Exploring the Potential for Reclaimed Wastewater Applications:

Designing a feasible and beneficial reuse process for the Upper Blackstone Water Pollution Abatement District

A Major Qualifying Project
submitted to the faculty of:
Worcester Polytechnic Institute
in partial fulfillment of the requirements of the
Degree of Bachelor's of Science

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Professional Licensure

In order to ensure that quality work is completed, it is important to have a Professional Engineer (PE) sign off on all engineering designs and recommendations. The PE licensure system is a way to signify that an engineer is qualified to consult on the work that they accepted. This role also comes with responsibility for any issues that arise from any design work that they sign off on. Before being eligible for PE licensing, one must pass the Fundamentals of Engineering (FE) exam and receive their Engineer-In-Training (EIT) certification. After receiving an EIT certification, an engineer must complete four years of professional practice and sometimes other professional development requirements, depending on the licensing state.

Getting a PE license is extremely beneficial to an engineer's career. It allows one to submit engineering work to public authorities and can seal work for public or private clients.[1] In many places companies are now limiting their contracts to only be with PE's, therefore making licensure a vital step in the career of many engineers. This license also holds the PE liable for damages and/or injury that may result from their design work.

The reuse system proposed would need the stamp of a licensed PE in order to be implemented. The recommendations provided in this report are preliminary and may require further design consultation. Ethical practices must also be adhered to during this process.

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[1] "Why Get Licensed?," NSPE, 2017, accessed February 10, 2017, https://www.nspe.org/resources/licensure/why-get-licensed.

Design Statement

The Millbury, MA Wheelabrator facility uses 700,000-800,000 gallons of city water per day for demineralized boiler water, cooling tower make-up, fire-suppression water, and potable water. This project proposes a design for 1 million gallons per day (MGD) to be transported to Wheelabrator from Upper Blackstone Water Pollution Abatement District (UBWPAD) for non-human contact processes. The final design plans for the system to operate for 24 hours a day, seven days a week.

Reuse of water at Wheelabrator requires that Massachusetts Wastewater Reuse Class A water quality standards are met. Through analysis of five years of UBWPAD's effluent, it was found that there were 96 instances when the total suspended solids (TSS) levels exceeded the Class A limit. Additionally, the fecal coliform requirement was not met for this class. In order to treat the effluent to Class A, an ultrafiltration (UF) unit and ultraviolet (UV) disinfection would be necessary following UBWPAD's current treatment system. A modular, polymeric membrane was selected for the removal of an adequate amount of TSS and to allow for future expansion of the system. In order to provide appropriate dosing of UV light to the design, thirty 800 W low pressure high output lamps are recommended using a 20 inch diameter through pipe.

Due to the fact that Wheelabrator is 139 feet higher in elevation and nearly a mile away from UBWPAD, a centrifugal pump is needed following the treatment units. To account for regular maintenance and possible pump failure, the design calls for two pumps in parallel. Each pump should be capable of providing at least 18,137 W of power, and up to 36,274 W in the event that the other is offline. Therefore the performance curve of the selected pump should comfortably operate between 24 and 49 hp. In order to maximize the efficiency of the pump, a 6x6 model is recommended, with the necessary fittings on either side to accommodate the changes in pipe diameter.

This project was designed to be economically and environmentally sustainable. Therefore the pipe is situated along the most direct route between the facilities. It follows Massachusetts Route 20 to minimize pressure loss and cost of materials, with a total length of 5,289 feet. Schedule 40 high density polyethylene (HDPE) pipe with a 12 inch diameter was chosen for this system to be compatible with Wheelabrator's current processes, since the water mains from Worcester and Millbury are 12 inches. Additionally, this would allow for up to 5 MGD to account for future expansion in the area. A Process Flow Diagram, Piping and Instrumentation Diagram, Equipment Summary Table, Stream Table, and recommended spare parts list are provided.

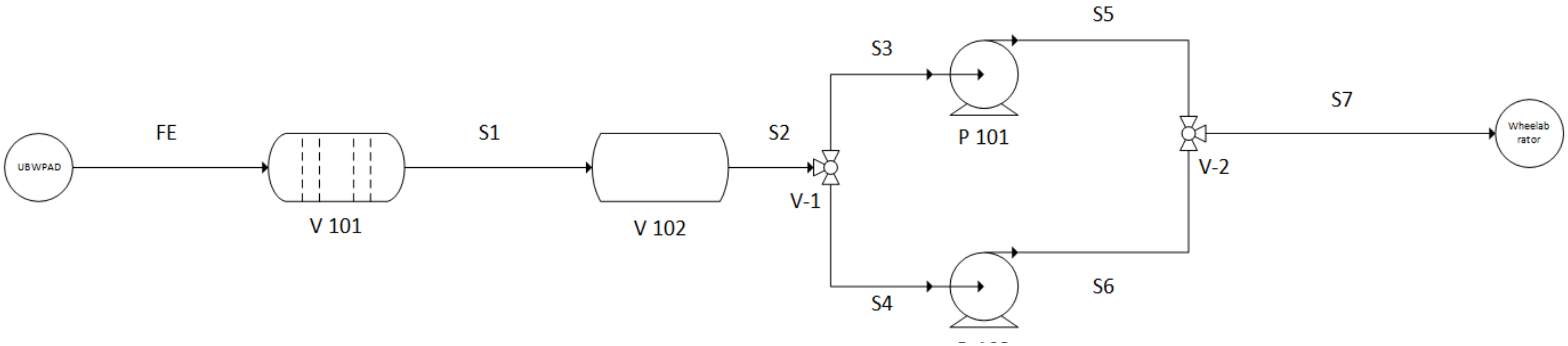

Figure 1: Process Flow Diagram

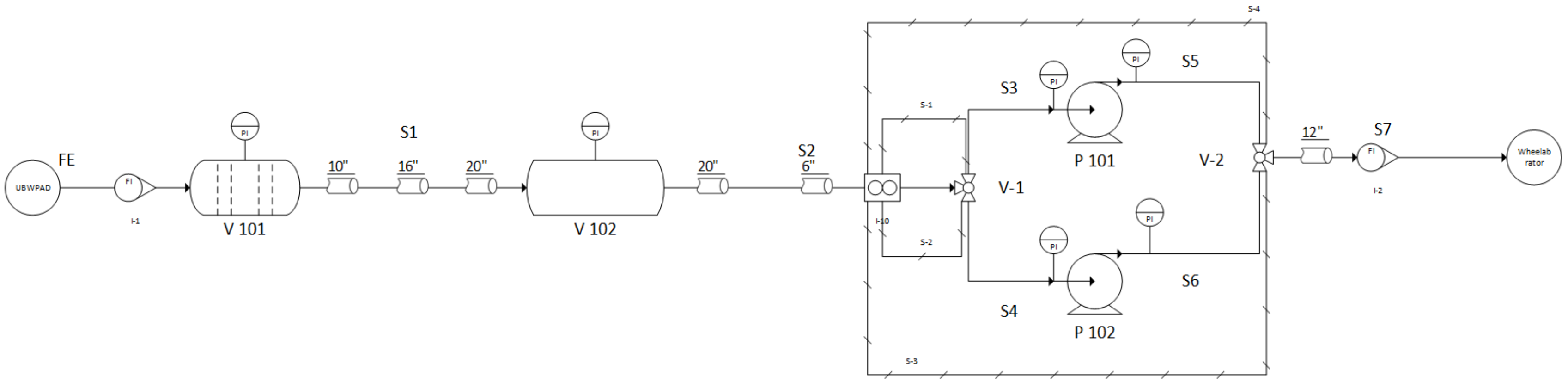

Figure 2: Piping and Instrumentation Diagram

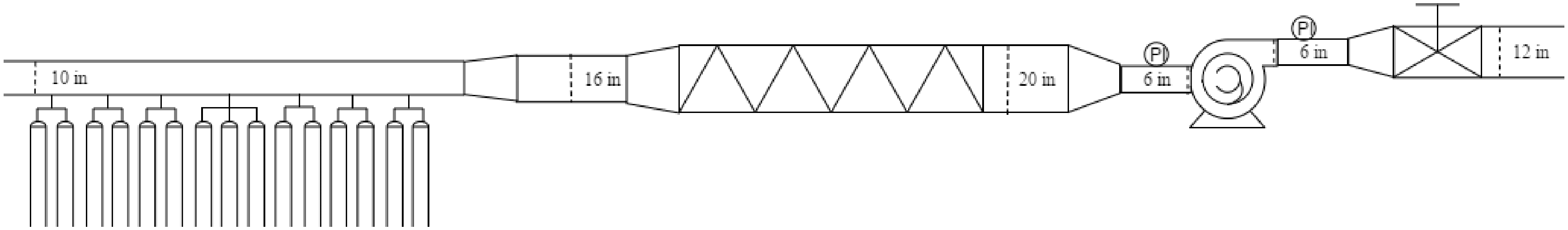

Figure 3: Process Schematic

Table 1: Equipment Summary Table

Equipment	**V-101**	**V-102**	**P-101**	**P-102**
MOC	Stainless Steel	Stainless Steel	Stainless Steel	Stainless Steel
Power (shaft) (kW)	–	–	36	36
Efficiency	–	–	70%	70%
Type/Drive	–	–	Centrifugal/Electric	Centrifugal/Electric
Pressure in (bar)	4.6	2.5	2.25	2.25
Pressure out (bar)	2.5	2.5	6.42	6.42
Diameter (ft.)	5.6	1.67	–	–
Height/length (ft.)	16.4	10	–	–
Orientation	Horizontal	Horizontal	–	–

Table 2: Stream Table

Stream Number	**1**	**2**	**3**	**4***	**5**	**6***	**7**
Temperature (°C)	15	15	15	15	15	15	15
Pressure (bar)	2.5	2.5	2.25	2.25	6.42	6.42	6.42
Vapor Fraction	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mass flow (ton/hr)†	1,313	1,313	1,313	1,313	1,313	1,313	1,313
Mole flow (kmol/hr)†	66,173	66,173	66,173	66,173	66,173	66,173	66,173

* Streams 4 and 6 are in redundancy of Steams 3 and 5 and are not always in operation

† The ultrafiltration membrane and ultraviolet disinfection remove solid particles and microorganisms respectively, but this is a very low value and has minimal impact on the total flowrate.

Table 3: Recommended Spare Parts List

Part	*Number Needed*
Centrifugal Pump	1
Valves	4
Ultrafilter Units	5
UV Bulbs	10
Pressure Indicators	10
Flowmeters	2
Rotameters	4
Nuts/Bolts	100 of each
Flanges	10
Gaskets	10

Contents

Table of Figures

Table of Tables

Abstract

This project provides recommendations for water reuse systems that would be beneficial to the Greater Worcester community, with specific focus on use at Wheelabrator Technologies. A treatment system capable of treating 1 MGD to meet Massachusetts Class A water reuse standards was designed with the intention of relieving industrial use of potable water in the town of Millbury. The proposed system consists of an ultrafiltration membrane unit to control suspended solid levels, an ultraviolet disinfection unit to control fecal coliform levels, and a pumping station. This system could be mutually beneficial to both the Upper Blackstone Water Pollution Abatement District and Wheelabrator Technologies.

Executive Summary

This project provides recommendations to UBWPAD for a wastewater reuse system partnering with Wheelabrator Technologies, Millbury. Regions in the United States that have not previously been hit by severe droughts are currently experiencing an increase in drought conditions, including the state of Massachusetts. Throughout the summer of 2016, a majority of the state was classified as being in Stage 3 Extreme Drought. This led to restrictions on outdoor water use and consumption in much of the state. Specifically, in Worcester, MA the following uses were restricted: water offered at restaurants; watering grass and plants with a hose, and filling pools.[2] As freshwater resources are increasingly strained due to climate change, alternatives such as reclaimed wastewater are becoming more important. Using reclaimed wastewater can significantly help decrease industrial water use and irrigation. However, there is much skepticism surrounding reuse, as many people fear waterborne disease outbreak. For this reason, there are strict water quality standards that must be achieved for reclaimed wastewater.

Wheelabrator Technologies is a trash-to-energy facility one mile away from UBWPAD that uses regularly uses between 700,000–800,000 gallons per day of Millbury's town water, provided by Aquarian Water. There is potential to use treated wastewater for many non-contact processes within the plant, such as cooling tower makeup water. Not only would recycled wastewater be more cost effective than potable water, this reuse would reduce a large strain on Millbury's potable water supply during times of drought. Because the cooling tower produces mist, the treated wastewater must comply with Massachusetts Class A standards, which have stricter fecal coliform and suspended solids limits than EPA standards.

In order to determine the need for additional treatment of UBWPAD's water, five years of effluent quality data was compared to Massachusetts Class A, B, and C reuse standards as well as Millbury's water quality. The WPI environmental laboratories were used to test parameters not included in the received data, including hardness, conductivity, and turbidity. These parameters were hardness, conductivity, and turbidity. UBWPAD's effluent and the water provided by Aquarian Water were compared and determined to be of similar quality with the exception of conductivity and hardness levels. UBWPAD's future plans to implement tertiary treatment steps will help lower these levels in the future. It was also found that to meet Class A reuse standards, suspended solids and fecal coliform levels would need to be improved.

The proposed system includes an ultrafiltration membrane unit to reduce suspended solids levels and an ultraviolet disinfection unit to address the fecal coliform levels. With these additions to UBWPAD's current treatment process the final effluent produced daily will consistently meet the Massachusetts Class A water reuse standards. This level of treatment will provide a safe resource for Wheelabrator to use daily as make-up water for their cooling tower. Using reclaimed water will be economically beneficial to Wheelabrator, as well as provide future security to the facility in times of water scarcity. This reuse system will remove a significant stress on potable water sources and is therefore a very environmentally beneficial project.

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[2] Annear, Steve. *Steve Annear*. (BostonGlobe.com), September 8, 2016.

1. Intro

During the summer of 2017, Massachusetts experienced a level D3 Extreme Drought across much of the state. This caused stress on freshwater resources leading to restrictions on water use and consumption. Due to climate change, it is expected that the world will continue to face droughts like this, even in places that are not historically drought prone. In order to decrease strain and demand on surface and groundwater sources, reclaimed wastewater can be used as an alternative. Examples of possible applications of wastewater reuse include, but are not limited to: industrial process water, dust suppression, irrigation, toilet flushing, and use in public work projects for the Greater Worcester area. However, the general public is often skeptical of reused wastewater due to fear of transmission of waterborne diseases and other public health concerns. The idea of reclaimed wastewater being used in ways that have high contact with people is usually met with disdain. If pursuing a reuse project, the reclaimed wastewater must meet strict water quality requirements outlined in state and federal permits. These permits specify limits for parameters such as biochemical oxygen demand (BOD), turbidity, pH, and E. coli levels depending on the intended use of the reclaimed wastewater.

The Upper Blackstone Water Pollution Abatement District (UBWPAD) is a wastewater treatment facility that services the Greater Worcester area and discharges into the Blackstone River. The treated effluent from this facility is of very high quality, and a suitable source for potential reuse applications. Due to the recent increase in severe droughts occurring in Massachusetts, reusing water both within the facility and in the surrounding community can alleviate stresses on drinking water sources. Several processes at the UBWPAD facility are already using recycled “plant water” and this internal reuse can be increased in the future. Additionally, UBWPAD has the potential to partner with many local businesses and surrounding municipalities provide reclaimed water for irrigation, construction, and industrial processes. An example of this is the Wheelabrator Technologies facility in Millbury, which is a trash-to-energy facility that currently uses drinking water for all their processes. Partnering UBWPAD with Wheelabrator can improve the sustainability of both facilities and help to build a public acceptance of wastewater reuse.

This project evaluated the potential reclaimed water reuse options for the UBWPAD, with specific emphasis on the opportunity to reuse water at Wheelabrator. Testing of several water quality parameters was performed on UBWPAD’s effluent, and based on the results the most feasible reuse system was determined. The following report is a preliminary engineering design for the recommended application of reused water at Wheelabrator. These recommendations and design will be presented to both UBWPAD and Wheelabrator in the form of an oral presentation and the written report.

2. Background

2.1 History of Water Reuse

2.1.1 Water Scarcity and Climate Change

Both water management and water recycling has become increasingly important in recent years as climate change has begun to seriously impact the environment.[3] As shown in Figure 4 below, approximately half of the United States has been experiencing increasing drought conditions over the past 60 years.

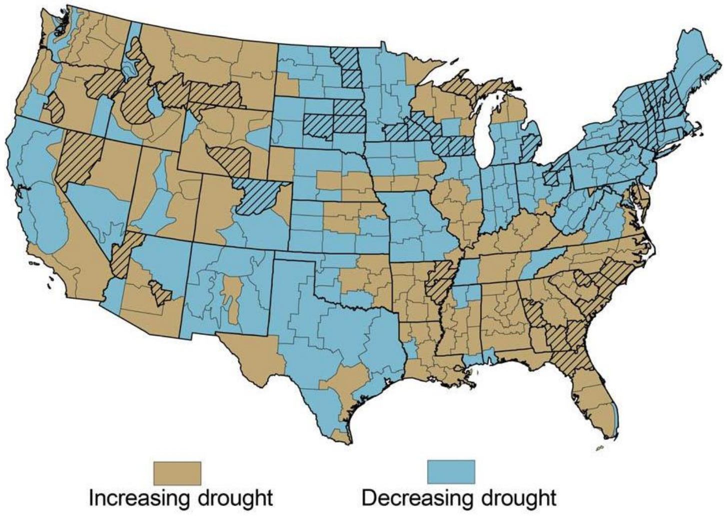

Figure 4: Drought Conditions across the United States from 1958 to 2007[4]

Massachusetts is an area that is currently experiencing increased problems with drought levels. As of September 2016, half the state was classified as experiencing a level D3 Extreme Drought, shown in Figure 5 below.

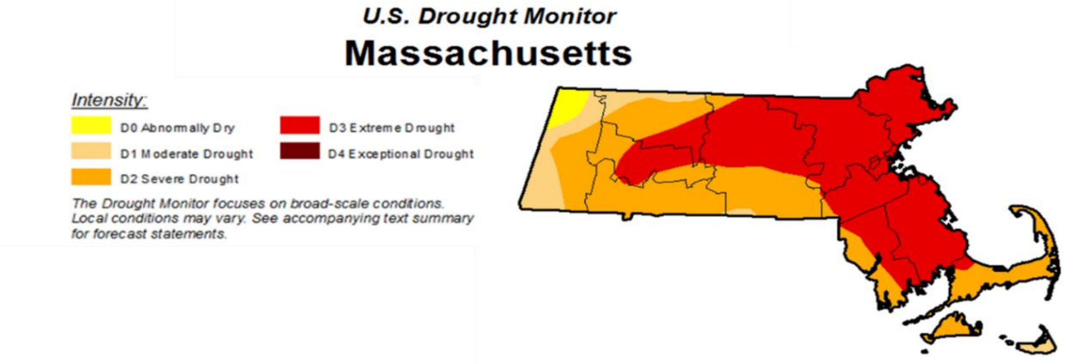

Figure 5: September, 2016 Drought Levels in Massachusetts[5]

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[3] Environmental Protection Agency. (2016, February 23). *Water Recycling and Reuse: The Environmental Benefits.*

[4] Guttman, N. B., and R. G. Quayle. "A Historical Perspective of U.S. Climate Divisions." Bulletin of the American Meteorological Society 77, no. 2 (1996): 293-303

[5] Artusa, A. (2016, September 20). *U.S. Drought Monitor – Massachusetts.*

Freshwater makes up only 1% of the Earth's water, much of which is trapped in glaciers and icecaps. This leaves only about 0.007% of the entire planet's water available for the world population.[6] Many surface waters that used be full of water are now becoming dried up, such as Lake Powell in Utah and Arizona, which is shown below in Figure 6. These surface water supplies, which are already strained, are under increasing stress from drought conditions. This creates a need for water reuse.

Figure 6: Water Levels in Lake Powell[7]

2.1.2 Water Reuse: What is it and how is it applied?

Water recycling, or water reuse, is a technique that can be employed to combat dwindling fresh water sources and is defined as the process of collecting water that has been used once by a population and treating it to be used again.[8] Many industrial facilities already recycle water onsite for cooling operations to decrease their demand of public water. Another common example of water reuse is for industries, colleges, and wastewater treatment plants to use treated wastewater for toilet flushing or on-site irrigation since the water quality does not need to be as high for these graywater applications. Many major cities such as Cincinnati and New Orleans are also reusing wastewater as "de facto" potable water. This term refers to water that is drawn from a source that

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[6] Freshwater Crisis. (n.d.). Retrieved September 22, 2016, from National Geographic.
[7] Environmental Protection Agency. (2016, February 23).
[8] Ibid.

is a wastewater discharge site for another municipality.[9] Since the discharged water has been significantly treated already, once it is mixed with a natural water source it is considered as clean as any drinking water resource. The adoption of de facto reuse has increased in the United States over the past 30 years, and the United States is current the world leader in wastewater reuse[10], as shown in Figure 7 below.

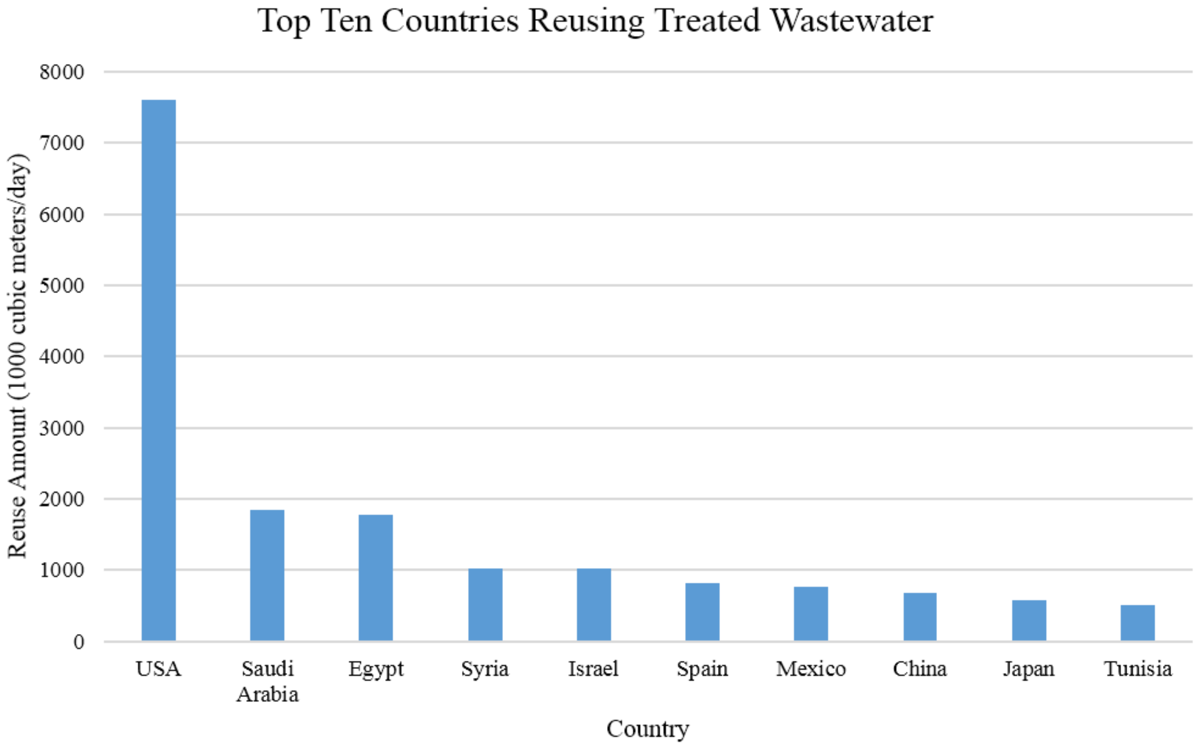

Figure 7: Comparison of Global Wastewater Reuse[11]

The EPA has done extensive research surrounding the level of treatment needed for various reuse methods. It has been determined that water is safe to be reused for all possible uses as long as it is treated to a sufficient level, the specifics of which are shown in Figure 8 on the following page. Many wastewater reuse opportunities are viable after applying secondary treatment that includes biological oxidation and/or disinfection. In general, when reused water will be in contact or close contact with humans, it is necessary to have a tertiary or advanced treatment such as chemical coagulation, filtration, and disinfection. There is still room for growth for new reuse applications in the United States.

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[9] Asano, T., Leverenz, H. L., & Tsuchihashi, R. (2007). *Water reuse: Issues, technologies, and applications* (1st ed.). New York, NY: McGraw-Hill.

[10] Jiménez, B., & Asano, T. (2008). Water reclamation and reuse around the world. *Water reuse: an international survey of current practice, issues and needs. IWA, London*, 3-26.

[11] Ibid.

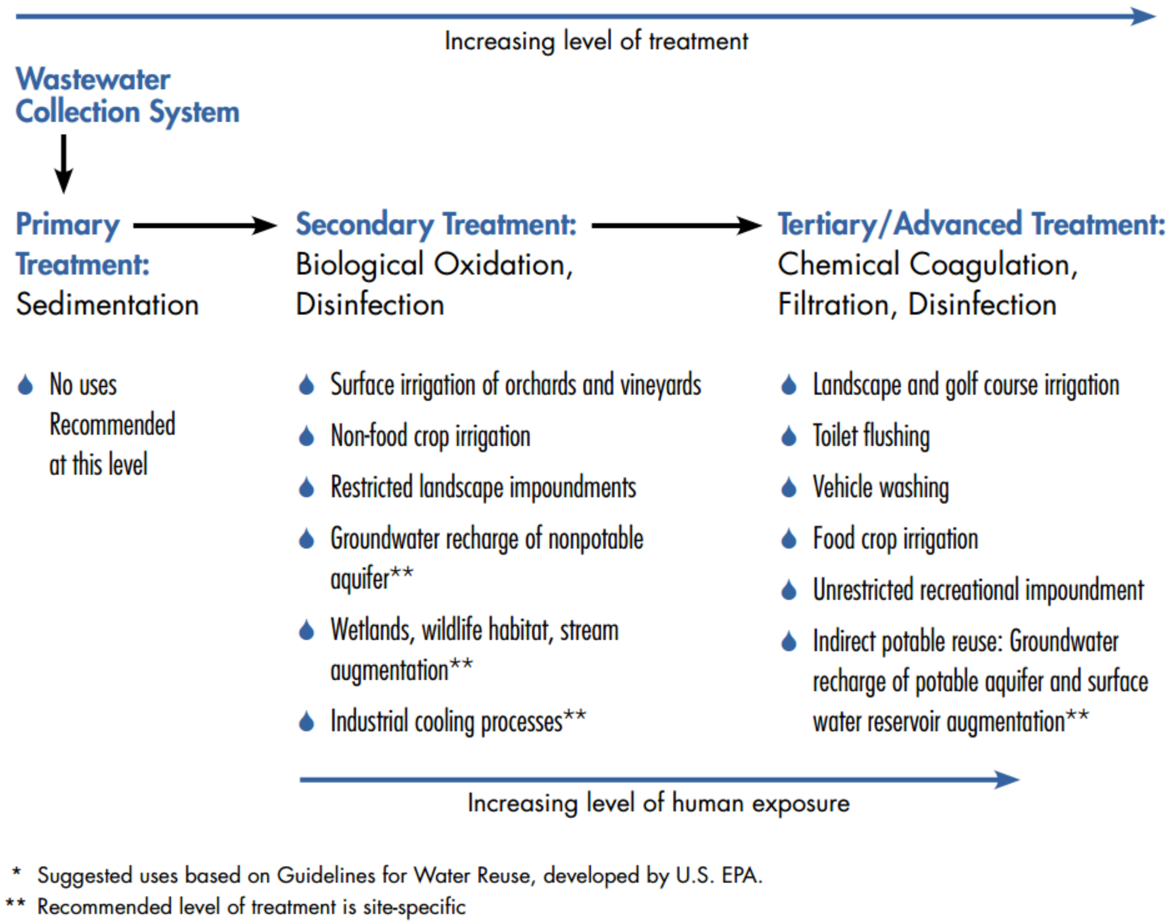

Figure 8: EPA Recommended Levels of Treatment[12]

2.1.3 Popularity of Wastewater Reuse

The idea of wastewater reuse for public purposes has been slow to gain popularity in the United States due to the fear of waterborne illnesses. Each year, billions of dollars are spent to treat water and only 10% is then used for direct human consumption.[13] This human consumption creates approximately 5.8 billion gallons of wastewater per day. Due to the scarcity of fresh water sources, the use of treated wastewater for some types of irrigation has gained popularity in the United States. For example, the amount of recycled water used for agricultural purposes in California increased from 80,000 acre-feet to over 200,000 acre-feet between 1993 and 2003.[14] Many communities in California are also looking to recycle their wastewater for potable reuse including major cities like Los Angeles, San Francisco and San Diego.[15] An initiative in Orange County is recycling up to 100 million gallons each day to send to 850,000 residents. This process treats the county's wastewater, mixes it with groundwater supply, and delivers it to homes. As the

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[12] Metropolitan Area Planning Council. (2005). *Once is not enough: A guide to water reuse in Massachusetts*.

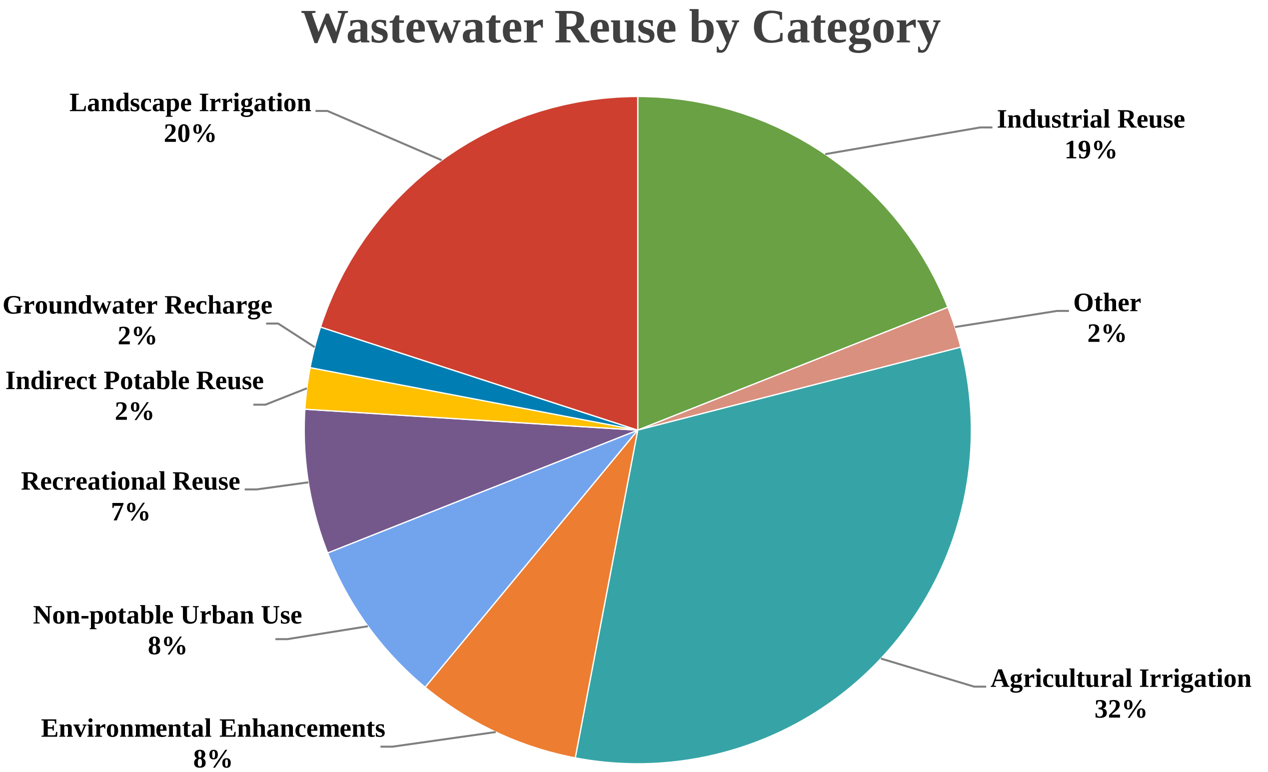
[13] Cho, R. (2011, April 4). From Wastewater to Drinking Water. *Earth Institute*.

[14] Schulte, P. (2010). California farm water success stories - Using Recycled Water on Agriculture: Sea Mist Farms and Sonoma County. Oakland, California: *Pacific Institute*.

[15] Monks, K. (2014). *From Toilet to Tap: Getting a taste for drinking recycled waste water*.

state faces its third consecutive year of drought, more applications of wastewater reuse are being explored.

Across the globe, countries and cities are adopting wastewater reuse policies and initiatives. In Australia, there has been an ongoing campaign to improve the public opinion of wastewater reuse for drinking water.[16] After three years of campaigning, there is 76% public support in the city of Perth for this initiative. Countries such as Namibia and Singapore are also employing initiatives like this to decrease freshwater demand. Worldwide trends in global water reuse show that most reclaimed water is used for purposes with little to no human contact. As seen in Figure 9, agricultural and landscape irrigation make up over 50% of all water reuse. The fear of waterborne disease outbreak has limited the amount of reuse that has high human contact.[17]



*Note: Indirect potable, recreational, and non-potable urban involve human contact

Figure 9: Water Use by Type[18]

In Massachusetts, the need for water reuse in the past has been relatively low. There has been no statewide push for water reuse, but there are many individual projects, such as Gillette Stadium's water reuse system, which was installed in 2002. The current facility can recycle up to 250,000 gallons per day, with possible expansion up to 1 million gallons.[19] The reclaimed water is used for toilet flushing and saves 65% of water consumption. Another example is the Wrentham

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[16] Monks, K. (2014).

[17] Asano, T., Leverenz, H. L., & Tsuchihashi, R. (2007).

[18] Lautze, J., Stander, E., Drechsel, P., da Silva, A. K., & Keraita, B. (2014). Global experiences in water reuse. Resource Recovery and Reuse Series, 4.

[19] Metropolitan Area Planning Council. (2005).

Premium Outlet Mall which has been treating wastewater onsite since 1997. The treatment plant provides 50,000 gallons of effluent that is then used for toilet flushing and groundwater recharge which decreases water demand by 50%. In a 2001, a Bayberry Hills project in Yarmouth, MA created a reuse system for a wastewater treatment plant that recycles up to 70% of its treated effluent for irrigation and groundwater recharge. Additionally, there are many industries recycling their water including Intel Corporation and EMC.[20] These examples show that there has been some wastewater reuse throughout the last two decades, however, the amount of water that is being reused is very minimal in comparison of the total water consumption in MA, which was 206.57 million gallons per day in 2015.[21]

2.1.4 Challenges Surrounding Wastewater Reuse

One of the biggest challenges facing reclaimed water use is public opinion. A survey in Kuwait found that 96% of respondents did not support wastewater reuse, noting that they were disgusted by the idea and concerned about health risks.[22] For this reason, there are many regulations surrounding the level of treatment for various reuse applications. In Massachusetts, there are three classes of treated final effluent that can be reused: Classes A, B, and C. The specifics of these water quality standards can be shown below in Table 4 and are discussed further in Section 2.2.3.

Table 4: Class A-C Water Quality Standards[23]

Class A	pH = 6.5-8.5 BOD < 10 mg/l TSS < 5 mg/l Turbidity < average of 2 NTU within a 24-hour period, cannot exceed five NTU more than 5% of the time within a 24-hour period, and cannot exceed ten NTU at anytime Total Nitrogen < 10 mg/l Median of no detectable fecal coliform/100 ml over continuous seven-day sampling periods, not to exceed 14/100 ml in any one sample Other parameters as specified by the Department
Class B	pH = 6.5-8.5 BOD < 30 mg/l TSS < 10 mg/l Total Nitrogen < 10 mg/l Median of 14 detectable fecal coliform/100 ml over continuous 7-day sampling periods, not to exceed 100/100 ml in any one sample Other parameters as specified by the Department
Class C	pH = 6.5-8.5 BOD < 30 mg/l TSS < 30 mg/l Total Nitrogen < 10 mg/l Median of 200 detectable fecal coliform/100 ml Other parameters as specified by the Department

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[20] Metropolitan Area Planning Council. (2005).
[21] Massachusetts Water Resources Authority. (2016, September 1). *MWRA - Water Supply and Demand*.
[22] Duong, K. & Saphores, J. (2015). Obstacles to wastewater reuse: an overview. *Wires Water*, *2*(3), 199-214.
[23] Ibid.

For example, Class C water can only be used for orchard or vineyard irrigation where there isn't direct contact between the fruit and the water, while Class B water can be used as the make-up water for cement. Class A water can be used for a wide variety of applications including irrigation, cooling water, toilet flushing, agriculture, industrial processes, commercial laundries/carwashes, snow making, fire protection, and wetland creation.[24] To obtain Class A water quality, tertiary treatment is usually required, and this is currently not very common in many wastewater treatment plants.

Another challenge with wastewater recycling is the cost associated with the treatment and transportation.[25] In Orange County, CA for example, the annual cost to produce enough water using indirect potable reuse for two families of four is \$800-850.[26] While this process is less expensive than desalination, it is an added cost to traditional treatment costs. The price of reclaimed water must be high enough to recover the cost of production. Individual households have been found to have a low willingness to pay for reclaimed water to be used inside their home, while being less against reuse for outdoor purposes.[27] In order to make the sale of reclaimed water more feasible, increased public education and creating a wider variety of public information about the treatment and recycling process is needed.

2.2 Water Reuse Regulations

2.2.1 Policies on Federal and State Projects

Large federal projects in the United States are required to undergo a review process to evaluate the project's economic and social impacts under the National Environmental Policy Act (NEPA). When NEPA was passed in 1970, it formed the Council on Environmental Quality (CEQ) and "laid the groundwork for almost all current environmental legislation except for Superfund and asbestos control legislation,"[28] including the Safe Drinking Water Act and the Water Pollution Control Act. Federal agencies that are involved in a water reuse project with significant suspected environmental impacts should prepare environmental impact statements. If effects are uncertain, an Environmental Assessment can be prepared instead. The steps of the NEPA process are demonstrated in the flow diagram shown in Figure 10 on the following page.

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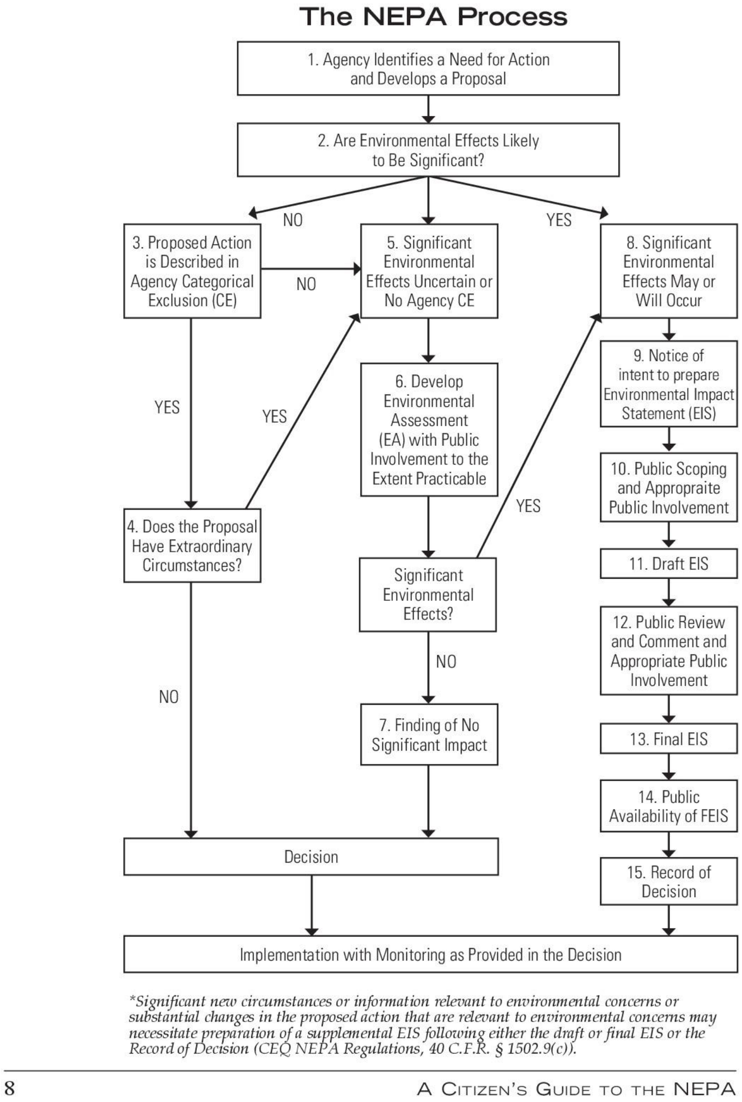
[24] Mass DEP (2009). 314 CMR 20.00: RECLAIMED WATER PERMIT PROGRAM AND STANDARDS.

[25] Duong, K. & Saphores, J. (2015).

[26] Cho, R. (2011, April 4).

[27] Duong, K. & Saphores, J. (2015).

[28] Alvin, Alm. (1988). *Epa.gov.* EPA Journal, January 1988.



**Significant new circumstances or information relevant to environmental concerns or substantial changes in the proposed action that are relevant to environmental concerns may necessitate preparation of a supplemental EIS following either the draft or final EIS or the Record of Decision (CEQ NEPA Regulations, 40 C.F.R. § 1502.9(c)).*

Figure 10: NEPA Permitting Process[29]

Massachusetts has its own version of this policy and process for smaller projects, called the Massachusetts Environmental Policy Act (MEPA). In this case state agencies must file a statement of intent with the Secretary of Environmental Affairs no less than 10 days after applying for a permit. If environmental complications or impacts are foreseen, an environmental impact report should be prepared, much like the environmental impact statement in NEPA. These processes do not affect whether a permit is obtained but allows the public to evaluate the impacts of a project and consider alternatives. MEPA requirements must be fulfilled before a permit is obtained for to water and wastewater projects.[30] The MEPA permitting process can be seen in Figure 11 on the following page.

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[29] *A Citizen's Guide to the NEPA: Having Your Voice Heard* (p. 8). Executive Office of the President.

[30] Commonwealth of Massachusetts (2008). *MEPA Statute.*

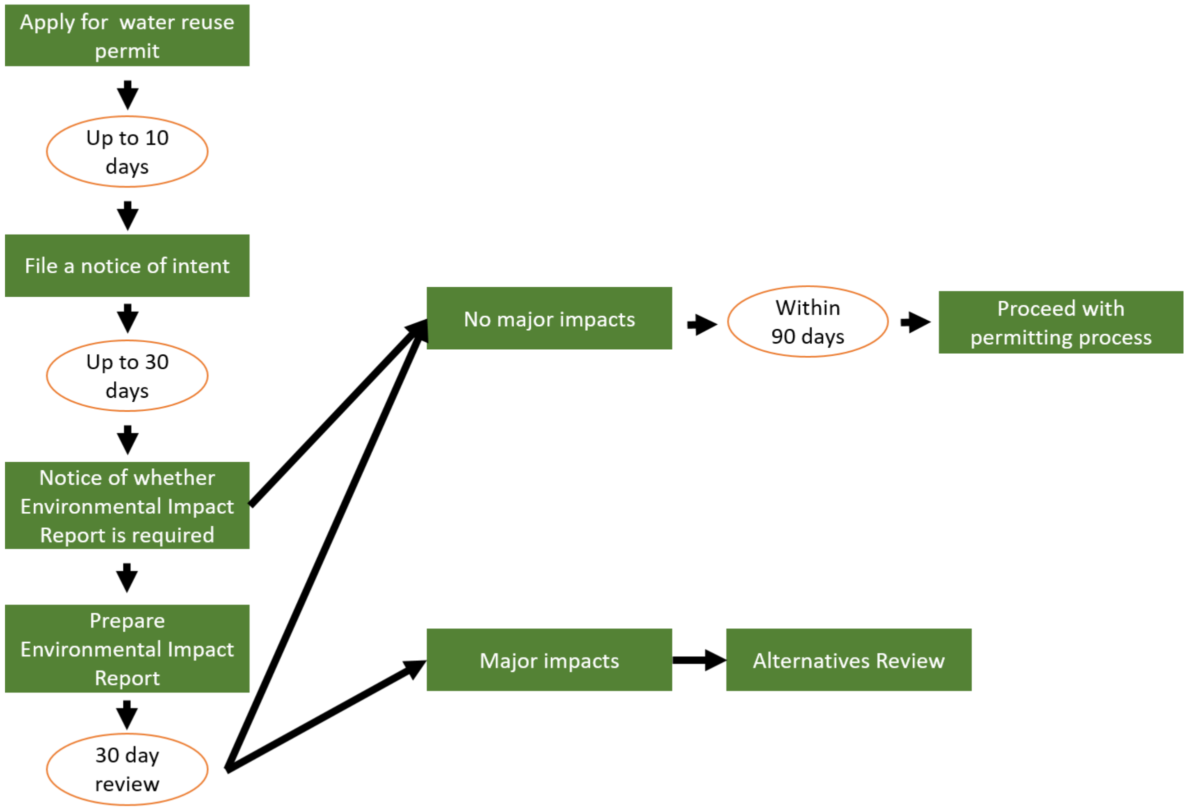

Figure 11: MEPA Permitting Process

2.2.2 Permits for Water Reuse Projects in Massachusetts

Section 20 of division 314 of the Code of Massachusetts Regulations outlines the permitting process for reclaimed water. Permits for reclaimed water that is used to recharge groundwater can be filed to 314 CMR 5.00, while those for replenishment of surface water can be filed to 314 CMR 3.00. All other uses of reclaimed water will be filed to 314 CMR 20.00. In all cases, the entity should submit a Water Management Plan along with the permit application including the volume of water and the part responsible for the management of the water. A valid Water Management plan will also describe how it is compliant with the Massachusetts Uniform Plumbing Code, 248 CMR 10.00. If any other entity is involved in the use, purchasing, or distribution of the reclaimed water a Service and Use Agreement should be established.

Reclaimed water plumbing and fixtures are colored purple and marked “NOTICE: RECLAIMED WATER - DO NOT DRINK”. The policy also states that:

> ...reclaimed water may be beneficially used only for the following purposes: irrigation, a source of water for recreational use, industrial or commercial cooling or air conditioning, toilet and urinal flushing, agricultural use, the creation of wetlands, commercial laundries, carwashes, industrial boiler feed, silviculture,

> snowmaking, fire protection, dust control, soil compaction, street cleaning, and aquifer recharge.[31]

The permit, titled BRP WP 84 - Reclaimed Water Use, can be found on the official website of the Massachusetts Executive Office of Energy and Environmental Affairs. Its application shall be filed 180 days before any action requiring the permit occurs.

2.2.3 Parameters Required for Water Reuse

The Massachusetts Department of Environmental Protection specifies limits for pH, Turbidity, BOD, TSS, Total Nitrogen, and fecal coliforms for the three classes of reclaimed water.[32] Class A reclaimed water may be used for non-potable irrigation, cooling water, toilet flushing, agricultural use, industrial processes, snowmaking, fire protection, and creation of wetlands or recreational compounds. This class has the most stringent limits. Class B can be used for highway and nursery irrigation, cooling water, pasture or non-contact agriculture, dust control, soil compaction, mixing concrete, and street cleaning. Finally, Class C can be used for vineyard irrigation, industrial process water, industrial boiler feed, and silviculture. Class C does not require very much treatment, with fairly high allowances of TSS and fecal coliform.

In order to keep public health a primary concern, this project will also utilize recommended effluent quality by the Environmental Protection Agency and the California Title 22 Code of Regulations. These recommendations are compared to those of Massachusetts in Appendix A: Comparison Requirements for Reclaimed Water Quality by Use. With the exception of coliforms, Massachusetts tends to hold the strictest standards for reclaimed water. If discharged to a surface water body, reclaimed water projects in Massachusetts will also need a Water Discharge Permit and to comply with the associated water quality standards within.

2.3 The Upper Blackstone River Valley Watershed

2.3.1 Watershed Significance

Beginning with the small streams in Worcester, the Blackstone River extends 48 miles to Rhode Island, and settles in Narragansett Bay. It provides twenty-nine communities with 1300 acres of water sources and amenities.[33] Each of these communities plays a part in maintaining the watershed for public use.

The Blackstone River Watershed is used for drinking water, food, energy, recreation, aesthetics, and aquatic life support.[34] Approximately ten of the Watershed’s rivers, streams, reservoirs, and ponds are a source of drinking water for surrounding towns, including the City of

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[31] MassDEP (2009).

[32] Ibid.

[33] Commonwealth of Massachusetts. (2016). *Blackstone River Watershed*. *Energy and Environmental Affairs*

[34] Commonwealth of Massachusetts. (2007). *BLACKSTONE RIVER WATERSHED 2003 - 2007 WATER QUALITY ASSESSMENT REPORT*.

Worcester. The river supports energy production for power plants like the Riverdale Mills Hydro Facility and the Ridgewood Power Facility.[35] It is also home to nineteen species of fish and eighteen other species including the osprey, the kingfisher, and the blue heron, which are all drawn to the watershed by the fish population.[36] Unfortunately, these aspects of the river and surrounding watershed are endangered by natural incidents and human interaction.

2.3.2 The State of the Watershed

The Upper Blackstone River Valley Watershed has historically been the dumping site for textile mill wastewater.[37] Because dredging could lead to the release of many dangerous chemicals, the bottom of the Blackstone River contains many toxins. In addition to this, algal blooms caused by nutrient buildup have occurred in many areas. A 2011 Report Card of the watershed's conditions revealed that two thirds of the Blackstone River monitoring sites had poor nutrient conditions, while the other third had fair nutrient conditions.[38] The invasive Asian water chestnut and purple loosestrife have been disrupting ecosystems in some areas, in conjunction with thermal pollution and high turbidity from storm water runoff. These factors have the potential to endanger fish and plant populations in the entire watershed.

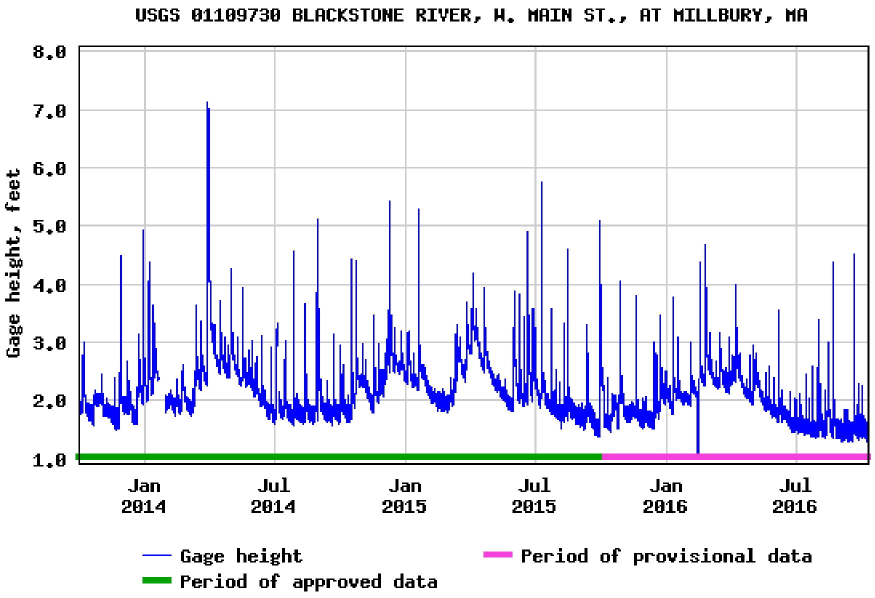

Figure 12: USGS Reported Levels of Blackstone River at Millbury, MA Metering Station[39]

Luckily, there are programs in place to address water quality and habitat disruption issues. The Blackstone River Watershed Association gathers more than 100 volunteers every year to help clean large items from the river, remove invasive species, and monitor conditions in the

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[35] Renewable Energy World. (2008). *Ridgewood Renewable Power To Develop 41-MW Landfill Gas Plant*.

[36] Blackstone River Coalition. (2008). *The Blackstone River ~ Clean by 2015.*

[37] BRWA (2016). *Blackstone River Challenges*.

[38] Blackstone River Coalition. (2016). *Report Card for 2011 Monitoring Season*.

[39] USGS. (2016). *Current Conditions for USGS 0110973 BLACKSTONE RIVER AT MILLBURY, MA.*

watershed.[40] While these efforts can improve conditions in the Watershed, the river water height is another concern. Water levels from January 2014 to July 2016 at the Millbury, MA monitoring site located near UBWPAD, can be seen in Figure 12 above. During the summer months of 2016, the level was below three feet. Human factors that affect the water level include hydroelectric facilities that hold and release water regularly as well as the withdrawals for drinking and industrial cooling.[41] People can cause large fluctuations in the water level, despite the measures that are in place to ensure that the water bodies do not run dry. Precautions to protect water sources become especially important in times of drought, such as the level D3 Extreme Drought effective in Massachusetts since September 2016.[42]

2.4 Upper Blackstone Water Pollution Abatement District

The Upper Blackstone Water Pollution Abatement District (UBWPAD) services 250,000 people in the greater Worcester area and treats roughly 30 million gallons a day (MGD).[43] The treated effluent from this facility is discharged into the Blackstone River, and is a major contributor to the river flow. Increasing the quality of the treated effluent for the benefit of both the river and local reuse applications will add to the Greater Worcester area's water security.

2.4.1 UBWPAD Current Operations

The current treatment process at UBWPAD can be seen in Appendix B: Upper Blackstone Treatment Process. Influent and trucked in septage are sent through preliminary treatment consisting of screening and an aerated grit chamber before being sent to primary clarification. Primary effluent flows by gravity through biological nutrient removal and the resultant mixed liquor is sent to a final settling tank before chlorination, dechlorination, and discharge to the Blackstone River.

Sludge from primary treatment is combined with thickened waste activated sludge from secondary treatment along with sludges from plants outside the District and is further thickened and dewatered before being combusted in an incinerator. The ash from the incinerators and the solids from preliminary treatment are removed and sent to a landfill. To monitor air pollution from the solids handling process, a biofilter is used to clean odorous air from the treatment processes and a series of scrubbers, particle precipitators and thermal oxidizers are used to clean the incinerator exhaust.

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[40] BRWA (2016).

[41] Friends of the Blackstone. (2016). *Causes of Blackstone River water level fluctuations*. *Blackstone River Watershed Council*.

[42] Artusa, A. (2016, September 20). *U.S. Drought Monitor - Massachusetts*.

[43] Upper Blackstone Water Pollution Abatement District, Treatment Process.

2.4.2 Water Quality and Plant Performance

UBWPAD's effluent water quality is of a very high level, and in 2014 the District was selected for the silver Peak Performance Award by the National Association of Clean Water Agencies.[44] Information about the effluent water quality and plant performance for the 2015 Fiscal Year is shown in Table 5 and Table 6 below.

Table 5: UBWPAD Effluent Levels[45]

Influent/Effluent	*Value*	*Units*
Average Daily Flow	29.4	MGD
Average Raw CBOD	176	mg/L
Average Final CBOD	2.2	mg/L
Average Raw SS	167	mg/L
Average Final SS	2.6	mg/L
Average Raw TN	27.7	mg/L
Average Final TN	5	mg/L
Average Final TN (May-Oct)	4.7	mg/L
Avg. Raw TP (entire year)	4	mg/L
Avg. Final TP (entire year)	0.24	mg/L
Avg. Final TP (Apr-Oct)	0.21	mg/L

Table 6: UBWPAD Plant Performance[46]

Plant Performance	*Value*
BOD Removal	98.8%
SS Removal	98.5%
TN Removal	82%
TP Removal	93%

As shown by both these data and the facility's awards, the final effluent of the UBWPAD is excellent quality and suitable for many reuse applications in its current state.

2.4.3 Opportunities for Water Reuse

Applications for water reuse will be separated into two categories: onsite reuse, which includes any water that is treated and recirculated for use within the facility; and offsite reuse, which includes any treated final effluent that is reused in the surrounding community.

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[44] "Plant Performance," Upper Blackstone Water Pollution Abatement District, accessed September 25, 2016, http://www.ubwpad.org/plantperformance1.html.

[45] Ibid.

[46] Ibid.

2.4.3.1 Onsite Reuse

UBWPAD already reuses “plant water” in many of their processes, including process washing, incinerator scrubbers, screenings removal, and chemical carry water. Plant water is defined as chlorinated final effluent. The use of plant water for these processes dramatically cuts down on the treatment facility’s potable water use by approximately 3 MGD[47]. Additional options for onsite plant water reuse include biofilter humidification chambers and domestic uses such as toilet flushing.

2.4.3.2 Offsite Reuse

There are three areas of offsite reuse applications that can prove to be beneficial to UBWPAD and the surrounding community: irrigation, industrial processes, and toilet flushing. Figure 13 below shows a map of the area surrounding the UBWPAD facility and possible partners for water reuse applications, all within a three and a half mile radius. Table 7 provides more detailed information about these partners.

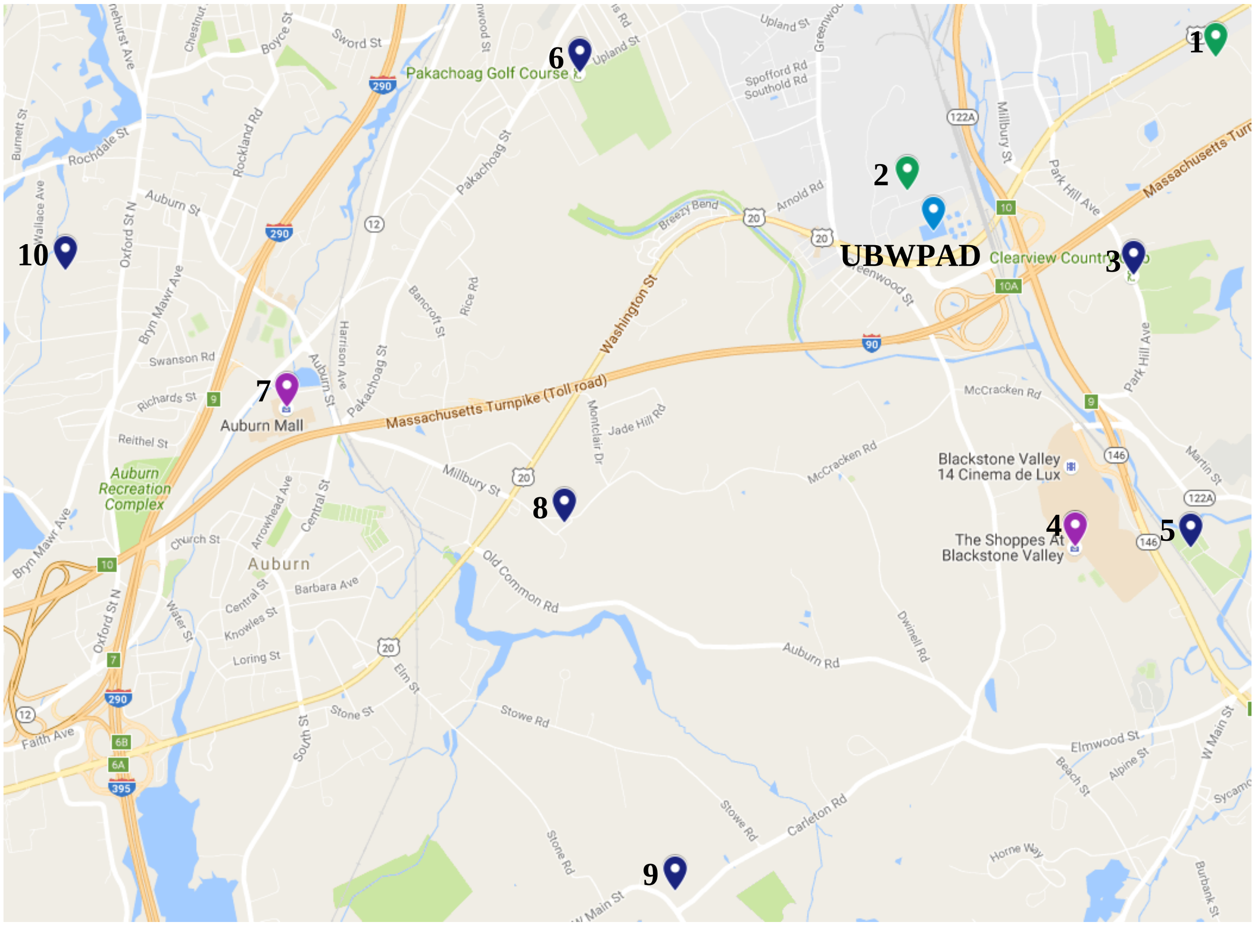

Figure 13: Potential Options for Wastewater Reuse near UBWPAD

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[47] Mark Johnson, personal interview 9/22/16

Table 7: Potential Partners for Wastewater Reuse

No.	*Facility Name*	*Potential Application*	*Distance to UBWPAD*
1	Wheelabrator	Industrial Process Water	1.23 miles
2	Schnitzer Northeast	Industrial Process Water	864 ft.
3	Clearview Country Club	Irrigation	0.757 miles
4	The Shoppes at Blackstone Valley	Irrigation/Toilet flushing	1.28 miles
5	St. Brigid's Cemetery	Irrigation	1.51 miles
6	Pakachoag Golf Course	Irrigation	1.43 miles
7	Auburn Mall	Toilet flushing	2.47 miles
8	The Farmer's Daughter	Irrigation	1.74 miles
9	Pearson's Elmhurst Dairy	Irrigation	2.62 miles
10	Luks Tree Farm	Irrigation	3.21 miles

Each of these reuse applications requires a different level of water quality and subsequent amount of treatment. The EPA and Massachusetts regulations for the reuse of treated effluent for irrigation with and without direct contact, industrial cooling water, and toilet flushing are met by the water quality of the treated effluent at UBWPAD. The applications for irrigation that we are recommending are: a cemetery, a restricted access golf course, the highway medians on The Shoppes at Blackstone Valley campus, graywater at the Auburn Mall, ornamental nursery stock, Christmas trees, and a dairy farm pasture. UBWPAD is currently looking into tertiary treatment options, and tertiary treated recycled water is also acceptable for these processes, so there will be no disruptions to water reuse in the future.

The city of Worcester and the town of Millbury are also potential partners that could benefit from reclaimed water. During the summer of 2016, the city of Worcester worked with UBWPAD to use plant water for hydrant flushing in certain sections of the city.[48] As the UBWPAD facility lies within both Worcester and Millbury, these municipalities could use plant water for future city projects including hydrant flushing, street cleaning, and cement make-up water for construction or sidewalk replacement.

Wastewater reuse is becoming increasingly important in today's society, and can particularly alleviate stress on drinking water sources in places experiencing extreme drought, like Massachusetts. The treated effluent at the Upper Blackstone Water Pollution Abatement District is of a high quality and is therefore suitable for many reuse applications in the surrounding area. These applications can strengthen UBWPAD's relationship with the community and help local businesses reduce their operating costs and impact on drinking water depletion.

2.5 UBWPAD and Wheelabrator Technologies

Wheelabrator Technologies is a "waste to energy" company that takes waste that would otherwise be sent to a landfill and converts it to energy through incineration. The branch in Millbury is located 1.23 miles from the UBWPAD facility, and could greatly benefit from recycled

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[48] Mark Johnson, personal interview 9/22/16.

wastewater. Wheelabrator regularly uses between 700,000–800,000[49] gallons of water per day, which is only 3% of UBWPAD's daily flow. Not only would recycled wastewater be more cost effective than potable water, but this reuse would reduce a large strain on potable water during times of drought. Creating a reuse system for this facility will be the main focus of this project.

There are four uses for water at the Millbury branch of Wheelabrator: potable water, demineralized boiler water, cooling tower make-up, and fire-suppression. Currently, all water is coming from a drinking water facility, and therefore all meet the Drinking Water Quality Standards. If reused wastewater were to be introduced as a water source, the potable water and fire-suppression water will still need to meet the Drinking Water Standards, which are stricter than Class A Reuse Regulations. The demineralized boiler water and cooling tower make-up will need to meet the MassDEP reuse standards outlined in Section 2.1.4 as well as any specific requirements to ensure smooth operation of the facility.

The facility's boilers use 30,000–40,000 gallons a day[50], and the boiler water needs to be demineralized in order to limit fouling and corrosion in the boilers. Currently, there is a Reverse Osmosis (RO) system as well as an Electrodeionization (EDI) system in place to treat this water. The water is pretreated before passing through the RO system with: carbon filtration is used to remove iron and suspended solids; antiscalant is added to prevent calcium based scaling; and caustic is added to increase the pH and lower CO_2 levels.[51]

These requirements will provide the baseline for treatment levels in the feasibility studies and designs throughout this project. Developing this reuse system will both save the facility money and reduce their environmental impact by removing a considerable strain on the community's drinking water supplies.

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[49] Erica Daigneault, personal interview 11/10/16.
[50] Erica Daigneault, personal interview 11/10/16.
[51] Ryan Pavlica, personal communication 12/14/16.

3. Laboratory Analysis

3.1 Methodology

3.1.1 Determining Parameters of Concern

Water quality data was collected from UBWPAD for the years from 2011 to 2016. The data was compared to permitting levels for Class A, B, and C water to determine the current quality of the effluent from UBWPAD. The parameters which do not regularly meet permitting requirements were marked as areas of concern to be further researched for improvement. The team also conducted formal discussions with the branch of Wheelabrator located in Millbury to determine specific water quality parameters that would affect their equipment and overall process. Based on these discussions the team decided to conduct laboratory testing in the WPI Kaven Laboratories for the following additional parameters: hardness, conductivity, and turbidity.

3.1.2 Laboratory Procedures

Hardness, conductivity, and turbidity of UBWPAD's effluent were tested in WPI's environmental laboratories. Basic jar tests were also conducted. The outcomes of these tests were then compared to the quality of Millbury water. *Standard methods for examination of water and wastewater (1st edition)*[52] were used for all lab procedures.

3.1.2.1 Jar Test

A 250 mL glass beaker was filled with approximately 200 mL of effluent. The smell, color, and pH were recorded. A 200 mL sample of distilled water was placed next to the effluent in a glass beaker for comparison.

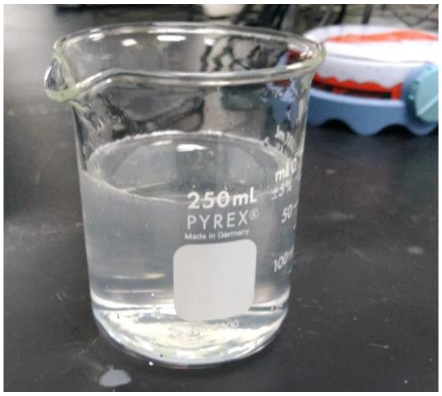

Figure 14: Jar Test on UBWPAD Final Effluent Sample 10-31-2016

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[52] Greenberg, A., Trussell, R., & Clesceri, L. (1985). *Standard methods for the examination of water and wastewater* (1st ed., pp. 2-37). Washington, DC: APHA.

3.1.2.2 Hardness

Standard Method 2340 was used to determine the hardness of UBWPAD’s effluent. Specifically, the EDTA titrimetric method was used, with some modifications based on available reagents. A 5 mL sample of effluent was diluted to 100 mL to reduce the amount of titrant needed and therefore increase the accuracy of the test. As an indicator, 10 drops of aqueous calgamite was added to produce a noticeable color change. An aqueous solution of 1.0 M EDTA was diluted in a glass beaker to produce a 0.001 M EDTA titrant. The amount of titrant added and time of titration were recorded for each run. To ensure integrity of the results, each member of the team performed at least one run. Finally, the hardness was calculated with the following equation for each run:

$$ {}^{mg}/_{L}\, CaCO_3 = \frac{1000 \times A \times B}{mL\ sample} $$

Where A is the mL of titrant added and B is the equivalent $CaCO_3$, in this case 0.1.

Figure 15: Indicators and Solutions for Harness Testing

3.1.2.3 Conductivity

Standard Method 2510 and an Orion Benchtop Conductivity Meter was used to measure conductivity. A sample of effluent was poured into a glass beaker such that the probe could be fully submerged. The conductivity cell was washed with distilled water and then submerged in the sample until a stable reading on the meter was achieved and recorded.

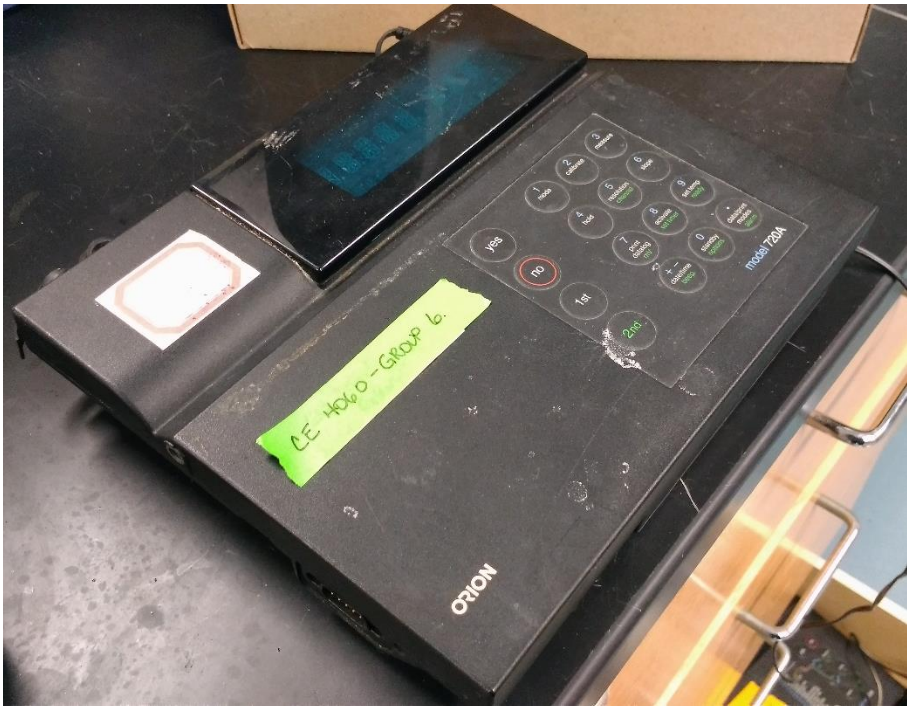

Figure 16: Orion Benchtop Conductivity Meter

3.1.2.4 Turbidity

A HACH 2100N Turbidimeter was used to measure turbidity of the effluent. Standard Method 8195 was followed for this measurement. The turbidity of distilled water was measured to ensure that the machine was calibrated correctly before the effluent sample was tested. A well-mixed sample of the effluent was poured into a turbidity tube and a reading was taken once the meter stabilized.

Figure 17: Turbidity Meter

3.2 Results and Discussion

3.2.1 Determining Parameters of Concern

Based on UBWPAD's water quality data from 2011 to 2016, the following comparisons were made between permit regulations and the existing quality of treated effluent, for more details, see Appendix C: UBWPAD Effluent Quality Compare to Regulations (2011-2016).

Table 8: UBWPAD Effluent Quality from 2011-2016 Compared to Permit Regulations

Parameter	**Exceedances between 2011 – 2016**		
	Class A	***Class B***	***Class C***
BOD	1 exceedance	None	None
pH	None	None	None
TSS	96 exceedances	19 exceedances	1 exceedances
Turbidity	None	N/A	N/A
Total Nitrogen	3 exceedances	3 exceedances	3 exceedances
Fecal coliform	Does exceed	Does exceed	None

It is important to note that the exceedances in Table 8 are the totals for the entirety of the aforementioned five year span. Based on this comparison, total suspended solids and fecal coliform were identified as areas of concern for Class A wastewater applications. In addition to this comparison, the quality of the water that Wheelabrator currently receives from Aquarian Water was also compared to UBWPAD's treated effluent.

There were two main concerns determined from this: total suspended solids (TSS) levels and fecal coliform levels. The daily measured values from UBWPAD for these two parameters can be seen in Figure 18 and Figure 19, where they are displayed against the permitted cutoffs for each class of water reuse and the current NPDES permit for UBWPAD.

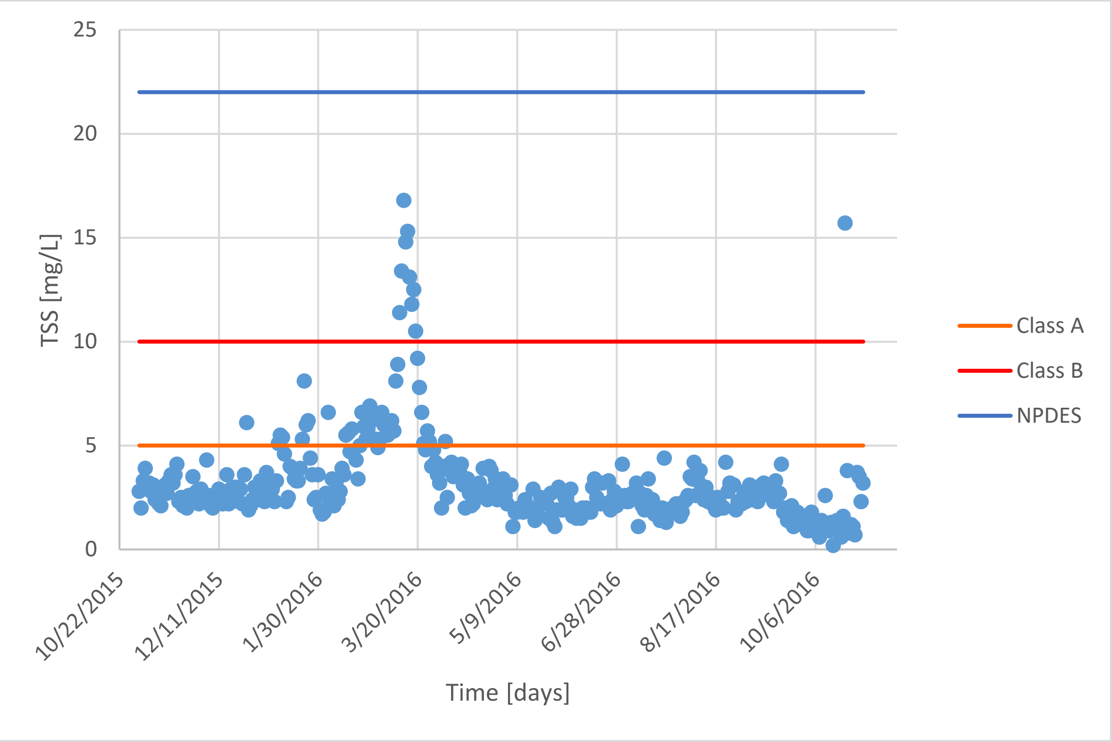

Figure 18: UBWPAD 2016 TSS Levels compared to Class A and B

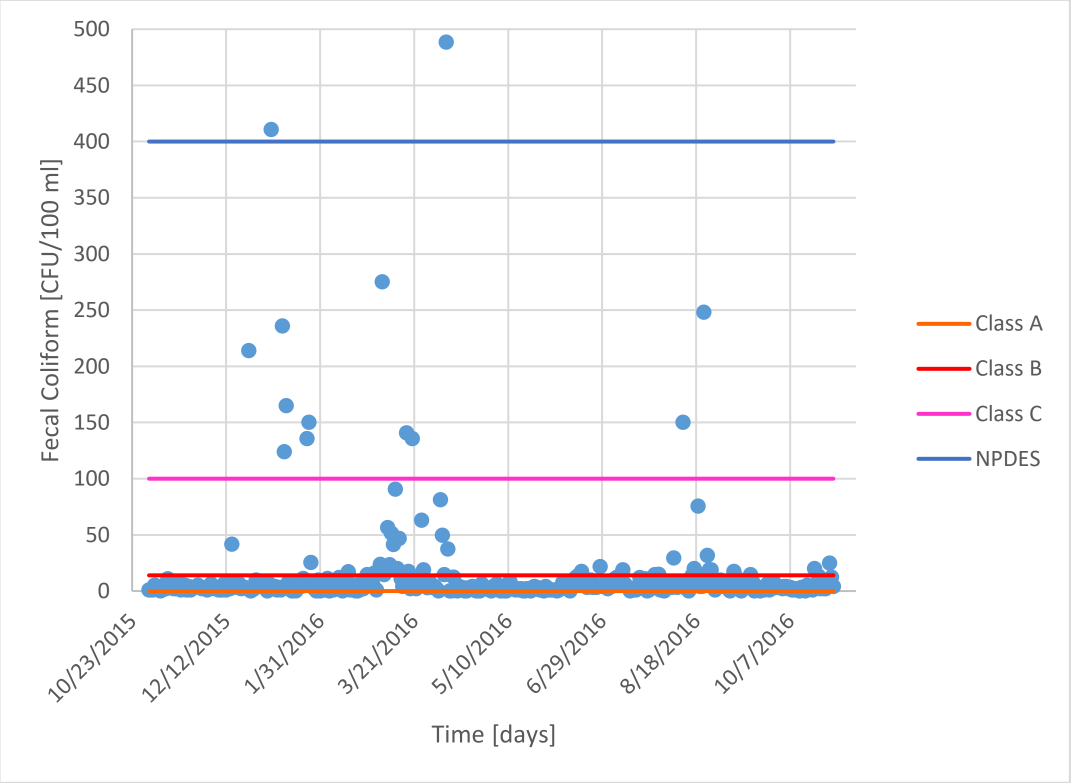

Figure 19: UBWPAD 2016 Fecal Coliform Levels compared to Class A, B, and C

As Wheelabrator currently receives their water from Millbury, MA, it was necessary to review the quality of the current water to see how it compares to the effluent from UBWPAD.

Table 9: Millbury Water Quality Average Levels from 2010-2016

Parameter	***Units***	***Average Level***
pH		7.23
Specific Conductivity	µS/cm	710.13
P-Alkalinity	mg/L	0.00
M-Alkalinity		52.34
Sulfur		17.58
Chloride		170.35
Total Hardness		74.31
Calcium Hardness		58.43
Magnesium Hardness		15.69
Copper		0.07
Iron		0.18
Sodium		112.75
Zinc		0.15
Manganese		0.04
Total Phosphate		1.55
Silica		7.72
Ortho Phosphate		0.60

Table 10: UBWPAD Water Quality

Parameter	***Yearly Average Nov 15-Oct 16 from UBWPAD***	***Measured by WPI Team (ave. values ± std. dev.)***	***Measured by GE Power & Water***	
			April 2015	**May 2015**
pH	7.24	7 ± 0.01	7.3	7.2
Conductivity (µS/cm)		1349.5 ± 2.12		
Alkalinity (mg/L as CaCO3)	104.1		93.2	120
Hardness (mg/L as CaCO3)		243 ± 24.1	142	173
Total Iron (mg/L)				0.11
Total Manganese (mg/L)			0.02	0.04
Phosphorous (mg/L)	0.35			
Silica (mg/L)			9.1	8.9
Nitrogen (mg/L)	4.88			
BOD (mg/L)	2.69			
COD (mg/L)	17.24			
Aluminum (mg/L)	24.54			
Total Suspended Solids, TSS (mg/L)	3.23		< 10	< 10
Turbidity (NTU)		1.8 ± 0.001		

It was found that there were many parameters where the effluent wastewater and influent Millbury water were of similar quality. The pH, manganese, and silica levels were approximately the same in both waters measured. Other measured parameters, like phosphorus and iron, were lower in the UBWPAD water while conductivity, alkalinity, and hardness were much higher.

The higher measured levels of these three parameters are not likely to be an issue since UBWPAD has plans to add tertiary treatment into their current system. Tertiary treatment such as algae has been proven to remove close to 70% of total hardness and significantly lower conductivity by removing high amounts of dissolved metals.[53][54] During photosynthesis, the algae can also decrease the alkalinity levels in the water by removing CO_2, though this may affect the pH.[55] For these reasons, the water quality of UBWPAD will be compatible with the Wheelabrator facility both now and in the future.

3.2.2 Laboratory Procedures

3.2.2.1 Jar Test and Turbidity

Observation of the water through jar tests and turbidity measurements proved that the effluent water from UBWPAD did not vary largely from Worcester tap water in terms of color and turbidity. The water was slightly discolored and had a few small particles in it. It smelled of chlorine and was reminiscent of glue, but not overly offensive. Based on these results, it was determined that reusing the effluent would not be met with resistance due to smell or discoloration.

3.2.2.2 Hardness

In lab measurements and data collected from Wheelabrator showed that the UBWPAD effluent was very hard.[56] This could cause problems with piping systems for transporting the water as it may lead to scaling within the pipes. Wheelabrator does have a softening system for their water already so they may be willing to soften the UBWPAD water as well.

3.2.2.3 Conductivity

It was found that the conductivity in the effluent wastewater was fairly high, at about 1350 μS/cm. This value is higher than standard drinking water values, as Worcester's drinking water has an average specific conductivity of 163 μS/cm.[57] High conductivity can cause corrosion which may be of concern to the piping system for this effluent. As previously mentioned, this will not be an issue when the tertiary treatment is added.

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[53] Worku, A., & Sahu, O. (2014). Reduction of Heavy Metal and Hardness from Ground Water by Algae.

[54] Ansa, E. D. O., Lubberding, H. J., Ampofo, J. A., & Gijzen, H. J. (2011) *Ecological Engineering*.

[55] Illinois State Water Survey. (1989, January 01).

[56] Perlman, H. (2016, December 15). Water Hardness.

[57] *2015 Water Quality Report* (Rep.). (2015). Worcester, MA: City of Worcester Water Operations.

4. Design Analysis

4.1 Methodology

After determining that suspended solids and fecal coliform levels are of the most immediate concern in this system, a three step system was designed and is proposed in the following sections.

4.1.1 Ultrafiltration Membrane Unit

For removal of TSS and, in part, some E. coli, a filtration unit would be required. In this case ultrafiltration should be employed due to the low incoming turbidity and particle size. The following design equation was used:

$$J_m = \frac{Q}{A_m}$$

Where J_m is the flux of filtrate through the membrane, Q is the flowrate, and A_m is the membrane area. Online research, product manuals, and ultrafiltration vendors were consulted to determine an appropriate flux rate. The flow rate was determined based on the anticipated needs of Wheelabrator and UBWPAD. This yields the total membrane area required, $A_{m,total}$. The following relationship provides the necessary number of membrane units for the given flow:

$$N_m = \frac{A_{m,total}}{A_{m,unit}}$$

Where N_m is the number of units and $A_{m,unit}$ is the area per membrane unit.

4.1.2 Ultraviolet Disinfection Unit

In order to ensure that the reused water always meets the very stringent Class A requirements on fecal coliform counts, the system requires some form of disinfection. UBWPAD chlorinates their effluent year round, so it was recommended that this system contain a small Ultraviolet (UV) disinfection system rather than an additional chlorination step.[58]

In water reuse systems that are following a membrane filtration step, the required dose of UV light is 80 mJ/cm^2. This dosage is "intended to provide 4 log of poliovirus inactivation with a factor of safety of about 2".[59] To determine the size of a UV system needed for this dosage and a flow of 1 MGD, an industry expert was consulted. Additionally, the required exposure time was calculated using the follow equation:

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[58] Mark Johnson, personal interview 1/20/17.

[59] Asano, pg 700.

$$D = I_{avg} \times t$$

Where D is the UV dosage, I_{avg} is the average UV intensity, and t is the necessary exposure time.

4.1.3 Pumping Station

The power required to pump UBWPAD's effluent to Wheelabrator was determined using the hydraulic pump power equation, where H is the height that the water must be lifted (in this case, the elevation change), Q is the flowrate, and η is the pump efficiency.

$$W = \frac{\rho g H Q}{\eta}$$

In order to determine a typical pump efficiency, research was conducted on available centrifugal pump models. Once the necessary power was computed, an analysis of pressure loss in the system was conducted to determine the appropriate number of pumps. Frictional pressure loss was calculated using the Darcy-Weisbach equation. A relative roughness of 0.0015 was assumed for HDPE and the Moody chart was used to find the friction factor based on Reynolds number calculations. This pressure loss was then combined with the pressure loss from the UV and ultrafiltration units.

$$P_{final} = P_{initial} - P_{friction} - P_{UF} - P_{UV}$$

Section 4.1.4 discusses pressure drop loss across diameter changes.

4.1.4 Piping

There are several diameter changes between each unit of this treatment system. The pressure loss across each of these expansions or compressions were calculated using the follow equation:

$$P_1 - P_2 = \frac{W^2}{2\rho} \times \left(\frac{1}{A_1^2} - \frac{1}{A_2^2}\right)$$

Where W = the mass flow in kg/s.

The necessary diameter of the pipe to connect the treatment system to Wheelabrator was determined using the Hazen-Williams equation:

$$h_f = \frac{10.44 \cdot Q^{1.85} \cdot L}{C^{1.85} \cdot D^{4.87}}$$

Where h_f is the head loss along the pipe route, Q is the flow in gallons per minute, L is the pipe length, C is the roughness coefficient of the chosen material, and D is the minimum diameter required. Head loss was determined based on the elevation change between UBWPAD and Wheelabrator and the length was estimated by developing a pipe route on ArcGIS.

4.1.5 Cost Analysis

Wheelabrator would be able to save a considerable amount of money using reclaimed wastewater instead of drinking water. The yearly savings for the facility were estimated based on the water usage and billing rate for the 2016 calendar year as provided by Wheelabrator, and the price of reused water in comparable systems.

The total cost of the system equipment was determined using a combination of quotes from vendors, heuristics, and CAPCOST. These calculations can be found in Appendix K: Cost Analysis. The operating and maintenance costs for one year of each unit were determined through similar fashions. With the Fixed Capital Investment (FCI) calculated, the payback period and rate of return on investment (ROROI) were determined using a straight line depreciation scheme over the course of 10 years, and a full project life of 25 years. The payback period was determined graphically from a cumulative after tax cash flow diagram. The ROROI was also calculated using this graph and the following equation:

$$ROROI = \frac{slope}{FCI} - \frac{1}{n}$$

Where n is the project life.

4.1.6 Sabotage Prevention

When dealing with water systems of any kind, it is important to include sabotage prevention in the design so as to protect those who are in direct contact with the water supply. As such, measures were taken to ensure that design plans will be kept secure and that all equipment will be placed under the appropriate surveillance.

4.2 Results and Discussion

Through the analysis of UBWPAD’s current water quality as compared to Millbury’s water quality, it was determined that a filtration and disinfection system would need to be added for the reuse application at Wheelabrator. After the current dechlorination step at UBWPAD, 1 MGD will be redirected to an ultrafiltration membrane and an ultraviolet disinfection unit. From this step the water is pumped directly to the Wheelabrator facility using centrifugal pumps. Once the water arrives at Wheelabrator, additional treatment may be necessary depending on the specific application of the water. The red rectangle on the map below shows the approximate location of the treatment and pumping system at UBWPAD.

Figure 21: UBWPAD Aerial View with Treatment System Location

4.2.1 Ultrafiltration Membrane Unit

The team indicated that turbidity and TSS were parameters of concern for the water being sent to Wheelabrator. To help alleviate these concerns and ensure high quality effluent, it was determined that ultrafiltration (UF) was appropriate due to its ability to remove particles with a diameter between 0.01 and 0.1 microns.[60] Because of this the technology has been proven to result in up to two log removal of various bacterium including Escherichia coli.[61] Research has shown that UF performs best under low initial TSS, which the effluent from UBWPAD would provide.[62]

For this design, a polymeric membrane filter unit similar to one available from DOW Chemical Company was chosen. Various ultrafiltration units are available from DOW including those for industrial applications.[63] Their filters are modular, which allows for future scale up opportunities for the reuse system at UBWPAD. In order to determine what unit would be appropriate, the specifications of the effluent were obtained. A list of maximum values for the feed water are available and can be seen in Table 11 below.

Table 11: DOW Specifications for Feed Water[64]

Parameter	Typical	Maximum
Turbidity, NTU	< 50	300
TSS, mg/L	< 50	100
TOC, mg/L	< 10	40
COD, mg/L	< 20	60
Cl_2 Continuous, mg/L	0.5	200
Oil/Grease, mg/L	0	< 2
pH Continuous	6 to 9	2 to 11
Temperature, °C	25	40
Particle Size (micron)	< 150	300

Upon comparing the UBWPAD effluent to the feed water requirements, it was determined that a DOW system would be more than adequate. The limiting factor for the determination was the flow rate of the influent to the filter. A higher flow rate requires more filter contact area and therefore more tubes. Each UF model from DOW has specifications for maximum flow rate per membrane and flux capacity. Based on vendor data and research, a flux of 40 gallons/ft^2/day (gfd) was chosen for the system.

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[60] *Ultrafiltration, Nanofiltration and Reverse Osmosis* [PDF]. (2008). Safewater.org.
[61] Abbadi, J., Saleh et al. *Journal of Environmental Science and Engineering*. Pg. 853
[62] Bourgeous, K. N., Darby, J. L., & Tchobanoglous, G. (2001). *Water Research*.
[63] The DOW Chemical Company. (2011). *Ultrafiltration: Product Manual* [Brochure]
[64] Ibid.

Our design would require a UF membrane similar to DOW IntegraFlux SFP-2880XP.[65] This membrane has a molecular weight cutoff (MWCO) of approximately 10 kDa, based on the product manual, which is sufficient for removal of E. coli which have a molecular weight of 25-500 kDa[66]. This membrane is suitable for industrial purposes with a filter area of 829 ft^2 per module. Based on the required flow rate and chosen flux, the required filter area is 25,000 ft^2 (see Appendix F: Ultrafiltration Membrane Calculations for calculations). This system is able to recover up to 90% of the feed stream as permeate, depending on the flowrate.[67] Given our flow rate of 40 gfd we can expect 80-85% feed recovery. Therefore, 31 SFP-2880XP membranes, or equivalent, would be required. The benefit of a modular system is that more membrane tubes could be added in the future to allow for higher use by Wheelabrator or UBWPAD if needed. This filtration system should be installed inside a building to protect the modules and allow for easy operation and maintenance access. There should also be an additional storage container to hold the reject water from the filtration unit until it can be properly handled. Disposal and handling of this waste is outside of the scope of this design recommendation. A schematic of the unit can be seen below in Figure 22.

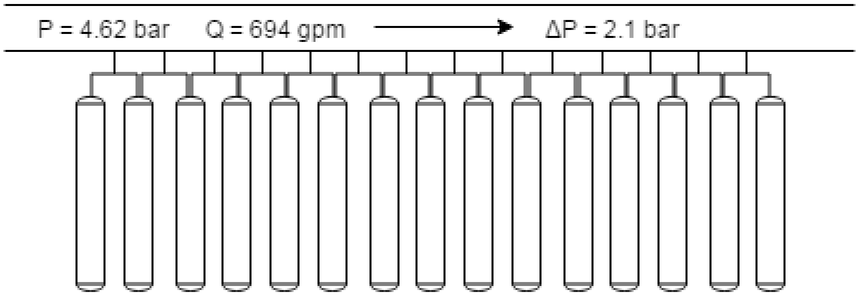

Figure 22: Ultrafiltration Membrane Unit

4.2.2 UV Disinfection Unit

It was determined that a Ultraviolet (UV) disinfection unit following the ultrafiltration unit would be the best option to ensure that the fecal coliform count would remain below Class A levels which state that: “Median of no detectable fecal coliform/100 ml over continuous seven-day sampling periods, not to exceed 14/100 ml in any one sample”.[68] The UV unit will be located after the UF unit to ensure that undesirable microorganisms are preliminarily filtered out along with the suspended solids. This will improve the efficiency of the UV disinfection as the suspended solids have a lower chance of interfering with the UV light and masking the microorganisms.

Based on recommendations received from Evoqua, and the understanding that the required dosage for reuse applications is 80 mJ/cm^2, a unit with thirty 800 W low pressure high output

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[65] The DOW Chemical Company. (2015). *Product Data Sheet: DOW IntegraFlux™ Ultrafiltration Modules* [Brochure].

[66] Chong, B. E., Wall, D. B., Lubman, D. M., & Flynn, S. J. (1997).

[67] *Deliverable 1.3 - Report On Innovative Membrane Technologies And Schemes For Water Reuse*. 2017.

[68] Duong, K. & Saphores, J. (2015).

lamps will be required for the system. The UV disinfection unit we recommend is the UVLW-30800-24 from Evoqua[69], or an equivalent unit. It will be approximately ten feet in length and should be installed inside a building. It was calculated that the exposure time for this unit will be 0.006 seconds. For full calculation see Appendix G: Ultraviolet Disinfection Unit Calculations. A schematic of this unit can be seen in Figure 23.

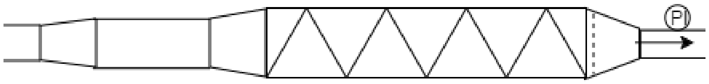

Figure 23: UV Disinfection Unit

4.2.3 Pumping Station

A centrifugal pump was chosen to transport the water from UBWPAD to Wheelabrator. It was found that only one pump was necessary, due to moderate elevation change and minimal frictional losses calculated using the Darcy-Weisbach equation. The required work of the pump was calculated using the hydraulic pump power equation and was found to be 36275 W. In order to account for pump maintenance and possible failure, 2 pump trains were designed. Each pump must be able to transport all 1 MGD of water independently in case the other is offline. Work was calculated for two scenarios: one pump operating on its own and two pumps operating in parallel. The resulting horsepower was found to be 48.62 and 24.31, respectively (see Appendix H: Centrifugal Pump Design Calculations). A standard motor size operating at 50 hp would be adequate for both scenarios. For two pumps operating in parallel, each must provide 18137 W of power. A variable-frequency drive (VFD) could also be added to the pump for cost efficiency and finer control of processes.[70] VFD's can cost anywhere from $3,000 for a 5 horsepower pump to $45,000 for a 300 horsepower one and have energy savings of up to 50%. A VFD is not necessary to carry out this project and is not included in the cost estimate, however it is recommended that this addition is considered by parties involved.

For two pumps operating in parallel, each must provide 18137 W of power. They must also both account for pressure loss in the system. Our calculations show that a pump pressure of 60.74 psi would lift the water to the desired elevation and achieve a residual pressure of 40 psi at the end of the pipe. Pump performance curves from various vendors were used to find a centrifugal pump that fit all of the criteria. The pump must be able to transport 1 MGD of water with a head of 139 feet at a horsepower between 24.31 and 48.62 at a pressure of at least 60 psi.

According the Gorman Rupp's performance curves, a 6" by 6" stainless steel self-priming centrifugal pump would be capable of providing 123 psi and therefore would effectively transporting the water with a 12.5 in diameter impeller at speeds between 850 and 1950 rpm. That being said, the size of the pump should suit the pipes which are affixed to it. In this case, the pipe following the UV disinfection step and the pipe which delivers the water to the Wheelabrator

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[69] Patrick Bollman, personal communication 2/6/2017.

[70] California Energy Commission. *Variable-Frequency Drive*. California: Government of California.

entrance will need to fit the respective openings of the pump. For this reason, a reducer and increaser will be needed on both openings of the pump to adjust the pipe diameter to the appropriate size. The following schematic is a simple representation of the pump configuration

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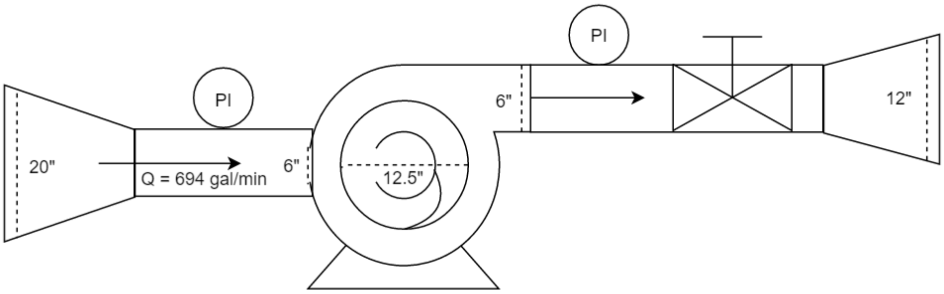


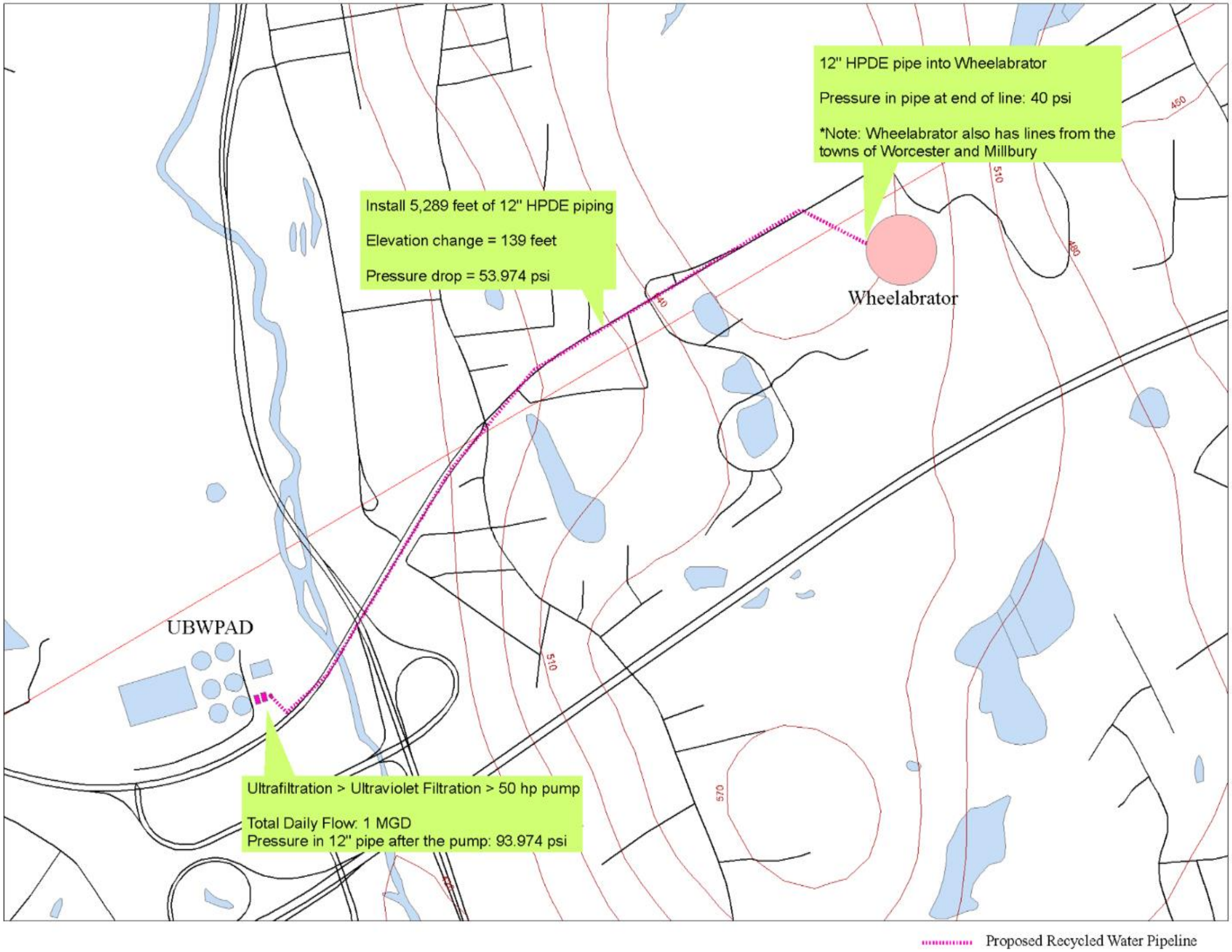
Figure 24: Pump schematic

The pump should have pressure gauges on either side to ensure operating pressure does not exceed the particular model's allowance, and a valve on the line entering Wheelabrator to allow for finer adjustment of inflow.

4.2.4 Piping

4.2.4.1 Pipe Route

There are many paths that the piping could follow to get the water from UBWPAD to Wheelabrator. However, since it is rather expensive to dig trenches and lay piping, a shorter route is more desirable to reduce capital costs. Therefore it would be more economic to follow Massachusetts Route 20, which results in a distance of only 5,289 ft. This route also results in significantly fewer directional changes and therefore fewer pipe fittings, decreasing the overall friction loss throughout the system. However, the piping following Route 20 has to cross both MA Route 122A as well as the Blackstone River, posing a significant obstacle. In order to overcome it the piping would need to be installed over a bridge, which could be difficult as space is generally limited on these crossings. These obstacles would still be an issue regardless of the chosen route, so it is most feasible to go with the shortest route despite the bridge crossing. The pipe route can be seen in Figure 25 on the following page.



12" HPDE pipe into Wheelabrator

Pressure in pipe at end of line: 40 psi

*Note: Wheelabrator also has lines from the towns of Worcester and Millbury

Install 5,289 feet of 12" HPDE piping

Elevation change = 139 feet

Pressure drop = 53.974 psi

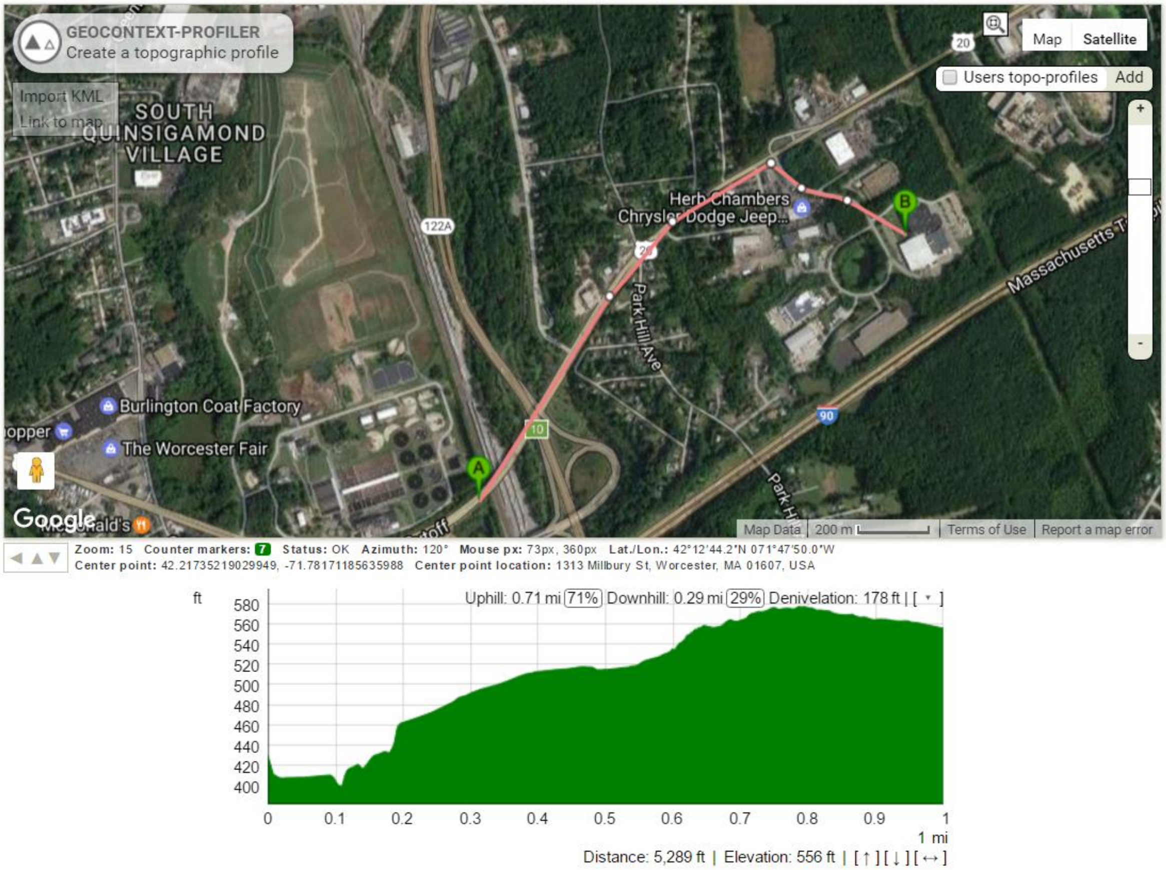
Ultrafiltration > Ultraviolet Filtration > 50 hp pump

Total Daily Flow: 1 MGD
Pressure in 12" pipe after the pump: 93.974 psi

Figure 25: Proposed Pipe route from UBWPAD to Wheelabrator

4.2.4.2 Pipe Material and Diameter

The material selected was schedule 40 HDPE pipe based on the strength of the material and its resilience to corrosion.[71] As shown below in Figure 26, the pipe route undergoes a very rapid elevation change between UBWPAD and Wheelabrator.



Zoom: 15 Counter markers: 7 Status: OK Azimuth: 120° Mouse px: 73px, 360px Lat./Lon.: 42°12'44.2"N 071°47'50.0"W
Center point: 42.21735219029949, -71.78171185635988 Center point location: 1313 Millbury St, Worcester, MA 01607, USA

Uphill: 0.71 mi 71% Downhill: 0.29 mi 29% Denivelation: 178 ft

Distance: 5,289 ft | Elevation: 556 ft

Figure 26: Elevation changes along pipe route

If the pipe were to follow MA Route 20, as recommended, the total length of the pipe would be 5,289 ft. The initial elevation is 417 ft., and the final is 556 ft., for a total elevation change of 139 feet which is equal to the head loss in the Hazen-Williams equation. The flowrate of 694 gal/min was determined based on the flowrate of 1 MGD and the assumption that Wheelabrator was operating 24 hours a day. The resulting diameter from these calculations was determined to be 6.12 inches, meaning a 6.5 inch or 7 inch diameter pipe would be used. Full calculations can be seen in Appendix I: Piping Calculations.

Overall, a schedule 40 HDPE pipe with a 12 inch diameter was chosen for this system based on the reasoning that the water mains from Worcester and Millbury that run to Wheelabrator for their current water use are 12 inches. Additionally, a 12 inch pipe would allow for up to 5 MGD under the system conditions and could account for future expansion in the area. This would eliminate the need to relay the pipe in the event of industrial expansion in the area.

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[71] "HEALTH ASPECTS OF PLUMBING." *10. Standards of Materials used in Plumbing Systems* 2006.

The pressure was evaluated throughout the proposed system to ensure that the piping would not be over- or under-pressurized. This was done using a modified Bernoulli equation and assuming negligible losses due to pipe material and fittings (see Appendix J: Pressure Drop Calculations). As the exact layout of the system is not yet determined, it is difficult to know the lengths of pipes that will be used and should not be a concern considering HDPE is a smooth material. It was determined that there would be no hazard for the system due to water pressure. The pipe will experience the highest pressure after the pump, about 6.45 bar, but much of this will be lost as the water undergoes elevation change before it reaches Wheelabrator.

4.2.5 Cost Analysis

It was determined that the FCI for this project would be $ 2,591,331 with a yearly operating and maintenance cost of $109,594. The costs are summarized in Table 12, which includes an additional 10% of the budget as possible extra expenditures. As this project is a preliminary design recommendation, our estimates include only raw materials and installation costs. However, there may be additional spending for police detail during construction, test pits, and unforeseen cost for installing over a bridge, also shown in Table 12. Further analysis for cost is done using the subtotal cost estimate. This would be offset by an annual savings in water costs of approximately $406,992. Full calculations can be seen in Appendix L: Wheelabrator Water Usage Data and Costs 2016. The cumulative after tax cash flow diagram can be seen below in Figure 27, with payback period noted. Assuming straight line depreciation over 10 years, the payback period for the project is 9 years. Assuming a full project life of 25 years, the ROROI is 6%.

Table 12: Opinion of Probable Project Cost

Opinion of Probable Project Cost - RAW MATERIALS & INSTALLATION ONLY				
UBWPAD – Wheelabrator Line				
Wastewater Reuse Line				
Worcester & Millbury, MA				
	Quantity	**Units**	**Unit Price**	**Total Cost**
12-Inch HPDE Piping	5,289	LF	$ 25	$ 132,225
Trench Repair and Repave	2,351	SY	$ 30	$ 70,530
6" x 6" Centrifugal Pump	3	EA	$ 51,000	$ 153,000
Ultraviolet Light Filtration Unit	1	EA	$ 250,000	$ 250,000
Membrane Ultrafiltration Unit	1	EA	$ 1,750,000	$ 1,750,000
Subtotal				$ 2,355,755
Adjustment for Additional Non-itemized costs: 10%				$ 235,576
Opinion of Probable Project Cost				**$ 2,591,331**
Additional costs may include (but are not limited to):				
Test Pits				
Emergency Generator				
Police Detail Allowance				
Meter Vault and Appurtenances				

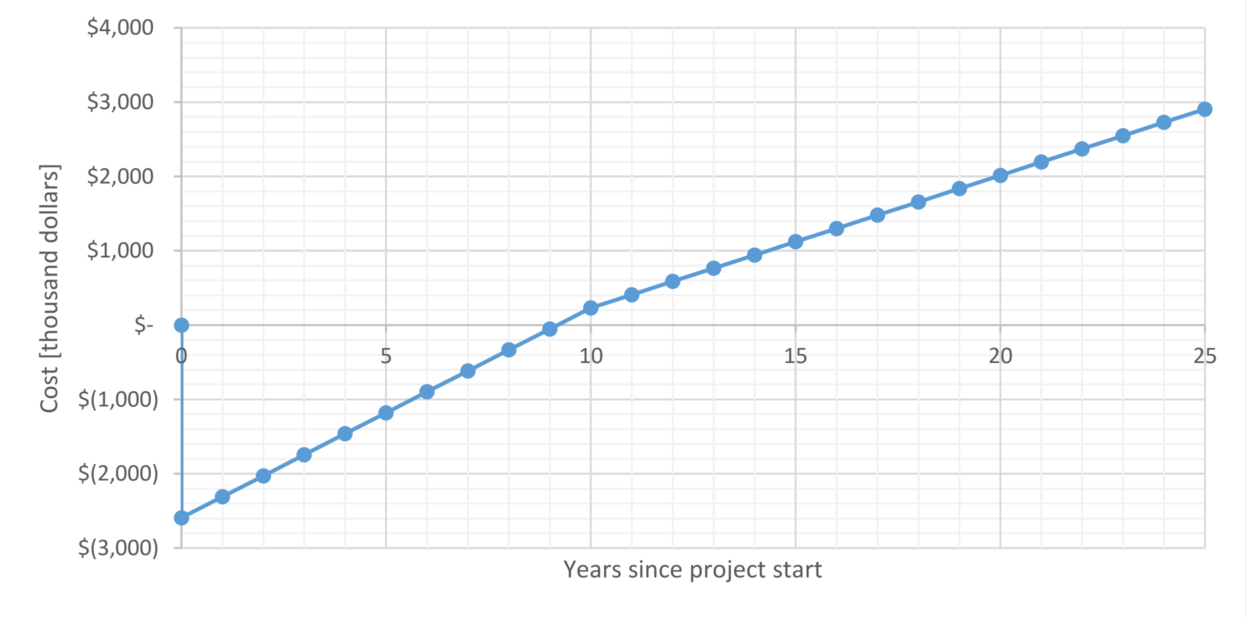


Figure 27: Cumulative after tax cash flow

While this is a relatively low ROROI, the project comes with additional benefits. By using reclaimed wastewater for the bulk of their process water, Wheelabrator will have increased water security from future shortages. This would save the facility money by keeping them subject from future increases in potable water prices during droughts. Additionally, as this is an environmentally beneficial project, Wheelabrator could receive grants and tax incentives from the government which would yield a higher ROROI.

4.2.6 Sabotage Prevention

To ensure that only the design engineers and necessary operators at both UBWPAD and Wheelabrator have access to the system design, copies of the plans will be kept in locked cabinets at both facilities. A record of who reads the plans will be kept as well.

As both UBWPAD and Wheelabrator operate on a 24 hour basis, the system needs sufficient back-up power to prevent any water loss or build up if there is a power outage. This could result in a damage to equipment at either facility, or cause the processes at Wheelabrator to overheat if there is a severe drop in the water supply. Therefore, it is necessary to have generators that can sufficiently power each unit in the system, including the pumps. It is recommended that Wheelabrator maintain their current connections for potable water from both Worcester and Millbury so that in the event of an emergency at UBWPAD, they could switch over to another water source.

5. Conclusions and Recommendations

5.1 Recommendations for Future Work

Going forward, UBWPAD has the potential for many other reuse systems. There are numerous other reuse opportunity that could be explored further, namely spray water for Schnitzer Northeast or irrigation at Clearview Country Club. As these two locations are less than one mile from UBWPAD, they would be the easiest applications to implement. They also do not require much additional treatment to UBWPAD's water to apply for a permit. Future students' Major Qualifying Projects (MQPs) could delve further into these two alternatives and create their own design for a reuse system. Additionally, more work could be done at Wheelabrator helping them design the distribution system of the UBWPAD effluent at their facility. Other areas of interest are the use of water for cement mixing or reviving the Blackstone River Canal. These ideas were not the most feasible of the evaluated options, but could be beneficial to the Worcester community.

5.2 Conclusions

The scarcity of freshwater resources has become especially important in recent years due to increasing impacts of global climate change. The use of reclaimed wastewater can significantly alleviate stress on freshwater resources by replacing potable water that is not used for direct human contact. Uses of reclaimed water can include irrigation, industrial cooling and boiler feed, snowmaking, fire suppression, recreation water, and more. Unfortunately, there are obstacles that make it difficult to implement treated wastewater projects. Many people are disgusted by the thought of their wastewater being used in areas where they might be exposed to it, regardless of the amount of treatment it has received. In addition, special permits must be filed in order to carry out a wastewater reuse project, ensuring that the water meets certain quality standards that are specific to the application. This project evaluated the reuse options for UBWPAD's effluent and presents a design for use in Wheelabrator Millbury. It demonstrates that wastewater reuse projects are worthwhile despite obstacles in initiating the project.

It was found that UBWPAD's effluent is of very high quality, already meeting Massachusetts Class C standards. Some areas of concern for viable reuse options included hardness, conductivity, and turbidity, so these were tested in the WPI environmental laboratories. The values were found to be higher than potable water quality, however due to the future addition of a tertiary treatment system at UBWPAD, they will not be a problem for this project. In addition, five years of water quality data from UBWPAD was evaluated and revealed fecal coliform and total suspended solids as areas of improvement. Because Wheelabrator is a short distance away from UBWPAD and they are very interested in using treated effluent for selected processes, it was decided that a reuse system would be designed to provide Class A water to Wheelabrator.

Through laboratory experiments, outreach to local experts, and online research, it was determined that reusing UBWPAD's water for Wheelabrator's cooling tower is a feasible operation. Using 12 inch diameter HDPE pipe and a 50 hp centrifugal pump, UBWPAD can successfully provide 1 MGD to Wheelabrator. In order to meet water quality standards for reuse purposes, an ultrafiltration and UV disinfection unit are required for the design preceding the pump and pipe. These address the high levels of total suspended solids and fecal coliform in the current effluent. The proposed system will treat the water to Class A Massachusetts permit standards and maximize efficiency of systems.

The reuse of UBWPAD's treated effluent at Wheelabrator, Millbury is a true example of sustainability. This reuse is economically, environmentally, and equitably beneficial to all stakeholders involved, see Figure 28. As many parts of the world are projected to face continued drought, it is important to implement projects such as this one to decrease impact on our environment. Like many environmentally conscious initiatives, this one values the long-term advantages over the upfront cost. It demonstrates that good community planning requires a big-picture perspective. While it may have obstacles to overcome, this concept study shows that doing the right thing does not always come at a high cost.

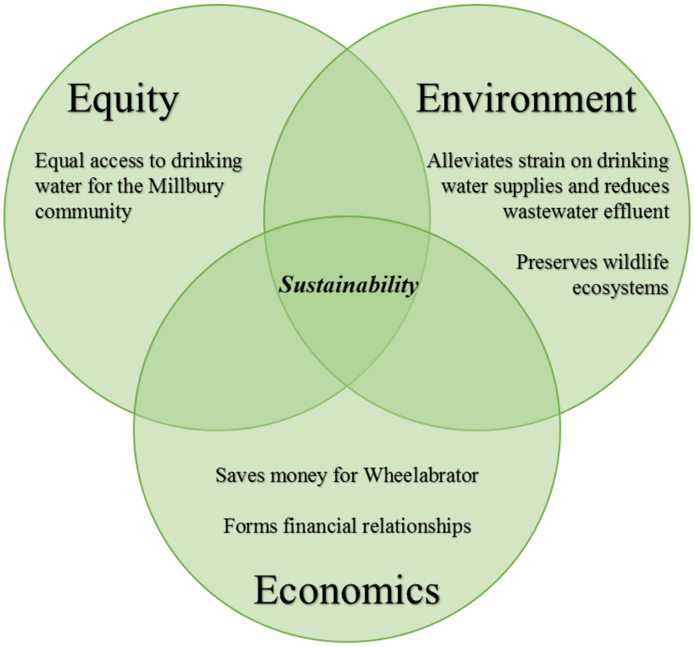


Figure 28: The Three "E's" of Water Reuse for Wheelabrator

References

2015 Water Quality Report (Rep.). (2015). Worcester, MA: City of Worcester Water Operations.

A Citizen's Guide to the NEPA: Having Your Voice Heard (p. 8). Executive Office of the President. Retrieved from https://ceq.doe.gov/nepa/Citizens_Guide_Dec07.pdf

Abbadi, J., Saleh, R., Nusseibeh, S., Qurie, M., Khamis, M., Karaman, R., & Bufo, S. A. (2012). Microbial removal from secondary treated wastewater using a hybrid system of ultrafiltration and reverse osmosis. *Journal of Environmental Science and Engineering. A*, *1*(7A), 853.

Alvin, Alm. (1988). NEPA established a national policy to protect the environment the same year Earth Day was first celebrated. *Epa.gov.* EPA Journal, January 1988. Retrieved 19 Sept. from, https://www.epa.gov/aboutepa/1988-article-nepa-past-present-and-future

American Water Works Association. (2008). Microfiltration and Ultrafiltration Membranes for Drinking Water (PDF). *Journal-American Water Works Association*, *100*(12), 84-97.

Anon, (2017). [online] Available at: http://www.hdpesupply.com/12-ips-sdr11-pe4710-black-hdpe-pipe-straight-length-per-foot/ [Accessed 14 Mar. 2017].

Annear, Steve. *Steve Annear*. (BostonGlobe.com), September 8, 2016. https://www.bostonglobe.com/metro/2016/09/08/facing-drought-worcester-moves-crack-down-water-use/z1AUfO3qdJRV6ZyADFDh4J/story.html.

Ansa, E. D. O., Lubberding, H. J., Ampofo, J. A., & Gijzen, H. J. (2011) The role of algae in the removal of Escherichia coli in a tropical eutrophic lake. *Ecological Engineering*, *37*(2), 317-324.

Asano, T., Leverenz, H. L., & Tsuchihashi, R. (2007). *Water reuse: Issues, technologies, and applications* (1st ed.). New York, NY: McGraw-Hill.

Artusa, A. (2016, September 20). *U.S. Drought Monitor - Massachusetts*. Retrieved September 26, 2016, from http://droughtmonitor.unl.edu/Home/StateDroughtMonitor.aspx?MA

Blackstone River Coalition. (2016). *Report Card for 2011 Monitoring Season*. Blackstone River Coalition. Retrieved from http://www.thebrwa.org/documents/2011_Report_Card.pdf

Blackstone River Coalition. (2008). *The Blackstone River ~ Clean by 2015*. Blackstone River Coalition. Retrieved 30 Sept. 2016, from http://zaptheblackstone.org/whatyoushouldknow/Publications/State_of_River.pdf

Bourgeous, K. N., Darby, J. L., & Tchobanoglous, G. (2001). Ultrafiltration of wastewater: effects of particles, mode of operation, and backwash effectiveness. *Water research*, *35*(1), 77-90.

BRWA (2016). *Blackstone River Challenges*. *Thebrwa.org*. Retrieved 30 September 2016, from http://www.thebrwa.org/challenges.htm

California Energy Commission. *Variable-Frequency Drive*. California: Government of California. Retrieved from http://www.energy.ca.gov/process/pubs/vfds.pdf

Cho, R. (2011, April 4). From Wastewater to Drinking Water. *Earth Institute*. Retrieved September 22, 2016, from http://blogs.ei.columbia.edu/2011/04/04/from-wastewater-to-drinking-water/

Chong, B. E., Wall, D. B., Lubman, D. M., & Flynn, S. J. (1997). Rapid profiling of E. coli proteins up to 500 kDa from whole cell lysates using matrix-assisted laser desorption/ionization time-of-flight mass spectrometry.

Commonwealth of Massachusetts. (2007). *BLACKSTONE RIVER WATERSHED 2003 - 2007 WATER QUALITY ASSESSMENT REPORT*. Worcester: Massachusetts Department of Environmental Protection.

Commonwealth of Massachusetts. (2016). *Blackstone River Watershed*. *Energy and Environmental Affairs*. Retrieved 30 September 2016, from http://www.mass.gov/eea/waste-mgnt-recycling/water-resources/preserving-water-resources/mass-watersheds/blackstone-river-watershed.html

Commonwealth of Massachusetts (2008). *MEPA Statute. mass.gov*. Retrieved 24 September 2016, from http://www.mass.gov/eea/agencies/mepa/about-mepa/statute-and-regulations/mepa-statute-generic.html

"Deliverable 1.3 - Report On Innovative Membrane Technologies And Schemes For Water Reuse". 2017. *Demoware*. http://demoware.eu/en/results/deliverables/deliverable-d1-3-report-on-innovative-membrane-technologies-and-schemes-for-water-reuse.pdf/view.

The DOW Chemical Company. (2011). *Ultrafiltration: Product Manual* [Brochure]. Edina, MN: DOW.

The DOW Chemical Company. (2015). *Product Data Sheet: DOW IntegraFlux™ Ultrafiltration Modules* [Brochure]. Author. Retrieved January 22, 2017, from http://www.dow.com/en-us/markets-and-solutions/products/DOWIntegraFluxUltrafiltrationModules/DOWIntegraFluxSFP2880XP

Duong, K. & Saphores, J. (2015). Obstacles to wastewater reuse: an overview. *Wires Water*, *2*(3), 199-214. http://dx.doi.org/10.1002/wat2.1074

Environmental Protection Agency. (2016, February 23). *Water Recycling and Reuse: The Environmental Benefits.* Retrieved September 22, 2016, from https://www3.epa.gov/region9/water/recycling/

Environmental Protection Agency. (2016, August 9). *Water Resources Impacts.* Retrieved September 22, 2016, from https://www3.epa.gov/climatechange/impacts/water.html

Friends of the Blackstone. (2016). *Causes of Blackstone River water level fluctuations*. *Blackstone River Watershed Council*. Retrieved 30 September 2016, from http://blackstoneriver.org/blackstone/?page_id=50

Freshwater Crisis. (n.d.). Retrieved September 22, 2016, from http://environment.nationalgeographic.com/environment/freshwater/freshwater-crisis/

Greenberg, A., Trussell, R., & Clesceri, L. (1985). *Standard methods for the examination of water and wastewater* (1st ed., pp. 2-37). Washington, DC: APHA.

“Hazen-Williams Coefficients.” Accessed January 23, 2017. http://www.engineeringtoolbox.com/hazen-williams-coefficients-d_798.html.

“HEALTH ASPECTS OF PLUMBING.” *10. Standards of Materials used in Plumbing Systems* 2006,. Accessed January 30, 2017. http://www.who.int/water_sanitation_health/hygiene/plumbing10.pdf.

Illinois State Water Survey. (1989, January 01). Using Copper Sulfate to Control Algae in Water Supply Impoundments. Retrieved February 17, 2017, from http://hdl.handle.net/2142/48968

Jiménez, B., & Asano, T. (2008). Water reclamation and reuse around the world. *Water reuse: an international survey of current practice, issues and needs. IWA, London,* 3-26.

Lautze, J., Stander, E., Drechsel, P., da Silva, A. K., & Keraita, B. (2014). Global experiences in water reuse. *Resource Recovery and Reuse Series,* 4.

MassDEP (2009). 314 CMR 20.00: RECLAIMED WATER PERMIT PROGRAM AND STANDARDS. Retrieved 25 September 2016, from http://www.mass.gov/eea/docs/dep/service/regulations/314cmr20.pdf

Massachusetts Water Resources Authority. (2016, September 1). *MWRA - Water Supply and Demand*. Retrieved September 26, 2016, from http://www.mwra.state.ma.us/04water/html/wsupdate.htm

Massachusetts Department of Environmental Protection. (2009). *Reclaimed Water Permit Program and Standards* (pp. 15-18). Boston, MA: Division of Water Pollution Control.

Metropolitan Area Planning Council. (2005). *Once is not enough: A guide to water reuse in Massachusetts*. Retrieved September 26, 2016, from http://www.mapc.org/sites/default/files/Once_is_Not_Enough_-_a_Guide_to_Water_Reuse_in_Massachusetts_-_November_2005.pdf

Monks, K. (2014). *From Toilet to Tap: Getting a taste for drinking recycled waste water*. Accessed July, 14, 2014.

Perlman, H. (2016, December 15). Water Hardness. Retrieved February 12, 2017, from https://water.usgs.gov/edu/hardness.html

Renewable Energy World. (2008). *Ridgewood Renewable Power To Develop 41-MW Landfill Gas Plant*. *Renewableenergyworld.com*. Retrieved 30 September 2016, from http://www.renewableenergyworld.com/articles/2008/12/ridgewood-renewable-power-to-develop-41-mw-landfill-gas-plant-54249.html

Schulte, P. (2010). California farm water success stories - Using Recycled Water on Agriculture: Sea Mist Farms and Sonoma County. Oakland, California: *Pacific Institute*. Retrieved on May, 30, 2011.

Silah, Andrea, Michael Kokernak, RSMeans, Means Engineering Staff, and John Wiley & Sons. *RSMeans Illustrated Construction Dictionary*. United States: Wiley, John & Sons, 2012.

Trussell, R. (2016). Types of Water Reuse. Retrieved September 22, 2016, from http://nas-sites.org/waterreuse/what-is-water-reuse/types-of-water-reuse/

Ultrafiltration, Nanofiltration and Reverse Osmosis [PDF]. (2008). Safewater.org.

USGS. (2016). *Current Conditions for USGS 0110973 BLACKSTONE RIVER AT MILLBURY, MA*. *Nwis.waterdata.usgs.gov*. Retrieved 9 October 2016, from http://nwis.waterdata.usgs.gov/usa/nwis/uv/?cb_00065=on&format=gif_default&site_no=01109730&period&begin_date=2013-10-01&end_date=2016-10-09

“Plant Performance,” Upper Blackstone Water Pollution Abatement District, accessed September 25, 2016, http://www.ubwpad.org/plantperformance1.html.

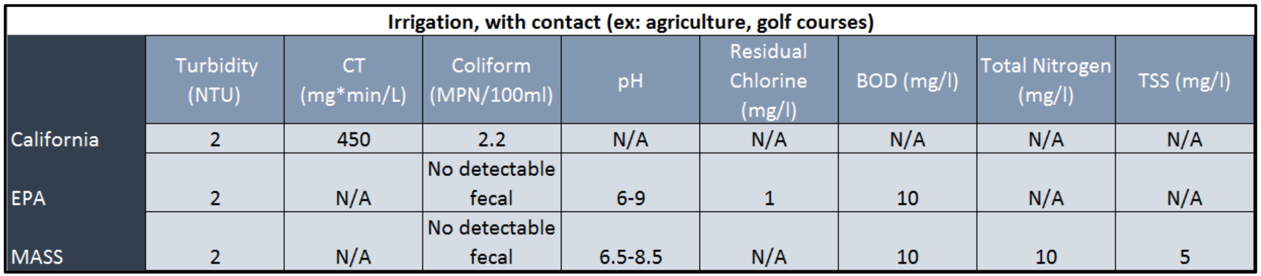
“Wastewater Technology Fact Sheet: UV Disinfection.” *United States Environmental Protection Agency*, no. EPA 832-F-99-064 (December 1999).

“Why Get Licensed?,” NSPE, 2017, accessed February 10, 2017, https://www.nspe.org/resources/licensure/why-get-licensed.

Worku, A., & Sahu, O. (2014). Reduction of Heavy Metal and Hardness from Ground Water by Algae. Journal of Applied & Environmental Microbiology, 2(3), 86-89. doi: 10.12691/jaem-2-3-5

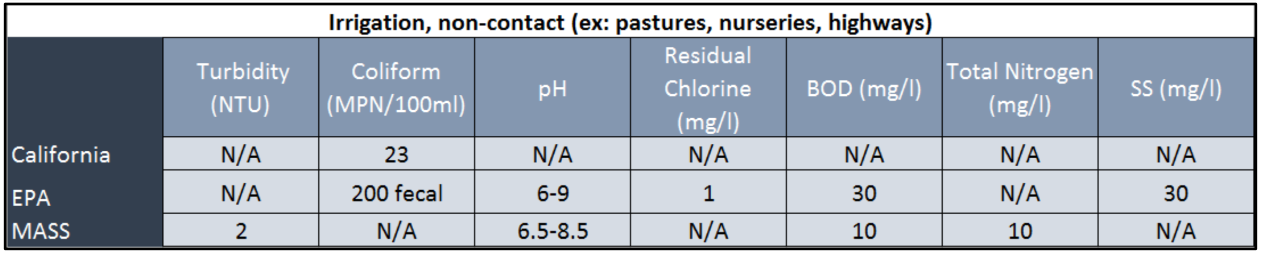
Appendices

Appendix A: Comparison Requirements for Reclaimed Water Quality by Use



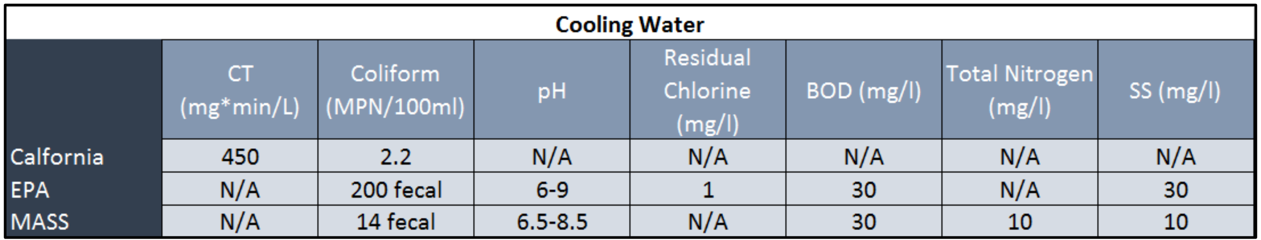
Irrigation, with contact (ex: agriculture, golf courses)

	Turbidity (NTU)	CT (mg*min/L)	Coliform (MPN/100ml)	pH	Residual Chlorine (mg/l)	BOD (mg/l)	Total Nitrogen (mg/l)	TSS (mg/l)
California	2	450	2.2	N/A	N/A	N/A	N/A	N/A
EPA	2	N/A	No detectable fecal	6-9	1	10	N/A	N/A
MASS	2	N/A	No detectable fecal	6.5-8.5	N/A	10	10	5



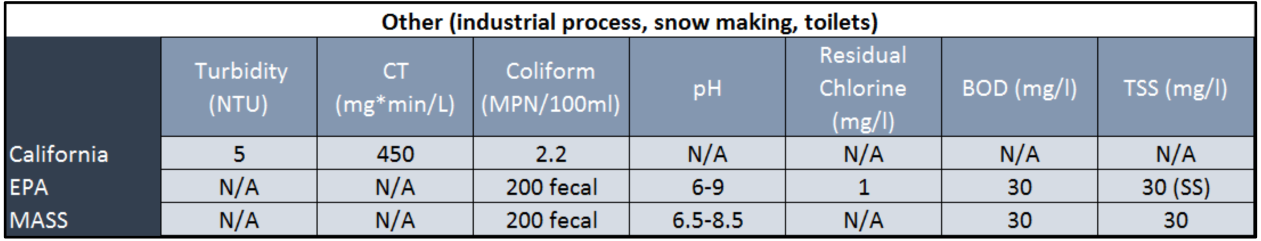
Irrigation, non-contact (ex: pastures, nurseries, highways)

	Turbidity (NTU)	Coliform (MPN/100ml)	pH	Residual Chlorine (mg/l)	BOD (mg/l)	Total Nitrogen (mg/l)	SS (mg/l)
California	N/A	23	N/A	N/A	N/A	N/A	N/A
EPA	N/A	200 fecal	6-9	1	30	N/A	30
MASS	2	N/A	6.5-8.5	N/A	10	10	N/A



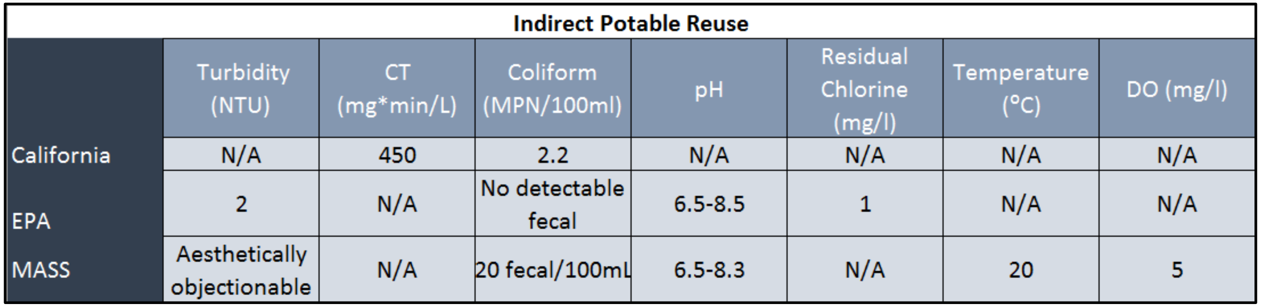
Cooling Water

	CT (mg*min/L)	Coliform (MPN/100ml)	pH	Residual Chlorine (mg/l)	BOD (mg/l)	Total Nitrogen (mg/l)	SS (mg/l)
California	450	2.2	N/A	N/A	N/A	N/A	N/A
EPA	N/A	200 fecal	6-9	1	30	N/A	30
MASS	N/A	14 fecal	6.5-8.5	N/A	30	10	10



Other (industrial process, snow making, toilets)

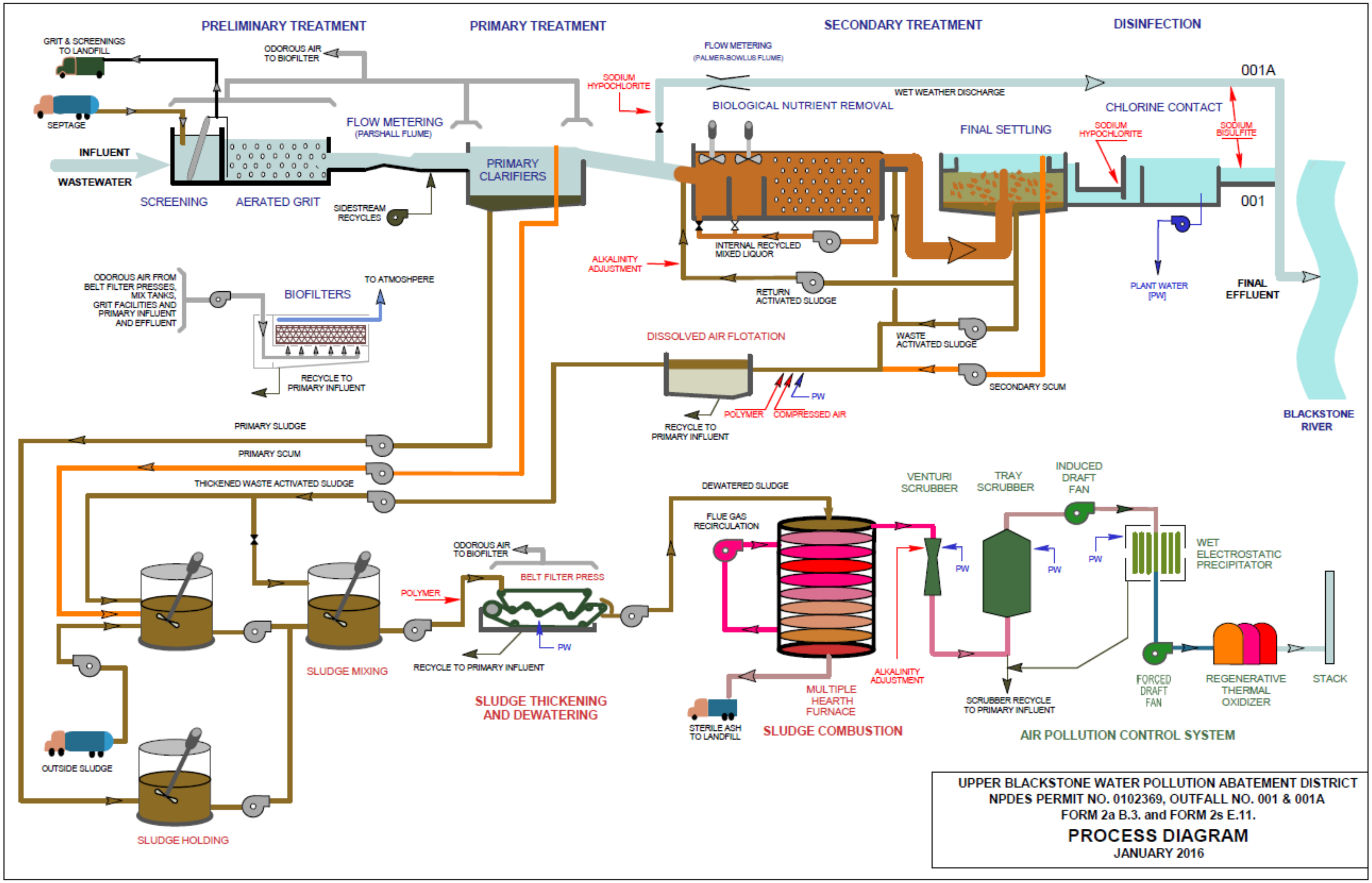
	Turbidity (NTU)	CT (mg*min/L)	Coliform (MPN/100ml)	pH	Residual Chlorine (mg/l)	BOD (mg/l)	TSS (mg/l)
California	5	450	2.2	N/A	N/A	N/A	N/A
EPA	N/A	N/A	200 fecal	6-9	1	30	30 (SS)
MASS	N/A	N/A	200 fecal	6.5-8.5	N/A	30	30



Indirect Potable Reuse

	Turbidity (NTU)	CT (mg*min/L)	Coliform (MPN/100ml)	pH	Residual Chlorine (mg/l)	Temperature (°C)	DO (mg/l)
California	N/A	450	2.2	N/A	N/A	N/A	N/A
EPA	2	N/A	No detectable fecal	6.5-8.5	1	N/A	N/A
MASS	Aesthetically objectionable	N/A	20 fecal/100mL	6.5-8.3	N/A	20	5

Appendix B: Upper Blackstone Treatment Process



Appendix C: UBWPAD Effluent Quality Compare to Regulations (2011-2016)

Parameter	**Regulation**	**Violations between 2011-2016**
	Class A	
BOD	< 10 mg/l	1 violation at 11.4mg/l
pH	6.5-8.5	None
TSS	< 5 mg/l	96 violations ranging from 5mg/l to 52.9mg/l, average = 3.8mg/l
Turbidity	< average of 2 NTU within a 24-hour period, cannot exceed five NTU more than 5% of the time within a 24-hour period, and cannot exceed ten NTU at any time.	Yes, 1.8 NTU measured on 12/6/16 in the WPI Kaven Laboratory
Total Nitrogen	< 10 mg/l	3 violations ranging from 11mg/l to 11.4mg/l, average = 4.77mg/l
Fecal coliform	none detectable	No, highest value = 1119.9CFU/ml, average detectable = 16.7CFU/100ml
	Class B	
BOD	< 30 mg/l	None
pH	6.5-8.5	None
TSS	< 10 mg/l	19 violations ranging from 10.3mg/l to 52.9mgl
Total Nitrogen	< 10 mg/l	3 violations ranging from 11mg/l to 11.4mg/l
Fecal coliform	Median of 14 detectable fecal coliform/100 ml over continuous 7-day sampling periods, not to exceed 100/100 ml in any one sample	No, highest value = 1119.9 CFU/100ml, median = 4.1 CFU/100ml
	Class C	
BOD	< 30 mg/l	None
pH	6.5-8.5	None
TSS	< 30 mg/l	1 violation at 52.9mg/l
Total Nitrogen	< 10 mg/l	3 violations ranging from 11mg/l to 11.4mg/l
Fecal coliform	Median of 200 detectable fecal coliform/100 ml	None

Appendix D: UBWPAD Effluent Quality Averages 2011 – 2016

Parameter	***Average Value ± Std. deviation 11/1/11-12/31/11***	***Average Value ± Std. deviation 1/1/12-12/31/12***	***Average Value ± Std. deviation 1/1/13-12/31/13***	***Average Value ± Std. deviation 1/1/14-12/31/14***	***Average Value ± Std. deviation 1/1/15-12/31/2015***	***Average Value ± Std. deviation 1/1/11-10/31/16***
Eff Total Flow (MGD)	48.41 ± 10.92	35.13 ± 7.67	38.46 ± 14.52	33.40 ± 15.11	28.68 ± 10.33	33.46 ± 12.77
Eff cBOD (mg/l)	1.20 ± 0.64	1.67 ± 0.84	1.90 ± 0.85	2.08 ± 0.97	2.56 ± 0.93	2.1 ± 0.98
Eff TSS (mg/l)	2.01 ± 0.59	2.94 ± 1.27	2.73 ± 3.18	2.64 ± 1.21	3.02 ± 1.79	2.84 ± 1.96
Eff pH (su)	7.01 ± 0.18	7.02 ± 0.20	7.09 ± 0.23	7.11 ± 0.18	7.18 ± 0.21	7.1 ± 0.22
Eff Total Alkalinity (mg/l)	71.76 ± 13.86	72.81 ± 11.00	91.58 ± 10.44	100.73 ± 15.41	102.37 ± 16.36	92.94 ± 18.41
Eff Total Nitrogen (mg/l)	2.67 ± 1.34	5.19 ± 1.35	4.80 ± 1.24	4.43 ± 1.30	4.90 ± 1.48	4.77 ± 1.44
Eff Total Phosphorous (mg/l)	0.39 ± 0.26	0.42 ± 0.34	0.18 ± 0.14	0.28 ± 0.36	0.27 ± 0.46	0.29 ± 0.37
Eff Fecal Coliform (CFU/100ml)	16.57 ± 36.16	9.93 ± 37.74	28.56 ± 89.35	17.16 ± 77.75	12.79 ± 38.75	16.71 ± 62.58
Eff VSS (mg/l)	1.81 ± 0.53	2.66 ± 1.14	2.38 ± 2.47	2.28 ± 1.01	2.73 ± 1.55	2.52 ± 1.61

Appendix E: WPI Lab Analysis of UBWPAD Effluent Quality

Appendix E.1: Hardness Testing

	EDTA initial (mL)	***EDTA final (mL)***	***EDTA added (mL)***	***Under 5 minutes?***	***Hardness (mg/L)***	***Rating***
Trial 1	15.2	21.3	6.1	Yes	244	Very Hard
Trial 2	21.3	27.2	5.9	Yes	236	Very Hard
Trial 3	27.2	34.3	7.1	Yes	284	Very Hard
Trial 4	34.3	40	5.7	Yes	228	Very Hard
Trial 5	40	45.6	5.6	Yes	224	Very Hard
				Average	*243.2*	*Very Hard*
				Standard Deviation	*24.1*	

Appendix E.2: Conductivity Testing

	µS/cm
Trial 1	1348
Trial 2	1351
Average	1349.5
Standard Deviation	2.1

Appendix F: Ultrafiltration Membrane Calculations

$$Flux\ equation\ through\ the\ membrane:$$

$$J_m = \frac{Q}{A_m}$$

$$Q = 1\ MGD$$

$$J_m = 40\ gfd$$

$$A_{m,total} = \frac{Q}{J_m}$$

$$A_{m,total} = \frac{1\ MGD}{40\ gfd}$$

$$A_{m,total} = 25{,}000\ ft^2$$

$$N_m = \frac{A_{m,total}}{A_{m,unit}}$$

$$A_{m,unit} = 829\ ft^2$$

$$N_m = \frac{25{,}000\ ft^2}{829\ ft^2}$$

$$N_m = 30.16\ \approx\ 31\ units$$

Appendix G: Ultraviolet Disinfection Unit Calculations

$$D = I_{avg} \times t$$

$$D = 80\ \frac{mJ}{cm^2}$$

$$I_{avg} = dosage, in\ \frac{mW}{cm^2}$$

$$Total\ Watts: 30\ bulbs \times 800\ W = 24{,}000\ W \rightarrow 24{,}000{,}000\ mW$$

$$Cross\ sectional\ area: A = \pi \times \frac{D^2}{4}$$

$$A = \pi \times \frac{50.8\ cm^2}{4}$$

$$A = 2025.8\ cm^2$$

$$I_{avg} = \frac{24{,}000{,}000\ mW}{2025.8\ cm^2}$$

$$I_{avg} = 11{,}847.2\ \frac{mW}{cm^2}$$

$$t = {80\ \frac{mJ}{cm^2}} \Big/ {11{,}847.2\ \frac{mW}{cm^2}}$$

$$t = 0.006753\ s$$

Appendix H: Centrifugal Pump Design Calculations

$Q = 1\ MGD = 694.44\ \frac{gal}{min} = 0.04381\ \frac{m^3}{s}$

$P_{initial} = 33.2\ psi = 2.22\ bar$

$L_{pipe} = 5289\ ft = 1612.09\ m$

$D_{pipe} = 12\ in = 0.3048\ m$

$H = height\ that\ water\ must\ be\ lifted = 139\ ft = 42.37\ m$

$\rho_{water}(25°C) = 997\ \frac{kg}{m^3}$

$g = 9.81\ \frac{m}{s^2}$

$\mu_{water}(25°C) = 0.00089\ Pa * s$

$Relative\ roughness\ of\ HDPE(typical) = 0.0015$[72]

$SG_{water}(25°C) = 1$

Calculating the Work Required for a Single Operating Pump with 50% Efficiency

$$W = \frac{\rho g H Q}{\eta}$$

$$W = \frac{(997\ \frac{km}{m^3})(9.81\ \frac{m}{s^2})(42.37\ m)(0.04381\ \frac{m^3}{s})}{0.5}$$

$$W = 36275.14\ \frac{J}{s}$$

Calculating the Work Required for each of Two Pumps in Parallel with 50% Efficiency

$$W_{pump\ 1} = W_{pump\ 2} = \frac{\rho g H \frac{Q}{2}}{\eta}$$

$$W = \frac{\left(997\ \frac{kg}{m^3}\right)\left(9.81\ \frac{m}{s^2}\right)(42.37\ m)\left(\frac{0.04381}{2}\frac{m^3}{s}\right)}{0.5}$$

$$W = 18137.57\ \frac{J}{s}$$

$$Total\ Work = W_{pump\ 1} + W_{pump\ 2} = 36275.14\ \frac{J}{s}$$

Calculating the Horsepower Required for Each Pump

$$1\ hp = 745.7\ \frac{J}{s}$$

$$Single\ Pump = 36275.14\ \frac{J}{s} \times \left(\frac{1\ hp}{745.7\ \frac{J}{s}}\right) = 48.62\ hp$$

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[72] Pipe Roughness. (2017). Pipeflow.com. Retrieved 2 February 2017, from http://www.pipeflow.com/pipe-pressure-drop-calculations/pipe-roughness

$$Two\ Pumps = 18137.57\ \frac{J}{s} \times \left(\frac{1\ hp}{745.7\ \frac{J}{s}} \right) = 24.31\ hp$$

Each pump must be able to operate between 24.31 and 48.62 horsepower.

Calculating Head Loss using the Darcy-Weisbach Equation

$$head\ loss\ due\ to\ friction = h_f$$

$$head\ loss\ due\ to\ elevation\ change = H$$

$$h_f = f\,\frac{Lv^2}{2Dg}$$

Finding the Darcy Friction Factor

$$Re = \frac{\rho v D}{\mu} = \frac{\left(997\,\frac{kg}{m^3}\right)\left(0.60045377657\,\frac{m}{s^2}\right)(0.3048\ m)}{0.00089\ Pa \times s} = 20{,}5000$$

Darcy friction factor for an Re value of 205000 and relative roughness of 0.0015 based on the Moody Chart[73] = 0.024

$$h_f = 0.024\,\frac{(1612.087\ m)\left(0.60045377657\,\frac{m}{s}\right)^2}{2(0.3048\ m)\left(9.81\,\frac{m}{s^2}\right)} = 2.34\ m$$

$$Total\ Head\ Loss = h_f + H = 2.34\ m + 42.37\ m = 44.71\ m$$

Converting Head Loss to Pressure Loss (equivalent to Pressure Supplied by the Pump)

$$P = 0.0981(h * SG)$$

$$P = 0.0981(42.37\ m)(1) = 4.16\ bar = pressure\ loss\ due\ to\ elevation$$

Determining Pump Pressure

In this case, the pressure loss from the UV disinfection unit is assumed to be so small that it is negligible according to a local vendor. The maximum pressure loss of the ultrafiltration unit we are recommending is 2.1 bar. P_{final} corresponds to the pressure measured at Wheelabrator. The minimal value of P_{final}, or residual pressure, is at least 40 psi, or 2.76 bar.

$$P_{final} = P_{initial} + P_{pump} - P_{friction} - P_{UF} - P_{UV} - P_{Diameter\ Chane} - P_{elevation}$$

$$2.76\ bar = 2.22\ bar + P_{pump} - 0.23\ bar - 2.1\ bar - 0\ bar + 0.082\ bar - 4.16\ bar$$

$$Ppump\ =\ 4.19\ bar\ =\ 60.74\ psi$$

Based on achieving a final pressure of 40 psi at Wheelabrator, no intermediate pump will be required.

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[73] Pressure Loss in Pipe – Neutrium. (2017). Neutrium.net. Retrieved 1 February 2017, from https://neutrium.net/fluid_flow/pressure-loss-in-pipe/

Determining Pump Operating Cost

Typical motor efficiency for a 50 hp pump = 90%

$$\dot{W} = \frac{W}{\eta_{motor}} = \frac{36275.14\ \frac{J}{s}}{0.9} = 40305.71\ \frac{J}{s}$$

For 24 hour operation:

$$40305.71\ \frac{J}{s} * \left(60\ \frac{s}{min}\right)\left(60\ \frac{min}{hour}\right)(24\ \frac{hours}{day}) = 3482413344\ \frac{J}{day}$$

Cost of electricity in Western/Central MA for industries = 8.3 cents/kWh

$$1\ kWh = 3600000\ J$$

$$3482413344\ \frac{J}{day}\left(\frac{1\ kWh}{3600000\ J}\right)\left(\frac{8.3\ cents}{kWh}\right)\left(\frac{1\ dollar}{100\ cents}\right)(\frac{365\ days}{year}) = \frac{\$29{,}305}{year}$$

The annual operating cost will be $29,305 not including regular maintenance.

Appendix I: Piping Calculations

$$Hazen - Williams\ equation:$$

$$h_f = \frac{10.44 \times Q^{1.85} \times L}{C^{1.85} \times D^{4.87}}$$

$$D = \left(\frac{10.44 \times Q^{1.85} \times L}{C^{1.85} \times h_f}\right)^{1/4.87}$$

$$Q = 1\ MGD$$

$$Operating\ time: 24\frac{hours}{day}$$

$$Q = 1\ MGD \times \frac{1\ day}{24\ hours} \times \frac{1\ hour}{60\ minutes} = 694.4\ \frac{gal}{min}$$

$$L = 5{,}289\ ft$$

$$C = 140^{74}$$

$$h_f = 556\ ft - 417\ ft = 139\ ft$$

$$D = \left(\frac{10.44 \times 694.4\frac{gal}{min}^{1.85} \times 5{,}289\ ft}{140^{1.85} \times 139\ ft}\right)^{1/4.87}$$

$$D = 6.28\ inches \sim 7\ inch\ pipe$$

$$If\ expanding\ to\ 5\ MGD:$$

$$Q = 5\ MGD \times \frac{1\ day}{24\ hours} \times \frac{1\ hour}{60\ minutes} = 3{,}472.22\ \frac{gal}{min}$$

$$D = \left(\frac{10.44 \times 3{,}472.22\frac{gal}{min}^{1.85} \times 5{,}289\ ft}{140^{1.85} \times 139\ ft}\right)^{1/4.87}$$

$$D = 11.57\ inch \sim 12\ inch\ pipe$$

Based on these calculations, any pipe between 7 and 12 inches can be used for the system. Currently, Wheelabrator received their water from Millbury with a 12 inch water main, therefore a 12 inch pipe is the most practical option as it is consistent both with the current water supply line and future expansion.

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[74] “Hazen-Williams Coefficients.” Accessed January 23, 2017. http://www.engineeringtoolbox.com/hazen-williams-coefficients-d_798.html.

Appendix J: Pressure Drop Calculations

$$Bernoulli\ Equation:$$

$$\frac{v_1^2}{2} + gz_1 + \frac{P_1}{\rho_1} = \frac{v_2^2}{2} + gz_2 + \frac{P_2}{\rho_2}$$

$$z_1 = z_2$$

$$\rho_1 = \rho_2 = \rho$$

$$\frac{v_1^2}{2} + \frac{P_1}{\rho} = \frac{v_2^2}{2} + \frac{P_2}{\rho}$$

$$P_1 - P_2 = \left(\frac{v_2^2}{2} - \frac{v_1^2}{2}\right) \times \rho$$

$$P_2 = P_1 - \left(\frac{v_2^2}{2} - \frac{v_1^2}{2}\right) \times \rho$$

$$Pressure\ in\ 16\ inch\ pipe\ between\ 10\ inch\ UF\ piping\ and\ 20\ inch\ UV\ piping:$$

$$P_2 = 33.2\ psi - \left(\frac{\left(66.4\ \frac{ft}{min}\right)^2}{2} - \frac{\left(170.1\ \frac{ft}{min}\right)^2}{2}\right) \times 62.441\ \frac{lbm}{ft^3} \times \frac{1\ s^2}{32.2\ ft} \times \frac{1\ min^2}{3600\ s^2} \times \frac{1\ ft^2}{144\ in^2}$$

$$P_2 = 33.254\ psi$$

$$Subsequent\ calculations\ were\ performed\ on\ all\ other\ pipe\ sizes:$$

Pipe Size (inches)	Pressure in Pipe (psi)	Pressure Change (psi)
10	33.2	–
16	33.354	0.154
20	33.26	0.094
6 (before pump)	32.773	0.486
6 (after pump)	93.513	60.74
12	93.974	0.461

Appendix K: Cost Analysis

Appendix K.1: Fixed Capital Investment

Membrane filtration unit[75]:
$1,750,000 initial capital expenditure (building and equipment)

Operation and Maintenance Costs for medium to high flux, for one year:
$0.08 per 1,000 gallons, per day

$$\$0.08 \times 1{,}000\ thousand\ gallons \times 365 = \$29{,}200\ per\ year$$

HDPE Piping:
Price per linear foot: $25[76]

$$\frac{\$25}{foot} \times 5{,}289\ ft = \$132{,}225$$

Installation: $30 per square yard[77]

$$4\ foot\ wide\ trench \times 5{,}289\ ft = 21{,}156\ ft^2 = 2{,}351\ yd^2$$

$$2{,}351\ yd^2 \times \frac{\$30}{yard} = \$70{,}520$$

Pump:

Pumps (with drives)	Pump Type	Power (kilowatts)	# Spares	MOC	Discharge Pressure (barg)	Purchased Equipment Cost	Bare Module Cost
P-101	Centrifugal	36	0	Stainless Steel	6.4	$ 10,300	$ 51,000
						Total Bare Module Cost	$ 51,000

Name	Total Module Cost	Grass Roots Cost	Utility Used	Efficiency	Actual Usage	Annual Utility Cost
P-101	$ 60,200	$ 77,000	Electricity	0.7	51.4 kilowatts	$ 25,900

Three pumps are needed: two for system, one for redundancy / spare

$$Capital\ Investment = \$51{,}000 \times 3$$

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[75] American Water Works Association. (2008). Microfiltration and Ultrafiltration Membranes for Drinking Water (PDF). *Journal-American Water Works Association*, *100*(12), 84-97.

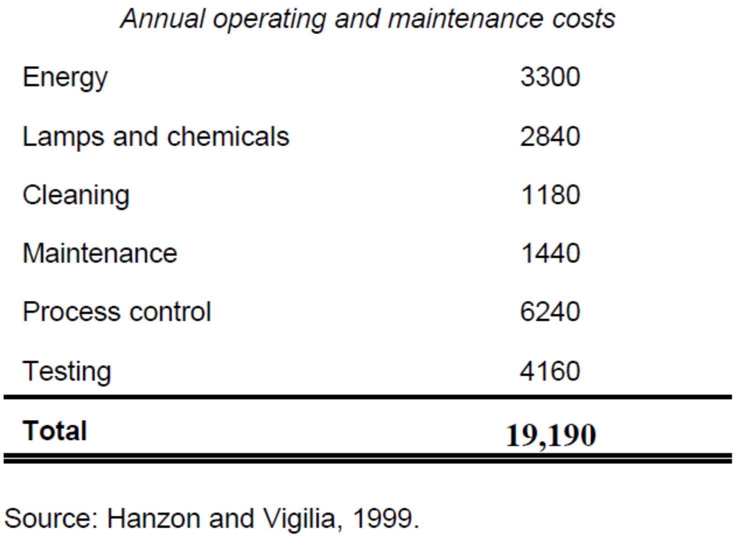
[76] (Anon, 2017).

[77] Abermale Sample Plans, Appendix E.

$$Capital\ Investment = \$153{,}000$$
$$Operation\ and\ Maintenance\ Costs = \$25{,}900\ \times 2$$
$$Operation\ and\ Maintenance\ Costs = \$51{,}800$$

<u>UV</u>:
Unit price: $250,000[78]

Operation and Maintenance costs:



Annual operating and maintenance costs

Energy	3300
Lamps and chemicals	2840
Cleaning	1180
Maintenance	1440
Process control	6240
Testing	4160
Total	**19,190**

Source: Hanzon and Vigilia, 1999. [79]

$$CEPCI\ 1999 = 390.6$$
$$CEPCI\ 2016 = 582$$
$$Cost\ in\ 2016 = Cost\ in\ 1999\ \times \frac{CEPCI\ 2016}{CEPCI\ 1999}$$
$$Cost\ in\ 2016 = \$19{,}190\ \times \frac{582}{390.6}$$
$$Cost\ in\ 2016 = \$28{,}594\ per\ year$$

$$Fixed\ Capital\ Investment = \$1{,}750{,}000 + \$132{,}225 + \$70{,}520 + \$153{,}000 + \$250{,}000$$
$$Fixed\ Capital\ Investment = \$2{,}355{,}745$$
$$FCI\ Adjusted = \ \$2{,}355{,}745 \times 1.1$$
$$FCI\ Adjusted = \$2{,}591{,}331$$

$$Operation\ and\ Maintenance\ for\ one\ year = \$29{,}200 + \$51{,}800 + \$28{,}594$$
$$Operation\ and\ Maintenance\ for\ one\ year = \$109{,}594$$

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[78] Patrick Bollman; Evoqua Water Technologies, personal communication. 2/6/17.

[79] "Wastewater Technology Fact Sheet: UV Disinfection." *United States Environmental Protection Agency*, no. EPA 832-F-99-064 (December 1999).

Appendix K.2: Depreciation and Payback Period

$$Revenue = \$406{,}992$$
$$COMd = O\&M$$
$$COMd = \$109{,}594$$

$$Depreciation = \frac{FCI}{n}$$
$$n = time\ until\ salvage\ value\ reached$$
$$n = 10\ years$$
$$Depreciation = \frac{\$2{,}591{,}331}{10\ years}$$
$$Depreciation = \frac{\$259{,}133.1}{year}$$

$$Assume\ taxation\ rate = 0.4$$

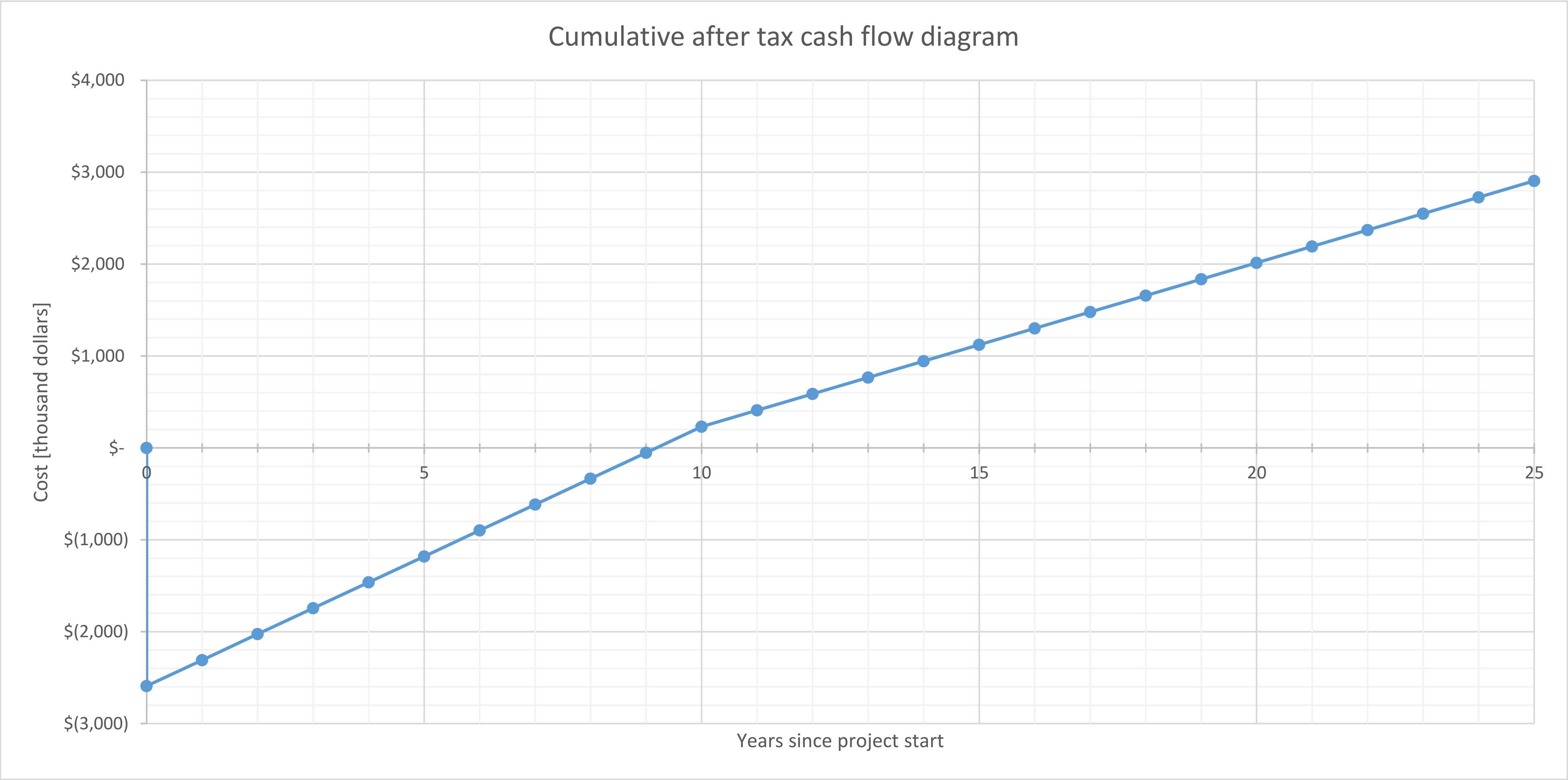
$$ROROI = \frac{slope}{FCI} - \frac{1}{n}$$

$$ROROI = \frac{259.1}{2{,}591.3} - \frac{1}{25}$$

$$ROROI = 0.059988 \times 100 = 6\%$$

Using a straight-line straight depreciation scheme over 10 years with an overall project live of 15 years, and a consistent revenue of $406,992 from savings in water costs, the following table and graph were produced.

Year	Investment	depreciation	FIC - dk	Revenue	COMd	(R-COMd-dk)*(1-t)+d	cash flow	cumulative cash flow	discounted cash flow	cumulative discounted cash flow
0	$ -		$ 2,591.3				$ -	$ -	$ -	$ -
0	$ 2,591.3		$ 2,591.3				$ (2,591.3)	$ (2,591.3)	$ (2,591.3)	$ (2,591.3)
1		$ 259.1	$ 2,332.2	$ 407.0	$ 109.6	$ 282.1	$ 282.1	$ (2,309.2)	$ 256.4	$ (2,334.9)
2		$ 259.1	$ 2,073.1	$ 407.0	$ 109.6	$ 282.1	$ 282.1	$ (2,027.1)	$ 233.1	$ (2,101.7)
3		$ 259.1	$ 1,813.9	$ 407.0	$ 109.6	$ 282.1	$ 282.1	$ (1,745.1)	$ 211.9	$ (1,889.8)
4		$ 259.1	$ 1,554.8	$ 407.0	$ 109.6	$ 282.1	$ 282.1	$ (1,463.0)	$ 192.7	$ (1,697.1)
5		$ 259.1	$ 1,295.7	$ 407.0	$ 109.6	$ 282.1	$ 282.1	$ (1,180.9)	$ 175.2	$ (1,522.0)
6		$ 259.1	$ 1,036.5	$ 407.0	$ 109.6	$ 282.1	$ 282.1	$ (898.8)	$ 159.2	$ (1,362.7)
7		$ 259.1	$ 777.4	$ 407.0	$ 109.6	$ 282.1	$ 282.1	$ (616.7)	$ 144.8	$ (1,218.0)
8		$ 259.1	$ 518.3	$ 407.0	$ 109.6	$ 282.1	$ 282.1	$ (334.6)	$ 131.6	$ (1,086.4)
9		$ 259.1	$ 259.1	$ 407.0	$ 109.6	$ 282.1	$ 282.1	$ (52.5)	$ 119.6	$ (966.8)
10		$ 259.1	$ -	$ 407.0	$ 109.6	$ 282.1	$ 282.1	$ 229.6	$ 108.8	$ (858.0)
11			$ -	$ 407.0	$ 109.6	$ 178.4	$ 178.4	$ 408.0	$ 62.5	$ (795.5)
12			$ -	$ 407.0	$ 109.6	$ 178.4	$ 178.4	$ 586.5	$ 56.9	$ (738.6)
13			$ -	$ 407.0	$ 109.6	$ 178.4	$ 178.4	$ 764.9	$ 51.7	$ (686.9)
14			$ -	$ 407.0	$ 109.6	$ 178.4	$ 178.4	$ 943.3	$ 47.0	$ (639.9)
15			$ -	$ 407.0	$ 109.6	$ 178.4	$ 178.4	$ 1,121.8	$ 42.7	$ (597.2)
16			$ -	$ 407.0	$ 109.6	$ 178.4	$ 178.4	$ 1,300.2	$ 38.8	$ (558.4)
17			$ -	$ 407.0	$ 109.6	$ 178.4	$ 178.4	$ 1,478.7	$ 35.3	$ (523.1)
18			$ -	$ 407.0	$ 109.6	$ 178.4	$ 178.4	$ 1,657.1	$ 32.1	$ (491.0)
19			$ -	$ 407.0	$ 109.6	$ 178.4	$ 178.4	$ 1,835.5	$ 29.2	$ (461.8)
20			$ -	$ 407.0	$ 109.6	$ 178.4	$ 178.4	$ 2,014.0	$ 26.5	$ (435.3)
21			$ -	$ 407.0	$ 109.6	$ 178.4	$ 178.4	$ 2,192.4	$ 24.1	$ (411.2)
22			$ -	$ 407.0	$ 109.6	$ 178.4	$ 178.4	$ 2,370.9	$ 21.9	$ (389.2)
23			$ -	$ 407.0	$ 109.6	$ 178.4	$ 178.4	$ 2,549.3	$ 19.9	$ (369.3)
24			$ -	$ 407.0	$ 109.6	$ 178.4	$ 178.4	$ 2,727.7	$ 18.1	$ (351.2)
25			$ -	$ 407.0	$ 109.6	$ 178.4	$ 178.4	$ 2,906.2	$ 16.5	$ (334.7)


Cumulative after tax cash flow diagram
$4,000
$3,000
$2,000
$1,000
$-
$(1,000)
$(2,000)
$(3,000)
Cost [thousand dollars]
0
5
10
15
20
25
Years since project start

Appendix L: Wheelabrator Water Usage Data and Costs 2016

Month	*Monthly Usage*	*Monthly Cost***	*Reuse Cost****	*Savings*
January	13,553,600	$29,768	$4,296.49	$25,471.39
February	18,857,300	$41,102.74	$5,977.76	$35,124.98
March	23,407,300	$50,645.17	$7,420.11	$43,225.06
April	21,240,000	$45,718.92	$6,733.08	$38,985.84
May	22,928,102	$47,787.71	$7,268.21	$40,519.50
June	24,064,401	$51,264.83	$7,628.42	$43,636.41
July	24,350,250	$51,142.80	$7,719.03	$43,423.77
August	24,499,502	$51,775.85	$7,766.34	$44,009.51
September	23,900,677	$50,868.04	$7,576.51	$43,291.53
October	21,115,101	$45,388.28	$6,693.49	$38,694.79
November*	5,771,900	$12,438.80	$1,829.69	$10,609.11
Total	**223,688,133**	**$477,901**	**$70,909.14**	**$406,991.88**

*through November 8th

**Current water price at: $2.12 per thousand gallons

***Comparable reuse water price at: $0.317 per thousand gallons