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The Future of Coes Reservoir: An Investigation of Removal Methods for Water Chestnuts

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Abstract

The water chestnut (*Trapa Natans*) is an invasive aquatic weed species that poses a threat to the water quality of Coes Reservoir in Worcester, MA. Literature review and evaluation of case studies were used to show that physical removal, water-level drawdowns, herbicide treatments, and aeration with bioremediation were potential treatment options for addressing water chestnuts. By developing comparison tables to evaluate attributes for these alternatives, the analyses showed that aeration and bioremediation is an appropriate removal option for Coes Reservoir.

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Executive Summary

Coes Reservoir is one of a number of water bodies located in Worcester, Massachusetts. The Worcester community utilizes these bodies of water for recreational activities and various other uses to benefit their daily lives. However, many forms of pollution can be carried into these bodies of water and create havoc within these urban watersheds. When pollutants enter a body of water, a series of negative impacts can occur, such as increased sediment depths, growth of algae and plants, and ultimately decreases water quality. Thus, the pollution can create larger, more challenging issues that can negatively affect lakes.

This decrease in water quality is the challenge that needs to be addressed in Coes Reservoir. Coes Reservoir has been impacted by the growth of an aquatic plant known as the water chestnut. The water chestnut is a floating, broad-leaved weed that displaces the native aquatic organisms and restricts sunlight from reaching the lake bottom. Water chestnuts can also lead to a rapid increase in sediment levels at the bottom of the reservoir due to the decomposition process of the plants. When the plants decompose, phosphorous is released and oxygen is depleted from the water, creating "dead-zones" which are inhabitable. This increase in sediment levels causes the lake bottom to become shallower and converts it into a sloppy concoction of slime and muck. This decreases water quality, lowers the property values of homes around the reservoir, and prohibits recreational activities.

The goal of this project was to determine the most effective solution for the treatment of the water chestnuts in Coes Reservoir. Removing the water chestnuts completely is an important step needed to improve the water quality and increase recreational usage of the reservoir. To meet this goal, it was not only necessary to determine a long-lasting and cost-effective solution but to assess the other impacts or consequences when using the solution as well. Through comprehensive

research on topics such as characteristics of invasive species, and various ecological aspects, we recommended the best treatment application specific to Coes Reservoir that would improve the health of the reservoir and improve the overall water quality. The approach was to gather background information, conduct thorough research on water chestnuts, compare and contrast effective removal treatments, and finally to determine the most effective solution to address the water chestnut problem.

A variety of different removal methods were studied to find the most applicable solution. The four treatments outlined in this IQP include physical removal, drawdowns, herbicides, and aeration and bioremediation. This project included a review and evaluation of the potential use of these four options in Coes Reservoir. The most basic treatment option is physically removing the water chestnuts. This is best achieved with a combination of two techniques: mechanical harvesting and hand-pulling. Mechanical harvesting is the removal of invasive weeds by a large machine called a mechanical harvester. These machines float on the water, run through weeds, cut them low enough so that their seeds are also removed, and store the weeds in the machine itself. The weeds are then taken to land where they can decompose or be thrown away. Most mechanical harvesters can only operate in the deeper, more open parts of the reservoir. However, there are more expensive variations, such as hydro-rakes, which can operate in shallower areas. Hand-pulling can get the water chestnuts in the hard to reach areas for the mechanical harvesters. A community effort would be recommended if there are several areas that require hand-pulling. People need to have canoes to get to the weeds and they need to dress accordingly. Muck, debris, and the sharp seeds of the plant can be messy and hazardous for the hand-puller. Physical removal is appealing because it is both time-efficient and proven to be effective in several case studies.

However, it is the most expensive treatment option (20 to 50 thousand dollars a year), requires an abundant amount of physical labor, and can be dangerous to hand-pullers.

A second treatment option is the lowering of the water level in the reservoir, otherwise known as a drawdown. This exposes invasive weeds on the shore to the air, and the harsh elements of winter will shear the exposed plants. Drawdowns must be approved by the city's conservation department several months in advance. Inspections by biologists and botanists can be done during this time to analyze if drawdowns will severely impact the biodiversity in the reservoir. These drawdowns are usually performed in October, after the growing season for invasive weeds. While most invasive weeds can be managed from use of this method, water chestnuts are not affected. This is because their seeds fall off during the summer, and any plants that are sheared after that will naturally die. Drawdowns are a cost-effective removal treatment that can decrease muck and improve dissolved oxygen levels. However, they can permanently affect biodiversity if the water level is lowered too quickly. Additionally, sediment depths in the middle of the pond can increase and, in some cases, cause more frequent algal and cyanobacteria blooms.

A third treatment option is the application of herbicides to mitigate the water chestnuts. Herbicides contain chemicals that disintegrate weed stems and roots to eliminate weeds and diminish their reproduction. There are numerous types of available herbicides to treat the various amounts of aquatic weed species. The size and severity of the infestation determine the amount and frequency of herbicides to apply to the lake or reservoir. To use this removal option in Massachusetts, a contractor must be hired in order to safely and correctly apply the herbicide. However, when these chemicals are being used in bodies of water, there can be health hazards for both humans and aquatic life that are in contact with them. When the plants die, they sink to the bottom of the reservoir and decompose, which could increase sediment depth even more. On the positive side, it is the least expensive treatment for Coes Reservoir.

A fourth treatment option is the combination of aeration and bioremediation. Aeration has been used to improve the water quality by introducing oxygen into oxygen-depleted water. This process increases the amount of dissolved oxygen in the water by injecting millions of air bubbles into the water. An increase in dissolved oxygen provides a healthier environment for beneficial bacteria to thrive. Bioremediation involves the increase of beneficial bacteria in a water body, which allow more nutrients to be consumed by the bacteria and throughout the fish food chain. This process deprives the nutrients from reaching the invasive species, resulting in their natural death, thus allowing the lake to restore its own health hereby reducing its problems dramatically.

In order to select the most applicable removal option for Coes Reservoir, the four treatments were evaluated with consideration to the following factors: likeliness of success, versatility, cost, negative effects, safety, community labor, immediate results time, disposal methods, and equipment. The importance of each of these factors was determined by what we as a group determined (based on our background research) and by the Tatnuck Brook Watershed Association (TBWA). The TBWA is a water sustainability group responsible for all related projects for Coes Reservoir and Patch Reservoir in Worcester. Nine rating tables were developed to describe how each treatment was related to each of the nine factors. One summative table was prepared to numerically compare and assess the effectiveness for the methods with respect to the nine factors. The summative table presented numerical evidence on which treatment would be the best option for the removal of water chestnuts at Coes Reservoir.

A summary table is shown in Table 1, which combines the techniques we used in making the nine rating tables and the one summative table. Table 1 lists the major benefits and drawbacks for our treatments we analyzed and a numerical ranking for recommendations. The recommended approach is listed as the first order of preference, while the other options are listed in decreasing preference (with the drawdown option shown as the 4th, or least preferred option, in regards to water chestnut removal).

Table 1. Summary table of treatment recommendations.

Order of Preference	Treatment	Major Benefits	Major Drawbacks
1st	Aeration and Bioremediation	• Versatility • Low negative effects • High safety	• Cost • Not proven to remove water chestnuts
2nd	Herbicides	• Low cost	• Negative effects on wildlife • Human safety
3rd	Hand-pulling	• Most likely to succeed • Low cost	• Lots of community work that needs dedication and commitment
4th	Drawdown	• Versatility • Low cost • High safety • Done annually at Coes	• Cannot remove water chestnuts under reasonable conditions • Negative effects on biodiversity and wildlife

Ultimately, combined aeration and bioremediation was determined to be the best treatment option to remove water chestnuts from Coes Reservoir because this approach has numerous benefits that are important. It performs better than the other options in the versatility category because it can potentially fix several water quality issues, which was determined to be a "most important" factor. Aeration and bioremediation can decrease all invasive weeds, improve sediment depths, and decrease levels of phosphorus and nitrogen in Coes Reservoir. It also succeeds in having low negative effects on the environment and high safety, which were determined to be "important" factors.

If the cost for aeration and bioremediation is too expensive, then use of the other treatments may be considered (since they can all cost considerably less). The first alternative option we recommend is herbicides because all the work is done by a company and there is evidence to suggest that it is a reliable invasive weed removal treatment. Second, if the negative effects on wildlife and safety for herbicides are too concerning, another alternate option to consider is community hand-pulling. Hand-pulling was found to be the third best option since it has been proven to work and it has no negative effects on the environment. Commitment is needed because hand-pulling really needs to be repeated multiple times a year for up to twelve years. It is often difficult to maintain that level of commitment for that long of a timespan. Finally, drawdowns are recommended, but are considered to be the least preferred option to remove water chestnuts. Because water chestnuts grow and drop seeds during the summer, drawdowns cannot control their spread in an effective way. However, if the goal is to manage perennial invasive weeds, such as coontail and water milfoil, then drawdowns is the second best option (behind aeration and bioremediation).

Ultimately, removing water chestnuts would improve the water quality tremendously. It is recognized that the inputs of nutrients and other contaminants also affect water quality in the Coes Reservoir, and additional projects are recommended to full understand the factors affecting water quality. However, this analysis should provide information that will be helpful in addressing the water chestnut problem. This step will help to improve water quality and encourage the use of the Reservoir for a variety of recreational activities, which will help to bring the city of Worcester closer together.

Chapter 1: Introduction

Invasive plant species have significant impacts on the water quality of water bodies throughout the United States. Increased sediment depths, decreased dissolved oxygen levels, increased phosphorus and nitrogen levels, and limited recreational activities and biodiversity can all result from these invasive species. The spread of these invasive plant species can be disastrous if the plants are not remediated quickly and effectively (Keller, R. P 2009).

The many types of invasive aquatic plants range from submerged to emergent plants and have different effects on the lake in which they inhabit. To assess the main causes of invasive plant problems that result from aquatic invasive species such as water chestnuts, Eurasian milfoil, and water hyacinth, it is necessary to understand the many factors that contribute to the deterioration of water quality in ponds. Some of these factors include pollution, geographic location, and runoff. These factors can lead to an increase in nutrients such as phosphorus and nitrogen, resulting in other issues such as invasive aquatic species and increased sediment depths that may completely alter the well-being of a water body. Once the relationship of these excess nutrients and invasive species are understood, a specific removal treatment can be recommended to remediate these issues.

Coes Reservoir, a vital recreational resource in the city of Worcester, Massachusetts, is in need of a strategy to remove the invasive water chestnuts. This reservoir is well-known around the Worcester area for the various projects conducted at the site. Recent projects include the planning of the relocation of a historical tavern, along with the addition of a multiuse all-access park located around the perimeter of Coes Reservoir. Unfortunately, the recreational activities are limited since the water chestnuts grow in thick populations that are nearly impenetrable from the surface of the reservoir. The floating leaves associated with the water chestnuts prohibit recreational swimming and fishing, and can impede canoes and kayaks from traveling through the reservoir. The leaves also restrict sunlight causing limited photosynthesis for native plants, and deplete oxygen levels in the water. This invasive weed can increase sediment levels when the water chestnut dies and decomposes on the bottom of the reservoir. This decomposition process releases phosphorus, creating thick muck instead of sandy soil for reservoir. With all the activities taking place around Coes Reservoir, and considering the negative impacts that the water chestnuts can have, it is essential to remove the water chestnuts. Removing the water chestnut from the reservoir will help improve the water quality and promote recreational activities.

The goal for this project was to determine the most effective solution for the treatment of the water chestnuts in Coes Reservoir. To meet this goal, it was not only necessary to determine a long-lasting and cost-effective solution but to assess the other impacts or consequences when using the solution as well. Through comprehensive research on topics such as characteristics of invasive species, and various ecological topics, we recommended the best treatment application specific to Coes Reservoir that would improve the health of the reservoir and also improve the overall water quality. The approach was to gather background information, conduct thorough research on water chestnuts, compare and contrast effective removal treatments, and finally to determine the most effective solution to address the water chestnut problem.

Throughout the report, we presented many of the common factors regarding watershed health in a descriptive manner so that these factors can be easily related to Coes Reservoir. We compared and analyzed four different treatments in order to determine which is most applicable to Coes Reservoir. We then summarized these comparisons in tables to allow for easy access by stakeholders with an interest in removing of water chestnuts from Coes Pond. The outcome of this

IQP is intended to provide specific recommendations on removing water chestnuts from Coes Reservoir.

Chapter 2: Background

This chapter begins with a brief history of Worcester, Massachusetts and Coes Reservoir. It discusses the significance of water quality, describes the characteristics of invasive species (especially the water chestnut), and finally, gives a detailed overview of the removal methods researched. The information in this chapter is important to develop an understanding of the removal of water chestnuts from Coes Reservoir.

2.1 Industrialization and Population

Worcester, Massachusetts became industrialized in 1825 in part due to the Blackstone canal and the linkage between Providence and Boston through railways (Worcester Historical Museum, n.d). Worcester became known for producing some of the best machinery, looms and wire products in the nation. The rise of these manufacturing jobs created a movement of working class citizens to join the rapidly increasing market (Worcester Historical Museum, n.d). The increase in population led to massive amounts of waste being accumulated in communities. This accumulation increased pollution levels from garbage and byproducts from households and factories into bodies of water. Heavy metals from machinery could remain in water bodies for decades, otherwise known as legacy pollution. However, the remaining elements of the metals could eventually decrease to a negligible amount in the water bodies over centuries.

2.1.1 Construction of Coes Reservoir

In many industrial locations, artificial retention ponds and reservoirs were built in order to produce hydraulic power and electricity for factories. Although coal was an effective source of energy and heat for powering machinery, it came with a hefty cost (Quaschning, 2015). Coal is a non-renewable fuel source with negative consequences such as producing two hundred pounds of carbon dioxide per kilowatt-hour, along with airborne mercury contamination. Some of the benefits of hydropower include continuous energy being produced by flowing water, and that it is a renewable fuel source with no ongoing costs to use it (Quaschning, 2015). To efficiently and economically run their factories, the Coes brothers, Loring and Aury built a twenty-one-acre reservoir with a dam to harness the power from this body of water (Antonelli, 2015).

In the 1800s the Coes brothers purchased three manufacturing plants that produced industrial blades for machinery and wrenches. Loring Coes invented and patented the monkey wrench in 1840, adding to Worcester's historical recognition for being the heart of the commonwealth (Eskin, 2015). In 1869, the brothers split up and purchased their third factory. In 1875, Aury died in a carriage accident leading to Loring taking sole ownership of the Coes industry (Eskin, 2015).

2.2 Watersheds

A watershed is an area of land "bounded peripherally by a divide and draining ultimately into a watercourse or a body of water" (Merriam Webster Online, n.d.). Streams or large bodies of water will either flow down and disperse into a main body of water, or will flow out to streams and smaller sub-watersheds (U.S. Geological Survey, 2015). When waterways are disconnected, there is no water flow to help aerate the lakes or ponds, which decreases water quality (U.S. Geological Survey, 2015). Man-made dams or roadways can disconnect waterways from one body of water to another.

2.2.1 Benefits to the Community

Healthy water bodies provide a plethora of habitats, with connecting streams that replenish oxygen to the water, making it beneficial for all organisms (McConnell, 2015). Connected bodies of water also supply the community with drinking and agricultural water, hydraulic power for manufacturing, and recreational activities. According to the Environmental Protection Agency (EPA), clean, healthy watersheds are an essential part of the community because they can produce more than $450 billion in food, fibers, manufactured goods, and tourism (Environmental Protection Agency, 2014). Humans have a major impact on the many benefits associated with watersheds such as economic value, intrinsic value, and numerous ecosystem benefits.

2.3 Urban Watershed Health

A watershed located in an urban environment is subjected to many complex situations unique to its specific location, such as pollution from litter, emissions from vehicles and factories, as well as contamination from runoff. Numerous harmful effects have been directly linked with human activity around the vicinity of the watershed including pollution and the industrialization of the area.

It is necessary to protect natural areas surrounding the places where we live in order to maintain a healthy environment. Since a watershed is located between surrounding streams, rivers, or basins, it is susceptible to accumulating runoff as well as transporting it to other bodies of water. In an urban setting, pollution is even more significant because of the large populations and industrialization of the surrounding area (Kaufman, Murray, & Rogers, 2011). Sustainable watersheds are associated with many positive aspects such as habitats for the hundreds of species that flourish in the area, the aesthetic image of the area, and environmental benefits. As human population constantly increases, there is a higher risk for environmental degradation and there must be common ground in order to achieve the sustainability of urban watersheds.

It is especially difficult to assess all of the issues in urban watersheds since it can be based on a large contribution of common problems. Whether the conditions and concerns date back hundreds of years or is a current dilemma, each scenario must be addressed. Common urban watershed problems range from topics such as legacy pollution, which is a point source pollution left from hundreds of years ago, to runoff and sediment build up that occurs to this day. In order to achieve sustainability, collaborative efforts must be put forth in regards to improving the current and underlying issues causing harm to urban watersheds.

2.4 Pollution in Watersheds

Pollution is usually the main cause in most cases for unacceptable water quality in watersheds. It is important to distinguish between the two major types of pollution, which are point source and nonpoint source pollution (NPS). There are many preemptive strategies used to prevent pollution from entering a watershed. By simply being aware of what is going down the drain, using fertilizers sparingly, and retrieving litter around the area, the community could significantly reduce its pollution contribution. Other beneficial systems that could be used to block and decrease pollutants from entering the watershed are accomplished by planting grass and shrubs to create a buffer zone around the area (Malone & Plummer, 2015).

2.4.1 Point Source Pollution

Point source pollution deals with the wastes from areas such as storm water and wastewater discharges (Malone & Plummer, 2015). Dating back hundreds of years, factories had little to no regulations regarding waste. Depending on the type of factory, dumping wastes into waterways could have serious if not fatal health effects. Different pollutants such as metals or oils could completely destroy ecosystems in a watershed. This could drastically change the ecosystem and allow nonnative invasive species, such as water chestnuts or water milfoil, to take hold in the watershed (Blossey & Greene, 2014). Although these sources of pollution could be a factor, discharge of waste should be heavily regulated, but still has the potential to be the cause of poor water quality (Environmental Protection Agency, 2014).

2.4.1.1 Effects of Wastewater Discharges

Any wastewater being discharged into a water body can pose tremendous negative threats to the ecosystem. These effects could include a decrease in the biodiversity of the water body due to the excess nutrients, contamination of the water, and pathogens. When significant amounts of organic materials enter a water body, negative effects occur quickly (Munawar et al 1993). This organic material significantly reduces the amount of dissolved oxygen in the water, which is necessary for the beneficial bacteria to live and other native organisms to survive. These low levels of dissolved oxygen pose serious threats to the macro organism population of that water body which endangers the ecosystem (Spietz, R.L et al 2015).

2.4.2 Nonpoint Source Pollution

A critical issue regarding pollution in surface water bodies is nonpoint sources. Unlike pollutants from point sources, which are easy to track, pollutants associated with non-point source pollution (NPS) pollutants are less visible because they are caused by runoff from rain or melting snow and collect contaminants while traveling through the watershed (Environmental Protection Agency, 2014). Pollutants associated with household chemicals and fertilizers, septic tanks and cesspools, and litter and waste all impact the water quality negatively. Conditions with heavy loads of pollutants can increase the nutrients in the water and can cause a large buildup of sediments, which decreases water depths and limit recreational uses dramatically. These factors are also directly correlated with the contribution of the growth and spread of invasive species. By locating and tracking the major sources of NPS pollution, it is possible to produce an effective strategy to reduce these contaminants (Malone & Plummer, 2015). There are many ways to prevent runoff from entering a watershed. Examples include systems that divert runoff, avoiding the use of common harmful fertilizers, and/or using a grass barriers to filter out the runoff (Malone & Plummer, 2015).

2.4.3 How Geography Affects Pollution

The topography of the area plays a major role in controlling what infiltrates into the watershed, followed by what exits from the watershed into surrounding rivers or streams. If the body of water is located at the bottom of a hill, pollutants located at the top will run down and enter the watershed when it rains. This creates a larger area that is possibly contributing to the runoff entering the watershed. Geographic information systems, or GIS, are systems that store geographic information in order to locate position distinctly and accurately (Gold, 2006). It is important to note where the location of the watershed is using GIS data and topographic maps. Once this is known, investigating land uses is helpful in finding a source for the runoff (Environmental Protection Agency, 2014).

2.4.4 Water Quality

The water quality in a pond or lake is often defined using specific variables such as the pH, dissolved oxygen, temperature, and sediment make-up that all affect the quality of the water. It is especially difficult to address one issue without being led into another that also needs to be investigated and addressed. The successful management and long-term solutions could provide beneficial results if executed effectively. In order to test the water quality, it is best to take many samples over time and evaluate the data. Depending on the pH levels, temperature, and sediments, this data could be valuable in deciding where the major problems lie (Waite, T. D., et al. 1984). These measurements could allow comparisons between a water body of interest and other bodies of water, which could provide beneficial information about the watershed being observed. Water flowrates, point and nonpoint source pollution, geography, and invasive species are vital factors that affect the water quality in substantial ways.

The water flowrates are vital factors for determining what enters and leaves the watershed. By knowing the activities conducted in the watershed area, one can then track and map many of the pollutant sources. In urban areas, this information may be challenging to assess because greater runoff volumes are generated from paved streets and parking lots. Therefore, controlling runoff from these areas is often helpful in controlling NPS pollution (Environmental Protection Agency. Office of Water, 2008).

2.5 Invasive Species Characteristics

Invasive species are a major issue in water quality control and management. Aquatic weeds such as water milfoil (*Myriophyllum),* coontail (*Ceratophyllum demersum*), and water chestnuts (*Trapa natans*) contribute to major problems that can spread throughout the watershed. A non-native species population can grow exponentially because it does not have a natural check or a predator to keep its numbers low and at equilibrium. The rapid spread of this invasive species could result in the displacement of native species, reducing the biodiversity of the infested bodies of water (Robinson, 2002). Invasive aquatic plants also drain the water and soil of nutrients and food resulting in fewer numbers of native plant species. More information regarding the nutrients that plants need to survive can be found in the appendix.

2.6 Characteristics of Water Chestnuts

The most prominent invasive species at Coes Reservoir is the European water chestnut (*Trapa natans*). It is not documented how exactly they infiltrated Coes, but research suggests they traveled down streams across New England, starting in Cambridge ("Water Chestnut (*Trapa natans L.*)," n.d.). Figure 1 shows where some of the densest clusters currently growing in Coes Reservoir are located. Given the impacts that the water chestnut has on the Reservoir and the importance in controlling this plant, this section provides information on the characteristics of the water chestnut.

Figure 1. Water chestnuts in Coes Reservoir, circled in white (Roger Parent, personal communication, interview on October 7, 2015).

Water chestnuts are found in Europe, Asia, Africa, and eastern North America. They live in "full sun and low-energy, nutrient-rich fresh waters", that range from 0.3 to 3.6 meters (m) deep (Mikulyuk & Nault, 2009). The plants live in freshwater because of "the seeds failure to germinate when salt concentrations surpass 0.1%" (Hummel & Kiviat, 2015). They thrive in shallow water such as ponds, lakes, and swampy areas with sediments in which their seeds can remain until germination. These freshwater plants "thrive in bodies of nutrient-rich water with a pH range of 6.7 to 8.2 and an alkalinity of 12 to 128 milligrams per liter of Calcium Carbonate" (Akash, Jasmine, & Shalabh, 2012). The water chestnut seeds can survive annual weather conditions and are hidden within the sediment bed of the body of water. “The species is disturbance-tolerant; it has been shown that sewage inputs create favorable conditions of increased alkalinity for the plant, and that increased nitrogen is correlated with increased petiole and fruit biomass” (Mikulyuk & Nault, 2009).

The water chestnut, also called the horned water chestnut or the water caltrop, is “an invasive aquatic plant released inadvertently into waters of the Northeast in the late 1800s”, and has spread throughout most of the Northeastern United States (“Water Chestnut (*Trapa natans L.*),” n.d.). It grows in thick populations that are nearly impenetrable from the surface of the water. Fish and waterfowl rarely eat the plants or seeds (Mikulyuk & Nault, 2009).

2.6.1 Why are They Considered Invasive?

Trapa natans are considered invasive species to habitats across North America for several reasons. Invasive species are non-indigenous to the land they infiltrate (“Invasive Species in a Changing World,” 2015). Most species do not survive in non-native environments due to several factors such as not adapting to a new environment. However, certain species like the water chestnut become labeled as “invasive” because they quickly adapt and thrive within a new environment without any natural predators. Journalists in North America tend to use descriptive terms such as “outbreak” or “take over” to explain their population growth. With a large population, the water chestnut can inflict environmental and economic damage on the community and water body. Environmental issues range from deprivation of oxygen in the water and sediment accumulation due to decomposition of dead aquatic weeds. Lastly, water chestnuts have “dependence on the ability to respond to natural selection versus physiological tolerance” (Marcel & Richardson, 2015). Natural selection refers to generations of species reproducing, which helped to adapt to habitats. Physiological tolerance is when organisms themselves bare the harsh elements of foreign lands. The water chestnuts belong to the *Trapa* family that has numerous species with distinct differences in the morphology of the fruits, which show that they depend on their response to natural selection (Marcel & Richardson, 2015).

2.6.2 Physical Description

The water chestnut is a rooted invasive herb that grows at the bottom of lakes or ponds. The leaves seen on the surface are 2-4 centimeters (cm) long and are green and flat. The leaves on the water chestnut submerged in water contain the seedlings. These leaves are much bigger and can grow to be approximately 15 cm long. The seeds can grow 2-4 cm long and are covered in spikes. The stems can reach massive lengths of up to 4.9 m, but normally are found in the 1.8-2.4 m range. In the middle of the water chestnut are white flowers ("Water Chestnut (*Trapa natans L.*)," n.d.). Figures 2 and 3 show what they look like.

Figure 2. Water chestnut drawing, with seed (U.S. Fish & Wildlife Service, 2010).

Figure 3. Size comparison of a hand and a water chestnut (Confrancesco, n.d.).

In the Northeastern states during the month of May, the small budding rosettes remain submerged as the stems and roots elongate to reach the water's surface. From June to September the rosettes begin to bud, where leaves bloom at a constant rate of one leaf per rosette per unit of time, which lasts about one month. The fruits mature from mid-July into September and are released by the rotting peduncles (Hummel, M. & Kiviat, E. 2015). The plants start making fruits in July and ripen into a seed after a month. The seeds then fall into the sediment below the water chestnuts, where they can start growing within a period of twelve years. One seed is capable of producing ten to fifteen plants, while one plant can produce up to twenty seeds (Robinson, 2002). When the seeds become too old, they rise to the top of the water. If the plants were to move downstream, the seeds still attached to the plant will move with them ("Water Chestnut (*Trapa natans L*.)," n.d.). The plants themselves rot and decompose on the bottom of the lake or pond at the end of the growing season (Robinson, 2002).

2.6.3 Origin

The water chestnut was first brought to North America in the 1870s. It was first introduced to the Cambridge botanical garden at Harvard University, and was later brought into other ponds and the Hudson River. As time passed, the water chestnuts moved down stream and travelled across rivers into other bodies of water all around New England ("Water Chestnut (*Trapa natans L.*)," n.d.). Figure 4 shows the distribution of the water chestnut in the United States.

Figure 4. Water chestnut distribution in North America, as of September 2014 (U.S. Department of Agriculture, 2014).

Millions of dollars have been spent to stop the water chestnut from taking over aquatic ecosystems in the United States. Many of these efforts prove to be insufficient because they cannot provide long-term relief from this invasive species.

2.6.4 Natural Predators and Diseases

In Europe, Asia, and Africa, there are native insects and parasites that eat the water chestnut ("Water Chestnut (*Trapa natans L.*)," n.d.). Some of these insects include weevils (*Curculionidae*), leaf beetles (*Chrysomelidae*), and snout moths (*Pyralidae*) (Pemberton 2004). These insects are not present in North America, however, which is one reason why the water chestnut population can get out of control at times ("Water Chestnut (*Trapa natans L.*)," n.d.). Bringing these insects over to this country to get rid of the water chestnut will not work. It is too expensive to import these insects. Additionally, these insects do not solely live off *Trapa natans*, so there is no guarantee they will even remotely improve the issue. There is also a disease that can be transferred to the water chestnut by a fungus (*Bipolaris tetramera*). It affects the leaves of the plant and can kill it (Pemberton, 2004).

These causes of death cannot be duplicated in the United States. The seeds are dropped during the summer, before the plant naturally dies in the autumn, so several more water chestnuts will grow in its place the following year. Since they are an invasive species, external removal options must be implemented to get rid of them.

2.6.5 Threats to the Body of Water

The mere presence of this plant species poses a threat to the environment, dominating areas wherever the seeds can take refuge in the soil. The seeds themselves can penetrate shoes with their barbs, which is hazardous to unsuspecting swimmers and fisherman. The water chestnut can prohibit recreational activities and displace native vegetation and other organisms in the body of water (Arim, 2006). The leaves of the water chestnut form thick dense mats, which block out sunlight and restrict photosynthesis to the plants below. This diminishes carbon dioxide consumption and oxygen production, making the areas known as "dead-zones," (Hummel & Kiviat, 2015). The leaves also trap organic material creating silt, which can harbor mosquitos and lead to an increase in sediment levels (Michelle, 2002). The increase in sediment levels can lead to a decrease in property value for residencies around the body of water (Hoyle & Kay, 2001).

2.6.6 Comparable Species

Another invasive aquatic weed, the water hyacinth (*Eichhornia crassipes*), infiltrates waterways around the world, and is very similar to the water chestnut. The water hyacinth is a free-floating weed consisting of broad leaves and rigid seedlings. The seeds can remain fertile for at least twenty years, while the plant itself can double its biomass every five days (Department of Primary Industries, 2015). Its broad leaves can form dense mats that mitigate native aquatic plant populations, restrict recreational use of waterways, and restrict sunlight (Department of Primary Industries, 2015). These outcomes have negative effects on the overall water quality, oxygen levels, and the community. The water hyacinth can be removed via physical removal, drawdowns, chemical treatments, and biological control.

Water chestnuts (*Trapa natans*), water hyacinths (*Eichhornia crassipes*), water milfoil (*Myriophyllum*), and coontail (*Ceratophyllum demersum*) are all present at Coes Reservoir. However, there is no one removal treatment that is effective for all of them. Water chestnuts grow during the summer, let go of their seeds between June and August, and die in the autumn. Their seeds can live up to twelve years. Hence, removal treatments must be done during the summer, and consistently, so that plants that bloom at different times will not be able to let their seeds fall. The water hyacinths, water milfoil, and coontail reproduce differently. These plants can essentially grow year round, and they do not drop their seeds, so removal methods can be applied any time (John Ferrarone, personal communication, February 16, 2016).

2.7 Coes Reservoir: In Need of Restoration

Recently, efforts have been made to restore Coes Reservoir to its original quality back when it was created in the 1800s. Starting in 2014, stakeholders have been trying to get Massachusetts more involved in dealing with the water quality because the state has more money and resources than any committee can provide. Stakeholders are encouraging the community to become educated about the water quality issues around Worcester, more specifically Coes Reservoir. If local people become aware that invasive species, pollution, and sediment runoff affect swimming, fishing, and other recreational activities, then they could put more of a demand that these issues be resolved (Worcester Magazine, 2014). Students from local colleges like Worcester Polytechnic Institute and Clark University have been studying these issues and are trying to come up with long-term remedies (John Ferrarone, personal communication, September 30, 2015).

2.7.1 Master Plan – Effort in Restoring the Area

Coes Reservoir has its limitations regarding public use. The Worcester community recognized that there were several problems regarding the quality of the area surrounding Coes Reservoir. This led to a master plan being constructed in 2006. It was made as a collaborative effort between the City of Worcester Department of Public Works and Parks, Weston & Sampson Engineers, Inc. and community stakeholders. The master plan was drafted to improve the public open space surrounding Coes, as asked for by local neighborhoods and residents. Key points of emphasis in the master plan were to redesign the playgrounds and beaches to make it more accessible to handicapped people, improve recreational opportunities, adding apartments around the reservoir, and educating local people and schools about the matters (City of Worcester Department of Public Works and Parks, 2006). Other master plans have been proposed at Coes Reservoir, which were essentially revisions of the first one, but they were never pursued (John Ferrarone, personal communication, October 7, 2015). These ideas are important when dealing with the current water quality issues because it shows that multiple stakeholders want Coes Reservoir to be restored. More scientific analysis is necessary to assess the water quality and facilitate progress.

In 2014, the Friends of Coes Reservoir committee was formed. Their goal was to make the area surrounding Coes Reservoir safer and cleaner. A website was launched to give the community updates and to have a better way to organize information. The Friends of Coes Reservoir was divided into three main committees. The park committee was to "discuss, plan and advise on the construction of Coes Reservoir's Inclusive Park and Playground" (Rosen, 2014). The reservoir committee was to "deal with the Mill St. Beach (including parking, bathhouse, dredging, signage, swimming, kayaking, etc.) and all water quality issues associated with Coes and neighboring water bodies, dam, etc.," (Rosen, 2014). Finally, the publicity and public relations committee was to "deal with all publicity, public relations, education, fundraising, politicking and lobbying at the local, state and federal levels" (Rosen, 2014). Due to the growing support from the community and other towns, the Friends of Coes Reservoir eventually divided into two new groups: the Coes Zone Task Force and the Tatnuck Brook Watershed Association (John Ferrarone, personal communication, September 30, 2015).

As of October 2015, only the Mill Street beach was improved from the master plan. It got new sand for the beach along with newly painted benches (John Ferrarone, personal communication, October 7, 2015). Monthly meetings organized by the Tatnuck Brook Watershed Association were held to talk about the issues of Coes Reservoir. They say the perimeter of the reservoir is acceptable the way it is now, and that the focus needs to change on more important issues, such as water quality (John Ferrarone, personal communication, October 7, 2015). They decided that there were too many water chestnuts (*Trapa natans*) in the reservoir and that they must be removed. Water chestnuts are invasive plants that affect water quality. By removing them, it will help to alleviate the water quality issues they cause. It also benefits the people that live around the reservoir by increasing their house's net worth and making the pond look cleaner (Lance Mckee, personal communication, October 1, 2015).

2.8 Invasive Weed Removal Treatments

There are many ways to treat the threat of invasive weeds such as physical removal (mechanical harvesting and hand-pulling), drawdowns, herbicides, and aeration techniques combined with bioremediation.

Physical removal is the process of manually removing the water chestnuts from the reservoir and disposing them on land. Mechanical harvesting is the process of using a large machine and removing large sums of weeds. This can also be paired with hand-pulling, a technique to remove the invasive weeds by hand.

Occasionally, drawdowns are employed as an effective treatment to remediate specific water quality issues. The relocation of the water must be carefully planned in order to prevent flooding and other disasters to the residents and environment downstream (Robinson, 2002). Also it is necessary to be sure the wildlife in the area will not be harmed (Su, X. et al 2012). Drawdowns do not typically treat water chestnuts because they are usually performed after the water chestnuts drop their seeds (John Ferrarone, personal communication, February 16, 2016).

Another option is to use chemicals and directly spray and kill the plants. This method also carries risks since the chemicals being used could have serious negative effects on the native organisms (Kaufman et al. 2011).

Aeration is commonly used to increase the dissolved oxygen in lakes and ponds and has been successfully implemented in many water bodies. Aeration can also be combined with bioremediation to more effectively improve water quality.

"The economic cost of *T. natans* in the northeastern United States was not well documented (Pemberton, 2002), but we do know that from 1982 to 2001, $4.3 million dollars were spent on *T. natans* control in the Lake Champlain basin alone (Naylor, 2003). The largest control program, which takes place in Vermont, was estimated to cost $500,000 in the year 2000 (Pemberton, 2002)," (Mikulyuk & Nault, 2009). These large costs play serious roles in the removal efforts of water chestnuts. If there are not enough funds present from the community or local government, then the spread of these invasive species will continue to increase. It is important to determine a cost effective, yet long-lasting solution in order to successfully remove these weeds. When assessing treatments, it is important to consider the likeliness of success, cost, negative effects, immediate results time, and other various categories regarding the application of the methods.

2.8.1 Physical Removal

The most basic method is the physical removal of the water chestnuts. Once removed, people would need to dispose them, where they can either be thrown away or decompose naturally on land. There are two ways that water chestnuts can be physically removed – mechanical harvesting and hand-pulling.

2.8.1.1 Mechanical Harvesting

Mechanical harvesting is the removal of invasive weeds by a large machine called a mechanical harvester, shown in Figure 5. These machines float on the water, run through weeds, cut them low enough so that their seeds are taken, and store them in the machine itself. The weeds are then taken to land where they can be disposed. In order for this to be a viable method of removal, it must be done before the seeds of the water chestnut mature, which happens around the middle of August. Most mechanical harvesters cannot access shallow areas or coves. Instead they need to run in the deeper, more open parts of the reservoir ("Water Chestnut (*Trapa natans L.*)," n.d.).

Figure 5. Typical mechanical harvester (Goehle, 2011).

Harvesters can vary in shape, but their functions are nearly identical. One type of harvester is a hydro-rake, which is “a floating backhoe, propelled by wheels, with a large rake attached to its bow. It operates by scratching the bottom of a selected area to remove plants. Hydro-rakes are able to operate in shallow areas, and can access the shores” (“Charles River Watershed Association,” 2015). Hydro-rakes function better than a typical mechanical harvester, but are more expensive (“Charles River Watershed Association,” 2015).

The immediate effects of using mechanical harvesting are that all plants on the surface will be gone, but this will not be permanent until there are no more seeds present in the watershed. Mechanical pulling needs to be done at least once a month during the growing season (John Ferrarone, personal communication, September 30, 2015). This ensures that new seeds will not drop down to the ground below. Every seed produces up to fifteen plants, so removing seeds is just as important as removing the plant (“Water Chestnut (*Trapa natans L.*),” n.d.). A machine should be used in large populations, but hand-pulling can be used in smaller areas or places that are difficult to access (Mikulyuk & Nault, 2009). The machines pull up any plant it goes over, so if there are other plants around a population of water chestnuts, they will go too. The plants are collected in the back of the mechanical harvester (“Water Chestnut (*Trapa natans L.*),” n.d.).

Mechanical harvesting also has some limitations. If the roots of the plant are not removed, then the plant can grow back. If the root or seeds fall out of the machine, then they can regrow elsewhere. John Tucci, president of the water management company Lake Savers, claims that these weeds can grow back even faster if they are just simply trimmed (Tucci, 2013). The mechanical harvester cannot differentiate different species of plants. As a result, if any other plant species are collected in a mechanical harvester, they will be killed as well. Aquatic life in general is in danger of being killed by a mechanical harvester. Renting a machine can be very expensive, costing thousands of dollars every time it cleans a watershed. They can be physically exhausting as well ("Water Chestnut (*Trapa natans L.*)," n.d.). Finally, this method can take up to twelve years for lasting results to be shown. It has to be done consistently so that no additional seeds will drop down in that time span.

2.8.1.2 Hand-Pulling

Water chestnuts can be removed by hand-pulling (Figure 6) since they are not strongly rooted. Hand-pulling can be completed in areas where mechanical harvesting machines cannot reach, such as in shallow depths and in small coves. It can be done throughout the whole reservoir, but the amount of people required and/or the amount of work they would have to do is unrealistic.

Figure 6. Hand-pulling water chestnuts at Coes Reservoir in 2011 (Ide, 2011).

Hand-pulling must be done carefully in order to avoid injury via the plant seeds. Guidelines can be followed (Water Chestnut (*Trapa natans*) Control, n.d.), which include:

- Remove prior to seed maturation, which occurs in the middle of August.
- Grab as low as possible.
- Do not start in the middle of the water chestnut population. Work your way inside.
- Dispose the land by trash or let them decompose on the land
- Wear old sneakers if you wade in the water.
- Wear gloves

This method of removal certainly has its benefits. It is most useful when done at the same time as mechanical harvesting, since that will cover as much area in as little time as possible. As long as the seeds are removed, then the plant will not grow back. It can be done by the community, either as a volunteer or paid effort (“Invasive Water Chestnut Harvesting,” 2015). Either way, the cost will be much less than the other treatment options. It also has immediate results, whereas with chemical spraying, for example, it takes longer to see the plants die.

Hand-pulling can be more work than other treatment options for weed removal. It involves physical labor and you can risk getting infections from the water if you are not careful. Hand-pulling can only be done prior to the middle of August effectively, so the time window is rather small. If performed later, then plants could drop their seeds. Hand-pulling needs to be repeated several times in that span in case some plants sprout later. If the seeds mature, then the plants will still come back the next year, so it is important to remove them with their seeds attached.

2.8.2 Drawdowns

Some invasive plants can be treated by shearing them during a drawdown. This method entails the release of water downstream in order to reduce water levels, shown in Figure 7. Drawdowns are usually done to prepare for a storm that will have a high amount of precipitation. However, they can be done to expose plant roots to freezing and loss of water, so that they can either be killed or removed. This only applies to plants on the shore ("Control – Water Level Drawdown," n.d.).

Figure 7. A drawdown being performed in the winter at St. Anthony Falls in Mississippi (Webster, 2015).

Dams are usually opened to release the water, but in cases where the body of water does not have a dam, then a pump can be used instead. Pumps generally take 2-3 weeks longer to lower the water the same amount a dam could, which can lower as quickly as 6 feet in two days. It takes several months to get a drawdown approved because biologists and botanists need to inspect the water to see if it will affect biodiversity severely. In the case where a drawdown is done to prepare for large volumes of precipitation, it only takes a few days to get approval since no inspection is needed. Permits are required to perform a drawdown, which can be purchased for roughly $3000 for a three-year or five-year renewal plan at Coes Reservoir. The city's watershed committees are usually in charge of performing drawdowns, but they still need approval from the city (John Ferrarone, personal communication, interview on February 16, 2016).

Diverse species of plants can respond differently to drawdowns, ultimately depending on how they grow and reproduce. A study by Dennis Cooke done in 1980 shows how various plants were affected. Invasive weeds that decreased in abundance included the watershield (*Brasenia*), pondweed (*Potamogeton*), yellow water lily (*Nuphar*), white water lily (*Nymphea*), spike rush

(*Eleocharis*), water milfoil (*Myriophyllum spp*) and pickerelweed (*Pontedaria*). The three invasive weeds that had no change were bladderwort (*Utricularia*), bur-reed (*Sparganium*) and tape grass (*Vallisneria*). The invasive weeds that increased in abundance were bulrush (*Scirpus*), arrowhead (*Sagittaria*) and 3-way sedge (*Dulichium*) (Control – Water Level Drawdown, n.d.). Notably, the study did not include water chestnuts (*Trapa natans*).

According to John Ferrarone, vice president of the Tatnuck Brook Watershed Association, drawdowns do not affect water chestnuts. This is because they grow and reproduce differently. Invasive weeds treated by drawdowns, such as coontail, reproduce during the winter because they drop turions to the bottom of the water during this period, which eventually develop into new plants in the spring. These types of drawdowns usually occur during October and shear the plants, killing them completely and not allowing them to drop turions. However, water chestnuts grow during the summer and drop their seeds then. Drawdowns done in October would be pointless since those water chestnuts are naturally dead and have already dropped their seeds. The seeds cannot be extracted if they are buried in the muck. If drawdowns were to be done during the summer, they would need to be done multiple times for late bloomers, which is unreasonable (John Ferrarone, personal communication, interview on February 16, 2016).

In order for a drawdown to be successful, several things must be taken into account. First, the amount that would be required to expose the invasive plants is important. Too little would not affect all the invasive plants, and too much could affect other organisms. A level that can expose the roots of the plant to the outside elements is ideal (Robinson, 2002). Second is that the water level must be lowered slowly so that wildlife can adapt to the new water level and water pressure. Third, careful planning must be applied throughout the time period when the drawdown is in effect. Winter drawdowns have to be active longer because of the snow and ice. If the water levels remain too low for too long, it could affect aquatic life. A drawdown would need to be performed at least once a year for invasive weed species to be managed ("Lake Drawdown for Aquatic Plant Control," n.d.). Also, if not done correctly, the snow could act as an insulator and not even kill the plants. Fourth, the people that run the drawdown must get permission from the city several months in advance so inspections can take place (John Ferrarone, personal communication, interview on February 16, 2016).

There are several benefits to implementing drawdowns every year. For one, they can remove invasive plants in a cost-effective manner. If the invasive weeds are removed, then native aquatic plants will grow in their population sizes. Loose sediments can fuse to the ground and become hard. Also, people can repair structures that are on the body of water that could not otherwise be fixed ("Control – Water Level Drawdown," n.d.).

Unfortunately, drawdowns have several negative effects that can eliminate them from being a viable long-term treatment. Lower water levels can affect nearby water wells, boat launching, and the pond aesthetics. They can drastically affect wildlife by "making it difficult to establish native aquatic plants for fish, wildlife, and waterfowl habitats" ("Control – Water Level Drawdown," n.d.). Some invasive plants have been proven to grow more. It is best to do drawdowns in the growing season, to kill the roots and to kill/remove the seeds. Otherwise, if done during the winter, the seeds from the plant will have already fallen off, so further seed removal efforts would have to be done ("Control – Water Level Drawdown," n.d.). Food web changes will happen, which results in an increase or decrease in aquatic organism populations. Additional algal or cyanobacteria blooms can occur, which are very toxic to humans ("Lake Drawdown for Aquatic Plant Control," n.d.). They also might affect downstream conditions if the drawdown is applied to a body of water connecting to a river (Robinson, 2002). Oxygen concentrations can decrease.

Sediments might be relocated and cause depth issues in other regions of the body of water ("Lake Drawdown for Aquatic Plant Control," n.d.). If water levels are lowered too quickly, flooding could happen downstream.

2.8.3 Herbicides

Invasive aquatic weeds are an issue that can be resolved using chemical removal, otherwise known as herbicidal treatment. There are two types of chemical treatment options, each having their own application technique for different scenarios. The first, being more applicable for a small number of aquatic plants, is known as "contact chemicals". Contact chemicals are put directly onto each individual plant and kill whatever part it comes into contact with. Examples of contact herbicides are diquat, endothall, and flumioxazin (Wagner, 2015). The second case is called a "systemic application" that is performed over an area of infestation. Systemic applications are spread through an area, then absorbed by the plant's roots and stems which causes it to die. Examples of systemic application herbicides are glyphosate, triclopyr, and fluridone (Wagner, 2015).

If herbicidal treatment is considered an option, rigorous tasks need completion to initiate the process. A biological survey must be compiled, including bathymetry, the invasive species of interest, and any organisms of concern (Aquatic Control Technology, 2015). The use of herbicides for several states in the United States require a permit which could take an average of six months to obtain (Samuels, 2004). In Massachusetts a contractor must be hired in order to safely and accurately apply the herbicide. Aquatic Control Technology LLC claims that the price per acre of infestation is $400-$600 (D. Meringolo, personal communication, January 12th, 2016). The price is minimal compared to other removal efforts such as dredging, or even mechanical harvesting

(Aquatic Control Technology, 2015). "Very few techniques can get a plant infestation under control quickly and at reasonable cost the way herbicides can, when properly chosen and applied" (Wagner, 2015). Herbicides must be applied and monitored for the "long-term", usually over an average of ten to twenty years. In the long run herbicides could be expensive to apply and monitor, however it is proven effective and the risks of weeds gaining resilience are low (Wagner, 2015).

The use of herbicides raises questions about its risks to the environment, the health of native species, and any negative effects on humans. Chemical treatments on lakes or ponds have proven not to effect the shoreline nor do they affect the sediments on the bottom of the water body ("Solitude Lake Management," 2015). However, if any organism comes into contact with the chemicals, irritation and hospitalization can occur with humans. Fatality can occur with fish and native plant species ("Solitude Lake Management," 2015).

2.8.3.1 Fluridone

Sonar A.S., or Fluridone, is a systemic chemical removal treatment for lakes, ponds, and reservoirs to control invasive aquatic weeds such as Eurasian watermilfoil, water-lily, and common coontail. This herbicide is selective in species depending on the amount used, season of the year, and water movement ("Solitude Lake Management," 2015). When treating a portion of the lake, Sonar A.S. should be a minimum of five-acres in size. "SePRO recommends contacting an aquatic specialist in determining when to choose application rates lower in the rate range to meet specific plant management goals" ("Solitude Lake Management," 2015). In the case of heavy rain fall the herbicide can be diluted, requiring a second or more applications to achieve desired effects ("Solitude Lake Management," 2015).

2.8.3.2 Triclopyr

Renovate OTF, or Triclopyr, is a systemic chemical treatment for lakes, reservoirs, and ponds that controls invasive aquatic weeds such as hybrid milfoil, alligatorweed, and the water chestnut. Triclopyr is applied using a mechanical spreader to the surface of the water for floating weeds. This herbicide must be applied per annual season while the weeds are growing to achieve best results. “It is impossible to eliminate all risks associated with use of this product,” (“Solitude Lake Management,” 2012). Plant injury and unintended results for the treatment are just a few consequences if Triclopyr is not applied properly (“Solitude Lake Management,” 2012).

2.8.3.3 Dichlorophenoxyacetic Acid

Navigate, or 2, 4-Dichlorophenoxyacetic Acid, is a successfully proven chemical treatment for ponds, reservoirs, and lakes that controls invasive aquatic weeds such as water milfoil, water stargrass, and the water chestnut. This herbicide “resists rapid decomposition in water, sinks quickly to lake or pond bottoms and release the weed killing chemical into the critical root zone area” (“Specimen Label,” 2013). This must be applied during the spring or early summer months, when the weeds begin growing, for optimum results. A minimum of roughly twenty-one day intervals between applications, and only two applications are permitted per season (“Specimen Label,” 2013).

2.8.4 Aeration and Bioremediation

Aeration is the process of putting “air or gas into something, such as soil or a liquid” (Merriam Webster Online, n.d.). Some bodies of water have low dissolved oxygen levels, and aeration is a common technique that can resolve the issue. It has been successfully implemented in many water bodies.

Invasive plants can thrive off excess phosphorus and nitrogen levels. Bioremediation balances the nutrient levels in the water by using beneficial bacteria to remove phosphorus and nitrogen. The combination of these two methods provides a promising approach when used to decrease the invasive species in a water body.

2.8.4.1 Aeration

Reviving the lake is the first step in promoting long-term success. The muck at the bottom of a lake is more than just a minor nuisance. When weed and algae growth continue to take over a lake, they also die and descend to the bottom where they begin to accumulate. This buildup not only decreases the depth of water of the lake, but also suffocates it by consuming the dissolved oxygen. As the dissolved oxygen continues to be deprived, the decaying weeds become muck.

Increasing the dissolved oxygen in a lake is necessary for the water quality to improve. Aeration can successfully accomplish this task by injecting air or pure oxygen, as well as mechanically mixing or agitating the water (Notes, 1997). Naturally, lakes and other water bodies receive their oxygen from the atmosphere from a process known as diffusion (Notes, 1997). Diffusion is the process of spreading and combining two or more different molecules from a more concentrated environment to a less concentrated environment. Diffusion is also a spontaneous process, which means proper application must be conducted when preforming artificial circulation (Bailey, 2014).

When a lake is unable to properly supply itself with oxygen obtained from the atmosphere, artificial aeration can be used to achieve this goal. This method interacts with the water in the lake in a way that circulates it, allowing the water to reach the surface where there is a greater amount of oxygen present. The process of destratifying a lake is accomplished by completely mixing all the water in the lake in order to prevent the stratification of the lake during the summer months. There are three different types of aeration that are commonly used to achieve the goal of destratification including air compressors, spray units, and impellor-aspirators systems. These three methods will be explored in the subsections below.

2.8.4.1.1 Air Compressors

Stratified lakes could cause temperature variations in the different layers of water, which directly impacts the ecosystem. Two different applications are used to achieve this goal, air injection diffusers and mechanical mixing. Both of these processes will result in the same goal, but use different executions for solving the problem (Notes, 1997).

The air injection diffuser is located on shore and is attached to pipes that are located in the deeper areas of the water body near the bottom. The end of the pipe should be above any muck, otherwise air released from the pipe can stir up loose sediments, potentially increasing muck depth altogether. Once the machine is powered on, it releases air directly into the water, which allows for the cooler air located towards the bottom of the lake, or the hypolimnion, to rise to the warmer surface of the lake, or the epilimnion (Notes, 1997). The interaction of the air bubbles to the surface of the water and atmosphere is what delivers oxygen into the previously deprived water molecules. Eventually, the warmer and cooler parts of the water are diffused together in order to obtain a uniform temperature of the lake. This method has been successfully implemented numerous times at lifting and mixing previously stratified areas of water to create an increase in dissolved oxygen throughout the lake (Notes, 1997). Figure 8 explains what an air injection system can look like.

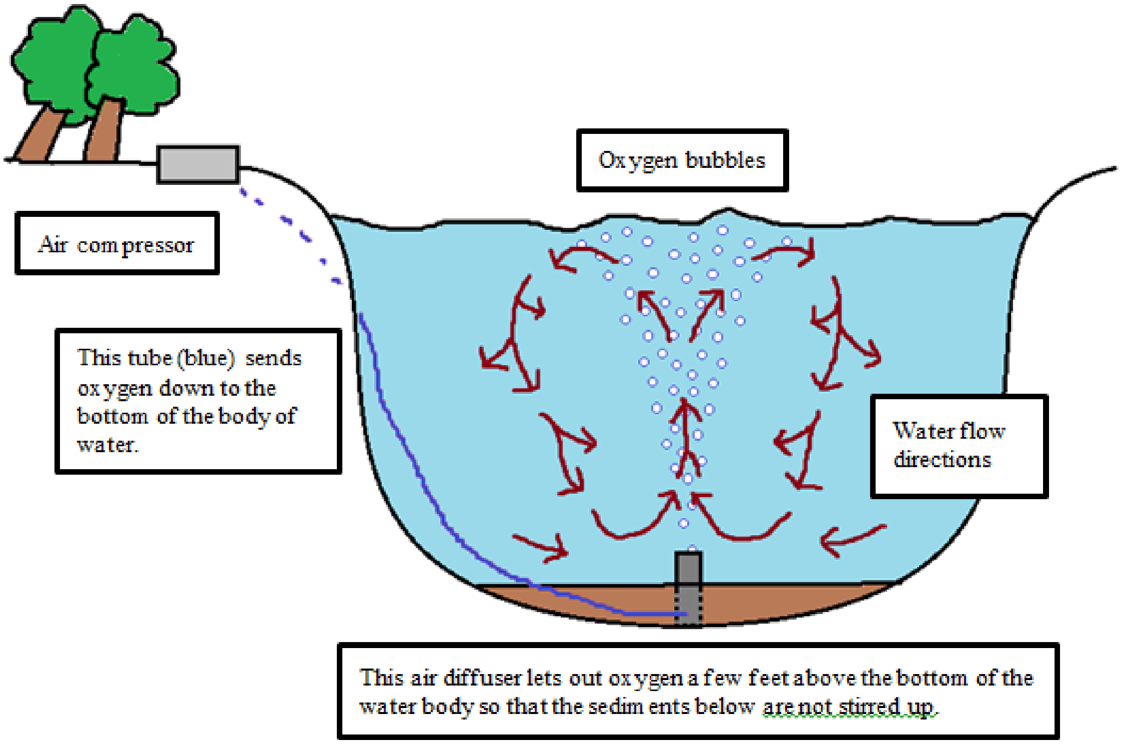

Figure 8. Air injection system. Adapted from (Md. Saidul Azam et al, 2014).

Mechanical axial flow pumps provide circulation starting from the top of the water and working its way increasingly deeper. A large propeller ranging from 6 feet to 15 feet is supported on a flotation platform that includes a frame, electric motor, drive shaft, and a gearbox (Notes, 1997). The propeller is located with proximity towards the surface of the lake in order to circulate the oxygen rich surface water with the deeper areas of the lake, as shown in Figure 9.

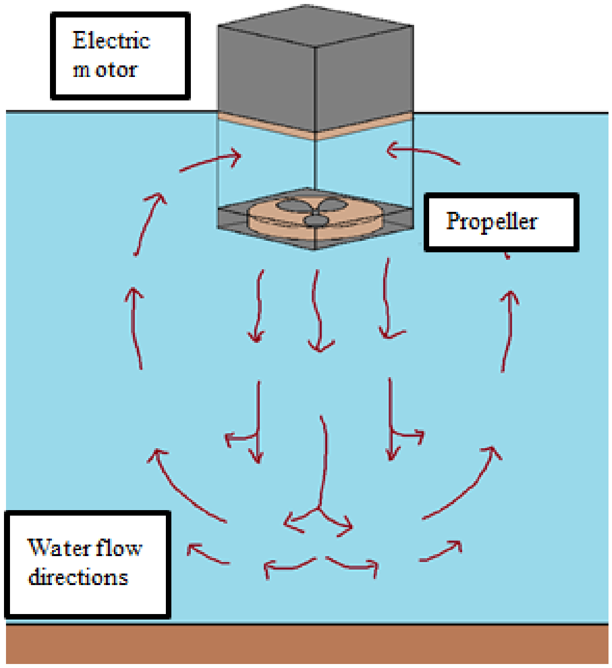

Figure 9. Mechanical axial flow pump. Adapted from (Products, E.P. 2011).

Mechanical axial flow pumps have a few drawbacks. For one, they are rather small and do not travel very far, so they do not cover a lot of the surface area of the body of water. Second, it is possible for the pumps to break if something crashed into it. Air injection systems are newer and favored over mechanical axial flow pumps, so these pumps are not implemented as often as they used to be (Notes, 1997).

2.8.4.1.2 Surface Spray and Impeller-Aspirator

Surface spray is a method that involves water being pulled up from a quickly spinning impeller and being ejected several feet in the air. This fountain-like method allows the water to receive more dissolved oxygen when it is in contact with the surface. However, in order to receive successful results, this application is limited to uses in lakes that are only up to 12 feet deep. If it is any deeper, then the oxygen cannot distribute to all the areas of the water body (Notes, 1997). Figure 10 explains what a surface spray system can look like.

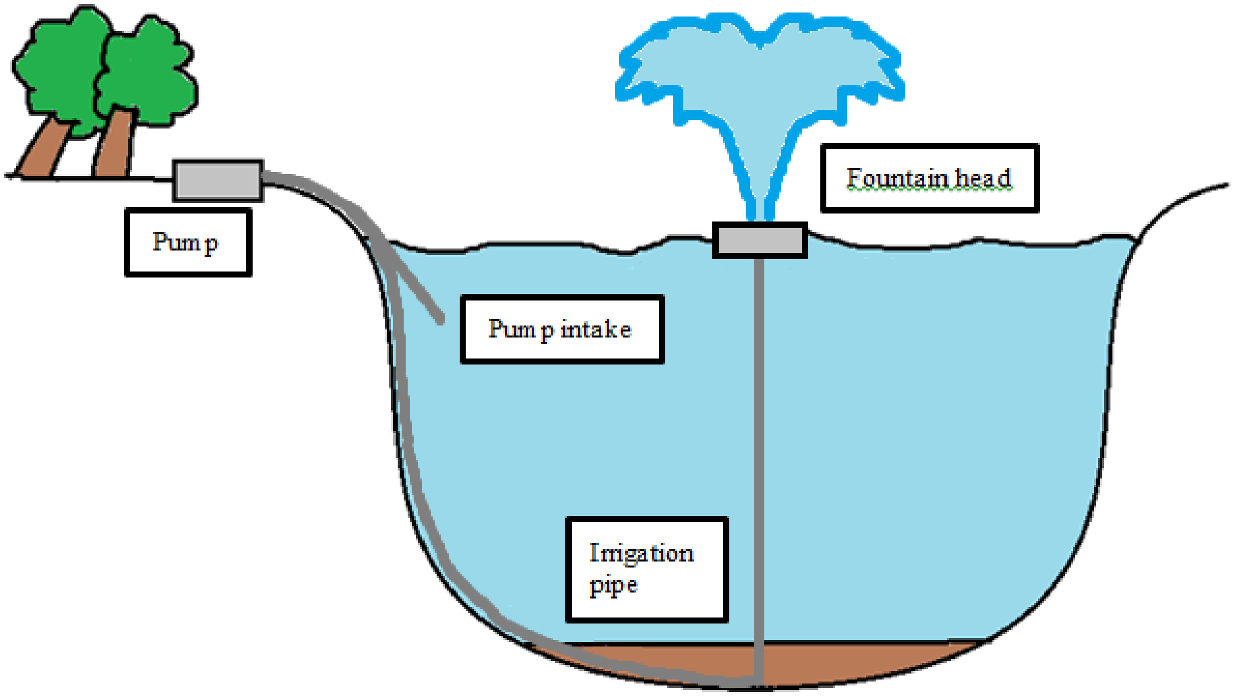

Figure 10. Surface spray system. Adapted from (Md. Saidul Azam et al, 2014)

The impeller-aspirator is similar to the surface spray mechanism since it includes an impeller that is powered by an electric motor as well. One significant difference between the two is the angle the hollow shaft is placed at the surface of the water, which allows air to be inserted into the deeper levels. The aeration is implemented when the air bubbles and the top layers of water diffuse (Notes, 1997). This mechanism is also limited to shallow lakes and is not commonly used anymore. Figure 11 explains what an air impeller-aspirator can look like.

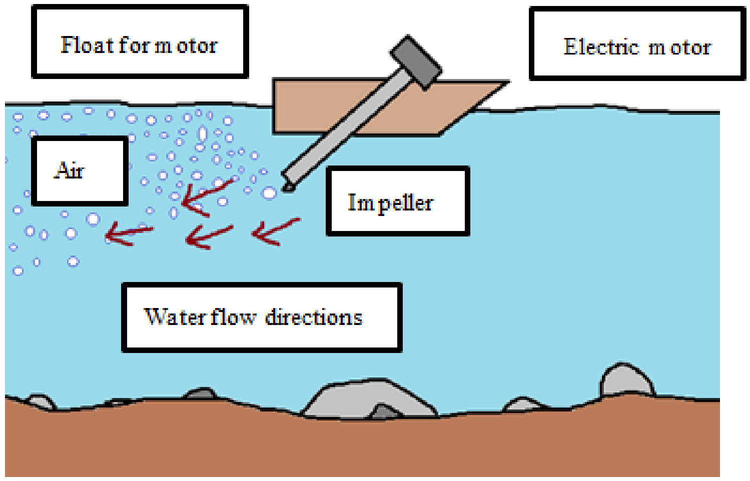

Figure 11. Impeller-aspirator. Adapted from (Md. Saidul Azam et al, 2014)

2.8.4.1.3 Risk of Aeration

The use of artificial circulation in a lake can provide help in receiving increased amounts of dissolved oxygen that has a stimulating effect on the surrounding ecosystem. Although this rise of dissolved oxygen is beneficial, many circumstances must be taken into consideration before choosing this method. Phosphorus levels and strategic designs must be carefully considered in order to successfully improve water quality.

During the summer seasons, phosphorus is naturally released into the colder, oxygen deprived water located at the bottom of the lake from the sediments due to an increase in solubility (Notes, 1997). When an artificial circulation system is used and the destratification process begins, the surface layers of water are now mixed into the bottom layers. Depending on the source of the phosphorous, the destratification process may potentially decrease phosphorous levels, or increase the levels of phosphorous at the surface of the lake, which can cause a destructive algal bloom (Notes, 1997). In deep, stratified lakes that contain phosphorous in anererobic sediments, a reduction in phosphorus may be possible. However, if the source of phosphorus is coming from an external source such as drainage pipes, runoff, or other sources of pollution, this decrease in phosphorous is unlikely (Notes, 1997).

Consulting an expert is essential when moving forward with artifical circulation. If the use of an air compressor is considered, it must be strategically placed in order to successfully aerate the lake. If the air compressor is located too high off the anerobic areas of the lake, it will be ineffective towards improving water quality (Notes, 1997). Another issue pertains to the sizing of the system being used. If the air compressor is not adequate for the lake, it will be ineffective. However, if the system is overdesigned and too large for the lake as well as located too close to the sediments, it will vigorously mix the sediments which can be catastrophic if the sediments contain hazardous elements such as metals (Notes, 1997). The proximity of the air injecter to the bottom of the lake also plays a role in spreading seeds that are imbedded in the sediments, which can possibly contribute to an increase in the coverage of invasive species.

An increase in dissovled oxygen levels will provide a healthier enviornment for beneficial bacteria to thrive, which can take part in consuming the unwanted nutrients. However, this may not provide enough support, which may need to be accomplished by discovering the source of the nutrients and implementing a solution in order to control this issue (“Clear as a Lake,” 2008).

2.8.4.1.4 Benefits of Aeration

Aeration is the major component in revitalizing a water body since it has a domino effect of positive benefits associated with it. This method increases the beneficial aerobic bacteria and microorganisms that can be attributed to consuming the muck. Substantial decreases in phosphorus and nitrogen levels from 30-50% have been reported, which directly correlates with a decrease in weed and algae growth (Tucci, 2013). Last, by introducing a healthy environment for aerobic bacteria in the lake, anaerobic bacteria begin to subside.

2.8.4.2 Bioremediation

Dissolved oxygen plays a crucial role in the health of a watershed. With low levels of dissolved oxygen in a lake, aerobic microbes cannot thrive. This effect can be felt across the ecosystem due to bacteria not being able to decompose organic material, insects not being able to mature, as well as fish not having a source of nutrition (Clark & Robinson, 1993). By first introducing an aeration system into the bottom of the lakebed, it allows these crucial microbes to be able to prosper and reduces the amount of muck as well as the phosphorus and nitrogen levels in the lake (Wu et al, 2014).

Water quality is significantly decreased with the presence of high phosphorus levels. Under these certain environmental conditions, phosphorus is released from the sediments, which could have detrimental effects on the temperature, pH levels, and dissolved oxygen levels (Wu et al, 2014). An increase in phosphorus from sediment release leads to a direct correlation with dissolved oxygen levels. Low dissolved oxygen levels are detrimental to fish and other aquatic species (Spietz et al, 2015). This type of water quality does not allow the ecosystem to flourish; instead, it contributes to the rise of invasive aquatic species that play a deadly role in water bodies.

Once dissolved oxygen levels in the lake have substantially improved, important bacteria and microbes are able to thrive. Diatoms and aerobic bacteria in the lake are responsible for consuming the muck that is present. Diatoms are a species of algae that comprise single transparent cell walls made of silicon dioxide. Diatoms are beneficial because they are the base of the fish food chain and provide food for a wide range of other aquatic species (Sweets, 2009). Other than being a food source for fish and other aquatic species, diatoms are effective in reducing the phosphorus and nitrogen that may reside in a water body (Sweets, 2009). Simply supplying air into the water of a water body is only a fraction of what needs to be accomplished. The increase in dissolved oxygen levels provides a healthier environment for microbes to prosper which benefits the water quality (Spietz et al, 2015). Once that the water quality has been improved to once again support microbes, diatoms are added to play a crucial role in the conversion of nutrients such as phosphorus, nitrogen, and carbon dioxide, which results in a further increase of dissolved oxygen. The presence of bigger fish due to the available amounts of nutrients results in the diatoms being consumed by fish and other aquatic life, instead of the invasive weeds.

Bioremediation can be accomplished by using a nano-silica based micronutrient formulation developed by various companies, such as Nualgi (Tucci, 2013). Nualgi is a nano-technology that enhances the sustainability of crop and fish growth as well as water treatment (Nualgi, 2014). A study was completed by the International Union of Biochemistry and Molecular Biology regarding the effectiveness of silica nanoparticles on microbial biomass. The study concluded with the fact that nano-silica plays a substantial role in influencing the quality of soil content by decreasing the sediment levels (Rangaraj, S. et al 2014). Depending on the severity of the water quality, a one-liter bottle can effectively treat 2-20 acres for as long as 1-4 weeks. Efficiently creating an influx of diatoms is affordable for most communities at the rate of $36 per acre (Tucci, 2013).

2.8.4.3 Lake Savers

The company Lake Savers uses a combination of well-known applications to remediate a body of water. Their four-step lake process includes advanced techniques to target issues such as invasive species, excess sediment accumulation, decreased dissolved oxygen, and increased phosphorous and nitrogen levels. Their sustainable methods do not just target the weeds, such as a chemical spray, but penetrate the source of the growth. This allows the lake to restore its own health and reduce a variety of problems.

The Lake Savers company started in 2007 to provide services to lakes suffering from invasive species, excess nutrients, or large sediment depths. The president, John Tucci, experienced rapid growth of water milfoil throughout the lake he lived on. After using chemical herbicide treatments for the lake, the problem worsened. As a result, Tucci developed the Lake Savers method consisting of four crucial steps in order to benefit the longevity and promote the restoration of a lake. It begins with first reviving the lake with aeration, followed by repairing it with bioremediation, protecting, and sustaining the watershed for long-term health.

2.8.4.4 Protection

The qualities of most watersheds do not start off in poor condition but are dependent on their location and land uses of surrounding areas. Due to the various reasons listed above (sec 2.4), an excess of nutrients and other sources of pollution could rapidly deteriorate a watershed. In order to prevent the same process from occurring again after the aeration system and beneficial bacteria have been implemented, it is important to protect the watershed. It takes a community effort in order to strategically avoid sending excess nutrients into the watershed. But this prevention can only be controlled to a point, since urban located watersheds have various sources of other pollutants.

Protection of a watershed could be achieved in many ways and can reduce the nutrient intake of the lake. Wetlands provide many diverse benefits to the health of a watershed such as filtering the water, controlling water levels, and purifying the water naturally (Guide, E. E. Healthy Watersheds, Healthy People, n.d.). One cost effective strategy used to mimic the wetland effects and achieve the same benefits is the use of lake coral. Using lake coral provides support to any degraded water body because it acts as a nutrient filter, fast tracks the growth of aerobic bacteria, and provides a sustainable habitat for diatoms to continue to regenerate (Tucci, 2013). This method could be installed quickly and effectively since the process is to simply drop the lake coral into the lake. In order to provide enough filtration throughout the lake, 250 pounds of lake coral is placed for every acre of wetland filtration (Tucci, 2013). With the use of this product and strategy the lake is able to filter the harmful nutrients and increase water quality.

Nutrizorb is another form of protection that has been adopted by the Lake Savers company due to its compatibility with aeration. Nutrizorb is a formulation of natural minerals with an active carbon layer that can be placed in the water in one of two ways, filter bags or a powder or a slurry mix (AerationTech, LLC. 2015). The many advantages associated with Nutrizorb are the chemical and electrical attractions created which draw in phosphorus and nitrogen due to the pore structure of Nutrizorb. This is a tremendous advantage since this application has successfully removed up to 30% of the phosphorus in as little as 30 days (AerationTech, LLC. 2015). The pore structure of this product allows nutrients to constantly continue to be absorbed, without the need of replacing any filters. This is accomplished by the fact that beneficial bacteria consume the nutrients trapped in the Nutrizorb, which cleans it out. Since this product is created from natural materials, it does not cause any harm or threat to the environment. Depending on the severity of the water quality, the price of Nutrizorb could range from 150-300 dollars per acre (AerationTech, LLC. 2015).

Chapter 3: Methods

The goal of our project was to assess the appropriateness of water chestnut removal techniques at Coes Reservoir in order to achieve long-term improvements in water quality. Based on the specific needs of Coes, we have developed the following project objectives in order to fulfill our project goal:

1. Research and establish connections between leading causes of the invasion of water chestnuts. This included plant characteristics such as origin, reproduction cycle, and preferred environment. It was also important to understand the root causes of this invasion and to determine if pollution, geographical location, or the nutrient levels in the water that contributed to this spread.
2. Build trust with the stakeholders and the Coes Reservoir communities in order to gain their perspective on the negative impacts and the harm caused. The residents and community surrounding Coes give useful suggestions throughout the lifetime of the project.
3. Determine the most applicable removal treatments for Coes Reservoir by examining how each treatment is used. Positive and negative possibilities, longevity of the treatment, and versatility play a major role in deciding the most effective treatment.
4. Develop case studies for similar bodies of water to Coes Reservoir. Creating graphs and tables and comparing all the data acquired will assist in the validity of the results.
5. Assess removal methods using surveys and analytical graphs to depict the most promising option for Coes Reservoir. Important variables such as likeliness of succeeding, versatility, cost, negative effects, safety, community labor, immediate results time, disposal methods, and equipment were considered.

3.1 Initiating the Research

The first objective of our research was to get familiar with Coes Reservoir and the water chestnut infestation. We made frequent site visits and attended several Tatnuck Brook Watershed Association (TBWA) meetings throughout the project. We collected information about topography, bathymetry, and even simple models of the entire watershed. The team took several day trips walking around, and also kayaking in Coes Reservoir to get a scope of the land and collect water samples. Residencies, main roads, and businesses surrounding Coes Reservoir assisted in possible sources of pollution and how far upstream the problem could be within the watershed. These factors were observed during the site visits and utilized to assess the most effective approach to water chestnut removal.

3.2 Understanding the Effects of Pollution

An important step was to understand if the pollution was contributing to the excessive growth of invasive species. Perhaps limiting the amount of nonpoint source pollution entering Coes would benefit the removal methods of the invasive species. It is difficult to establish every source of pollution in an urban watershed so the focus was on specifically the major sources. The next step in determining the probable sources of pollution at Coes was to identify common contaminants.

In order to understand the problems at Coes Reservoir we used secondary sources, interviews and site visits. Emails and meetings with the TBWA were useful for finding out facts about Coes Reservoir that were not available online, which included opinions regarding the best removal options, local case studies, and research done by its members.

On September 30th, 2015, we attended a meeting at the Knights of Columbus in Worcester, MA and we talked to some members of the TBWA. The meeting was about fixing the water quality issues in an effort to restore the watershed to a healthier state. This would benefit the ecosystem and the values of the houses on the water property. Most of the stakeholders were agreeing that invasive species were the biggest issue, but acknowledged the pollution and sediment were important as well (John Ferrarone, personal communication, September 30, 2015).

We ultimately decided to focus on the invasive water chestnut species. This was the problem that was most commonly identified as an issue that needed to be resolved, and by removing the water chestnuts, it would improve the aesthetics of the ponds and improve the health of the ecosystem. Water chestnuts are generally difficult to get rid of, but the other problems, according to various members of the committee, were not as big of an issue (John Ferrarone, personal communication, September 30, 2015). There was also a previous attempt to remove water chestnuts that had failed.

3.3 Case Study Analysis Criteria

"A (case) study design is the approach used to collect, control, and manipulate variables needed to answer the research question and/or hypotheses and to evaluate potential relationships among variables in a given research sample" (Hahn, 2014). We implemented the use of various case studies in order to analyze the effectiveness of various removal techniques. We found and evaluated four potential solutions: physical removal, drawdowns, herbicides, and aeration and bioremediation. In order to arrive at the best solution, we eliminated any obviously ineffective methods. To evaluate each case study, we created a list of criteria to enhance our overall perception of the information at hand. Applicability to Coes reservoir was our main criteria when choosing the top treatments to consider. We created tables with a ranking system to evaluate the applicability of each method. Many factors were considered, such as likeliness of succeeding, cost, and the longevity of the application.

During the case study analysis, we found it beneficial to create a list of target questions to be answered. The knowledge of these questions allowed us to determine the most applicable treatment for Coes Reservoir by creating a comparison chart.

1. Overall effectiveness of the treatment. Did this method effectively overcome the challenges in that specific watershed? Why or why not?
2. How long did the treatment last before signs of growth? Was this a long-term or short-term solution?
3. What was the percentage of invasive weeds removed? How many will grow back? Is it only effective for one specific invasive weed?
4. How much did the method cost? What is the breakdown of charges used in order to determine the ultimate price?
5. How relatable are the other watersheds to Coes Reservoir?
6. Why would this method be the best option for Coes Reservoir?
7. What other aspects contributed to the growth of invasive species?
8. What would be the outcome if nothing were done at Coes Reservoir?
9. What effects did this removal option have on other native species?
10. Did this method have any negative effects?

By answering these questions, we were able to create tables and effectively compare the treatments based off the answers found. Once we determined the most applicable solutions, case studies were used to identify each treatment's strengths and weaknesses. By comparing each solution side-by-side in a table and evaluating the same criteria, we were able to rate each solution.

3.4 Comparison of Treatment Criteria

In order to decide which removal effort was the best option for Coes Reservoir, various options were compared. Before any comparisons could be made, we narrowed down the focus by outlining several guidelines. The guidelines are general assumptions that apply to every method so that there is a common way to compare them. This approach helped to ensure that there were no variables that could change, depending on how readers viewed the comparisons.

3.4.1 Guidelines for Comparisons

Several general assumptions were made to make the comparisons easier. First, all the removal efforts had at least one case study with positive results, since the effectiveness of efforts needed to be established. It was assumed that each removal effort would be attempted in similar conditions. They would be done in Coes Reservoir, in which the volume of water chestnuts, temperature, water levels, and size of the reservoir would not change. The treatments would be performed on all water chestnuts in a short time span (a few days maximum, depending on the treatment), rather than doing small increments per week. The assumed goal is to remove as many water chestnuts as possible in as little time as possible.

The background and case studies all showed significant decrease in the number of invasive plants per year. Depending on the type, some treatments would need to be repeated multiple times a year to get the best results. Physical removal, drawdowns, and herbicides need to be repeated on several occasions per year to continually remove new invasive plants and their seeds, since they can grow at any point during the growing season (June to August) within a period of twelve years. The aeration and bioremediation treatment simply needs to have the steps executed one time, and only maintenance would need to be completed in the future. This benefitted the results of the application due to a significant decrease in cost compared to the methods that had to be re-applied annually.

3.4.2 Analysis via Important Factors

As first described in the methodology, we created a list of factors that were essential for the treatments to be compared. The factors are:

- **Likeliness of Succeeding:** Based on background research and case studies, has this method been proven to work?
- **Cost:** How much will it cost each year?
- **Negative Effects:** Are there any negative impacts on the environment/ecosystem?
- **Versatility:** Can this method fix other problems in the reservoir?
- **Safety:** Are there any significant threats to humans or animals?
- **Community Effort:** How much work do humans need to do to ensure the best results?
- **Immediate Results Time:** How long until all the water chestnuts are removed for each attempt?
- **Disposal Methods:** How are the weeds ultimately removed? Does it require extra effort to dispose of them?
- **Equipment:** Are there any tools or items required to execute the method? Are they easy to put back when done using them?

On January 6, 2016, a meeting was organized by the TBWA to further talk about invasive weed removal efforts at Coes Reservoir. We decided this would be a great opportunity to ask the people that attended the meeting to rank the importance of the factors we created when deciding which treatment option to use. An analysis of the survey and the results can be found in the Appendix. Table 1 summarizes the results of the survey.

Table 2. Ranking the factors, from most important to least important.

Most Important Factor
Likeliness of Succeeding
Important Factors
Cost
Negative Effects
Versatility
Safety
Human Labor
Least Important Factors
Immediate Results Time
Disposal Methods
Equipment

As a group, we decided that "versatility" was an important factor along with "likeliness of succeeding." By having a method that can resolve multiple issues in the body of water, it could possibly fix them all, resulting in improvement to the health of the watershed. No further treatments would need to be performed for those other water quality issues as well, so it could end up saving money.

3.4.3 Tables with Descriptions of Treatments

We wanted to create ways of comparison that not only could "...display and compare..." the treatments, but could "...quantify the extent to which the criteria are fulfilled, rather than simply ranking them," (Clark et al, 1993). Two types of tables (nine rating and one summative) were made to compare the removal treatments.

The first nine tables contain direct qualitative descriptions for how each treatment was related to that comparison factor. Then, the treatments were compared to each other, with the comparisons summarized in one numerical table. The color surrounding the treatment description from the first nine tables depicts how each treatment was compared; a green-highlighted treatment is ideal, a yellow-highlighted treatment is not the best, yet not the worst, and a red-highlighted treatment is not good.

3.4.3.1 Format of Tables for Rating the Treatments

First, nine tables were created to assign ratings for each individual removal option and to put them in a format so that they are comparable. The treatments each had a description based on how they applied to each of the nine factors. One table was made per factor to accurately compare the treatments to each other, so that they could be color-coded accordingly.

These color-coded comparisons are similar to comparison methods described by Jennifer Clark, Carl Patton, and David Sawicki, from their guide on "Basic Methods of Policy Analysis and Planning." The comparisons of the treatments are analogous to the comparisons of the alternatives, where a dominant alternative is "an alternative that is superior to others on all criteria," and a dominated alternative is "an alternative that is inferior to at least one other option on at least one criterion" (Clark et al, 1993). The treatments would be ranked to determine which one was dominant for each of the nine factors, and to determine shortcomings for the dominated treatments.

The descriptions came from a mixture of the background research and the case studies analyses. The colors for the comparisons would later be used for the summative table. An example of one of the nine rating tables can be found in the Appendix, which gives a walkthrough of how to read each of the descriptive tables.

3.4.3.2 Format of Summative Table

Next, numerical results were calculated based on how ideal each treatment was for each factor and by weight of factors. Using the previous nine tables, each treatment was rated on a scale of one to three based on how ideal they were for each factor, as shown below. The numbers shown apply to each table.

- Green = ideal (Value of 3)
- Yellow = not the best, yet not the worst (Value of 2)
- Red = not good (Value of 1)

The treatments were then compared by weight of the factors, divided into three categories. These categories were decided by the survey done at the Tatnuck Brook Watershed Association meeting, where the members ranked the nine factors into three categories. The members assigned the factors based on majority vote. We combined their thoughts of the rank of importance with ours.

- Most important factors (Value of 3)
- Important factors (Value of 2)
- Least important factors (Value of 1)

One summative table was developed which uses the ratings from the nine qualitative tables and compares the ratings. Numeric values are assigned based on the rating for ideality (or color of the treatments). Addition and multiplication was used to calculate the results. First, the sum of the assigned value based on the qualitative comparison colors was determined three times for each group of factors (most important, important, and least important). Then, the sums were multiplied by the level of importance for the factors. Finally, the products were all added together to create a total for each of the four treatments. The total number for each treatment was used to make two types of comparative rankings, one based on the assumption that all treatments could remove water chestnuts, and one that takes into account treatments that would most likely not work.

This summative table was used to make two types of comparisons, which were derived from some comparison methods described by Jennifer Clark, Carl Patton, and David Sawicki, from their guide on "Basic Methods of Policy Analysis and Planning." The first comparison is based on the alternatives-consequence matrix, in which "each cell in the matrix is filled with...a numerical ranking...for minor criteria (the factors)" (Clark et al, 1993). This would be equivalent to the color-based numbers established in the first nine descriptive tables we came up with, where the numbers would be used in this summative table to make the comparisons. The second comparison is based on the equivalent-alternatives method, which is "a method of selecting among alternatives in which the values of estimating how much of a quantifiable benefit of one alternative you would be willing to trade for an improvement in how well it meets other criterion" (Clark et al, 1993). This would allow us to provide recommendations for all the removal treatments by providing alternate ways around the largest drawbacks each treatment has. A walkthrough for the summative table we created is provided in the Appendix for further clarification. This method was chosen because the factors should not all be considered equally important. Some are hard to determine which is more important, so it was best to have general rankings of them.

3.5 Researching Companies

Watershed management companies that provide these methods of applications are readily available for almost any location. Some of the companies we examined during this IQP were Outdoor Water Solutions, Solitude Lake Management, and Lake Savers. Our IQP team took particular interest in the company Lake Savers since they effectively combine the use of aeration and bioremediation in their four-step solution. In depth research was conducted on the processes of this company such as the products and systems they use, however a few bids should be acquired before committing to any company.

Chapter 4: Results

Our project evaluated approaches that could be used to permanently eradicate invasive water chestnuts from Coes Reservoir. Case study analyses and quantitative and qualitative comparisons were completed for the following four approaches for removing invasive weeds: physical removal, drawdown, herbicides, and aeration and bioremediation. Even though drawdowns are not considered to be an effective long-term approach for treating invasive water chestnuts, this application was still included when making comparisons since it has been found to be effective for treating other invasive weed problems and improving water quality. This chapter includes detailed results for case study analyses and treatment comparisons. Section 4.1 summarizes the case study analyses and section 4.2 provides the comparisons of the treatments, as well as the treatment we determined to be most appropriate for Coes Reservoir.

4.1 Case Studies Analyses

In order to successfully compare the four invasive weed removal treatments, it was necessary to evaluate case studies on bodies of water with similar issues to Coes Reservoir. At least one case study for each of the treatment alternatives was discussed and analyzed.

4.1.1 Physical Removal

Physical removal has many case studies that back it up as a reliable removal treatment, such as attempts at the Chesapeake Bay Watershed in Maryland (Naylor, 2003) and at the Charles River Watershed in Massachusetts (Charles River Watershed Association, 2015). Mechanical harvesting and hand-pulling are often combined to have the best results. Mechanical harvesters get the water chestnuts from the deeper, more open areas of the body of water, while hand-pullers get the water chestnuts from shallow areas and coves.

4.1.1.1 Coes Reservoir Previous Attempt

The city of Worcester invested 20 thousand dollars in a two-year span to remove water chestnuts from Coes Reservoir in 2012 with mechanical harvesting. The Tatnuck Brook Watershed Association, a water sustainability group in Worcester, hired the company Lycott Environmental, Inc. (now owned by Aquatic Control Technology) to remove the water chestnuts (John Ferrarone, personal communication, September 30, 2015). Worcester was not able to continue to invest the money needed to continually use mechanical harvesters, so they stopped paying Lycott Environmental, Inc. for their services, and the water chestnuts grew back (John Ferrarone, personal communication, September 30, 2015).

Water chestnut seeds can live unattached to the plant for up to twelve years until they rise from the sediments to the upper surface of the water ("Water Chestnut (*Trapa natans L.*)," n.d.). Mechanical harvesting needs to be continued for at least those twelve years to get rid of all the seeds, and therefore no more plants will grow. By only doing it for two years, too many seeds remain below that can still germinate.

4.1.1.2 Mechanical Harvesting: Chesapeake Bay Watershed, MD

Water chestnuts were a major issue in the Chesapeake Bay Watershed until a removal program was implemented. It was prepared by Mike Naylor, who is part of the Maryland Department of Natural Resources. He documented water chestnuts that were removed from the

Bird and the Sassafras River, which were connected to the Chesapeake Bay watershed. He recorded the amount that was harvested in a span of four years, as shown in Figure 12 below.

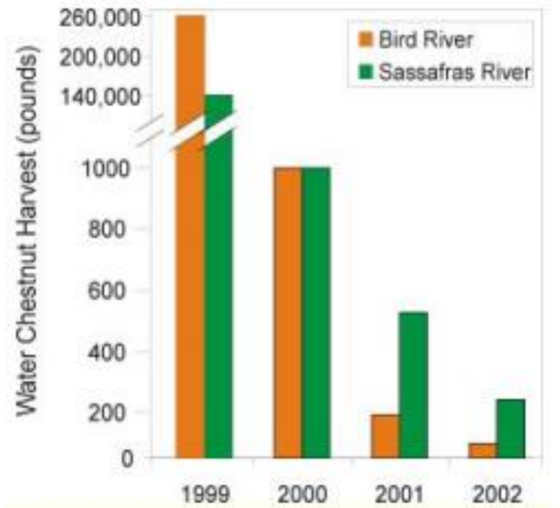

Figure 12. Bar chart of the amount of water chestnuts harvested in four years at the Bird and Sassafras River (Naylor, 2003).

In the bar chart, the weight of water chestnuts harvested in the figure started at roughly 260 thousand pounds and decreased to 1 thousand pounds in the following year. In 2003 and beyond, the amount of water chestnuts present in the rivers was so low that it was not necessary to use any other removal treatments, such as using chemicals (Naylor, 2003). The decrease in population was very successful.

With the positive results from the Bird and Sassafras River, Naylor suggested that similar removal techniques could be used in other bodies of water in the watershed (Naylor, 2003). In order to make sure the whole removal effort would be successful, he elaborated on several key points, summarized in Table 2:

Table 3. Summary of key points for future water chestnut removal efforts at the Chesapeake Bay Watershed (Naylor, 2003).

Category	**Key Points**
Leadership, Coordination, & Regulatory Authority	• Create a Regional Coordinating Group to promote effective coordination across jurisdictions.
Prevention	• Educate the public and natural resource managers on preventing future introductions. • Expand capacity and coordination of water chestnut monitoring programs. • Encourage local government and municipalities to take a proactive role in water chestnut prevention.
Control & Management	• Clarify the various threats water chestnut poses to the environment. • Develop state specific Regional Maps of Infestations in order to delineate priority areas in need of management action. • Review Eradication and Control measures that are currently available and determine which measures could be implemented in the Chesapeake Bay Watershed. • Develop site-specific Integrated Pest Management (IPM) Guidelines for control. • Implement eradication and control measures at priority sites identified by state. • Evaluate the potential for obtaining a regional permit for application of 2,4-D, an herbicide for controlling aquatic weeds in water.
Communication & Information Access	• Develop and implement a public knowledge and attitude survey. • Hire a Regional Coordinator to work on developing, implementing, and overseeing communication and outreach programs and activities. • Create website on Aquatic Nuisance Species in the Chesapeake Bay. • Produce and distribute new posters and identification (ID) cards. • Identify and disseminate existing science education programs to educators and the public.

4.1.1.3 Mechanical Harvesting: Charles River Watershed, MA

A third physical removal effort was conducted at the Charles River watershed in Massachusetts. The Charles River Watershed Association (CRWA) website advertised a volunteer effort to remove water chestnuts from the Lakes District of the Charles River in Newton, MA. They provided free canoe rental and a tutorial on how to pull the weeds. They also advised volunteers to wear old and protective clothing. It was not documented how well the effort went ("Invasive Water Chestnut Harvesting," 2015).

Several removal efforts were organized at the Charles River since 2013. Removal efforts were conducted during various weeks of the growing season, between June and September. Over time, results have shown a decrease in the area of water chestnuts before and after the growing season for each year, as shown in Figure 13.

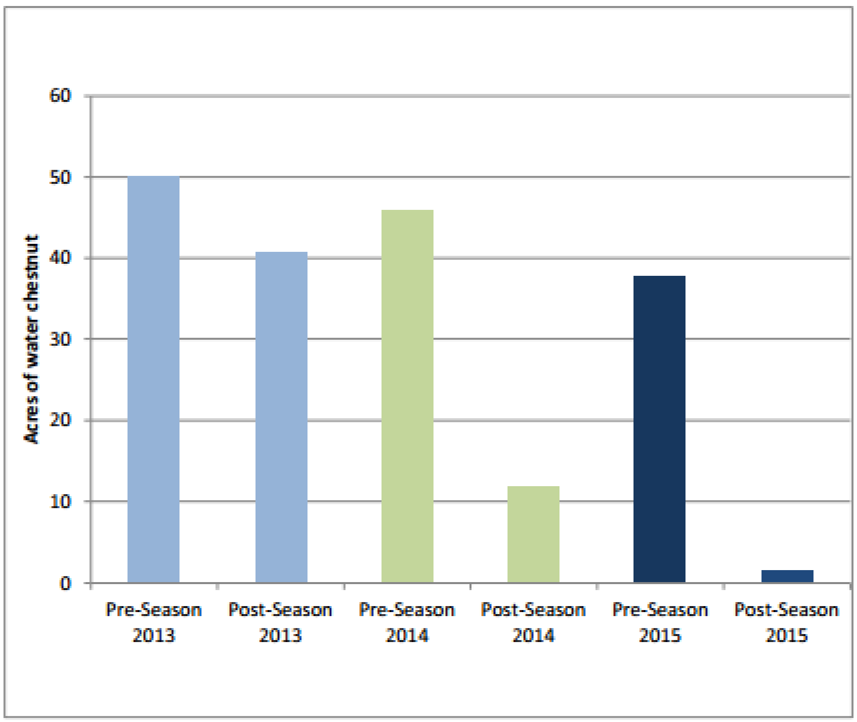

Figure 13. Acreage of water chestnut coverage in Charles River over time (Charles River Watershed Association, 2015).

Based on Figure 14, water chestnuts may eventually be completely eradicated, if the volunteer hand-pulling is done as consistently. However, constant monitoring of the river should be done in case the water chestnuts return, either from seeds that fell off plants or by waterfowl travel.

For the growing season of 2015, careful documentation was done by the CRWA for all the hand-pulling events. Four hundred and seventeen volunteers helped hand-pull water chestnuts from the Charles River in a span of roughly two months. They eliminated over 80 thousand pounds of water chestnuts. The cumulative total was documented in the graph below (Charles River Watershed Association, 2015).

Figure 14. Line graph of day by day collection of water chestnuts by hand-pulling, just in 2015 alone (Charles River Watershed Association, 2015).

The graph itself is linear, meaning the amount of water chestnuts removed each day was constant, so there was minimal variance. They likely stopped in August because that is when the seeds are done maturing, and future plants that appear for the rest of the season will not reproduce (Charles River Watershed Association, 2015).

While the hand-pulling was occurring near the shores and shallow areas, mechanical harvesting was conducted in the deeper parts of the water body. Funding came from the FY2015 state budgets (75 thousand dollars) and the Massachusetts Department of Conservation and Recreation's Public Private Partnership Grant. Committees raised 25 thousand dollars and they hired Aquatic Control Technologies of Sutton, MA to do the harvesting over two time periods: 6/8-30 and 8/10-25 (Charles River Watershed Association, 2015).

Water quality tests were conducted in 2015, between April 29 and August 12, with mixed results. They were taken in two locations – the Newton Historic Boathouse and at the disposal site off Charlesbank Road. One test was temperature measurements, where both locations were roughly equivalent, depending on the time of year. Another was dissolved oxygen levels measurements, as shown in the Figure 15.

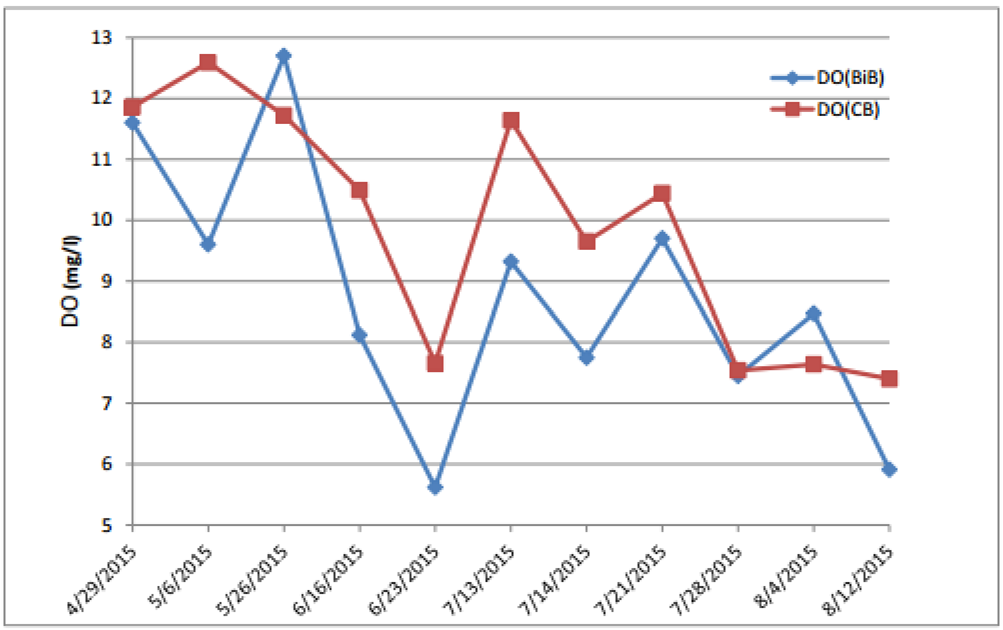

Figure 15. Dissolved oxygen levels for the Newton Historic Boathouse (blue line) and the disposal site off Charlesbank Road (red line), completed in 2015 (Charles River Watershed Association, 2015).

The maximum dissolved oxygen for the Newton Historic Boathouse was measured on May 6, at roughly 12.6 milligrams per liter (mg/L). The maximum for the disposal site was measured on May 26, at roughly 12.75 mg/L. From there, the oxygen levels seemed to trend downward. By August 12, the Newton Historic Boathouse and the disposal site reached their minimums, at 7.5 mg/L and 6 mg/L, respectively. This testing seems to contradict what would normally happen if invasive weeds were removed – dissolved oxygen levels should go up. This testing shows that they go down, but not consistently. This test was only conducted for one year, so there were not any other years to compare the results to. Additionally, it was not documented what time of day it was tested or what the weather conditions were like, where photosynthesis could be affected. Photosynthesis produces dissolved oxygen, and it is done mostly when the sun is out. If it is done at nighttime or during a storm, there could be less dissolved oxygen in that particular area measured. Sources of error could be the differences in the location and human error (Charles River Watershed Association, 2015).

This case study provides some valuable recommendations on running hand-pulling events. First, it is suggested that finding volunteer hand-pullers be done well in advance, and meetings are held to get to know them. Several meetings were conducted with volunteer groups to ensure that they were committed and understood how to pull out the water chestnuts in the safest way possible. This also made last-minute cancellations less likely to happen. Second, it is important that the organizers do a good job of getting the point across and of running the event. The CRWA made it clear what their intentions were for this volunteer effort and the importance of it as well. They also scheduled the events well in advance in case scheduling conflicts occurred. Third, monitoring the watershed after the events should be done regularly from June to September. This is to ensure that the weeds grow back in lower quantities than before (Charles River Watershed Association, 2015).

4.1.2 Drawdown

Drawdowns do not have many case studies documenting impacts on water chestnut populations. This is because drawdowns normally are performed during the autumn, and water chestnuts grow and drop their seeds during the summer. Multiple drawdowns would have to occur throughout the summer to control the water chestnuts, but this not realistic because of the effects on biodiversity it would have.

However, drawdowns have been proven as an effective method of managing invasive weeds that grow perennially, such as coontail and Eurasian milfoil. Several case studies support the use of drawdowns to manage perennial invasive weeds, such as ones at Bare Hill Pond (Bare Hill Pond Watershed Management Committee, n.d.), Lake Shirley (Lake Shirley Improvement Corporation, 2015), and Indian Lake in Massachusetts (Beth Proko, personal communication, February 24, 2016), the latter of which was analyzed.

4.1.2.1 Drawdown: Indian Lake, MA

The Indian Lake Watershed Association (ILWA), a water sustainability group, removes invasive weeds from Indian Lake in Worcester, MA every year. At this lake, Eurasian water milfoil (*Myriophyllum spicatum*) and water naiads (*Najas*) grow throughout much of the lake year-round, making it nearly unusable for recreational activities. Members of the ILWA wanted a treatment that was cost-effective and could manage the invasive weeds. They hired the company Lycott Environmental, Inc. (now owned by Aquatic Control Technology) to complete a diagnostic and feasibility study, in which this company recommended the use of drawdowns to control the weeds (Beth Proko, personal communication, February 24, 2016).

Drawdowns began in the early 1990s at Indian Lake and are still being used today. The water is lowered by a dam near the end of Mattson Avenue. Members of the ILWA lowered the water volume every October by four feet (six feet starting in 2015), and filled it back up each February, with great results. The Eurasian water milfoil and water naiads completely disappeared in the spring. Starting in mid-August, the Eurasian milfoil and naiad returned, with large populations returning before the winter. In the summer, recreational activities can cause perennial invasive weed populations to spread. For example, driving a boat through the weeds can break them up and distribute them, which allows them to grow over a bigger area. This makes it difficult to figure out where the populations originate from, and hence, makes it difficult to target that specific area for management (Beth Proko, personal communication, February 24, 2016).

The drawdowns not only manage the invasive weed problems, but they also manage cyanobacteria, excessive nutrient and sediment depth problems. In the summer of 2014, there was a major cyanobacteria bloom where swimming advisories were posted. Large cyanobacteria blooms can occur because of excess nutrients in the water, which in turn are exacerbated by sediment depth issues. The ILWA learned that exposing sediments to the cold air can release nutrients in the air. They made more of an effort to expose the sediments for the 2015 spring drawdown (lowered the water from four feet to six feet), and the summer of 2015 showed a major decrease in sediment depth, nutrient levels, and cyanobacteria (Beth Proko, personal communication, February 24, 2016).

Since the Eurasian milfoil and water naiads are perennial, there is no way for them to disappear permanently. However, the yearly drawdowns can control the growth and spread of these plant species, and also can help to manage sediment depth, excess nutrient levels, and cyanobacteria blooms (Beth Proko, personal communication, February 24, 2016). It is a reasonably priced treatment approach, where the only costs are associated with diagnostic companies and the costs of purchasing the permit every three years (John Ferrarone, personal communication, February 16, 2016).

4.1.3 Herbicides

Three case studies were analyzed in regards to herbicides. Both fluridone and triclopyr were used at Saratoga Lake, New York from 2000 to 2008. Another case study was analyzed for herbicide treatment using 2, 4-Dichlorophenoxyacetic acid (2, 4-D) on Loon Lake, Washington. The 2, 4-D and triclopyr are proven effective against the water chestnuts on their product label. However, both case studies were made against the Eurasian water milfoil. Aquatic Control Technology LLC claims to have success with the 2, 4-D and not the triclopyr, when removing the water chestnut (D. Meringolo, personal communication, January 12th, 2016). Chemical treatment case studies were not found to be done on water chestnuts, so it should be noted that the results from removing them are not necessarily analogous to the results from removing the water milfoil.

4.1.3.1 Fluridone: Saratoga Lake, NY

Aquatic Control Technology, LLC preformed a chemical treatment on the Saratoga Lake in Saratoga County, New York. Demonstration treatments in 2000 through 2003 were performed using the herbicide Sonar (product label) or fluridone (the chemical name). These treatments were then established as an “Aquatic Vegetation Management Plan as part of an overall lake and watershed management initiative” (Aquatic Control Technology, 2015). Eurasian water milfoil was the target in 2007, covering 200-acres out of the 4,000-acre lake, whose treatment was ruled successful. However, the challenge in this study was applying several doses for the weeds to be affected by the herbicide (Aquatic Control Technology, 2015).

4.1.3.2 Triclopyr: Saratoga Lake, NY

In 2008 the herbicide triclopyr was used in the removal effort of the Eurasian water milfoil. This herbicide is a systemic treatment with shorter contact time than the fluridone herbicide treatment. Triclopyr also has no significant impact to the shore line or sediment bottom. 300-acres of Saratoga Lake was infested with Eurasian water milfoil and was treated successfully. Overall this herbicide was proven to be an effective method of removal for the following year (Aquatic Control Technology, 2015).

4.1.3.3 2, 4- Dichlorophenoxyacetic Acid: Loon Lake, WA

In 2001, an herbicide application was applied on Loon Lake in Washington to eliminate Eurasian water milfoil. The water milfoil was scattered in patches along this lake, making the use of GPS necessary for points of interest (Department of Ecology, Washington, 2001). On top of acquiring GPS coordinates, applicators must restrict their use of this herbicide to the timing of the Washington salmon runs, which included endangered salmon populations. Using 2, 4-Dichlorophenoxyacetic acid at recommended label concentrations proved very effective in eradicating 98 percent of the Eurasian water milfoil biomass (Department of Ecology, Washington, 2001). A few days after application, observers could see milfoil strands bent and abnormally shaped. One to two weeks after that, dead water milfoil sunk to the bottom of the lake.

4.1.4 Aeration and Bioremediation

The company Lake Savers claims to have made a significant impact on many water bodies in the northeast region of America. Their combination of utilizing technologies is successfully treating invasive species, decreasing muck accumulation, and increasing dissolved oxygen levels while simultaneously decreasing phosphorus levels. Combined, these claims of positive results increase the potential for the overall health of a water body and revive it to its natural state (Tucci, 2013).

4.1.4.1 Lake Savers: Collins Lake, NY

In 2006, Collins Lake in Scotia, New York was suffering from severe growth of Eurasian Water milfoil and pondweed, which subsequently contributed to the accumulation of decayed organic sediment and a decrease in overall water quality. Since this watershed also includes a public beach, urgency in restoring the water quality to its original state was felt across the community. Due to the excess amounts of fecal bacteria fueling this weed growth, the public beach was closed for two years (Tucci, 2013).

Collins Lake contained 60 acres of contaminated water in the summer of 2006. This is nothing new for the community since the public beach had been closed for two consecutive years. Previous attempts of eliminating the excess weed growth using herbicidal treatment were conducted but proved to be ineffective. After the herbicidal treatment was implemented in 2006, high hopes of decreases in plant growth and an increase in the clarity of the water was expected. Instead, after tests were done the following week, it was concluded that the lake continues to remain in an inoperable condition since the bacterial counts were significantly above the states safety regulations. This was because the treatment was targeted to improve the water for a short-term period, not to control the fecal bacteria (Tucci, 2013). The temporary fix that herbicidal treatment offered was not enough to restore the health of the lake enough to be open to the public.

A new innovative method was needed in order to remediate this water body. Lake Savers was contacted and contracted to conduct analysis and apply a custom solution. Due to the significant amounts of fecal bacteria and runoff from fertilizers, the lake suffered from high levels of phosphorus and nitrogen. This caused excessive invasive weed growth, as well as contributed to the significant accumulation of muck on the bottom of the lake (Tucci, 2013).

The Lake Savers applications needed to be applied immediately in order to restore this watershed back to its original state. In June 2006, an exception was made and another herbicidal treatment was applied to the watershed in order to temporarily clear the surface of the lake allowing it to be navigable and allow for the installation of an aeration system. As stated previously in the background (Sec 2.8.4.1), this aeration system circulated dissolved oxygen and allowed for essential bacteria to flourish. One month later in July 2006, the beneficial bacteria and enzyme treatment was applied to the watershed. The added bacteria increased the consumption of the muck and provided the base of the fish food chain (Tucci, 2013).

In just one month, after two years of being closed, the public beach was reopened in the summer of 2007. In just one season, the implementation of these methods provided a significant increase in dissolved oxygen which decreased the amounts of phosphorus and nitrogen, prevented regrowth of invasive species, and led to a significant muck reduction. Three years later in 2010, Collins Lake was examined and still functions in usable conditions. The “Lake Savers” method seemed to have a positive influence in restoring a lake in failing condition (Tucci, 2013).

Constant monitoring is important in order to maintain the long-standing performance of the implemented system. Lake Savers believes it is essential to continue to thoroughly conduct these tests in order to guarantee continuous annual results. The results from their four step treatment process appear to treat invasive weeds and increase water quality, however some questions are still left unanswered. “Lake Savers” has not used these four steps to target water chestnuts. However, “Lake Savers” has been successful at treating water hyacinth in the past, which shares many similar qualities with water chestnuts. These unknowns play a role in deciding whether or not to recommend this method to be used at Coes Reservoir.

The average price to lease the Lake Savers technology is under $2.00 per house per day (Tucci, 2013). This number initially seems attractive, however many considerations must be taken. For example, the community may wonder if this fee is temporary or is required for the entire lifetime of the system. After contacting John Tucci, he said that the lease cost is an annually reoccurring fee. However, purchasing the equipment is a cheaper alternative than leasing for a water body the size of Coes. This could be beneficial as time progresses, with maintenance and electric fees being the only reoccurring cost.

4.2 Comparison of Treatments

Based on the case study analyses and survey results, nine tables were made that summarize how each treatment is related to one of these nine factors:

- **Likeliness of Succeeding:** Based on background research and case studies, has this method been proven to work?
- **Versatility:** Can this method fix other problems in the reservoir?
- **Cost:** How much will it cost each year?
- **Negative Effects:** Are there any negative impacts on the environment/ecosystem?
- **Safety:** Are there any significant threats to humans or animals?
- **Community Effort:** How much work do humans need to do to ensure the best results?
- **Immediate Results Time:** How long until all the water chestnuts are removed for each attempt?
- **Disposal Methods:** How are the weeds ultimately removed? Does it require extra effort to dispose of them?
- **Equipment:** Are there any tools or items required to execute the method? Are they easy to put back when done using them?

Next, the nine tables were used to develop a summative table. It gives numerical values to the qualitative data so that factors can be weighted depending on the importance level of the factors and how ideal each treatment was for each factor. The extent to which the treatment was ideal was summarized by the color of the box for that treatment in the descriptive tables, which was decided by us with consideration to make comparisons (Section 3.4.3.1). Green indicates the treatment is very ideal for the factor, yellow indicates it is moderately ideal for the factor, and red indicates it is not ideal for that factor.

4.2.1 Rating the Treatments per Factor

The nine tables that contain descriptions of how each treatment is related to each factor are given below in Tables 4-12. Summaries of each table are found after each one.

Table 4. Descriptions of treatments in regards to "Likeliness of Succeeding"(Based on background research and case studies, has this method been proven to work?).

Drawdown Not a good long-term solution. Might not even remove water chestnuts.	**Aeration and Bioremediation** Has been successful in combatting many types of invasive weeds, however the combination has not been tested for water chestnuts.
Physical Removal Has been shown by several case studies to eliminate water chestnuts for that year.	**Herbicides** Case studies have shown to effectively remove and mitigate various aquatic weeds.

For “Likeliness of Succeeding,” physical removal is very likely to succeed because it has lots of supporting evidence. Aeration and bioremediation, on the contrary, lacks the evidence to work with water chestnuts, and drawdowns will probably not work under reasonable conditions. Drawdowns could work if they are done several times throughout the summer. However, this is not recommended since the constant lowering of water levels could limit recreational activities and have harmful effects of biodiversity. Herbicides can work but do not have as much supporting evidence as physical removal.

Table 5. Descriptions of treatments in regards to "Versatility" (Can this method fix other problems in the reservoir?).

Drawdown Can fix sediment depth issues as well as improve oxygen levels. Civil engineering projects can be worked on while the water levels are lowered. Effective to buffer against large volumes of precipitation.	**Aeration and Bioremediation** Fixes sediment depth issues, dissolved oxygen levels, decreases phosphorus and nitrogen levels, and removes invasive weeds.
Physical Removal Removes any type of floating weed	**Herbicides** Can remove any type of weed.

For “Versatility,” aeration and bioremediation and drawdowns can fix many water quality issues, while physical removal and herbicides cannot.

Table 6. Descriptions of treatments in regards to "Cost" (How much will it cost each year?).

Drawdown Fees only for drawdown permit. Renewed every 3-5 years. Estimated between $600 and $1000 dollars per year.	**Aeration and Bioremediation** The average cost to buy the Lake Savers system is estimated to be a one-time fee of $40,000-$60,000 with minimal continuing maintenance and electric fees.
Physical Removal Mechanical harvesting can cost anywhere from $4,000 to $10,000 per acre, depending on type of harvester and days rented. Hand-pulling can have no cost, if volunteers are used and boats and canoes are donated.	**Herbicides** $200 - $2,000 per acre

For “Cost,” drawdowns and herbicides have the lowest cost per year. Aeration and bioremediation has a large one-time fee. Physical removal eventually costs the most after a few years.

Table 7. Descriptions of treatments in regards to "Negative Effects" (Are there any negative impacts on the environment / ecosystem?).

Drawdown Can permanently impact the ecosystem. Food webs can change. Native species can die out. Sediments can move to other parts of the lake, increasing their depth.	**Aeration and Bioremediation** There were no known negative effects attributed with this method of removal.
Physical Removal Mechanical harvesting can kill other animals and plants.	**Herbicides** When any organism comes into direct contact with herbicides, there are chances of being harmed by the chemicals in the herbicide. Decomposition of invasive weeds increases sediment depth, however.

For "Negative Effects," aeration has no known negative effects. Physical removal can harm organisms in the water, and herbicides have chemicals that can affect several species, including humans. Drawdowns can permanently affect biodiversity.

Table 8. Descriptions of treatments in regards to "Safety" (Are there any significant threats to humans?).

Drawdown Flooding can occur downstream if the water level is lowered too quickly.	**Aeration and Bioremediation** No known safety issues.
Physical Removal If humans are in the way of the harvester, could pose significant injuries. Safe to operate otherwise. Pluckers take risk in cutting themselves on the water chestnut seeds.	**Herbicides** Humans must wear protective equipment (Eye protection, suit) when applying herbicides. If chemicals are ingested herbicides can be fatal.

For "Safety," physical removal is not dangerous if done carefully, and herbicides can kill humans. Drawdowns and aeration and bioremediation have little to no known safety issues.

Table 9. Descriptions of treatments in regards to "Community Effort" (How much work do humans need to do to ensure the best results?).

Drawdown Removal of seeds, but that could also be done by the city.	**Aeration and Bioremediation** The employees of Lake Savers take part in the installation. A neighborhood effort is needed in order to prevent additional nutrients from entering the watershed.
Physical Removal Hired people to operate the harvesters. Lots of labor to pluck and get to water chestnuts. Must dispose weeds. By far the most work of all the methods.	**Herbicides** A hired team of two contractors, the applicant and a herbicide water treatment specialist.

For "Community Effort," only physical removal might need a community effort to hand-pull the water chestnuts.

Table 10. Descriptions of treatments in regards to "Immediate Results Time" (how long until all the water chestnuts are removed for each attempt?).

Drawdown Gets rid of most invasive weeds, but not water chestnuts.	**Aeration and Bioremediation** Significant decreases in sediment levels of up to 10 inches per season are common. An increase in dissolved oxygen begins immediately as well as decreases in phosphorus and nitrogen.
Physical Removal Results instant per plant, takes one to two days to remove all plants per session.	**Herbicides** After two-three weeks significant numbers are weakened

For "Immediate Results Time," physical removal is instant. Aeration and bioremediation and herbicides will take some time for the water chestnuts to start disappearing. Drawdowns will more than likely not work.

Table 11. Descriptions of treatments in regards to "Disposal Methods" (How are the weeds ultimately removed? Does it require extra effort to dispose of them?).

Drawdown The seeds from the sheared plants must be removed, which can be difficult if the ground hardens and the seeds get stuck in the ground.	**Aeration and Bioremediation** The weeds are decomposed naturally due to the bacteria consuming the plants.
Physical Removal Must dispose on land when harvester is full. Several trips per person to dispose water chestnuts for hand-pulling.	**Herbicides** After application and the weeds die, they sink to the bottom which then builds up sediment.

For "Disposal Methods," aeration and bioremediation and herbicides do not require exterior help to remove them, while physical removal and drawdowns do.

Table 12. Descriptions of treatments in regards to "Equipment" (Are there any tools or items required to execute the method? Are they easy to put back when done using them?).

Drawdown Requires a permit from the city's conservation department. A pump is necessary for bodies of water that do not have a dam.	**Aeration and Bioremediation** Offshore air compressor (large and permanent)
Physical Removal Requires mechanical harvester (very large). Hand-pullers need boats, canoes, and buckets to hold water chestnuts, and protective clothing such as gloves and old sneakers.	**Herbicides** Mechanical spreader or pipette.

For "Equipment," aeration requires one offshore compressor. Physical removal requires multiple boats, canoes, and buckets, as well as a mechanical harvester, which is the most amount of items between the three methods. Herbicides only need a mechanical spreader or pipette, which are easy to transport. Drawdowns simply need a permit and maybe a pump if there is no dam to release the water.

4.2.2 Summative Comparisons

Combining the descriptive tables above into a summative numerical table enhanced comparisons between the treatments. All the boxes for the nine tables are colored either green, yellow or red, depending on if that treatment was ideal, not the best yet not the worst, or not good, for that comparison factor. These were then assigned numerical values as follows:

- Green = ideal (Value of 3)
- Yellow = not the best, yet not the worst (Value of 2)
- Red = not good (Value of 1)

By taking these numbers into consideration, as well as the importance value of those factors, we can now make that table showing the comparisons in a quantitative way. That way we can list an appropriate order for recommending the best treatment, since each one has its own benefits and drawbacks. Table 13 shows the results.

Table 13. Numerical table for the comparisons.

Most Important Factors (3)	Physical Removal	Drawdown	Herbicides	Aeration and Bioremediation
Likeliness of Succeeding	3	1	2	2
Versatility	2	3	2	3
Total Here (Sum*3)	5*3 = 15	4*3 = 12	4*3 = 12	5*3 = 15
Important Factors (2)	**Physical Removal**	**Drawdown**	**Herbicides**	**Aeration and Bioremediation**
Cost	1	3	3	2
Negative Effects	2	1	1	3
Safety	2	3	1	3
Community Effort	1	3	3	3
Total Here (Sum*2)	6*2 = 12	10*2 = 20	8*2 = 16	11*2 = 22
Least Important Factors (1)	**Physical Removal**	**Drawdown**	**Herbicides**	**Aeration and Bioremediation**
Immediate Results Time	3	1	2	2
Disposal Methods	1	1	3	3
Equipment	1	3	3	2
Total Here (Sum*1)	5*1 = 5	5*1 = 5	8*1 = 8	7*1 = 7

Cumulative Total	15+12+5 = 32	12+20+5 = 37	12+16+8 = 36	15+22+7 = 44
Ranking (based on numbers / they treat invasive weeds)	4th	2nd	3rd	1st
Ranking for this IQP (if they treat water chestnuts)	3rd	Does not remove water chestnuts	2nd	1st

With consideration to the most important factors, physical removal and aeration and bioremediation are the best treatments (highest scores) because of their high likeliness of succeeding and for their versatility, respectively. For the four important factors, aeration and bioremediation is the best, followed by drawdown, then herbicides, and physical removal. For the least important factors herbicides are the best, followed by aeration and bioremediation, then a tie for physical removal and drawdowns. It was determined that treatment by aeration and bioremediation is the best treatment to get rid of the invasive weeds at Coes Reservoir.

Chapter 5: Recommendations and Conclusion

The purpose of our IQP was to investigate different types of treatments that would be successful in treating invasive water chestnuts at Coes Reservoir. We recognized that water chestnut infestation is a primary concern that is contributing to water quality degradation at the Reservoir. Water chestnuts at Coes Reservoir contribute to the depletion of dissolved oxygen in the water, increasing the depths of sediments, and prohibiting recreational activity at Coes Reservoir. Our team focused on five common solutions to remediate this issue. We analyzed drawdowns, aeration and bioremediation, mechanical harvesting, hand-pulling, and chemical herbicidal treatments to provide information on the advantages and disadvantages of these methods. Extensive research on each of the methods as well as case studies aided in the comparison of the removal methods to be effective at Coes Reservoir. Comparison tables were developed to provide comparisons between these treatment options.

In this chapter, we provide our recommendations as well as discuss the long-term implications this method poses, who could benefit from our IQP, where our recommendations can be used, and the limitations of our project. The comparison tables revealed that aeration and bioremediation is the best method to eradicate the water chestnut infestation at Coes Reservoir, and ultimately increase the water quality. We also have included individual recommendations for every treatment, if the aeration and bioremediation treatment is too expensive. Each method was analyzed with respect to its applicability to Coes Reservoir to provide potential consideration for future use.

5.1 Recommendations for Controlling Water Chestnuts in Coes Reservoir

The recommendations are presented in order proceeding from the most applicable (recommended) alternative (Section 5.1.1) to the least applicable treatment (in Section 5.1.4).

5.1.1 Aeration and Bioremediation: Recommendation

The literature and available data indicates that aeration and bioremediation provides the most promising solution regarding the long-term improvements of Coes Reservoir. The use of this method at Coes Reservoir has potential to improve the water quality, decrease the amount of phosphorous and nitrogen levels, increase the amount of dissolved oxygen, decrease the sediment depths, benefit the aquatic ecosystem, and decrease the invasive species present at the body of water compared to the other methods. Many positive attributes are associated with this method, which is what differentiated this treatment from the others. These benefits will provide long-term relief in the efforts of restoring this body of water to its original, uncorrupt condition. The beneficial characteristics expressed above such as a decrease in invasive species, sediment depths, and phosphorus and nitrogen levels are likely to occur in as little as one season. With this treatment, Coes Reservoir will have an increased chance of protection from invasive weeds for a long time period after the commencing the treatment.

Initially, Lake Savers had a unique four-step approach to remediate similar issues that Coes is facing. One major concern lies in the cost of this product and an exact cost still needs to be determined. Due to the size and depth of Coes, John Tucci recommended purchasing the equipment necessary instead of leasing. The equipment being used would cost between $40,000-$60,000, and there would also be maintenance, electrical (7.38 cents/kWh), and installation fees. All these fees were taken into consideration when determining the most effective solution for Coes

Reservoir. The Tatnuck Brook Watershed Association must find the means of acquiring this amount of money in order to use this method in its totality. Our IQP team recognized this major issue, which is why we provided alternative recommendations that may be more economical. These alternatives are included in the next subsections.

5.1.2 Alternative Option #1: Herbicides

Herbicides have been proven to be effective against both large and small plant infestations with large reduction in plant biomass. It has been shown that herbicides do not disturb the sediments at the bottom of lakes and ponds and cause minimal harm to the shorelines. Manufacturer's literature and other documentation indicate that the herbicides dissipate and leave no trace after two to three weeks.

However, these herbicides do have negative consequences when using them. The herbicides themselves can be toxic to humans. They can also cause organism casualties when applying over a large area. To effectively remove the generations of seedlings to bloom, the herbicide should be applied anywhere from five to twenty years, and once to twice per year. This can add to the expenses since Massachusetts requires that a licensed contractor is hired to perform herbicidal treatment. After the plant absorbs the herbicides and dies, there is still biomass that sinks to the bottom and builds up sediments. Lastly, some weeds can become resistant to the same herbicide rendering the treatment useless.

5.1.3 Alternative Option #2: Physical Removal

Physical removal has been considered in several case studies, such as at the Chesapeake Bay Watershed (Naylor, 2003) and the Charles River Watershed (Charles River Watershed Association, 2015), that support it as a reliable invasive weed treatment. While this method has a very high chance of removing water chestnuts, it cannot fix other problems with the pond, such as oxygen levels and sediment depth. Waterfowl and even people can bring in foreign water chestnut seeds into the pond, where they can multiply and grow again.

Mechanical harvesters are not recommended for use at Coes Reservoir because they are too expensive to be used every year (20,000 dollars to 50,000 dollars a year) for the long time period required for water chestnut removal (often considered to be twelve years). Hand-pulling is recommended as a cost-friendly alternative to the aeration and bioremediation method. Hand-pulling can be dangerous for the people removing the water chestnuts because of the sharp seeds underneath the leaves. Canoes, life preservers, and buckets are needed for workers, so there is a lot more equipment needed for hand pulling than the other methods.

While constant communication is required to ensure commitment, hand-pulling can be very inexpensive. Getting enough people to organize and pull out water chestnuts several times a year for a long time period is the most difficult part. If hand-pulling is to be used, suggested guidelines written by Mike Naylor from the Chesapeake Bay Watershed can be followed, and are highly recommended in order to have organized hand-pulling events. Table 14 lists key points (as provided by Naylor, 2003).

Table 14. Summary of key points for future water chestnut removal efforts (Naylor, 2003).

Category	**Key Points**
Leadership, Coordination, & Regulatory Authority	• Create a Regional Coordinating Group to promote effective coordination across jurisdictions.
Prevention	• Educate the public and natural resource managers on preventing future introductions. • Expand capacity and coordination of water chestnut monitoring programs. • Encourage local government and municipalities to take a proactive role in water chestnut prevention.
Control & Management	• Clarify the various threats water chestnut poses to the environment. • Develop state specific Regional Maps of Infestations in order to delineate priority areas in need of management action. • Review Eradication and Control measures that are currently available and determine which measures could be implemented in the Chesapeake Bay Watershed. • Develop site-specific Integrated Pest Management (IPM) Guidelines for control. • Implement eradication and control measures at priority sites identified by state. • Evaluate the potential for obtaining a regional permit for application of 2,4-D, an herbicide for controlling aquatic weeds in water.
Communication & Information Access	• Develop and implement a public knowledge and attitude survey. • Hire a Regional Coordinator to work on developing, implementing, and overseeing communication and outreach programs and activities. • Create website on Aquatic Nuisance Species in the Chesapeake Bay. • Produce and distribute new posters and identification (ID) cards. • Identify and disseminate existing science education programs to educators and the public.

5.1.4 Alternative Option #3: Drawdown

Drawdowns have been used for controlling a variety of invasive plants, and are being considered as an option for Coes Reservoir. However, drawdowns will not likely reduce the population of water chestnuts significantly because of the way these plants grow and reproduce (see Section 2.8.2). If performed during the summer, drawdowns could decrease the amount of water chestnuts. However, they would need to be repeated several times in a short time span (to get all the water chestnuts) which can harm the wildlife in the reservoir. Therefore, they are not highly recommended to fix this problem.

Few studies discuss how water chestnuts are affected (positively or negatively) by drawdowns. However, studies have shown drawdowns can decrease other invasive weeds populations from spring until winter. Drawdowns can be great to manage invasive weeds, but great care must be taken so that drawdowns do not permanently affect biodiversity for the worse. If they are performed too quickly or for too long, food webs can change and native plants and animals can die out.

At the same time, drawdowns can fix other water quality issues with the reservoir. They can harden muck at the shorelines, reducing some sediment depth issues. Drawdowns are recommended for bodies of water that have multiple water quality issues. If invasive weeds are one of these issues, drawdowns can manage most weeds with perennial growth and reproduction patterns. Drawdowns are cost-effective and pose no danger to people. They require little, if any, additional equipment. Water bodies that have drawdowns in October to prepare for high levels of precipitation could use them to treat the invasive weed issues as well. It is best to perform drawdowns on these invasive weeds at least once a year to properly manage their growth and spread. Inspections should be done to prevent any potential environmental or ecological problems.

5.2. Long-Term Implications

If aeration and bioremediation were to be implemented, the literature and case studies indicate that Coes Reservoir could essentially revive itself. This removal treatment would cover the entire twenty-one-acres of Coes reservoir and, based on the information reviewed, the installation fee should pay for itself with several beneficial attributes. Removal of invasive species, reduction of sediment depth, and continuously oxidized water are major and necessary improvements to restore this body of water. Fish and other organisms should return, creating a more stable food chain, and flourish in the improved reservoir to maintain a viable ecosystem. The bioremediation should produce diatoms within Coes, which should support natural food chains. Clean, manageable water quality would ensure recreational use, and considerable property value around Coes, to increase over time. Coes reservoir can be a recreational hot-spot in the city of Worcester providing many benefits to the community. Removal of the water chestnut can encourage safer swimming and recreational activities in the reservoir. Fishermen would not have to worry about tangling their lines, and kayakers would not be impeded when traversing through Coes. This long-term restoration method would be implemented for years to come, and possibly removing many, if not all, of the invasive aquatic weeds such as the water chestnut.

5.2.1 Beneficiaries of Improved Water Quality at Coes Reservoir

Several people around Worcester will benefit from improved water quality at Coes Reservoir. First, the people living on the pond will have more benefits. Houses that currently have water chestnuts at the shorelines are limited in recreational activities on the pond. With the water chestnuts gone, the pond will be more amenable for swimming and canoeing. When the sediment depths are resolved, there will be solid ground to walk on, and they will not have to worry about ruining their clothes. In addition, their house values will increase.

Second, people that use Coes Reservoir for recreational purposes will benefit. They are free to swim, fish, waterski, and do other recreational activities. The water at the beaches will be safer to swim in and will not be cluttered in populations of invasive weeds.

Third, aquatic life and broader ecosystems will benefit. With the application of aeration and bioremediation, invasive weed levels will decrease and oxygen levels will increase. Native species can grow back and biodiversity will be more consistent. The reduction of excess nutrient loads and pollution will lead to a healthier ecosystem, providing benefits for the whole Blackstone River watershed.

5.3 Applications Beyond Coes Reservoir

Our work can be used by others who are dealing with similar water quality issues. Many water quality issues are related to each other, depending on the source of the problem. For example, when invasive weeds die naturally, they cause an increase in the sediment depth at the bottom of the lake, which in turn could deplete dissolved oxygen levels. If several water quality issues exist, then aeration and bioremediation is the recommended method. If invasive weeds are the only issue, then perhaps a more economic approach like the use of herbicides, hand-pulling or even drawdowns (if invasive weeds are not or similar to water chestnuts) could be taken. Community hand-pulling would require dedication, but it would be the lowest cost to remove the water chestnuts.

5.4 Conclusion

This project provided a review and assessment of alternative approaches for controlling water chestnuts in Coes Reservoir. Our IQP team was first introduced to the local water body, Coes Reservoir, in September, 2015. The initial goal was to investigate the most common problems that negatively impact urban watersheds such as different types of pollution, internal water properties, and invasive species. All of these factors were associated with the poor water quality at Coes reservoir. After attending our first Tatnuck Brook Watershed Association meeting where the stakeholders discussed various issues at Coes Reservoir, it became clear that there was a need to target the water chestnut, invasive plant species growing widely in the reservoir. Immediately, we began investigating the origins, living conditions, and plant characteristics of water chestnuts in order to better understand why this aquatic plant causes so many problems. This step was crucial in being able to provide a method that was completely viable for this specific water body.

For the analysis in this project, we discussed and researched many potential methods that could address the problem at Coes Reservoir. Four methods selected for assessment were aeration and bioremediation, drawdowns, mechanical harvesting, and chemical herbicides. Once we chose these methods, we thoroughly investigated all potential benefits and consequences of the applications. After analyzing the case studies for each method, we compared them using various charts regarding different factors including the likeness of succeeding, cost, negative effects, and many more factors.

Our results showed that aeration and bioremediation would be the most applicable application for the removal of water chestnuts from Coes Reservoir. This method also entailed many other benefits such as improvement of water quality, decreases of phosphorous and nitrogen levels, increases in dissolved oxygen levels, decrease in the sediment depths, and benefits the aquatic ecosystem. Although our analysis shows that Lake Savers could be used for Coes Reservoir, we acknowledge that there may not be sufficient funds present to conduct this method. In order to accommodate for this issue we recommended hand-pulling as the best next removal method to be considered. Hand-pulling is relatively inexpensive and there are already annual summer gatherings at Coes for this practice. Although it does not completely remove the invasive weeds from the water, it does help to remove a significant amount of the weeds. The community and activists surrounding Coes Reservoir truly contribute many personal hours attaining to the problems associated with Coes. They have made significant accomplishments over the years and they will now have a complete understanding of the removal methods for water chestnuts.

5.4.1 Limitations of the Project

There were a few limitations when obtaining information in the team's method of choosing aeration and bioremediation. When the survey was passed out to the Tatnuck Brook Watershed Association (TBWA), not all of the members were present. If all members were present, it would have given the team a better idea of their opinion on what attributes they thought the removal method should have. It must be noted that characteristics of the Tatnuck Brook watershed and different nutrients have a significant effect on the growth of invasive aquatic weeds in Coes reservoir. However, there is no substantial or recorded information about these nutrients or other contaminants entering Coes. This project was based on analyzing literature and case studies on water chestnut removal treatments and their applicability to Coes reservoir. It is recommended that additional research be conducted on water quality and watershed characteristics for the future of Coes reservoir and water chestnut removal. Nevertheless, there were no case studies that confirmed the use of drawdowns, herbicides, or aeration with bioremediation was successful in removing the water chestnut.

The cost of aeration and bioremediation is estimated to be a one-time cost of $40,000-$60,000 (excluding maintenance fees, etc.) which is no small fee for the stakeholders in the Worcester Community. Purchasing the removal method rather than taking a loan out for it would be a better economic decision. The interest on the loan would be more than the amount Worcester will pay for in excess charges. The city of Worcester cannot apply aeration and bioremediation without the help of contractors, so purchasing this method by one way or another is the only option to see the same results. However, community hand-pulling would be the best economic treatment that is proven to remove water chestnuts.

By taking steps towards removing the water chestnuts, Coes reservoir can become a vital part of the community if action is taken to revive the Coes of its poor condition. Recreational activities such as fishing, swimming, and kayaking as well as the property value around Coes will improve due to the increase in water quality. Similar to the Coes brothers, the city of Worcester will benefit from this valuable resource in the future.

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Appendix

Nutrients that Plants Need to Survive

A description of the nutrients that plants needed to survive is included in this appendix, since is it is useful as a topic that is relevant to growth of aquatic plants, but not essential for the background section of the report. In order for plants to be healthy and to survive, they need access to chemical elements naturally found in their ecosystem. The sixteen elements can be broken down into two groups: non-mineral and mineral.

There are three non-mineral nutrients: hydrogen, oxygen, and carbon. Plants create their own food and energy via photosynthesis, where they use energy from the sun to convert water and carbon dioxide into starches and sugars. They release the oxygen molecules into the air ("Plant Nutrients," n.d.). The nutrients are found in the air and water. Invasive plants can cause the oxygen levels in water to be much lower than they should be, which can result in decreased water and ecosystem quality.

There are thirteen mineral nutrients found in the soil. These elements can be dissolved by water and then the plant can absorb them. Minerals can be broken down into two subgroups. Macronutrients are needed in large quantities for plant survival, and micronutrients are only needed in small quantities. Both are essential for plants to survive ("Plant Nutrients," n.d.).

Primary macronutrients are nitrogen, phosphorus, and potassium. Secondary macronutrients are calcium, magnesium, and sulfur. Secondary macronutrients are more commonly found in soil than primary macronutrients ("Plant Nutrients," n.d.). Descriptions of all the macronutrients can be found in Table 15.

Table 15. Descriptions of the six macronutrients ("Plant Nutrients," n.d.).

Nitrogen (N)	**Calcium (Ca)**
• Nitrogen is a part of all living cells and is a necessary part of all proteins, enzymes and metabolic processes involved in the synthesis and transfer of energy. • Nitrogen is a part of chlorophyll, the green pigment of the plant that is responsible for photosynthesis. • Helps plants with rapid growth, increasing seed and fruit production and improving the quality of leaf and forage crops. • Nitrogen often comes from fertilizer application and from the air (legumes get their N from the atmosphere, water or rainfall contributes very little nitrogen)	• Calcium, an essential part of plant cell wall structure, provides for normal transport and retention of other elements as well as strength in the plant. It is also thought to counteract the effect of alkali salts and organic acids within a plant. • Sources of calcium are dolomitic lime, gypsum, and superphosphate.
Phosphorus (P)	**Magnesium (Mg)**
• Like nitrogen, phosphorus (P) is an essential part of the process of photosynthesis. • Involved in the formation of all oils, sugars, starches, etc. • Helps with the transformation of solar energy into chemical energy; proper plant maturation; withstanding stress. • Effects rapid growth. • Encourages blooming and root growth. • Phosphorus often comes from fertilizer, bone meal, and superphosphate.	• Magnesium is part of the chlorophyll in all green plants and essential for photosynthesis. It also helps activate many plant enzymes needed for growth. • Soil minerals, organic material, fertilizers, and dolomitic limestone are sources of magnesium for plants.
Sulfur (S)	**Potassium (K)**
• Essential plant food for production of protein. • Promotes activity and development of enzymes and vitamins. • Helps in chlorophyll formation. • Improves root growth and seed production. • Helps with vigorous plant growth and resistance to cold. • Sulfur may be supplied to the soil from rainwater. It is also added in some fertilizers as an impurity, especially the lower grade fertilizers. The use of gypsum also increases soil sulfur levels.	• Potassium is absorbed by plants in larger amounts than any other mineral element except nitrogen and, in some cases, calcium. • Helps in the building of protein, photosynthesis, fruit quality and reduction of diseases. • Potassium is supplied to plants by soil minerals, organic materials, and fertilizer.

The micronutrients are boron, copper, iron, chloride, manganese, molybdenum and zinc. They are more easily accessible than macronutrients. Humans can recycle organic matter to provide plants with micronutrients (“Plant Nutrients,” n.d.). Descriptions of all the micronutrients can be found in Table 16.

Table 16. Descriptions of the seven micronutrients ("Plant Nutrients," n.d.).

Boron (B)	**Copper (Cu)**
• Helps in the use of nutrients and regulates other nutrients. • Aids production of sugar and carbohydrates. • Essential for seed and fruit development. • Sources of boron are organic matter and borax	• Important for reproductive growth. • Aids in root metabolism and helps in the utilization of proteins
Manganese (Mn)	**Chloride (Cl)**
• Functions with enzyme systems involved in breakdown of carbohydrates, and nitrogen metabolism. • Soil is a source of manganese.	• Aids plant metabolism. • Chloride is found in the soil.
Zinc (Zn)	**Iron (Fe)**
• Essential for the transformation of carbohydrates. • Regulates consumption of sugars. • Part of the enzyme systems which regulate plant growth. • Sources of zinc are soil, zinc oxide, zinc sulfate, zinc chelate.	• Essential for formation of chlorophyll. • Sources of iron are the soil, iron sulfate, iron chelate.
	Molybdenum (Mo)
	• Helps in the use of nitrogen • Soil is a source of molybdenum.

Analysis of Survey on Factor Importance

We attended a meeting held by the Tatnuck Brook Watershed Association on January 6, 2016. We asked them if they could fill out a survey in which they ranked our list of factors based on importance. We gave them a sheet with the following table:

Table 17. Survey of what the weight of the factors should be.

Factors	Most Important	Important	Least Important
Likeliness of Succeeding: Based on background research and case studies, has this method been proven to work?			
Cost: How much will it cost each year?			
Negative Effects: Are there any negative impacts on the environment/ecosystem?			
Versatility: Can this method fix other problems in the reservoir?			
Safety: Are there any significant threats to humans or animals?			
Human Labor: How much work do humans need to do to ensure the best results?			
Immediate Results Time: How long until all the water chestnuts are removed for each attempt?			
Disposal Methods: How are the weeds ultimately removed? Does it require extra effort to dispose of them?			
Equipment: Are there any tools or items required to execute the method? Are they easy to put back when done using them?			

Their task was to put a checkmark in the column in which they thought the factor belonged in. We wanted to ask the stakeholders specifically because of three things. First, since they are there, they have obvious concerns about the water quality at Coes Reservoir. Second, some of these people have dealt with water quality issues before. Third, they would give a different perspective than us. We wanted to compare what we thought to what they chose and combined the results.

We put the results into two categories – those that live on/near Coes Reservoir, and those that do not. These measures were taken in case there were differences in their opinion as to what is more important. For example, the people that live on Coes Reservoir might feel safety is most important because they have to handle the weeds more often than those that do not live there. The results are outlined in Tables 18 and 19, where the number of people that checked the box are given.

Table 18. Results of survey of people that lived on/near Coes Reservoir (n = 5).

Factors	Most Important	Important	Least Important
Likeliness of Succeeding: Based on background research and case studies, has this method been proven to work?	5		
Cost: How much will it cost each year?	1	3	1
Negative Effects: Are there any negative impacts on the environment/ecosystem?	3	1	1
Versatility: Can this method fix other problems in the reservoir?	1	4	
Safety: Are there any significant threats to humans or animals?	2	3	
Human Labor: How much work do humans need to do to ensure the best results?	1	4	
Immediate Results Time: How long until all the water chestnuts are removed for each attempt?		3	2
Disposal Methods: How are the weeds ultimately removed? Does it require extra effort to dispose of them?		1	4
Equipment: Are there any tools or items required to execute the method? Are they easy to put back when done using them?		1	4

Table 19. Results of survey of people that lived away from Coes Reservoir (n = 4).

Factors	Most Important	Important	Least Important
Likeliness of Succeeding: Based on background research and case studies, has this method been proven to work?	3	1	
Cost: How much will it cost each year?	1	3	
Negative Effects: Are there any negative impacts on the environment/ecosystem?	2	1	1
Versatility: Can this method fix other problems in the reservoir?	1	3	
Safety: Are there any significant threats to humans or animals?	1	2	1
Human Labor: How much work do humans need to do to ensure the best results?	1	2	1
Immediate Results Time: How long until all the water chestnuts are removed for each attempt?		2	2
Disposal Methods: How are the weeds ultimately removed? Does it require extra effort to dispose of them?	1	1	2
Equipment: Are there any tools or items required to execute the method? Are they easy to put back when done using them?		2	2

It was universally agreed that "Likeliness of Succeeding" is the most important factor, while "Immediate Results Time", "Disposal Methods", and "Equipment" all are not as important as the other factors. With that being said, everything in between depended on where they lived. "Negative Effects" and "Safety" were considered slightly more important that "Versatility", "Human Labor" and "Cost" for the people that lived on Coes Reservoir. "Cost", "Negative Effects" and "Versatility" were considered slightly more important than "Safety" and "Human Labor" for the people that lived away from Coes Reservoir.

If the two categories are not taken into consideration, and the total votes are the only things that matter in the survey, then the results look like this:

Table 20. Results of survey for all people (n = 9).

Factors	Most Important	Important	Least Important
Likeliness of Succeeding: Based on background research and case studies, has this method been proven to work?	8	1	
Cost: How much will it cost each year?	2	6	1
Negative Effects: Are there any negative impacts on the environment/ecosystem?	5	2	2
Versatility: Can this method fix other problems in the reservoir?	2	7	
Safety: Are there any significant threats to humans or animals?	3	5	1
Human Labor: How much work do humans need to do to ensure the best results?	2	6	1
Immediate Results Time: How long until all the water chestnuts are removed for each attempt?		5	4
Disposal Methods: How are the weeds ultimately removed? Does it require extra effort to dispose of them?	1	2	6
Equipment: Are there any tools or items required to execute the method? Are they easy to put back when done using them?		3	6

When the results are added together, the factors can be divided into three general categories: agreed to be the most important, agreed to be the least important, and everything in the middle. Everything in the middle is equivalent to the factors whose results varied depending on where the people lived, so they would be “Cost”, “Negative Effects”, “Versatility”, “Safety” and “Human Labor”.

Additionally, we decided to rename “Human Labor” to “Community Effort” to clarify that we meant extra work done by unpaid people.

Rating the Treatments Example

An example table of the nine qualitative descriptive tables can be found below.

Table 21. Example descriptions of treatments in regards to "Safety" (Are there any significant threats to humans?).

Drawdown Flooding can occur downstream if the water level is lowered. *Since it cannot get much safer than this, this description is ideal, so it is green.*	**Aeration and Bioremediation** Very low safety danger. *Since it cannot get much safer than this, this description is ideal, so it is green.*
Physical Removal If humans are in the way of the harvester, could pose significant injuries. Safe to operate otherwise. Pluckers take risk in cutting themselves on the water chestnut seeds. *Since it poses minor danger to humans, it is in the middle of ideal and not ideal, so it is yellow.*	**Herbicides** Humans must wear protective equipment (Eye protection, suit) when applying herbicides. If chemicals are ingested can be fatal. *Since its danger is lethal, no treatment can be worse. It is NOT ideal, so it is red.*

Summative Table Walkthrough

A walkthrough of the quantitative numerical table can be found below. It contains three figures. The walkthrough contains three figures – 16, 17, and 18.

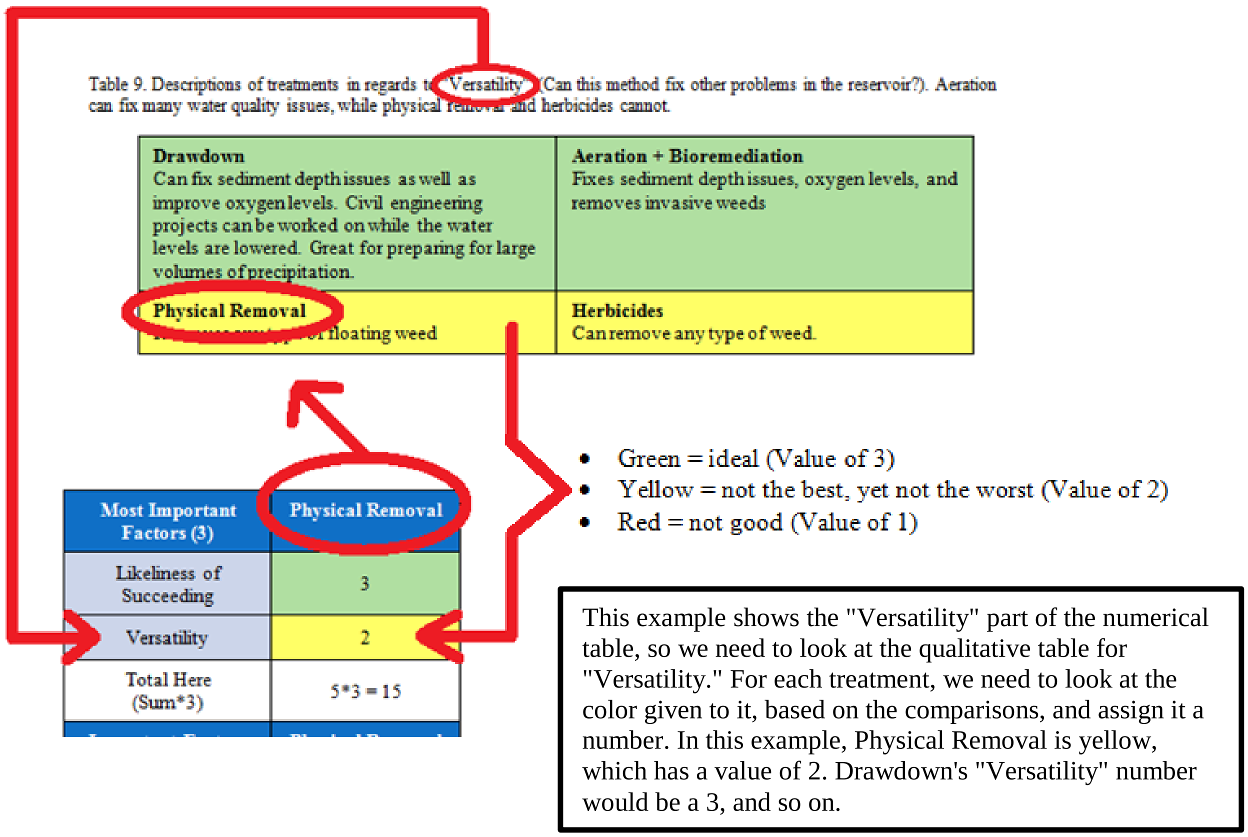

Figure 16. Quantitative example 1 of 3.

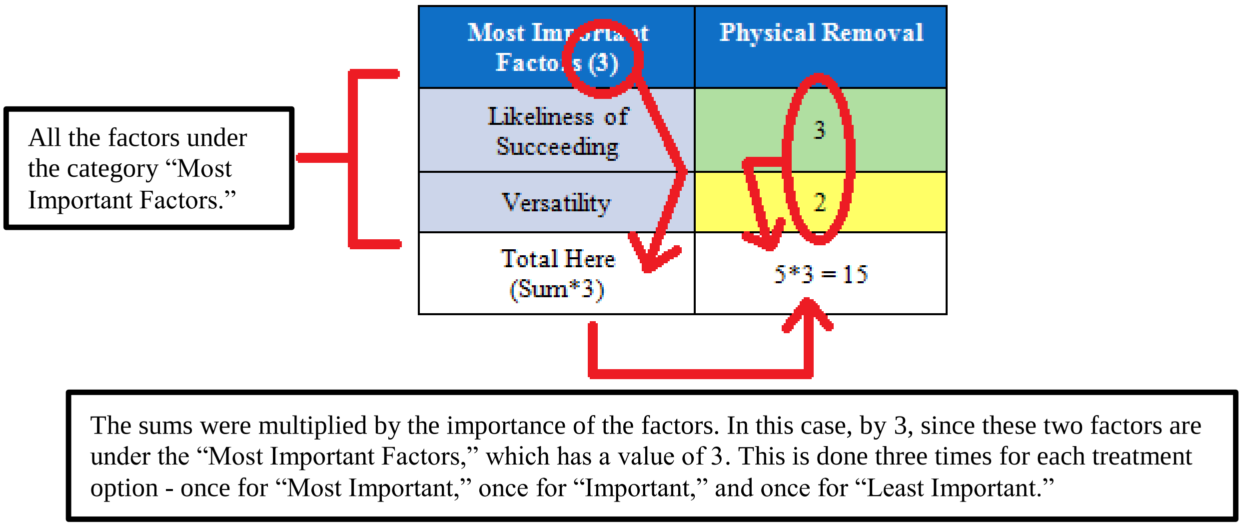

Figure 17. Quantitative example 2 of 3.

Most Important Factors (3)	Physical Removal
Likeliness of Succeeding	3
Versatility	2
Total Here (Sum*3)	5*3 = 15

Important Factors (2)	Physical Removal
Cost	1
Negative Effects	2
Safety	2
Community Effort	1
Total Here (Sum*2)	6*2 = 12

Least Important Factors (1)	Physical Removal
Immediate Results Time	3
Disposal Methods	1
Equipment	1
Total Here (Sum*1)	5*1 = 5

Cumulative Total	15+12+5 = 32

- Most important factors (Value of 3)
- Important factors (Value of 2)
- Least important factors (Value of 1)

The three products for each treatment were all added together to make a final numerical result. Whichever treatment has the highest total is our best recommendation.

Figure 18. Quantitative example 3 of 3.

Authorship

Name	Chapters Contributions	Task Contributions
Jibreel Mustafa	1 Introduction 2 Background Introduction 2.3 Urban Watershed Health 2.4 Pollution in Watersheds 2.4.1 Point Source Pollution 2.4.1.1 Internal Effects of Wastewater Discharge 2.4.2 Nonpoint Source Pollution 2.4.3 How Geography Affects Pollution 2.4.4 Water Quality 2.8 Invasive Weed Removal Treatments 2.8.4 Aeration and Bioremediation 2.8.4.1 Aeration 2.8.4.1.1 Air Compressors 2.8.4.1.2 Surface Spray and Impeller-Aspirator 2.8.4.1.3 Risk of Aeration 2.8.4.1.4 Benefits of Aeration 2.8.4.2 Bioremediation 2.8.4.3 Lake Savers 2.8.4.4 Protection 3 Introduction to Methods 3.1 Initiating the Research 3.3 Case Study Analysis Criteria 3.5 Researching Companies 4 Introduction to Results 4.1.4 Aeration and Bioremediation 4.1.4.1 Lake Savers: Collins Lake, NY 5 Recommendations and Conclusion Introduction 5.1.1 Aeration and Bioremediation Recommendation 5.4 Conclusion	• Researching how to write methodology • Setting up meetings at writing center and library • Taking notes at meetings and interviews • Editing report • Creating weekly agendas • Creating weekly goals • Attending monthly meetings for the Tatnuck Brook Watershed Association • Took water samples from Coes Reservoir • Created structure and outline of Ch. 5

Name	Chapters Contributions	Task Contributions
Ryan Smolenski	Title Page Acknowledgements Table of Contents List of Figures List of Tables 2.6.2 Physical Description 2.6.3 Origin 2.6.4 Natural Predators and Diseases 2.7.1 Master Plan – Effort in Restoring the Area 2.8.1 Physical Removal 2.8.1.1 Mechanical Harvesting 2.8.1.2 Hand-Pulling 2.8.2 Drawdowns 3.4 Comparison of Treatments Criteria 3.4.1 Guidelines for Comparisons 3.4.2 Analysis via Important Factors 3.4.3 Tables with Descriptions of Treatments 3.4.3.1 Format of Tables for Rating the Treatments 3.4.3.2 Format of Summative Table 4 Results 4.1 Case Studies Analyses 4.1.1 Physical Removal 4.1.1.1 Coes Reservoir Previous Attempt 4.1.1.2 Mechanical Harvesting: Chesapeake Bay Watershed, MD 4.1.1.3 Mechanical Harvesting: Charles River Watershed, MA 4.1.2 Drawdown 4.1.2.1 Drawdown: Indian Lake, MA 4.2 Comparison of Treatments 4.2.1 Rating the Treatments per Factor 4.2.2 Summative Comparisons 5 Recommendations and Conclusion 5.1.3 Alternative Option #2: Physical Removal 5.1.4 Alternative Option #3: Drawdown 5.2.1 Beneficiaries of Improved Water Quality at Coes Reservoir 5.3 Applications Beyond Coes Reservoir Works Cited Appendix Authorship	• Researching how to include figures and tables • Formatting/editing of list of figures and tables • Formatting/editing of report • Asking questions at meetings and interviews • Creating and formatting removal method comparison tables. • Creating Figures 9-12 • Creating survey for treatment factors and analyzing results • Presented a power point presentation to the Tatnuck Brook Watershed Association

Name	**Chapters Contributions**	**Task Contributions**
Ryan Sullivan	Abstract Executive Summary 2.1 Industrialization and Population 2.1.1 Construction of Coes Reservoir 2.2 Watersheds 2.2.1 Benefits to the Community 2.5 Invasive Species Characteristics 2.6 Characteristics of Water Chestnuts 2.6.1 Why are They Considered Invasive? 2.6.5 Threats to the Body of Water 2.6.6 Comparable Species 2.7 Coes Reservoir: In Need of Restoration 2.8.3 Herbicides 2.8.3.1 Fluridone 2.8.3.2 Triclopyr 2.8.3.3 Dichlorophenoxyacetic Acid 3.2 Understanding the Effects of Pollution 4.1.3 Herbicides 4.1.3.1 Fluridone: Saratoga Lake, NY 4.1.3.2 Triclopyr: Saratoga Lake, NY 4.1.3.3 2, 4-Dichlorophenoxyacetic Acid: Loon Lake, WA 5.1.2 Alternative Option #1: Herbicides 5.2 Long-Term Implications 5.4.1 Limitations of the Project	• Taking notes at meetings and interviews • Editing report • Reorganizing the chapters of the entire report • Brochure/Pamphlet • Sections in Power Point • Attending monthly meetings for the Tatnuck Brook Watershed Association • Took water samples from Coes Reservoir • Presented a power point presentation to the Tatnuck Brook Watershed Association