84	29.63	33.26	36.74	40.37	8.44	mg VSS/L

Equations for Nitrogen

Effluent ammonia concentration

Variable NH_4^{out}

Equation [illegible]

	Low									High	Reference	
NH4_OUT	0.71	0.71	0.72	0.74	0.76	0.79	0.82	0.85	0.88	0.91	0.71	mg/L

Effluent nitrate concentration

Variable NO_3^{out}

Equation $\theta\mu_{max}^{nit}\left(\frac{NH_4^+}{NH_4^+ + k_{sat}^{NH_4^+}}\right)\left(\frac{O_2}{O_2 + k_{sat}^{O_2}}\right)X_{out}^{bact}\left(\frac{1}{Y}\right)$

	Low									High	Reference	
NO3_OUT	61.5	61.9	62.1	62.2	62.2	62.3	62.3	62.3	62.3	62.3	61.9	mg/L

Settled Solids

SS	24.6	23.6	22.8	22.2	21.6	21.1	20.6	20.2	19.7	19.3	23.6	mg/L

Bacterial Death

Death	0.57	0.58	0.58	0.57	0.56	0.55	0.54	0.53	0.52	0.50	0.58	mg/L

Table E-1 (Continued)

Silk Caye											
Variable:	O_2										
	Low									High	
	0.1	0.4	0.7	1	1.3	1.6	1.9	2.2	2.5	3	
Influent to Anaerobic Biodigestor 1											
	∀Blackwater/Flush =	1	gal/flush	=	3.78	L/flush					
	Flush/visitor =	1									
Qinfluent =	75.6	L/day									
Qeffluent =	75.6	L/day									
	$HRT = \forall_{Tank} \times f_L \times (Q_{influent})^{-1}$										
	∀Tank =	1500	L								
	$f_L = \frac{\forall_{Liquid}}{\forall_{Tank}} = 1 - f_s - f_G$										
	fL =	0.85	0								
		0	0								
HRT =	17	**days**									
	405	**hours**									
Effluent Inert Solids concentration											
	Variable	X_{OUT}^{int}									
	Equation	$\frac{X_{IN}^{int}}{(1 + k_{sett}^{int}\theta)}$									
	Low									High	
X_OUT^int	22.3	22.3	22.3	22.3	22.3	22.3	22.3	22.3	22.3	22.3	**mg/L**
Effluent fecal Solids concentration											
	Variable	X_{OUT}^{fec}									
	Equation	$\frac{X_{IN}^{fec}}{(1 + k_{sett}^{fec}\theta) + (k'^{fec}_{hydro}X_{OUT}^{bact}\theta)}$									
	Low									**High**	
X_OUT^fec	1.89	2.01	1.99	1.99	1.99	1.98	1.98	1.98	1.98	**1.98**	mg/L
	2.43	2.00	1.99	1.99	1.98	1.98	1.98	1.98	1.98	**1.98**	Solver equ
Effluent substrate concentration											
	Variable	S_{OUT}									
	Equation	$\frac{[(k_{sat}^{sub})(\theta b + \theta k_{sett}^{bact} + 1)]}{\left[\theta\mu_{max}^{bact}\left(\frac{O_2}{O_2 + k_s^{O_2}}\right) - \theta b - \theta k_{sett}^{bact} - 1\right]}$									
	Low									**High**	
S_OUT	118.90	12.79	9.19	7.93	7.29	6.91	6.65	6.46	6.32	6.15	ng BOD/L
Effluent bacterial Solids concentration											
	Variable	X_{OUT}^{bact}									
	Equation	$\frac{S_{in} - S_{out}}{\left(\theta\left(\frac{1}{Y}\right)\mu_{max}^{bact}\left(\frac{O_2}{O_2 + k_s^{O_2}}\right)\left(\frac{S_{out}}{S_{out} + k_{sat}^{sub}}\right)\right) - (\gamma k'^{fec}_{hydro}X_{out}^{fec}\theta)}$									
	Low									**High**	
X_OUT^bact	5.94	8.11	8.17	8.19	8.20	8.21	8.21	8.22	8.22	8.22	mg VSS/L
Equations for Nitrogen											
Effluent ammonia concentration											
	Variable	NH_4^{out}									
	Equation	[illegible]									
	Low									High	
NH4_OUT	37.88	1.91	1.12	0.91	0.81	0.75	0.72	0.69	0.67	0.65	mg/L
Effluent nitrate concentration											
	Variable	NO_3^{out}									
	Equation	$\theta\mu_{max}^{nit}\left(\frac{NH_4^+}{NH_4^+ + k_{sat}^{NH_4^+}}\right)\left(\frac{O_2}{O_2 + k_{sat}^{O_2}}\right)X_{out}^{bact}\left(\frac{1}{Y}\right)$									
	Low									High	
NO3_OUT	**30**	**61**	**62**	**62**	**62**	**62**	**62**	**62**	**62**	**62**	mg/L
Settled Solids											
SS	17.6	23.4	23.6	23.6	23.7	23.7	23.7	23.7	23.7	23.7	mg/L
Bacterial Death											

Table E-1 (Continued)

Silk Caye										
Variable:										
	Low					**Reference**				High
Salinity	0.005	0.405	0.805	1.205	1.605	2.01	2.405	2.805	3.205	4
Maximum growth rate	10.80	10.21	9.63	9.04	8.46	7.87	6.75	5.63	4.51	3.39
Yield	0.4	0.4	0.4	0.4	0.4	0.40	0.4	0.4	0.4	0.4
Maxium Growth Rate (nitrogen)	0.9	0.73	0.67	0.62	0.57	0.52	0.53	0.48	0.43	0.37
Death Rate	0.021	0.024	0.027	0.029	0.032	0.03	0.038	0.040	0.046	0.067
Fecal hydrolysis rate coefficient	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24
Bacterial settling constant	0.96	1.03	1.092	1.158	1.224	1.29	1.356	1.422	1.488	1.558

Influent to Anaerobic Biodigestor 1

∀Blackwater/Flush = 1 gal/flush = 3.78 L/flush

Flush/visitor = 1

Qinfluent = 75.6 L/day
Qeffluent = 75.6 L/day

$$HRT = \forall_{Tank} \times f_L \times (Q_{influent})^{-1}$$

0 0

∀Tank = 1500 L

$$f_L = \frac{\forall_{Liquid}}{\forall_{Tank}} = 1 - f_s - f_G$$

fL = 0.85

HRT = 17 **days**
405 **hours**

Effluent Inert Solids concentration

Variable X^{int}_{OUT}

Equation $\frac{X^{int}_{IN}}{(1 + k^{int}_{sett}\theta)}$

	Low					**Reference**				High	
X_OUT^int	22.3	22.3	22.3	22.3	22.3	**22.3**	22.3	22.3	22.3	22.3	**mg/L**

Effluent fecal Solids concentration

Variable X^{fec}_{OUT}

Equation $\frac{X^{fec}_{IN}}{(1 + k^{fec}_{sett}\theta) + (k'^{fec}_{hydro} X^{bact}_{OUT}\theta)}$

	Low					**Reference**				High	
X_OUT^fec	1.60	1.68	1.76	1.84	1.91	**1.98**	2.06	2.13	2.22	2.35	mg/L
	1.60	1.68	1.76	1.84	1.91	**1.98**	2.06	2.13	2.22	2.35	Solver equ

Effluent sB34strate concentration

Variable S_{OUT}

Equation $\frac{[(k^{sub}_{sat})(\theta b + \theta k^{bact}_{sett} + 1)]}{\left[\theta\mu^{bact}_{max}\left(\frac{O_2}{O_2 + k^{O_2}_s}\right) - \theta b - \theta k^{bact}_{sett} - 1\right]}$

	Low					**Reference**				High	
S_OUT	3.22	3.69	4.24	4.88	5.65	6.58	8.56	11.78	18.00	35.82	mg BOD/L

Effluent bacterial Solids concentration

Variable X^{bact}_{OUT}

Equation $\frac{S_{in} - S_{out}}{\left(\theta\left(\frac{1}{Y}\right)\mu^{bact}_{max}\left(\frac{O_2}{O_2 + k^{O_2}_s}\right)\left(\frac{S_{out}}{S_{out} + k^{sub}_{sat}}\right)\right) - \left(\gamma k'^{fec}_{hydro} X^{fec}_{out}\theta\right)}$

	Low					**Reference**				High	
X_OUT^bact	11.15	10.42	9.78	9.20	8.68	8.21	7.77	7.35	6.91	6.25	mg VSS/L

Equations for Nitrogen

Effluent ammonia concentration

Variable NH_4^{out}

Equation [illegible]

	Low					**Reference**				High	
NH4_OUT	0.22	0.31	0.37	0.45	0.56	0.71	0.74	0.97	1.40	2.59	mg/L

Effluent nitrate concentration

Variable NO_3^{out}

Equation $\theta\mu^{nit}_{max}\left(\frac{NH_4^+}{NH_4^+ + k^{NH_4^+}_{sat}}\right)\left(\frac{O_2}{O_2 + k^{O_2}_{sat}}\right)X^{bact}_{out}\left(\frac{1}{Y}\right)$

	Low					**Reference**				High	
NO3_OUT	62	62	62	62	62	62	62	62	62	61	mg/L

Settled Solids											
SS	23.5	23.5	23.6	23.6	23.7	23.7	23.7	23.6	23.3	22.4	mg/L

Bacterial Death											
Death	2.93	2.74	2.57	2.42	2.28	2.16	2.04	1.93	1.82	1.64	mg/L

APPENDIX F: VERIFICATION OF MODEL THROUGH MATERIAL BALANCE OF NITROGEN

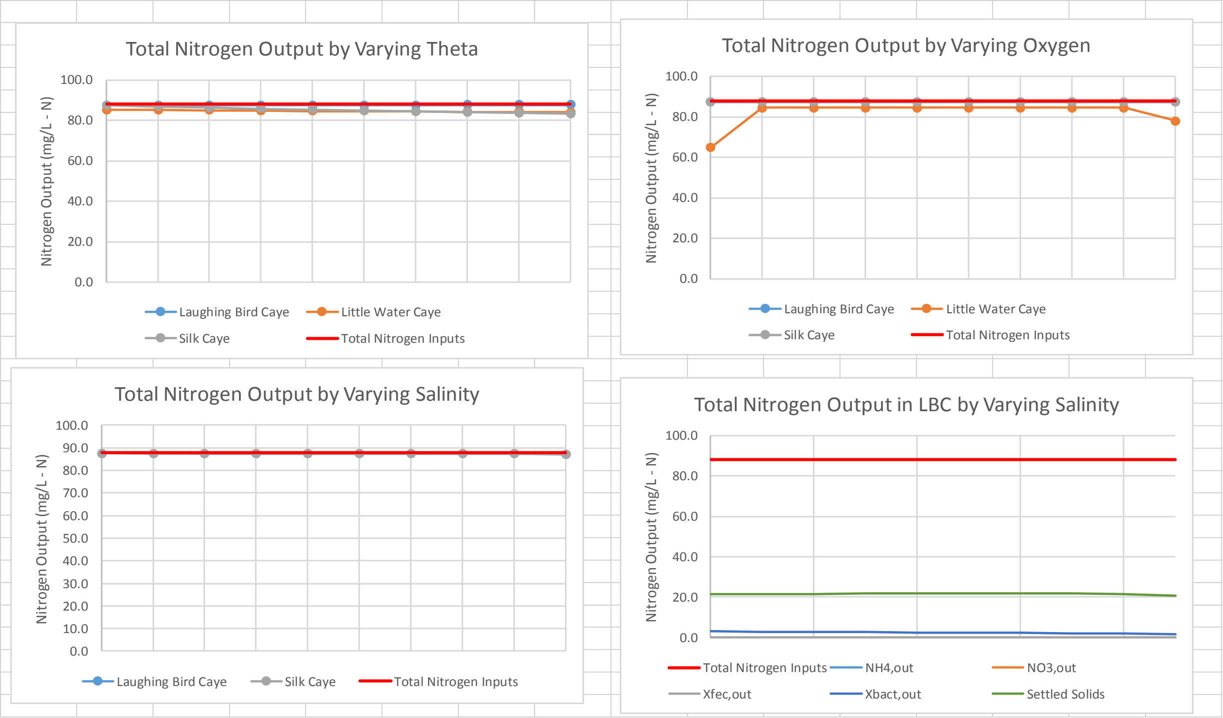


Figure F-1: Graphical Results of Nitrogen Mass Balance within the Developed Model

Table F-1: Calculations of Nitrogen Mass Balance within the Developed Model

Inputs											
	NH4,in =	78	mg/L - NH4								
	NO3,in =	3	mg/L - NO3								
	Xfec,in =	100	mg/L - VSS								
		7.0	mg/L - N								
	TOTAL	**88.0**	**mg/L - N**								
Outputs											
	Theta										
		Laughing Bird Caye									
NH4,out	0.7	0.7	0.8	0.8	0.9	0.9	1.0	1.1	1.1	1.2	mg/L - NH4
NO3,out	61.9	62.2	62.2	62.3	62.3	62.3	62.2	62.2	62.2	62.1	mg/L - NO3
Xfec,out	2.0	2.4	2.6	2.8	3.0	3.1	3.2	3.4	3.5	3.6	mg/L - VSS
as N	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	mg/L - N
Xbact,out	8.2	16.1	23.5	30.3	36.5	42.3	47.7	52.8	57.5	61.9	mg/L - VSS
as N	1.0	1.9	2.8	3.6	4.4	5.1	5.7	6.3	6.9	7.4	mg/L - N
Settled So	23.7	22.4	21.4	20.5	19.7	19.0	18.3	17.7	17.1	16.6	
TOTAL	87.4	87.4	87.4	87.5	87.5	87.5	87.5	87.5	87.5	87.6	**mg/L - N**

Table F-1 (Continued)

	Little Water Caye										
NH4,out	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	mg/L - NH4
NO3,out	61.8	62.0	62.3	62.4	62.5	62.6	62.7	62.7	62.7	62.8	mg/L - NO3
Xfec,out	0.01	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.10	mg/L - VSS
as N	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	mg/L - N
Xbact,out	0.000	0.000	0.000	0.000	0.001	0.001	0.002	0.002	0.003	0.004	mg/L - VSS
as N	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	mg/L - N
Settled Sol	23.2	22.9	22.4	22.1	21.8	21.6	21.5	21.3	21.2	20.9	
TOTAL	85.2	85.1	84.9	84.8	84.6	84.5	84.4	84.2	84.1	83.9	**mg/L - N**
	Silk Caye										
NH4,out	0.7	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.9	0.9	mg/L - NH4
NO3,out	61.5	61.9	62.1	62.2	62.2	62.3	62.3	62.3	62.3	62.3	mg/L - NO3
Xfec,out	1.53	2.03	2.28	2.45	2.58	2.69	2.79	2.88	2.96	3.05	mg/L - VSS
as N	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	mg/L - N
Xbact,out	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	mg/L - VSS
as N	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	mg/L - N
Settled Sol	24.6	23.6	22.8	22.2	21.6	21.1	20.6	20.2	19.7	19.3	
TOTAL	87.4	86.9	86.3	85.8	85.3	84.9	84.4	84.0	83.6	83.2	**mg/L - N**
	Oxygen										
	Laughing Bird Caye										
NH4,out	55.9	3.3	1.4	1.0	0.9	0.8	0.8	0.7	0.7	0.7	mg/L - NH4
NO3,out	5.4	60.2	61.8	62.0	62.1	62.2	62.2	62.2	62.2	62.3	mg/L - NO3
Xfec,out	2.4	2.6	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	mg/L - VSS
as N	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	mg/L - N
Xbact,out	21.3	19.4	19.7	19.8	19.8	19.9	19.9	19.9	19.9	19.9	mg/L - VSS
as N	2.6	2.3	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	mg/L - N
Settled Sol	23.3	21.5	21.8	21.8	21.9	21.9	21.9	21.9	21.9	21.9	
TOTAL	87.4	87.5	87.4	87.4	87.4	87.4	87.4	87.4	87.4	87.4	**mg/L - N**
	Little Water Caye										
NH4,out	33.4	0.7	0.4	0.4	0.4	0.3	0.3	0.3	0.3	0.3	mg/L - NH4
NO3,out	8.6	62.5	62.5	62.6	62.6	62.6	62.6	62.6	62.6	60.7	mg/L - NO3
Xfec,out	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00	mg/L - VSS
as N	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	mg/L - N
Xbact,out	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	mg/L - VSS
as N	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	mg/L - N
Settled Sol	23.0	21.6	21.7	21.7	21.7	21.7	21.7	21.7	21.7	17.1	
TOTAL	65.0	84.7	84.7	84.6	84.6	84.6	84.6	84.6	84.6	78.2	**mg/L - N**
	Silk Caye										
NH4,out	55.5	2.9	1.3	1.0	0.8	0.8	0.7	0.7	0.7	0.6	mg/L - NH4
NO3,out	5.5	60.2	61.5	61.7	61.8	61.9	61.9	61.9	61.9	61.9	mg/L - NO3
Xfec,out	1.89	2.01	1.99	1.99	1.99	1.98	1.98	1.98	1.98	1.98	mg/L - VSS
as N	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	mg/L - N
Xbact,out	8.8	8.0	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	mg/L - VSS
as N	1.1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	mg/L - N
Settled Sol	25.2	23.3	23.5	23.6	23.7	23.7	23.7	23.7	23.7	23.7	
TOTAL	87.4	87.4	87.4	87.4	87.4	87.4	87.4	87.4	87.4	87.4	**mg/L - N**
	Salinity										
	Laughing Bird Caye										
NH4,out	0.2	0.3	0.4	0.5	0.6	0.8	0.8	1.0	1.5	2.9	mg/L - NH4
NO3,out	62.6	62.6	62.5	62.4	62.3	62.2	62.3	62.2	62.0	61.6	mg/L - NO3
Xfec,out	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.9	3.1	mg/L - VSS
as N	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	mg/L - N
Xbact,out	26.3	24.8	23.4	22.1	20.9	19.9	18.9	17.9	16.9	15.2	mg/L - VSS
as N	3.2	3.0	2.8	2.6	2.5	2.4	2.3	2.1	2.0	1.8	mg/L - N
Settled Sol	21.4	21.5	21.6	21.7	21.8	21.9	21.9	21.9	21.6	20.6	
TOTAL	87.6	87.5	87.5	87.5	87.5	87.4	87.4	87.4	87.4	87.2	**mg/L - N**
	Silk Caye										
NH4,out	0.2	0.3	0.4	0.5	0.6	0.7	0.7	1.0	1.4	2.6	mg/L - NH4
NO3,out	62.4	62.3	62.2	62.1	62.0	61.9	61.9	61.8	61.7	61.3	mg/L - NO3
Xfec,out	1.60	1.68	1.76	1.84	1.91	1.98	2.06	2.13	2.22	2.35	mg/L - VSS
as N	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	mg/L - N
Xbact,out	11.2	10.4	9.8	9.2	8.7	8.2	7.8	7.4	6.9	6.2	mg/L - VSS
as N	1.3	1.3	1.2	1.1	1.0	1.0	0.9	0.9	0.8	0.7	mg/L - N
Settled Sol	23.5	23.5	23.6	23.6	23.7	23.7	23.7	23.6	23.3	22.4	
TOTAL	87.5	87.5	87.5	87.5	87.4	87.4	87.4	87.4	87.4	87.2	**mg/L - N**

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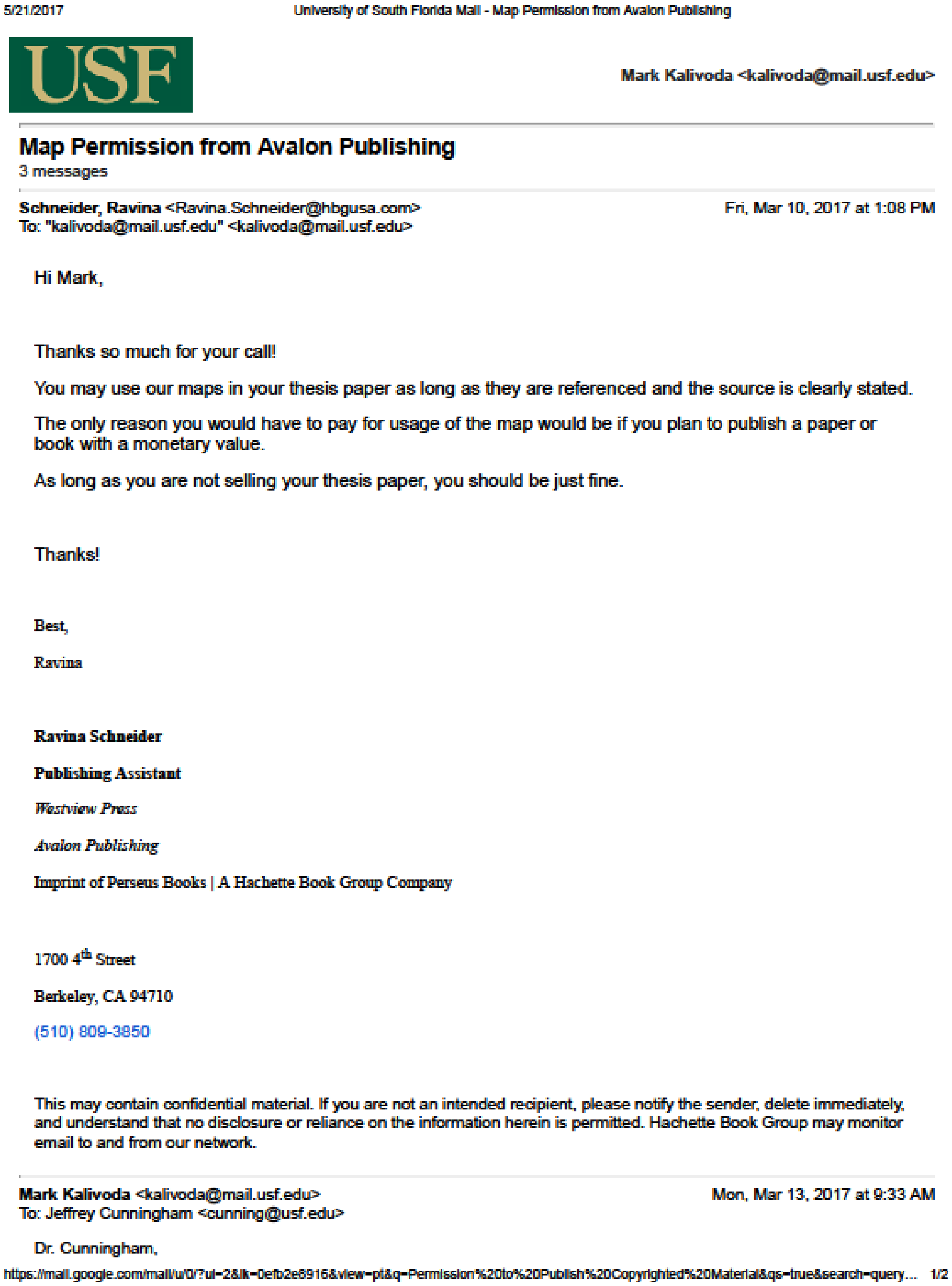

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G-2. Copyright Status of House Used in Figure 3: Leach Field of a Soil Adsorption System

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ABOUT THE AUTHOR

Mark Kalivoda was born and raised in Gainesville, Florida, attending the International Baccalaureate program at Eastside High School. After high school, Mark postponed college for a semester and traveled around the United States. The majority of his time was spent living and working at a women’s and children’s shelter in St. Louis, Missouri, and at a homeless shelter and soup kitchen in New York City. Mark eventually enrolled at the University of Florida, where he became heavily involved with the Engineers Without Borders organization. The work with EWB led him to pursue the Peace Corps after college. Mark graduated from UF in the spring of 2012 with B.S. degrees in Environmental Engineering and Civil Engineering, and subsequently joined the Master’s International Program at USF. The Master’s International Program served as an opportunity that he could obtain his M.S. degree in Environmental Engineering and also in the United States Peace Corps.

Mark served 26 months in the United States Peace Corps as a Water and Sanitation Engineer in the rural town of Changuillo, Peru. His projects in the Peace Corps include installation of chlorination systems for drinking water systems, pour-flush bathrooms with septic tank WWTS, remediation and installation of solar panels, and implementation of an environmental education program for the local elementary and high schools.

Currently Mark Kalivoda is a staff engineer at GSE Engineering and Consulting, Inc. in Gainesville, Florida. He has assisted with geotechnical site explorations, settlement analyses, soil classifications, and stormwater related design. In addition, has performed Phase I and Phase II Environmental Site Assessments, and has monitored remedial action plan implementation.