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An Evaluation of the Living Systems Laboratory's Capacity to Treat Stormwater

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An Evaluation of the Living Systems Laboratory's Capacity to Treat Stormwater

A Major Qualifying Project Report

Submitted to the Faculty of
Worcester Polytechnic Institute
In partial fulfillment of the requirements for the
Degree of Bachelor of Science

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Abstract

Stormwater runoff often causes contamination of surface water bodies. The Living Systems Laboratory (LSL) is a series of natural processes that treats water from the Blackstone Canal. This project evaluated the capacity of this system to treat stormwater. Flowrates were measured and lab analyses were performed on water samples collected from the LSL and surrounding water bodies to determine treatment efficiency. Design of the current system was evaluated and recommendations were provided for increasing the capacity of the LSL.

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Capstone Design Requirement

Design Problem & Approach

This Major Qualifying Project satisfies the Worcester Polytechnic Institute Environmental Engineering capstone design requirement. The result of this project was a design to expand the Living Systems Laboratory's treatment capacity to manage stormwater. The design was developed based on constructed wetlands wastewater treatment processes and their associated modeling equations. A stormwater analysis of the drainage basin for the area was conducted to determine the capacity of stormwater the LSL needs to be able to handle. The difference between the volume of canal water currently treated versus the annual water quality volume that should be treated were evaluated. Designs for an improved treatment system at the site were created and recommendations were proposed to further increase the system's efficiency. These recommendations consisted of maximization of the influent flowrate of the jet pump, increased cycle time for operation, an expansion to the system for myco-reactors and aquatic cells, and outlines for further testing in these areas. All aspects of engineering design were considered, including economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability concerns.

Environmental

The primary focus of the project was the treatment of stormwater, a common factor in the pollution of waterbodies as it often contains nutrients and heavy metals. Both federal and local environmental regulations were considered and was a driving factor in what constituents were measured in the laboratory. Also taken into consideration were constraints involved with calculating the volume of runoff, which provided parameters for the system capacity increase. Additional background on stormwater can be found in the background section 2.4 Stormwater Analysis.

Ethical

Contaminated waters must be properly treated to maintain the health and safety of the public, as is standard ethical practice. This is especially the case in a municipality/residential area such as

Grafton, Massachusetts. This project aims to treat more stormwater, and remove more contaminants from the water to improve the community's water quality.

Social

Clean, treated water benefits the surrounding environment. For this project, the Living Systems Laboratory and the surrounding park area were the direct environment impacted. The goal of the treatment system is to prevent contaminants from harming community members and park visitors. The LSL also provides an educational opportunity for the community to learn about the importance of keeping the canal and surrounding environment clean and the biological processes behind the water treatment.

Political

The Town of Grafton is required to properly treat stormwater/contaminated water before discharging it into a body of water. The recommended improvements to the Living Systems Laboratory help the town in fulfilling this requirement, as we reviewed relevant regulations pertaining to proper discharge.

Health and Safety

This project directly impacted the health and safety of the surrounding communities as it focused on treating the contaminated Blackstone Canal, particularly from harmful heavy metals.

Manufacturability

The recommended improvements for the Living Systems Laboratory incorporated design components that are feasible to build. The ease in making improvements feasible is in making changes that will require minimal construction. We considered this when increasing the system influent flowrate of the current jet pump instead of the purchase and installation of a new one. Additionally, instead of recommending the installation of larger retention tanks to store more influent water, we designed for an increase in both the system influent flowrate and cycle time.

Sustainability

This project incorporated design that was sustainable, and did not require constant maintenance after implementation. The system itself incorporated sustainability concepts not found in

commercial water treatment, including biological systems that use the water for plant growth. The Living Systems Laboratory capitalizes on natural treatment processes such as the uptake of metals via plant roots in the aquatic cells or the breakdown of hydrocarbons using sawdust and fungi which ensures the sustainability of the project as these natural processes will continue to occur as long as the system is maintained.

Economic

Recommendations were developed for design that were cost-effective for town of Grafton. We worked within the existing system, attempting to reduce the amount of new parts needed for the proposed expansion. We also took into account the lack of funding to make changes without an additional monetary grant.

Professional Licensure

Why Licensure?

The overarching purpose of professional licensure for engineers is to protect the health, safety, and welfare of all people (Commonwealth of Massachusetts 2017). These are ethical considerations that are held uppermost in the professional engineering field, since the profession directly impacts society, and its overall quality of life (NSPE Code of Ethics, 2007). For this reason, engineers are held to the highest standards of honesty and integrity (NSPE Code of Ethics, 2007). Acquiring professional licensure is crucial in the engineering industry. Receiving the status of professional engineer is recognized as a label of quality assurance and skill. The license demonstrates a mastering of the profession, and proves to be impressive to employers and clients alike. Becoming certified as a professional engineer (PE) also increases career flexibility. Only professional engineers are permitted to prepare, sign, seal, and submit engineering plans and drawings for public use. Professionally licensed engineers are the only ones allowed to seal engineering work for private companies as well. Nowadays, having a professional license is a necessity for engineering consulting and private practice. In most states, it is legally required for those in charge of engineering work to be professionally licensed. Also, there is an increasing amount of government agencies, educational institutions, and private companies requiring hiring and contract only with licensed professional engineers (Why Get Licensed, 2017).

Professional Licensure Process

The steps for professional licensure include obtaining an undergraduate degree from an accredited program, passing the FE exam, gaining sufficient professional experience, and passing the PE exam. The first step in the process for becoming a professional engineer is to graduate from an accredited engineering school (EAC/ABET). Around the time of graduation, the FE Exam, administered by the National Council of Examiners for Engineering and Surveying (NCEES), must be passed in order to achieve the status of "Engineer-in-Training" (National Council, 2017) (How to Get Licensed, 2017). Passing the exam shows knowledge of all applicable background information, and mastery of engineering fundamentals in your field. After this certification, at least four years of proper engineering work experience under supervision of a licensed professional

engineer is required by all states. It is advised to become familiar with your state's regulations regarding qualifications for the PE exam, as each state has its own licensure board, and requirements can vary from state to state (How to Get Licensed, 2017). After fulfilling those requirements, as well as producing proper proof of education, character and experience references, you can apply to take the PE exam (Commonwealth of Massachusetts, 2017). Upon passing the PE exam, you will receive your license as a professional engineer.

Executive Summary

Stormwater is one of the leading causes of pollution in freshwater bodies. The nutrients, metals, hydrocarbons and other contaminants that are carried in urban stormwater can affect biological growth and habitat health in surface water bodies. Because of this, it is important to characterize the constituents present in stormwater and quantify the runoff flows entering the given body of water. Best Management Practices (BMPs), are often used to improve runoff water quality, control flooding, and reduce erosion from storm events (MassDEP, 2008). However, natural treatment systems have been used for many years in stormwater treatment.

The Living Systems Laboratory (LSL), located in Grafton, MA is a natural treatment system that uses biological processes to metabolize contaminants that are present in the Blackstone Canal. Water is pumped from the canal into a greenhouse, where it is subject to a four-stage treatment process. The LSL is located at the site of the old Fisherville Mill, which like most sites along the Blackstone River dating back to the Industrial Revolution, contains high amounts of hydrocarbon and metal contaminants. These contaminants, which inhibit ecological growth, often enter the canal through stormwater runoff. Because of this, the Town of Grafton wants to determine the LSL's capacity for treating runoff entering the canal.

The goal of this project was to determine the Living System's Laboratory current and potential capacity to treat stormwater runoff for the area surrounding the Blackstone Canal. The objectives accomplished in completing this project were the quantification of flowrates entering and leaving both the canal and LSL, the measurement of contaminants in the canal water during both dry and storm conditions, and an analysis of the volume of runoff entering the canal. First, the flowrates entering and leaving LSL and canal were measured. Samples were then collected from various sampling locations and analyzed for indicators of water quality. GIS was then used to analyze the features of the surrounding area. The volume of runoff entering the canal was quantified using the NRCS method, which yielded the main parameter for design upgrades. Current design was also evaluated for comparison. Recommendations were provided on how to expand the LSL to accommodate the volume of runoff from the NRCS.

The first step to completing our objectives and accomplishing our goal was measuring flow rates at the influent, midpoint, and effluent of the LSL, as well as at the canal effluent. Water samples were collected at nine different locations throughout the LSL and the canal. Three of the samples

were collected directly from the canal: one at a location directly upstream of the LSL, one at the location water is pumped from the canal and sent to the LSL, and one at the canal effluent. Another three samples were collected at the influent, midpoint, and LSL. The last three samples were collected during a storm event: one from a drainage pipe adjacent to the canal, one from a stream of runoff entering the canal, and one from the same location where water is pumped from the canal and sent to the LSL. These samples were tested for several water quality indicators such as turbidity, total suspended solids, total organic carbon, total inorganic carbon, dissolved oxygen, modified BOD_5, metals, total phosphorus, ammonia, nitrate, pH, and alkalinity. The lab data was analyzed to determine the treatment efficiency between each stage of treatment in the LSL, in addition to the overall treatment efficiency. It was found that there were especially large reductions in metals and total suspended solids throughout each treatment stage, proving that each stage was a necessity.

A Geographical Information System (GIS) was used to analyze geographical data about the surrounding area, including topography, soil composition, and land use. Two areas were identified as draining into the canal. Using these data, a stormwater analysis was conducted by using the NRCS method. The runoff volumes were determined for storms of three different intensities: a 1-year storm, a 2-year storm, and a 0.5 in. storm. The annual rainfall distribution for the area was also examined, to determine the annual runoff volume entering the canal from one of the areas. The smaller area was used for design criteria because it had a more direct effect on the canal and a more manageable runoff volume. Finally an annual Water Quality Volume (WQV) was found in order to provide a realistic treatment goal for the LSL. Determining an annual WQV of 320,000 cubic ft. was helpful in determining the scale of expansion that needs to occur to the LSL, which currently only treats 33,945 cubic ft. annually.

A design evaluation was conducted on the LSL's capacity to treat the water quality volume of runoff, by analyzing the current system constraints and proposing design improvements. One proposed change was to increase the current influent flowrate two-fold, using a second jet pump in parallel to the initial pump. Research showed that using two parallel jet pumps with a constant head at the influent would double the inflow rate (de Costa Bortoni et. al., 2008). This change would double the current influent flowrate from a maximum of 0.03 cfs to 0.06 cfs, and would require an expansion of the current retention tank and sump pumps. A second change that was proposed to increase the hydraulic capacity of the LSL was increasing the cycle time from 43-minute cycles, four times a day, to two-hour cycles, four times a day. This change would allow for

the necessary 876 cubic feet per day required to meet the WQV, while allowing the current pump to operate at its max flow of 0.3 cfs. In order to handle influx of stormwater, it was recommended that the number of myco-bed reactors increase from eight to 19, while maintaining the same individual myco-bed size. It was then found that twelve aquatic cells in addition to the existing six, would need to be added to manage the WQV, in three trains of six cells due to spacing constraints and keeping a feasible hydraulic retention time.

This project took into consideration environmental, ethical, social, political, economic, sustainability, manufacturability, and health and safety aspects in order to propose a feasible design solution that would allow for the application of stormwater treatment for the Living Systems Laboratory. This evaluation of the LSL was important in understanding the current and potential capacity for treating stormwater. By implementing new design components, the treatment capacity of the LSL would significantly increase.

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1.0 Introduction

Stormwater is one of the leading causes of pollution in freshwater bodies (Erickson et. al, 2013). The nutrients, metals, hydrocarbons and other contaminants that are carried in urban stormwater can affect biological growth and habitat health in surface water bodies. Given the impacts of these contaminants, it is important to characterize the constituents present and quantify the runoff flows entering the given body of water. Because stormwater can have such a vast impact on water quality, environmental regulations limit the flowrates and contaminant levels of runoff that are allowed to enter waterbodies. Therefore, stormwater usually has to be treated using Best Management Practices (BMPs), which can improve runoff water quality, control flooding, and reduce erosion from storm events (MassDEP, 2008).

Natural treatment systems have been used for many years in wastewater and stormwater treatment. The Eco Machine, located at the Omega Center for Sustainable Living in NY, is one example. Designed by John Todd, the same ecological designer that designed the LSL, the Eco Machine treats around 52,000 gallons of wastewater per day using only ecological processes. The Living Systems Laboratory (LSL), located in Grafton, MA is a natural treatment system that processes 700 gallons of water per day from the Blackstone Canal. It uses biological processes to metabolize the nutrients and hydrocarbons that are present in the Blackstone River watershed from years of industrial activity. Water is pumped from the canal into a greenhouse, where it is subject to a four-stage treatment process. This treatment process is discussed in further detail in Section 2.4. The contaminants mentioned above often enter the canal through stormwater runoff. Because of this, the Town of Grafton wants to determine the LSL's capacity for treating runoff entering the canal.

The LSL is located at the site of the old Fisherville Mill, in South Grafton, Massachusetts (Figure 1). Like most sites along the Blackstone River dating back to the Industrial Revolution, the Fisherville Mill site contains high amounts of hydrocarbon and metal contaminants. The site is now a park, which the LSL is a part of. The Town's vision for the park is a community center for the residents of South Grafton, and there is currently a plan for developing the northern part of the site into a residential complex. The purpose of the LSL is to display some of the innovative

techniques that can be used for sustainable water treatment. In addition to simply being a method for water treatment, it is also meant to serve in an education and recreational capacity for the community of Grafton.

Figure 1: Fisherville Mill Site via ARCGIS; Scale 1:250

The goal of this Major Qualifying Project was to determine the Living System's Laboratory current and potential capacity to treat stormwater runoff for the area surrounding the Blackstone Canal. The flow rates of the system and the canal were first characterized to understand the movement of water throughout the system. Samples from several points throughout the system and the canal were then collected and analyzed for various water quality indicators to determine the effectiveness of current treatment, particularly between stages of treatment. Next, the stormwater runoff volumes entering the canal were quantified using the NRCS method and a land use, topography, and Geographic Information System (GIS). Finally, a design evaluation was completed on the LSL's capacity to treat stormwater and design recommendations were proposed in order to expand the system. Since the LSL is still somewhat experimental, there were many unknown factors regarding its operation. There were a variety of constraints in the scope and timing of this project, including

2

measuring samples during low temperatures with low microbial activity and the difficulty of characterizing the biological behavior found in the LSL. Nevertheless, this project provides insight into the applicability of the LSL to treat stormwater runoff. The methods used in completing this goal are described in Section 3.0. The results gathered from data collected in the field are discussed in Section 4.0.

2.0 Background

In order to complete our stormwater analysis of the Living Systems Laboratory (LSL), we had to do extensive research to learn more about stormwater, the LSL, and the history of the site. This section begins by discussing the importance of stormwater and how to conduct a stormwater analysis. Various types of natural treatment systems and their applications are then discussed. Lastly, the LSL and a detailed description of each of the treatment components are introduced. Finally, we discuss the history of the Fisherville Mill in Grafton, MA.

2.1 Stormwater Analysis

Stormwater is essentially any runoff from rain or snow that does not infiltrate into the ground (EPA, 2016). Expansion of urban development has increased stormwater runoff volumes due to the creation of impervious land, which leads to decreased infiltration (Stadelmann 2002). These quick spurts of stormwater runoff make it hard to retain all of it in collection basins, which makes controlling the path of the stormwater difficult, causing stormwater runoff to enter other bodies of water, such as rivers, lakes, oceans, and surface water reservoirs. The EPA (2016) states, "Population growth and the development of urban/urbanized areas are major contributors to the amount of pollutants in the runoff as well as the volume and rate of runoff from impervious surfaces." Because of expanding urban areas, stormwater is a problem that needs to be addressed, now more than ever.

2.1.1 Watersheds and Drainage Basins

In most cases, stormwater is analyzed for a specific area. When looking at sections of urban or residential land, it is important to know exactly how much runoff is being introduced, and how much is leaving. Watersheds are defined areas of runoff associated with certain hydrological bodies. For example, the Blackstone River has its own watershed, encompassing all runoff sources that contribute to the river from stormwater. Some water bodies are smaller, and do not have a defined watershed. For instance, in the case of this project, an estimated "drainage basin" for the Blackstone Canal is necessary to better determine all stormwater constituents, and analyze all inflows and outflows impacting the hydrological body directly. This estimation and data collection

is done using specific technology designed for the visualization and analysis of geography by utilizing topographical data (Erickson, 2013).

2.1.2 Characterizing Stormwater

It is important when dealing with stormwater to examine the various contaminants that are present, because stormwater is a leading cause of pollution to fresh and brackish receiving waters (Erickson et. al, 2013). The greatest concern is the impact on biological integrity and habitat alteration due to nutrients, metals, hydrocarbons, and other contaminants that are found in urban stormwater. Nutrients, such as nitrogen and phosphorus, can cause problems when introduced to freshwater bodies. Large concentrations of nutrients can reduce water clarity and increase algae populations, which can consume dangerous amounts of dissolved oxygen (Erickson et. al, 2013). Metals such as copper, zinc, and lead can inhibit reproduction, growth, and may in some cases be lethal for aquatic organisms. Likewise, hydrocarbons can also impact the survival of aquatic species, by bioaccumulation and the consumption of oxygen.

2.1.2a Dissolved Oxygen and pH

Dissolved oxygen, or the amount of oxygen gas dissolved in a water sample, is often used to determine water quality as it is necessary for organisms to perform cellular respiration for their survival. Dissolved oxygen concentrations vary due to specific plant activity, temperature, decaying organic matter present, stream flow, and pressure of each water body, but typically read from 0 to 15 mg/L (Research Gate, 2016). Dissolved oxygen levels of 7-11 mg/L is optimal for most stream wildlife, whereas measurements ranging from 0-2 mg/L mean that the waterbody does not have enough oxygen for wildlife to exist (Behar, 1997).

The pH is an indicator of H^+ and OH^- concentrations present in a water sample; the lower the pH, the more H^+ ions present and thus more acidic. A higher pH will occur when more OH- ions are present than H^+ ions, resulting in a more basic sample. Rainfall typically has a pH of 5-6.5 where lakes typically have a pH 7-8.5. pH is often tested in water bodies as living organisms are sensitive to pH change and typically thrive in waters with a pH from 6.5 to 8.2 (Research Gate, 2016).

Turbidity is the measure of how clear a body of water is; higher turbidity waters appear cloudy whereas water with a low turbidity appear clear. Turbid waters tend to warm easily due to the particle absorption of sunlight and reduces photosynthesis in the waters as the sun is absorbed by these particles which is harmful for organisms living in those water bodies. Surface water has a turbidity of between 1 and 50 NTU, although tends to be higher in storm events, and lower in still waters (Research Gate, 2016).

Total Suspended Solids (TSS) is defined as organic and inorganic particles that are carried by wastewater into a receiving water. TSS is the cause of turbidity in many surface waters, containing both organic and inorganic particles. Some organic suspended solids may exert additional oxygen demand. Inorganic particles can be commonly discharged from construction sites, which is a major concern for future development on the north undeveloped lot near the LSL. When turbidity increases, light penetration through the water thus decreases, and aids in the increase of bacteria populations. Deposited solids on the bottom of the water body can destroy the habitat for benthic organisms, thus making the testing for TSS important, so that improvements can be made (Davis, 2009).

2.1.2c Total Organic Carbon, Modified BOD_5, Alkalinity, and Total Inorganic Carbon

Total organic carbon (TOC) is a measurement of organic matter in a waterbody. It is important to take note of organic content in water as it most importantly affects biogeochemical processes, nutrient cycling, and biological activity. Organic matter contains various components including compounds, colloids, particles, and dissolved macromolecules (Barber, 2007). Dissolved organic content may range between concentrations of 1-20 mg/L, from alpine streams to polluted or tropical waters (Spitzy et. al).

Modified BOD_5 is the reduction of dissolved oxygen concentrations over a certain period of time. A modification of the traditional biochemical oxygen demand (BOD), modified BOD_5 is a measure of consumed oxygen, which in turn is representative of the presence of organic matter in a water body (Delzer et. al., 2003). Modified BOD_5 is the difference in DO concentration in mg/L over a 5-day time period. The higher the oxygen depletion, the more organic matter is present in the sample. Refer to section 2.1.2a for optimal and dangerous dissolved oxygen levels.

Alkalinity is a measure of water's ability to neutralize acids and resist changes in pH. Alkalinity is important to measure in this application because it is an indicator of how well a body of water will react to various types of pollutants. Alkalinity is dependent on the amount of buffering materials, such as bicarbonate (HCO_3-) and carbonate (CO_3^{2}-) that are present in the water. Waters with low alkalinity are more susceptible to changes in pH, whereas water with high alkalinity can better resist changes in pH. In general, levels of 20-200 mg/L are normal for fresh water bodies, while levels below 10 mg/L are susceptible to pH changes from pollutants and natural causes (Murphy, 2007). Alkalinity is measured in units of mg/L of $CaCO_3$.

Total inorganic carbon (TIC) is the measure of carbon in a sample of water that is derived from ores and minerals and is often found in the form of carbon monoxide or carbon dioxide. Both of these carbon compounds are gases, and both can be extremely harmful to wildlife. Carbon monoxide can be toxic to inhabiting species in doses as small as 0.001 gram. Carbon dioxide becomes fatal to wildlife at concentrations of 15% or more. Carbon dioxide may also affect habitats via greenhouse effect, which in turn increases the surrounding temperature (Chemistry of Carbon, 2016).

2.1.2d Ammonia and Nitrate

Ammonia is a form of Nitrogen that is a toxin to aquatic environments. Typically, ammonia is introduced to a water body via agricultural fertilizers, decomposition of organic matter, human and animal waste, forest fires, gas exchange within the atmosphere, or nitrogen fixation. Large concentrations of ammonia in a water body leads to a buildup of the constituent in aquatic animals, which can be fatal. According to the Environmental Protection Agency, acute criteria for ammonia is regulated at 7.3 ppm at pH 7 and 30 degrees Celsius to 24 ppm at a pH of 7 and 0 degrees Celsius. Chronic criteria is regulated at 0.99 ppm ammonia at a pH of 7 and 30 degrees Celsius to 4.4 ppm ammonia at a pH of 7 at 0 degrees Celsius. Acute criteria referring to concentrations of ammonia that enter the water body in a short period of time, whereas chronic criteria refers to long-time exposure of the waterbody to ammonia. Ammonia concentrations are a function of both pH and temperature; below a certain temperature freshwater invertebrates become less sensitive to ammonia and below a certain temperature range fish become more sensitive (EPA, 2016).

Nitrate ions provide nitrogen to living organisms in freshwater which is needed for the synthesis of amino acids and proteins. Nitrate ions are most commonly introduced to a water source via runoff, wastewater, automobile/industrial emissions, and plant and animal decomposition. Nitrate concentrations for freshwater samples typically range from 0.1 mg/L to 4 mg/L (100 ppb to 4,000 ppb). High nitrate concentrations may lead to eutrophication, causing an imbalance in the environment (Research Gate, 2016).

2.1.2e Total Phosphorus and Phosphate

Phosphorous is beneficial for waterbodies in small doses as it is a necessary nutrient for plant growth. In large concentrations, phosphorous is a factor in eutrophication, increased Biochemical Oxygen Demand (BOD), and decreased dissolved oxygen (DO), all of which can be extremely problematic in an aquatic habitat. Phosphorous enters water bodies primarily via human, animal, industrial, and agricultural wastes and human land disturbance. Total phosphorus concentrations above 0.1 mg/L (100 ppb) will encourage plant growth (Research Gate, 2016). Total phosphorus concentrations between 0.01 mg/L and 0.03 mg/L in surface water bodies is typically a safe concentration to avoid algal blooms (NCSU Water Quality Group, 2016).

Phosphates are mainly introduced to water bodies via human and animal wastes and in small doses (0.1 mg/L or 100 ppb) encourage plant growth. Excessive concentrations of phosphate encourage eutrophication which creates an imbalance in the environment, and reduces dissolved oxygen (DO) levels, and increases biochemical oxygen demand (BOD) (Research Gate, 2016).

2.1.2f Metals

Heavy metals are often considered contaminants, and therefore often regulated. Heavy metals such as aluminum, iron, nickel, zinc, cadmium, lead, and arsenic are often monitored and have suggested concentrations according to the EPA. The following heavy metals have both acute and chronic regulations in such order: aluminum (750 ppb, 87 ppb), iron (N/A, 1,000 ppb), nickel (470 ppb, 52 ppb), zinc (120 ppb, 120 ppb), cadmium (1.8 ppb, 0.72 ppb), lead (65 ppb, 2.5 ppb), and arsenic (340 ppb, 150 ppb) (Environmental Protection Agency, 2016).

2.1.3 Geographical Information Systems (GIS)

Geographical Information System (GIS) is a tool that is used to visualize and interpret geographical data (ESRI, 2017). Geographical information is stored in data layers which are imported and displayed over a map. Examples of information contained in these data layers are roads, topography, wetlands, and soil composition. Data layers are generated from satellite images and supplied through the state's GIS office (ESRI, 2017). GIS is used in a variety of different fields, from city planning to geology. It is an especially helpful tool for water studies, including stormwater management. It can also be used to study the stormwater infrastructure and topography of an area. It also provides information necessary for various methods of stormwater analysis.

2.1.4 NRCS/SCS Method

The NRCS/SCS method is a method for estimating volume and rate of runoff in small watersheds. This process was developed by the USDA's Soil Conservation Service (SCS). This method of stormwater analysis uses characteristics of the drainage area along with precipitation data to estimate a volume of runoff (SCS, 1973). A Curve Number (CN) is used to describe the watershed characteristics that influence runoff (SCC, 1973). The curve number is dependent on the watershed's land use and soil type. The CN value is then used along with precipitation data to find the runoff value (Figure 2).

Curves on this sheet are for the case $I_a = 0.2S$, so that

$$Q = \frac{(P-0.2S)^2}{P + 0.8S}$$
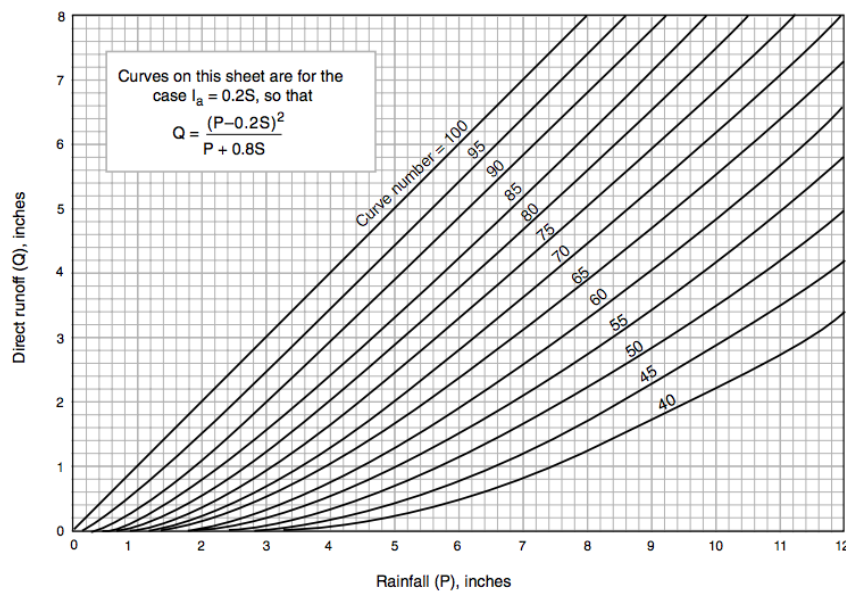
Figure 2: Solution of Runoff Equation (USDA, 1986)

2.1.5 Stormwater Treatment Best Management Practices (BMPs)

There are a variety of best management practices (BMPs) for the treatment of stormwater. BMP's can be structural, vegetative, or managerial and were created in order to improve runoff water quality, control flooding, and reduce erosion from storm events (DemoInfo). The Massachusetts Department of Environmental Protection (2016) further categorizes BMP's into five main categories: Pretreatment, Treatment, Infiltration, Conveyance, and Other. The main focus of this project, Treatment BMP's, include, but are not limited to, bio retention areas and rain gardens, constructed stormwater wetlands, extended dry detention basins, proprietary media filters, sand and organic filters, and wet basins (MassDEP Stormwater Handbook, 2008). BMP's are controlled by a higher authority, often local ordinances, to ensure proper construction and continued maintenance (DemoInfo).

2.2 Natural Treatment Systems

Natural systems have been used for water treatment for millennia (Rozkošný et al., 2014). Although the LSL is currently being applied for stormwater treatment, traditionally natural systems have been used for wastewater. One of the first noted systems of this kind was that of a sewage farm located in Edinburgh, Scotland in the mid 1600's that used soil to purify wastewater (Environmental Protection Agency, 1979). It was in the late 19th century that humans began to see the limitations of such natural systems, noticing that when too much waste was applied to the crops in the sewage farms, they would overload and fail (Environmental Protection Agency, 1979). Today, these natural systems are being adopted in alternative, small-scale settings in an effort to utilize natural resources and reduce energy consumption (Rozkošný et al., 2014). These modern natural treatment systems often feature constructed wetlands, soil filters, aquatic plants, and floating islands as a means of treatment processes (Rozkošný et al., 2014). Some examples of natural treatment systems that have similar principles to the LSL include reed beds, the Living Machine Technology, and the Eco Machine.

2.2.1 Reed beds

One example of a simple application of natural wastewater treatment is reed beds. Aquatic reeds are a chosen flora for this technology due to their ability to handle large floods of water, while also

able to withstand very dry periods (How Reedbeds Work). Reed beds are macrophytes planted in a basin lined with an impermeable membrane and filled with gravel (Lismore City Council, 2005). Wastewater is introduced to the system where the reed roots provide a home for the microbes to reproduce and decompose the contaminants and toxins in the water, while simultaneously processing the nutrients. Aeration of the substrate material accelerates both of these anaerobic and aerobic processes. Once the waste runs through the system, the water is generally clean enough for either reuse or discharge back into the surrounding environment (How Reedbeds Work). Reed beds are also specifically helpful in treating septic effluent in areas with less permeable soil types (Lismore City Council, 2005).

2.2.2 Living Machine Technology

Other natural systems are used in combination with more modern treatment methods. The Living Machine Technology, developed by Tom Worrell beginning in 1999 is a key example of this category of technology. In the Living Machine, tidal motions are used to mimic natural wetland conditions (Living Machine, 2012). When wastewater enters the system, it first enters a primary settling tank where gravity allows for solids to settle to the bottom. The water then moves to sequential wetland cells that play a large role in controlling the flow, filling and draining twelve times per day. Miniature ecosystems grow and thrive, allowing for the consumption and removal of nutrients via microbes (O'Connell, 2011). Once the water passes through these steps, it then moves on to final treatment measures, which for the Living Machine Technology, includes filtration and disinfection using chlorine. The water is then transported to a reuse tank where the water is set to be reused for other purposes. The Living Machine Technology aids in recycling thousands of gallons a day, using a system with partial natural processes (Living Machine, 2012).

2.2.3 Eco Machine

Complex natural systems have also been designed to treat water, combining various treatment processes in sequence, in order to produce better results from an all-natural system. The Eco Machine, designed by ecological designer John Todd, is located at the Omega Center for Sustainable Living where 52,000 gallons of domestic wastewater per day produced by the center is treated by Todd's system (John Todd Ecological Design, 2017). First, the water is held in a settling tank in order for solids to settle out. Solids are then injected with microorganisms to speed

up the decomposition process (Omega, 2016). The water is then sent to an equalization tank where, similar to the Living Machine Technology, the water flows are controlled, allowing for the system to remain small-scale. Wastewater is sent to anoxic tanks where organisms are used to digest the nutrients and contaminants in the water (Droste, 1997), before moving to man-made wetlands. There, native plants reduce Biochemical Oxygen Demand (BOD) and harvest nutrients. The water is further purified to highly oxygenated lagoons where fungi, algae, and tropical plants, in addition to more microorganisms, continue to convert toxins to less harsh elements. Sand filters out any remaining particulates and the clean water is released back to the water table underneath the center's parking lot (Omega, 2016). The Eco Machine combines various natural processes to ensure safe water is released back into the environment.

Various natural systems have been applied to modern day practices as a way to capitalize on the opportunity to use surrounding natural resources. Although natural treatment systems have been used for centuries, this technology is now being used for sustainable water treatment.

2.3 Constructed Wetlands in Wastewater Treatment

Understanding such a unique natural treatment system requires comparison to already engineered systems. The best possible model for the LSL was found to be biological treatment, specifically constructed wetlands applications for wastewater treatment. This was determined so due to the similarities in the presence of organic matter and varying types of vegetation, much like a pond and/or wetland setting. Defining the most accurate engineering model for the LSL was important to be able to quantify the behavior of the system.

2.3.1 Nitrogen & Phosphorus Removal

Two common constituents commonly found in stormwater are nitrogen and phosphorus. Nitrogen is removed from by several processes in pond systems. Additionally, algal, plant, and bacteria biomass absorb ammonia and nitrate. For phosphorus removal, anaerobic microorganisms remove phosphorus through growth, but release phosphorus through self-digestion. Suspended aerobic microorganisms can also remove phosphorus from solution. Quasi-equilibria among processes such as these will not result in significant phosphorus removal. Large plants in ponds take up both nitrogen and phosphorus. Certain plants can also help give suitable habitats for both nitrifying and

denitrifying bacteria For example, water hyacinths (Eichhornia crassipes) are plants that can grow in ponds (specifically warm climates). They are seeded into ponds, and grow rapidly. Regular harvest of such plants improves nutrient removal, and can also provide other beneficial effects on metals removal (Droste, 1997).

2.4 Fisherville Mill Site, Grafton, MA

The Fisherville Mill, which is located in South Grafton, was one of the largest wool mills on the Blackstone River. In 1999, the mill was involved in a fire that led to copious amounts of chemicals to be released into the air. This led to action to restore the area, including the establishment of the Mill Villages Park, where the construction of the LSL gave way (Sengel, 2015).

The LSL is located in the Mill Villages Park in south western Grafton, in between the Blackstone River and Blackstone Canal. The site is located on a brownfield and a lot of work has gone into remediation. Plans have been developed to create a community center that educates the public about historical uses of the site and how to move forward with the potential applications of the LSL (Collins et al., 2015).

2.4.1 History of Site

In 1790, Samuel Slater, an Englishman experienced in the textile mill industry, developed a cotton-spinning factory on the Blackstone River, which no one at the time could have predicted how large of an impact it would create (National Park Service, 2016). Unfortunately, because the Blackstone River became such an industrial hotspot in the late 18th century- early 19th century, it left a scar on the quality of the river's waters. The river had become polluted with raw sewage, industrial wastes, and heavy metals and toxins, which at one point in 1990, led to the Blackstone's title of "Most Toxic River in America". In 2014, attention was brought to the river once again when it was designated a National Historical Park. At the same time, an extension of the John H. Chafee Blackstone River Valley National Heritage Corridor was initiated. Essentially, the Heritage Corridor Commission collaborates with agencies at the federal, state, and local level in order to ensure protection of both the sites and resources of the Blackstone River Valley (Blackstone River Coalition, 2016).

Another component of the Blackstone River that was highly utilized during the 19th century was the Blackstone Canal. The Blackstone Canal was a large accomplishment at the time, allowing for transportation to occur on this body of water, something that was no longer possible on the river itself, with the increase of dams used for water power (Worcester Historical Museum, 2006). Presently, the canal still exists, left as a more stagnant body of water still ridden with leftover toxins and contaminants from the Industrial Revolution.

2.5 Living Systems Laboratory

The Living Systems Laboratory (LSL) is an eco-machine designed by John Todd (2013), located at the Fisherville Mill site on the Blackstone Canal in Grafton, MA. The LSL was created to treat hydrocarbons and nutrients that are present in the river from years of industrial activity using biological processes. It is part of a recently developed park on the historical site of the Fisherville Mill. In addition to being a treatment system for the Blackstone Canal, the LSL is meant to serve in an educational capacity, by which students, educators, and scientists can study the effects of eco-machines on contaminated sites (Todd, 2013).

The system consists of a greenhouse, which houses the biodiversity that drives the treatment processes, and an Aqua Restorer in the canal at the system's outlet (Todd, 2013). Water from the Blackstone Canal is pumped into the LSL, where contaminants are removed, and then released back into the canal. The system contains four different components; Sediment digesters (1), myco-reactors (2), aquatic cells (3), and a floating restorer (4) (Figure 3).
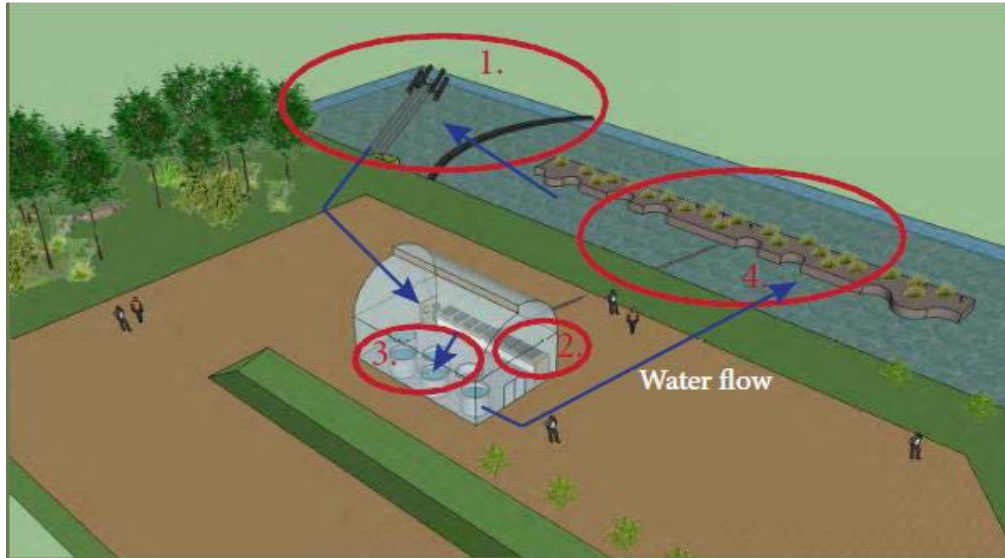
Figure 3: System Diagram (John Todd Ecological Design, 2013)

2.5.1 Sediment Digesters

Water enters into the system through sediment digesters, which are located in the canal beneath the soil. They consist of perforated plastic pipes, which are filled with biologically colonized gravel particles. The increased surface area of the gravel causes the oil to accumulate, at which point the microbes inhabiting the digesters begin the process of breaking it down (Todd, 2013).

2.5.2 Myco-Reactors

The water then enters a wood chip media containing mycelium, which is the web-like structure of fungi. The water is trickled into the media, where the fungi release enzymes that break down the hydrocarbons. This process turns the wood chip media into soil, which then supports other organism such as maggots and worms. Because fungi are primary decomposers, they play a critical role in the system by beginning the decomposition of the hydrocarbons. The enzymes produced in this stage travel to other components in the system, where they continue to break down the (Todd, 2013).

2.5.3 Aquatic Cells

The next component is a series of six 700-gallon open tanks, which contain a variety of plants as well as numerous types of algae, bacteria, protozoa, and fish. As the water moves through each of

these six tanks, it encounters these organisms and is both purified and aerated (Todd, 2013). Some of these organisms are carried out with the water, increasing the biodiversity of the canal.

2.5.4 Floating Restorer

Finally, the water is released back into the canal by being pumped through a floating raft of plants. This floating island acts as an oasis for biodiversity in the canal. The clean water from the treatment process is oxygen and organism rich, which attracts organisms such as insects, minnows, turtles, and frogs (Todd, 2013).

In addition to the removal of hydrocarbons and nutrients from the water, one of the main purposes of the LSL is to facilitate the rebound of the canal's ecosystem. As more organisms are introduced back into the canal, the process occurring in the LSL will begin to replicate itself in the canal (Todd, 2013). By removing contaminants from the water, while at the same time introducing microbes that continue the decomposition, the LSL has had a significant impact on the biodiversity of the canal.

2.6 Stormwater Impact

The Town of Grafton is currently facing a problem with stormwater at the Fisherville Mill site. One of the main purposes of the LSL is to minimize the impacts of runoff contamination in the Blackstone Canal. The contamination from the surrounding area, in particular the northern lot, enters the Blackstone Canal via stormwater, affecting all life forms in this environment. The canal then runs into the Blackstone River, which is a much larger body of water, with even greater environmental impacts to the ecosystems of the river area. Finding a way to treat the stormwater is essential to preserve the site and properly clean the Blackstone Canal water.

3.0 Methodology

The goal of this project was to assess the Living Systems Laboratory's current and potential capacity to treat stormwater runoff. In order to complete this analysis, first the flowrates of the LSL and canal were measured. The samples were then collected from the site and analyzed for various indicators of water quality. Information about the surrounding area was analyzed using GIS. Finally, the runoff volumes going into the canal were quantified using the NRCS method.

3.1 Project Scope and Objectives

The Town of Grafton is interested in determining the Living Systems Laboratory's capacity for treating stormwater entering the Blackstone Canal. They hope the LSL will be able to minimize the impact of contaminants entering the canal via stormwater and improve the overall the ecology of the Canal. This Major Qualifying Project completed the following objectives in conducting this stormwater analysis:

1. Analyze the flowrates of the system.
    a. Quantify influent to retention tank, influent to Myco-Reactors, and effluent leaving the system.
    b. Quantify volume of water exiting the Blackstone Canal downstream of the LSL.
2. Obtain samples from both the Blackstone Canal and the LSL and analyze them for various regulated components in order to determine the current treatment efficiency of the system.
3. Use GIS to evaluate the characteristics of the surrounding area (topography, land use, and soil composition).
4. Conduct a stormwater analysis using the NRCS method to quantify the runoff volumes from the northern lot entering the Blackstone Canal.
5. Design system improvements using the current treatment data, volume of watershed runoff entering the Blackstone Canal, and predicted runoff from frequent storm events.

3.2 Major Task List

The major tasks that were completed to obtain the project objectives are as follows:

1. Review literature on ecological design, history of the Fisherville Mill site, hydrology, stormwater analysis, stormwater regulations.
2. Complete site measurements of flowrates and complete sample collection.
3. Complete lab analysis on water samples.
4. Gather geographical information using GIS.
5. Conduct stormwater analysis using NRCS method.
6. Analyze results in terms of design constraints.
7. Evaluate current system design.
8. Develop design modifications to recommend an improved system.
9. Write, finalize, and submit final report.

The procedures followed for these tasks are outlined in the following section.

3.3 Flowrate Measurements

Flowrates were determined at some of these sampling locations in order to understand all current design components of the LSL and for use in future recommended design improvements. Flowrates were measured at the system influent, Myco-Reactor influent, system effluent, and canal effluent. Flowrates measured throughout the LSL were helpful in determining the volume of water treated by the system each day when coupled with system cycle durations and daily cycle count. The flowrate measured at the canal effluent sampling location was helpful in determining the volume of water leaving the watershed, which was used in developing our stormwater analysis. Flowrates measured in the LSL were measured using a volumetric bucket. At each sampling location, the bucket was filled to 1L while being timed. This was done at each sampling location five separate times, where the times were then averaged to get a flowrate of liters per minute. The flowrate of the canal effluent was measured by measuring the height of the weir, the height of the water a few feet back from, and to the right of, the weir, and the width of the weir and using the Francis Formula to determine the flowrate exiting the watershed area. The Francis Formula measures the flow through a rectangular weir. See equation 1 below, where q= flowrate in ft^3/s, h= head on the weir (ft.), and b=width of the weir (ft.) (USDA, 1986). All measurements were later converted to cubic feet per second (cfs) as it is a standard unit of measurement for flowrates.

Equation 1: Francis Formula

$$q = 3.33 \, (b - 0.2h)h^{3/2}$$

3.4 Sampling

Analyzing both water and stormwater samples is crucial in understanding a water body's constituents, especially where stormwater regulations are applicable. Characterizing stormwater allows for an initial inspection of the water's components and provides a baseline to determine any changes that may occur when new engineering projects are implemented (need citation). Quantifying concentrations of common pollutants, heavy metals, and natural properties was particularly useful in analyzing the initial water quality in the Blackstone Canal adjacent to the LSL and will be helpful for future comparison to recent regulations adopted by the Town of Grafton (Environmental Protection Agency, 2009). In order to decipher which regulations were most important to meet, we met with Joe Laydon, the planner for the Town of Grafton, who stated that those regulations put forth by the Town of Grafton Stormwater Bylaw were most critical (J.Laydon, 2016).

We collected nine water samples from different locations throughout the site, which were then tested for a variety of constituents. Constituents tested include pH, turbidity, alkalinity, total suspended solids (TSS), ammonia, phosphorous, dissolved oxygen, total organic carbon, 16 different metals, and 7 different anions (see Appendix A: Laboratory Procedures for a full description of laboratory procedures). These specific constituents were chosen as they are critical indicators of water quality (Research Gate, 2016). In order to obtain accurate results, standard laboratory procedures were practiced following <u>Standard Methods for the Examination of Water and Wastewater</u> (Eaton, Clesceri, Greenberg, Franson, 1998) using materials and instruments provided to us by Worcester Polytechnic Institute's Environmental Laboratory.

Four of the nine samples were collected directly from the canal (Figure 4):
- At the point where the canal enters the Blackstone River (canal effluent) (1)
- At the canal intake point for the system (canal intake) (2)
- Upstream of the LSL (canal upstream) (3)

Samples were then collected from three separate locations throughout the Living Systems Laboratory (Figure 4):

- The location where the canal water enters the system after passing through the sediment digesters (system influent) (6)
- The midpoint of the system, which was collected from the sump pump after Myco-Reactor treatment (system midpoint) (6)
- The effluent of the system before it reenters the canal (system effluent) (6)

Lastly, two other samples were collected during a stormwater event (Figure 4):

- One from a local stormwater drain entering the canal upstream of the LSL (stormwater-drainage pipe) (4)
- The second from runoff entering the canal from the western side of the lot (stormwater-ground). Sampling locations are discussed in more detail in section 3.5.1. (5)
- Canal intake location during a stormwater event (stormwater-canal Intake) (2).

Figure 4: Map of Sampling Locations on Site (Google Maps)

3.4.1 Canal Upstream

The canal upstream samples were collected at location 3 (Figure 4), just north of the LSL on the eastern side of the canal. A sample was taken at this location in order to determine the water quality of the canal before water enters the LSL for treatment. Figure 5 shows a view of the canal upstream sampling location.

Figure 5: Canal Upstream Sampling Location

3.4.2 Canal Intake

The canal intake samples were collected at location 2 (Figure 4), south of the treatment center on the eastern side of the canal. A sample was collected from this location because it is where water is pulled from the canal to enter the LSL. It was important to sample this water at this location as it aided in determining water quality right before entering the sediment digesters treatment stage. Figure 6 shows the canal intake sampling location.

Figure 6: Canal Intake/Stormwater Canal Intake Sampling Location

3.4.3 Canal Effluent

The canal effluent samples were collected from location 1 (Figure 4), southeast and downstream of the LSL. This sampling location is where the canal meets the Blackstone River and was important to sample from as it is a point at which water treated from the LSL has both reentered and thoroughly mixed back into the waterbody. Figure 7 shows a view of the canal effluent sampling location.

Figure 7: Canal Effluent Sampling Location

3.4.4 System Influent

The system influent samples were collected the Living Systems Laboratory (Figure 4). Water at this location was collected from a pipe pumping water into the initial retention tank. This was an important sampling location as it helped to determine the quality of the water after preliminary filtering, but before it completes any further treatment. Measuring contaminants in this location was also critical so that it could be used as a starting point to compare to the system effluent in order to determine how effective the LSL was in treating the canal water. Figure 8 shows a view of the system influent sampling location.

Figure 8: System Influent Sampling Location

3.4.5 System Midpoint

The system midpoint samples were collected from the Living Systems Laboratory (Figure 4). A sample was collected from the system midpoint because it is a good indicator of water quality after phase one of treatment, the Myco-Reactors, which helped to determine how effective the Myco-Reactors were in treating the canal water. Figure 9 shows a view of the system midpoint sampling location.

Figure 9: System Midpoint sampling location.

3.4.6 System Effluent

The system effluent samples were collected from the Living Systems Laboratory (Figure 4). A sample was collected from the system effluent because it is a good indicator of water quality after phase two of treatment, the Aquatic Cells, which helped to determine how effective the Aquatic

Cells were in treating the canal water. This sample was also critical in determining the quality of water after treatment was completed, and was used in comparison to the system influent in order to determine the effectiveness the overall treatment of canal water. Figure 9 shows a view of the system effluent sampling location.

Figure 10: System Effluent Sampling Location

3.4.7 Stormwater-Canal Intake

The stormwater-canal intake sample was collected from the same location as the canal intake sample, location 2 (Figure 4), but was measured during a stormwater event. This sample was important to test in order to compare the water quality of water entering the LSL during regular conditions vs. the water quality of water entering the LSL during stormwater conditions. Figure 6 for a view of the stormwater-canal intake sampling location.

3.4.8 Stormwater-Drainage Pipe

The stormwater-drainage pipe sample was collected from location 4 (Figure 4), north of the LSL on the western side of the canal. This sample was collected from a local drainage pipe entering the canal and was useful in determining the quality of the water entering the canal during a storm event from the surrounding area. Figure 11 shows a view of the stormwater-drainage sampling location.

Figure 11: Stormwater- Drainage Pipe Sampling Location

3.4.9 Stormwater-Ground Sample

The stormwater-ground sample was collected from location 5 (Figure 4), directly west of the LSL on the eastern side of the canal. A sample was taken from this location in order to determine the water quality of nearby runoff entering the canal during a storm event. Figure 12 shows a view of the stormwater-ground sampling location.

Figure 12: Stormwater- Ground Sampling Location

3.4.10 Sampling Procedure

Samples were collected in standard 250mL plastic collection bottles at all locations and for testing all constituents except for total suspended solids, total organic carbon, and dissolved oxygen. In

order to collect samples using the 250mL sample bottles, gloves were used and the bottles were filled with water from each source, making sure to avoid stirring up any settled contaminants or particles that could be present in the water. This same procedure was carried out for samples tested for total suspended solids, except 1L plastic collection bottles were used as the test requires larger volumes of water. For dissolved oxygen and total organic carbon testing, 300mL glass BOD bottles were used to ensure oxygen does not enter the bottle before the sample is tested. Similarly, samples were collected in these bottles by filling them with water from the source, making sure to fill the bottles to the brim without any air bubbles, placing the stopper in the bottle, and capping the bottle. All samples taken were then taken to the Worcester Polytechnic Institute Environmental Laboratory and stored in a refrigerator, incubator, or in room temperature conditions based on what tests were to be completed on them.

3.5 Laboratory Analysis

Laboratory procedures were performed on collected water samples in order to determine water quality at each sampling location. Water quality is a critical part of ensuring that water bodies meet local and federal regulations, and preserving wildlife in the setting. Water samples were tested for a variety of constituents including dissolved oxygen, alkalinity, pH, turbidity, total suspended solids, phosphorous, ammonia, phosphate, and nitrate, 12 metals, and 5 anions. The following constituents in this section were deemed those most important to determine water quality. Full laboratory procedures for all tested constituents can be found in Appendix A.

3.5.1 Dissolved Oxygen and pH

Dissolved Oxygen measurements were taken using a modification of the Standard Methods 4500. To measure the DO concentration, a DO probe was calibrated and then placed directly into a BOD bottle storing a sample making sure to avoid adding oxygen to the system. The DO was then displayed on the monitor and recorded.

In the laboratory, pH was found according to Standard Methods 4500 (Appendix A) using a pH electrode probe. The probe was first calibrated using three different buffers of varying pH values and standardized at each buffer. To record pH of the water samples, the electrode was then

immersed in the water sample and the pH value was recorded once displayed as stable on the probe's monitor.

3.5.2 Turbidity and Total Suspended Solids

Turbidity was found for each water sample by using a turbidimeter as outlined in 2130 Standard Methods for Turbidity, found in Appendix A. Each sample was poured into a small turbidity vial to the white line, and then capped. The vial was then inverted several times to mix the sample. Reagent grade water was then used to rinse the outside of the vial, and a Kimwipe was used to remove any dust or fingerprints. After this, the sample was placed in the turbidimeter with the arrow on the vial facing the line inside the machine, and the machine lid was shut. The readout, in units of NTU, was watched for around 20-30 seconds until judgement could be used to get a turbidity reading. This process was repeated for each sample.

To test for TSS of a sample, a vacuum pump was plugged in, and a glass flask, the plastic magnetic catch basin, and the filter, were rinsed with deionized water. Procedure outlined in Standard Methods 2540 for TSS was used as a guide. Aluminum pans were acquired to place the filters in the oven overnight after filtering through the sample. Using tweezers, a 1.5 micrometer filter paper was placed on the black circular pump screen. Deionized water was filtered through the paper first using the pump. Tweezers were then used to remove the filter paper from the pump and placed in the aluminum pan labeled for what sample would be filtered through it. The aluminum pan and filter were placed for 24 hr. After this time, the aluminum pan was zeroed and the filter paper was weighed on the scale. The results were recorded. The process was repeated for sample water points at the system effluent, canal intake, and stormwater-drainage pipe. The amount of suspended solids was calculated for each sample by using the following equation:

Equation 2

$$Total\ Suspended\ Solids = m_{initial} - m_{sample\ water}$$

3.5.3 Total Organic Carbon, Modified BOD$_5$, Alkalinity, and Total Inorganic Carbon

Total organic carbon (TOC) was measured for each designated water sample via the TOC-5000A Analyzer as outlined in 5310 Standard Methods for total organic carbon, found in Appendix A. A Stock Primary Standard, an Intermediate Standard, and 3 Working Standards were prepared and with the samples, placed first into autosampler vials then the autosampler itself where they were analyzed for non-purgeable organic carbon (NPOC). The standards were used to create a calibration curve so that the TOC data for the samples collected may be interpolated. The TOC Analyzer then sparged, or bubbled a chemically inert gas through, the standards and samples at approximately 100 mg/L and displayed the results on a paper receipt printed by the Analyzer.

Modified BOD$_5$ was found using a modification of Standard Methods 4500. To measure the DO concentration, a DO probe was calibrated and then placed directly into a sample-filled BOD bottle to avoid adding oxygen into the sample. The DO concentration was displayed on the monitor and recorded. The BOD bottle was then capped, placed in a dark, 20 degree Celsius incubator in order to avoid photosynthesis, and re-measured in 24-hour increments for five days.

In the laboratory, alkalinity was measured according to an adaptation of Standard Methods 2320 (Appendix A) using an alkalinity-specific titration instrument. To obtain alkalinity of the samples, HCl was first standardized. Alkalinity was then measured by titrating HCl into a volume of the water sample while simultaneously measuring and recording pH until a pH of four was reached. Numerical values for alkalinity were then found by entering titrated volumes and corresponding pH values into an excel calculator provided by Professor Mathisen, which then converted these values from meq/L to the standard unit of measurement, mg/L CaCO$_3$ for each sample.

Total inorganic carbon (TIC) was not measured via a laboratory procedure, but rather as a function of pH and alkalinity, both of which were measured in the laboratory. In order to calculate total inorganic carbon, a TIC calculator was used by entering the measured pH and alkalinity into a table, calculating TIC via the "Gran Alkalinity" approach.

3.5.4 Ammonia

Ammonia was measured according to Standard Methods 4500, using a color spectrophotometer and standards to produce a calibration curve (Appendix A). Vials were then filled with volumes of sample water, Mineral Stabilizer, Polyvinyl Alcohol Dispersing agent, and Nessler Reagent, allowed a one-minute reaction time, and then measured for ammonia. The calibration curve was then used to find ammonia concentrations (ppm) via interpolation on an ammonia concentration (ppm) vs. absorbance line graph.

3.5.5 Total Phosphorus

Total phosphorus was measured in the lab according to Standard Methods 4500, using a color spectrophotometer and standards to produce a calibration curve. A vial was filled with volumes of sample water, 5N NaOH, phenolphthalein, deionized water, and Molybdovanadate and given a 3-minute reaction time before placed in the spectrophotometer for a reading. The calibration curve was then used to find total phosphorus concentrations (ppm) via interpolation on a total phosphorus concentration (ppm) vs. absorbance line graph.

3.5.6 Metals, Phosphate, and Nitrate

Metals, phosphate, and nitrate were measured in water samples using an Ion Chromatography machine. Full laboratory procedures for this analysis can be found in Appendix A. Samples, blanks, and standards were all prepared in vials and then placed in the Autosampler. A Sequence was then run in order to obtain metal and anion concentrations in each of the samples, blanks, and standards. The blanks and standards were used as reference points to create a calibration curve in order to more accurately determine the concentrations in the water samples.

3.6 GIS Analysis

GIS was used to gather valuable geographical data about the surrounding area. This information was essential for the stormwater analysis discussed in Section 3.6. ArcGIS version 10.4.1 was the program used for GIS analysis. GIS data from MassGIS.com and data supplied by the Town Grafton was used. Various data layers, containing geographical information of the surrounding

area, were examined: topography, land use, soil composition, and stormwater infrastructure. These were then used to approximate an area that would drain into the canal.

First the topography of the area surrounding the Blackstone Canal was examined. This was done in order to determine the directions of runoff flow in a storm event. Then a layer detailing land-use designations was analyzed. This data layer separated the land into various categories based on their zoning (Medium Density Residential, Forest, Commercial, etc.).

Next a layer containing information about the various soil compositions was examined. Along with this layer came a table that described various characteristics about each soil type, such as its slope, area, and soil type. An additional table from the GIS database was joined to this table, in order to obtain the hydrological groups of each soil type (Section 3.7). A data layer showing Grafton's stormwater infrastructure was also studied. It contained the locations of drainage mains, catch basins, and outlet points. To see maps of all these data layers reference Appendix B.

Using information from the topography and stormwater infrastructure layer, we approximated an area of land that drained into the canal. This was done by locating high points in the landscape and areas that showed signed of erosion due to previous storm events. Two main areas were examined. The first area was located to the west of the canal. Another lot that is north of the LSL, and is considered impermeable, was also considered (Section 4.3.1). These areas were calculated and used in the NRCS method (Section 4.3.2). The percent pervious and impervious areas of these of these two areas were also determined.

3.7 Stormwater Analysis (NRCS/CN Method)

The NRCS/CN method was used for determining the volume of water that flows from the drainage area into the Blackstone Canal. The information gathered from the land use and soil composition layers were used in conducting this analysis, as well as the area of the drainage basin that was calculated. This information was used to determine the Curve Number (CN) value, which is used to calculate the volume of runoff for a given storm. This analysis was done for three different storm intensities over a 24-hour period; 1-year, 2-year, and a 0.5 inch storm. In addition, the annual rainfall distribution for the Worcester area was examined to determine the annual rainfall.

First the CN value was found using the information from the land use and soil layers. The CN value is a function of an area's land use and its soil hydrologic group (Table 1). The CN value ranges from 0 to 100 and characterizes how much water will runoff in a rain event. The hydrologic group of a soil sample is a value between A-D, which is assigned based on its rate of infiltration, with A being the most impervious and D being the least (USDA, 1986). The hydrological group for each soil type was determined using a table from the GIS database and a Soil and Water Features Table (Appendix D).

Table 1: Runoff Curve Numbers for Urban Areas (USDA, 1986)

Cover description		Curve numbers for hydrologic soil group			
Cover type and hydrologic condition	Average percent impervious area [2/]	A	B	C	D
Fully developed urban areas (vegetation established)					
Open space (lawns, parks, golf courses, cemeteries, etc.) [3/]:					
Poor condition (grass cover < 50%)		68	79	86	89
Fair condition (grass cover 50% to 75%)		49	69	79	84
Good condition (grass cover > 75%)		39	61	74	80
Impervious areas:					
Paved parking lots, roofs, driveways, etc.					
(excluding right-of-way)		98	98	98	98
Streets and roads:					
Paved; curbs and storm sewers (excluding					
right-of-way)		98	98	98	98
Paved; open ditches (including right-of-way)		83	89	92	93
Gravel (including right-of-way)		76	85	89	91
Dirt (including right-of-way)		72	82	87	89
Western desert urban areas:					
Natural desert landscaping (pervious areas only) [4/]		63	77	85	88
Artificial desert landscaping (impervious weed barrier,					
desert shrub with 1- to 2-inch sand or gravel mulch					
and basin borders)		96	96	96	96
Urban districts:					
Commercial and business	85	89	92	94	95
Industrial	72	81	88	91	93
Residential districts by average lot size:					
1/8 acre or less (town houses)	65	77	85	90	92
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	86
1/2 acre	25	54	70	80	85
1 acre	20	51	68	79	84
2 acres	12	46	65	77	82

Since there are multiple land use categories and soil types present in the drainage area we used a weighted CN value. First, the land use and soil layers were merged on GIS (Section 4.3.1). This created new units, each with a unique hydrologic group and land use category. The area for these new units were calculated in cubic feet. These areas were then entered into a pivot table where they were categorized based on land use type and hydrological group (Appendix E). The weighted CN value was then calculated by taking the weighted average of the areas. Once the CN value was

obtained, it was used in the NRCS method to determine the rainfall excess, or runoff. First, the infiltration volumes were found using the CN value (Equation 3). Then the infiltration volume was used along with an average precipitation value for the specified storm to determine the rainfall excess (Equation 4). Precipitation data was supplied by the *Extreme Precipitation in New York and New England* web tool maintained by Cornell and funded by the NRCC and NRCS. This value, which was in inches, was then multiplied by the total area to get a volume and flowrate of water flowing into the canal. All flowrates are provided in cubic feet per second (cfs).

Equation 3

$$S = \frac{1000}{CN} - 10$$

Equation 4

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)}$$

The annual rainfall distribution for the area of Worcester was used to determine the annual volume of runoff from the northern lot entering the canal. Data on the intensity and frequency of storm events for the year of 2016 was supplied by another MQP team (Kling & Weiss, 2017). The runoff volumes for each storm intensity were determined using the NRCS method. These volumes were then multiplied by the annual frequency and summed up to determine the total annual volume entering the canal from the northern lot. This analysis was only done for this area, because the northern lot has a more direct impact on the quality of the canal. This annual runoff volume was used in the design evaluation.

3.8 Evaluate Design Approach

The LSL needed to be evaluated from an engineering design perspective to characterize its operation, and identify areas for change. First, the current design of the LSL was analyzed, and once the water quality volume was found from the stormwater analysis, was applied to each treatment stage of the LSL (system intake, myco-reactors and aquatic cells) to produce a recommended design plan.

3.8.1 Current Design Approach

Evaluation of the current design included characterization of the system flowrate, myco-reactors, and aquatic cells, The first step for evaluating the current LSL design approach was to find the cycle time, which was needed to determine the overall system flowrate. The system was assumed to be operating on 4 cycles per day, but the exact time of each cycle needed to be calculated to further calculate how much water the system was processing per cycle. The cycle time was also calculated assuming that the system effluent flowrate was the best representation of flow leaving the LSL. This was done by using Equation 5 to calculate the current cycle time, factoring in the approximate 100 cfs of water processed per day:

Equation 5

$$T_{cycle} = \frac{V}{Q}$$

Where V is the volume of water being processed per cycle (cubic feet/cycle), and Q is the system effluent flowrate (cubic feet/minute), to calculate a cycle time T_{cycle} in minutes.

Experimentation to further quantify design aspects of the myco-reactors and aquatic cells was also completed. For instance, Darcy's law was recommended to help quantify the hydraulic capacity of the myco-reactors, since the equation best models the conductivity of water through sediment in this case (Equation 6). Full recommendations can be found in Section 6.0.

Equation 6

$$Q = KA_c \left(\frac{\Delta h}{\Delta L}\right)$$

Where K is the hydraulic conductivity (m/s), A_c is the cross-sectional area of one myco-reactors (m^2), Δh is the change in height of the water (m), and ΔL is the change in soil height (m). This

model was recommended to find the hydraulic capacity of the system to later compare to the laboratory-measured breakpoint (Section 6.0).

The aquatic cells also required characterization. Specifically, the best design model to represent the behavior of the aquatic cells was determined to be an application in wastewater treatment: a complete-mixing model for ponds in series (Equation 7).

Equation 7

$$\frac{S_e}{S_o} = \frac{1}{(1 + k\theta_d)^n}$$

where S_e is the effluent BOD_5 (mg/L), S_o is the influent BOD_5 (mg/L), k is the decay rate constant of organic matter in the aquatic cells, θ_d is the hydraulic retention time of the water in the cells (days), and n is the number of aquatic cells in series. It was recognized that this equation is approximate, but was consider to be appropriate for assessing system scale up requirements. Applying this equation, a series of tables were created to observe the impacts that changing k, θ_d (varying volume of each tank and influent flowrate into the aquatic cells, each), and number of cells would have on the BOD ratio. A k range from 0.0055 to 0.30 $1/days$ was chosen as a range that would represent decay rates for constructed wetlands systems (Droste, 1997). The closer the value was to zero, the more BOD was removed from the aquatic cell influent to the effluent. This procedure was done to better understand the behavior of the aquatic cells. Further laboratory experimentation was recommended to acquire a site-specific experimental value for k by taking samples from each cell, and creating a curve to compare to the calculated k value and further understand the behavior of the aquatic cells.

3.8.2 Recommended Design Alterations

Using the suggested increase of water intake in the LSL (based on the water quality volume), and cycle time, the required flowrate was calculated to determine how much the system intake flowrate needed to increase by to sufficiently process a feasible amount of stormwater. To calculate how much water the LSL needed to treat each day, the annual water quality volume was divided by 365

35

days. This value was then converted to a volume per cycle, using the assumed four cycles per day. Equation 8 was then used to calculate the required flowrate in cubic feet per minute, and converted to cubic feet per second.

$$Q = \frac{V}{T}$$

Where V is the water quality volume ($ft^3/cycle$), and T is the cycle time.

The maximum flowrate on the system intake jet pump (0.03 cfs) was found to be greater than the measured system influent flowrate (0.011 cfs), showing that the pump was not operating at its maximum rate. A table was then developed, using a constant water quality volume of approximately 219 cubic feet per cycle, and varying influent flowrates to generate cycle times in minutes by using a variation of Equation 8.

The recommended design alterations for the myco-reactors was determined by applying the concept of surface loading rate to aid in calculating the approximate amount of additional beds required for the increase water volume. Using the Equation 9 to find the current surface-loading rate for all eight active myco-reactors did this:

$$SLR = \frac{Q}{A}$$

where Q is the myco-reactor influent flowrate (cfs), A is the total cross sectional area of the active myco-reactors in square feet, and SLR is the surface loading rate in units of $\frac{\frac{ft^3}{s}}{ft^2}$. Then the current SLR and surface area of one myco-reactors were used to compare varying flowrates to amount of required myco-reactors. This yielded results that were used to recommend a quantifiable increase in the myco-reactors to compensate for the increased water volume.

Similarly, the amount of aquatic cells needed to treat the water quality volume that was calculated. From the procedure outlined in section 3.8.1 for aquatic cell design, the number of additional aquatic cells was determined based on the amount of BOD that was removed in the process, while keeping the hydraulic retention time relatively low. These analyses provided an indication of the required modifications that may be needed to accommodate stormwater flows.

4.0 Results

The goal of this project was to conduct an analysis to determine the potential and provide recommendations for using the existing natural treatment system at the Living Systems Laboratory (LSL) to treat stormwater from the local area. This section summarizes the data collected in completion of this goal. The flowrates entering and leaving both the LSL and the Blackstone Canal are summarized in Section 4.1. Section 4.2 discusses the contaminant levels measured in water samples taken from the system, the canal, during a storm event, and patterns of this data. The GIS and runoff flow information is summarized in Section 4.3. Sections 4.4 and 4.5 outline and summarize current design evaluations.

4.1 Flow Characterization

The flowrates of the system influent, myco-reactor influent, system effluent, and canal effluent were calculated to better quantify the current capacity of the LSL and the Blackstone Canal. Each flowrate was measured while the system was in operation and compared to an assumed daily average flowrate. Table 2 outlines the resulting average flowrates taken one time each. From these calculations, the influent flowrate of the system was found to be 0.013 cfs, the effluent flowrate of the system was found to be 0.009 cfs, and the flowrate leaving the canal was found to be 0.046 (Table 2). The slight variation in system effluent and system influent can be attributed to the fact that the pumps operate at different rates, which are discussed later on in the section. These flowrates provide an approximate characterization of the hydraulics of the current system and canal conditions. The results provided current conditions to use for later comparison against runoff flowrates from various storm events. Based on information from the system's owner, Eugene Bernat, the system was assumed to be operating in two-hour cycle periods, four separate times a day, processing a daily total of 93 cubic ft. (approximately 700 gallons or one aquatic cell). This process is described in further detail in this section. Detailed calculations can be found in Appendix C.

Table 2: System and Canal Flowrates

Test Point	Flowrate (cfs)
System Influent	0.011
Myco-Reactor Influent	0.013
System Effluent	0.009
Canal Effluent	0.046

The system influent, myco-reactor influent, and system effluent flowrates were specifically taken to characterize key points along the LSL process. The canal effluent flowrate was found to later help in calculating the total runoff volume from the drainage area. The complete flow diagram for the LSL further depicts the direction of water flow (Figure 13).
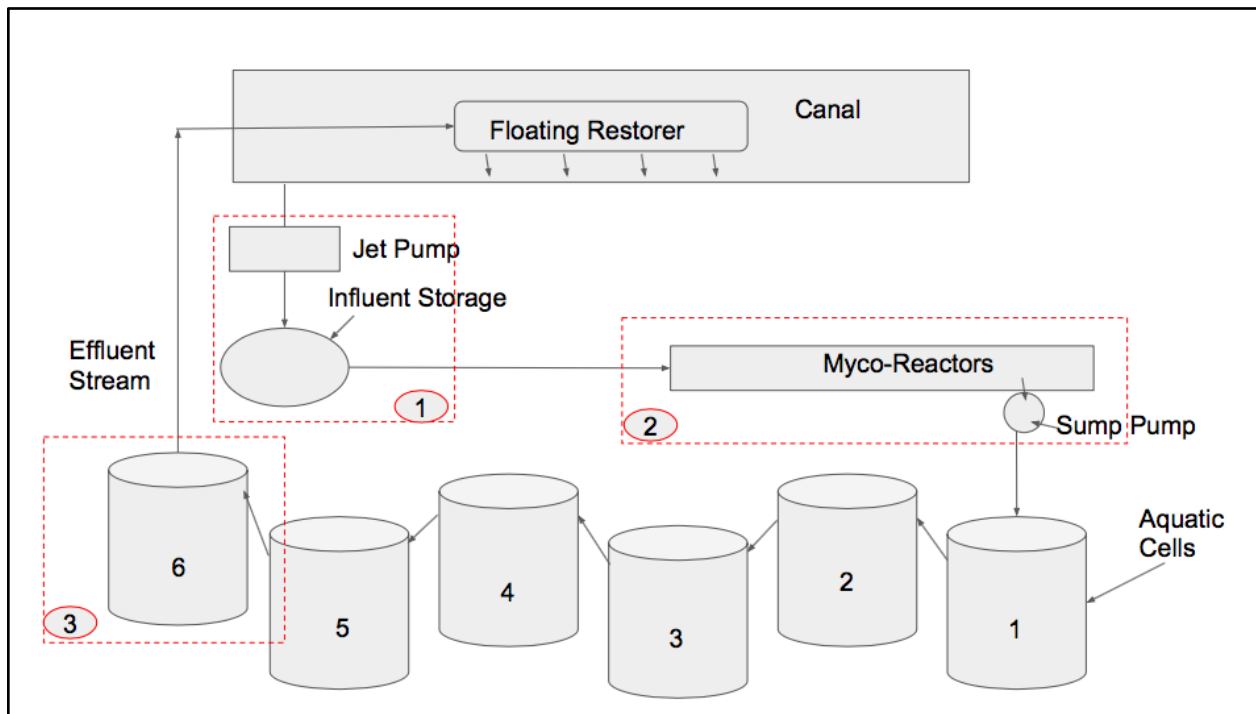
Figure 13: Overall LSL Flow Diagram

The system influent flowrate was taken at the point where the jet pump releases the water that it has taken from the canal bed/sediment digesters, and distributed it into the influent storage

(Figure 14). This point was important for our calculations because knowing at what rate the system is taking in water will allow for a later comparison to necessary storm event flowrates, aiding in drawing the conclusion of how much the LSL needs to be increased in capacity.
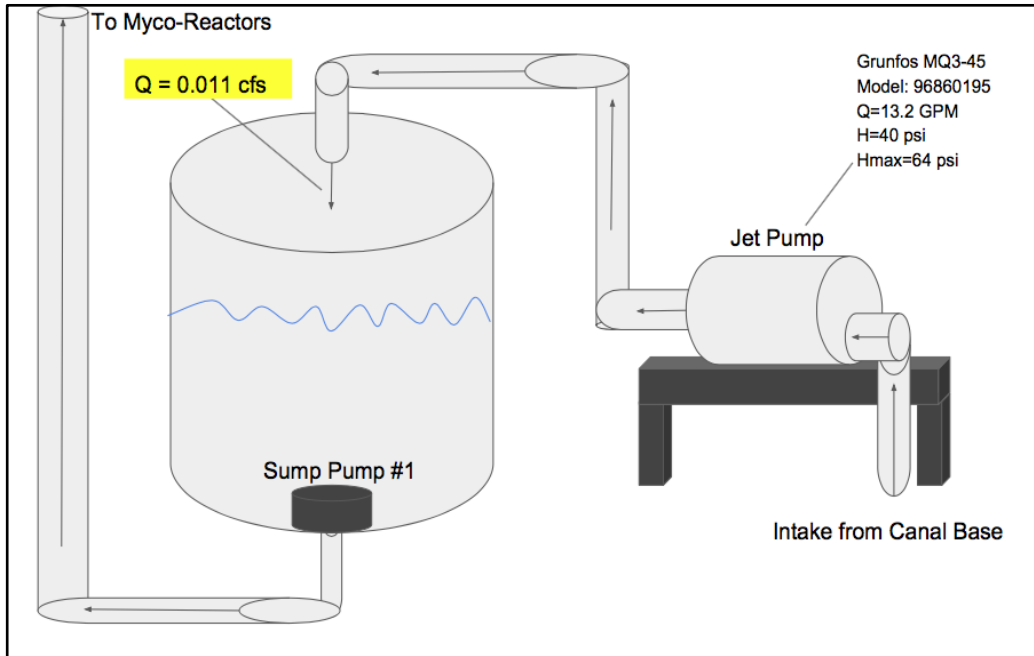
Figure 14: System Influent Flowrate in Relation to System

The myco-reactor influent flowrate was found to quantify the amount of flow entering the myco-reactor filtration stage of treatment (Figure 15). This point of the system was assumed to be the best representation to quantify the flow entering the myco-reactor filtration stage of treatment. This would identify the flow capacity of Sump Pump #1 (Figure 14), and potentially prove useful for further use in later hydraulically quantifying the capacity of the myco-reactors.
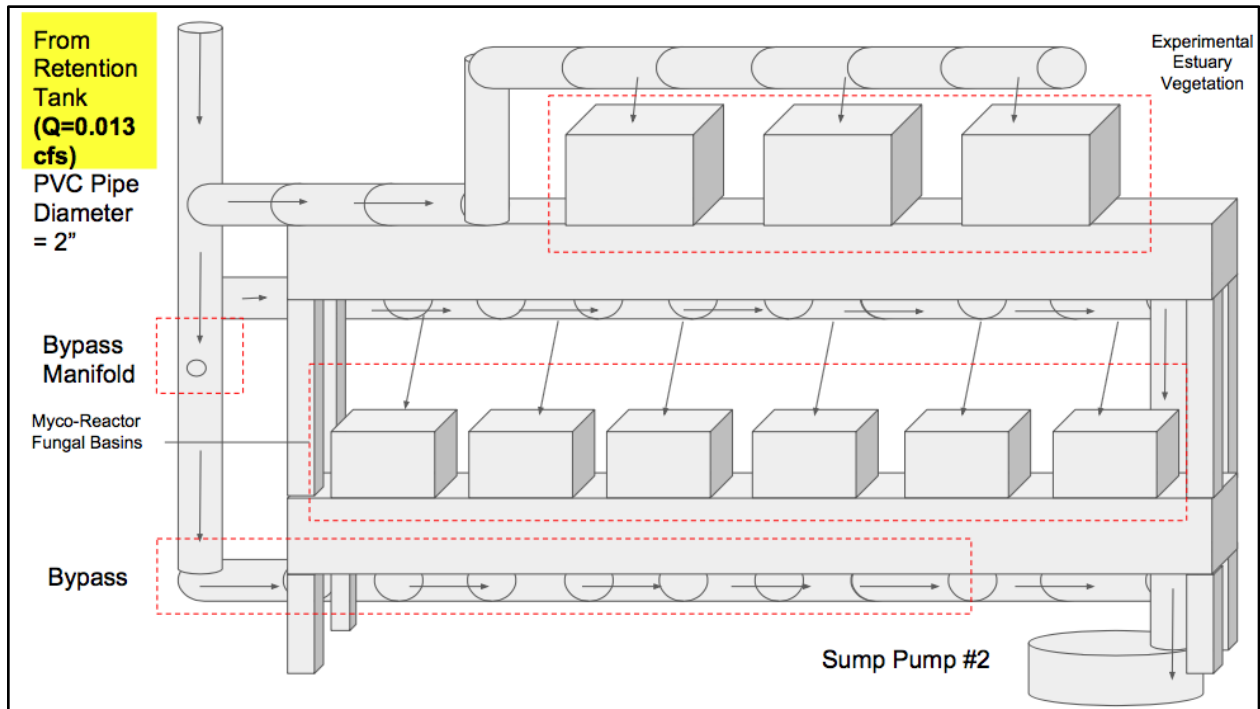
Figure 15: Myco-Reactor Influent Flowrate in Relation to System

The system effluent flowrate was found to quantify how fast water was leaving the system during operational periods (Figure 16). This proved important for the estimation of contributing runoff back into the Blackstone Canal, and how much water the LSL was processing.
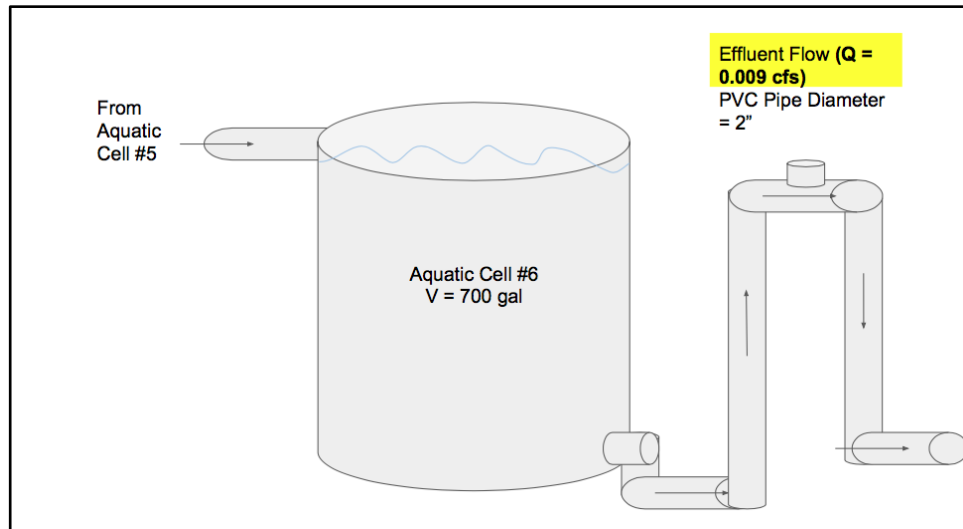
Figure 16: System Effluent Flowrate

The canal effluent flowrate was found for subsequent use to provide a comparison with the flow estimates obtained with the NRCS method to quantify the total volume of runoff from the LSL drainage area during a defined storm event. This was important to know because this runoff information would allow for comparison between normal conditions and storm events, aiding in drawing the conclusion of how much the LSL needs to be increased in capacity to account for this difference. All flowrates and their relative location can be found in Figure 17.
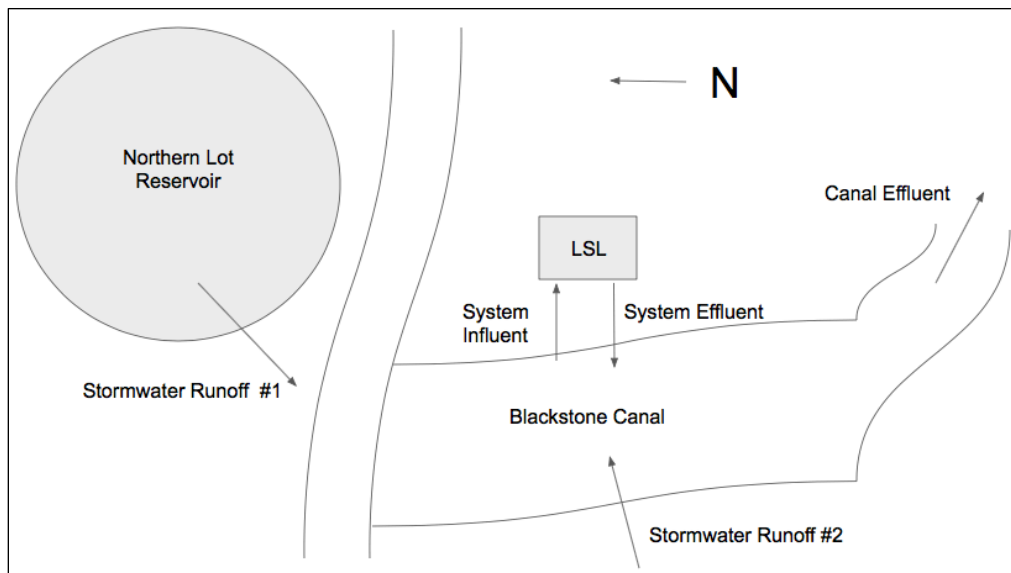
Figure 17: Flow Diagram of Blackstone Canal Drainage Area

4.2 Water Quality Characterization

This section discusses laboratory data gathered over the course of our project including measurements of each constituent at each sampling location, percent change of measured constituents throughout the LSL, and a comparison between water and stormwater samples. Full laboratory procedures may be found in Appendix A. Table 3 displays measurements of pH, turbidity, alkalinity, TOC, TIC, TSS, total phosphorus, ammonia, DO, modified BOD_5, phosphate, and nitrate for each sampling location within the LSL: system influent, system midpoint, and system effluent. Table 4 features measurements for the same measured constituents, but for all of the sampling locations in the canal: canal upstream, canal intake, and canal effluent. Table 5 contains these same measurements for the stormwater samples: stormwater- canal intake, stormwater- ground, and stormwater- drainage pipe, where the stormwater- canal intake sample was collected at the same location as the canal intake sample, but during a storm event to be used as a comparison. Samples that were not measured for a specific constituent are represented by a (-) symbol, whereas samples that were measured for a specific constituent, but below detection limit, are marked as BDL. Lastly, Table 6 summarizes the percent change of measured constituents between each stage of treatment and Table 7 summarizes percent change in constituents measured at the canal intake sampling location in dry vs. storm conditions. These tables will be further discussed in this section. It is noted that these samples were collected during the fall, thus in cold weather conditions where there is typically a lower amount of microbial activity.

Table 3: Summary of Laboratory Tests and Measurements from System Sampling Locations

Location	System Influent	System Midpoint	System Effluent
pH	7.01	6.95	6.97
Turbidity (NTU)	9.3	3.48	0.7
Alkalinity (mg/L of CaCO3)	37	32	37
TOC (mg/L)	3.15	3.92	3.33
TIC (mg/L)	0.1	0.028	0.075
TSS (mg/L)	-	-	0.64
Total Phosphorus (ppm)	0.51	0.11	0.47
Ammonia (ppm)	0.37	0.25	0.08
DO (mg/L)	6.23	9.23	10.55
Modified BOD_5 (mg/L)	0.45	-2.23	-3.16
Phosphate (ppm)	BDL	BDL	BDL
Nitrates (ppm)	2.89	2.2	0.46

Table 4: Summary of Laboratory Tests and Measurements from Canal Sampling Locations

Location	Canal Upstream	Canal Intake	Canal Effluent
pH	8.08	7.13	7.24
Turbidity (NTU)	6.63	14.3	5.52
Alkalinity (mg/L of CaCO3)	60	14.3	-
TOC (mg/L)	3.3	5.49	3.85
TIC (mg/L)	0.06	0.076	-
TSS (mg/L)	-	11.44	-
Total Phosphorus (ppm)	0.66	2.07	0.52
Ammonia (ppm)	0.42	0.06	0.33
DO (mg/L)	7.66	5.8	7.4
Modified BOD_5 (mg/L)	-0.65	-0.21	-1.61
Phosphate (ppm)	BDL	0.61	BDL
Nitrates (ppm)	2.78	3.59	3.59

Table 5: Summary of Laboratory Tests and Measurements from Stormwater Sampling Locations

Location	Drainage Pipe	Ground	Canal Intake
pH	9.28	6.94	7.01
Turbidity (NTU)	8.34	138	6.78
Alkalinity (mg/L of CaCO3)	-	-	-
TOC (mg/L)	-	-	-
TIC (mg/L)	-	-	-
TSS (mg/L)	22.76	-	-
Total Phosphorus (ppm)	0.93	1.5	1.03
Ammonia (ppm)	0.04	0.1	0.2
DO (mg/L)	-	-	-
Modified BOD_5 (mg/L)	-	-	-
Phosphate (ppm)	BDL	0.08	0.61
Nitrates (ppm)	0.07	2.61	3.63

Table 6: Percent Change of Constituents between Treatment Stages

Constituent	% Change Between Treatment Stages			
	Sediment Digesters	Myco-Reactors	Aquatic Cells	Overall
pH	-1.7	-0.9	-12.7	-14.9
Turbidity	-35	-62.6	-79.9	-95.1
Ammonia	516.7	-32.4	-68	33.3
Nitrate	-19.6	-24	-79	-87
Total Phosphorus	-75.9	-78	327.3	-77.3
Phosphate	-100	-	-	-
TSS	-94.4	-	-	-
Dissolved Oxygen	7.4	48.2	14.3	81.9
TOC	-42.6	24.4	-15.1	-39.3
Alkalinity	158.7	-13.5	15.6	158.7
TIC	31.6	-72	167.9	-1.3

Table 7: Percent Change of Constituents Measured at the Canal Intake Sampling Point in Dry vs. Storm Conditions

Constituents	% Change at Canal Intake
	Dry vs. Storm Conditions
pH	-1.7
Turbidity	-52.6
Ammonia	233.3
Nitrate	1.1
Total Phosphorus	-50.2
Phosphate	0

4.2.1 Dissolved Oxygen and pH

Dissolved Oxygen (DO) was measured at the system influent, system midpoint, system effluent, canal upstream, canal effluent, and canal intake sampling locations (Figure 4). Measured concentrations of DO can be found in Tables 3, 4 and 5. DO levels increased from 5.8 mg/L at the canal intake to 10.55 mg/L at the system effluent, with the largest increase occurring during the Myco-Reactor treatment stage as seen in Table 6. Overall, there was an 81.9% increase in DO throughout all stages of treatment. The overall increase in DO is an improvement in water quality in the case of the canal, because the increase in oxygen from its low levels allows wildlife to flourish.

The pH was measured at all nine sampling locations (Figure 4). Measured pH values at each of these sampling locations can be found in Tables 3, 4, and 5. The water was found to be the most acidic at the stormwater-ground sampling location with a pH of 6.94, whereas the water that was most basic was at the stormwater-drainage pipe location with a pH of 9.28. It was found that as water passes through the LSL, it generally becomes more acidic (pH of 7.13 at canal intake, 7.01 at system influent, 6.95 at system midpoint, and 6.97 at system effluent) with a small fluctuation from the system midpoint to system effluent. Overall, there was a 14.9% reduction in pH through the collective stages of treatment as seen in Table 6. The largest drop in pH occurred during the Aquatic Cell treatment stage. This reduction in pH throughout treatment should have little to no effect on the water quality of the canal as wildlife typically thrives in waterbodies within a pH range of 6.5-8.2 (Research Gate, 2016), which all measured pH values lie between. There was a slight drop of 1.7% in pH from the canal intake sample during regular conditions vs. the canal intake sample during a stormwater event (Table 7).

4.2.2 Turbidity and Total Suspended Solids

Turbidity was measured at all nine sampling locations. All turbidity measurements are presented in Tables 3, 4, and 5. The sampling location with the highest turbidity was the stormwater-ground sample which gave a turbidity of 138 NTU, whereas the sampling location with the lowest turbidity was the system effluent with a measurement of 0.7 NTU. It was found that turbidity significantly decreases throughout the LSL, from the canal intake (14.3 NTU) to the system effluent (0.7 NTU). The canal upstream sampling location also proved to have a higher turbidity (6.63 NTU) than that of the canal effluent sampling location (5.52 NTU). Overall, there was a 95.1% decrease in turbidity throughout the treatment system, with the largest decrease (79.9%) occurring during the Aquatic Cell treatment stage as seen in Table 6. The largest decrease in turbidity most likely occurred during the Aquatic Cell treatment stage due to the water passing through a clarifier at the end of the treatment stage in order to settle out any remaining particles. This drastic decrease in turbidity throughout the LSL greatly improved the water quality as waterbodies with high turbidity tend to warm faster, affecting organisms living in the water (Research Gate, 2016). There was a 52.6% reduction in turbidity between the regular canal intake sample and the stormwater- canal intake sample (Table 7).

Three sampling locations were tested for total suspended solids; system effluent, canal intake, and stormwater-drainage pipe (Figure 4). The TSS for each measured sampling location is presented in Tables 3, 4, and 5. At the canal intake point, the TSS was found to be 11.44 mg/L, whereas at the system effluent, the TSS was found to be 0.64 mg/L, a drastic reduction in solids. For comparison, a TSS test was conducted at the stormwater-drainage pipe location and found to be 22.76 mg/L, much higher than even the solid count at the canal intake location whose sample was more turbid than that of the drainage pipe's. There was a 94.4% reduction in TSS during the sediment digesters treatment stage of the LSL, as shown in Table 6. This drastic reduction in TSS during the sediment digesters treatment stage is important, as high levels of TSS may induce bacterial growth or exert additional oxygen demand (Davis, 2009). The stormwater-drainage pipe TSS concentration was most likely so much higher than both other samples because a majority of the sample water is runoff from the surrounding area that is introduced to the canal via the drain pipe.

4.2.3 Total Organic Carbon, Modified BOD$_5$, Alkalinity, and Total Inorganic Carbon

Total organic carbon (TOC) was measured at the system influent, system midpoint, system effluent, canal upstream, canal effluent, and canal intake sampling locations (Figure 4). All corresponding TOC concentrations were presented in Tables 3, 4 and 5. Total organic carbon concentrations were measured during different environmental conditions than the rest of the measured constituents; TOC samples were taken and measured in January of 2017 rather than October/November of 2016 as the other samples were so results may vary. TOC was found to have the highest concentration at the canal intake sampling location with a concentration of 5.49 mg/L. The lowest TOC concentration was measured at the system influent location with a concentration of 3.15 mg/L. Overall, there was a 39.3% reduction in TOC throughout all phases of treatment as seen in Table 6. Although TOC concentrations decreased throughout both the sediment digesters and aquatic cell treatment stages, TOC concentrations increased by 24.4% during the myco-reactor treatment stage. Figure 18 represents TOC concentrations throughout the LSL treatment stages in a visual form.
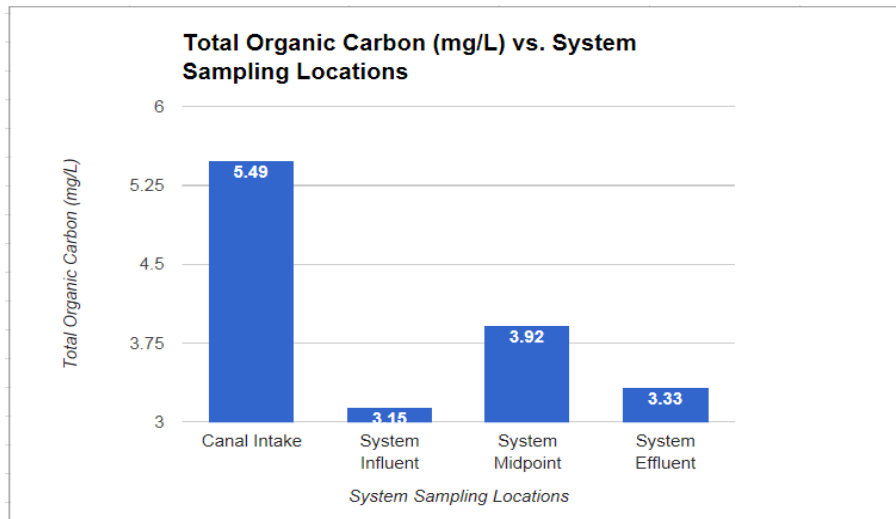
Figure 18: Total Organic Carbon (mg/L) vs. System Sampling Location

Modified BOD_5 was an extension of the dissolved oxygen testing in that the dissolved oxygen levels at the system influent, system midpoint, system effluent, canal upstream, canal effluent, and canal intake sampling locations (Figure 4) were measured every 24-hours for 5 days at 20°C. All sampling locations saw a decrease in DO from day 1 to day 5 except for the system influent sampling location whose DO increased by 0.45 mg/L overall. The largest decrease in DO throughout the five-day test occurred at the system effluent sampling location with a decrease of 3.16 mg/L. All modified BOD_5 measurements may be found in Tables 3, 4, and 5. It was also found that there was larger modified BOD_5 throughout each stage of treatment in the LSL. The increase in modified BOD_5, particularly in the myco-reactor and aquatic cell treatment stages, may be due to an increased concentration of organic matter present in the biological-based processes.

Alkalinity was measured at the system influent, system midpoint, system effluent, canal upstream, and canal intake sampling locations (Figure 4). Measured concentrations at these sampling locations can be found in Tables 3, 4 and 5. The sampling location with the lowest concentration of alkalinity was the canal intake (14.3 mg/L as $CaCO_3$), whereas the sampling location with the highest concentration of alkalinity was the canal upstream location (60 mg/L as $CaCO_3$). Overall, there was a 158.7% increase in alkalinity throughout all treatment phases, with the largest increase in alkalinity occurring during the sediment digesters treatment stage as seen in Table 6. The increase in alkalinity throughout the system is an improvement in water quality as waterbodies

with high alkalinity can better resist changes in pH, which in turn protects resident wildlife. The data is also represented in the form of a bar graph, as seen in Figure 19, in order to provide a better visual representation of alkalinity concentrations after each treatment phase in the LSL.
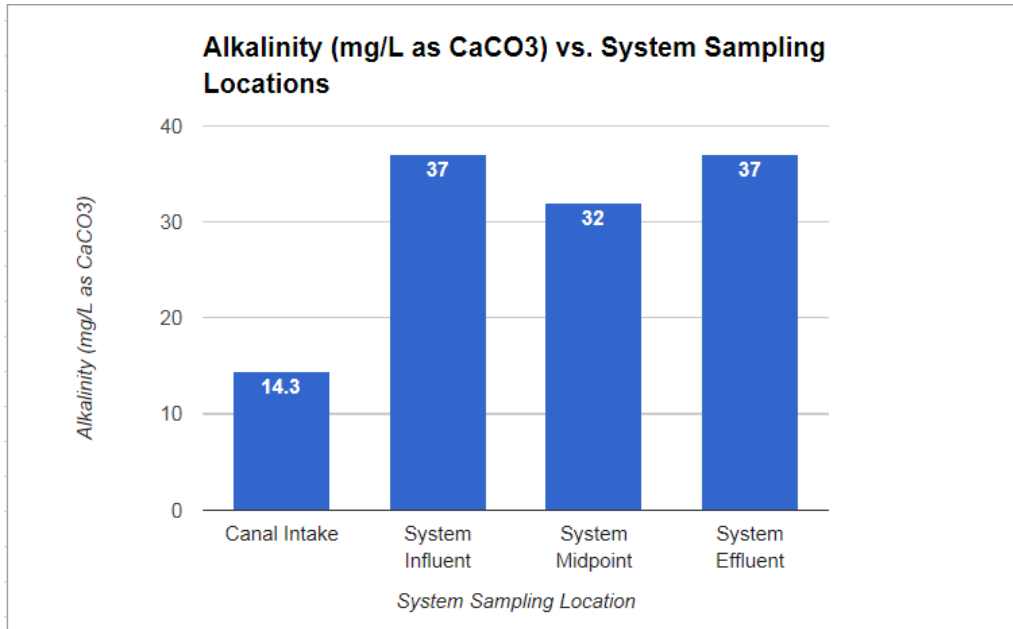
Figure 19: Alkalinity Concentration Graph

Total inorganic carbon (TIC) concentrations were determined at the canal upstream, canal intake, system influent, system midpoint, and system effluent sampling locations (Figure 4) using their corresponding pH and alkalinity measurements. The largest TIC concentration was found at the system influent location (0.1 mg/L) whereas the lowest TIC concentration was measured at the system midpoint (0.028 mg/L) (Tables 3, 4, and 5). No real pattern was established from this data as the system effluent concentration then increased to 0.075 mg/L. Although there was a large percent reduction in total inorganic carbon during the myco-reactor treatment stage and an even larger percent increase in total organic carbon during the aquatic cell treatment stage, the overall treatment process only saw a 1.3% reduction in total inorganic carbon (Table 6).

4.2.4 Ammonia and Nitrate

Each sampling location was tested for ammonia and each corresponding concentration was presented in Tables 3, 4, and 5. The canal upstream sampling location had the highest concentration of ammonia (0.42 ppm) and the stormwater- drainage pipe sampling location that had the lowest concentration of ammonia at (0.04 ppm). It appeared that as the water moved throughout the LSL, ammonia concentrations decreased; from the system influent (0.37 ppm), to the system midpoint (0.25 ppm), to the system effluent (0.08 ppm). It was also found that ammonia concentrations were lower at the canal effluent (0.33 ppm) when compared to the canal upstream sampling location (0.42 ppm). Overall, there was a 33.3% increase in ammonia throughout the total treatment processes (Table 6). There was a large discrepancy in percent reduction of ammonia between each treatment stage. It was found that there was a 516.7% increase in ammonia in the sediment digesters treatment stage. There was then a 32.4% reduction in ammonia after the water passed through the Myco-Reactor treatment stage. Lastly, it was found that there was a 68% reduction in ammonia after the Aquatic Cell treatment stage. The ammonia concentrations throughout the system sampling locations are also presented in a bar graph (Figure 20) in order to provide a visual representation of ammonia concentrations as the water moves throughout the LSL. Ammonia concentrations were then compared between the canal intake sample and the stormwater-canal intake where it was found that there was a 233.3% increase in ammonia from the canal intake sample during regular conditions to the canal intake sample during a storm event (Table 7). Reductions in nutrients such as ammonia and nitrate in a waterbody prevent eutrophication, overall improving the water quality.
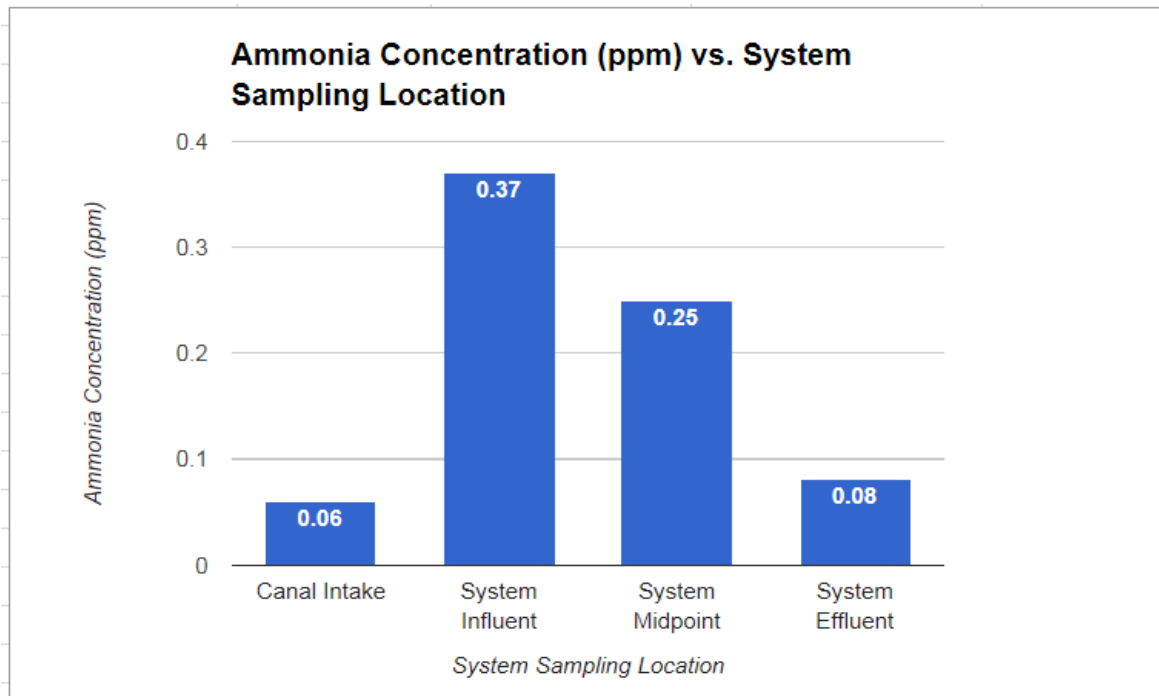
Figure 20: Ammonia Concentration

Nitrate concentrations were measured at all nine sampling locations. The highest nitrate concentration was measured at the stormwater-canal intake sampling location with a concentration of 3.63 ppm, whereas the sampling location with the lowest nitrate concentration was the stormwater-drainage pipe with a concentration of 0.07 ppm (Tables 3, 4, and 5). Nitrate concentrations decreased significantly throughout the LSL with a system influent concentration of 2.89 ppm, midpoint concentration of 2.2 ppm, and effluent concentration of 0.46 ppm. Nitrate concentrations decreased from the canal upstream sample (2.78 ppm) to the canal effluent sample (2.74 ppm). Overall, the nitrate concentration was reduced by 87% throughout the LSL (Table 6), with a bulk of the nitrate reduction occurring during the Aquatic Cell treatment phase. This decrease in nitrate is positive in that in prevents eutrophication. There was a 1.1% increase in nitrate during stormwater conditions at the canal intake compared to regular conditions (Table 7).

4.2.5 Total Phosphorus and Phosphate

All nine sampling locations were tested for total phosphorus. All sampling locations are presented with their corresponding total phosphorus concentrations in Tables 3, 4, and 5. Total phosphorus was highest at the canal intake point at 2.07 ppm and was lowest at the system midpoint at

0.11ppm. It was found that the total phosphorus levels dropped from the canal intake point to the system influent (0.51 ppm) and from the system influent to the system midpoint (0.11 ppm), but increased from the system midpoint to the system effluent (0.47 ppm). Additionally, total phosphorus appears to be higher at the canal upstream sampling location (0.66 ppm) than the canal effluent (0.52 ppm). Overall, there was a 77.3% reduction in total phosphorus throughout all stages of treatment (Table 6). It was found that during the sediment digesters and myco-reactor treatment stages there were 75.9% and 78% reductions in total phosphorus concentrations, respectively, whereas there was a 327.3% increase in total phosphorus concentrations after the aquatic cell treatment stage. These results may suggest that the plant-filled retention basins could play a role in the large increase in total phosphorus as they may provide excess nutrients (Droste, 1997). Total phosphorus is found mainly in samples with a high solids concentration, so it is also normal to see concentrations fluctuate with solids concentrations. The total phosphorus concentrations were also presented in a chart (Figure 21) in order to better visualize the fluctuation in concentrations throughout the LSL. There was a 50.2% reduction in total phosphorus from the sample taken at the canal intake during regular conditions to the sample taken at the canal intake during stormwater conditions (Table 7).
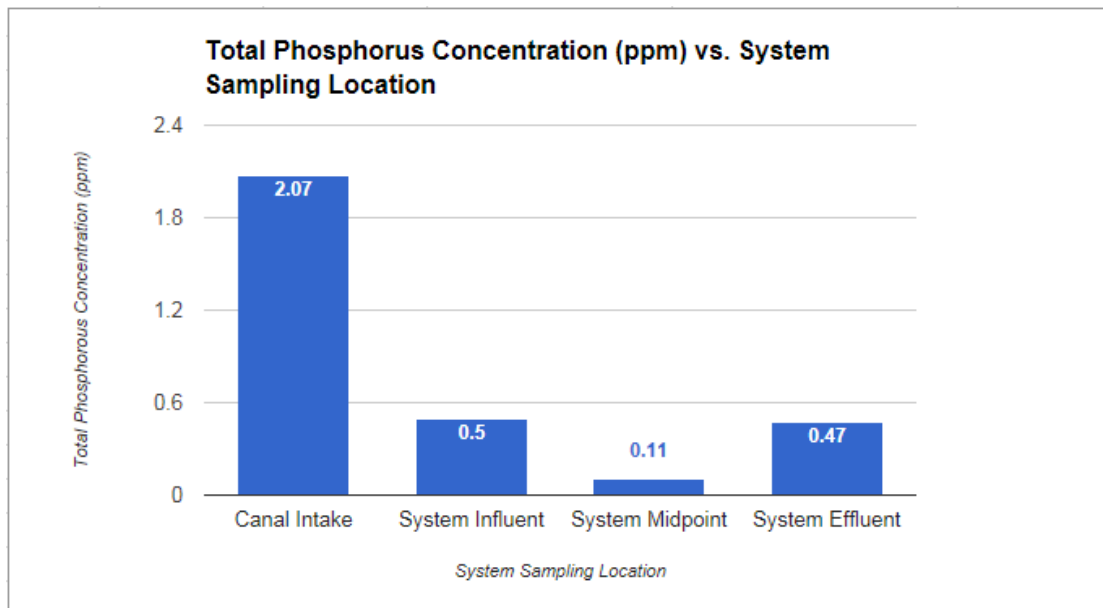
Figure 21: Total Phosphorus Concentration

Phosphate, one of the two anions that was focused on in this project, was measured at all nine sampling locations. All sampling locations and corresponding phosphate concentrations can be found in Tables 3, 4, and 5. The phosphate concentration was found to be the highest at the canal intake sampling location with a concentration of 0.61 ppm, whereas there was technically no sampling location with the lowest concentration as the system influent, system midpoint, system effluent, canal upstream, canal effluent, and stormwater-drainage pipe sampling all had phosphate concentrations below detection limit (BDL). There was a 100% decrease in phosphate concentration in the Sediment Digesters stage of the LSL as shown in Table 16. There was a 0% reduction in phosphate during a stormwater event at the canal intake when compared to the canal intake during a regular event (Table 7).

4.2.6 Metals

There were a variety of metals tested for in the samples including sodium, magnesium, potassium, calcium, aluminum, vanadium, chromium, manganese, iron, cobalt, nickel, copper, zinc, arsenic, cadmium, and lead. These were analyzed using the Inductively Coupled Plasma Mass Spectrometry (ICP-MS) system. All metal concentrations were measured at the system influent and system effluent sampling locations (Figure 4). Lead, manganese, chromium, and iron were the metals that saw the highest percent reductions from the system influent to the system effluent with percent reductions of 96.5%, 94.1%, 93.3%, 92%, respectively. The reduction of these metals during water treatment is imperative as high levels of hard metals negatively affect the resident wildlife. Calcium, potassium, and magnesium were the metals that saw a percent increase in metal concentrations with percent increases of 17.5%, 23.1%, and 23.5% respectively (Table 8). Overall, the reduction of metals was significant throughout the LSL.

Table 8: Metal Concentrations and Percent Change between System Influent and System Effluent Sampling Locations

Metal	System Influent (ppm)	System Effluent (ppm)	% Change
Sodium (Na)	92.25	11.51	-87.5
Magnesium (Mg)	11.1	13.71	23.5
Potassium (K)	9.99	12.3	23.1
Calcium (Ca)	12.39	14.56	17.5
Aluminum (Al)	0.53	0.14	-74.3
Vanadium (V)	0.004	0.001	-82
Chromium (Cr-1)	0.01	0.001	-93.3
Manganese (Mn)	0.21	0.01	-94.2
Iron (Fe-1)	1.93	0.16	-92
Colbalt (Co)	0.001	0.0004	-61.2
Nickel (Ni)	0.04	0.01	-67
Copper (Cu)	0.04	0.02	-47.4
Zinc (Zn)	0.04	0.02	-44
Arsenic (Ar)	0.01	0.002	-72.5
Cadmium (Cd)	0.001	0.0002	-72
Lead (Pb)	0.03	0.001	-96.5

4.2.7 Summary of Water Quality Characterization Results

Various positive results came from the laboratory testing for water quality. Many metals exhibited significant concentration reductions - in particular lead, manganese, chromium, and iron, which saw the most drastic reductions. These results are positive, showing that the LSL is properly removing metals from the water. Significant decreases also occurred in total suspended solids (11.44 mg/L at canal intake, 0.64 mg/L at system effluent). Another reduction occurred in overall total phosphorus. Although there was a spike from the system midpoint (0.11 ppm) to the system effluent (0.47 ppm), there was a still an overall decrease from the system influent (0.50 ppm) to the system effluent (0.47 ppm). This again shows that the system is treating for phosphorus, although improvements could be made to account for the spike, which occurred in the aquatic cell treatment stage, as outlined in the recommendations section. The increase in modified BOD_5 can be accounted for in the aquatic cells, as part of the purpose of the LSL is to add organic matter to the canal in order to support ecosystem regrowth.

There are also key aspects of the water quality characterization that prove that the LSL can be applied to stormwater treatment. One main constituent exemplifying this is pH. Between the canal intake sample at dry conditions to the canal intake sample during a storm event, there is only a pH

reduction from 7.13 to 7.01 respectively. Both pH values are relatively neutral, showing that the LSL can be applied to stormwater. In terms of turbidity, there was a higher value (14.3 NTU) in the canal intake sample during dry conditions than canal intake sample during a storm event (6.78 NTU). This also proves that the LSL can treat for turbidity in both conditions, since there were significant reductions in turbidity in the canal intake sample during dry conditions. The same conclusion can be drawn from the results for total phosphorus (2.07 ppm vs. 1.03 ppm respectively). Also, the fact that phosphate levels were equal in canal water and stormwater at the canal intake (0.61 ppm vs. 0.61 ppm, respectively) shows another very similar constituent in both. Together, these prove that the LSL can have treatment applications for both canal water during dry conditions and canal water during a storm event, thus proving that design applications and recommended alterations would apply to both.

Overall, the data shows that the system is operating properly. With the comparison to canal intake at dry conditions to stormwater conditions, it can be concluded that the LSL has the capability to treat water at these levels, and thus proving that design alterations for the system would apply to both conditions. Although the treatment processes are generally producing positive results, the LSL needs to increase its capacity for increased water volume to treat the proper amount of stormwater runoff.

4.3 Stormwater Characterization

The quantity of runoff entering the canal was determined by using GIS and the NRCS Method. GIS was used to obtain geographical information of the surrounding area. The complete collection of maps containing this information can be found in Appendix B. Land use and soil data were used in combination with the NRCS method to determine runoff flowrates from the northern lot and drainage area for a 1-year, 2-year, and 0.5 inch storm (Table 7). In addition, the rainfall distribution for the Worcester area was examined to determine an annual runoff volume for the northern lot.

4.3.1 Watershed/GIS

First the topography of the area surrounding the Blackstone Canal was examined. The figure below (Figure 22) shows the contours and elevations of this area.

Figure 22: Topography map via ArcGIS; Scale 1:833

Using these contours, the two areas that drain into the canal were determined. Figure 23 shows the approximation of these areas. The area to the west of the canal is referred to as drainage area, and the part to the north is the northern lot. The area of drainage area was found to be 143 acres (6,263,402 sq. ft.), and the northern lot is 9 acres (392,054 sq. ft.).
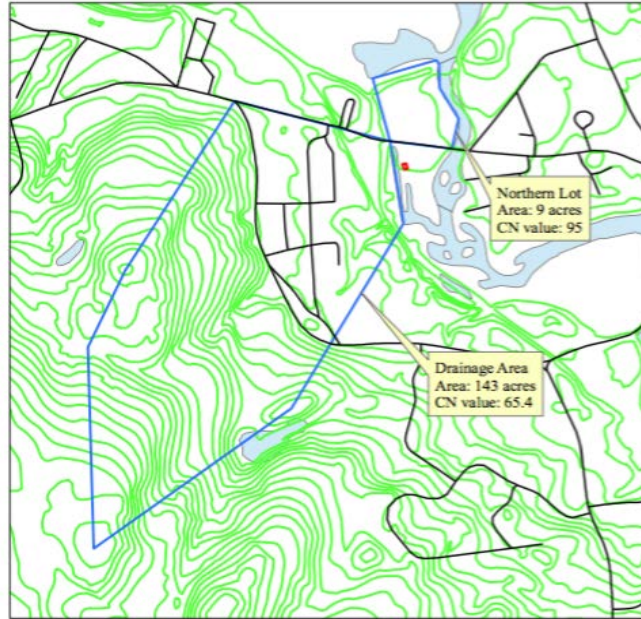
Figure 23: Drainage area map via ArcGIS; Scale 1:833

Next, the land uses of the area within drainage area were examined (Figure 24). Land use and soil composition were not examined for the northern lot because we assumed a CN value of 95 due to the area being impervious. The area was divided into the following land use categories: commercial, forest, forested wetlands, low density residential, medium density residential, multi-family residential, open land, participation recreation, transportation, urban/public institution, and water. The largest land use area was forest (3,726,984 sq. ft.), while the smallest area was forested wetlands (21,506 sq. ft.). Table 19 shows each of these categories and their areas.
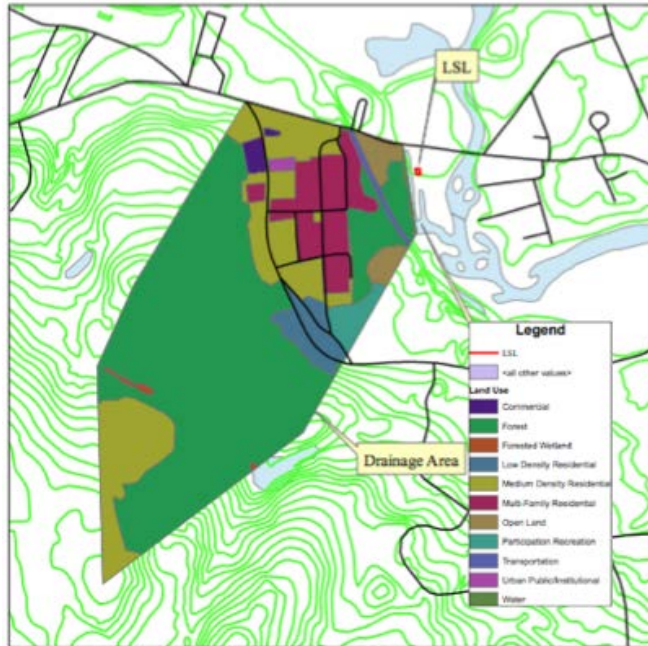
Figure 24: Land Use map via ArcGIS

Table 6: Land Use Areas

Land Use	Area (Sq ft.)
Commercial	58,000
Forest	3,700,000
Forested Wetland	21,000
Low Density Residential	227,000
Medium Density Residential	1,200,000
Multi-Family Residential	607,000
Open Land	160,000
Transportation	46,000
Urban Public/Institutional	24,000
Participation Recreation	125,000
Total	**6,200,000**

The soil composition of the drainage area was also analyzed. Soils were categorized based on soil type and their hydrological group, which is a value A-D characterizing the soil's permeability. An attribute table describing each soil and their characteristics can be found in Appendix D. Figure 25 shows the soil compositions based on hydrological groups.
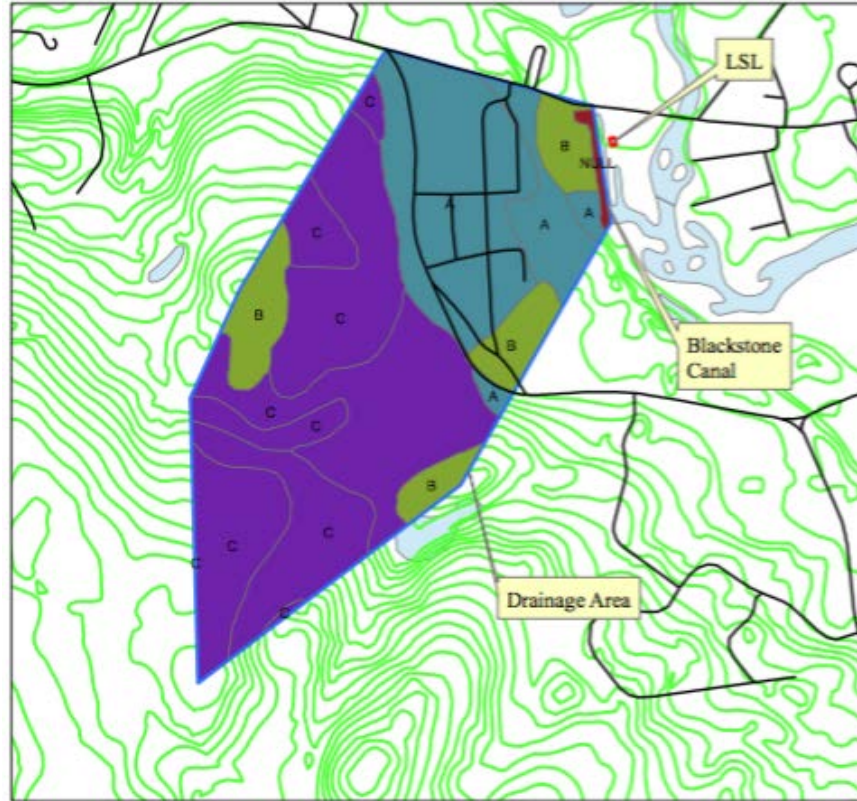
Figure 25: Soil Hydrologic Groups Map via ArcGIS

Then, the soil and land use layers were merged together. This yielded new features, each with their own land use designation and hydrological group. The attribute table describing these new features can be found in Appendix D.

Finally, the pervious and impervious areas of the drainage area and northern lot were determined (Table 8). For the drainage area, the pervious area was found to 5.4 million sq. ft. and the impervious area was 280,000 sq. ft. The northern lot was found to have an impervious surface of 129,000 sq. ft.. The drainage area was 5% impervious surface and the northern lot was 15% impervious surface.

4.3.2 NCRS/Flow Volume

In order to determine the runoff flows entering the canal from the drainage area, a weighted CN value needed to be determined. No weighted CN value was needed for the northern lot because it had an assumed value of 95. A pivot table was used to categorize the information gathered from

GIS. The weighted CN value for the drainage area was found to be 65.4. See Appendix E for the pivot table and calculations used to determine the weighted CN.

The CN values were then used in equations from the NRCS method to determine the volume and runoff of water for three storm events (Table 7). Data for a 1-year storm over a 24 hour period was found to be 2.65 in. for the Grafton, MA area, and for a 2-year storm 3.24 in (Cornell, 2016). For an average storm precipitation was assumed 0.5 in over a 24 hr. period (Kling & Weiss, 2017). The drainage area yielded a flowrate of 2.22 cfs for a 1-year storm, 3.85 cfs for a 2-year storm, and 0.4 cfs for a 0.5 in. storm. The northern lot yields a flowrate of 0.8 cfs for a 1-year storm, 1.01 cfs for a 2-year storm, and 0.06 cfs for 0.5 in storm.

Table 7: Storm Event Runoff Flowrates and Volumes

	Area (sq. ft.)	Weighted CN	1-Year Storm: P= 2.65 in/24 hr.		2-Year Storm: P= 3.24 in/24 hr.		Ave Storm: P= 0.5 in/24 hr.	
			*Volume (Cubic ft.)	Avg. Flowrate (cfs)	Volume (Cubic ft.)	Avg. Flowrate (cfs)	Volume (Cubic ft.)	Avg. Flowrate (cfs)
Drainage Area	6,263,402	65	192,184	2.22	332,534	3.85	34,353	0.4
Northern Lot	392,054	95	68,891	0.80	87,692	1.01	5,527	0.06

*Volume of runoff for 24 hr. period

4.3.3 Water Quality Volume

Once the runoff volumes were determined, it was necessary to define a Water Quality Volume (WQV), which is a volume of water which accounts for the majority of contaminants needed to be treated. In accordance with the MassDEP (2008) Stormwater Handbook, this volume was assumed to be 0.5 inches over the total impervious area. Using the impervious areas from Section 4.3.1, this volume of water was calculated (Table 8). The northern lot was chosen to do this analysis for, because its runoff volume was a much more realistic goal for the LSL. The impervious area for the northern lot was 129,000 sq. ft. The volume of water accounting for 0.5

in. of precipitation over this area was 5,000 cubic ft. This is the volume of runoff that will be used to gauge the LSL's capacity to treat stormwater in Section 4.3.5.

Table 8: Volume of Runoff from 0.5 in. of Precipitation over Impervious Area

Area	Pervious Area (sq ft.)	Impervious Area (sq ft.)	% Impervious	Volume (cubic ft)
Drainage Area	5,419,000	280,000	5	12,000
Northern Lot	885,000	129,000	15	5,000
Total	6,304,000	409,000		17,000

4.3.4 Annual Rainfall Distribution

The annual rainfall distribution for the Worcester area was used to determine the annual volume of runoff from the northern lot entering the canal (Table 9). Rainfall distribution data was provided courtesy of the *Coes Pond: Stormwater Management* (2017) MQP team. The runoff volumes for storms of various intensities were determined using the NRCS method. These volumes were then multiplied by their yearly frequency to determine their annual runoff volumes. In total there were 64 storms, yielding an annual runoff volume of approximately 745,000 cubic ft. A WQV of 5000 cubic ft. was assumed for each storm, yielding a total annual WQV of 320,000 cubic ft.

Table 9: Annual Rainfall Distribution and Runoff Volumes

Storm Intensity (in./24 hr)	Runoff Volume (in.)	Runoff Vol (Cubic ft)	Frequecy (yearly)	Annual Runoff Volume (Cubic ft)	WQV:0.5 in. (Cubic ft)	Annual WQV (Cubic Ft)
0.5	0.169173184	5,527	50	276,354	5,000	250,000
1	0.563353276	18,405	7	128,838	5,000	35,000
1.5	1.012617722	33,083	4	132,334	5,000	20,000
2.5	1.96325341	64,142	2	128,284	5,000	10,000
3	2.449393432	80,025	1	80,025	5,000	5,000
Total	-	-	64	745,834	-	320,000

4.3.5 Stormwater Characterization Discussion

The stormwater analysis conducted in this section characterized the flowrates and volumes entering the Blackstone Canal during several rain events. This was considered for two areas: the largest of which was the drainage area at 6,263,402 sq. ft., and northern lot, which was found to be 392,054 sq. ft. The northern lot had an assumed CN value of 95 because it is largely impermeable due to construction that was done in the area. The weighted CN value was found to be 65 for the drainage area, meaning that much more runoff infiltrates here than in the northern lot. The percent impervious area for the drainage area is 5%, while for the northern lot it's 15%. However, since the drainage area is so much larger its runoff volume is still greater.

The analysis was done for rain events of three different intensities: 1-year storm, 2-year storm, and 0.5 in. storm. As expected, the 2-year storm had the highest average daily flow rate, 332,534 cubic ft. for the drainage area and 87,692 cubic ft. for the northern lot. The 1-year storm had runoff volumes of 192,184 cubic ft. and 87,692 cubic ft. for the drainage area and northern lot, respectively. The 0.5 in. storm had volumes of 34,353 cubic ft. for the drainage area and 5,527 cubic ft. for the northern lot. The Blackstone Canal acted as a natural storage unit for this stormwater, allowing for the LSL to intake and treat this runoff source.

These volumes are much larger than the LSL's capacity of 93 cubic ft. per day (700 gal), so it would be unrealistic to design for it to treat the entire volume. Therefore, since the volume of runoff from the northern lot would have a more direct impact on the canal, and its flow rate is more manageable, this area was chosen to use for a design criteria. Furthermore, we assumed a water quality volume (WQV) in an attempt to maximize the majority of pollutants captured. In effect, this states the LSL should be capable of treating 0.5 inches of precipitation over the total impervious area. The impervious area for the northern lot was 129,000 sq. ft. Assuming 0.5 in. over this area yields a WQV of 5,000 cubic ft. So we assume the LSL should be treating roughly 5,000 cubic ft. from any given rainstorm. This is volume is still much higher than the LSL's current capacity of 93 cubic ft. per day.

The annual rainfall distribution was also taken into account. It was determined that the annual runoff volume for the northern lot was 745,834 cubic ft. (Table 10). This is the amount of runoff that enters the canal from the northern lot each year. In comparison, the annual WQV was 320,000 cubic ft., which is the amount of runoff the LSL would be treating annual, under ideal conditions. If the LSL were operating at this ideal condition, it would be treating approximately 43% of the runoff entering the canal, which is very efficient. Currently, it only treats 33,945 cubic ft. annual (93 cubic ft. /day), at a treatment percentage of 4.5% of the total annual volume. In order to reach the WQV levels, the LSL would have to treat approximately 286,000 cubic ft. more runoff annually, or 784 cubic ft. /day. This would require a large increase for the LSL's treatment capacity. We provide some recommendations for achieving this in Section 6.0.

Table 10: Annual WQV vs. Current Annual Treatment

Volume	(Cubic Ft)
Annual Runoff Vol (Cubic Ft)	745,000
Annual WQV (Cubic Ft)	320,000
% Treatment	43%
Current Annual Treatment	33945
% Treatment	4.50%

4.4 Design Evaluation

This section provides a design evaluation for increasing the capacity of the LSL to better accommodate the stormwater runoff entering the canal. First, the current capacity of the LSL was evaluated by examining the system's flowrates, as described in Section 4.1. The annual runoff and water quality volume (WQV) were then examined to determine how much runoff enters the canal and what percentage of this runoff the LSL should treat. As discussed in Section 4.2.7, the water quality analysis results showed that characteristics for canal water and stormwater conditions were similar. Therefore it was assumed that all design considerations incorporated both canal water and stormwater. Finally, we discuss the required increase in capacity that would be required to properly treat the runoff volume, along with some recommended approaches for achieving this goal.

4.4.1 Current System Constraints

For system design, the current constraints of the system were initially determined. The measured system effluent flowrate of 0.009 cfs was assumed to be the best representation of the flow leaving the LSL. It was also assumed that the LSL operated at four cycles per day and processed approximately 100 cubic feet of water per day. Using these assumptions, the cycle time was calculated to know how long per day the system was actually processing water. Refer to Appendix H for the equation used to determine cycle time. It was determined that the system operates 43 minutes for each cycle. This value was used then in the calculation to determine the required system intake flowrate. It was later determined that the system in factwas running for one, 3 hour cycle per day during a field observation period in February 2017. However, since this was the reported operating principle under normal operating conditions, the assumption of four cycles per day was used for the design criteria for this analysis.

4.4.2 Stormwater Runoff Volumes

The runoff volumes for two areas draining into the canal were calculated (Section 4.3.2). The first area, designated as *drainage area*, is located west of the canal, and is much arger area. The second area, called *northern lot,* lies to the north of the LSL and has been designated for residential development. The runoff volume for the northern lot was chosen as a design basis because it represents a more feasible goal for the LSL's treatment capacity, and it has a more direct impact on the quality of the canal. The annual runoff volume for the northern lot is approximately 745,000 cubic ft. (Table 10). Since even this volume greatly exceeds the LSL's current estimated capacity (33,945 cubic ft. /yr.), a smaller amount was selected. The annual WQV was used for a more realistic treatment goal. In accordance with the WQV, the LSL should ideally be treating 320,000 cubic ft. annually or 876 cubic ft. /day, which is approximately 43% of the total amount of runoff entering the canal from the northern lot. In order to reach this goal, the LSL would need to process approximately 286,000 cubic ft. more water annually.

4.4.3 Operational Design Requirements

To accommodate the annual WQV, the LSL needs to treat approximately 876 cubic feet per day. With the assumption that the LSL operates at four cycles per day, each cycle would need to process approximately 219 cubic feet. There are several different approaches that could be taken to increase the LSL's capacity to treat this volume. These approaches are outlined in this section.

4.4.3a Cycle Time and Pump Flowrate

The influent flowrate was measured as 0.011 cfs while the system was in operation, so there needed to be a change to account for this increase in water volume. Altering the system influent flowrate, or altering the cycle time could address this. According to the design specs for the jet pump, it has a maximum flowrate of 0.03 cfs (13.5 gpm), which means that the pump is not being operated at its capacity. It was decided that a combination of increasing both the influent flowrate and the cycle time were necessary to best serve the system. A table was created to compare varying influent flowrates to cycle times to determine what cycle time would be required to treat the 219 cubic feet per day required. The results, shown in Table 11, show that, to achieve the maximum pump flowrate of 0.03, the cycle time of the system would also need to be increased from 45 minutes per cycle to approximately two hours per cycle (121.8 minutes).

Table 11: Influent Flowrate vs. Cycle Time

Q (New System Influent) (cfs)	Volume (Cubic ft./cycle)	Time of Cycle (min)
0.01	219	365
0.02	219	183
0.03	219	121
0.04	219	91
0.05	219	73
0.06	219	61
0.07	219	52
0.08	219	45
0.09	219	40
0.1	219	37

Assuming a 43 minute cycle time and four cycles per day, the required flowrate was calculated to be 0.085 cfs. This calculated flowrate is much higher than current pump's maximum of 0.03 cfs. This difference in flowrates could be minimized by placing pumps in a parallel configuration. For identical pumps placed in parallel, with the head kept constant, the flowrate is twice the amount of a single pump (de Costa Bortoni et. al., 2008). Therefore, placing another Grundfos MQ3-45 G96860195 Booster Pump in parallel with the current one would increase the maximum influent flowrate to 0.06 cfs. However, this increase would require a bigger retention tank, or bigger sump pumps to accommodate the increased flow. It would also be important to assess the impacts of these changes on the myco-reactors and aquatic cells in the system.

4.4.3b Myco-Reactor Alterations

The volume increase required for the LSL to meet the WQV also had an impact on the myco-reactors. The increase in the number of myco-reactor beds was calculated by first determining the

surface loading rate for all eight active myco-reactors. This was found to be $0.000352 \frac{\frac{ft^3}{s}}{ft^2}$. It was assumed that this loading rate represented a maximum rate that could be accommodated by this system. This surface-loading rate was then entered into a table of varying influent flowrates to determine the required number of myco-reactors for each condition (Appendix H). It was decided that the most reasonable flowrate for the myco-reactors influent would be 0.03 cfs, which resulted in a required amount of 19 myco-reactors. The flowrate of 0.03 cfs was selected to match the system intake increased flowrate, to ensure that the myco-reactor stage would be able to withstand the water volume increase. This calculation did not take into account the biological or hydrologic functionalities of the myco-reactors, as these considerations are addressed in the recommendations section for further experimentation. Future alterations to the myco-reactors could incorporate increased individual bed size in addition to an increased number of beds.

4.4.3c Aquatic Cell Alterations

Calculations were conducted taking into account BOD concentrations, hydraulic retention time, and six aquatic cells in series. Tables in Appendix H were constructed using Equation 7 to find trends. This equation related the effluent concentration the influent concentration, a first-order decay rate constant (k), the hydraulic retention time (days), and n is the number of aquatic cells in series. For the first table, a range of k values were considered. A k value of 0.3 days^{-1} (recommended by Droste (1997) for fully mixed reactors) was used for assessing the significance of volume and number of cells in relation to flowrate. An increase in the volume of each tank would result in a greater decrease in effluent BOD concentration. Increasing the flowrate entering the aquatic cells at current conditions increased the effluent BOD concentration, as it did for an increased amount of aquatic cells as well. When varying the number of aquatic cells, it was found that larger number of cells t in series resulted in a greater decrease in the effluent BOD concentration decreased. Full calculations and tables can be found in Appendix H. For the purpose of the LSL, adding 18 cells in series was not feasible, due to spacing constraints. Also, to maintain cycle time, the influent flowrate to the aquatic cells would need to drastically increase to process the amount of water necessary for the new LSL capacity. Having 18 aquatic cells would also require too long of a hydraulic retention time. Instead, it was recommended that there be three sets of six aquatic cells in series, which would still provide a significant decrease in BOD concentration, while still providing organic matter for the Blackstone Canal, and keeping the

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hydraulic retention time in the cells reasonable. Maintaining series of six cells would allow for a manageable increased influent flowrate of 0.03 cfs to each of the three series. This flowrate was kept the same, since increasing the current aquatic cell influent flowrate would increase the amount of BOD concentration in the effluent. It is noted that a lower number of cells (or series of cells) would provide for a lower level of treatment but could still be a valuable option. Another recommended considerations would be to pursue possible addition of a storage unit for influent canal and stormwater. This would allow for the water to be able to be treated over multiple days, and thus reduce the necessity of the hydraulic retention time in the aquatic cells to be lower.

4.4.4 Summary

The LSL currently treats approximately 100 cubic ft. per day, or 3,945 cubic ft. annually, which is much less than the volume of runoff entering the Blackstone Canal from the northern lot. Ideally, the LSL should be treating the WQV, which is 320,000 cubic ft. annually, or 876 cubic ft. /day. There are several approaches that could be taken to increase the system's flows to meet the WQV, including changing the cycle time, adding more pumps, and increasing the size and number of myco-reactors and aquatic cells. The best solution would like involve a combination of these approaches. It should be noted that the design evaluation for the myco-reactors and aquatic cells were solely volumetric, because the exact biological mechanisms driving the treatment process were unknown. In order to more fully characterize the efficiency of the LSL, further study will need to be done into the exact driving mechanisms. Recommendations are provided in Section 6.0 for ways to increase the LSL's capacity to treat the WQV, as well as ways to conduct further research on the LSL's efficiency.

5.0 Conclusion

The Living Systems Laboratory was analyzed for both current hydraulic and treatment capacity and assessed for potential stormwater applications. Water samples were acquired at various locations throughout and surrounding the LSL and were tested for a variety of constituents considered indicators of water quality. The flowrates of water moving throughout the LSL and canal were calculated to better understand the present conditions and hydraulic capacity of each. GIS was used to gather data on land use, topography, and soil composition of the surrounding area which was then used to better understand the size of the drainage area whose runoff enters the canal near the LSL. Using the results from the laboratory testing, GIS analysis, and flowrate measurements, the hydraulic and treatment capacity of the system were better understood. Future design modifications were proposed in order to allow the system to treat typical storm events. The implementation of these designs in the LSL will provide for better stormwater treatment, particularly with the addition of impervious space to occur in the lot just north of the LSL. This section includes a brief summary of results and the proposed design modifications based on these results.

5.1 Results

The stormwater analysis conducted predicted an annual water quality volume (WQV) of 320,000 cubic ft., which is the ideal quantity of water that should be treated by the LSL each year. These results drastically differ from the calculated WQV that the LSL is currently treating, 33,945 cubic ft. per year. Design modifications were proposed to accommodate this new WQV and are discussed later in this section. The laboratory results reflected a large reduction in most heavy metal concentrations, turbidity, total suspended solids, nitrate, and phosphate, proving significant treatment occurring throughout the LSL. Increases in dissolved oxygen, alkalinity, ammonia, and metals magnesium, potassium, and calcium occurred throughout treatment. There were a variety of similarities found between canal water during dry conditions and canal water during a storm event that confirmed that it is possible for the LSL to be applied to stormwater treatment. Primarily, both stormwater and canal water had similar neutral pH values, and it was found that turbidity, total phosphorus, and phosphate levels were lower in stormwater samples than canal water samples. With design modifications such as proper maintenance of aquatic cells, increased influent

flowrate, or increased operation time, these results may improve and the LSL will be able to better accommodate stormwater.

5.2 Design Approach

Various design modifications were proposed to expand the LSL's capability to treat stormwater. First, an increase in cycle time and influent flowrate can be used to expand the hydraulic capacity of the LSL . In order to best meet the new WQV, it was found that the assumed the current cycle times (with 43-minute cycles that ran four times a day) should be increased to 2-hour cycle times, four times a day. In order to increase the influent flowrate, one approach would be to acquire a second jet pump and use it in parallel to the initial pump, which has been proven from literature to approximately double flowrates. Additionally, it was found that increasing the amount of the myco-reactors and aquatic cells would be extremely useful in expanding the LSL's capacity to treat stormwater. It was suggested that an additional 11 myco-reactors and 12 aquatic cells be installed in the LSL in order to account for the increase in water volume that needs to be treated. I A smaller number of myco-reactors and aquatic cells would treat a smaller volume (or would treat the WQV to a lower level of treatment), but could still be a valuable option. In addition, careful use of the storage that is available in the canal could be used to significantly reduce the number of additional units required. Recommendations are provided in Section 6.0 for ways to increase the LSL's capacity and to conduct further research.

6.0 Recommendations

The capacity of the Living Systems Laboratory should be increased if this system is to be used to accommodate stormwater treatment. Having the ability to treat for increased levels of canal water will allow for the system to be able to treat the initial flush of contaminated stormwater during an event. These improvements will not add additional continued maintenance for the system, since the system will always be operating to account for storm levels; therefore, there will not be a need for an operator to go to the site every storm to adjust intake. In general, the system will need continued maintenance and upkeep to make sure it is operating at maximum efficiency. These recommendations will aid to further perfect the Living Systems Laboratory, and prepare eco systems like this one for potential applications at other points along the Blackstone River to increase overall stormwater treatment in the area.

6.1 System Intake

It is recommended that an increase in system influent flow from 0.011 cfs 0.03 cfs to occur in tandem with an increased cycle time from 43 minutes to approximately two hours. This would come from the increase in flowrate for the current pump to maximize its flow potential, while adjusting the timer to four, two-hour cycles per day. Increasing the pump flowrate could also be accomplished by adding two pumps in parallel to double the possible system influent flowrate.

6.2 Myco-Reactors

Further lab testing should occur to supplement the findings for hydraulic capacity of the Myco-filters. It is important to determine the efficiency of the Myco-filter beds at this new myco-bed influent flowrate of 0.03 cfs. It is recommended that lab tests are conducted on all of the constituents outlined in the Lab Sampling section (Section 3.5), and compare the results from the original system state. This will determine whether or not the adjusted flowrate will maintain treatment efficiency, which will help to better decide what flowrate will best treat the inbound water, while maintaining it at the highest possible rate.

Also, utilizing Darcy's Law to determine hydraulic capacity is recommended to further quantify the myco-bed filters. This would result in a hydraulic capacity that takes into consideration

hydraulic conductivity through the soil, and water/soil levels in each myco-reactors. This would aid in providing a maximum capacity that could be compared to the laboratory capacity to ensure myco-reactors functionality at the increased water volume intake of the LSL.

Another option to determine the capacity of the myco-reactors is to conduct breakpoint experimentation as outlined in Appendix G. Using the two procedures, one can further determine through creating an influx of water in the system, proper sample collection from the system influent and midpoint of the system, and the corresponding lab testing and analysis, the capacity of water that the myco-reactors can treat without compromising efficiency. Testing for all constituents under the same conditions will also eliminate any outliers in data, and make data sets easier to compare and draw conclusions from.

Using the bypass experimentation from Appendix G, further system improvements could potentially be made. If it is concluded that bypassing the myco-reactors still efficiently treats the water, then a bypass route could be constructed for higher flows, and the myco-reactors could be used for smaller flows. Essentially, this would allow for more water to be treated, and potentially, allowing for the LSL to increase its water volume intake even more.

6.3 Aquatic Cells

It is suggested that the LSL add 12 aquatic cells with the existing six units to accommodate the water quality volume. The units should be assembled in series of six each, as to relatively minimize hydraulic retention time. It is also recommended that samples be taken from each aquatic cell for testing, then assessed via a curve to better understand what is occurring at each step of the series. Use of a lower number of cells could treat a smaller stormwater volume (or the full water quality volume to a lower level of treatment, but could still be valuable.

Nitrogen and phosphorus removal is another area of recommended improvements. Regularly harvesting the plants in the aquatic cells and replacing them will increase nitrogen and phosphorus removal. The plants only have a certain capacity of nitrogen and phosphorus intake, and thus can only treat for so much (Droste, 1997). Replacing them on a scheduled basis will improve the

removal of nitrogen and phosphorus, two major constituents when dealing with stormwater. Cleaning of the tanks on this schedule will also help in these same regards, and is highly recommended. Re-conducting the BOD testing will also yield better results. Using proper dilution factors for incubated BOD samples will give more accurate DO, and thus BOD, data for use with the complete mixing model for ponds in series.

The LSL proves to be prepared for greater stormwater treatment applications upon application of the above recommendations. Further research and experimentation will solidify this ability, and allow for applications of these processes downstream on the Blackstone River, and in the surrounding area as well. Broader application of such natural stormwater treatment promises a bright future for stormwater treatment in the greater Grafton area.

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8.0 Appendices

Appendix A: Laboratory Procedures

Turbidity

Standard Methods 2130

1. Gently pour the sample water into a turbidity vial, making sure to fill up the vial to the line. Cap the vial.
2. Carefully invert the vial multiple times to ensure a uniform sample to test with.
3. Rinse the outside of the vial with reagent grade water and wipe down with a Kimwipe as a dirty vial will alter the results.
4. Place the vial in the turbidimeter with the arrow on the vial facing the line inside the meter and shut the cover.
5. Watch the readout on the machine for 20-30 seconds, using judgement to determine the turbidity (NTU).

Total Suspended Solids

Standard Methods 2540

1. Prepare filters by first setting up the vacuum pump.
2. Label Aluminum pans to be used for baking the filters.
3. Using tweezers, place a 1.5 um filter paper in the pump.
4. Filter deionized water through the filter paper using the pump.
5. Use tweezers to remove the filter paper from the pump and placing it on the aluminum pan labeled "Initial".
6. Place the aluminum pan and filter in the oven for a few hours.
7. Zero the aluminum pan, weigh the baked filter, and record results.
8. Repeat steps 2-8 with sample water, making sure to label the aluminum pan "Sample Water".
9. Calculate the amount of suspended solids using the equation

$$\text{Total Suspended Solids} = m_{initial} - m_{sample\ water}$$

pH

Standard Methods 4500

1. Calibrate the Accumet Basic AB15 pH meter
   a. Immerse the electrode in the pH 4 buffer
   b. To access standardization mode, press "std"
   c. Wait until the display reads "STABLE"
   d. Press "std" again to store the standard and the screen will read "GOOD ELECTRODE"
   e. Repeat steps a-d for pH 7 buffer and pH 10 buffer
2. Immerse the electrode in the sample and record

Alkalinity

Standard Methods 2320

1. Calibrate the Accumet Basic AB15 pH meter and follow instructions for pH standardization
2. Place 100 mL of the sample into a beaker
3. Place the beaker on a stir plate and put a magnetic stirrer in the beaker
4. Set up digital titrator
5. Place the pH probe into the sample and record pH value
6. Continuously tirate acid into the sample while recording each volume of acid added and its corresponding pH
7. Titrate until the slope of the titration graph equals approximately one

Dissolved Oxygen

Standard Methods 4500-O

1. Calibrate the membrane electrode according to the manufacturer's instructions in distilled water
2. Dip DO probe into the sample-filled bottle, ensuring to submerge the entire membrane in the sample
3. Wait for the electrode to stabilize and record DO value displayed on screen

Modified BOD$_5$

4. Repeat all steps under dissolved oxygen to determine the initial DO concentration of each 300mL bottle

5. Incubate each of the 300mL sample-filled bottles at 20 degrees in the dark

6. After 24 hours, measure the DO for each sample following steps X-X under dissolved oxygen and record

7. Complete steps 1-3 in 24 hour increments over a 5-day period

8. Modified BOD$_5$ over the 5-day period was calculated using the equation

$$Dissolved\ Oxygen\ Depletion = DOinitial - DOfinal$$

Total Phosphorus

Standard Methods 4500

1. Blank 25 mL of sample under a fume hood
   a. Add 5 mL of nitric acid
   b. Add 1 mL of sulfuric acid
   c. Bring sample to fumes of sulfuric acid

2. Use the HACH DR/3000 Spectrophotometer after it has been on for multiple hours

3. Prepare a blank Spectrophotometer sample
   a. Add one drop of phenolphthalein to a vial
   b. Using 5 N NaOH, titrate to a red color
   c. Add 1 mL of Molybdovanadate to the vial and mix
   d. Fill the rest of the vial with deionized water

4. Pour sample created in step 1 into a vial
   a. Add a drop of phenolphthalein
   b. Using 5 N NaOH, titrate to a red color
   c. Add 1 mL of Molybdovanadate to the vial and mix
   d. Fill the rest of the vial with deionized water

5. Turn on the Spectrophotometer on

6. Input 3 minutes into the timer and start

7. Insert the blank vial with the line facing outwards and read

8. Press "Abs" and then "Zero"

9. Insert the sample and then read the result and record

Metals and Anions

Standard Methods 3125

<u>Creating a Program</u>

1. Under "File," select "New…"

2. When dialog box appears, select "Program File"

3. Timebase: Select "CEE11_1" under "my computer"

4. Pump_ECD Options:

   - Gradient Type   Isocratic
   - Pressure Limits   200-3000
   - Flow rate $1.2\mu l/min$

5. Eluent generator Options:

   - Mode   Isocratic
   - Start   38.00
   - CR-   TC   On

6. Sample Preparation Options:

   - Loop Mode
   - Delivery Speed   4ml/min
   - Flush Factor   2
   - Edit   Mode   Basic
   - Volume   From Sequence
   - Bleed   None

7. Acquisition Options:

   - Acquisition Time   0 to 23 minutes
   - Only need to check ECD_1.Acq since we will use the autozero function

8. Options:

   - "Yes" on autozero
   - Cell temperature= 35 degrees Celsius
   - Column temperature (depends on column)= 30 degrees Celsius for the anion column

9. Accept next three screens

10. "Title" and review

11. Save to folder CEE11_1\Programs\

Creating a Shutdown Program

1. Use the Autosampler Program as a base

2. Open in Command View

3. Delete "Acqoff" command at end

4. "Semicolon out" (entering a semicolon before a command line tells the program to ignore that command) the following commands that the shutdown program will not be using

 Deliver Speed

- Delay Volume
- Flush factor
- Sampler Load Position
- Deliver Sample
- End Sample Prep
- Wait
- Inject
- ECD_Acqon

5. Delete "Begin Overlap" at 0.5

6. At 0.5 minute, press F8 (or control-command) to get a list of program commands

7. In the Pump_ECD folder, select the following 3 commands:

- Suppressor_Mode >>> off >>> select "ok"
- CR_TC >>> off >>> select "ok"
- Eluent Generator\Mode >>> off >>> select "ok"

8. At 1.6 minutes, press F8 (or control-command) to get a list of program commands

- Pump_ECD >>> off (in menu)

9. Save to folder CEE11_1\Programs\

Starting Up the IC

1. Start the Hardware first

2. Next, start the computer

3. Then, start the panels

- Check connected
- Pump – start with half flow rate (0.6 ml/min) >> once the PSI has reached a value higher than 1000, increase the pump rate to 1.2 ml/min

- If PSI levels are bouncing, there is probably an air bubble in the system. This can be resolved by turning the valve and selecting "prime"

4. Next, turn on the suppressor (mode = on) after checking that the current is appropriate for the column installed (113 for the anion column)

5. Turn on EG and CR-TC

6. Blue Dot >> Acquire all (optional)

7. Let sit for about 30 minutes to establish a baseline

Creating a Sequence

1. Under "File," select "New…Sequence"

2. When dialog box appears, select "create sequence using wizard"

3. Timebase: Select "CEE11_1" under "my computer"

4. Unknowns >> this screen is where you set up for each sample
- number of vials = number of samples
- start position >> make sure you account for appropriate number of standards/blanks that will precede the samples
- volume of sample = volume of loop being used

5. Standards >> same inputs as unknowns

6. CEE Laboratory Manager typically includes one blank at beginning of sequence – it should be entered as an "unknown" with a start position of 1.

7. Two blanks should be included at the end of each sequence as well. The first should be entered as "unknown," similar to the first blank. The last sample should be entered as a "blank." After the sequence is created, the program for the last sample should be changed to the Shutdown program. This sample will not actually be injected, it is merely a placeholder to allow for the activation of the shutdown program.

8. Methods and Reporting >> using the "browse" function, select the appropriate program, method, and report files (use default and modify later if unknown)

9. Preferred Channel = CEE11_1

10. Sequence Name >> use date that sequence is run in the file name and store in Directory CEE11_1\Sequences

Loading the Auto Sampler

1. Open the Auto sampler lid

2. Press the "Carousel Release" button – this will allow free rotation of the carousel

3. Remove any vials from previous runs

4. Use the vial stand to fill vials with blanks, standards, and samples using the position number identified in the sequence.

5. Vials should be filled to the upper level of the vial stand.

6. Place black cap with pointy end up in vial.

7. Use tool (black rod) to press vial caps down: center on one side; then push down with flat side until vial cap is flush with top of vial.

8. Place vials in appropriate tray locations.

9. Press "Carousel Release" button to lock carousel. Watch to ensure that loading arm is positioned over vial #1.

Running a Sequence

1. Under "New," select "Batch"

2. Select "Start" (perform a "ready check first")

3. Watch to ensure that first position vial is delivered and injected properly.

Viewing Results

- Double-clicking on a sample from the sequence pane will display the results for that sample

- "Peak Calipers" shows the window of expected retention time. When viewing results, right-click on the graph window and select "decoration." The peak caliber tab can be used to select "show peak calipers" and "show all caliper drop lines"

Creating a Method

1. From within a sequence, double-click on any sample to open the method window (Details regarding that sample will appear)

2. On the menu bar, select QNT Editor to manipulate the method

3. Within the QNT Editor, follow the bottom tabs across as indicated below. "General"

- How are results interpreted? – Enter dimension amount (usually PPB

- Mode of Calibration
  - Total – all samples in sequenced that are labeled as "standards" will be used to calibrate
  - Fixed – standards from previous sequences can be utilized

- Blank run and matrix subtraction is available on this tab if needed

"Detection"

1. Minimum area – arbitrary amount (typically has been set to .005)

2. This is the tab where "inhibit integration" can be turned on or off at specified times – which will eliminate the detection of negative peaks or others that the User would like to not include in the reported results, because they are not accurately reflecting constituents or amounts.

"Peak Table"

Autogenerate peak table

- Right-click on line 1
- select "autogenerate peak table"
- pop-up window – click "ok"
- Name peaks by clicking on "default - #" cell
- right-click and select "edit field"
- rename appropriately
- Save before closing window
- Double-click on a standard
- Click "QNT Editor" button
- "Assign Standards on Basis of…" select >Name<
- Select all standards
- Auto generate
- Apply
- ok
- In table, manually type in standard concentrations
- Calibration Type – set to "linear" – the program will automatically force the calibration curve through zero. This can be changed by double-clicking "calibration type" and unchecking "force through zero" in the pop-up window "Amount Table" & "Peak Tracking"
- no changes "Calibration"
- If "ok" appears, then all the peaks were found in the specified time intervals
- If using standards from a previous sequence for calibration
    - o Mode in "general tab" should be set to "fixed"
    - o Right-click on line and select "append standard"
    - o Using "browse" function, select standards of choice
  The last two tabs in QNT editor are not likely to be used

Ammonia

Procedure using the DR/3000 (Refer to DR/3000 Procedure Code N.3 – 34 STORED PROGRAM)

1. Shake sample
2. Filter sample if necessary
    a. Fold #4 filter twice and insert into funnel
    b. Filter sample into beaker or graduated cylinder
3. Dilute sample if necessary
    a. Fill a 25 mL volumetric flask with sample
    b. Transfer to appropriately sized volumetric flask to achieve the correct dilution (ex. 50 mL for 2x dilution, 100 mL for 4x dilution)
    c. Fill to line with DI water
4. Fill a clean sample cell to the 25 mL mark with sample
5. Fill a second cell with 25 mL of E-pure water as blank
6. Add 3 drops of Mineral Stabilizer to each cell. Stopper. Invert several times to mix.
7. Add 3 drops of Polyvinyl Dispersing Agent to each cell- hold the dropping bottle straight vertically. Stopper. Invert several times to mix.
8. Pipette 1 mL of Nessler Reagent into each cell. Stopper. Invert several times to mix.
    a. Note: Nessler reagent is toxic and corrosive. Use a pipet filler when pipetting and pipette carefully.
    b. Note: A yellow color will develop if ammonia is present. The blank will be a fait yellow color.
    c. Note: Complete steps 6-10 within 5 minutes after adding Nessler's Reagent.
9. Press: TIMER-1-TIMER
    a. Note: A one-minute reaction period will begin. The display will indicate 1 minute and then decrease in increments of tenths until zero is reached.
10. To calibrate Spec:
    a. Press: Manual Program, then rotate the wavelength selector dial to a setting of 425 nm.
    b. After the timer beeps, place the blank into the cell holder. The 25 mL mark on the cell should face the front of the instrument for proper orientation. Close the compartment door.

     c. Zero the instrument by pressing Zero abs. Or Zero % T, then display should read 0.000 Abs or 100%T, respectively. If not, press the ZERO key again.

11. Place the prepared sample in the cell holder. Close the sample compartment door. Press Abs. Read the absorbance or %T from the display.

12. Calculate result
     a. Divide absorbance value by calibration number
     b. Multiply by dilution factor if applicable

13. Rinse vial and stopper several times before next sample

14. Pour any waste with the Nessler Reagent into the appropriate toxic waste bottle

Total Organic Carbon

Operation of Shimadzu Analyzer

The TOC Analyzer must be warmed up for approximately 1 hour before analysis.

A. Turn on the TOC-5000A Analyzer. Wait for the word "initializing" to become "initialized"

B. Place autosampler tray in autosampler, lining up the positioning slot in the tray with the positioning pin on the autosampler. Place the turntable cover on top, making sure the arrow on the cover lines up with the arrow on the autosampler. Press ASI Initial (F5). Wait until the autosampler is recognized. The **Initial Start** screen will reappear when instrument is ready.

C. Establish gas flow from the cylinder to the analyzer (carrier gas is "Ultra Zero" grade air). Do this by turning knob on top of cylinder to "Open." Do not use the regulator knob to establish gas flow. Regulator should be set when cylinder is installed and should read between 70-85 psi.

D. Verify the following and adjust if necessary:
    I. Gas cylinder pressure is above 500 psi
    II. Regulator pressure is between 70-85 psi
    III. Rinse water bottle (located behind autosampler) is full and end of tubing is at the bottom of the bottle. If not full, fill with Epure water and re-adjust tubing.
    IV. Open front door of analyzer to check the following:
        a) Carrier gas pressure gage reads between 4 and 5 kgf/cm2.

b) Carrier gas flowmeter reads 150 mL/min

   NOTE: (a) and (b) should always be at these settings. If they are not, check that the cylinder knob is opened properly. Incorrect readings on the pressure gage and flowmeter may indicate blockage in the gas lines.

c) IC reaction vessel is bubbling

   d) Humidifier water level is near top white line. Unscrew black cap and fill with Epure water from a squeeze bottle if necessary.

e) Dehumidifier drain container is full.

E. Choose *Next* from the **Initial Start** screen. This accesses the **Main Menu**. Select *3, General Conditions*. On **General Conditions** screen, scroll down with the arrow keys to "Furnace On/Off" and type *1* followed by the *Enter* key. This turns the oven on. DO NOT CHANGE ANY OTHER SETTINGS ON THIS PAGE.

F. Choose *Main Menu*, and from the **Main Menu** screen choose *6, Monitor*. This screen shows the status of the analyzer. Allow analyzer to warm up for approximately 1 hour.

G. While analyzer is warming up, prepare standards and samples (see below for procedures to prepare standards and samples). Load the standards and samples into the autosampler tray using the autosampler vials (see sections II, III, and IV for preparation of samples and standards).

H. After warm-up time, all status indicators on the **Monitor** screen should read "OK". The baseline, shown on the graph, should be flat. Note that it does not matter if the baseline reads zero, just that it is near zero and flat. Place the tray into the autosampler and the turntable cover on top, making sure to line up positioning pins and arrows.

I. *Return* to the main menu and select *9, Autosampler.* This accesses the **Sample Measurement (ASI)/ Conditions** Screen. Input information regarding standards, samples and analysis conditions as follows:

#Sample group If all samples are to be analyzed under the same conditions, all information is entered under sample group number 1. For multiple sample groups, enter information in more than one group number.

Type <u>Type of analysis</u> Choices are NPOC (non-purgeable organic carbon), TC (total carbon), and IC (inorganic carbon). Most work will use *#4*, *NPOC* to analyze for TOC and DOC. Note that for TOC analysis, use #4, NPOC (not #3, TOC).

IS <u>Initial Sample</u> The vial number of the first sample.
FS <u>Final Sample</u> The vial number of the final sample.

C1-C3 and F1-F3

> C1-C3 specify the <u>generation of calibration curve</u> from standards in the autosampler. F1-F3 specify using a calibration curve that was previously generated and <u>stored in a file</u>. In general, when the analyzer has been shut off and turned back on, a new calibration curve must be created. However, if more than 16 samples (capacity of tray) are to be analyzed, a curve can be initially generated, stored in a file, and used for all samples.

> To specify use of a calibration curve from file, enter the number of the calibration curve under F1.

> To create a new calibration curve, enter the number under which the new curve will be stored under C1 (from 2 to 18). The **Calibration (ASI)/ Conditions** screen will appear. Enter the following information:

TYPE	1 (1=TC for NPOC; 2=IC for IC)
1st STD CONC, VIAL # etc.	Enter the conc. in ppm and vial # for each standard. Standards must be in conc. order with the highest conc. standard first
RANGE	Automatically set based on standard conc's
INJ VOL	Automatically set based on standard conc's
NO OF INJECTS	3 (The # of injections for repetitive measurement of each standard)
MAX NO OF INJ	5 (The maximum # of injections for each standard)
SD	200 (default value for allowable standard deviation between repetitive measures)
CV	2.0% (default value for coefficient of variation between repetitive measures)
SPARGE TIME	3 min (for NPOC analysis)
SHIFT TO ORIGIN	2 (Off)
ACID ADDITION	2 (Off: standards/samples are pre-acidified)

Choose *Return*.

Choose *Next*. The **ASI Conditions** screen is accessed. These conditions control operation of the autosampler. Enter information as shown in the table below.

	Typical Value	Comments
RINSE	1	Always choose 1=Rinse (prevents cross-contamination)
NO OF NEEDLE WASHES	1 or 2	Prevents build up of salt. Higher number for samples w/ more particulates & salts
FLOW LINE WASHES	3	Prevents clogging. Choose 3 if samples are pre-acidified
CALIBRATION BEFORE	2	Analyzes each sample group separately
PRINT INFORMATION	2	Prints data report for samples
AUTO ADDITION OF ACID	2	2=Off (samples are pre-acidified)
ACID VOLUME	0	Not used
RINSE AFTER ADDITION	2	Not used
KEY LOCK	2	2=Unlock (retain keypad control during analysis)
FINISH OR RUNNING	1	Choose 1=Finish to shut off analyzer after analysis or 3=No Change to leave oven on after analysis

Select *Next*.

As instructed on the screen, press the START button. Wait while the needles move into the first standard or sample to ensure proper needle position. After sparging has begun, verify the sparge gas flowmeter reads approximately 100 mL/min. If not, open front door of analyzer and adjust the flowrate. Note that the sparge gas flowrate takes some time to stabilize and may need to be adjusted again (re-check in 20 to 30 min).

J. Shutting down the Shimadzu Analyzer

(i) If "Finish" was chosen on the **ASI Conditions** screen, the analyzer will shut off the oven after the last sample is run. A countdown will appear on the screen. When the countdown is complete you can turn off the analyzer.

(ii) If "No change" was chosen on the **ASI Conditions** screen, analyzer must be used again or may be shut down manually. To shut down, choose 7, *Standby Options* from the **Main Menu** screen. Choose 1=FINISH and press [Standby] to initiate. Follow procedure in (i).

II. PREPARATION OF STANDARDS FOR CALIBRATION CURVE

A. Stock Primary Standard

(1) Dry about 0.75 gm of Potassium Hydrogen Phthalate in oven at 103-110 degrees Celsius for 30 min. Cool in desiccator for 20-30 min.
(2) Weigh exactly 0.5314 gm using analytical balance. Add to a 250 mL volumetric flask and fill to mark with Epure water.
(3) Result in stock primary standard (1000 mg/L).
(4) Store in brown glass bottle. Label with your name, the date and "1000 mg/L KHP standard."
(5) Store in refrigerator, discard after 2-3 weeks.

B. Intermediate Standard

(1) Prepare on the day TOC/DOC samples will be analyzed.
(2) Make a volumetric dilution of the Stock Primary Standard. Pour about 15 mL of the Stock Primary Standard into a beaker. Transfer 10 mL of the stock primary standard with

a volumetric pipette to a 100 mL volumetric flask half filled with Epure water. Fill to mark with Epure.

(3) Intermediate stock concentration is 100 mg/L TOC. Store in refrigerator. Discard after 2 days.

C. Working Standards

(1) Prepare 3 working standards that bracket the sample concentrations. For example, for low level TOC and DOC analysis, a typical calibration curve consists of a 5, 2, and 0 ppm standard.

(2) Use three 100 mL volumetric flasks. Fill each halfway with Epure water. Add 100 µl of 6N HCl to each flask (addition for NPOC analysis).

(3) Add appropriate volume of intermediate stock to each flask (number of mL of intermediate stock= concentration in mg/L of working stock). Fill to mark with Epure water. An example for low level TOC and DOC analysis as shown below.

Working Std. (mg/L)	Volume added (mL)
5	5 mL of intermediate stock
2	2 mL of intermediate stock
0	0

III. SAMPLE COLLECTION AND PREPARATION

A. TOC Samples
   a. Collect sample. Preserve with 100 µl of 6N HCl per 100 mL of sample. Sample should be below pH of 2 after acid addition.
   b. If sample is collected in the field, transport to lab cold.
   c. Store sample in refrigerator at 4 degrees Celsius until sample is analyzed Shimadzu analyzer. Analyze within 1 week.

B. DOC Samples
   a. Collect sample.
   b. If sample is collected in the field, transport to lab cold.

c. Filter sample through a Whatman GF/C glass fiber filter that has been pre-washed with 30 mL of Epure water.

d. Preserve with 100 μl of 6 N HCl per 100 mL of sample. Sample should be below pH 2 after acid addition.

e. Store sample in refrigerator at 4 degrees Celsius until sample is analyzed with Shimadzu analyzer. Analyze within 1 week.

Appendix B: GIS Maps

Project Map

Project Area
Fisherville Mill Site
Grafton, MA

Living Systems Laboratory MQP
Advisors: Paul Mathisen, Derren Rosbach
Evan Pereira, Nathan Meersman, Sierra
Fraioli

Legend

— LSL

● Intake Point

— Island

Scale: 1:250

Wetlands

Wetlands
Fisherville Mill Site
Grafton, MA

Living Systems Laboratory MQP
Advisors: Paul Mathisen, Derren Rosbach
Evan Pereira, Nathan Meersman, Sierra
Fraioli

Scale: 1:500

Legend

— LSL

▨ Wetlands

Topography

Topography Map
Fisherville Mill Site
Grafton, MA

Living Systems Laboratory MQP
Advisors: Paul Mathisen, Derren Rosbach
Evan Pereira, Nathan Meersman, Sierra
Fraioli
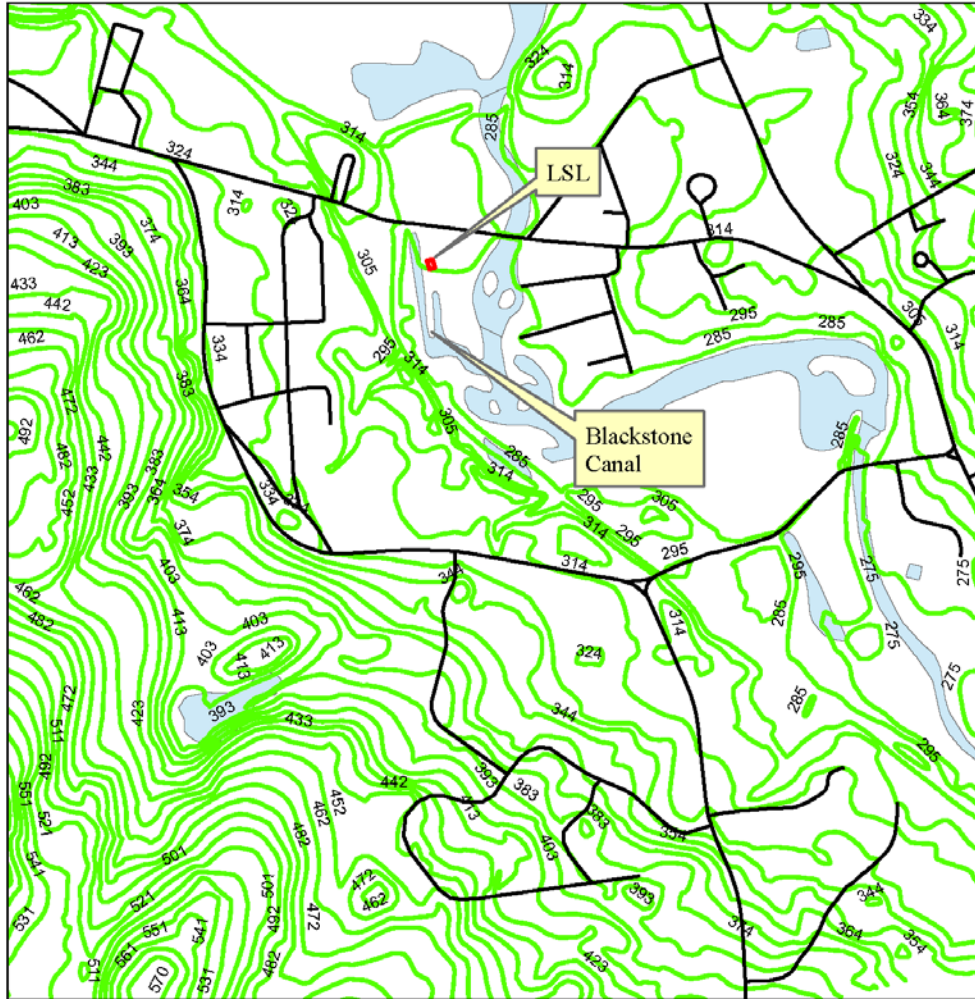
Scale: 1:833

Legend

— LSL

— Contours

— Roads

Stormwater Infrastructure
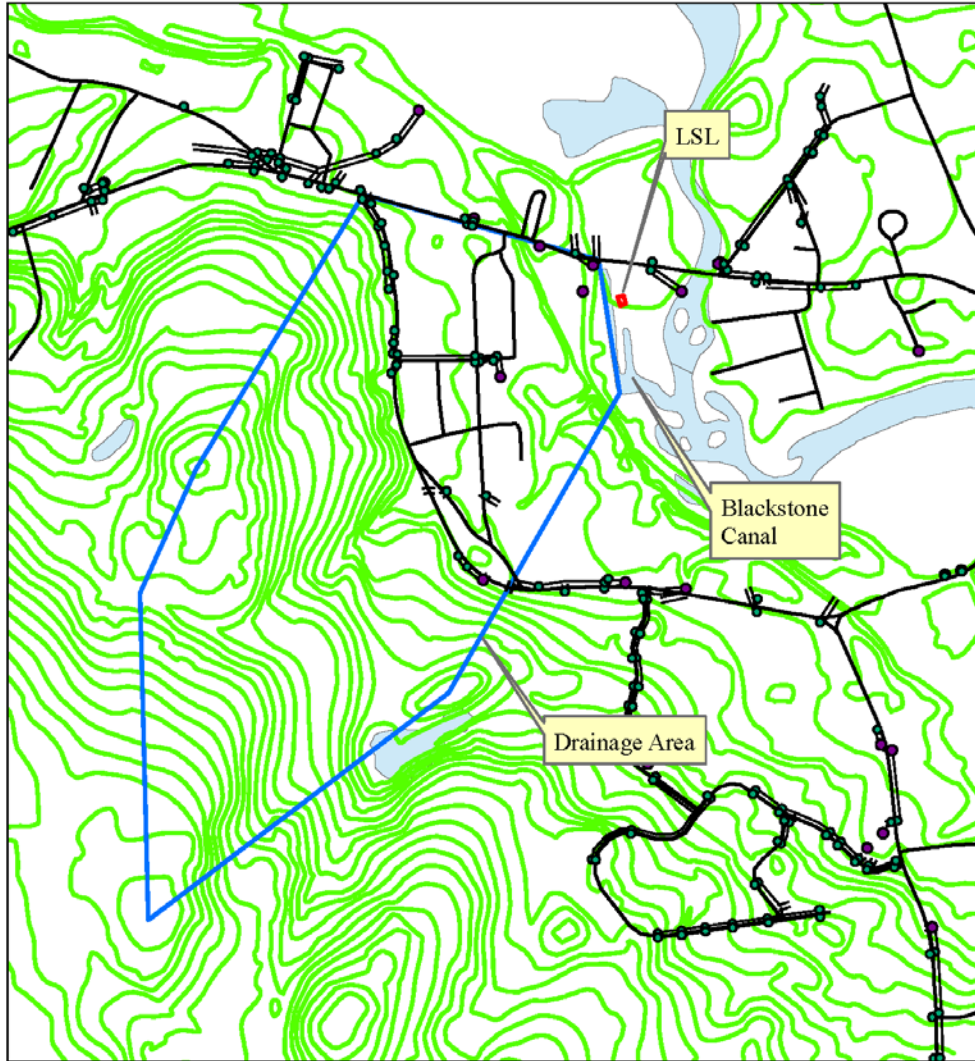
Legend

- LSL
- Catch Basin
- Outfall
- Stormwater Pipe
- Drainage Area

Storm Water Map
Fisherville Mill Site
Grafton, MA

Living Systems Laboratory MQP
Advisors: Paul Mathisen, Derren Rosbach
Evan Pereira, Nathan Meersman, Sierra Fraioli

Scale: 1:833

LSL

Blackstone Canal

Drainage Area

N

Drainage Areas

Northern Lot
Area: 9 acres
CN value: 95

Drainage Area
Area: 143 acres
CN value: 65.4
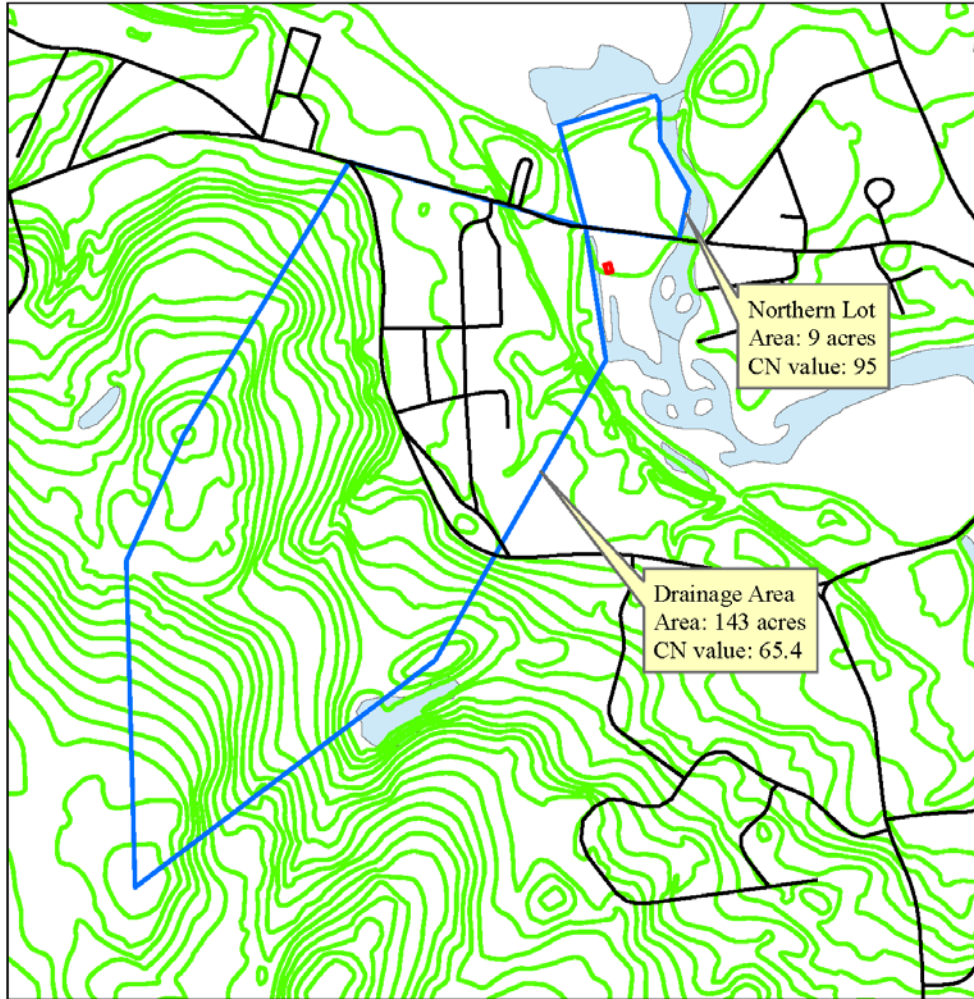
Drainage Areas
Fisherville Mill Site
Grafton, MA
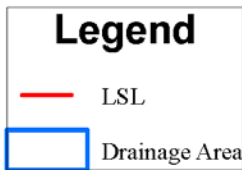
Living Systems Laboratory MQP
Advisors: Paul Mathisen, Derren Rosbach
Evan Pereira, Nathan Meersman, Sierra
Fraioli

Scale: 1:833

Legend

LSL

Drainage Area

N

Land Use

Legend

—	LSL
	<all other values>

Land Use

	Commercial
	Forest
	Forested Wetland
	Low Density Residential
	Medium Density Residential
	Multi-Family Residential
	Open Land
	Participation Recreation
	Transportation
	Urban Public/Institutional
	Water
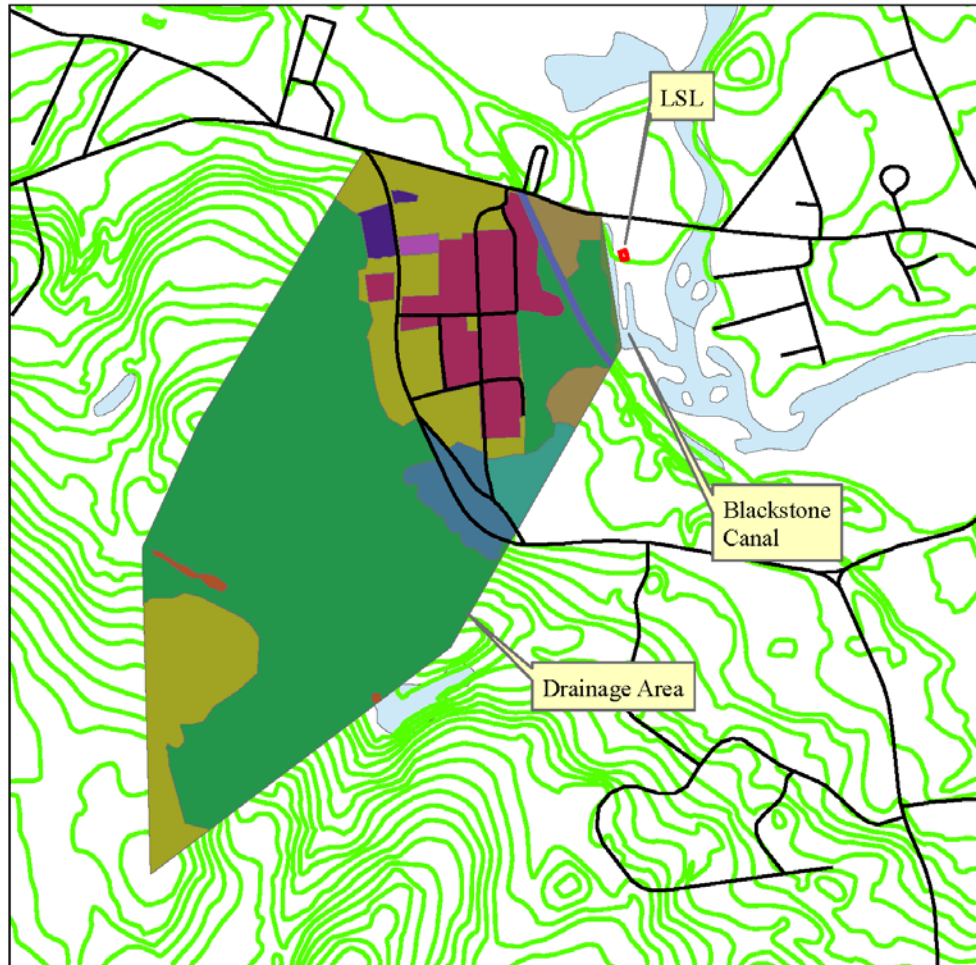
Land Use of Drainage Area
Fisherville Mill Site
Grafton, MA

Living Systems Laboratory MQP
Advisors: Paul Mathisen, Derren Rosbach
Evan Pereira, Nathan Meersman, Sierra
Fraioli

Scale: 1:833

N
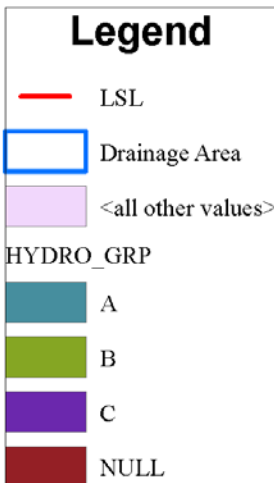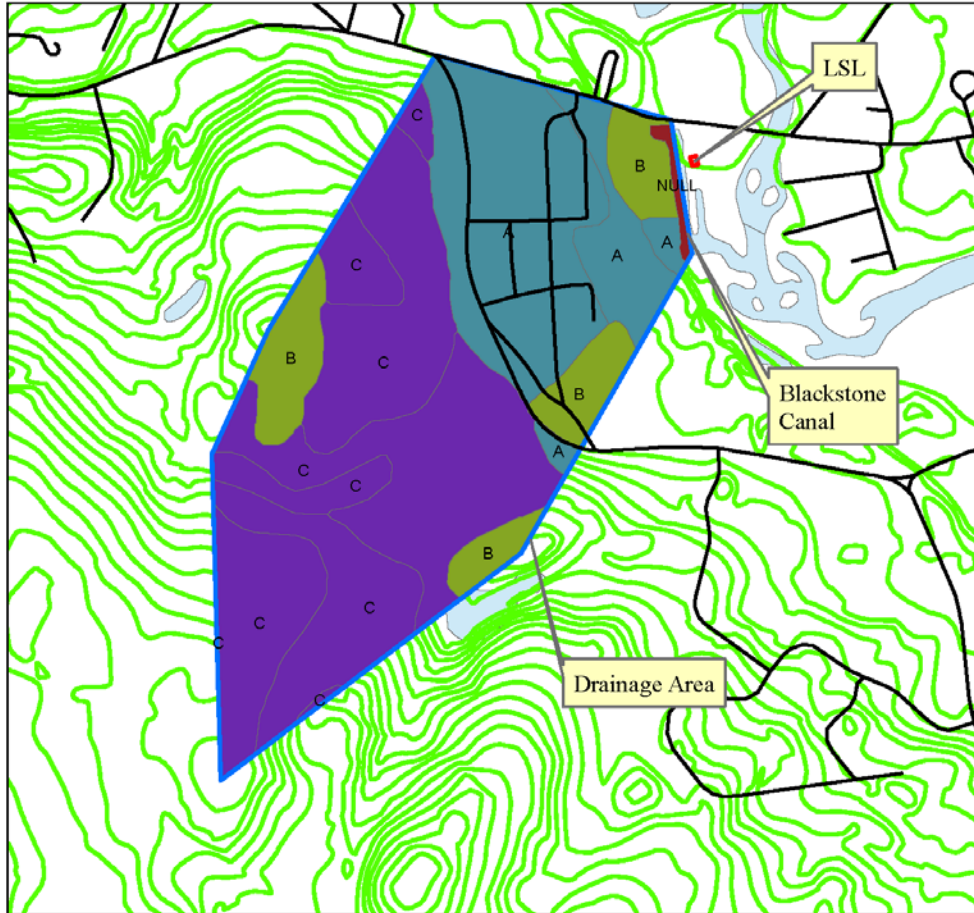
Soil Composition

Soil Composition of Drainage Area
Fisherville Mill Site
Grafton, MA

Living Systems Laboratory MQP
Advisors: Paul Mathisen, Derren Rosbach
Evan Pereira, Nathan Meersman, Sierra Fraioli

Scale: 1:833

Land Use-Soil Merged

Land Use and Hydrological Group
Fisherville Mill Site
Grafton, MA

Living Systems Laboratory MQP
Advisors: Paul Mathisen, Derren Rosbach
Evan Pereira, Nathan Meersman, Sierra Fraioli

Scale: 1:833
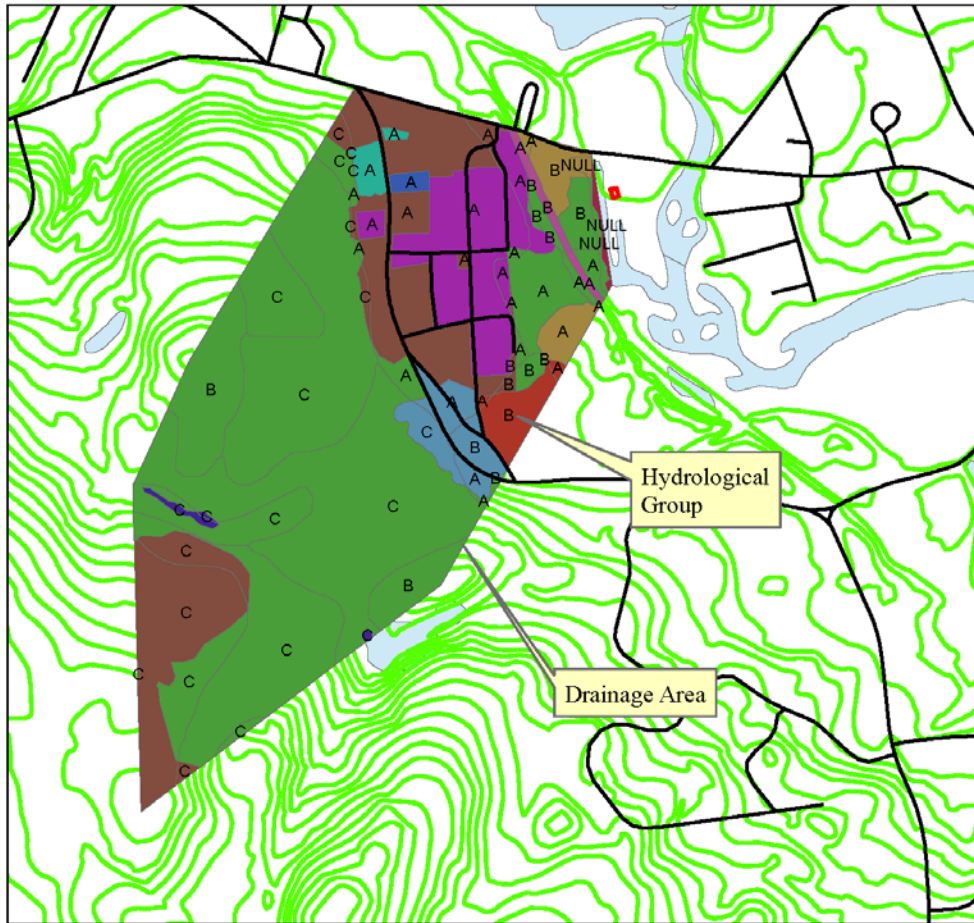
Legend

LSL	
<all other values>	
LU05_DESC	
	Commercial
	Forest
	Forested Wetland
	Low Density Residential
	Medium Density Residential
	Multi-Family Residential
	Open Land
	Participation Recreation
	Transportation
	Urban Public/Institutional
	Water

Appendix C: Flowrate Calculations

System Influent Time Table

Test	Volume (L)	Time (s)
1	2	6.6
2	2	6.55
3	2	6.65
4	2	6.62
AVG:		6.61

System Influent Flowrate

$$\frac{2\,L}{6.61\,s} = 0.30\,L/s$$

$$0.30\frac{L}{s} * \left(0.264\frac{gal}{L}\right) = 0.08\,gal/s$$

$$0.08\frac{gal}{s} * \left(\frac{1\,ft^3}{7.48\,gal}\right) = \mathbf{0.011\,cfs}$$

Myco-Reactor Influent Time Table

Myco-Reactor Influent	seconds	liters
1	2.8	1
2	2.7	1
3	2.9	1
4	2.85	1
5	2.4	1
avg:	2.73	

Myco-Reactor Influent Flowrate

$$\frac{1\,L}{2.73\,s} = 0.37\,L/s$$

$$0.37\frac{L}{s} * \left(0.264\frac{gal}{L}\right) = 0.10\,gal/s$$

$$0.10\frac{gal}{s} * \left(\frac{1\,ft^3}{7.48\,gal}\right) = \mathbf{0.013\,cfs}$$

System Effluent Time Table

New Effluent	seconds	liters
1	3.88	1
2	4	1
3	3.65	1
4	4.09	1
5	3.72	1
avg:	3.868	

System Effluent Flowrate

$$\frac{1\,L}{3.868\,s} = 0.26\,L/s$$

$$0.26\frac{L}{s} * \left(0.264\frac{gal}{L}\right) = 0.07\,gal/s$$

$$0.07\frac{gal}{s} * \left(\frac{1\,ft^3}{7.48\,gal}\right) = \mathbf{0.009\,cfs}$$

Canal Effluent Flowrate

$$q = 3.33\,(b - 0.2h)h^{\frac{3}{2}}$$
$$q = 3.33\,\left(7.9\,ft - (0.2 * 0.042\,ft)\right) * (0.042\,ft)^{\frac{3}{2}}$$

$$q = 0.046\,cfs$$

Appendix D: GIS Attribute Tables

Soil Attribute Table

FID	Shape *	MUSYM	CODE	SS_AREA	STATELEG	SLOPE	SS_CODE	MUSYM_AREA	MUKEY	MAPUNITNAM	HYDRO_GRP	AREA
0	Polygon	2459	2538	WORS	2459	B	2538_WORS	2459_WORS	278040	Hinckley sandy loam, 3 to 8 percent slopes	A	225570.195765
1	Polygon	307C	307C	WORS	307C	C	307C_WORS	307C_WORS	278073	Paxton fine sandy loam, 8 to 15 percent slopes, extremely stony	C	125889.258075
2	Polygon	3059	3059	WORS	3059	B	3059_WORS	3059_WORS	278089	Paxton fine sandy loam, 3 to 8 percent slopes	C	94504.811096
3	Polygon	245C	253C	WORS	245C	C	253C_WORS	245C_WORS	278041	Hinckley sandy loam, 8 to 15 percent slopes	A	69391.609847
4	Polygon	254A	254A	WORS	254A	A	254A_WORS	254A_WORS	278043	Merrimac fine sandy loam, 0 to 3 percent slopes	A	171691.424309
5	Polygon	651	651	WORS	651	D	651_WORS	651_WORS	278143	Udorthents, smoothed	B	60832.362206
6	Polygon	102C	102C	WORS	102C	C	102C_WORS	102C_WORS	277897	Canfield-Hollis-Sevil outcrop complex, 3 to 15 percent slopes	B	45309.612681
7	Polygon	307B	307B	WORS	307B	B	307B_WORS	307B_WORS	278072	Paxton fine sandy loam, 3 to 8 percent slopes, extremely stony	C	24112.813265
8	Polygon	651	651	WORS	651	D	651_WORS	651_WORS	278143	Udorthents, smoothed	B	41613.462855
9	Polygon	307B	307B	WORS	307B	B	307B_WORS	307B_WORS	278072	Paxton fine sandy loam, 3 to 8 percent slopes, extremely stony	C	126165.146357
10	Polygon	422C	422C	WORS	422C	C	422C_WORS	422C_WORS	278116	Canton fine sandy loam, 8 to 15 percent slopes, extremely stony	B	252915.786946
11	Polygon	1	w	WORS	1	D	w_WORS	1_WORS	278094	Water	NULL	219567.06587
12	Polygon	307E	307D	WORS	307E	E	307D_WORS	307E_WORS	278074	Paxton fine sandy loam, 15 to 35 percent slopes, extremely stony	C	83118.853079
13	Polygon	71A	71A	WORS	71A	A	71A_WORS	71A_WORS	278159	Ridgebury fine sandy loam, 0 to 3 percent slopes, extremely stony	C	49405.653369
14	Polygon	310B	310B	WORS	310B	B	310B_WORS	310B_WORS	278076	Woodbridge fine sandy loam, 3 to 8 percent slopes	C	56072.695901

Land Use and Soil Attribute Table

FID	Shape *	FID_Draina	Soil_Type	Area	HYDRO_GRP	LandUse_DESC
0	Polygon	0	Hinckley sandy loam, 3 to 8 percent slopes	29426	A	Low Density Residential
1	Polygon	0	Hinckley sandy loam, 3 to 8 percent slopes	13895	A	Forest
2	Polygon	0	Hinckley sandy loam, 3 to 8 percent slopes	13606	A	Transportation
3	Polygon	0	Hinckley sandy loam, 3 to 8 percent slopes	171	A	Open Land
4	Polygon	0	Hinckley sandy loam, 3 to 8 percent slopes	22830	A	Forest
5	Polygon	0	Hinckley sandy loam, 3 to 8 percent slopes	7250	A	Forest
6	Polygon	1	Paxton fine sandy loam, 8 to 15 percent slopes, extremely stony	93666	C	Medium Density Residential
7	Polygon	1	Paxton fine sandy loam, 8 to 15 percent slopes, extremely stony	537504	C	Forest
8	Polygon	2	Paxton fine sandy loam, 3 to 8 percent slopes	436371	C	Medium Density Residential
9	Polygon	2	Paxton fine sandy loam, 3 to 8 percent slopes	128086	C	Forest
10	Polygon	3	Hinckley sandy loam, 8 to 15 percent slopes	151914	A	Forest
11	Polygon	3	Hinckley sandy loam, 8 to 15 percent slopes	6354	A	Open Land
12	Polygon	3	Hinckley sandy loam, 8 to 15 percent slopes	81144	A	Multi-Family Residential
13	Polygon	3	Hinckley sandy loam, 8 to 15 percent slopes	8919	A	Transportation
14	Polygon	3	Hinckley sandy loam, 8 to 15 percent slopes	73473	A	Open Land
15	Polygon	3	Hinckley sandy loam, 8 to 15 percent slopes	6895	A	Participation Recreation
16	Polygon	3	Hinckley sandy loam, 8 to 15 percent slopes	22626	A	Medium Density Residential
17	Polygon	4	Merrimac fine sandy loam, 0 to 3 percent slopes	73003	A	Low Density Residential
18	Polygon	4	Merrimac fine sandy loam, 0 to 3 percent slopes	7268	A	Medium Density Residential
19	Polygon	4	Merrimac fine sandy loam, 0 to 3 percent slopes	12889	A	Forest
20	Polygon	4	Merrimac fine sandy loam, 0 to 3 percent slopes	24216	A	Urban Public/Institutional
21	Polygon	4	Merrimac fine sandy loam, 0 to 3 percent slopes	500186	A	Multi-Family Residential
22	Polygon	4	Merrimac fine sandy loam, 0 to 3 percent slopes	23951	A	Multi-Family Residential
23	Polygon	4	Merrimac fine sandy loam, 0 to 3 percent slopes	4156	A	Participation Recreation
24	Polygon	4	Merrimac fine sandy loam, 0 to 3 percent slopes	49212	A	Commercial
25	Polygon	4	Merrimac fine sandy loam, 0 to 3 percent slopes	8279	A	Commercial
26	Polygon	4	Merrimac fine sandy loam, 0 to 3 percent slopes	662381	A	Medium Density Residential
27	Polygon	4	Merrimac fine sandy loam, 0 to 3 percent slopes	46527	A	Forest
28	Polygon	5	Udorthents, smoothed	21731	B	Forest
29	Polygon	5	Udorthents, smoothed	79725	B	Open Land
30	Polygon	5	Udorthents, smoothed	2235	B	Multi-Family Residential
31	Polygon	5	Udorthents, smoothed	24	B	Water
32	Polygon	5	Udorthents, smoothed	23201	B	Transportation
33	Polygon	5	Udorthents, smoothed	62332	B	Forest
34	Polygon	6	Chatfield-Hollis-Rock outcrop complex, 3 to 15 percent slopes	277747	B	Forest
35	Polygon	7	Paxton fine sandy loam, 3 to 8 percent slopes, extremely stony	1127	C	Commercial
36	Polygon	7	Paxton fine sandy loam, 3 to 8 percent slopes, extremely stony	17610	C	Medium Density Residential
37	Polygon	7	Paxton fine sandy loam, 3 to 8 percent slopes, extremely stony	218596	C	Forest
38	Polygon	8	Udorthents, smoothed	58636	B	Low Density Residential
39	Polygon	8	Udorthents, smoothed	24430	B	Forest
40	Polygon	8	Udorthents, smoothed	37	B	Multi-Family Residential
41	Polygon	8	Udorthents, smoothed	243	B	Open Land
42	Polygon	8	Udorthents, smoothed	114533	B	Participation Recreation
43	Polygon	8	Udorthents, smoothed	8495	B	Medium Density Residential
44	Polygon	8	Udorthents, smoothed	1	B	Forest
45	Polygon	9	Paxton fine sandy loam, 3 to 8 percent slopes, extremely stony	66847	C	Low Density Residential
46	Polygon	9	Paxton fine sandy loam, 3 to 8 percent slopes, extremely stony	2348	C	Forested Wetland
47	Polygon	9	Paxton fine sandy loam, 3 to 8 percent slopes, extremely stony	2569	C	Forested Wetland
48	Polygon	9	Paxton fine sandy loam, 3 to 8 percent slopes, extremely stony	1077516	C	Forest
49	Polygon	10	Canton fine sandy loam, 8 to 15 percent slopes, extremely stony	117432	B	Forest
50	Polygon	11	Water	10685	NULL	Open Land
51	Polygon	11	Water	17674	NULL	Water
52	Polygon	11	Water	15402	NULL	Forest
53	Polygon	12	Paxton fine sandy loam, 15 to 35 percent slopes, extremely stony	15597	C	Medium Density Residential
54	Polygon	12	Paxton fine sandy loam, 15 to 35 percent slopes, extremely stony	837662	C	Forest
55	Polygon	13	Ridgebury fine sandy loam, 0 to 3 percent slopes, extremely stony	16589	C	Forested Wetland
56	Polygon	13	Ridgebury fine sandy loam, 0 to 3 percent slopes, extremely stony	156097	C	Forest
57	Polygon	14	Woodbridge fine sandy loam, 3 to 8 percent slopes	1323	C	Medium Density Residential
58	Polygon	14	Woodbridge fine sandy loam, 3 to 8 percent slopes	12545	C	Forest

Appendix E: Weighted CN Pivot Table

PIVOT TABLE

Sum of Shape_Area	Column Labels				Total area		Curve Number Estimates				CN_i* A_i	CN Numbers for Individual areas
Row Labels	A	B	C	(blank)	Grand Total		A	B	C	D		
Commercial	57491		1127		58618		89	92	94	95	5222637	89.09613088
Forest	255305	503673	2968006		3726984		25	55	70	77	241845060	64.89028662
Forested Wetland			21506		21506		25	55	70	77	1505420	70
Low Density Residential	102429	58636	66847		227912		54	70	80	85	14983446	65.74224262
Medium Density Residential	692275	8495	564567		1265337		57	72	81	86	85801242	67.80900424
Multi-Family Residential	605281	2272			607553		61	75	81	86	37092541	61.05235428
Open Land	79998	79968			159966		49	69	79	84	9437694	58.9981246
Transportation	22525	23201			45726		95	95	95	95	4343970	95
Urban Public/Institutional	24216				24216		89	92	94	95	2155224	89
(blank)							80	80	80	80	0	#DIV/0!
Participation Recreation		11051	114533		125584		39	61	74	80	7417502	59.06406867
Grand Total	1850571	790778	3622053		6263402							

				area (ft^2)	6263402						Sum(CN_i * A_i)	Weighted CN
				area(ac)	1547.7203						409804736	65.42845821
			area (acres)		143.78266							
				Area of Northern lot (ac):	9						Sum Northern Lot	Weighted CN
				Ft^2	392054.3649					N. Lot:	37245164.66	95
										CN= 95		

Appendix F: NRCS Calculations

Drainage Area:

Area: 6,263,402 sq. ft.

CN Value: 65

1-Year Storm:

P: 2.65in/24 hr.

$$S = \frac{1000}{CN} - 10$$

$$S = \frac{1000}{65} - 10 = \mathbf{5.2905}$$

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)}$$

$$Q = \frac{(2.65 - 0.2 * 5.2905)^2}{(2.65 + 0.8 * 5.2905)} = \mathbf{0.3682} \frac{\boldsymbol{in}}{\mathbf{24\ hr}}$$

$$V = \frac{Q}{12\ in} * A$$

$$V = \left(\frac{0.3682}{12}\right) * 6{,}263{,}402 = \mathbf{192{,}184} \frac{\mathbf{cubic\ ft}}{\mathbf{24\ hrs}}$$

$$Average\ Runoff\ Flow = \left(\frac{V}{24}\right) * \left(\frac{1}{60}\right) * \left(\frac{1}{60}\right)$$

$$Average\ Runoff\ Flow = \left(\frac{192{,}184}{24}\right) * \left(\frac{1}{60}\right) * \left(\frac{1}{60}\right) = \mathbf{2.22\ cfs}$$

2-Year Storm:

P: 3.24 in/24 hr.

$$S = \frac{1000}{65} - 10 = \mathbf{5.2905}$$

$$Q = \frac{(3.24 - 0.2 * 5.2905)^2}{(3.24 + 0.8 * 5.2905)} = \mathbf{0.6371}\ \frac{in}{24\ hr}$$

$$V = \left(\frac{0.6371}{12}\right) * 6{,}263{,}402 = \mathbf{332{,}534}\ \frac{\text{cubic ft}}{24\ hrs}$$

$$Average\ Runoff\ Flow = \left(\frac{332{,}534}{24}\right) * \left(\frac{1}{60}\right) * \left(\frac{1}{60}\right) = \mathbf{3.85\ cfs}$$

Average Storm (2016):

P: 0.5 in/24 hr.

$$S = \frac{1000}{65} - 10 = 5.2905$$

$$Q = \frac{(0.5 - 0.2 * 5.2905)^2}{(0.5 + 0.8 * 5.2905)} = \mathbf{0.0658}\ \frac{in}{24\ hr}$$

$$V = \left(\frac{0.0658}{12}\right) * 6{,}263{,}402 = \mathbf{34{,}353}\ \frac{\text{cubic ft}}{24\ hrs}$$

$$Average\ Runoff\ Flow = \left(\frac{34{,}353}{24}\right) * \left(\frac{1}{60}\right) * \left(\frac{1}{60}\right) = \mathbf{0.4\ cfs}$$

Northern Lot:

Area: 392,054 sq. ft.

CN Value: 95

1-Year Storm:

P: 2.65 in/24 hr.

$$S = \frac{1000}{95} - 10 = \mathbf{0.5263}$$

$$Q = \frac{(2.65 - 0.2 * 0.5263)^2}{(2.65 + 0.8 * 0.5263)} = \mathbf{2.1086} \; \frac{\boldsymbol{in}}{\mathbf{24} \; \boldsymbol{hr}}$$

$$V = \left(\frac{2.1086}{12}\right) * 392{,}054 = \mathbf{68{,}891} \; \frac{\textbf{cubic ft}}{\mathbf{24} \; \textbf{hrs}}$$

$$Average \; Runoff \; Flow = \left(\frac{68{,}891}{24}\right) * \left(\frac{1}{60}\right) * \left(\frac{1}{60}\right) = \mathbf{0.8} \; \boldsymbol{cfs}$$

2-Year Storm:

P: 3.24 in/24 hr.

$$S = \frac{1000}{95} - 10 = \mathbf{0.5263}$$

$$Q = \frac{(3.24 - 0.2 * 0.5263)^2}{(3.24 + 0.8 * 0.5263)} = \mathbf{2.6841} \; \frac{\boldsymbol{in}}{\mathbf{24} \; \boldsymbol{hr}}$$

$$V = \left(\frac{2.6841}{12}\right) * 392{,}054 = \mathbf{87{,}692} \; \frac{\textbf{cubic ft}}{\mathbf{24} \; \textbf{hrs}}$$

$$Average \; Runoff \; Flow = \left(\frac{87{,}692}{24}\right) * \left(\frac{1}{60}\right) * \left(\frac{1}{60}\right) = \mathbf{1.01} \; \boldsymbol{cfs}$$

Average Storm (2016):

P: 0.5 in/24 hr.

$$S = \frac{1000}{95} - 10 = \mathbf{0.5263}$$

$$Q = \frac{(0.5 - 0.2 * 0.5263)^2}{(0.5 + 0.8 * 0.5263)} = \mathbf{0.1691} \frac{\boldsymbol{in}}{\mathbf{24\ hr}}$$

$$V = \left(\frac{0.1691}{12}\right) * 392{,}054 = \mathbf{5{,}527} \frac{\textbf{cubic ft}}{\mathbf{24\ hrs}}$$

$$Average\ Runoff\ Flow = \left(\frac{5{,}527}{24}\right) * \left(\frac{1}{60}\right) * \left(\frac{1}{60}\right) = \mathbf{0.064\ cfs}$$

Appendix G: Breakpoint Analysis Experimentation

To determine the capacity of the system via hydraulics and system efficiency, two different experiments should be conducted to retrieve a relationship between the two. Also, a temporary bypass of the myco-reactor filtration stage would aid in determining whether or not this part of the LSL process could be skipped during a high storm event to allow for more stormwater to be taken in. This will directly pertain to increased system capacity, since it will determine if hydraulic capacity matches treatment efficiency, and what gap needs to be closed to match the two. Also, if a bypass situation were to work, it would allow for an increased volume of stormwater to be taken in. A quantitative method for obtaining these results was needed, thus methods for doing so were prepared for further testing and laboratory investigation. It was decided that there was a need to conclude whether or not an influx of influent water during a high storm event would still be effectively treated if the myco-reactor filtration stage of the system were temporarily bypassed, yielding results as to how much inflow the stage can handle while maintaining proper treatment. Also, we needed to quantitatively determine at what point the system would fail to treat influent water effectively. These results would allow us to determine the maximum volume of water the system could handle at once, and if bypassing the myco-reactor filtration stage during a high storm event to treat more water was feasible and/or necessary.

Myco-Reactor Filtration Bypass Experiment Procedure

To prepare an accurate environment to get results on effective Myco-filter treatment, we first closed the manifolds to the fungal bypass and experimental growth basins to stop the flow to those areas. Then the manifold to the bypass pipeline was opened. Once the path for the influent water was set, the system was turned on and allowed to run for one complete cycle of two hours. After this time period, water samples were taken at the midpoint of the system (immediately following the Myco-filter bypass), and at the system effluent point in 250 mL test bottles. The samples were taken back to the lab to test for the constituents deemed most important. The results of the experiment were then compared to the results of the system at normal conditions to draw a conclusion on the feasibility of the system's ability to temporarily bypass the Myco-filters to treat more water faster during a high storm event.

Hydraulic Capacity vs. Treatment Efficiency Experiment Procedure

The system needed to first be set to proper conditions to yield the desired results. The system was turned from automatic timer to manual mode. This was done to maintain control of how long water was being processed into the system. Before the experiment was completed, a probe was used to determine the amount of water that is filtered into the system per regular two-hour period. This would allow for the calculation of volume of water being processed during the experiment in the comparison and conclusion stages. Initial samples were taken at the system intake point, midpoint of the system, and effluent of the system for later comparison after experimentation at the same conditions. The system was allowed to operate for three hours, extending the automatic run period by one hour. After the three-hour period, the system was turned off entirely, and samples were again taken at the system intake point, midpoint of the system, and effluent of the system. All six samples were then taken back to the lab and tested for the same constraints as the fungal basin bypass experiment. The results of the samples taken before experimentation were compared to the results taken after the three-hour period. The experiments were then compared to data taken during normal system proceeding, and conclusions were drawn about the point at which the system stopped treating the water as efficiently as before.

Appendix H: Design Calculations

Cycle Time Calculations

Assumptions:

*System Effluent Flowrate ($0.009\frac{ft^3}{s}$) is best representation of flow leaving the LSL.

*4 cycles per day

$$T_{cycle} = \frac{\left(\left(92.3\frac{ft^3}{day}\right)/\left(4\frac{cycles}{day}\right)\right)}{(0.009\frac{ft^3}{s} * 60\frac{s}{min})} = 42.7 \min \approx 43 \, min$$

Required Flowrate Increase for System Intake

Assumptions:

*43 minutes per cycle

$$320{,}000\frac{ft^3}{yr} * \frac{1 \, yr}{365 \, day} = 876.7\frac{ft^3}{day} \; (for \; Water \; Quality \; Volume) \; vs. \, 92.3\frac{ft^3}{day}$$

$$876.7\frac{ft^3}{day} * \frac{1 \, day}{4 \, cycles} = 219.175 \, ft^3/cycle$$

$$Q = \frac{V}{T} = \frac{219.175\frac{ft^3}{cycle}}{43\frac{min}{cycle}} = 5.097 \, ft^3/min$$

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$$\left(5.097\,\frac{ft^3}{\text{min}}\right) * \left(\frac{1\,min}{60\,s}\right) = 0.085\,\frac{ft^3}{s}\,(for\,Water\,Quality\,Volume)\,vs.\,0.009\,ft^3/s$$

Jet Pump Capacity

$$\left(13.2\,\frac{gal}{\text{min}}\right) * \left(\frac{1\,ft^3}{7.48\,min}\right) * \left(\frac{1\,min}{60\,s}\right) = 0.03\,ft^3/s$$

Q (New System Influent) (cfs)	Volume (Cubic ft./cycle)	Time of Cycle (sec)	Time of Cycle (min)
0.01	219.2	21917.5	365.3
0.02	219.2	10958.8	182.6
0.03	219.2	7305.8	121.8
0.04	219.2	5479.4	91.3
0.05	219.2	4383.5	73.1
0.06	219.2	3652.9	60.9
0.07	219.2	3131.1	52.2
0.08	219.2	2739.7	45.7
0.09	219.2	2435.3	40.6
0.1	219.2	2191.8	36.5

Assumptions:

*219.2 $ft^3/cycle$ is the required water quality volume to properly treat enough stormwater.

*The time of cycle was calculated by the equation

$$T_{cycle} = \frac{V(Water\ Quality\ Volume)}{Q(New\ System\ Influent)}$$

Myco-Reactor Increase

Current Conditions

Q (cfs)	Total area	Area per bed (sq.ft)	SLR ((cfs)/(sqft))	# of Beds
0.013	36.96	4.63	0.000352	8

Predicted Behavior

Q (cfs)	SLR ((cfs)/(sqft))	Total area	Area per bed (sq.ft)	# of beds req'd
0.013	0.000352	36.96	4.63	7.98
0.02	0.000352	56.86	4.63	12.28
0.03	0.000352	85.29	4.63	18.42
0.04	0.000352	113.72	4.63	24.56
0.05	0.000352	142.15	4.63	30.70
0.06	0.000352	170.58	4.63	36.84
0.07	0.000352	199.02	4.63	42.98
0.08	0.000352	227.45	4.63	49.12
0.09	0.000352	255.88	4.63	55.26
0.085	0.000352	241.66	4.63	52.19

Aquatic Cell Increase

Varying Volume

V (cf)	k (1/day)	HRT (days)	Se/So
93	0.3	0.083	0.86
95	0.3	0.085	0.86
100	0.3	0.089	0.85
105	0.3	0.093	0.85
110	0.3	0.098	0.84
115	0.3	0.102	0.83
120	0.3	0.107	0.83
125	0.3	0.111	0.82
130	0.3	0.116	0.81
135	0.3	0.120	0.81
140	0.3	0.125	0.80
145	0.3	0.129	0.80
150	0.3	0.134	0.79
155	0.3	0.138	0.78
160	0.3	0.142	0.78
165	0.3	0.147	0.77
170	0.3	0.151	0.77
186	0.3	0.166	0.75

Varying Flowrate

Q (cfs)	Q (cf/day)	k (1/day)	HRT (days)	Se/So
0.013	1123.2	0.3	0.083	0.863
0.02	1728	0.3	0.054	0.908
0.03	2592	0.3	0.036	0.938
0.04	3456	0.3	0.027	0.953
0.05	4320	0.3	0.022	0.962
0.06	5184	0.3	0.018	0.968
0.07	6048	0.3	0.015	0.973
0.08	6912	0.3	0.013	0.976
0.09	7776	0.3	0.012	0.979
0.1	8640	0.3	0.011	0.981
0.11	9504	0.3	0.010	0.983
0.12	10368	0.3	0.009	0.984
0.13	11232	0.3	0.008	0.985
0.14	12096	0.3	0.008	0.986
0.15	12960	0.3	0.007	0.987
0.16	13824	0.3	0.007	0.988
0.17	14688	0.3	0.006	0.989

Varying Number of Aquatic Cells

n (# of cells)	HRT (days)	k (1/days)	Se/So
6	1	0.3	0.207
7	1	0.3	0.159
8	1	0.3	0.123
9	1	0.3	0.094
10	1	0.3	0.073
11	1	0.3	0.056
12	1	0.3	0.043
13	1	0.3	0.033
14	1	0.3	0.025
15	1	0.3	0.020
16	1	0.3	0.015
17	1	0.3	0.012
18	1	0.3	0.009

Increasing Flowrate to Match the Myco-Filter Influent

Q (cfs)	Q (cf/day)	k (1/day)	HRT (days)	Se/So
0.03	2592	0.3	0.03587963	0.938

Appendix I: Proposal

<u>Living Systems Laboratory:</u>

<u>Stormwater Analysis</u>

Proposal

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October 13, 2016

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1. Introduction

The Living System Laboratory is located at the site of the old Fisherville Mill along the Blackstone River in Grafton, Ma. It is an Eco Machine that uses biological processes to treat water from the Blackstone Canal, which is stagnant and extremely polluted from years of industrial use in the area. It consists of a greenhouse, which houses aquatic cells and a fungus filled media, and a floating island in the canal, which is the where the water exits the system. The LSL makes use of the metabolic processes of these organism to break down the hydrocarbons and nutrients present in the water (Todd, 2013). At the same time, the treated water carries these microorganisms out into the canal, propagating the rebound of the surrounding ecosystem.

In addition to simply being a means for treating the canal, there is an interest for finding other ways to make use of the LSL. The LSL is also meant to function in an educational capacity by providing students and researchers a way to study the effects and benefits of using biological processes as a means of water treatment (Todd 2013). They are also looking into ways to use the treated water to irrigate the surrounding park. In particular, there is an interest in using the LSL to treat stormwater flowing into the canal.

The operators of the LSL want to determine if it can handle the stormwater flowing into the canal from the surrounding area. This would involve doing a stormwater analysis to see if the system could handle high flow events, as well as determining the maximum flow the system could handle while still being effective. The effluent of the system would also need to meet any EPA and DEP regulations. Modifications to the system (i.e. larger retention tanks or addition plant cells) could then be made so that the LSL can better handle stormwater. The LSL may provide an alternative method for treating stormwater, while also helping the surrounding ecosystem rebound.

2.0 Background Chapter

2.1 Hydrology

Before any analysis can occur, first one must understand the type of science behind the Living Systems Laboratory. Hydrology is the science of understanding water processes on Earth (Perlman 2016). It focuses on the relationship of water with the surrounding environment: more specifically, water's characteristics, and distribution throughout the planet. To achieve our project objectives, we will be focusing specifically on three aspects of hydrology: surface water, groundwater, and most importantly, stormwater (Perlman 2016).

Surface water is best defined as the water used in reservoirs. This type of water is mainly used for drinking water sources, in addition to swimming and other industrial purposes. The use of surface water can sometimes be restricted though due to pollution (Perlman 2016). After storms occur, the rainwater either collects in the reservoirs, or eventually ends up there from runoff from surrounding areas. This runoff brings in unwanted contaminants to the source, which would directly impact those downstream that use the source for drinking water. This is one major reason why treating and containing stormwater is pivotal for the health of the general population.

Groundwater is another source of water used for public drinking water. Groundwater is often a better alternative to surface water for several reasons: one being because it is less vulnerable to pollution; two, there is more groundwater than the entire capacity of surface water in the U.S; and three, in some areas, groundwater is the only option (Perlman 2016). The downfall to using groundwater as a water source is that if it does become polluted, it is much more difficult to clean. Most times, groundwater is polluted from improper disposal of wastes on land (Perlman 2016). In the case of the Living Systems Laboratory, the pollution of the canal mainly stems from runoff from the soil from the Fisherville mill site. The soil still contains some contaminants from the mill's activity during the industrial revolution. To solve the contamination issue, we first had to understand what stormwater is, and the need for analysis.

2.1.1 Importance of Stormwater Analysis

Stormwater is essentially any collected water from rain, thunderstorms, hurricanes, and other types of weather. The water usually runs off into other bodies of water, such as rivers, lakes, oceans, and surface water reservoirs. The expansion of urban areas creates more impervious land, which leads to decreased infiltration, and thus more runoff in short bursts (Stadelmann 2002). These quick spurts of stormwater runoff make it hard to retain all of it in collection basins, which makes controlling the path of the stormwater difficult. This is why there is a need for stormwater treatment now, especially since storm patterns and occurrences are quite unpredictable.

The Living Systems Laboratory at the mill site is still dealing with this issue of runoff. The contamination from the Industrial Revolution in the soil runs off into the Blackstone Canal from stormwater, and impacts all life forms in the area. The Canal also runs into the Blackstone River, which is a much larger body of water, with even greater environmental impacts to the ecosystems of the River area. That is why finding a way to treat the stormwater is essential to preserve the site, and properly clean the Blackstone Canal water.

2.2 Natural Systems for Wastewater Treatment

Natural systems have been used as an alternative to wastewater treatment for centuries, whether it be due to the lack of current technology or as a means of environmental conscientiousness. Beginning in the mid-19th century and lasting until the end of the century, major developments were made in the area of land treatment, a method that uses natural resources to treat domestic wastewater. One of the first noted systems of this kind was that of a sewage farm located in Edinburgh, Scotland in the mid 1600's. The system was very basic, people at the time only seeming to understand that the combination of waste and soil created a sort of purifying effect. It was in these years between 1840 and 1890 that humans began to see the limitations of such natural systems, noticing that when too much waste was applied to the crops in the sewage farms, they would overload and fail. This turning point led to new developments in wastewater treatment: activated carbon absorbtion, chemical precipitation, biological contact beds, and sand filters among the rest, leaving natural systems as an alternative, rather than primary, method of

treatment. Today, these natural systems are being adopted in small-scale settings in an effort to utilize natural resources and reduce energy consumption. Whether it be simple or complex applications, a piece of an engineered treatment system or a series of natural components to form a whole, natural systems are each unique in their own (Environmental Protection Agency).

2.2.1 Reedbeds

One example of a simple application of natural wastewater treatment are reedbeds. Aquatic reeds are a chosen flora for this technology due to their ability to handle large floods of water, while also able to withstand very dry periods. Reedbeds are simply aquatic reeds planted in an inorganic substrate such as sand or gravel, making sure to pay attention to porosity to ensure a correct retention time in order to enable contaminant processing. Wastewater is introduced to the system where the reed roots provide a home for the microbes to reproduce and decompose the contaminants and toxins in the water, while simultaneously processing the nutrients. Aeration of the substrate material accelerates both of these anaerobic and aerobic processes. Reedbeds also encourage biodiversity and are aesthetically pleasing. Once the waste runs through the system, the water is generally clean enough for either reuse or discharge back into the surrounding environment. Reedbeds have been used to treat agricultural and contaminated wastewater, contaminated waters, and sludge (How Reedbeds Work).

2.2.2 Living Machine Technology

Other natural systems are used in combination with more modern treatment methods. The Living Machine Technology, developed by Tom Worrell beginning in 1999 with the creation of his company, Worrell Water Technologies, is a key example of this category of technology. In the Living Machine, tidal motions are used to mimic natural wetland conditions. When wastewater enters the system, it first enters a primary settling tank where gravity allows for solids to settle to the bottom. The water then moves to an equalization tank that plays a large role in controlling the flow, buffering both high and low flows, steadying the stream of water entering the system. Next, cells filled with media are flooded and drained various times throughout the day, creating a tidal-type motion, where miniature ecosystems grow and thrive, allowing for the removal of nutrients via microbes. Some wastewater will then move to stage 2, composed of smaller media,

allowing for more rapid treatment. Once the water passes through these steps, it then moves on to final treatment measures, which for the Living Machine Technology, includes filtration and disinfection using chlorine. The water is then transported to a reuse tank where the water is set to be reused for other purposes. The Living Machine Technology aids in recycling thousands of gallons a day, using a system with partial natural processes (Tidal Flow Wetland Living Machine System).

2.2.3 Eco Machine

Lastly, complex natural systems have also been designed to treat water, combining various treatment processes in sequence, in order to produce better results from an all-natural system. The Eco Machine, designed by ecological designer John Todd, is located at the Omega Center for Sustainable Living where all of the domestic wastewater produced by the center is treated by Todd's system. The machine treats 52,000 gallons of water a day in the peak season using a seven-step process. First, the water is held in a settling tank in order for solids to settle to out and solids are injected with microorganisms in order to speed up the decomposition process. The water is then sent to an equalization tank where, similar to the Living Machine Technology, the water flows are controlled, allowing for the system to remain small-scale. Wastewater is sent to anoxic tanks where organisms are used to digest the nutrients and contaminants in the water before moving to man-made wetlands. There, native plants reduce Biochemical Oxygen Demand (BOD) and harvest nutrients. The water is further purified to highly oxygenated lagoons where fungi, algae, and tropical plants in addition to more microorganisms continue to convert toxins to less harsh elements. Sand filters out any remaining particulates and the clean water is released back to the water table underneath the center's parking lot. The Eco Machine combines various natural processes to ensure safe water is released back into the environment (Eomega.org).

Various natural systems have been applied to modern day practices as a way to capitalize on the opportunity to use surrounding natural resources. Although using land treatment as a way to treat wastewater is nothing new, many are bringing this old technology to a new light in an environmentally conscious way.

2.3 Living Systems Laboratory (LSL)

The Living Systems Laboratory (LSL) is an Eco-machine designed by John Todd, located at the Fisherville Mill site on the Blackstone Canal in Grafton, Ma. Its purpose is to use biological processes to treat hydrocarbons and nutrients that are present in the river from years of industrial use (Todd, 2013). The LSL is part of a recently developed park on the historical site of the Fisherville Mill. In addition to being a treatment system for the Blackstone Canal, the LSL is meant to serve in an educational capacity, by which students, educators, and scientists can study the effects of Eco-Machines on contaminated sites (Todd, 2013).
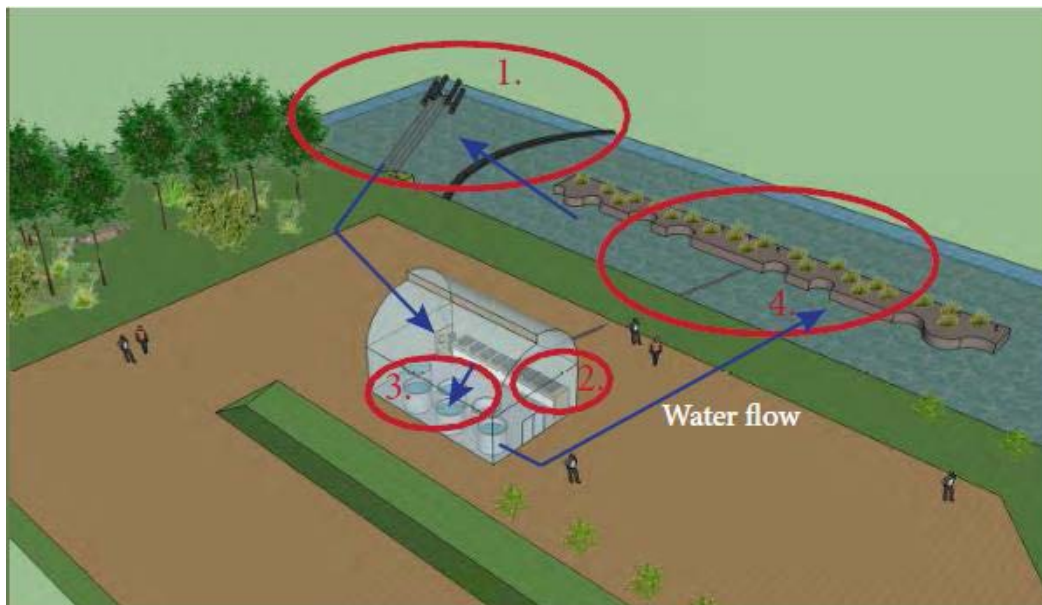

Figure 1: System Diagram (John Todd Ecological Design, 2013)

The system consists of a greenhouse, which houses the biodiversity that drives the process, and an Aqua Restorer in the canal at the system's outlet (Todd, 2013). Water from the Blackstone canal is pumped into the LSL, where contaminants are removed, and then released back into the canal. The system contains 4 different components; Sediment digesters, myco-reactors, aquatic cells, and a floating restorer.

2.3.1 Sediment Digesters

Water enters into the system through sediment digesters, which are located in the canal beneath the soil. They consist of perforated plastic pipes, which are filled with biologically colonized

gravel particles (Todd, 2013). The increased surface area of the gravel causes the oil to accumulate, at which point the microbes inhabiting the digesters begin the process of breaking it down (Todd, 2013).

2.3.2 Myco-Reactors

The water then enters a wood chip media containing mycelium, which is the web-like structure of fungi. The water is trickled into the media, where the fungi release enzymes that break down the hydrocarbons (Todd, 2013). This process turns the wood chip media into soil, which then supports other organism such as maggots and worms. Because fungi are primary decomposers, they play a critical role in the system by beginning the decomposition of the hydrocarbons. The enzymes produced in this stage travel to other components in the system, where they continue to break down the contaminants.

2.3.3 Aquatic Cells

The next component is a series of six 650 gallon open tanks, which contain a variety of plants as well numerous types of algae, bacteria, protozoa, and fish. As the water moves through each of these six tanks, it comes into contact with these organism and is purified and aerated (Todd, 2013). Some of these organism are carried out with the water, increasing the biodiversity of the canal.

2.3.4 Floating Restorer

Finally, the water is released back into the canal by being pumped up through a floating raft of plants. This floating island acts as an oasis for biodiversity in the canal. The clean water from the treatment process is oxygen and organism rich, which attracts organisms such as insects, minnows, turtles, and frogs (Todd, 2013).

In addition to the removal of hydrocarbons and nutrients from the water, one of the main purposes of the LSL is to facilitate the rebound of the canal's ecosystem. As more organisms are introduced back into the canal, the process that is occurring in the LSL will begin to replicate itself in the canal. By removing contaminants from the water, while at the same time introducing

microbes that continue the decomposition, the LSL has had a significant impact on the biodiversity of the canal.

2.4 Project Setting and Historical Significance

The area of focus and location of the existing Living Systems Laboratory is Grafton, MA. The town is one of many located along the Blackstone River, one of the most historically significant bodies of water in the United States.The Blackstone River, which is shared by both Massachusetts and Rhode Island, is often considered the "Birthplace of the American Revolution", making it one of the most historically significant locations in the United States. In 1790, Samuel Slater, an Englishman experienced in the textile mill industry, developed a cotton-spinning factory on the Blackstone River which no one at the time could have predicted how large of an impact it would create (National Park Service). Unfortunately, because the Blackstone River became such an industrial hotspot in the late 18th century- early 19th century, it left a scar on the quality of the river's waters. The river had become polluted with raw sewage, industrial wastes, and heavy metals and toxins, which at one point in 1990, led to the Blackstone's title of "most toxic river in America". In 2014, attention was brought to the river once again when it was designated a National Historical Park. At the same time, an extension of the John H. Chafee Blackstone River Valley National Heritage Corridor was initiated. Essentially, the Heritage Corridor Commission partners with agencies at the federal, state, and local level in order to ensure protection of both the sites and resources of the Blackstone River Valley (zaptheblackstone.org).

Another component of the Blackstone River that was highly utilized during the 19th century was the Blackstone Canal. The Blackstone Canal was a large accomplishment at the time, allowing for transportation to occur on this body of water, something that was no longer possible on the river itself, with the increase of dams used for water power. The canal, which connects the two major cities of Worcester, MA and Providence, RI, allowed for trade and commerce to thrive at the time. The canal caused a rise in development along the river as well a surge in economics and social life. Eventually, the canal lost its effect on the population, due to the introduction of a new, faster, and more efficient mode of transportation, the railroad (worcesterhistory.org). Presently, the canal still exists, left as a more stagnant body of water still ridden with leftover toxins and contaminants from the industrial revolution.

2.4.1 Fisherville Mill, Grafton, MA

Historically, one of the largest mills on the Blackstone River, a wool mill, was located in Fisherville. In 1999, the mill was involved in a fire that led to copious amounts of chemicals to be released into the air. This led to action to restore the area, including the establishment of the Mill Villages Park, where the construction of the Living Systems Laboratory gave way. The Fisherville Mill site contains one of the last mill ponds left on the Blackstone River and one of the largest areas of water left. The site consists of mainly empty floodplains, but does feature old mill housing where villages once were (Sengel, 2015).

Grafton is a small town located in East Central Massachusetts, home to almost 18,000 residents (About Grafton). The Living Systems Laboratory is located in the Mill Villages Park in south western Grafton, directly next to the Blackstone Canal. The site is located on a brownfield and a lot of work has gone into remediation. Plans have been developed to create a community center that educates the public about historical uses of the site and how to move forward with the potential applications of the Living Systems Laboratory (Collins, Ferguson, Frisch, 2015).

3. Methodology

We will determine the Living Laboratory System's current and potential capacity to treat stormwater, in particular high-flow events, and propose recommendations for expanding the system.

Objectives:

1. Obtain samples from the Blackstone Canal adjacent to the LSL and analyze them for various regulated components.
2. Use GIS to evaluate the characteristics of the surrounding area (topography, hydrography, land use, soil composition).
3. Analyze the flows of the system.
   a. LSL: influent and effluent of the LSL
   b. Look at flows into the canal: Rain data, infiltration

3.1 Stormwater Sampling

Analyzing stormwater samples is crucial in understanding the water's constituents, especially where storm water regulations are applicable. Characterizing stormwater will allow for an initial inspection of the water's components and will provide a baseline to determine any changes that may occur when new engineering projects are implemented. Quantifying concentrations of common pollutants, heavy metals, and natural properties will be particularly useful in analyzing the initial water quality in the Blackstone Canal adjacent to the Living Systems Laboratory for comparison to recent regulations adopted by the Town of Grafton (Environmental Protection Agency, 2009). In order to decipher which regulations are most important to meet, we will meet with Joe Laydon, the Town of Grafton's Planner.

We plan to test for various natural properties such temperature, dissolved oxygen, 5-day Biochemical Oxygen Demand, and pH in addition to turbidity, total suspended solids, alkalinity, phosphorus, and various common heavy metals (see Appendix A: Laboratory Procedures for a full description of laboratory procedures). In order to obtain the most accurate results possible, all procedures will be followed as written in the <u>Standard Methods for the Examination of Water and Wastewater</u> (Eaton, Clesceri, Greenberg, Franson, 1998) using materials and instruments

provided to us by Worcester Polytechnic Institute's Environmental Laboratory. We will collect samples from three different areas of the site, one sample that essentially represents the machine influent as it will be collected from the initial retention tank, one sample downstream of the Living Systems Laboratory, and one sample of treated water located directly before it is to be released back into the canal.

Once we have narrowed down which regulations are most important to meet, we will be sure to make note of which regulations are currently not met by the canal water and begin to design changes to the Living Systems Laboratory in order to meet, or exceed, these criteria. By examining the water released from the system and comparing it to the sample data from those collected at the influent, it becomes clear what changes the Living Systems Laboratory has made in improving the water quality. We will be recording all of this information for comparison later and to keep record of water quality at that time.

3.2 GIS Mapping

GIS was an important tool in studying the hydrology of the surrounding area. Using GIS, we were able to see the topography, hydrography, land use, and soil of the surrounding area. We used ArcGIS version 10.4.1 for our GIS analysis. We used GIS data from MassGIS.com and data supplied by the Town Grafton. For the base map we used ortho photos from MassGIS.

3.2.1 Topography

To study the topography of the area we used data layers for the towns of Grafton and Sutton, which were downloaded from the MassGIS website. This layer contained contours describing the elevations of the surrounding area. By studying these contours, we were able to understand the general trends of stormwater flow into the canal.

3.2.2 Hydrography

The hydrography GIS data shows all the bodies of water, including lakes, rivers, and ponds. It is important know the locations of these bodies of water. Any stormwater in the area will be

flowing into the Blackstone Canal, the Blackstone River, or the Fisherville Pond. We were concerned with the Blackstone Canal in particular, because that is where the LSL draws from.

3.2.3 Land Use

Mapping the land use in an area is an important part of a stormwater analysis. We used the land use data layer from MassGIS to see what exactly was on the land surrounding the canal. Land use is an important factor because different structure will affect stormwater in various ways (Goonetilleke et.al., 2004) . For example, impermeable surfaces, such as streets and parking lots, will cause more more runoff during a storm than permeable surfaces would.

3.2.4 Soil Composition

Using GIS data we were able to study the various soil compositions in the area. We did this because different types of soils have varying levels of permeability. This in turn, could have an effect on the flow of stormwater.

3.3 Analysis of System Flows

3.3.1 Regulations

To understand what government-regulated parameters the system had to abide by, we met with Joe Laydon, Town Planner of Grafton, Massachusetts to understand the most important specifications to ensuring proper environmental operations. He notified what regulations that we should be focusing on in our design plans, and what the Town's vision for the system was. In order for our designs to be plausible, they would have to abide by all EPA, Mass DEP, and local environmental protection rules and regulations. Keeping these regulations in mind, we were then able to begin on our analysis of the mechanics and capacity of the Living Systems Laboratory.

3.3.2 Flows of the System

After identifying important characteristics in the stormwater samples, and the topography of the area surrounding the Living Systems Laboratory, we had to analyze the influent and effluent

flows of the system. Specifically, this meant that we needed to measure the influent flow rate of the stormwater entering the system, and the flow rate of the jet pump feed into the basins, the flow rate of the sump pump feeding the large treatment tanks, and the flow leaving the system. We were able to obtain this information by looking up serial information online for each pump, and calculating the influent flow rate at the faucet, and the effluent flow rate at the exit pipe. This was done by filling up a bucket of water to a specified volume, and timing how long it took to fill up. By doing this, we were able to understand how much water the system could withstand.
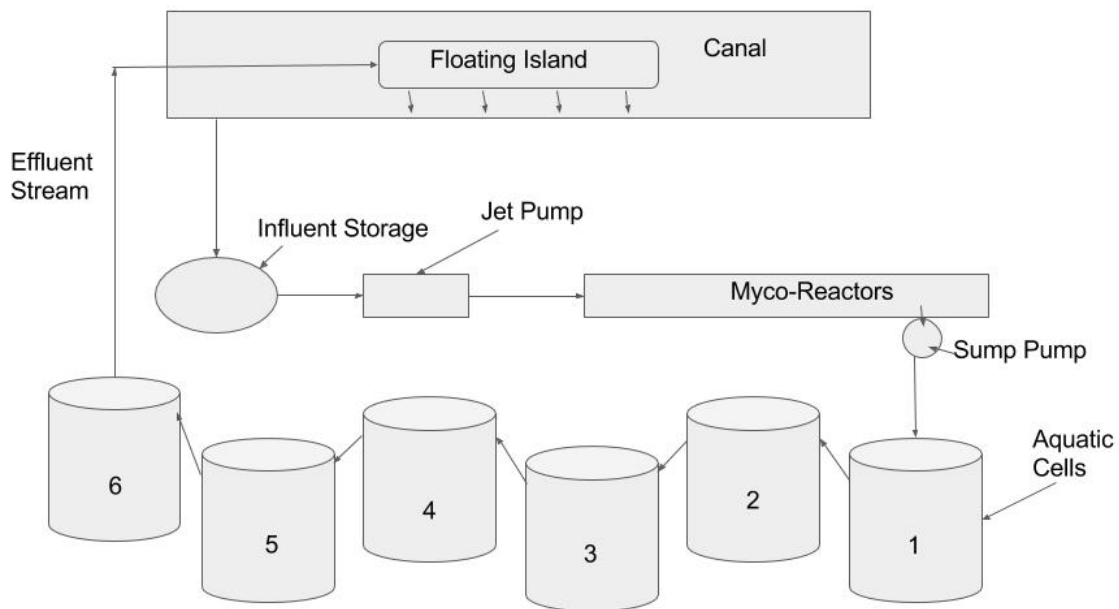

Figure 2: System flow diagram

3.3.3 Volume & Retention Time

After calculating flow rates at key points in the process, we needed to find the total volume of the system, and the retention time (time that it takes to move a batch of water through the entire system from input to output). To find this out, we had to acquire the times per day that water was pumped through the system, how much was cycled through each time. Knowing the volumes of the retention tank, each basin, and the large treatment tanks, in addition to how many of each were in the greenhouse, gave us ample information to calculate the total volume of the system at critical points, and the retention time of one complete cycle.

3.3.4 Breakpoint

Although the system can hold so much water, we needed to identify whether or not there was a certain flow rate and/or volume of water that essentially caused for the system's treatment to become ineffective. This point is called a breakpoint. To find this breakpoint, we had to test the characteristics of the influent and effluent water at different volumes and flow rates to determine at what levels the system was incapable of treating the stormwater. This aided us in the development of new design parameters for an upgraded version of the Living Systems Laboratory that could withstand larger amounts of stormwater.

3.3.5 Storm Events

Most likely this point would occur during a one, two, or three-year storm event. Thus, we researched rainfall data for such storms in Grafton, Massachusetts. We then matched up these data to the system's total volume and retention time to determine whether or not the system could withstand these events, were they to occur again. This gave us accurate parameters to model our new design plans around, thus making the system more likely to withstand greater storms in the future.