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A Comparative Sustainability Study for Treatment of Domestic Wastewater: Conventional Concrete and Steel Technology vs. Vegetated Sand Beds (VSB's) and Their Relative Differences in CO2 Production

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A COMPARATIVE SUSTAINABILITY STUDY FOR TREATMENT OF DOMESTIC WASTEWATER:

CONVENTIONAL CONCRETE AND STEEL TECHNOLOGY VS. VEGETATED SAND BEDs (VSBs) AND THEIR

RELATIVE DIFFERENCES IN CO$_2$ PRODUCTION

A Thesis Presented

by

ALICIA M. MILCH

Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
Of the requirements for the degree of

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ABSTRACT

A COMPARATIVE SUSTAINABILITY STUDY FOR TREATMENT OF DOMESTIC WASTEWATER:

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RELATIVE DIFFERENCES IN CO₂ PRODUCTION

MAY 2016

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Directed by Dr. Ron Lavigne

Conventional wastewater treatment in the U.S. is an energy dependent and carbon dioxide emitting process. Typical mechanical systems consume copious amounts of energy, which is most commonly produced from fossil fuel combustion that results in the production of CO_2. The associated organic load is also metabolized by microorganisms into CO_2 and H_2O. As the desire to reduce CO_2 output becomes more prominent, it is logical to assess the costs of conventional treatment methods and to compare them to alternative, more sustainable technology. Vegetated Sand Bed (VSB) and Reed Bed (RB) systems are green technologies that provide environmentally superior treatment to conventional systems at a fraction of the cost both environmentally and economically. Using mass balance equations the net CO_2 produced from wastewater treatment at 3 conventional facilities, (Amherst, MA, Ithaca, NY and Shelburne-Buckland, MA) and 3 VSBs, (Lloyd, NY, Shushufindi Slaughterhouse, Ecuador and Shushufindi Municipal Facility, Ecuador), will be estimated. Carbon dioxide sources considered are BOD_5 microbial respiration, power demand, and sludge treatment. Using the BOD_5 reduction and the average daily flow from each of the conventional facilities, hypothetical VSB and RB systems will be sized for the 3 conventional systems. The land area for each hypothetical VSB and RB and the CO_2 reduction for equal treatment are estimated for each conventional facility. Estimates of annual CO_2 production for Amherst, Ithaca, and Shelburne-Buckland, are 3,021 metric tons, 5,575 metric tons, and 158 metric tons of, respectively. The annual CO_2 reduction potential for the conventional facilities Amherst, Ithaca, and Shelburne-Buckland, when compared to VSB and RB technology is estimated to be 74.0%, 83.2%, and 86.3% respectively. VSB and RB technology also provide promising results for sustainable wastewater treatment and reuse. Ammonium and nitrate reduction at the Joseph Troll Turf Plot VSBs were 72% and 88% respectively. The mean ammonium microbial growth rate constant was $- 0.14$ d^{-1} and the mean nitrate microbial growth rate constant was $- 0.23$ d^{-1}. The implications are ammonium and nitrate reduction is possible with VSB and RB technology. Further

investigation to understand the processes and fate of nitrogen including separate testing of ammonium and nitrate reduction are recommended.

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CHAPTER 1

INTRODUCTION

Due to increasing environmental damage to waterways of the U.S. prior to 1971, mounting concern and increasing political pressure led to the passing of the Federal Water Pollution Control Act Amendment of 1972 (PBS 2002). Also called the Clean Water Act (CWA 1972), it was the first amendment pertaining to wastewater discharge in the United States of America, (EPA 2007). The primary purpose of the CWA was "to make rivers and lakes fishable and swimmable" (CWA 1972), which established a foundation for regulating wastewater discharge into rivers (EPA 2007). Failing to foresee the long-term environmental and economic costs of conventional treatment and with little attention to public health, the discharge limit was and still is typically set at 30mg/L of BOD_5 and 30mg/L of SS to ensure sufficient oxygen in the water for fish and adequate clarity for swimming (EPA 2014). The CWA made it illegal to discharge wastewater into navigable waters from a point source without a permit (EPA 2014) so the National Pollutant Discharge Elimination System (NPDES) permit program was established to regulate the release of pollutants (EPA 2007).

According to the U. S. Environmental Protection Agency (EPA) over 75% of the current 320 million people in the US are served by centralized wastewater collection and treatment systems (EPA 2007). The United States Geological Survey (USGS) estimates that the average person uses 100 gallons of potable water per day which results in 24 billion gallons of sewage per day or 9.1×10^7 m^3 per day entering the municipal wastewater treatment plants across the country . The wastewater treatment at these conventional concrete and steel facilities most often relies on constant mechanical aeration powered by electricity produced primarily from fossil fuel combustion. The greatest demand for energy at a conventional wastewater treatment plant is due to the continuous aeration necessary for biological treatment ranging from 40% to 60% of the total plants energy demand (EPRI 2002).

Another environmental impact comes from the organic constituents in sewage which are broken down into the greenhouse gas carbon dioxide (CO_2) and H_2O using O_2 for the aerobic oxidation process. This indicates that with the increasing amount of wastewater entering treatment facilities, more CO_2 will be emitted into the atmosphere each year. The objective of this research is to investigate the sustainability of conventional wastewater treatment technology compared to Vegetated Sand Bed (VSB) and Reed Bed (RB) technology from a water reuse, CO_2 production, and energy consumption standpoint. For each conventional facility, a hypothetical VSB and RB system capable of receiving the same average daily flow and reducing the same concentration of BOD_5 will be postulated. The primary focus will be on total CO_2 production compiling the three major contributing sources: biological breakdown of wastewater, fossil fuel demands of operating the systems, and CO_2 produced from sludge processing.

The limitations of conventional technology for treating nutrients and complex organics like estrogen, antibiotics, and other pharmaceuticals and personal care products (PPCPs) have also become an international concern (CSS 2013). The new VSB treatment facility built and made operational in 2015 at the UMASS Turf Plots will be briefly discussed along with early influent and effluent nutrient data that will be used to model the kinetics of first order microbial decay for NH_4^+ and NO_3^-.

1.1 Wastewater Treatment Technology Overview

1.1.1 Conventional Technology

The most common wastewater treatment methods in the United States today utilizes concrete and steel systems designed to achieve improvement in the quality of wastewater (World Bank Group 2014). Primary treatment involves the partial physical separation of the liquids and suspended solids, ranging from rags on the collection screens to fats and sludge collected in the primary clarifier through sedimentation and flotation (EPA 2007). Secondary treatment involves the biological degradation of

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the dissolved organic matter in the wastewater converting it into new bacteria cells, carbon dioxide, and other by-products (EPA 2007). In the USA, <u>activated sludge</u> (AS) is the most commonly used conventional treatment particularly for new plants larger than 1 million gallons per day (MGD) (Pabi *et al.* 2013). This technology uses aeration and mixing to provide oxygen for the bacteria, fungi, and protozoa that metabolize the organic matter though respiration (NESC 2003). The aeration and mixing requirements of secondary treatment are noted as the single largest energy users in AS treatment plants (Carlson and Walberger 2007). Discharge from these facilities is typically directly into rivers that run into the ocean changing the partially treated fresh wastewater effluent into salt water.

1.1.2 Conventional Sludge Treatment

<u>Conventional sludge treatment</u> can involve various mechanisms to process solids and therefore can account for up to one third of overall plant energy use, (Pabi *et al.* 2013).   Sludge processing and the formation of biosolids as outlined by the United Nations Environment Program (UNEP) involves thickening, stabilization, and dewatering of the sludge before it can be disposed of most commonly by landfilling, land application, or incineration (2000). After wastewater treatment, sludge represents about 5% of the overall plant flow and contains about 2% dry solids, (Pabi *et al.* 2013). Thickening of sludge is often accomplished by gravity belts, centrifuges, or dissolved air flotation, all of which are energy consumers (Pabi *et al.* 2013). Stabilization is often accomplished by anaerobic or aerobic digestion but can also be accomplished by composting, (Pabi *et al.* 2013). A common mechanism for dewatering is by belt filter press and can achieve approximately 25%-35% solids, (Pabi *et al.* 2013). Dewatered sludge greater than 20% solids may be disposed of by landfilling. Alternatives to landfilling include incineration and land application (EPA 2006). Figure 1 shows the treatment steps in typical conventional activates sludge treatment.

Conventional Activated Sludge Technology
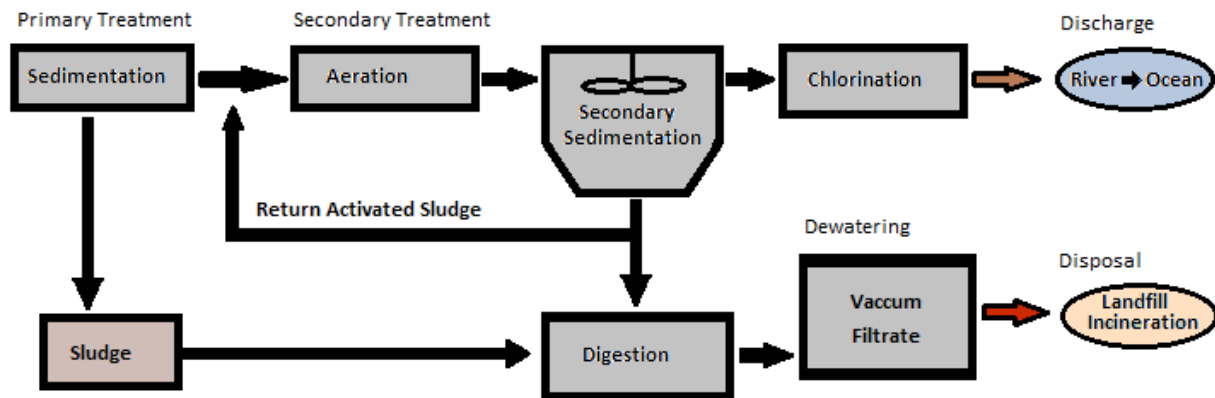
Figure 1. FATE OF WASTEWATER USING TYPICAL ACTIVATED SLUDGE TREATMENT

Conventional wastewater treatment facilities may not use all of the processes from Figure 1 or may include additional processes.

1.1.3 Vegetated Sand Bed (VSB) Technology

Conventional wastewater treatment is currently the most commonly used method in the United States however this study explores green technology. Vegetated Sand Beds (VSBs) are manmade treatment systems designed to emulate the biological capability of natural wetland processes to break down and remove contaminants from wastewater (R. Lavigne and K. Gloger 2008). A vertical sub-surface flow VSB receives wastewater distributed over the total area of the sand bed. The wastewater moves vertically through the beds where it is metabolized by communities of bacteria that have accumulated on the media. Similar to AS treatment this technology relies on the respiration of bacteria, fungi, and protozoa to metabolize the contaminants in the wastewater however, it has several characteristics which make it a more sustainable system.   Higher surface area on the media in VSB systems allow the establishment of attached growth microbes which strengthens treatment. The vegetation planted in VSBs is facultative wetland species which transport oxygen from the atmosphere

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into the root zone eliminates the need for mechanical aeration (James Hairston 2001). Figure 2

illustrates the flow of wastewater in a top fed vertical flow sub-surface Vegetated Sand Bed. Discharge

from VSB's can occur through evapotranspiration, infiltration, irrigation, or reuse of the treated water.

These mechanisms allow for treated water to re-enter the water cycle as well as recharge the

groundwater table which is being depleted by anthropogenic activity in many parts of the world.
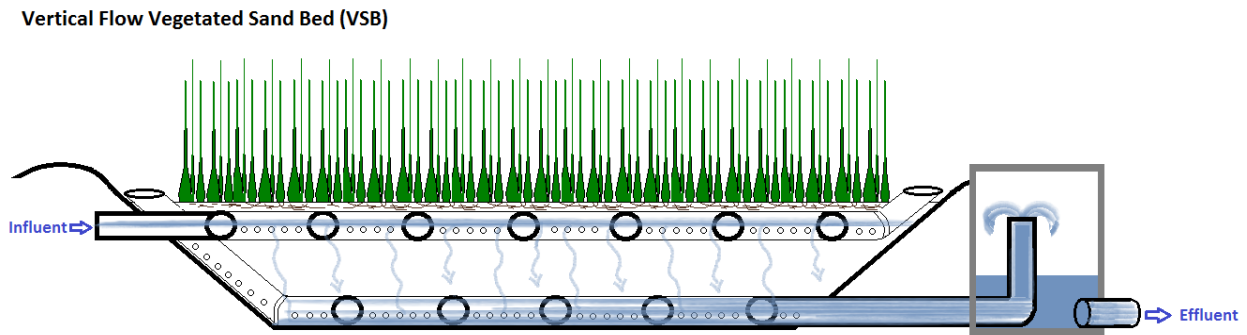
Figure 2. TOP-FED VERTICAL FLOW SUBSURFACE VEGETATED SAND BED CROSS-SECTIONAL AREA

Vegetated Sand Beds typically function in parallel trains or in a series with wastewater passing

through two or more beds. Figure 3 illustrates a typical vertical flow sub-surface VSB system.
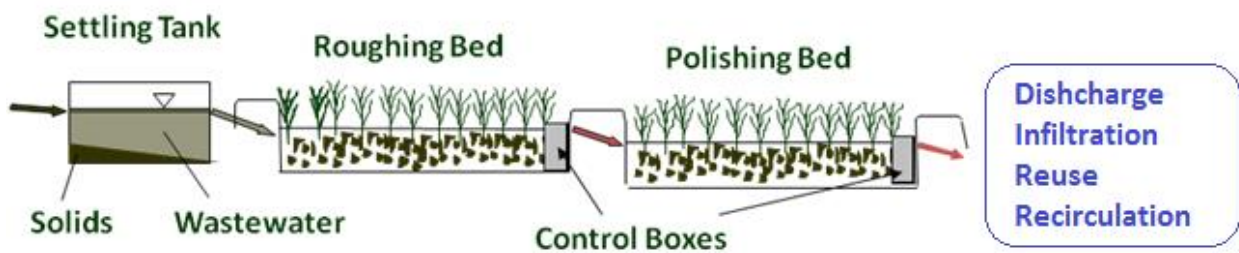
Figure 3. VEGETATED SAND BED SYSTEM (Adapted from Lavigne and Spokas 2008)

Figure 4 shows the processes of wastewater treatment when using VSB and RB technology as well as the fate of the water.

Vegetated Sand Bed (VSB) Technology with Reed Bed Dewatering Technology
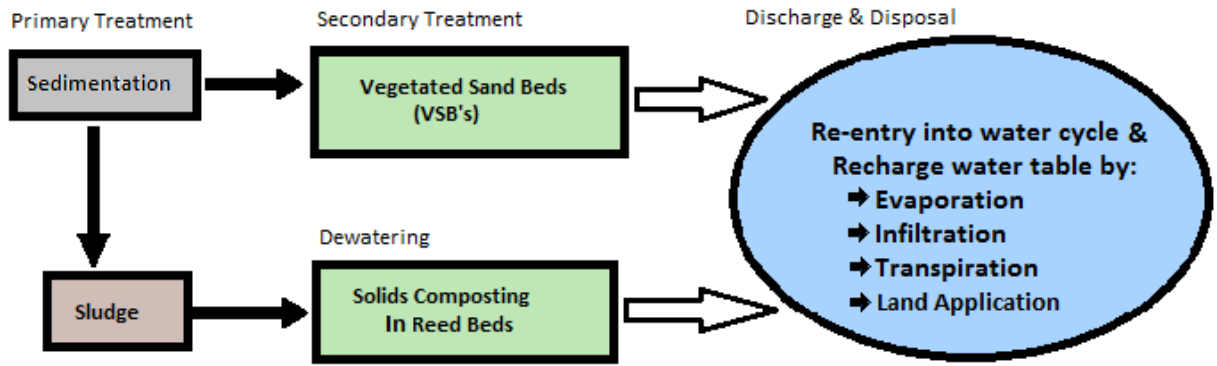
Figure 4. FATE OF WASTEWATER USING VEGETATED SAND BED TECHNOLOGY

1.1.4 Reed Bed (RB) Technology

Reed Beds are a natural alternative sludge management technology that dewaters, decomposes, and stabilizes sludge through drainage, evapotranspiration, plant uptake, and microbial degradation (Uggetti *et al.* 2012). A large portion of the energy used with conventional sludge treatment is aimed at reducing the water content. Reed Beds receiving sludge with 2% solids can eliminate approximately 95% of the water at a greatly lower cost. Over the course of 15+ years, an accumulative application of up to 130 feet of sludge reduces to 5 feet of dry biosolids in a Reed Bed system. Reed Beds are lined basins with a gravel and sand drainage network planted with *Phragmites australis*. They require no sludge removal between applications (Uggetti *et al.* 2011). Approximately 4" of sludge is applied to the Reed Bed every two weeks and dewaters as the liquid percolates through the media. The reeds transport oxygen to the rhizosphere aerating and enhancing the microbial breakdown (Brix *et al.* 1994).

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Similar to the VSBs, the Reed Beds require minimal energy input and maintenance. This technology replaces the steps required for sludge thickening, conditioning with polymers, dewatering, and frequent disposal which lowers the overall cost of sludge management (Kim and Smith 1997). Figure 5 illustrates the cross-sectional view of Reed Bed technology and how it dewaters, stores, and composts sludge over time (A. Krueger 1991).
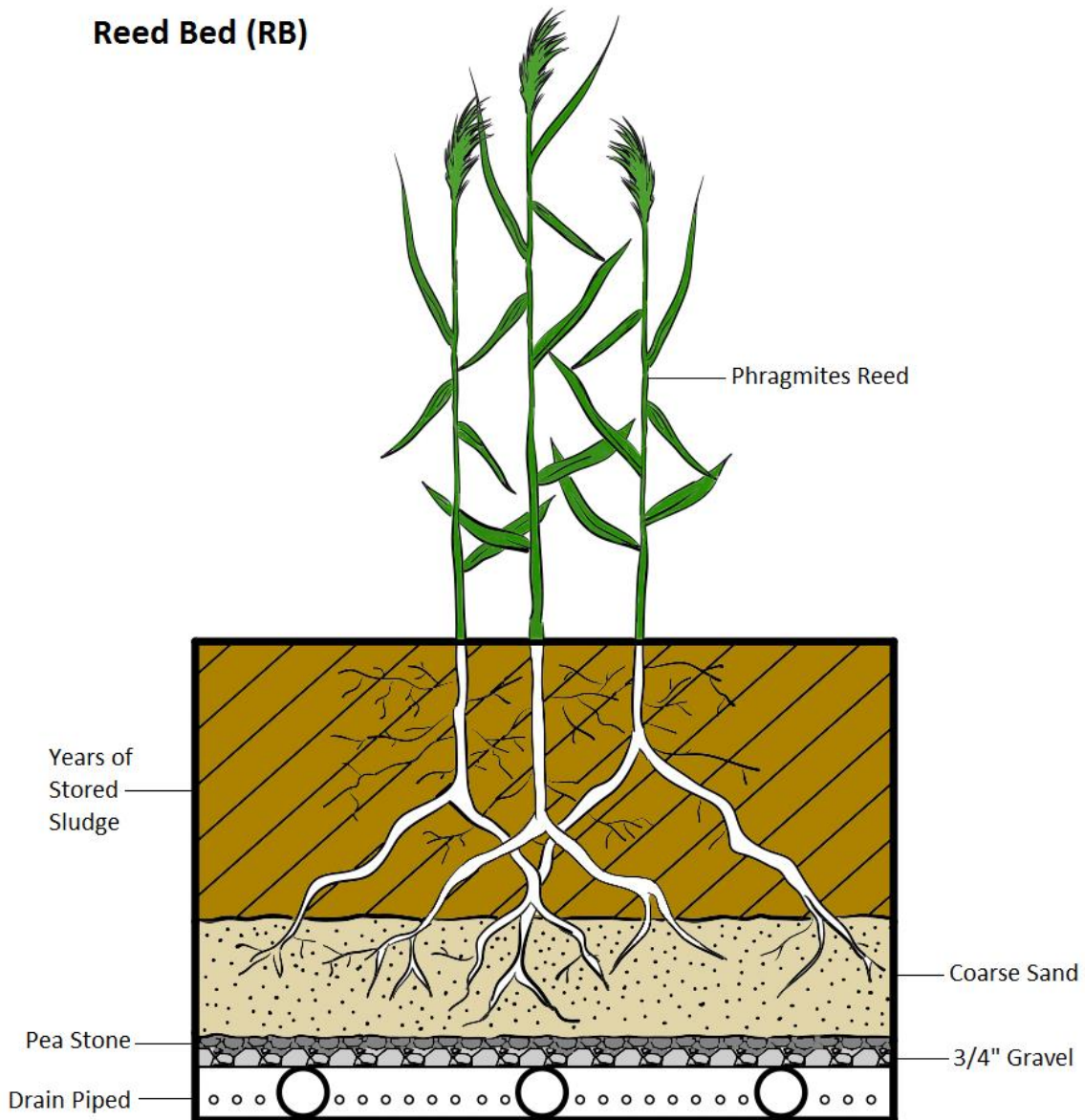
Figure 5. SLUDGE DEWATERING AND ACCUMULATION WITH REED BED TECHNOLOGY

(Adapted from A. Krueger (1991) Beds: A Low-Cost Sludge Treatment System)

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1.2 Vegetated Sand Bed Processes

1.2.1 Biochemical Oxygen Demand Removal

The removal of BOD_5 in a subsurface-flow VSB is enhanced by the aerobic and anaerobic microbial interactions that facilitate a variety of metabolic pathways for attached growth organisms. The solid media in the Vegetated Sand Bed provides a large fixed surface area where organisms can build up populations that are not flushed through the system. Coarse sand with a diameter of 2 mm has the surface area of approximately 10^{-3} m^2/cm^3, (G. Hirasaki 2004), which translates to 1000 m^2/m^3 surface area in addition to any root surfaces present. A comparable volume in free-water-surface wetland might have 15-50 m^2/m^3 available surface area, (Reed *et al.* 1995).

The size of the aerobic and anaerobic zones in a VSB fluctuate due to multiple conditions and plays an important role in the type of treatment accomplished. Oxygen gas is pumped by the facultative wetland plants to the root zone where the excess diffuses into the VSB media (Spokas and Lavigne 2008). An oxic annulus is created around the roots which results in a zone of aerobic biological and chemical processes such as the oxidation of carbon and nitrogen (Kahl 2004). Figure 6 shows the cross sectional area of a root found in a VSB. The size of the annulus is determined by the demand of oxygen from aerobic processes as well as the plants' ability to provide oxygen to the roots. Influent wastewater with high concentrations of BOD_5 can result in bacteria using available O_2 at faster rates and therefore can cause the oxygen annulus around the roots to decrease. An additional source of oxygen in the VSB system is found in top-loading vertical flow VSBs where the suction created by percolation water, draws oxygen into the subsurface of the system.
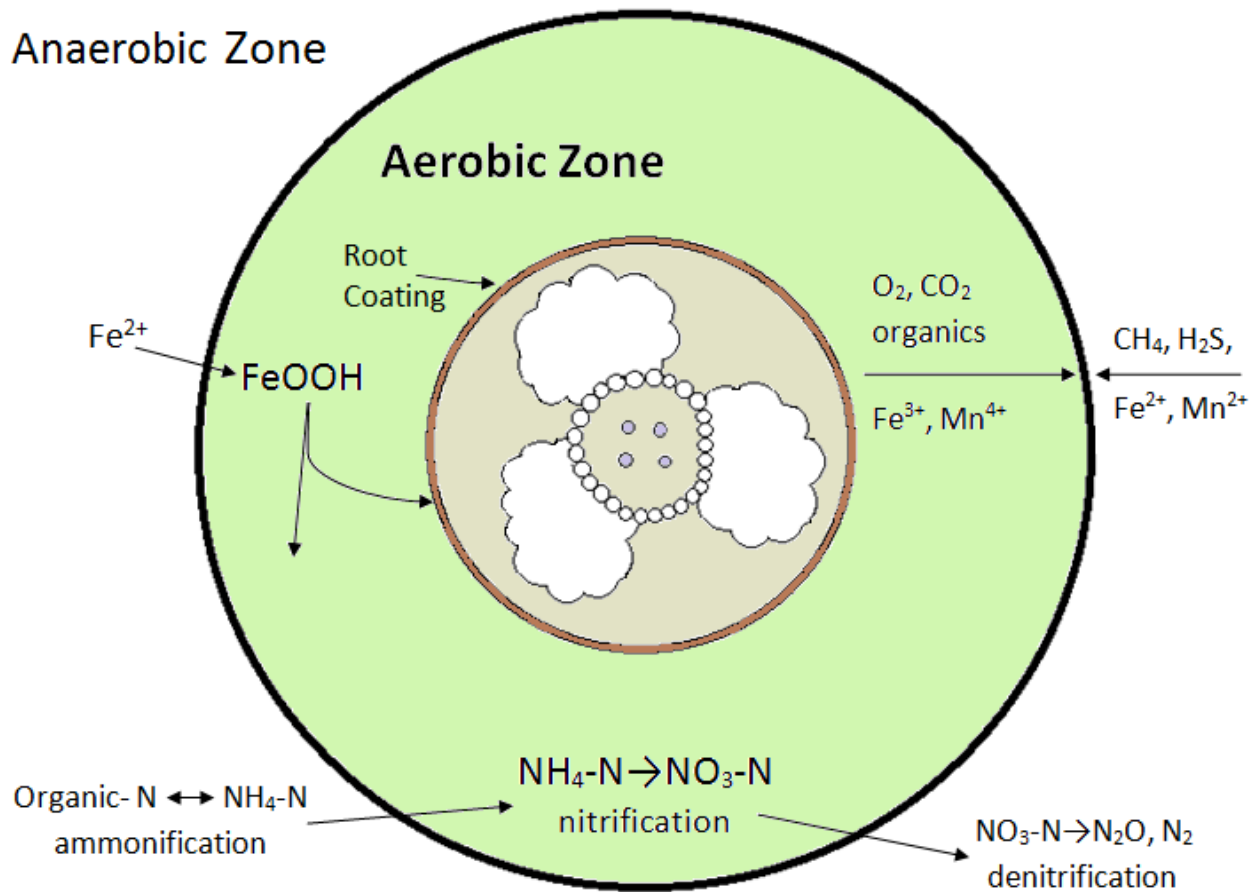
Figure 6. CROSS-SECTION OF WETLAND ROOT ANNULUS
Dynamics of root-growth media interface (Adapted from Reed *et al.* 1995).

Figure 7 illustrates a side view of the distribution of oxygen in the root zone of a VSB or RB.

New plants will have minimal root systems and overloading the system with high concentrations of

BOD_5 or ammonium could deplete the oxygen levels and stress the plants. The operation of a VSB must

be monitored to maintain the quantity of oxygen needed to support the aerobic treatment processes

and to provide oxygen needed for the growth of the vegetation.
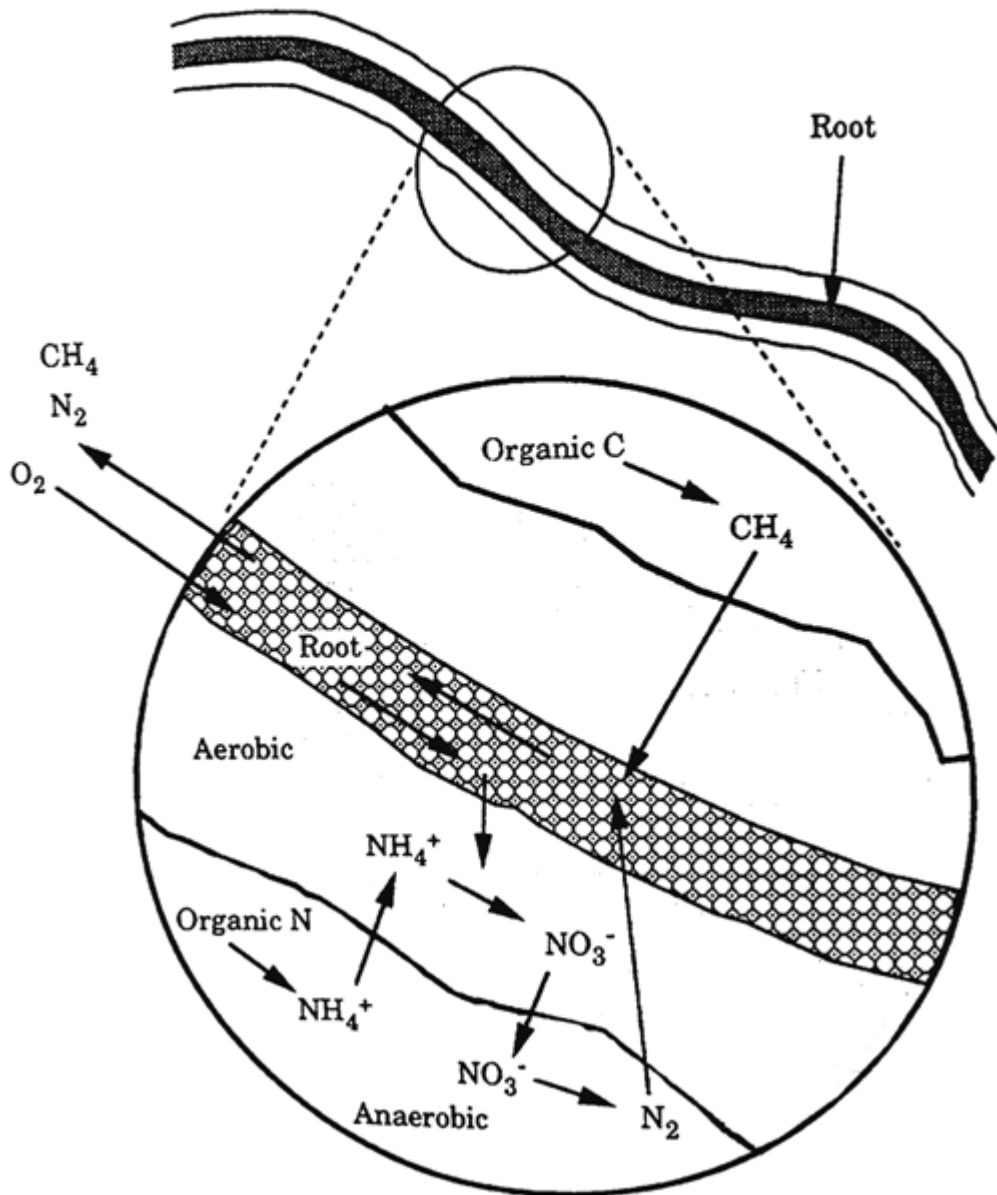
Figure 7. DISTRIBUITION OF AERATION FROM WETLAND PLANT ROOT SYSTEMS
(Adapted from Kadlec and Knight, 1995)

The distribution of oxic and anoxic zones is not solely a function of depth. The oxygen

distribution found in VSBs and RBs is dependent on the depth and extensiveness of the root system.

1.2.2 Kinetics of VSB Design

The desired treatment time in a VSB system is typically calculated using a first order decay

model for BOD_5 reduction (Kahl 2004) see equation [1].

$$\frac{dC}{dt} = -k \cdot C \qquad [1]$$

Where C= the concentration of BOD_5 remaining in mg/L

   t= treatment time in days

   k= typical domestic sewage first order decay rate constant 1.2 days^{-1} for temperate

   climates and 1.5 days^{-1} in tropical climates

The first order decay rate constant can be adjusted for different ambient temperatures using

equation [2].

$$\frac{k_T}{k_{20}} = 1.06^{T-20} \qquad [2]$$

After separating the variables *C* and *t* and integrating, equation [1] can be expressed in terms of

concentration or time shown in equation [3] and equation [4].

$$C_t = C_0 \times e^{-k \cdot t} \qquad [3]$$

$$t = \frac{1}{k} \ln \left(\frac{C_0}{C_t} \right) \qquad [4]$$

Where C_0= initial concentration of BOD_5 (mg/L)

   C_T= concentration of BOD_5 at time t (mg/L)

Once the required treatment time is calculated using initial and desired effluent concentration,

the size of the wetland can be calculated using equation [5].

$$Q = \frac{A \cdot h \cdot f}{t} \qquad [5]$$

Where Q= daily flow rate (volume/time)

      t= treatment time in days (t)

      A=wetland area (L^2)

      h=wetland depth, (L)

      f= porosity of media (dimensionless)

CHAPTER 2

MATERIALS AND METHODS

Most wastewater systems receive influent with organic matter in the form of proteins, carbohydrates, and fats which are the biomass produced from photosynthetic activity. For the following mass balance, the BOD_5 in the wastewater will be represented as glucose because it and the organics have a basic stoichiometric relationship. The fats, carbohydrates, and proteins in BOD_5 are expressed as glucose in equation [6].

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O \qquad [6]$$

This equation stoichiometrically converted to kilograms, provides a foundation with which the amount of CO_2 sequestered and released can be approximated. Using changes in the BOD_5 influent and effluent, the amount of organic matter respired during treatment can be estimated. Equation [7] predicts the amount of CO_2 produced.

180kg $C_6H_{12}O_6$ + 192kg O_2 ↔ 264kg CO_2 + 108kg H_2O (Lavigne and Gloger, 2008)   [7]
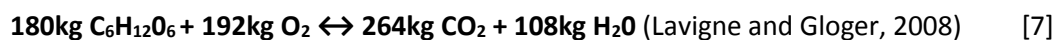
Example Calculations:

Assuming raw wastewater BOD_5 of 200mg/L and desired effluent BOD_5 of 25mg/L

BOD_5 removal = 175 mg/L =.175kg/m^3

Applying this reduction to the total U.S. sewage production of $9.1 \times 10^7 m^3$/day, 1.7×10^7 kgBOD_5/day are biodegraded to CO_2 and water.

Using equation [7], the CO_2 emissions from microbial respiration is 25 million kg CO_2/day.

2.1 Conventional Wastewater Treatment Sites-Three Case Studies

Photo 1, 2, & 3 Amherst Wastewater Treatment Plant (Courtesy of Treatment Plant Operator 2013)

2.1.1 Amherst Wastewater Treatment Plant, MA

The Amherst Wastewater Treatment Plant (AWWTP) processes the municipal wastewater from the Town of Amherst and the University of Massachusetts. The facility uses activated sludge (AS) to accomplish secondary treatment. The technology is powered by continual aeration and electric pumps move the wastewater to the various stages and locations. The plant receives an average daily flow of 3.85MGD with a peak of 8.54MGD in 2014. The final treatment step is chlorination that occurs in the

pipe that discharges the effluent into the Connecticut River (AWWTP 2014). Sludge management at the

Amherst Wastewater Treatment facility is a multiple step process. Sludge from the primary clarifier is

combined with sludge from the secondary clarifiers with an average 4% solid before it is sent to the

gravity belt thickener where it is partially dewatered. The Thickened Waste Activated Sludge (TWAS)

has 6% solids and it is stored until pumped into tanker trucks and transported to Hartford landfill in

Connecticut. In Hartford it is dewatered, incinerated, and landfilled. The AWWTF produces

approximately 4.2MG/year of sludge with 6% solids.

Photo 4 Ithaca Area Wastewater Treatment Facility (Courtesy of the Ithaca Journal 2008)

2.1.2 Ithaca Area Wastewater Treatment Facility, NY

The Ithaca Area Wastewater Treatment Facility (IAWWTF) treats residential wastewater from the city, two universities, and industrial waste from Emerson Power Transmission Company. The average daily flow is 6.5MGD (Wastewater Treatment Ithaca 2006). Secondary treatment is accomplished by activated sludge with four aeration basins operating in a plug-flow mode, each having 0.5 MG of volume and a fine bubble diffuser system.   Disinfection occurs in the pipe that discharges the effluent into Cayuga Lake which is part of the Great Lakes Basin, (MWWT 2005). Primary and secondary sludge are combined and pumped to two gravity thickeners. The sludge with an average of 4% solids is pumped to a belt filter press that operates five days per week.   The dewatered sludge leaves the facility at about 22% solids and the sludge cake is landfilled, (NYSERDA 2005).

Photo 5 Shelburne-Buckland Reed Bed (Courtesy of NEWS-USA 2002)

2.1.3 Shelburne- Buckland Wastewater Treatment Plant, MA

The Shelburne-Buckland Wastewater Treatment Plant was constructed in 1974 to serve two densely populated business districts. The facility uses activated sludge treatment with aerobic sludge digestion and was built with a maximum capacity of 0.25MGD. On average this wastewater treatment plant processes 0.144MGD (J. S. Begg *et al.* 2001), and the effluent is discharged into the Deerfield River. Sludge management originally utilized sand drying beds followed by trucking of the cake to the town landfill. Limitations with the sand drying beds included solids washing out during rain events, limited sludge storage in the digester, (approximately 52,000 gallons or 6 weeks), and the inability to dewater during the winter, (D. Fleuriel 2008). In 1984 a sludge storage lagoon was constructed but due to an

inadequately sized surface aerator, the sludge lagoon went anaerobic causing significant odor problems.

Alternative solutions were attempted by renting a belt filter press for dewatering during winter months,

but costs remained high and odor problems continued. Finally, in 1992 the decision was made to

convert the sludge management program to Reed Bed Technology.

By 1995, the Shelburne-Buckland wastewater treatment plant had three operational Reed Beds

with a total surface area of 12,000 square feet. The beds dose on a 3 week schedule receiving

approximately 25,000 gallons per dose and 450,000 gallons per year with 1.5% solids.   Over the course

of a 6 year study, the dewatering efficiency of the Reed Bed system was determined to be 93%, (J.S.

Begg *et al.* 2001). The average BOD_5 effluent concentrations leaving the Reed Bed systems were found

to normally be around 6mg/L which is well below regulatory standards and therefore could be

discharged directly into the river (J.S. Begg *et al.* 2001). Electrical demands for the plant include

pumping sewage from the two villages, recirculating the wastewater, and aeration in the aeration tanks

and digester (D. Fleuriel 2008). The only waste removed from the site is grit and screenings collected at

the head works.

2.2 Vegetated Sand Bed Technology

Photo 6 Lloyd Vegetated Sand Beds (Courtesy of NEWS-USA 2006)

2.2.1 Zumtobel Staff Lighting VSB Lloyd, NY

Zumtobel Staff Lighting is located in the Town of Lloyd NY, and is one of the largest employers in the area. In 2000, their conventional septic system went into failure and the company seemed to have only two options: connect to the nearest sewer line for 3 million dollars or to replace the mound system using an area previously dedicated for the future expansion of the company. Another alternative solution was to relocate the company to New Jersey. Before a decision was made, the sewer and water commissioner, John Jankiewicz proposed the implementation of a Vegetated Sand Bed; a sustainable green plant-powered alternative technology that decentralizes wastewater treatment.   Considering the

costs of connecting to the municipal AS treatment system, the loss of local jobs, and the expansion of the company versus the benefits of a VSB for wastewater treatment, the failing septic system in Highland NY went green.

The Lloyd VSB design consists of four treatment cells in series with each bed constructed at 2,500 ft^2 for a total area of 10,00ft^2. The septic tank effluent has wastewater first passing through the two beds planted with *Phalaris arundinacea,* commonly known as Reed Canary Grass and then through two beds planted with *Phragmites communis.* The design flow rate was 10,000 GPD with an average daily flow of 1,200 GPD in 2005. The system was oversized at 400% to facilitate possible future connections from other wastewater sources in the area (Lavigne and Spokas 2009). The effluent is discharged to a small pond (Kahl 2004).

2.2.2 Shushufindi, Ecuador, S.A.

Shushufindi is a town in Ecuador, South America, at the headwaters of the Amazon River. Due to the expansion of the oil industry, the population of Shushufindi has grown rapidly over the years. This development has led to degradation in the environment of the town and consequently other settlements down river. To compensate for the continual increase of wastewater that received little to no treatment, Texaco donated money to build a sewage collection system in 1997. After assessing the total cost, longevity, and treatment quality, the wastewater management technology selected for use was Vegetated Sand Beds. The first system was implemented at the town slaughterhouse, where previously the facility discharged its untreated wastewater directly into the Rio Shushufindi (Kahl 2004).

Photo 7 Slaughterhouse Vegetated Sand Beds, Shushufindi, Ecuador (Courtesy of NEWS-USA 1999)

2.2.2.1 Shushufindi Slaughterhouse VSB, Ecuador

The VSB system at the slaughterhouse was designed to treat 6,600 gallons/ day or 25m^3/d of slaughtered animal wash water. The influent primarily consists of blood, urine, feces, and undigested plant material making it a high BOD$_5$ and suspended solids wastewater. After passing through two settling tanks in series with a total volume of about 10,000 gallons or 38m^3, the wastewater passes through two wetland cells also operated in series, with an area of 8,600 ft^2 or 800m^2. The treatment cells are planted with a local wetland plant *Echinochloa polystachya*, or commonly known as German Grass. The grass has a primary productivity of 4kg/m^{2}yr (Kahl 2004). The VSBs require minimal maintenance because they were designed to operate by gravity. The system does not use any electricity (Kahl 2004).

Photo 8 Municipal Vegetated Sand Beds, Shushufindi, Ecuador (Courtesy of NEWS-USA 2008)

2.2.2.2 Shushufindi Municipal VSB, Ecuador

The Shushufindi Municipal VSBs were designed to treat 0.53 MGD or 2000 m^3/d of municipal wastewater. Four 13,200 gallon or 250 m^3 settling tanks start the treatment and connect to four parallel treatment trains. Each train has two VSBs with a total of 8 units each unit being 21,500 ft^2 or 2,000 m^2. Similar to the VSB at the Shushufindi slaughterhouse treatment units operate by gravitational flow and they are planted with German Grass. The Shushufindi Municipal VSB also has 4 Reed Beds located adjacent to the settling tanks that are used to dewater the sludge (Kahl 2004).

CHAPTER 3

COMPARATIVE DATA

The objective of this study was to compare the sustainability of conventional wastewater treatment systems to Vegetated Sand Bed and Reed Bed technology.   In order to accomplish such a comparison, it was necessary to categorize and group the most critical impacts of wastewater treatment which include the fate of fresh water, CO_2 production, and energy consumption. Energy consumption and the production of carbon dioxide will be compared by estimating the metric tons of CO_2 produced from BOD_5 microbial respiration and power demand at each facility.

3.1 Current Treatment

3.1.1 Amherst Wastewater Treatment Plant, MA

3.1.1.1 Biochemical Oxygen Demand

The average flow in 2015 was 3.51 million gallons per day (MGD) and it was the lowest flow of 2012, 2013, 2014, and 2015. Figure 8 illustrates the average daily flow to Amherst WWTP from 2012 to 2015.
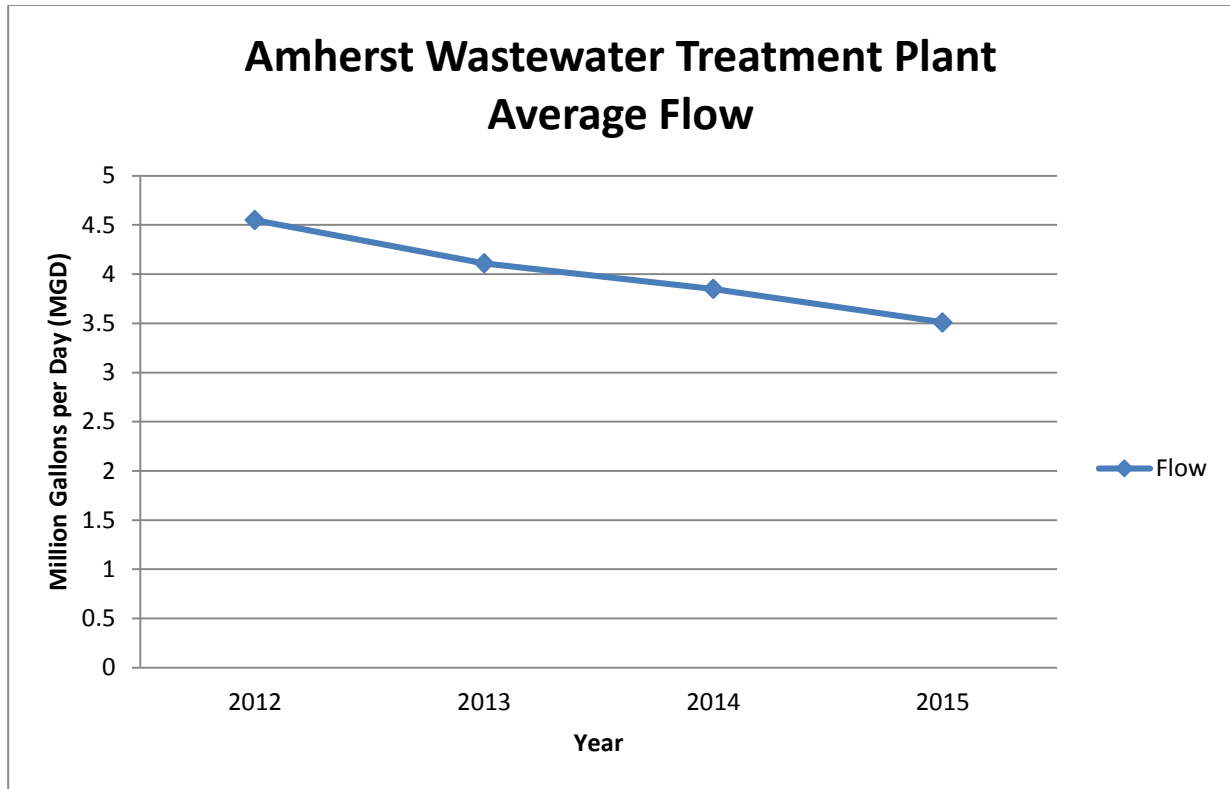
Figure 8. AVERAGE FLOW AT AMHERST WASTEWATER TREATMENT PLANT 2012-2015
Data from Amherst Wastewater Treatment Facility

The wastewater at Amherst enters the plant with an average 227mg/L of BOD_5 and typically leaves at 2mg/L resulting in an average 99% removal rate for 2015. Figure 9 presents the influent and effluent BOD_5 values at Amherst WWTP from 2012-2015. The change in influent BOD_5 and effluent BOD_5 can easily be compared to determine the amount of BOD_5 removed.
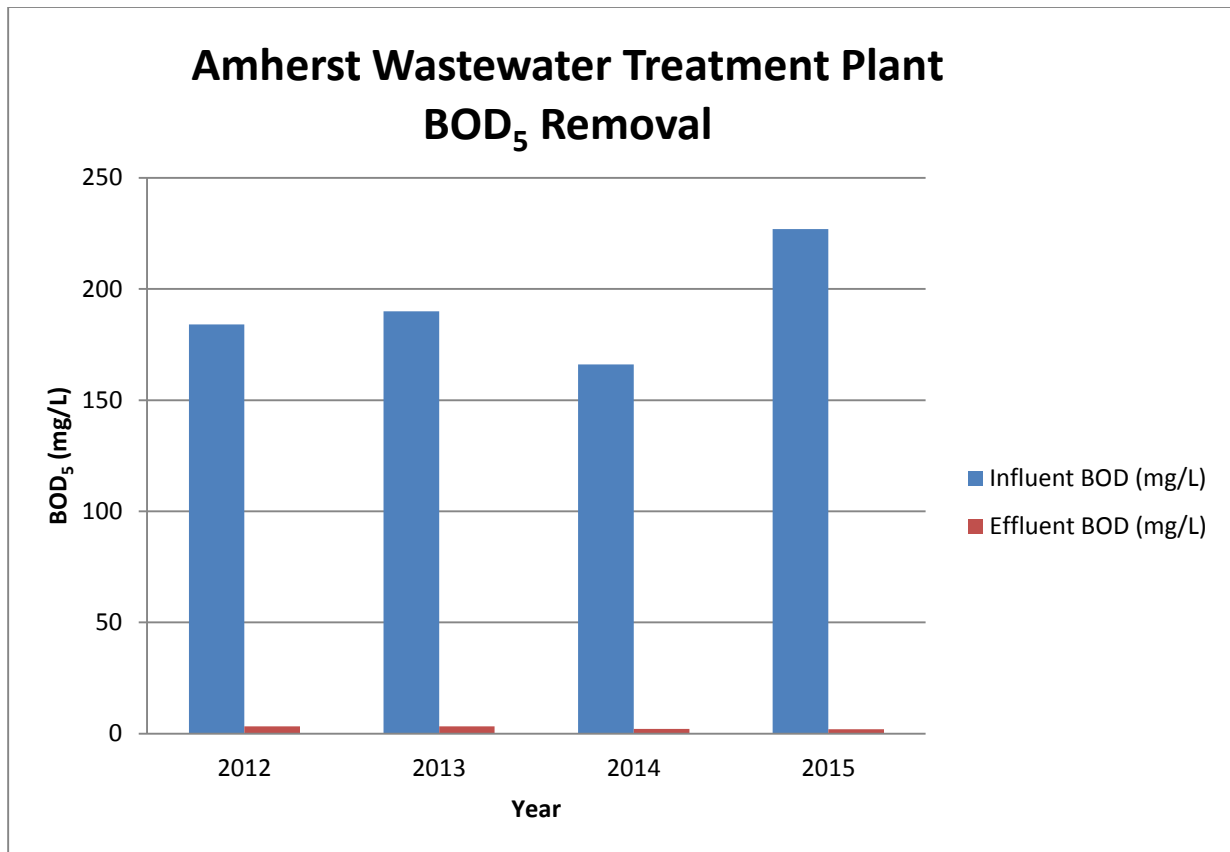
Figure 9. AVERAGE INFLUENT AND EFFLUENT BOD$_5$ AT AMHERST WWTP 2012-2015.

Table 1 provides values for average daily flow, influent BOD$_5$, and effluent BOD$_5$ per day and per year from 2012-2015. Data was obtained from Amherst Wastewater Treatment Plant.

Table 1. AVERAGE DAILY FLOW, INFLUENT BOD$_5$, AND EFFLUENT BOD$_5$

Amherst WWTP				
Year	**2012**	**2013**	**2014**	**2015**
Average Flow (MGD)	4.55	4.11	3.85	3.51
Influent BOD$_5$ (mg/L)	184	190	166	227
Effluent BOD$_5$ (mg/L)	3.25	3.25	2.14	2.00

Provided data from AWWTP manipulated to show average flow, BOD$_5$ influent and effluent per day.

3.1.1.2 Carbon Dioxide

The carbon dioxide produced from BOD_5 degradation at the Amherst Wastewater Treatment Facility was calculated using the average daily flow. The average BOD_5 microbial respiration in mg/L was calculated per day using the values from Table 1. Multiplying the average BOD_5 removal concentration by the average daily flow, the total BOD_5 in kilograms removed per day was calculated. Estimating CO_2 produced from the average BOD_5 reduction is calculated by applying equation [7] which stoichiometrically expresses the relationship between BOD_5, represented as glucose, and CO_2 production. Table 2 presents the calculated values.

In 2015, the average influent BOD_5 was 227mg/L and the effluent BOD_5 was 2mg/L

BOD_5 removal = 225 mg/L =0.225kg/m^3

$$0.225 \frac{kg}{m^3} \cdot \frac{1 m^3}{264\ gal.} = 8.52 \text{ x } 10^{-4} \text{ kg of } BOD_5 \text{ per gallon}$$

Average Flow of 3.51MGD

$$3,510,000\ \frac{gallons}{day} \cdot 8.53\ x\ 10^{-4}\ \frac{kgBOD_5}{gallon} = 2,990 \text{ kg } BOD_5 \text{ per day}$$

Using equation [7], CO_2 emissions from microbial respiration, 1.47 kg of CO_2 is produced for every 1 kg of $C_6H_{12}O_6$, (represented by BOD_5).

180kg $C_6H_{12}O_6$ + 192kg O_2 $\leftrightarrow$ 264kg CO_2 + 108kg H_2O [7]
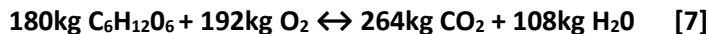
2,990 kg BOD_5 /day x 1.47kg CO_2/ 1 kg BOD_5

Estimated CO_2 production from microbial respiration is **4,400 kg/ day** or **1,600,000 kg/year.**

TABLE 2. AVERAGE BOD$_5$ REMOVAL AND ESTIMATED CO$_2$ PRODUCED

Amherst WWTP				
Year	**2012**	**2013**	**2014**	**2015**
Average Flow (MGD)	4.55	4.11	3.85	3.51
BOD$_5$ Removed (mg/L)	181	187	164	225
Average BOD$_5$ total (kg/day)	3,120	2,910	2,390	2,990
Average CO$_2$ Produced (kg/day)	**4,590**	**4,280**	**3,520**	**4,400**
Average CO$_2$ Produced (kg/year)	**1,680,000**	**1,560,000**	**1,280,000**	**1,600,000**

Flow and BOD$_5$ data was obtained from Amherst Wastewater Treatment Plant.

The average daily flow to Amherst WWTP has continually decreased from 2012-2015. Figure 10 plots the relationship between CO$_2$ production and average daily flow from 2012-2015. It is clear that the CO$_2$ produced from the biological processes in wastewater treatment is influenced by both the flow of the plant and by the BOD$_5$ metabolized.
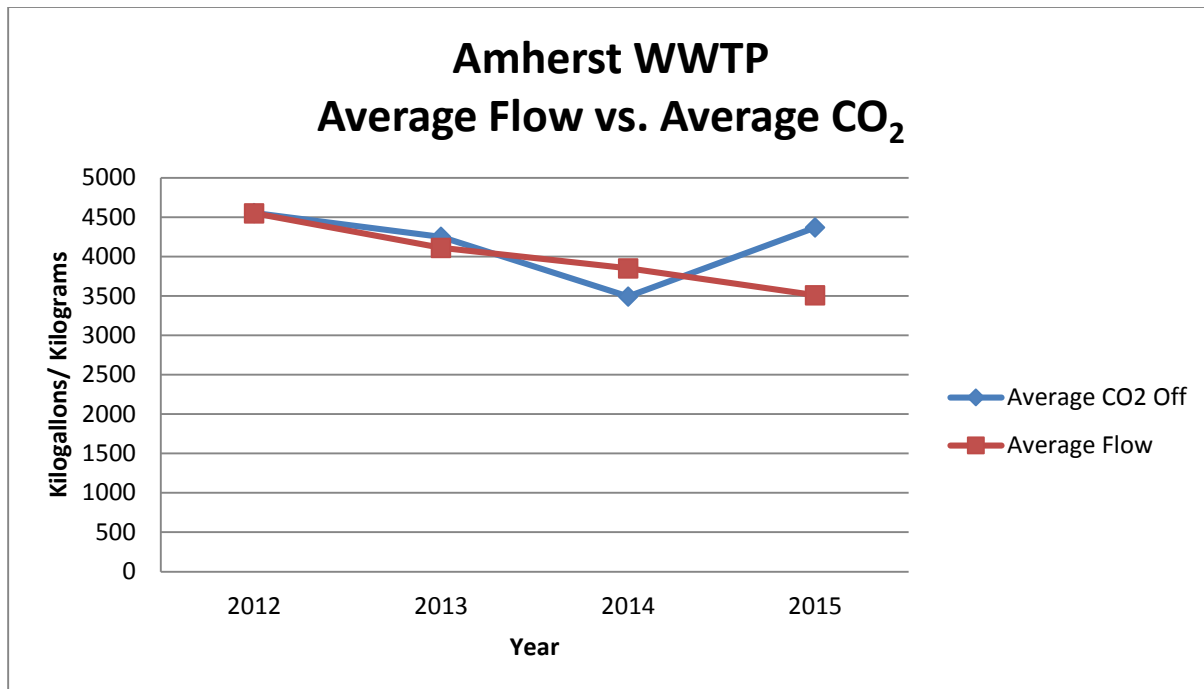
Figure 10. AVERAGE DAILY FLOW AND AVERAGE CO₂ PRODUCED AT AMHERST WWTP

Flow data from Amherst Wastewater Treatment Plant. Provided average daily flows from AWWTP plotted against estimated kilograms of CO_2 produced from microbial respiration of BOD_5.

3.1.1.3 Power Demand

The electric meter at the Amherst Wastewater Treatment Facility includes all onsite power usage from lights, pumping, and aeration. Not included in these figures are the power demands from the 20 pumping stations located across Amherst and the sludge transport and incineration costs in Hartford, CT. Figure 11 presents the relationship between the average flow and the electrical demand used for treatment. The electrical demand per MGD treated increased over the past three years. Figure 11 suggests that an increase of BOD_5 microbial respiration in conventional facilities can result in greater energy demands per MGD.

28
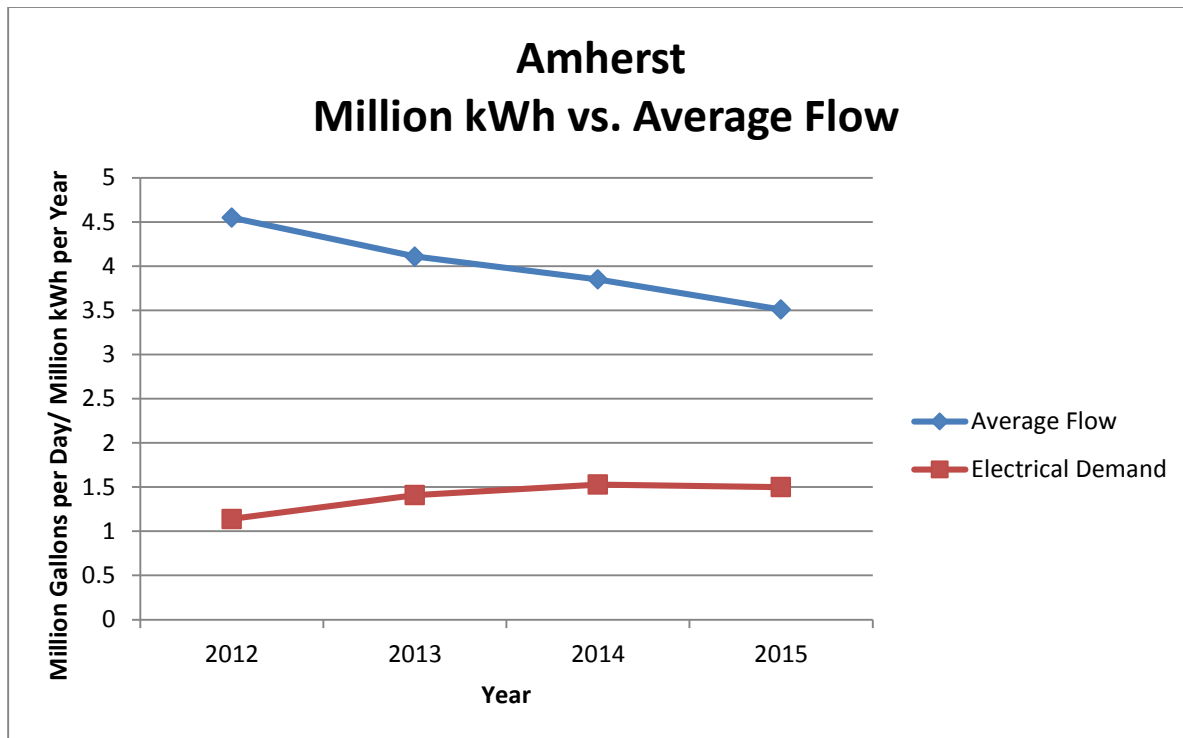
Figure 11. AVERAGE DAILY FLOW COMPARED WITH AVERAGE KWH DEMAND
Flow and power data obtained from Amherst Wastewater Treatment Plant. Data provided by AWWTP
shows average daily flow and average electrical demand from 2012-2015.

The Amherst Wastewater Treatment Facility reported using 1,500,000 kWh in 2015. Using the

CO_2 output conversion rate, (EPA 2014), it is estimated that 1,030 metric tons of carbon dioxide was

produced in 2015.

$$6.89551 \times 10^{-4} \text{ metric tons } CO_2 \text{ / kWh} \qquad \text{(EPA 2014)}$$

$$1{,}500{,}000 \text{ kWh} \cdot 6.89551 \times 10^{-4} \text{ metric tons } CO_2 \text{ / kWh} = \textbf{1,030 metric tons } CO_2 \text{ in 2015}$$

Table 3 shows the average daily flow, annual kWh usage, kWh per MG treated, and total annual

metric tons of CO_2 produced. Despite the decreasing flow from 2012-2015, the annual electrical

demands increased.   As shown in Table 3, the CO_2 produced per MG treated has increased from 2012-

2015 at Amherst.

Table 3. AVERAGE DAILY FLOW, KWH USAGE, AND ESTIMATED CO₂ PRODUCTION

Amherst WWTP	Power	Demand		
Year	**2012**	**2013**	**2014**	**2015**
Average Flow (MGD)	4.55	4.11	3.85	3.51
Annual Usage kWh	1,140,000	1,410,000	1,530,000	1,500,000
KWh/MG	684	940	1,090	1,170
Total Annual Metric tons of CO₂	**786**	**972**	**1,060**	**1,030**

Provided average daily flow and power demand data from Amherst WWTP 2012-2015. Calculated annual metric tons of CO_2 produced from power demand.

Figure 12 presents the calculated kWh use per million gallons treated taken from Table 3. The data shows the continual increase in kWh demand per MG from 2012-2015.
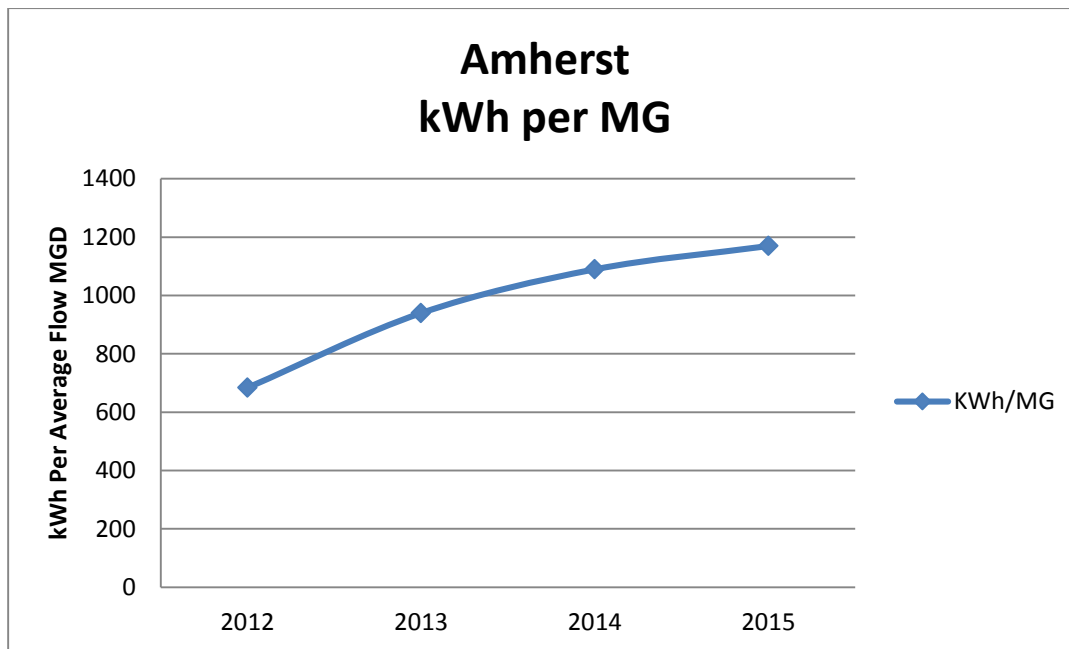
Figure 12. RELATIONSHIP OF KWH PER MILLION GALLONS OF WASTEWATER
Provided data for 2012-2015 from AWWTP.

3.1.1.4 Sludge Treatment

Sludge processing at the AWWTP is done by partial dewatering using a gravity belt thickener. The Thickened Waste Activated Sludge in its final state consists of 6% solids and is stored until it can be transported. No further electrical demands are included in the summary of the power needs for the AWWTP. In order to have a more complete account of the energy demand required to process wastewater with conventional treatment, the final sludge treatment processes were estimated.

In 2015, AWWTP sent 622 tractor trailers of liquid sludge with 6% solids to the Hartford Incinerator. According to the United States Bureau of Transportation, the average combination truck fuel consumption in 2013 was 5.8 miles/gallon. The round trip from AWWTP to the Hartford Incinerator is 106 miles.

$$\frac{1 \ gallon}{5.8 \ miles} \cdot 106 \text{ miles} \cdot \frac{622 \ trucks}{year} = 11{,}400 \text{ gallons of diesel} \cdot year^{-1}$$

According to the US EPA, the average CO_2 emissions resulting from diesel fuel is 10.1kg of CO_2 / gallon of diesel (2005).

$$\frac{11{,}400 \ gallons}{year} \cdot \frac{10.1 \ Kg}{gallon \ of \ diesel} = 115{,}000 \text{ kg of } CO_2/\text{year or 115 metric tons of } CO_2/\text{year}$$

Photo 9 Hartford Incinerator (Courtesy of CTRA News)

The final treatment is accomplished by a Nichols-Herreshoff Multiple Hearth Incinerator at the Hartford landfill in Connecticut. According to the equipment and operation permit issued by the Bureau of Air Management, this incinerator has nine hearths with a zero hearth afterburner and a Venturi-Pak scrubber as an air quality control unit, (Bureau of Air Management 2013). The maximum annual sludge charging rate is 21,060 Dry Tons (DT)/yr, and the primary fuel fired in the unit is sewage sludge. The auxiliary burner system operates on natural gas and the maximum annual fuel firing rate is 180,000 therms/year (Bureau of Air Management 2013). With this information we can calculate the approximate carbon dioxide produced during the final sludge treatment process. Table 4 shows the calculated CO_2 production estimates from Amherst sludge using known energy demands from the processes.

Table 4. PRODUCTION OF CO$_2$ FROM SLUDGE INCINERATION AND TRANSPORT

Year	2013	2014	2015
INCINERATION	Dry	Ton Sludge/ Year	(DT/yr)
Amherst WWTP	1040	1000	1020
Hartford Incinerator (HI)	21,100	21,100	21,100
Percent of HI Use by AWWTP	4.93%	4.74%	4.83%
Natural Gas (Therms/ year)	88700	85300	87000
Metric Tons of CO$_2$/year	469	455	463
TRANSPORT	Diesel	Consumption	
Amherst Trucks/ year	652	634	622
Gallons Consumed/ year	11,900	11,600	11,400
Metric Tons of CO$_2$/ year	120	117	115
Total Offsite Metric Tons CO$_2$	**589**	**572**	**578**

Provided annual sludge data from AWWTP. Estimated energy values for transport and incineration of sludge at Hartford Incinerator.

3.1.2 Ithaca Area Wastewater Treatment Facility, NY

3.1.2.1 Biochemical Oxygen Demand

The average Flow from Ithaca was 7.03 MGD in 2003. The wastewater entered the plant with an average 178mg/L of BOD$_5$ and left at 8.7 mg/L resulting in an average 95% removal rate. Table 5 provides values for average daily flow, influent BOD$_5$, and effluent BOD$_5$ from 2002-2003.

Table 5. AVERAGE DAILY FLOW, INFLUENT BOD$_5$, AND EFFLUENT BOD$_5$

Ithaca AWWTF		
Year	**2002**	**2003**
Average Flow (MGD)	6.48	7.03
Influent BOD$_5$ (mg/L)	194	178
Effluent BOD$_5$ (mg/L)	14.4	8.7

Provided average flow, influent BOD$_5$, and effluent BOD$_5$ from Ithaca WWTF, (NYSERDA 2005).

3.1.2.2 Carbon Dioxide

The carbon dioxide produced by the plant was calculated from the average BOD_5 microbial respiration and the average daily flow. Applying the values from Table 5, the average BOD_5 removed per day was calculated. Using the removal concentration of BOD_5 and the average daily flow, the total BOD_5 was calculated. The CO_2 produced was estimated by applying equation [7]. Table 6 presents the calculated values in kilograms per day for Ithaca.

In 2003, the average influent BOD_5 was 178mg/L and effluent BOD_5 left at 8.7mg/L.

BOD_5 removal = 169 mg/L =0.169kg/m^3

$$0.169\frac{kg}{m^3} \cdot \frac{1m^3}{264\ gal.} = 6.40 \text{ x } 10^{-4} \text{ kg of } BOD_5 \text{ per gallon}$$

Average Flow of 7.03MGD

$$7{,}030{,}000\ \frac{gallons}{day} \cdot 6.40\ x\ 10^{-4}\ \frac{kgBOD_5}{gallon} = 4{,}500 \text{ kg } BOD_5 \text{ per day}$$

Using equation [7], CO_2 emissions from microbial respiration, 1.47 kg of CO_2 is produced for every 1 kg of $C_6H_{12}O_6$, represented by BOD_5.

180kg $C_6H_{12}O_6$ + 192kg O_2 ⟷ 264kg CO_2 + 108kg H_2O [7]
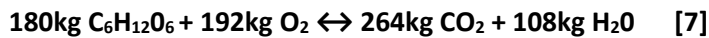
4,500 BOD_5 /day x 1.47kg CO_2/ 1 kg BOD_5

Estimated CO_2 production from microbial respiration is **6,620 kg/ day** or **2,410,000 kg/ year.**

Table 6. AVERAGE BOD$_5$ REMOVAL, AND ESTIMATED CO$_2$ PRODUCED

Ithaca AWWTF		
Year	**2002**	**2003**
Average Flow (MGD)	6.48	7.03
Average BOD$_5$ Removal (mg/L)	180	169
Average BOD$_5$ total (kg/day)	4,420	4,500
Average CO$_2$ Produced (kg/day)	**6,490**	**6,620**
Average CO$_2$ Produced (kg/year)	**2,370,000**	**2,410,000**

Provided flow and BOD$_5$ removal from Ithaca WWTF, (NYSERDA 2005). Estimated average CO$_2$ produced

for 2002-2003.

3.1.2.3 Power Demand

The highest electrical demands are from the aeration system blowers, pumping systems,

heating, and ventilation. The aeration during secondary treatment is done with a fine bubble diffusers,

and represents 42.7% of the power demand. The processing of sludge is done by a belt filter press,

reducing the water content from 94% to 78%. The belt filter press uses 0.5% of the total power

demand, however, the start to finish processing of solids uses up to 10% of the total power. The cake at

22% solids is trucked to the landfill.

The Ithaca Area Wastewater Treatment Facility reported using 3,520,000 kWh in 2003. Using

the CO$_2$ output conversion rate, (EPA 2014), it is estimated that 2,430 metric tons of carbon dioxide was

produced in 2003.

$$6.89551 \times 10^{-4} \text{ metric tons CO}_2 \text{ / kWh} \qquad \text{(EPA 2014)}$$

$$3,520,000 \text{ kWh} \cdot 6.89551 \times 10^{-4} \text{ metric tons CO}_2 \text{ / kWh} = \textbf{2,430 metric tons CO}_2 \text{ in 2003}$$

Table 7 summarizes the average daily flow, annual kWh usage, kWh per MG treated, and total annual metric tons of CO_2 produced. Ithaca uses natural gas for some facility power so the average annual therms, average therms/MG, and the annual metric tons of CO_2 produced from natural gas is included. The conversion rate of therms to metric tons CO_2 is applied to estimate average annual production.

0.005302 metric tons of CO_2/therm   (EPA 2014)

140,000 therms x 0.005302 metric tons of CO_2/therm =**742 metric tons of CO_2** in 2003

Table 7. AVERAGE DAILY FLOW, KWH USAGE, THERM USAGE, AND ESTIMATED CO_2 PRODUCTION

Year	2002	2003
Ithaca		**Electricity**
Flow (MGD)	6.48	7.03
Average Annual Use kWh	3,450,000	3,520,000
Average kWh/MG	532,000	501,000
Annual Metric Tons of CO_2	2,380	2,430
		Natural Gas
Average Annual Therms	129,000	140,000
Average Therms/MG	19,900	19,900
Annual Metric Tons of CO_2	682	742
Total Annual Metric Tons CO_2	**3,060**	**3,170**

Provided daily power demand from Ithaca WWTF, (NYSERDA, 2005). Estimated CO_2 emitted from power used for 2002-2003.

3.1.3 Shelburne-Buckland Wastewater Treatment Plant, MA

3.1.3.1 Biochemical Oxygen Demand

At the Shelburne-Buckland Wastewater Treatment Plant the recorded average flow in 2015 was 0.133 MGD. The influent BOD_5 was 189 mg/L and the effluent left at 4.7mg/L resulting in a 98% removal rate. Figure 13 presents the change in average daily flow to Shelburne-Buckland WWTP from 2012-2015.
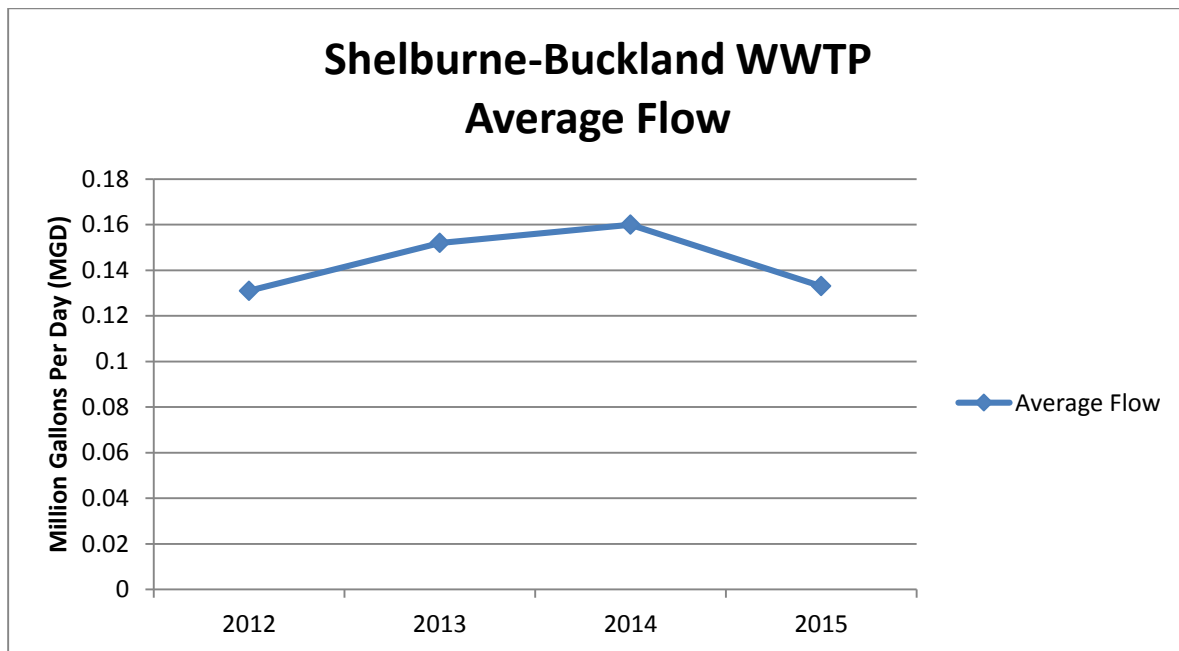
Figure 13. AVERAGE DAILY FLOW FROM SHELBURNE-BUCKLAND WWTP 2012-2015
Data provided flow in million gallons per day for 2012-2015 from Shelburne-Buckland WWTP

Figure 14 shows the difference of influent and effluent BOD_5 since 2012. The change of total BOD_5 removed can also be seen in Figure 14, with the highest removal rate in 2015.
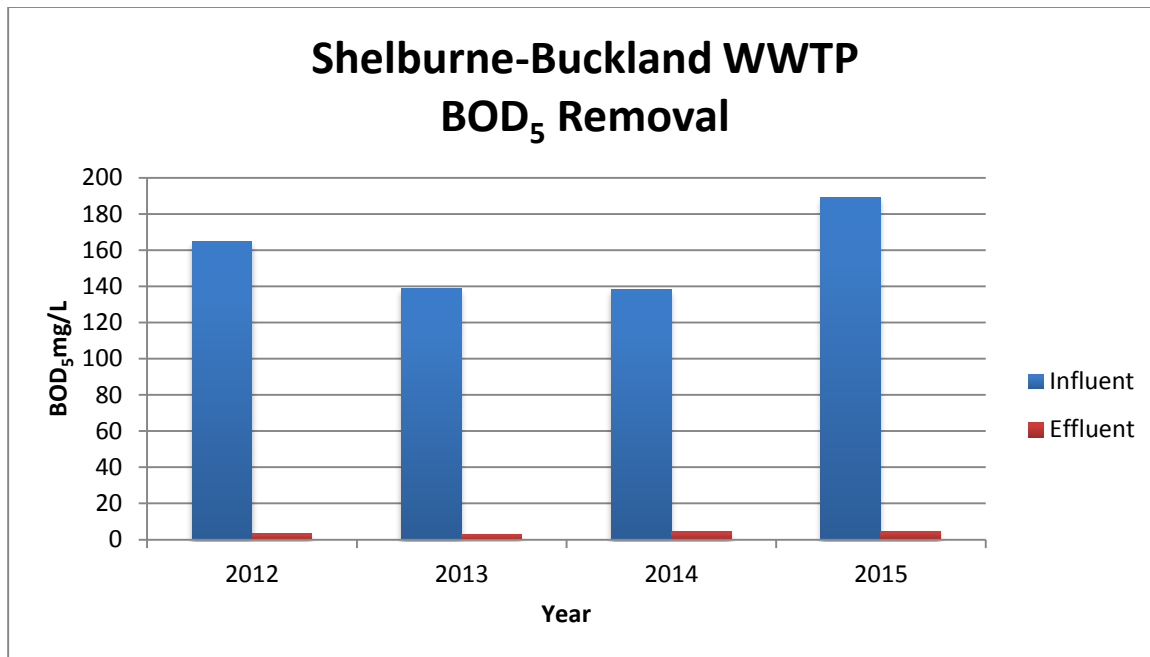
Figure 14. AVERAGE INFLUENT AND EFFLUENT BOD$_5$ AT SHELBURNE-BUCKLAND WWTP 2012-2015
Provided influent and effluent BOD$_5$ for 2012-2015 by Shelburne-Buckland WWTP.

Table 8 presents values for average flow, influent BOD$_5$, and effluent BOD$_5$ per day and per year

from 2012-2015 at Shelburne-Buckland WWTP.

Table 8. AVERAGE DAILY FLOW, INFLUENT BOD$_5$, AND EFFLUENT BOD$_5$

Shelburne-Buckland WWTP				
Year	**2012**	**2013**	**2014**	**2015**
Average Flow (MGD)	0.131	0.152	0.160	0.133
Influent BOD$_5$ (mg/L)	165	139	138	189
Effluent BOD$_5$ (mg/L)	3.3	2.9	4.4	4.7

Provided flow, influent BOD$_5$, and effluent BOD$_5$ from Shelburne-Buckland WWTP for 2012-2015.

3.1.3.2 Carbon Dioxide

The carbon dioxide produced by the BOD_5 degradation at the Shelburne-Buckland Wastewater

Treatment Plant was calculated using the average daily flow. The average BOD_5 microbial respiration in

mg/L was calculated per day using the values from Table 8. Multiplying the average BOD_5 removal

concentration by the average daily flow, the total BOD_5 in kilograms removed per day was calculated.

Estimating CO_2 produced from the average BOD_5 reduction is calculated by applying equation [7] which

stoichiometrically expresses the relationship between BOD_5, represented as glucose, and CO_2

production. Table 9 presents the calculated values in kilograms per day.

In 2015, influent BOD_5 was 189mg/L and the effluent BOD_5 was 4.7mg/L

BOD_5 removed = 184 mg/L =0.184kg/m^3

$$0.184 \frac{kg}{m^3} \cdot \frac{1m^3}{264\ gal.} = 6.97 \text{ x } 10^{-4} \text{ kg of } BOD_5 \text{ per gallon}$$

Average Flow of 0.133 MGD

$$133,000 \frac{gallons}{day} \cdot 6.97\ x\ 10^{-4} \frac{kgBOD_5}{gallon} = 92.7 \text{ kg } BOD_5 \text{ per day}$$

Using equation [7], CO_2 emissions from microbial respiration, 1.47 kg of CO_2 is produced for

every 1 kg of $C_6H_{12}O_6$, (represented by BOD_5).

180kg $C_6H_{12}O_6$ + 192kg O_2 ↔ 264kg CO_2 + 108kg H_2O [7]
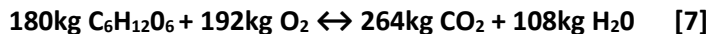
92.7 kg BOD_5 /day x 1.47kg CO_2/ 1 kg BOD_5

Estimated CO_2 production from microbial respiration is **136 kg/ day** or **49,700 kg/year.**

Table 9. AVERAGE BOD$_5$ REMOVAL AND ESTIMATED CO$_2$ PRODUCED

Shelburne-Buckland WWTP				
Year	**2012**	**2013**	**2014**	**2015**
Average Flow (MG)	0.131	0.152	0.160	0.133
BOD$_5$ Removed (mg/L)	162	136	164	184
Average BOD$_5$ total (kg)	80.3	78.4	81	92.9
Average CO$_2$ off (kg/day)	**118**	**115**	**119**	**136**
Average CO$_2$ off (kg/year)	**43,100**	**42,000**	**43,400**	**49,700**

Provided flow and BOD$_5$ removal from Shelburne-Buckland . Estimated production of CO$_2$ for 2012-2015.

3.1.3.3 Power Demand

The power demand at Shelburne-Buckland includes two main processes: pumping and aeration. Pumping can be divided into two purposes, transporting the sewage to the plant and recirculating or transferring fluids from one point to another within the facility. The power demand for aeration is driven by the three blowers found in the aeration tank and the digester. Both blowers are fine bubble diffused aeration technology.

The Shelburne-Buckland Wastewater Treatment Facility reported using 167,000 kWh in 2015. Using the CO$_2$ output conversion rate, (EPA 2014), it is estimated that 115 metric tons of carbon dioxide was produced in 2015 from SBWWTP. Table 10 shows the estimated CO$_2$ produced from 2012-2015 due to power use.

$$6.89551 \times 10^{-4} \text{ metric tons CO}_2 \text{ / kWh} \qquad (\text{EPA 2014})$$

$$167,000 \text{ kWh} \cdot 6.89551 \times 10^{-4} \text{ metric tons CO}_2 \text{ / kWh} = \textbf{115 metric tons CO}_2 \text{ in 2015}$$

Table 10. AVERAGE DAILY FLOW, KWH USAGE, AND ESTIMATED CO$_2$ PRODUCED

Shelburne-Buckland				
Year	2012	2013	2014	2015
Average Flow (MGD)	0.131	0.152	0.160	0.133
Annual Usage kWh	164,000	154,000	170,000	166,000
kWh/MG	1,250,000	1,010,000	1,060,000	1,250,000
Total Annual Metric tons of CO$_2$	113	106	117	115

Provided data 2012-2015. Calculated annual metric tons of CO$_2$ produced from power demand.

3.1.3.4 Reed Bed Sludge Treatment

The greatest difference with Shelburne-Buckland Wastewater Treatment Plant as a conventional system is the use of Reed Bed Technology for onsite sludge processing. At the facility, the Reed Beds dewater, compost, and store the sludge for over 15 years. Dewatering efficiencies from 1992-1995 were calculated to be 96.9% (J.S. Begg *et al.* 2001). The Reed Beds provide on-site treatment of sludge, a higher volume and water reduction, and no power requirements for the treatment in the Red Beds. Additional benefits are the products of photosynthesis from the growth of the highly productive *Phragmites*. The total above and below ground primary productivity (TPP) for *Phragmites australis* was documented between 3.7 kg/m^2/year 9.39 kg/m^2/year (Kadlec and Wallace 2008). Using the reverse of equation [7], we can calculate the approximate values of annual CO$_2$ used in photosynthesis by the Shelburne-Buckland Reed Beds.

TPP Phragmites = 3.7 kg/m^2/year

Total Reed Bed area= 12,000ft^2 = 1,111m^2

Total Plant Biomass= 4,100kg/ year

Using the reverse of equation [7] we can stoichiometrically calculate the CO_2.

264kg CO_2 + 108kg H_2O ↔ 180kg $C_6H_{12}O_6$ + 192kg O_2   [7]

Estimated CO_2 = **6,027 kg/year**

3.1.4 Zumtobel Staff Lighting Vegetated Sand Beds Lloyd, NY

3.1.4.1 Biochemical Oxygen Demand

The average flow from Zumtobel Staff Lighting is 1,200 gallons per day or 0.0012MGD. In 2007, the influent BOD_5 was 287mg/L and the effluent was below 4mg/L, resulting in a 99% removal rate. Table 11 provides values for average daily flow, influent BOD_5, and effluent BOD_5 from 2001-2007 at Lloyd VSB.

Table 11. AVERAGE DAILY FLOW, INFLUENT BOD_5, AND EFFLUENT BOD_5

Lloyd VSB							
Year	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**
Average Flow (MG)	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012
Influent BOD_5 (mg/L)	289	323	357	310	300	285	287
Effluent BOD_5 (mg/L)	5.14	6	<4	<4	<4	<4	<4

Provided flow, influent BOD_5, and effluent BOD_5 from Lloyd VSB (Lavigne and Spokas 2008)

Figure 15 presents the influent and effluent BOD$_5$ values at Lloyd VSB from 2001-2007. The fluctuation of influent and effluent BOD$_5$ can easily be compared along with the change in BOD$_5$ removal.
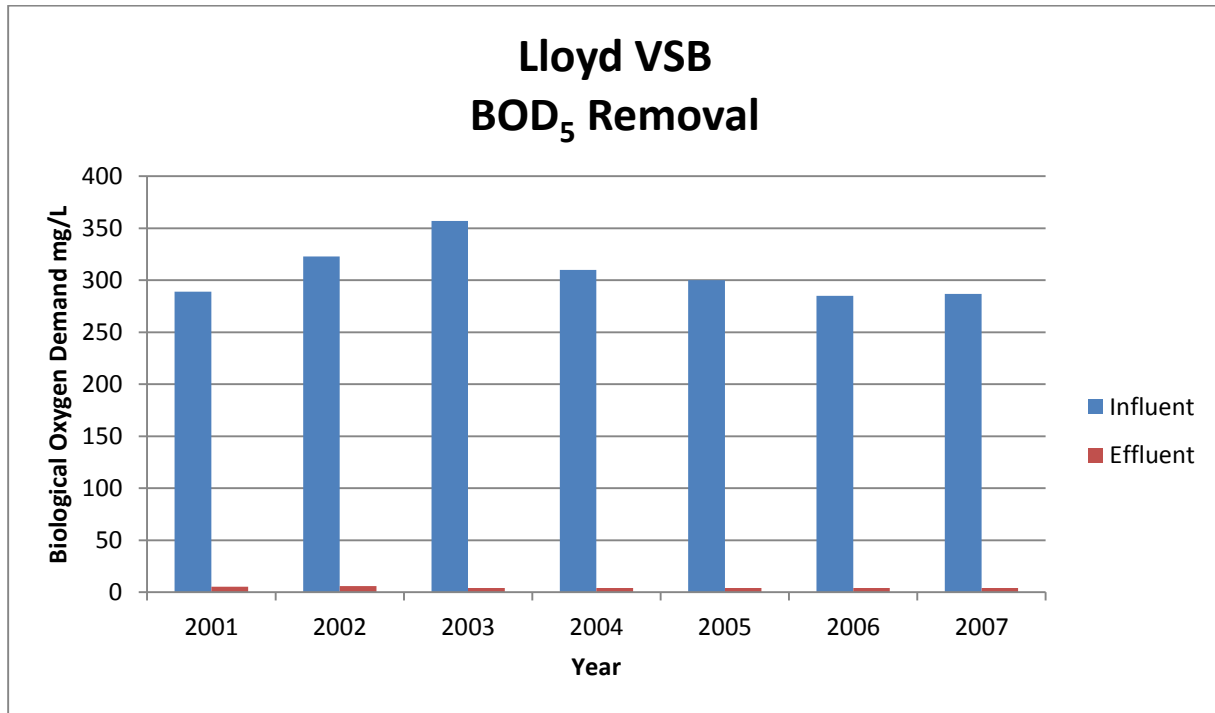
Figure 15. AVERAGE INFLUENT AND EFFLUENT BOD$_5$ LLOYD VSB 2001-2007
Provided influent and effluent BOD$_5$ from 2001-2007 at Lloyd VSB (Lavigne and Spokas 2008).

3.1.4.2 Carbon Dioxide

The Carbon dioxide produced by the Lloyd Vegetated Sand Beds was calculated from the average BOD_5 removal and the average daily flow. Table 12 shows the CO_2 produced 2001-2007.

In 2007, the average influent BOD_5 was 287mg/L and effluent BOD_5 left at 4mg/L

BOD_5 removed = 283 mg/L =0.283kg/m^3

$$0.283 \frac{kg}{m^3} \cdot \frac{1m^3}{264\ gal.} = 1.07 \text{ x } 10^{-3} \text{ kg of } BOD_5 \text{ per gallon}$$

Average Flow of 1,200 gallons per day

$$1,200\ \frac{gallons}{day} \cdot 1.07\ x\ 10^{-3}\ \frac{kgBOD_5}{gallon} = 1.29 \text{ kg } BOD_5 \text{ per day}$$

Using equation [7], CO_2 emissions from microbial respiration, 1.47 kg of CO_2 is produced for every 1 kg of $C_6H_{12}O_6$, (represented by BOD_5).

180kg $C_6H_{12}O_6$ + 192kg O_2 ↔ 264kg CO_2 + 108kg H_2O [7]
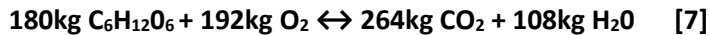
1.29 kg BOD_5 /day x 1.47kg CO_2/ 1 kg BOD_5

Estimated CO_2 production from microbial respiration is **1.89 kg/ day** or **690 kg/year**.

Table 12. AVERAGE BOD_5 REMOVAL AND ESTIMATED CO_2 PRODUCED

Lloyd VSB							
Year	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**
Average Flow (MG)	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012
BOD_5 Removed (mg/L)	284	317	353	306	296	281	283
Average BOD_5 total (kg)	1.29	1.44	1.60	1.39	1.35	1.23	1.29
Average CO_2 off (kg/day)	**1.90**	**2.12**	**2.36**	**2.04**	**1.98**	**1.88**	**1.89**
Average CO_2 off (kg/year)	**692**	**773**	**861**	**746**	**722**	**685**	**690**

Provided flow and BOD_5 removal from Lloyd VSB (Lavigne and Spokas 2008). Estimated production of CO_2 for 2001-2007.

3.1.4.3 Photosynthesis

The benefit of CO_2 uptake from photosynthesis is calculated using the documented total primary productivity (TPP) of *Phragmites australis* and *Phalaris arundinacea* of 3.7kg/m^2/year (Kadlec and Wallace, 2008), and 2.03kg/m^2/year respectively, (Lyons, 2005).

Bed Area 1+2 with *Phalaris arundinacea* = 463 m^2 (2.028kg/m^2/year) = 939kg/ year

Bed Area 3+4 with *Phragmites australis* = 463 m^2 (3.7kg/m^2/year) = 1,713 kg/year

Total Plant Biomass = 2,650 kg/ year

Using the reverse of equation [7] we can stoichiometrically calculate the CO_2 used in photosynthesis.

264kg CO_2 + 108kg H_2O $\longleftrightarrow$ 180kg $C_6H_{12}O_6$ + 192kg O_2   [7]

    2,650 kg biomass / year x 1.47kg CO_2/ 1 kg biomass

Estimated CO_2 = **3,900 kg/year**

3.1.5 Shushufindi Slaughterhouse VSBs, Ecuador, S. A.

3.1.5.1 Biochemical Oxygen Demand

The design flow from the Shushufindi slaughterhouse Vegetated Sand Beds is 25 m^3/day. The influent BOD_5 was recorded at 288 mg/L and the effluent left at 3mg/L, resulting in a 99% removal rate, in 2000. Table 13 presents values for average flow, influent BOD_5, and effluent BOD_5 per day from 1999-2000 at the Shushufindi slaughterhouse VSB.

Table 13. AVERAGE DAILY FLOW, INFLUENT BOD_5, AND EFFLUENT BOD_5

Shushufindi Slaughterhouse VSB		
Year	**1999**	**2000**
Design Flow (m^3/day)	25	25
Influent BOD_5 (mg/L)	185	288
Effluent BOD_5 (mg/L)	5	3

Provided flow, influent BOD_5, and effluent BOD_5 from the Shushufindi slaughterhouse VSB (Kahl 2004).

Figure 16 provides the influent and effluent BOD_5 values at the Shushufindi slaughterhouse VSB from 1999-2000. The increase of influent BOD_5 and effluent BOD_5 can easily be compared along with the change in BOD_5 respired.
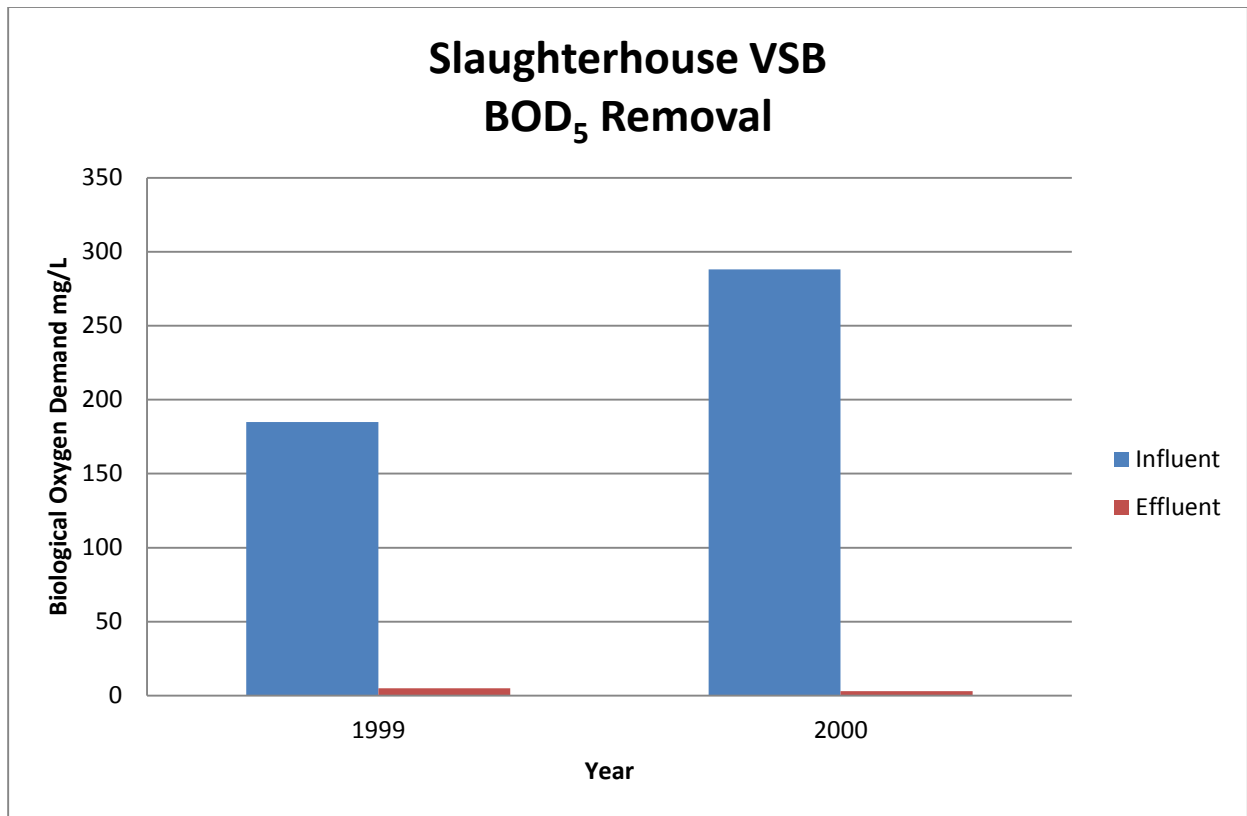
Figure 16. AVERAGE INFLUENT AND EFFLUENT BOD$_5$ AT SHUSHUFINDI SLAUGHTERHOUSE VSB

Provided influent and effluent BOD$_5$ from 2001-2007 at the Shushufindi slaughterhouse VSB (Kahl 2004).

3.1.5.2 Carbon Dioxide

The Carbon dioxide produced by the Shushufindi slaughterhouse VSBs was calculated from the average BOD_5 removal and the average daily flow. Table 14 shows the CO_2 produced in 1999 and 2001.

In 2000, the average influent BOD_5 was 288mg/L and effluent BOD_5 was 3mg/L

BOD_5 removed = 285 mg/L =0.285kg/m^3

Average Flow of 25m^3/day

$$25 \ \frac{m^3}{day} \cdot 0.285 \ \frac{kgBOD_5}{m^3} = 7.13 \text{ kg } BOD_5 \text{ per day}$$

Using equation [7], CO_2 emissions from microbial respiration, 1.47 kg of CO_2 is produced for every 1 kg of $C_6H_{12}O_6$, (represented by BOD_5).

180kg $C_6H_{12}O_6$ + 192kg O_2 ↔ 264kg CO_2 + 108kg H_2O [7]
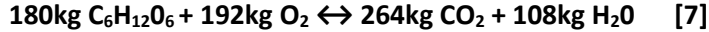
7.13 kg BOD_5 /day x 1.47kg CO_2/ 1 kg BOD_5

Estimated CO_2 production from microbial respiration is **10.5 kg/ day** or **3,820 kg/year**.

Table 14. AVERAGE BOD_5 REMOVAL AND ESTIMATED CO_2 PRODUCED

Shushufindi Slaughterhouse VSB		
Year	**1999**	**2000**
Design Flow (m^3/day)	25	25
BOD_5 Removed (mg/L)	180	285
Average BOD_5 total (kg)	4.5	7.13
Average CO_2 off (kg/day)	6.62	10.5
Average CO_2 off (kg/year)	2,410	3,820

Provided flow and BOD_5 removal from Shushufindi Slaughterhouse VSB (Kahl 2004).

3.1.5.3 Photosynthesis

The benefit from CO_2 uptake during photosynthesis is calculated using the documented total primary productivity of German Grass, scientifically *Echinochloa polystachya* of $4kg/m^2/year$ (Kahl 2004).

Total VSB Area = 775 m^2 · ($4kg/m^2/year$) = 3,100 kg/year

Using the reverse of equation [7] we can stoichiometrically calculate the CO_2 used in photosynthesis.

264kg CO_2 + 108kg H_2O ↔ 180kg $C_6H_{12}O_6$ + 192kg O_2   [7]

3,100 kg biomass / year x 1.47kg CO_2/ 1 kg biomass

Estimate CO_2 = **4,560 kg/year**

3.1.6 Shushufindi Municipal VSBs Ecuador, S.A.

3.1.6.1 Biochemical Oxygen Demand

The design flow from Shushufindi Municipal Vegetated Sand Beds is 2,000 m^3/day. The influent

BOD_5 was recorded at 288mg/L and the effluent left at 1 mg/L, resulting in a 99% removal rate, in 2000.

Table 15 gives the values for average daily flow, influent BOD_5, and effluent BOD_5 from 1999-2000 at the

Shushufindi municipal VSB.

Table 15. AVERAGE DAILY FLOW, INFLUENT BOD_5, AND EFFLUENT BOD_5

Shushufindi Municipal VSB		
Year	**1999**	**2000**
Design Flow (m^3/day)	2,000	2,000
Influent BOD_5 (mg/L)	185	288
Effluent BOD_5 (mg/L)	5	1

Provided flow, influent BOD_5, and effluent BOD_5 from Shushufindi Municipal VSB (Kahl 2004).

Figure 17 shows the influent and effluent BOD_5 values at the Shushufindi Municipal VSB from

1999-2000. The increase of influent and effluent BOD_5 can easily be compared along with the change in

BOD_5 removed.
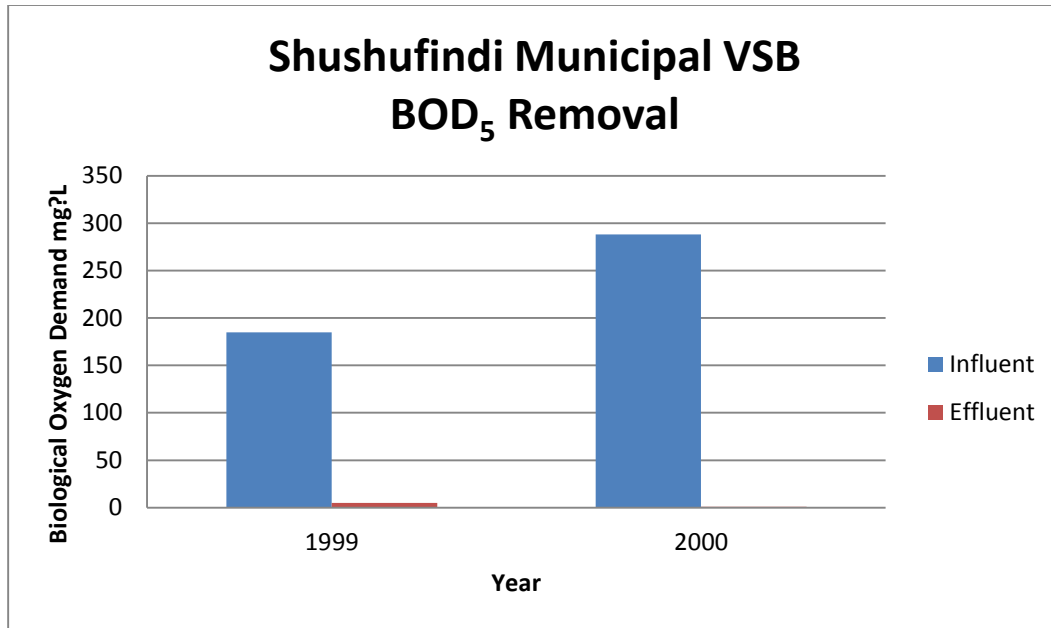
Figure 17. AVERAGE INFLUENT BOD₅ AND EFFLUENT BOD₅ AT SHUSHUFINDI MUNICIPAL VSB

Provided influent and effluent BOD_5 from 1999-2000 at Shushufindi Municipal VSB (Kahl 2004).

3.1.6.2 Carbon Dioxide

The Carbon dioxide produced by the Shushufindi Municipal Vegetated Sand Beds was calculated from the average BOD_5 removal and the average daily flow.

In 2000, the average influent BOD_5 was 288mg/L and effluent BOD_5 was 1mg/L

BOD_5 removed = 287 mg/L =0.287kg/m³

Average Flow of 2,000m³/day

$$2,000 \ \frac{m^3}{day} \cdot 0.287 \ \frac{kgBOD_5}{m^3} = 574 \text{ kg BOD}_5 \text{ per day}$$

Using equation [7], CO_2 emissions from microbial respiration, 1.47 kg of CO_2 is produced for every 1 kg of $C_6H_{12}O_6$, (represented by BOD_5).

$$180kg\ C_6H_{12}O_6 + 192kg\ O_2 \leftrightarrow 264kg\ CO_2 + 108kg\ H_2O \quad [7]$$
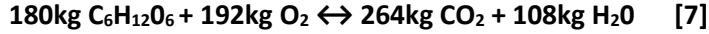
574 kg BOD_5 /day x 1.47kg CO_2/ 1 kg BOD_5

Estimated CO_2 production from microbial respiration is **844 kg/ day** or **308,100 kg/year**.

Table 16 presents the estimated CO_2 produced in 1999 and 2000 Municipal VSBs.

Table 16. AVERAGE BOD$_5$ REMOVAL AND ESTIMATED CO$_2$ PRODUCED

Shushufindi Municipal VSB		
Year	**1999**	**2000**
Design Flow (m^3/day)	2,000	2,000
BOD$_5$ Removed (mg/L)	180	287
Average BOD$_5$ total (kg)	360	574
Average CO$_2$ off (kg/day)	529	844
Average CO$_2$ off (kg/year)	193,000	308,100

Provided flow and BOD$_5$ removal from Shushufindi Municipal VSB (Kahl 2004).

3.1.6.3 Photosynthesis

The benefit of CO_2 uptake from photosynthesis is calculated using the documented total primary

productivity of German Grass, scientifically *Echinochloa polystachya* of 4kg/m^2/year (Kahl 2004).

Total VSB Area = 16,300 m^2 · (4kg/m^2/year) = 65,200 kg/year

Using the reverse of equation [7] we can stoichiometrically calculate the CO_2 used in

photosynthesis.

$$264kg\ CO_2 + 108kg\ H_2O \leftrightarrow 180kg\ C_6H_{12}O_6 + 192kg\ O_2 \quad [7]$$

65,200 kg biomass / year x 1.47kg CO_2/ 1 kg biomass

Estimated CO_2 = **95,800 kg/year**

3.2 Estimated Reduction of CO₂ with Hypothetical Reed Bed Treatment

Sludge processing at Amherst and Ithaca represent two typical conventional methods for sludge management: Gravity Belt Thickener to an Incinerator and Belt Filter Press to a landfill. Two hypothetical Reed Bed systems will be sized using the sludge production values from each facility. The land area necessary for treatment and the reduction of carbon dioxide production will be estimated.

3.2.1 Amherst Wastewater Treatment Plant, MA

3.2.1.1 Land Area Needed

The recommended loading rate for Reed Bed technology is 55 gallons sludge/ ft^2/ year with 26 applications, (M. Watson 2002). Amherst transports approximately 5 million gallons of sludge per year.

$$\text{Estimated Total Area} = \frac{5,000,000 \ gallons}{year} \div \frac{55 \ gallons}{ft^2 \cdot year^{-1}} = 90,900 ft^2 \text{ or } \textbf{8,440 m}^2$$

3.2.1.2 Annual Carbon Dioxide Reduction

Using the total land area of 8,440 m², the known total above and below ground primary

productivity for *Phragmites australis* documented as 3,700g/m²/year with (Kadlec and Wallace, 2008),

and the reverse of equation [7], we can calculate the approximate CO_2 values.

TPP *Phragmites australis* = 3.7 kg/m²/year

Total Reed Bed area= 8,440 m²

Total Plant Biomass

(3.7 kg/m²/year) x (8,440 m²) = 31,200 kg Plant Biomass/ year

Using the reverse of equation [7] we can stoichiometrically calculate the CO_2 sequestered.

264kg CO_2 + 108kg H_2O ↔ 180kg $C_6H_{12}O_6$ + 192kg O_2   [7]

31,200 kg biomass / year x 1.47kg CO_2/ 1 kg biomass

Estimated CO_2 sequestered = **45,900 kg/year** or **45.9 metric tons of CO_2**

Current Sludge Management = 578 metric tons of CO_2

Estimated CO_2 sequestered using Reed Bed technology= - 45.9 metric tons of CO_2

Estimated Net Change = -624 metric tons of CO_2 per year

Figure 18 presents the estimated metric tons of CO_2 produced from conventional technology at

Amherst from sludge transport and incineration from 2013-2015. The estimated net reduction of CO_2

produced when replacing conventional sludge management with the hypothetical Reed Bed technology

is also included.
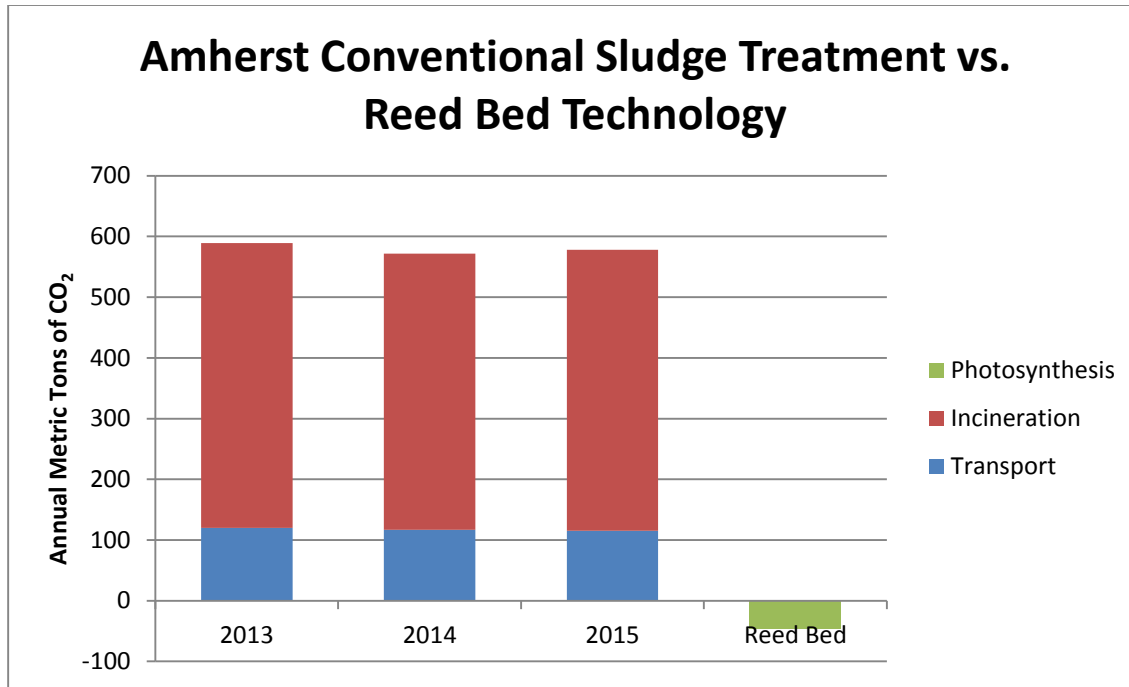
Figure 18. ANNUAL CO$_2$ PRODUCTION USING CONVENTIONAL AND RB TECHNOLOGIES AT AMHERST
Estimated metric tons of CO$_2$ produced by conventional sludge treatment and Reed Bed treatment for Amherst WWTP.

3.2.2 Ithaca Area Wastewater Treatment Facility, NY

3.2.2.1 Land Area Needed

Ithaca pumps approximately 65.7 million gallons of sludge per year to the gravity belt thickeners.

$$\text{Estimated Total Area} = \frac{65,700,000 \; gallons}{year} \div \frac{55 \; gallons}{ft^2 \cdot \, year^{-1}} = 1{,}190{,}000 \text{ ft}^2 \text{ or } \textbf{111,000 m}^2$$

3.2.2.2 Annual Carbon Dioxide Reduction

Using the total land area of 111,000 m^2, the known total above and below ground primary

productivity for *Phragmites australis* documented as 3.7 kg/m^2/year (Kadlec and Wallace 2008), and the

reverse of equation [7], we can calculate the approximate CO_2 values.

TPP Phragmites = 3.7 kg/m^2/year

Total Reed Bed area= 111,000 m^2

Total Plant Biomass= 411,000 kg/ year

Using the reverse of equation [7] we can stoichiometrically calculate the CO_2 used in

photosynthesis.

264kg CO_2 + 108kg H_2O $\leftrightarrow$ 180kg $C_6H_{12}O_6$ + 192kg O_2   [7]

411,000 kg biomass / year x 1.47kg CO_2/ 1 kg biomass

Estimated CO_2 = **604,000 kg/year** or **604 metric tons of CO_2**

Current Sludge Management = 317 metric tons of CO_2

Estimated CO_2 sequestered using Reed Bed technology = - 604 metric tons of CO_2

Net Production = **-921 metric tons of CO_2 per year**

Figure 19 illustrates the distribution of annual CO_2 produced from conventional sludge

management at Ithaca for 2002-2003. The estimated net CO_2 uptake from photosynthesis in the

hypothetical Reed Beds is also included.
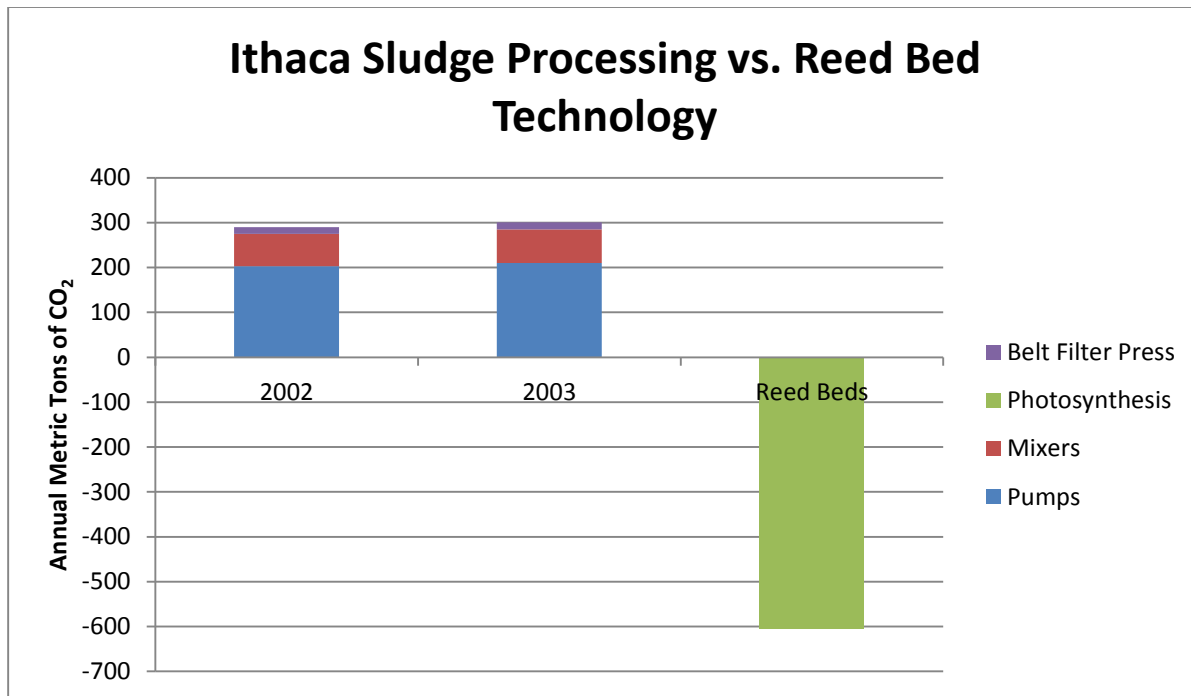
Figure 19. ANNUAL CO$_2$ PRODUCTION: CONVENTIONAL AND RB TECHNOLOGIES AT ITHACA

Figure 19 shows estimated metric tons of CO$_2$ produced by conventional sludge treatment and Reed Bed treatment for Ithaca. The sludge leaving the Ithaca is about 22% solids and is trucked to a landfill. After treatment in the Reed Beds, the sludge is about 99% solids and requires minimal maintenance. Depending on the design and depth of Reed Beds, the accumulated sludge may not need removal for 15+ years.

3.3 Estimated Reduction of CO_2 with Hypothetical VSB Technology

Applying the kinetics equations of Vegetated Sand Bed technology, we can estimate the necessary land area for equal treatment. Using equation [4] and [5], the treatment time and the total area can be calculated.

$$t = \frac{1}{k} \ln \left(\frac{C_0}{C_t} \right) \qquad [4]$$

Where C_0= Average initial concentration of BOD (mg/L)

C_t= Average concentration of BOD_5 at time t (mg/L)

k= 1.2 day^{-1}

$$Q = \frac{A \cdot h \cdot f}{t} \qquad [5]$$

Where Q= Average daily flow rate

t= Treatment time in days

A=Wetland area

h=Wetland depth, assumed 0.61m

f= Porosity of media (.35)

3.3.1 Amherst Wastewater Treatment Plant, MA

The Amherst Wastewater Treatment Plant receives wastewater pumped from Amherst, North Amherst, and the University of Massachusetts with an average daily flow is 3.85 MGD in 2015. Using the total MGD the estimated necessary land area for Vegetated Sand Bed technology can be calculated.

3.3.1.1 Land Area Needed

Known Values:

C_0= 227 mg/L

C_t = 2 mg/L

k = 1.2 day^{-1}

$$t = \frac{1}{1.2 \cdot \text{day}^{-1}} \ln\left(\frac{227\ mg/L}{2\ mg/L}\right) \qquad [4]$$

t= 3.9 days

Known Values:

Q_{Total}= 3.85 MGD or 13,300 m^3/day

h= 0.61m

f= 0.35

t= 3.0 days

$$13,300 m^3/day = \frac{A \cdot (0.61m) \cdot (0.35)}{3.9\ days} \qquad [5]$$

VSB Area Amherst = 243,000 m^2

3.3.1.2 Annual Carbon Dioxide Reduction

Using the total land area of **243,000 m^2,** the known total primary productivity (TPP) for *Phalaris arundinecea,* Reed Canary Grass documented as 2.03kg/m^2/year (Lyons, 2005), and using the reverse of equation [7], we can calculate the approximate CO_2 values.

TPP Reed Canary Grass = 2.03 $kg/m^2/year$

Total Vegetated Sand Bed area= 243,000 m^2

Total VSB Plant Biomass= 493,000 kg/ year

Using the reverse of equation [7] we can stoichiometrically calculate the CO_2.

264kg CO_2 + 108kg H_2O ↔ 180kg $C_6H_{12}O_6$ + 192kg O_2   [7]

493,000 kg biomass / year x 1.47kg CO_2/ 1 kg biomass

CO_2 sequestered = **725,000 kg/year** or **725 metric tons of CO_2/year**

Average Power Demand for Treatment = **1,030 metric tons of CO_2/year**

Estimated CO_2 sequestered with Vegetated Sand Bed = **- 725 metric tons of CO_2/year**

Net Change with VSB Technology = **-1,760 metric tons of CO_2/year produced**

Figure 20 illustrates the proportion of CO_2 produced from BOD_5 microbial respiration and power demand at the current conventional WWTP. The entire treatment process currently produces approximately 3,210 metric tons of CO_2 annually. Figure 20 also includes the estimated CO_2 production when treating with the hypothetical Vegetated Sand Beds and Reed Beds. The estimated reduction of CO_2 produced when replacing conventional methods with VSB and RB technology was 74.4%%.
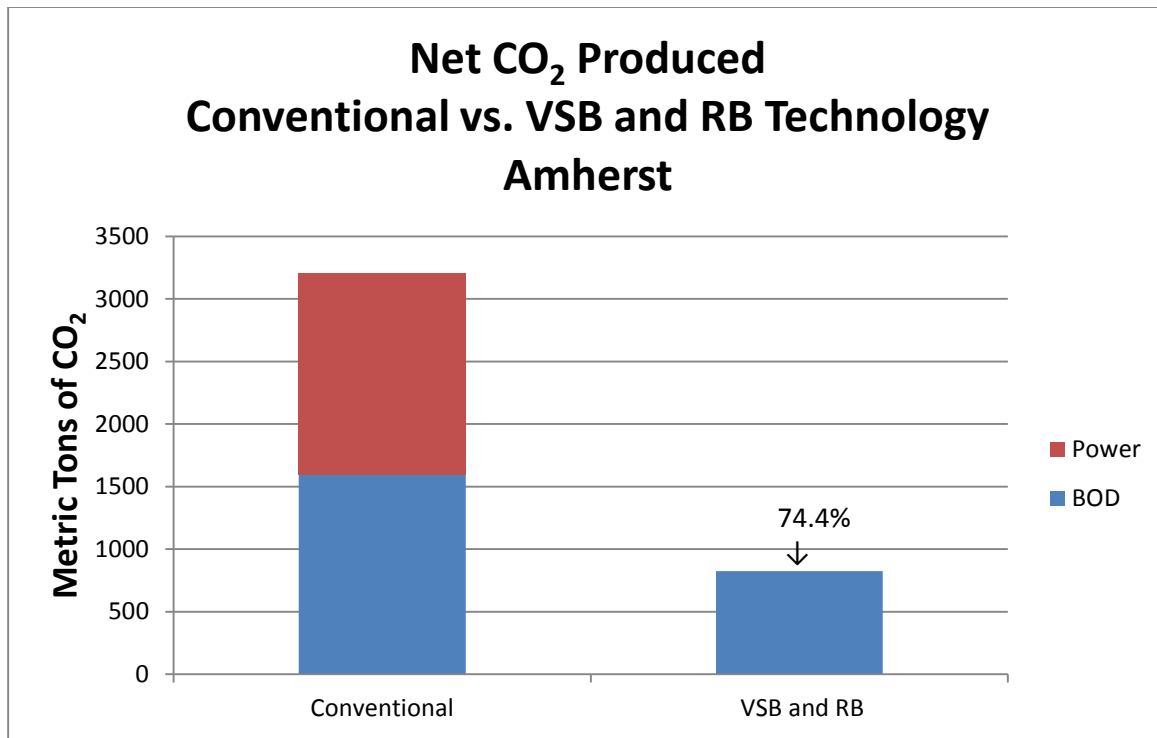
Figure 20. ANNUAL CO$_2$ PRODUCTION: CONVENTIONAL VS. VSB AND RB TECHNOLOGIES AT AMHERST

Estimated CO$_2$ production from current conventional Amherst WWTP in 2015 and estimated carbon dioxide reduction with Vegetated Sand Bed and Reed Bed technology.

3.3.2 Ithaca Area Wastewater Treatment Plant, NY

The Ithaca Area Wastewater Treatment Plant receives wastewater an average 7.03 MGD pumped from Ithaca City. The average influent and effluent BOD$_5$ were 186 mg/L and 8.7 mg/L respectively.   Using these values the estimated necessary land area for Vegetated Sand Bed technology can be calculated.

3.3.2.1 Land Area Needed

Known Values:

C$_0$= 186 mg/L

C$_t$ = 8.7 mg/L

k = 1.2 day^{-1}

$$t = \frac{1}{1.2 \cdot \text{day}^{-1}} \ln \left(\frac{186 \; mg/L}{8.7 \; mg/L} \right) \qquad [4]$$

t= 2.55 days

Known Values:

Q$_{Total}$= 7.03 MGD or 26,600 m^3/day

h= 0.61m

f= 0.35

t= 2.55 days

$$26,600 m^3/day = \frac{A \cdot (0.61m) \cdot (0.35)}{2.55 \; days} \qquad [5]$$

VSB Area Total = 318,000 m^2

3.3.2.2 Annual Carbon Dioxide Reduction

Using the total land area of **318,000 m^2,** the known total primary productivity (TPP) for *Phalaris arundinecea,* Reed Canary Grass documented as 2.03kg/m^2/year respectively, (Lyons, 2005), and using the reverse of equation [7], we can calculate the approximate CO$_2$ values.

TPP Reed Canary Grass = 2.03 kg/m^2/year

Total Vegetated Sand Bed area= 318,000 m^2

Estimated Total Plant Biomass= 645,000 kg/ year

Using the reverse of equation [2] we can stoichiometrically calculate the CO_2.

264kg CO_2 + 108kg H_2O ↔ 180kg $C_6H_{12}O_6$ + 192kg O_2   [7]

      645,000 kg biomass / year x 1.47kg CO_2/ 1 kg biomass

CO_2 sequestered = **948,000 kg/year** or **948 metric tons of CO_2**

Average Power Demand for Treatment = **2,850 metric tons of CO_2/year**

Estimated CO_2 sequestered with Vegetated Sand Bed = **- 948 metric tons of CO_2/year**

Net Change with VSB = -**3800 metric tons of CO_2/year emitted**

Figure 21 presents the proportion of CO_2 produced from the BOD_5 microbial respiration and power demand at the conventional facility. The entire treatment process at Ithaca produced approximately 5,580 metric tons of CO_2 annually. Figure 21 also includes the estimated CO_2 production when treating with the hypothetical Vegetated Sand Beds and Reed Beds. The estimated reduction of CO_2 produced when replacing conventional methods with VSB and RB technology is 84.6%.
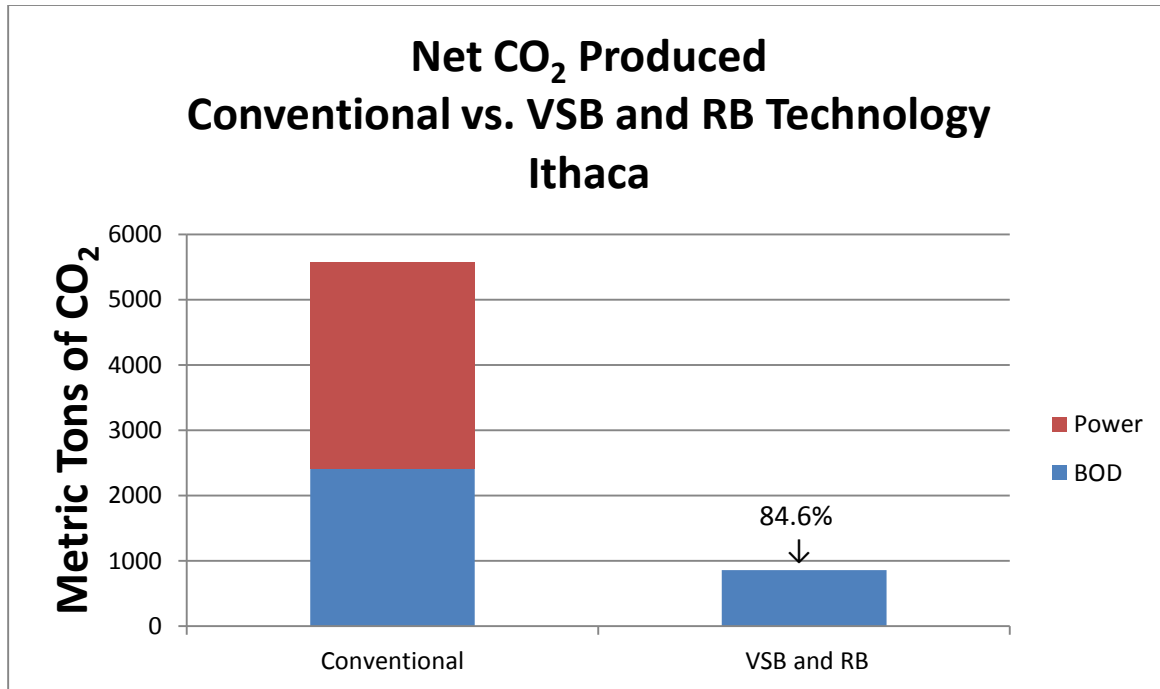
Figure 21. ANNUAL CO_2 PRODUCTION: CONVENTIONAL VS. VSB AND RB TECHNOLOGY AT ITHACA
Estimated CO_2 production from conventional Ithaca and estimated carbon dioxide reduction with
Vegetated Sand Bed and Reed Bed technology.

3.3.3 Shelburne-Buckland Wastewater Treatment Plant, MA

Shelburne-Buckland Wastewater Treatment Plant uses activated sludge technology with aerobic

sludge digestion. The facility processes on average 0.133MGD, with an average influent BOD_5 of 158

mg/L and an average effluent of 4.7 mg/L (Begg *et al.* 2001). Using these known values, the land area

needed for VSB treatment can be estimated.

3.3.3.1 Land Area Needed

Known Values:

C_0= 158 mg/L

C_t = 4.7 mg/L

k = 1.2 day^{-1}

$$t = \frac{1}{1.2 \cdot \text{day}^{-1}} \ln \left(\frac{158 \, mg/L}{4.7 \, mg/L} \right) \qquad [5]$$

t= 3.07 days

Known Values:

Q_{Total}= 0.133 MGD or 503 m^3/day

h= 0.61m

f= 0.35

t= 3.070 days

$$503 m^3/day = \frac{A \cdot (0.61m) \cdot (0.35)}{3.07 \, days} \qquad [6]$$

VSB Area Total = 7,230 m^2

3.3.3.2 Annual Carbon Dioxide Reduction

Using the total land area of **7,230 m^2**, the known total primary productivity (TPP) for *Phalaris arundinecea,* Reed Canary Grass documented as 2.03kg/m^2/year (Lyons 2005), and with the reverse of equation [7], we can calculate the approximate CO_2 values.

TPP Reed Canary Grass = 2.03 kg/m^2/year

Total Vegetated Sand Bed area= 7,230 m^2

Total Plant Biomass= 14,700 kg/ year

Using the reverse of equation [2] we can stoichiometrically calculate the CO_2 sequestered.

264kg CO_2 + 108kg H_2O ↔ 180kg $C_6H_{12}O_6$ + 192kg O_2   [7]

     14,700 kg biomass / year x 1.47kg CO_2/ 1 kg biomass

Estimated CO_2 sequestered = **21,600 kg/year** or **21.6 metric tons of CO_2/year**

Average Power Demand for Secondary Treatment = **115 metric tons of CO_2/year**

Estimated CO_2 sequestered with Vegetated Sand Bed = - **21.6 metric tons of CO_2/year**

Net Change = -**137 metric tons of CO_2/year produced**

Figure 22 presents the total carbon dioxide produced from current conventional treatment at Shelburne-Buckland. The entire conventional treatment process with RB sludge processing produced approximately 159 metric tons of CO_2 annually. Figure 22 also includes the estimated net CO_2 production using the hypothetical Vegetated Sand Beds for treatment. The estimated reduction of CO_2 produced when replacing conventional methods with VSB technology is 86.2%.
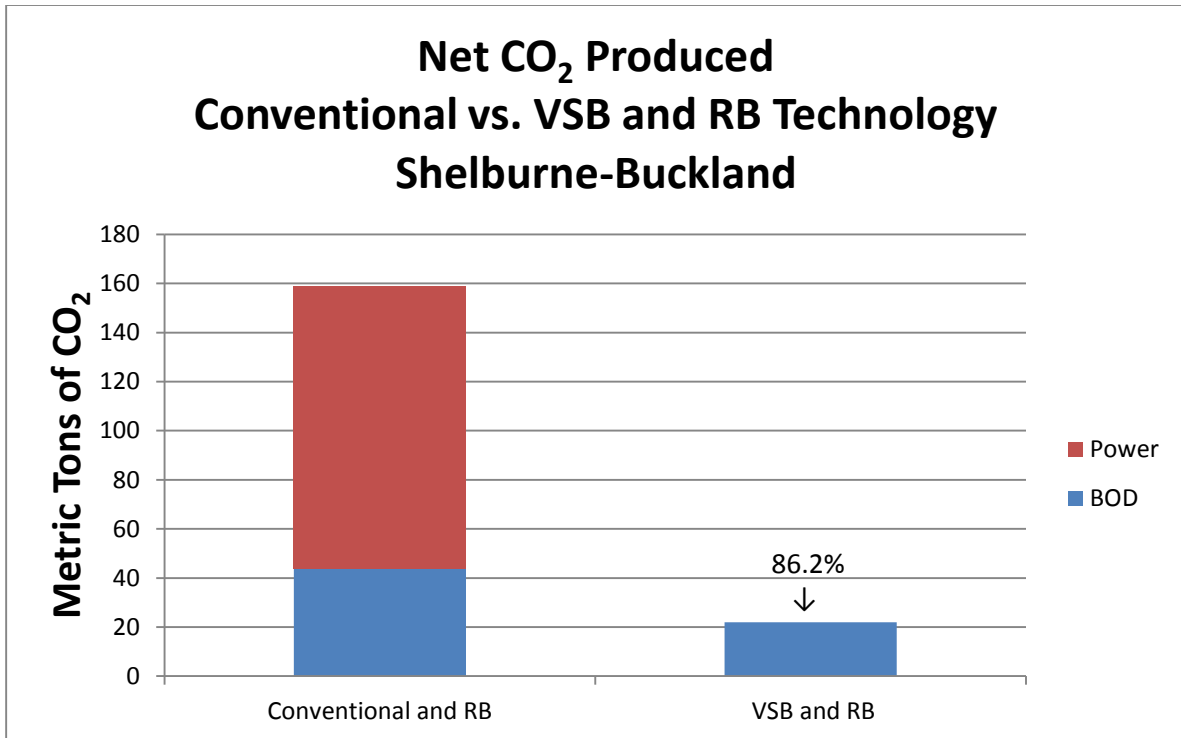
Figure 22. ANNUAL CO$_2$ PRODUCTION: CONVENTIONAL VS. VSB AND RB TECHNOLOGY AT SHELBURNE-BUCKLAND

Estimated CO$_2$ production from Shelburne-Buckland WWTP in 2015, with projected reduction when using Vegetated Sand Bed technology.

CHAPTER 4

DISCUSSION

This study investigates the sustainability of conventional wastewater treatment compared to Vegetated Sand Bed and Reed Bed technology with focus on CO_2 production. The three main sources of CO_2 production considered were BOD_5 microbial respiration, power demand, and sludge processing. The production of CO_2 from each source was estimated and totaled for each facility allowing for the comparison between individual processes and treatment technology as a whole.

4.1 Conventional Treatment Efficiency

When comparing the total metric tons of CO_2 produced per million gallons of wastewater treated, it is important to consider the average daily flow of the facility. As shown in the collaboration of *Electricity Use and Management in the Municipal Water Supply and Wastewater Industries* report from 2013, electricity use per MG increase greatly as the average daily flow of the facility decreases. Figure 23 illustrates the relationship between energy demand and average plant flow in MGD. With conventional technology, facilities with the lowest average plant flow have the greatest electrical demand and total CO_2 production per MG of wastewater treatment. Electricity use in kWh/MG for hypothetical VSB and RB systems is also shown in Figure 23. The average electrical demand is estimated to be negligible and is not dependent on plant flow.
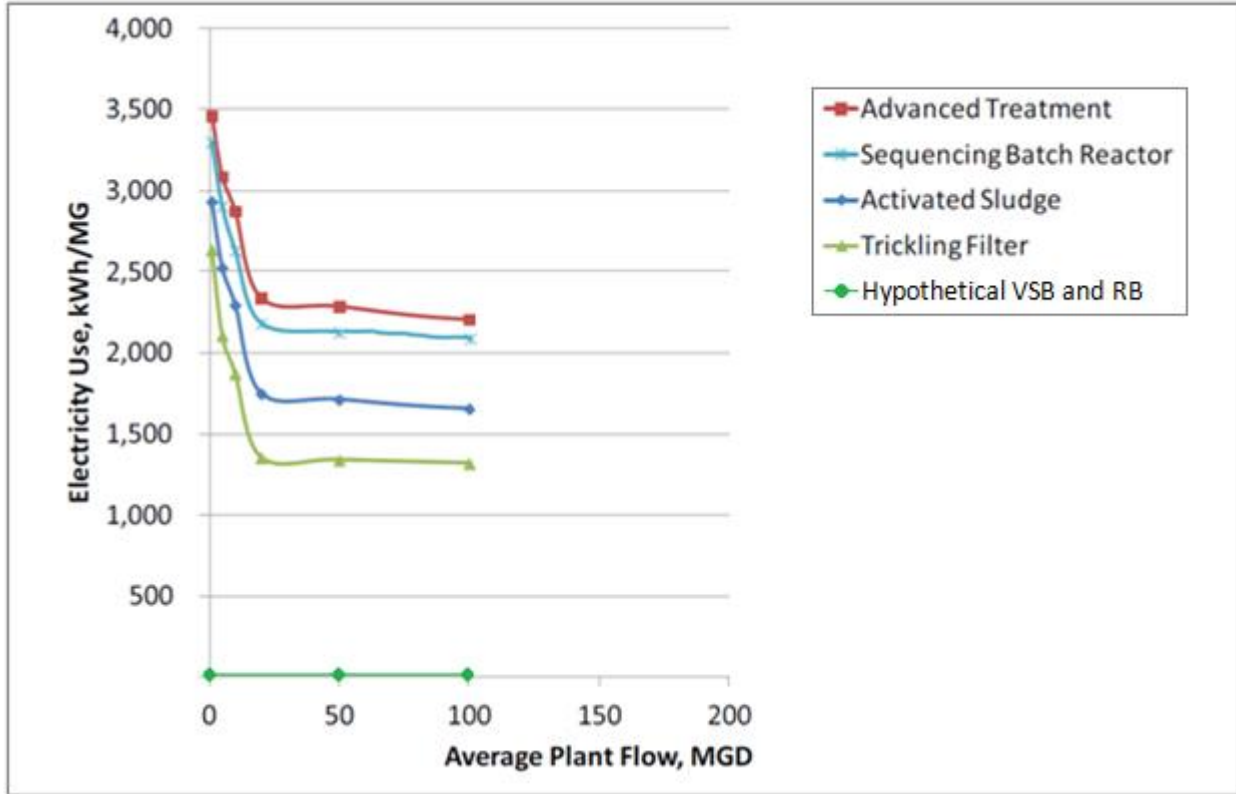
Figure 23. DAILY ELECTRICAL USE COMPARED TO AVERAGE PLANT FLOW IN MGD
Adapted from the Electricity Use and Management in the Municipal Water Supply and Wastewater
Industries report from 2013, Figure 23 presents electricity compared to average plant flow. Electricity
for hypothetical VSB and RB systems are also included showing the electricity use is not dependent on
average facility flow.

4.2 Conventional Treatment Comparison

When comparing efficiency and CO_2 production between conventional facilities, it is necessary

to understand the average daily flow. Shelburne-Buckland uses 1.25 million kWhrs per MG of

wastewater treated producing 1,240 metric tons of CO_2 per MG. Ithaca uses 501,000 kWhrs per MG and

only 899 Metric tons of CO_2 per MG. The total annual metric tons produced by each facility is 6,320 at

Ithaca and only 159 metric tons of CO_2 from Shelburne-Buckland. Figure 24 presents the relationship of

annual CO_2 produced to plant flow. The plant with the lowest average flow produces the highest metric

tons of CO_2 per million gallons treated.
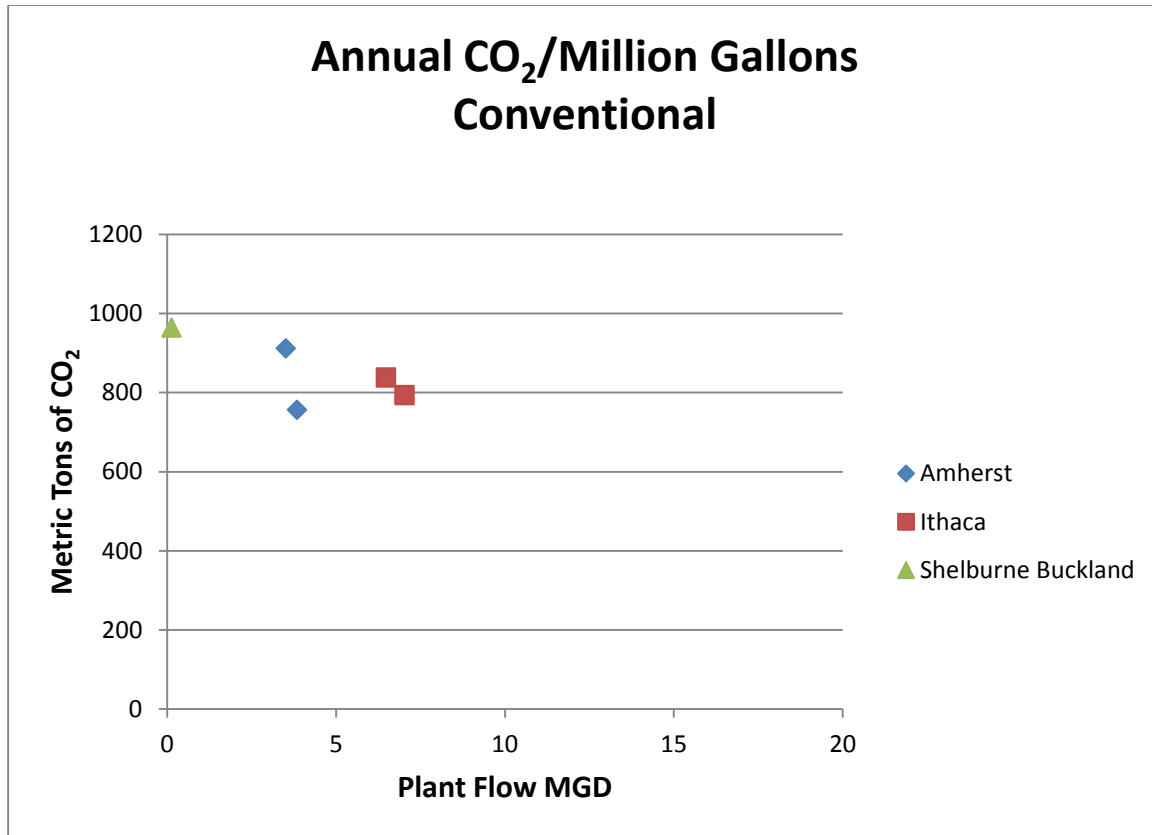
Figure 24. CO$_2$ PER MILLION GALLONS AT AMHERST, ITHACA, AND SHELBURNE-BUCKLAND
Data provided from Amherst, Ithaca, and Shelburne-Buckland used to estimate CO$_2$ produced.

Figure 25 shows the total annual metric tons of CO$_2$ at the three conventional facilities. When

just looking at the total production, the annual CO$_2$ produced is a function of plant flow. Figure 25 does

not address the CO$_2$/MG efficiency of the conventional facilities.
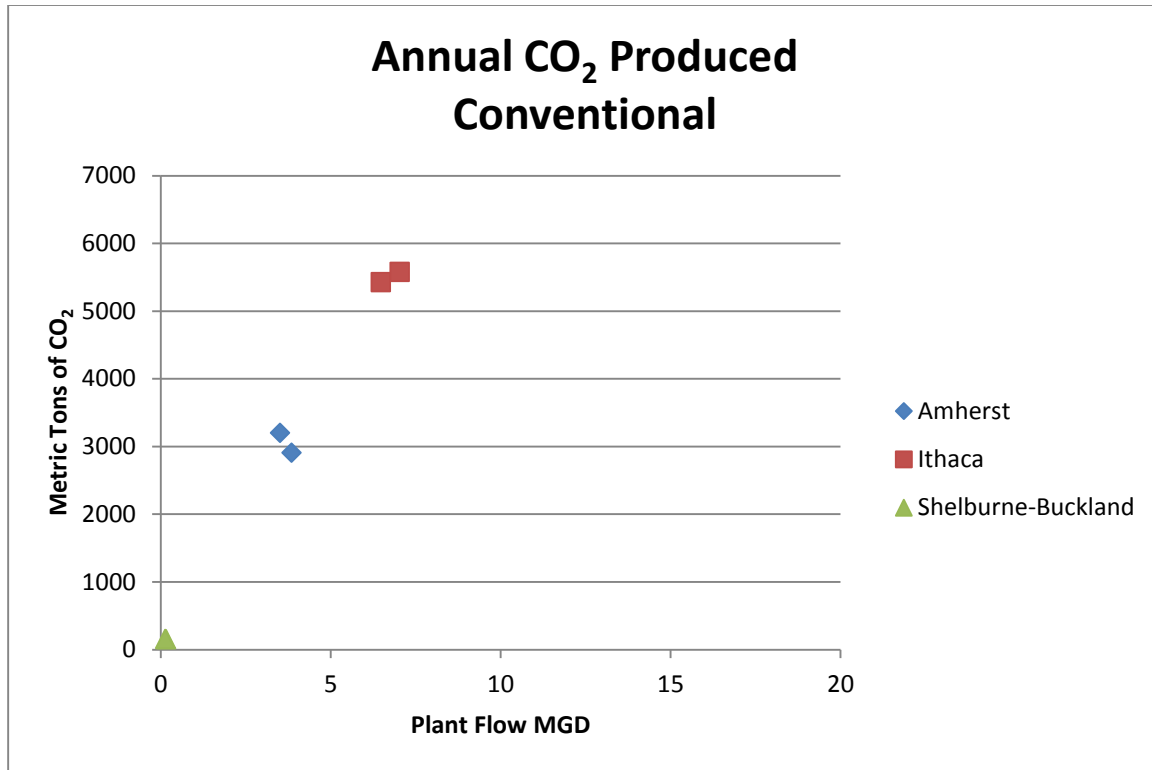
Figure 25. ANNUAL CO$_2$ PRODUCED AT AMHERST, ITHACA, AND SHELBURNE-BUCKLAND
Data provided from Amherst, Ithaca, and Shelburne-Buckland used to estimate CO$_2$ produced.

4.3 Annual CO$_2$ Produced: Conventional vs. VSB and RB Technology

The total metric tons of CO$_2$ produced from treatment at each conventional facility are broken down in Table 17. The power use for conventional treatment and treatment in the hypothetical VSB and RB systems are presented. The CO$_2$ uptake during photosynthesis in the VSB and RB systems are calculated. Using the values in Table 17 the net total CO$_2$ produced from VSB and RB treatment is estimated. Finally, the percent reduction of metric tons of CO$_2$ produced when converting conventional wastewater treatment to VSB and RB technology is calculated.

Table 17. TOTAL ANNUAL CO$_2$ PRODUCED FROM CONVENTIONAL FACILITIES

Metric Tons of CO$_2$ Produced	Amherst	Ithaca	Shelburne-Buckland
BOD$_5$ Microbial Respiration	1,590	2,410	44
Power Use Conventional	1,610	3,170	115
Power Use VSB and RB	0	0	0
Photosynthesis in VSB and RB	-771	-1,550	-22
Net Total with VSB and RB	819	858	22
Percent Reduction from Conventional	**74.4**	**84.6**	**86.2**

Estimated annual metric tons of CO$_2$ are compiled in Table 16. Values are calculated using provided data from each facility.

Figure 26 presents the current conventional power use production of metric tons of CO$_2$ and the estimated reduction with the use of VSB and RB technology.   Unlike the conventional treatment, the power use with VSB and RB technology regardless of average daily flow, is zero. The CO$_2$ produced from BOD$_5$ microbial respiration is reduced with VSB and RB application due to the CO$_2$ uptake from photosynthesis. The reduction of CO$_2$ production from the Amherst, Ithaca, and Shelburne-Buckland are 74.4%, 84.6%, and 86.2% respectively.
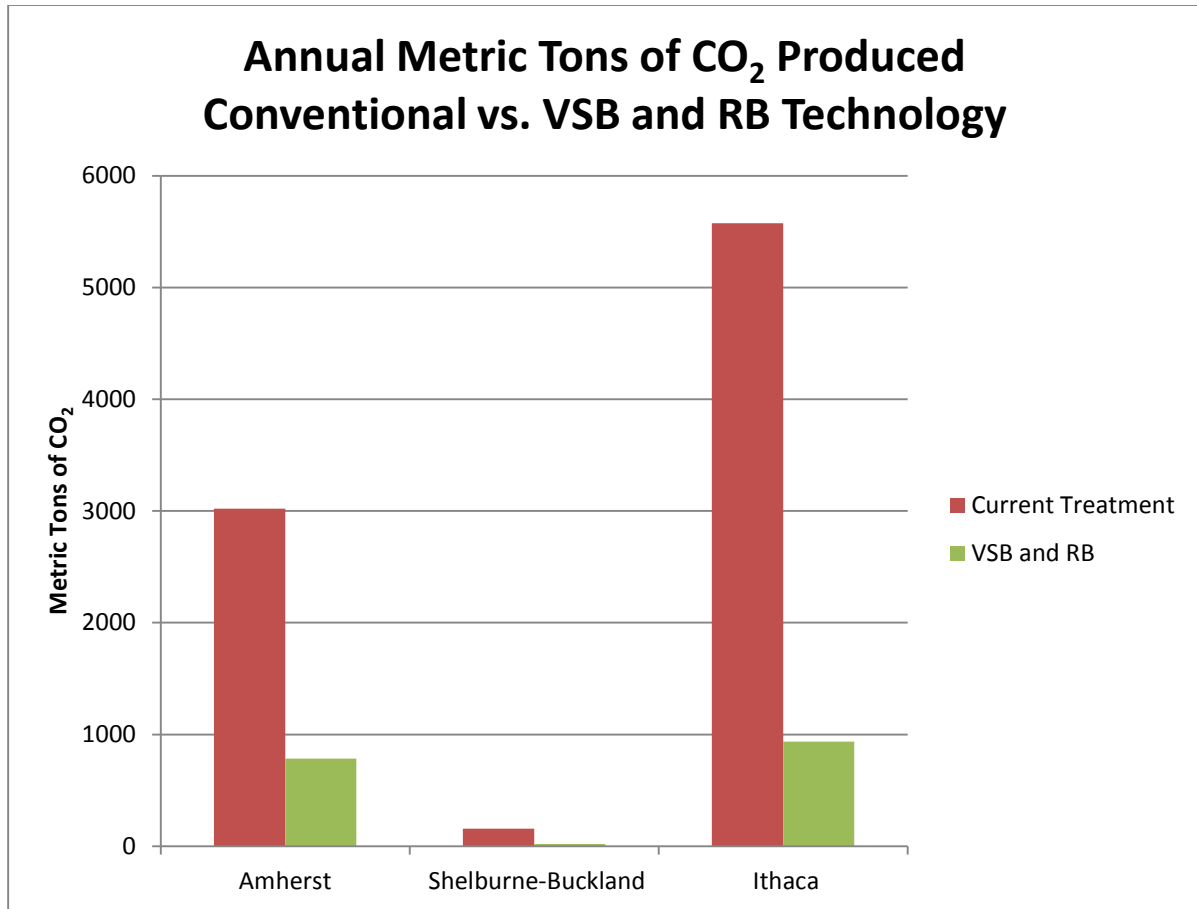
Figure 26. ANNUAL CO$_2$ PRODUCED: COMPARISON OF CONVENTIONAL, VSB, AND RB TECHNOLOGY

Figure 26 shows the annual metric tons of CO$_2$ produced at Amherst, Shelburne-Buckland, Ithaca, Lloyd, Shushufindi Slaughterhouse, and Shushufindi Municipal. The hypothetical VSB and RB systems for Amherst, Shelburne-Buckland, and Ithaca are also included showing total net CO$_2$ produced. Data provided from Amherst, Ithaca, and Shelburne-Buckland used to estimate CO$_2$ produced using current conventional technology and hypothetical VSB and RB technology.

In Figure 27, the only CO$_2$ production at the Lloyd VSB, Shushufindi slaughterhouse VSB, and Shushufindi Municipal VSB, was from the BOD$_5$ microbial respiration in the systems. Due to the photosynthesis occurring in each VSB and RB system, the net CO$_2$ emission values were further reduced. The annual metric tons of CO$_2$ from Figure 27 are presented in Table 18 showing the reduced CO$_2$ production from wastewater treatment when converting conventional treatment to VSB and RB

73

technology. The net CO_2 value for the Lloyd VSB and the Shushufindi Slaughterhouse VSB was estimated

at -3.21 metric tons of CO_2 and -1.6 metric tons of CO_2 suggesting the possibility of CO_2 sequestering

systems .
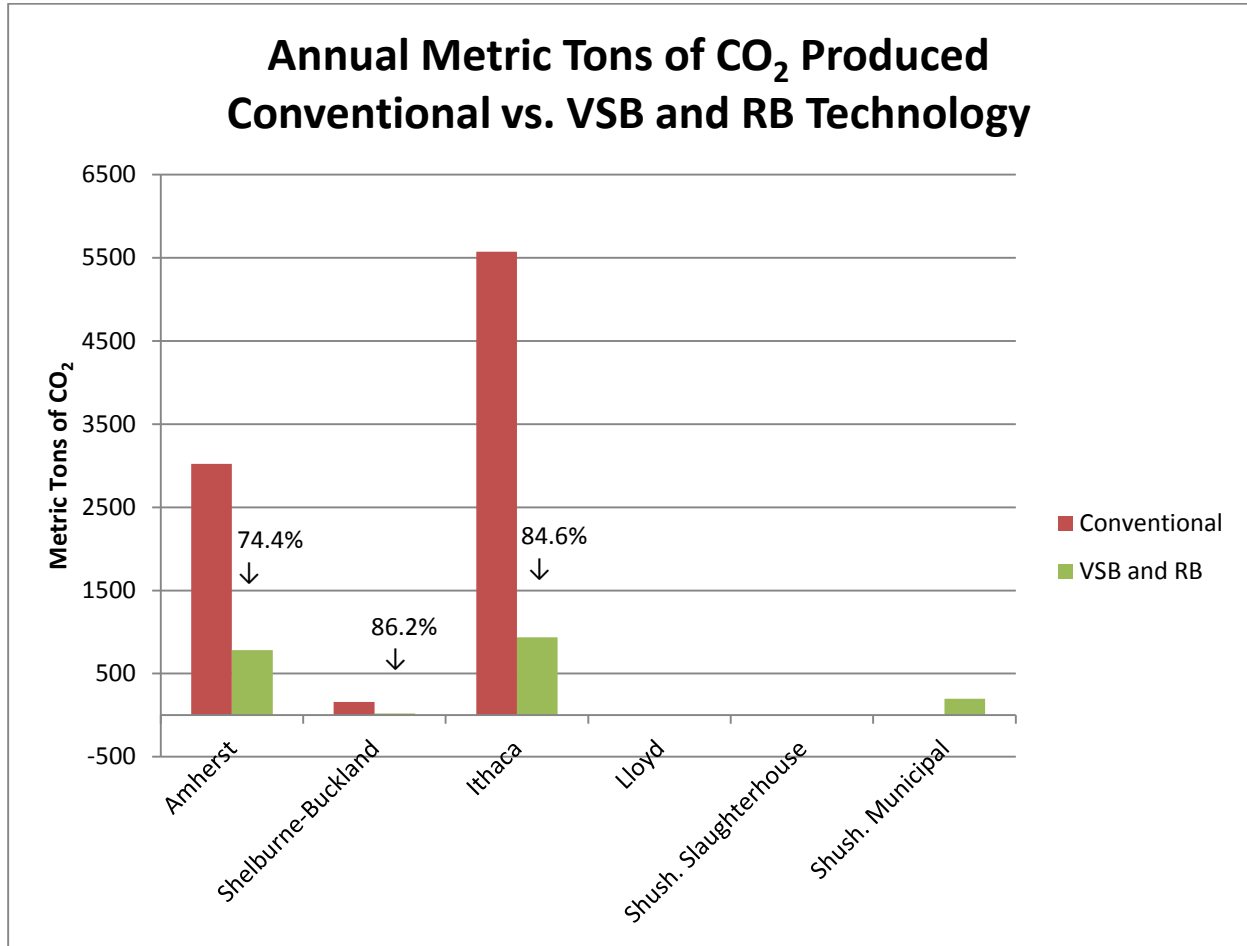
Figure 27. METRIC TONS OF CO₂ PRODUCED: APPLYING HYPOTHETICAL VSB AND RB TECHNOLOGY
Data provided from Amherst, Ithaca, and Shelburne-Buckland WWTP, Lloyd (Lavigne and Spokas 2008),
Shushufindi Slaughterhouse (Kahl 2004), and Shushufindi Municipal, (Kahl 2004) used to estimate CO_2
produced.

Table 18. ANNUAL CO₂ PRODUCED: CONVENTIONAL VS. VEGETATED SAND BED AND REED BED TECHNOLOGY

Annual Metric Tons of CO₂	Amherst	Shelburne-Buckland	Ithaca	Lloyd	Shush. Slaughterhouse	Shush. Municipal
Conventional	3,210	159	5,580	N/A	N/A	N/A
VSB and RB	823	22	930	-3.21	-1.6	212

4.4 CO_2 Produced per Million Gallons: Conventional vs. VSB and RB Technology

Figure 28 illustrates the relationship between average daily flow and energy use per MG at conventional facilities. With the application of the hypothetical Vegetated Sand Bed and Reed Bed technology, the CO_2 production is greatly reduced and the size of the facility no longer independently determines the CO_2 per MG relationship.
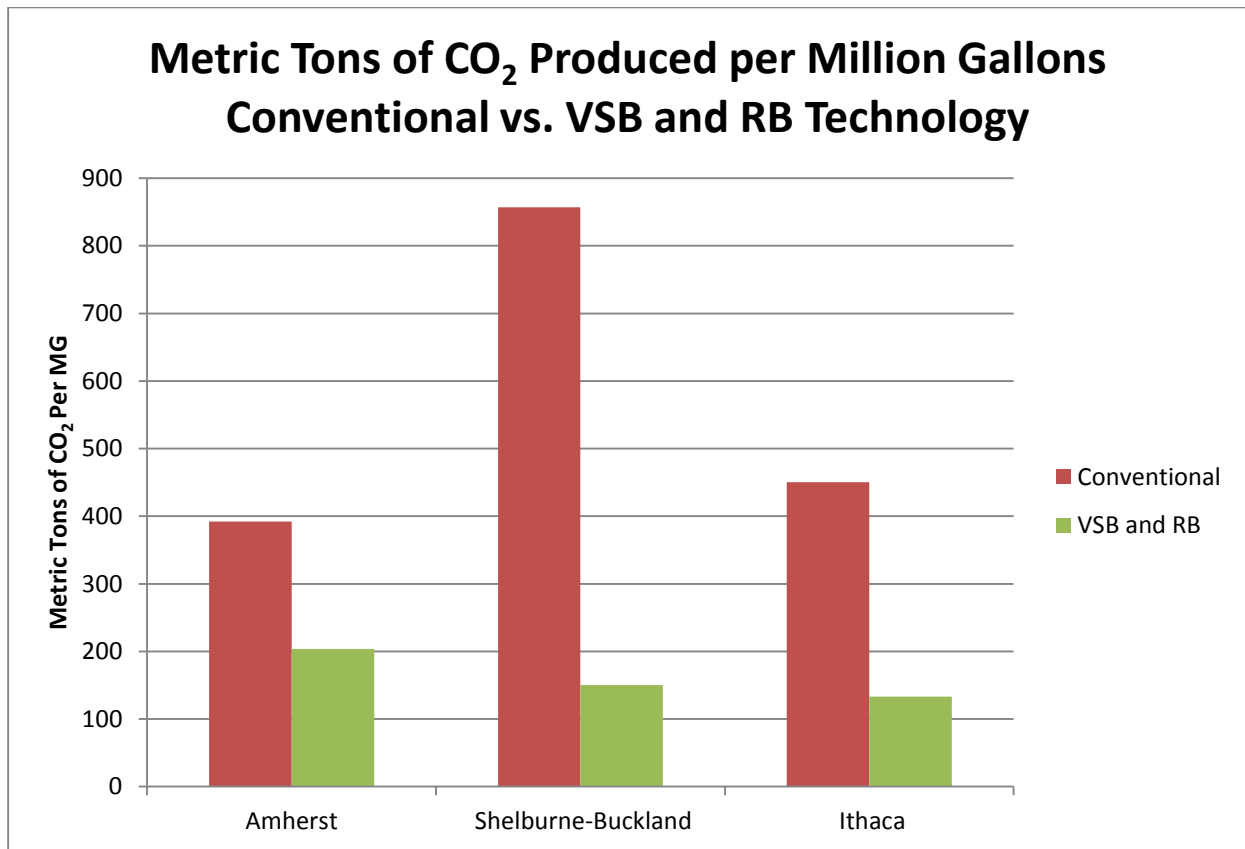
Figure 28. CO_2 PRODUCED PER MGD: COMPARISON OF CONVENTIONAL TREATMENT VS. VEGETATED SAND BED AND REED BED TECHNOLOGY
Estimated CO_2 production at conventional facilities compared to CO_2 production applying hypothetical VSB and RB technology. Data provided from Amherst, Ithaca, and Shelburne-Buckland used to estimate CO_2 produced.

CHAPTER 5

CONCLUSION

The objective of this research is to compare the sustainability of conventional wastewater treatment with Vegetated Sand Bed and Reed Bed technology considering the fate of fresh water, CO_2 production, and total energy consumption.

Vegetated Sand Bed and Reed Bed technologies are sustainable systems that could shift conventional treatment towards greener water management methods. Conventional wastewater treatment is the product of linear thinking and is not sustainable. In the United States, the anthropogenic water use cycle extracts fresh water from the environment and puts it through treatment. The treated water is contaminated or wasted and sent back to a treatment facility. The treated effluent is disinfected, often with chlorine, before it is discharged into a river ending up in the ocean. The United States needs to start managing water as a resource to recycle rather than waste of which to dispose. VSB and RB technology can be the shift in wastewater treatment to more sustainable methods. Using VSB and RB systems provides high quality treatment that can work without the high energy input required at most conventional wastewater facilities.

Greater than half the total CO_2 produced at conventional facilities was due to the power demand at every conventional facility. Table 19 shows the carbon dioxide produced from BOD_5 microbial respiration and power demand. The reduction or elimination of the power use from conventional treatment could decrease the total CO_2 produced by over 50%.

Table 19. TOTAL ANNUAL CO₂ PRODUCED AT CONVENTIONAL FACILITIES FROM POWER DEMAND

Annual Metric tons CO_2	Amherst	Shelburne-Buckland	Ithaca
Average Flow (MGD)	3.51	0.133	7.03
BOD_5 Removal	1,510	44	2,410
Power Demand	1,610	115	3,170
Total Metric tons CO_2	**3,120**	**159**	**5,580**

Data provided from Amherst, Ithaca, and Shelburne-Buckland used to estimate CO_2 produced.

Vegetated Sand Bed and Reed Bed technology can eliminate the power demand for sewage treatment, resulting in greater than 50% reduction of CO_2 produced. Additionally, the facultative wetland plants in each VSB and RB system photosynthesize further reducing the net CO_2 produced during wastewater treatment.

Figure 29 compiles the net annual CO_2 production from all conventional and VSB systems in this study. The sources of CO_2 are BOD_5 microbial respiration, power use, and photosynthesis.
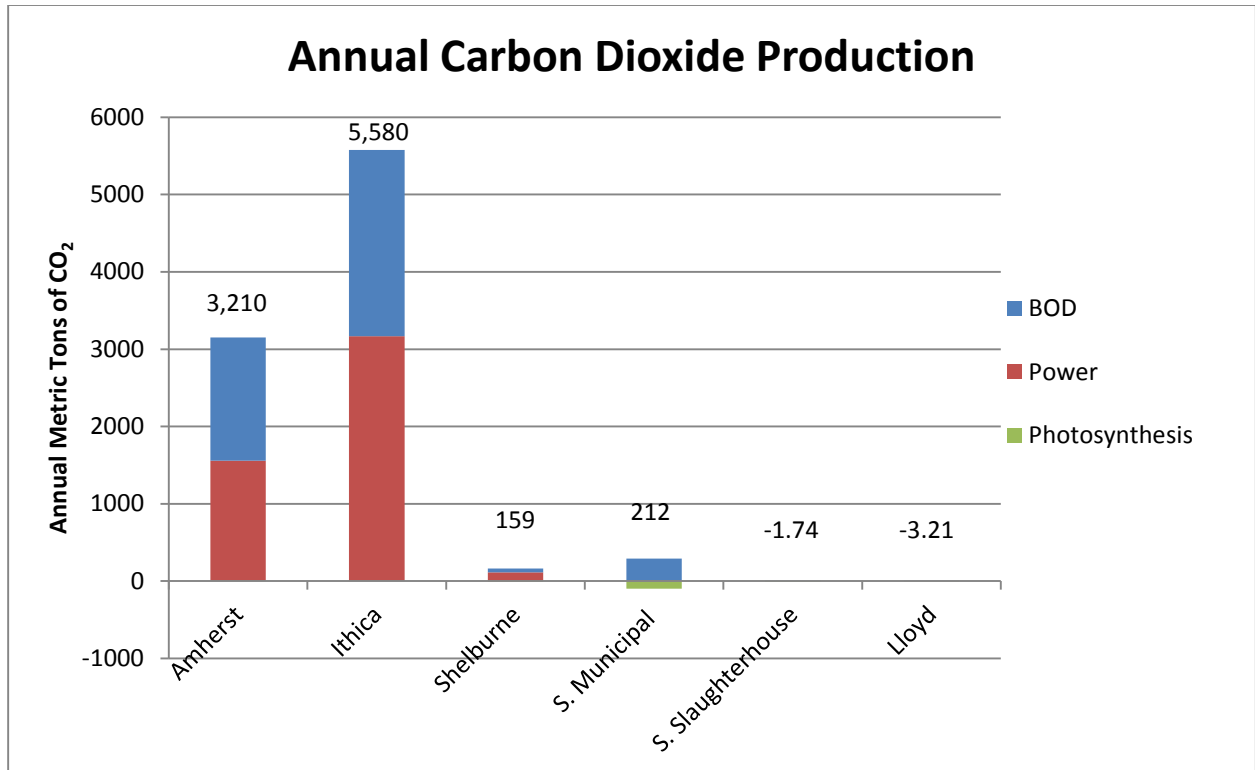
Figure 29. ANNUAL CO$_2$ PRODUCED FROM CONVENTIONAL AND VSB FACILITIES

Estimated CO$_2$ values from BOD$_5$ microbial respiration, power use, and photosynthesis for conventional, Amherst, Ithaca, Shelburne-Buckland and Vegetated Sand Bed treatment, Lloyd , Shushufindi Municipal, and the Shushufindi Slaughterhouse.

Figure 30 compares the change of CO$_2$ production per MG treated from conventional treatment to VSB and RB technology. This shows the CO$_2$ produced/MG at conventional facilities is dependent on the size of the facility. Smaller facilities produce much higher CO$_2$ which is due to higher power use/ MG treated. Also shown on this graph is the CO$_2$ production from the hypothetical VSB and RB systems. The VSB and RB systems require no power and this is apparent on the graph. This graph suggests the efficiency of conventional treatment is dependent on the average flow of the facility. Also, when using VSB and RB technology in place of conventional, the efficiency will be greatly reduced and no longer dependent on the facility size.
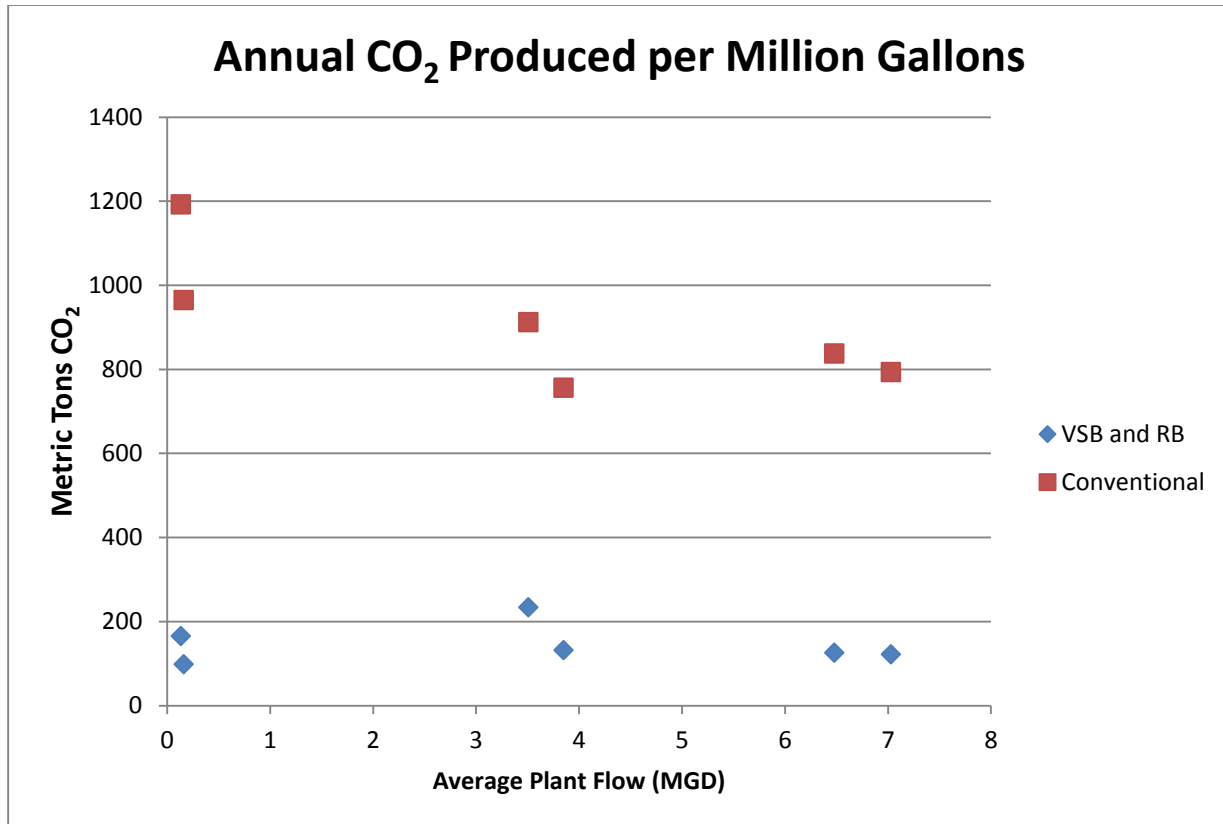
Figure 30. TOTAL METRIC TONS OF CO_2 PRODUCED PER AVERAGE PLANT FLOW IN MGD
Data provided from Amherst, Ithaca, and Shelburne-Buckland used to estimate CO_2 produced from current conventional treatment and treatment using hypothetical VSB and RB technology.

One limitation of Vegetated Sand Beds many address is the physical limitations and high costs of land area. VSB and RB systems require more land area so they cannot simply replace established treatment facilities. Along with rethinking the approach on water management, typical methods can be challenged. VSB and RB systems fit in many undesirable plots of land. One example of an innovative location to implement VSB and RB technology would be an established wetland when no one can build. Many wetlands run along roads, farms, and industries receiving contaminates from non-point sources. Building VSBs and RBs in locations such as these could establish new green wastewater treatment facilities as well as improve the quality of water entering the environment; many places receive elevated levels of nutrients or contaminants due to non point source discharge. Many processes in Vegetated Sand Beds are not understood and present opportunities for further investigation.

CHAPTER 6

THE JOSEPH TROLL TURF RESEARCH CENTER- A CASE STUDY OF VSB's USED TO TREAT COMPLEX ORGANICS AND NUTRIENTS

Photo 10. West View Joseph Troll Turf Research Center VSBs

In 2011 the Golf Course Superintendents of America (GCSAA) financed an experimental VSB project to see if the technology can treat several of the chemicals used in golf course maintenance. They can generally be described as nutrients, herbicides, pesticides, and fungicides. With the permission of Dr. Ronald Lavigne owner of U.S. patent number 7,510,649; Lavigne, 2009, a four cell VSB was constructed and put online in the summer of 2015. Figure 31 illustrates the cross sectional view of the facility and Figure 32 shows the plan view.

Photo 11. East View Joseph Troll Turf Research Center VSBs

Photo 12. South View Joseph Troll Turf Research Center VSBs

Figure 31. CROSS-SECTIONAL AREA OF JOSEPH TROLL TURF PLOT RESEARCH VSB
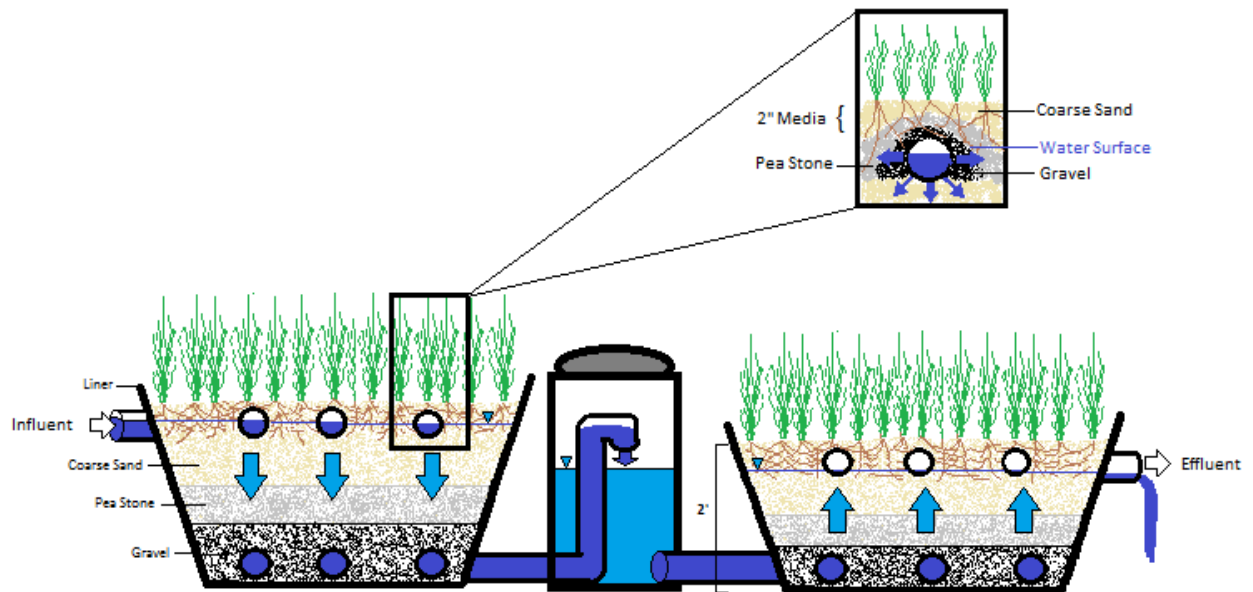
Figure 32. PLAN VIEW JOSEPH TROLL TURF PLOT VSB

Plan View Joseph
Troll Turf Plot VSBs

- Wash Pad
- D- Box
- Roughing Bed
- Polishing bed
- Holding Tank
- Collection Bay
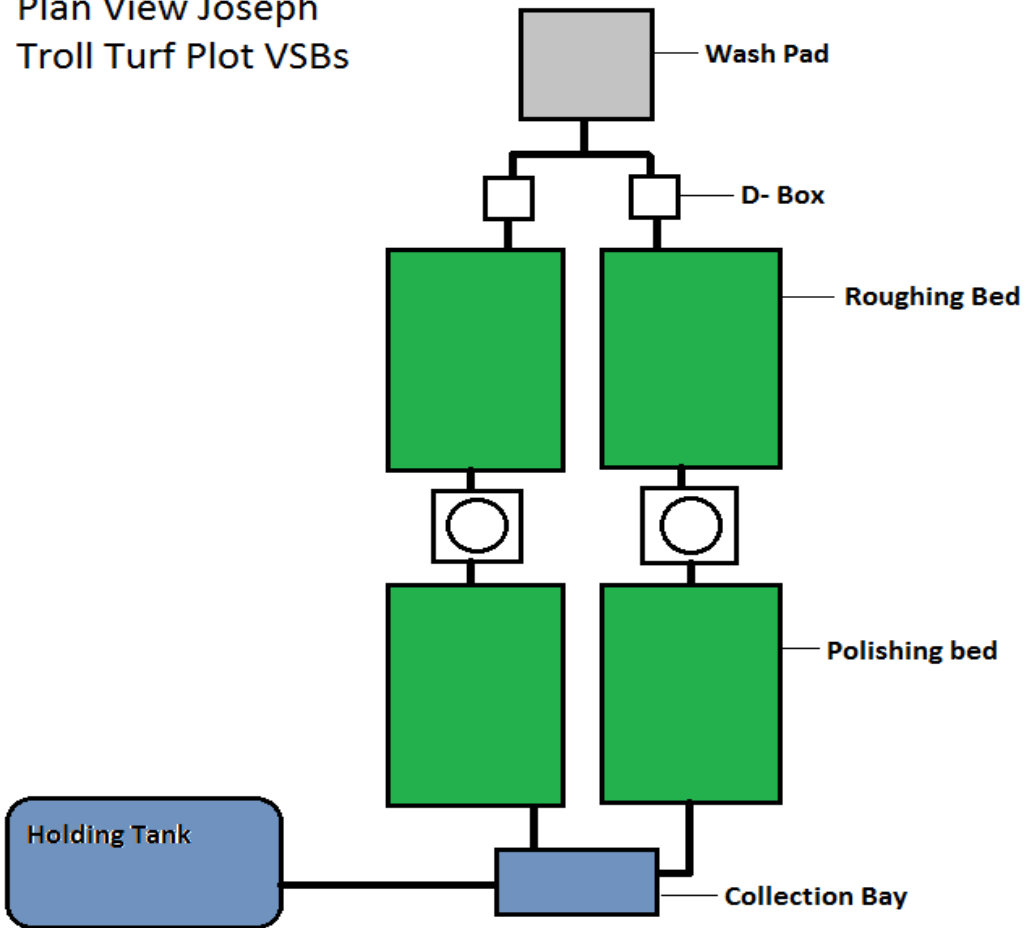
Nitrogen compounds are an increasing concern in wastewater and because of their role in eutrophication, their effect on oxygen levels on receiving waters, and their toxicity to vertebrate and invertebrate species, (Kadlec and Knight 1996). Ammonium is an inorganic compound that can greatly impact wetland environments when released into the environment. It is the preferred nutrient form of nitrogen for most wetland plants as well as for autotrophic bacteria. Ammonium is readily oxidized in natural waters resulting in significant O_2 consumption and it is also toxic to many forms of aquatic life at low concentrations (Kadlec and Knight 1996). An excess release of nitrate in wastewater can lead to eutrophication of surface waters because it is an essential nutrient for plant growth. It is also a concern

with water control because it is toxic to infants and linked to methylglobanemia (Kadlec and Knight

1996). The focus of the fate of ammonium and nitrate was spurred by the rising problem of nitrate in

groundwater on Cape Cod where golf courses have been pressed to eliminate potential nitrogen runoff.

Early objectives were to:

I.   Determine the hydraulic retention time of treatment within the system

II.   Operate the facility in the "batch mode" with varying retention time to secure concentration vs.

       time data

III.   See if the microbial reduction of organic and inorganic species would follow a first order decay

       model.

$$\frac{dC}{dt} = -k \cdot C \qquad [8]$$

Where C= the concentration (mg/L)

            t= treatment time (days)

            k= first order decay rate constant (t^{-1})

$$\ln C_t = -kt + lnC_0 \qquad [9]$$

Where Ct= concentration at time *t* (mg/L)

            C$_0$= concentration at time zero (mg/L)

By late fall preliminary data had been assembled and by separating variables and integrating

equation [8], a linear form of the first order decay model is lnC= -kt + lnC$_0$. The plot of that data is

illustrated in figure 33. The slope of the plot indicates a rate constant of approximately 0.14 days^{-1} for

ammonium removal with an average 72% reduction of NH_4^+. A similar study conducted by L. A. Spokas,

S. C. Simkins, P. L. Veneman, and S. C. Long investigated the performance of a constructed wetland

removing NH_4^+ and NO_3^- primary domestic wastewater effluent.   In this study, the VSB PB1 had an

influent and effluent concentration of 30.4 ± 9.2 mg/L and 9.8 ± 7.9 mg/L with a mean ammonium rate

constant of 0.13 ± 0.08, (Spokas *et al.* 2010). The Joseph Troll Turf Plot VSBs had an influent and effluent

concentration of 26.43 mg/L and 6.19 mg/L of NH_4^+ shown in Figure 34.
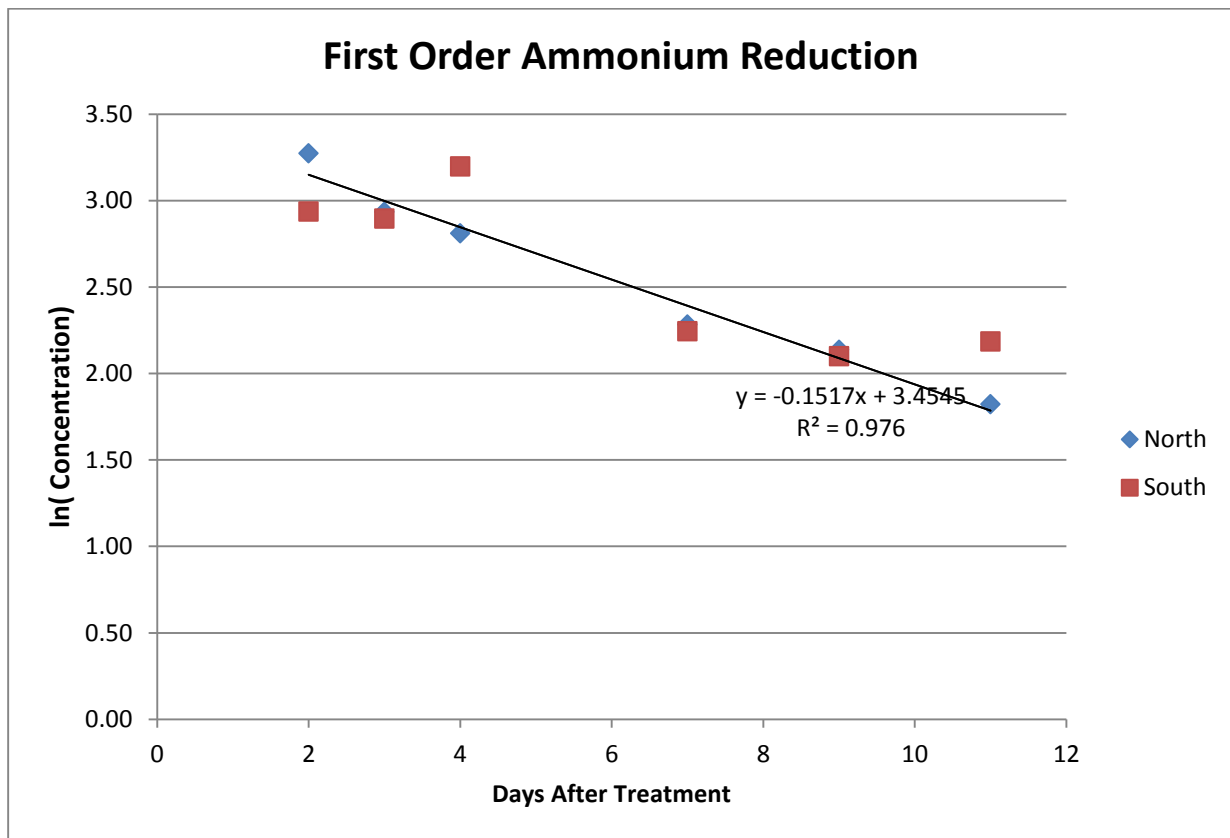
Figure 33. FIRST ORDER AMMONIUM REDUCTION

Figure 33 shows promising preliminary results for ammonium reduction in a Vegetated Sand

Bed. The reduction of ammonium suggests the VSB provides sufficient oxygen in the media to support

nitrification.   This also suggests the VSB has a population of nitrifiers in the system.
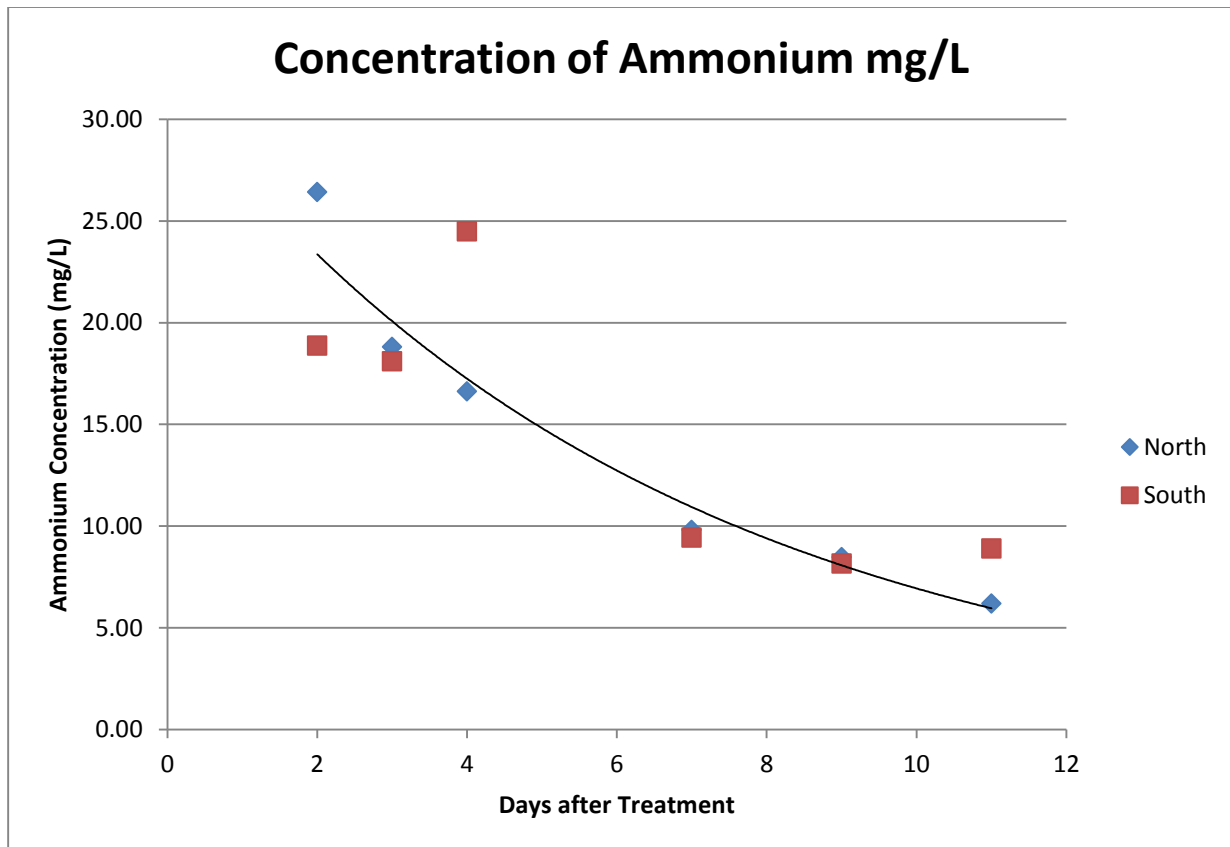
Figure 34. CHANGE IN AMMONIUM CONCENTRATION OVER TIME

Figure 35 presents the first order decay rate of 0.23 days^{-1} for NO_3^-. Figure 36 shows the nitrate concentration reduction over the span of 12 days with an average 88% removal. The data presented in Figures 33- 36 represent the removal of nitrate and ammonium in the fall and further investigation is needed to understand the seasonal variations.

First Order Nitrate Reduction

$y = -0.2221x + 3.1588$
$R^2 = 0.9806$

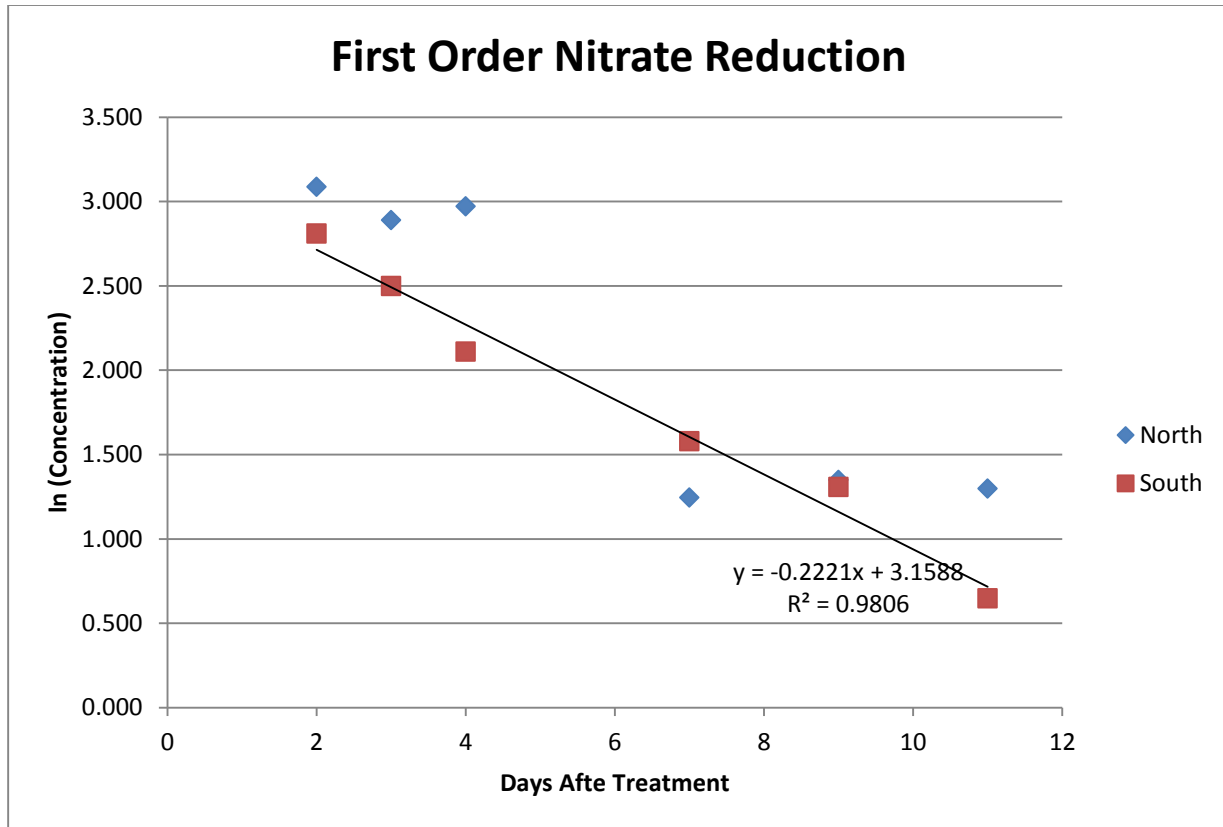ln (Concentration) vs Days Afte Treatment

North
South

Figure 35. FIRST ORDER NITRATE REDUCTION

Figure 35 shows promising preliminary results for the reduction of nitrate in a Vegetated Sand Bed. These results suggest the VSB system provides sufficient anaerobic zones to support denitrifying microorganisms. It is not know if the denitrifiers are heterotrophs or autotrophs, but the denitrification did not appear to be limited by insufficient carbon source.   The effect of nitrification of ammonium occurring simultaneously was not accounted for and needs further investigation.
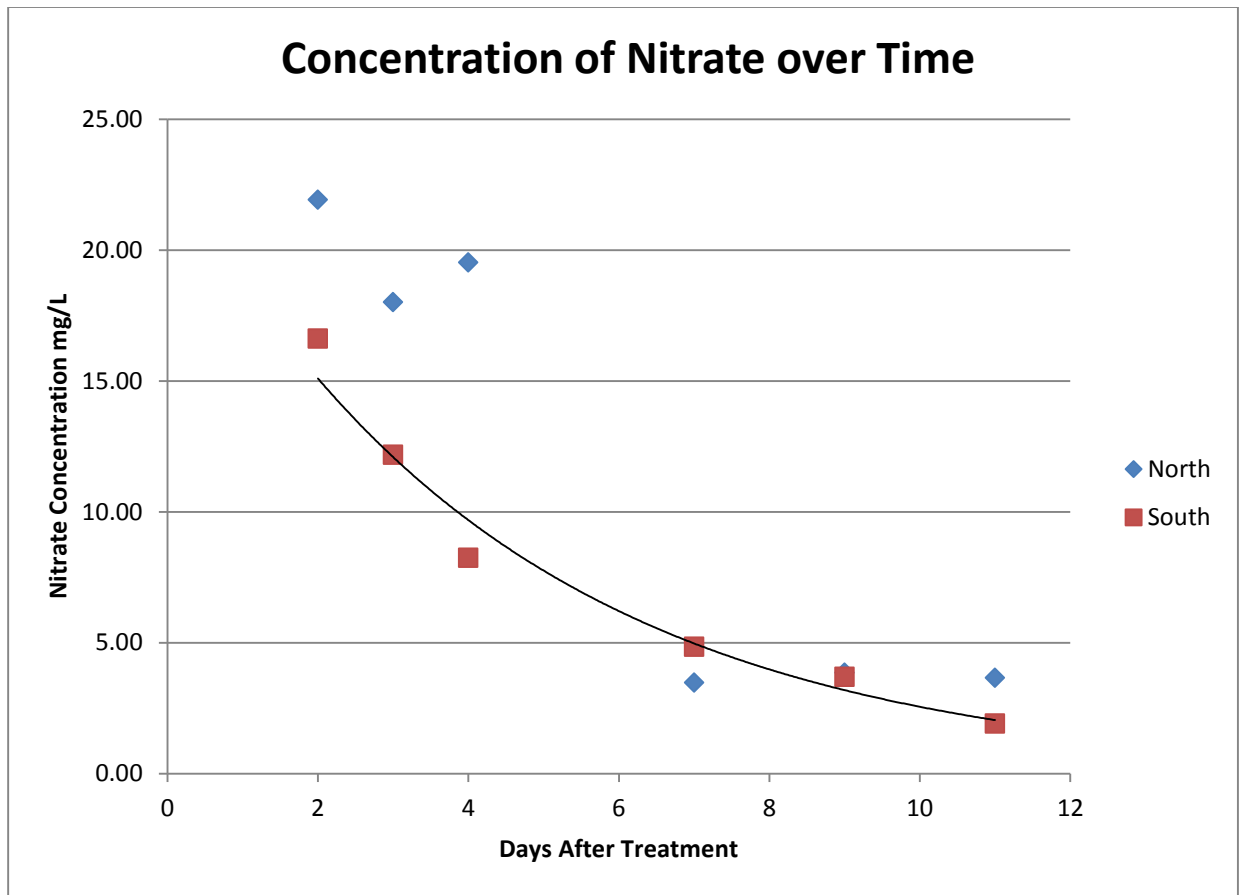
Figure 36. CHANGE IN NITRATE CONCENTRATION OVER TIME

The removal of organic and inorganic nitrogen from wastewater before it is discharged is important for the future health of the environment and all who depend on it. The preliminary ammonium and nitrate removal testing at the Joseph Troll Turf Plot Research VSB suggest both can be removed with this technology. Further research can investigate the processes occurring in the VSB to provide the removal of the contaminant and the fate of the nitrogen. Testing the ammonium and nitrate separately will also give a better representation of the rate of removal as well as the concentration in the VSB.

CHAPTER 7

FUTURE

In the spring and summer of 2016, the batch studies will be expanded to include more complex organics with the objective of refining a design model for multiple parameters. Construction of a full scale VSB facility will begin during the summer of 2016 at the Yarmouth Massachusetts Bayberry Hill Country Club with design, construction supervision, and monitoring by UMASS and New England Waste Systems U.S.A. (NEWS-USA). It is expected that other golf courses around the country will employ the technology to protect the environment including ground and surface water resources.

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