The Assabet River and Phosphorus Removal Options

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1.0 Introduction

This project will focus on phosphorus as the Massachusetts Department of Environmental Protection recently lowered its maximum allowable levels in the waste effluent of wastewater treatment plants on the Assabet River. The decrease in allowable levels of phosphorus was in response to the eutrophication of the Assabet River. In order for wastewater treatment plants to comply with the new levels, they must upgrade with new phosphorus removal technology. Test results from pilot study for the phosphorus removal at the Westborough Wastewater Treatment Facility will be used to evaluate the following three phosphorus removal technologies on both economic and performance merits: Blue Pro™; CoMag™; Actiflo®. The design portion of this project will be a wastewater treatment plant with an average of three million gallons per day (MGD) and 3 trains. The footprint for the three technologies will be calculated for the same hypothetical plant. In the end, the positive and negative sides of each technology will be discussed. It is important to note that this paper is theoretical, due to the test results coming from a pilot study on only one plant. Each wastewater treatment plant should conduct its own bench scale test in order to determine which phosphorus removal method is most efficient and cost effective for their unique needs.

The role of phosphorus in river water chemistry and its effects on local human and animal populations is an important issue for wastewater treatment plants, and communities that live along any water bodies. Phosphorus, a non metallic element found in the nitrogen group, is essential element for all living organisms. Phosphorus has the four following different allotropic forms: white, which can be separated into alpha and beta; red, which is also referred to as yellow phosphorus; scarlet; and black. The last three allotropes are formed from white phosphorus.

Phosphorus is commonly found in nature in different combinations with minerals. One of these mineral combinations is phosphate rock, which is an important source of this element and found in large quantities.[1]

Some forms of phosphorus are extremely poisonous, with a fatal dose for non-white phosphorous being about 50 mg and even less for white phosphorus.[2] However, phosphorus is useful and relatively harmless in many applications. Red phosphorus is used to make fireworks, smoke bombs, safety matches, and pesticides. Other common applications of phosphorus are in china, baking soda, fertilizers, detergents, water softeners, television sets, and soft drinks.[3] While high phosphorus levels can cause death, kidney failure, or osteoporosis, an insufficient amount of phosphorus can be just as harmful for humans. Over time, humans have influenced the supply of phosphorus in nature via the following examples: fertilizers; cleaning solutions; industrial, commercial, and human waste. The increased amounts of phosphorus have led to excessive plant growth in water bodies which is an issue for both the environment and human usage of the water body.

2.0 Impact of Phosphorus on Water Bodies

Plant growth requires a certain amount of nutrients - such as nitrogen, carbon, trace minerals, and phosphorus - to be present in the water. Usually nitrogen and phosphorus are considered the limiting nutrients for plant growth because the other nutrients are easily

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[1] http://periodic.lanl.gov/elements/15.html

[2] http://periodic.lanl.gov/elements/15.html

[3] http://education.jlab.org/itselemental/ele015.html

replenished through the environment. Plants use carbon dioxide for the carbon source which is introduced into the water via the atmosphere. Trace minerals, which is needed only in very small amounts, can be mainly introduced into the water either through weathering of the rocks or through wastewater effluent, though trace elements are hard to remove during the treatment process.[4] In a majority of fresh water bodies, there is not enough phosphorus available for the plants to grow at their maximum rates.[5] In some cases, eutrophication, the process where excess nutrients in water bodies leads to rampant plant growth, can occur especially in areas where human activities impact the water source.[6]

Phosphorus and nitrogen are the easiest nutrients needed for plant growth to be controlled via human intervention. These two nutrients can be introduced into the river water through nonpoint sources, such as runoff from fertilized land, and point sources, such as combined sewage overflow system (CSO), the effluent of wastewater treatment plants, and industrial discharge. However excessive plant growth can be controlled by limiting the amount that the total amount of these nutrients in the wastewater water treatment plant effluent.[7] Phosphorus is measured in both total phosphorus and ortho-phosphate, which is the soluble inorganic form of phosphate that plants require for growing.[8]

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[4] "Principles of Environmental Engineering and Science," Davis and Masten, 2004

[5] "StreamWatch and Water Quality Monitoring Program Final Report – Summer 2002," Organization for the Assabet River, December 2002

[6] http://toxics.usgs.gov/definitions/eutrophication.html

[7] "Principles of Environmental Engineering and Science," Davis and Masten, 2004

[8] "StreamWatch and Water Quality Monitoring Program Final Report – Summer 2002," Organization for the Assabet River, December 2002

Excessive plant growth has several negative impacts on the quality of the river. At first the plant growth, especially algae blooms, leads to poor light penetration which is needed for the photosynthesis process of the bottom dwelling plants. Due to the lack of sunlight, these plants die, including the natural death of the algae blooms. As the dead plant matter settles to the bottom of the water body, three issues arise. One issue is the settled plant matter fills in the water body. The second issue is that dissolved oxygen is used up as bacterium breaks down the decaying plant matter. Low enough levels of dissolved oxygen, which can be achieved due to large amounts of dead plant matter, leads to the death of many aquatic organisms. The last issue is more of an aesthetic issue, while the decaying plant matter is broken down by the bacterium, a sulfur smell is produced.[9]

3.0 Assabet River and Watershed

The Assabet River headwaters are located in Westborough and winds for 32 miles with a 320 feet drop to Concord, MA where it merges with the Sudbury River to form the Concord River. The Assabet River Basin is the watershed that feeds the Assabet River. This watershed covers 177 square miles, includes nine tributaries, and is home to 170,000 people. Appendix A contains a map that shows the Sudbury, Assabet, and Concord Watersheds in Massachusetts.[10]

Twenty towns are located in this watershed and the population in these towns has increased by 15 percent, which is about three times the statewide average, between 1990 and 2000. This large increase in population has resulted in increased amounts of ground water being

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[9] http://www.bbc.co.uk/schools/gcsebitesize/chemistry/usefulproductsair/nitrogenousrev4.shtml

[10] http://www.assabetriver.org/map.html

used and increased wastewater effluent. Due to the increased demands for water, the amount of water entering the Assabet River from aquifers and the tributaries has decreased. Therefore the ratio of ground water and wastewater effluent in the river has tipped in favor of a higher percentage of the river water being made up by wastewater effluent. Figure 1 shows the water use, disposal, and transfer within the Assabet River Basin from 1997 to 2001. “Blue lines indicate withdrawal or import of water for use; brown lines indicate discharge, disposal, or import of wastewater; and orange lines indicate consumptive use.”[11] UNACC stand for unaccounted for water and I/I stand for infiltration to sewers.[12]

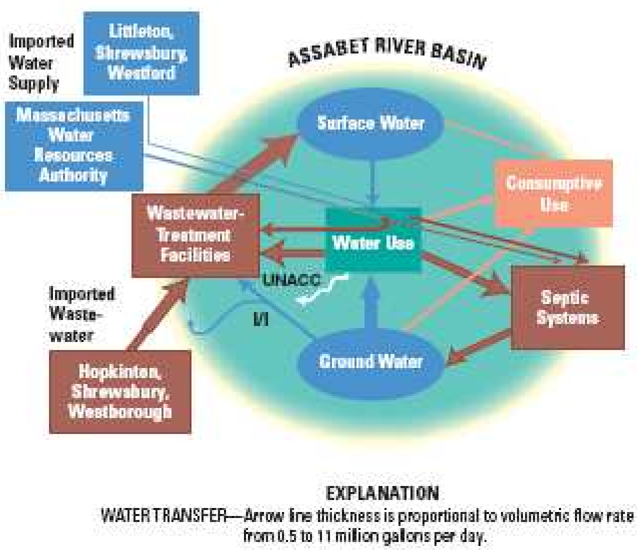

Figure 1: Water Use, Disposal, and Transfer in the Assabet River Basin from 1997 to 2001[13]

The decreasing amount of ground water feeding the tributaries and river has led to the following issues: the loss of habitat for many organisms; alteration of the watersheds; and the

[11] “People and Water in the Assabet River Basin, Eastern Massachusetts,” USGS, April 2005

[12] “People and Water in the Assabet River Basin, Eastern Massachusetts,” USGS, April 2005

[13] “People and Water in the Assabet River Basin, Eastern Massachusetts,” USGS, April 2005

Assabet River becoming eutrophic during the summer. As of 2004, the Assabet River has failed most appropriate water-quality standards due to the eutrophic state.[14] Figure 2 is a picture depicting what parts of the Assabet River looks like during the summer. The green blanket on the top of the water is made up of algae and floating duckweed. This blanket of plant matter hides from view the large amounts of aquatic plants that are growing in the shallow sediments. This large amount of plants on both the surface and the bottom has led to conditions of a eutrophic water body as mentioned above which has resulted in the river failing to pass "state water quality for 'fishable and swimmable' waters."[15]

Figure 2: Assabet River in its Eutrophic State[16]

Majority of the nutrients enter the river via wastewater effluent, which is dumped into the river by the seven wastewater treatment plants located on the river, and nonpoint sources. The nine dams along the river have resulted in an accumulation of nutrient rich sediments. The

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[14] "People and Water in the Assabet River Basin, Eastern Massachusetts," USGS, April 2005

[15] http://www.assabetriver.org/issues.html

[16] http://www.assabetriver.org/issues.html

nutrients in these sediments also increase the amount of nutrients available to the aquatic plants.[17]

The Assabet River is used for recreational uses, such as kayaking, canoeing, and fishing. However, one must look not just at the human uses for the river, but also the environmental role of the river. The river has to have a sufficient amount of water to sustain life in it, support the human uses of the river, and dilute the storm water, nonpoint sources, and wastewater effluent. The water quality issues of the Assabet River are worsened by the low amount of water that is entering the river from the aquifers and tributaries during the summer.[18] Since there is less ground water to dilute the wastewater effluent, the best way to increase the quality of the Assabet River is to place minimum allowable limits in the wastewater treatment plant effluent on the limiting nutrient of the plant growth and to address the issues concerning nonpoint sources.[19]

4.0 Environmental Organizations

There are two different types of organizations that help with addressing the water quality issues of rivers, such as the Assabet River. Community based organizations, such as the Organization of the Assabet River (OAR), and government oversight organizations like the Massachusetts Department of Environmental Protection (Mass DEP) have some overlapping roles but also have slightly different roles in combating poor water quality. When these two

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[17] http://www.assabetriver.org/issues.html

[18] http://www.assabetriver.org/issues.html

[19] "People and Water in the Assabet River Basin, Eastern Massachusetts," USGS, April 2005

types of groups work together, then most issues that contribute to poor water quality can be fixed.

4.1 Community Based Organizations

Community based organizations' main strength is reaching the public. It is necessary to get the public involved in cleaning up and protecting environment so they feel the desire to reduce the human impact on the habitat in question. These organizations can also help pressure government organizations and commercial and industrial operations to reduce their impact on the environment and help protect it.

OAR deals with following five aspects in regards to cleaning up the Assabet River: water in regards to water quality and flows; habitat; recreation; cultural and historic resources; and stewardship and education. OAR is working towards the Assabet River and its tributaries achieving "Class B water quality standards throughout the watershed," having "most of the river… returned to its free-flowing state, flow approximate natural cycles, and any manmade impoundments… free of sediments."[20] In regards to OAR educating the public, the organization wishes help residents realize that their actions affect the Assabet River, especially in regards to using too much phosphorus containing substances like fertilizers and cleaning solutions, creating situations that exacerbate the issues with nonpoint sources, and ground water usage.[21]

4.2 Government Organizations

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[20] http://www.assabetriver.org/vision.html

[21] http://www.assabetriver.org/vision.html

The main governmental organizations that would be involved in monitoring and implementing regulations to help clean up the Assabet River would be the Mass DEP and the New England Environmental Protection Agency (New England EPA). The Mass DEP is the state agency responsible for preservation of wetlands and ensuring clean water. Laws and regulations concerning anything that impacts the environment, along with monitoring water bodies and wastewater treatment plants are also responsibilities of the Mass DEP.[22] In the state of Massachusetts, the National Pollutant Discharge Elimination System permits (NPDES) are distributed by the New England EPA. The NPDES was created in 1972 under the Clean Water Act. "'NPDES prohibits [discharges] of pollutants from any given point source into the nation's waters except as allowed under an NPDES permit.' The program gives the EPA the authority to regulate discharges into the nation's waters by setting limits on the effluent that can be introduced into a body of water from an operating and permitted facility."[23]

5.0 Massachusetts Department of Environmental Protection and the Assabet River

Once a water source is deemed impaired, the Mass DEP is required by the Federal Clean Water Act to develop a plan for revitalization. The plan must bring the water body into compliance with the current Massachusetts Water Quality Standards. During the development of this plan, a pollution budget is created in regards to the level of toxicity. The total maximum daily load (TMDL) or the pollution budget is created for all sources of pollution, both point and nonpoint sources. There are four major wastewater treatment plants (WWTP) and three minor WWTP that release their effluent into the Assabet River. The four major WWTPs, also known

[22] http://www.mass.gov/dep/about/missionp.htm

[23] http://www.epa.gov/region1/npdes/history.html

as public owned treatment plants or POTW, are the Westborough WWTP, Hudson WWTP, Marlborough WWTP, and Maynard WWTP. The Concord WWTP is located on the Concord River in Concord, MA. The quality of the Concord River is affect by the quality of the Assabet River because as mentioned above, the Assabet River feeds the Concord River.

Due to the recorded levels of total phosphorus, the Mass DEP has labeled the Assabet River as an impaired body of water. The quality of water in the Assabet River falls under the category of Class B with qualifiers of warm water in accordance to the Massachusetts Surface Water Quality Standards (314 CMR 4.00). A classification of Class B means that the water body is "designated as a habitat for fish, other aquatic life, and wildlife… and for primary and secondary contact recreation. Where designated in 314 CMR 4.06, they shall be suitable as a source of public water supply with appropriate treatment… Class B waters shall be suitable for irrigation and other agricultural uses and for compatible industrial cooling and process uses. These waters shall have consistently good aesthetic value."[24]

In 1998, it was determined that the Assabet River was suffering from low dissolved oxygen and was nutrient enriched. As a result, thirteen field investigations were conducted from July 1999 to October 2000 with the goal of preventing future damage to the water quality and to rehabilitate the river. All sources of pollutants were located and the four main nutrients, - total phosphorus, ortho-phosphorus, total nitrogen, and nitrate- were quantified as percentage of nutrient loading from point sources as can be seen in Table 1.[25]

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[24] "314 CMR 4.00: Massachusetts Surface Water Quality Standards", Mass DEP, January 2007

[25] http://www.assabetriver.org/wq/tmdl.html

Table 1: Percentage of Nutrient Loading From Point Sources[26]

	Percentage of Nutrient Loading From Point Sources*			
	Total Phosphorus	Ortho- Phosphorus	Total Nitrogen	Nitrate
Dry Weather Surveys	82-97%	97-98%	70-97%	78-99%
Wet Weather Surveys	23-91%	88-98%	32-88%	41-99%
*(Point sources, the four major WWTPs: Westborough, Marlborough, Hudson, and Maynard.)Adapted from ENSR 2001)				

Seven segments of the Assabet River were listed in the "2002 Massachusetts Integrated List of Waters" were listed as Category 5, which are the parts of water bodies that require a TMDL or pollution budget. There were multiple causes of impairment for the different segments that are listed in Appendix B, but the primary two causes were nutrients and organic enrichment/low dissolved oxygen. These two causes can be addressed via control of phosphorus entering the river water. As a result of the 2002 list, a TMDL for nutrients, mainly for total phosphorus, was formed. The TMDL can be summed up in the following equation which takes into account the phosphorus that is provided to the plants from the sediment:

Equation 1: Total Maximum Daily Load

TMDL = BG + WLAs + Sediment + NPS + MOS

The abbreviations above are the following: TMDL = loading capacity of receiving water; BG = natural background; WLAs = portion allotted to point sources; Sediment = portion allotted to sediment; NPS = non-point source loadings other than sediment; and MOS = margin of safety.[27]

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[26] http://www.assabetriver.org/wq/tmdl.html

[27] "Assabet River Total Maximum Daily Load for Total Phosphorus," Massachusetts Department of Environmental Protection, Division of Watershed Management, 2002, CN: 201.0, Report Number: MA82B-01-2004-01

As a result of the TMDL report for the Assabet River in 2002, the Mass DEP instituted the following two phase management plan to address the phosphorus levels in the river:

> "Phase 1 will establish POTW effluent total phosphorus limits of 0.1 mg/l at all major POTWs discharging to the Assabet River and allow the communities sufficient time to fund and implement a detailed evaluation of impoundment sediment as a potential alternative to lower permit limits. DEP believes that some sediment and/or dam removal options will allow the Assabet River to achieve water quality standards faster and, possibly, be more cost effective, than establishing lower POTW total phosphorus limits and waiting for the system to respond over time.
>
> Requirements will be incorporated into the NPDES permits to be developed and issued in 2004. Phase 1 will require that all POTWs be upgraded to achieve 0.1 mg/l of effluent phosphorus by April 2009 and the design should be consistent with adding new technology in the future to achieve further reductions if deemed necessary. Based upon the modeling results current permitted flows will be allowed. However, any request to increase a discharge beyond currently permitted volumes would require supporting documentation satisfying DEP’s Antidegradation Policy that no other feasible alternative exists including, but not limited to, the discharge of additional treated effluent to groundwater to help restore tributary flows. Phosphorus limits will be seasonal. DEP and EPA will jointly develop an implementation strategy in the Spring of 2008 to decide if, when, and to what level additional upgrades will be needed based upon the results and recommendations of the sediment evaluation.

Phase 2 limitations will be established in permits to be reissued in 2009 if sediment remediation, based upon the results of the sediment/dam evaluation, is not pursued, and/or new phosphorus criteria that may be developed in the interim by DEP and USEPA are applicable. If the communities choose to pursue sediment remediation alternatives, a revised schedule and work plan will be negotiated in the summer and fall of 2008. If the communities choose not to pursue sediment remediation alternatives they will be required to complete phase 2 improvements during the second 5-year permit cycle and begin operating by April 2013 and achieve the new limits by April 2014.

In the interim, prior to facility upgrades in 2009, the POTWs will be required to continue optimization of seasonal removal of total phosphorus in their effluents to meet the 2000 interim NPDES permit limits for total phosphorus of 0.75 mg/l.

Long-term monitoring of the Assabet River is essential to determine the efficacy of the adaptive management controls as they are implemented, to determine whether water quality standards have been achieved, or if additional source controls will be required. EPA and DEP will develop a detailed monitoring plan prior to implementation of Phase 1 upgrades. The agencies or their agents will implement the plan with assistance from the Assabet communities to evaluate and document water quality improvements and environmental indicators after POTW upgrades are completed during Phase 1.

This TMDL can be achieved through the continued cooperation, effort, and oversight of federal, state and municipal agencies along with the watershed stakeholders."[28]

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[28] http://www.assabetriver.org/wq/tmdl.html

Due to the new regulations put out by the Massachusetts DEP, all four major WWTPs on the Assabet River have studied and selected new phosphorus removal technology in order to conform to the new limit of 0.1 mg/L for the phosphorus in the effluent. While one can look at figures and calculations from other plants, it does not replace an actual bench scale test on the plant's own water to determine which method of removal is best for its distinctive wastewater. In the process of selecting of a phosphorus removal method, it is best to look at the economic feasibility, performance for not just phosphorus removal, and the footprint.

6.0 Phosphorus Removal Technology

Beginning in 1970's, the need to remove phosphorus from wastewater effluent became evident and was acknowledged as a necessary part of treatment. Originally phosphorus was removed unintentionally via chemical and biological methods that were used to target and remove organic material to lower the biochemical oxygen demand. However modern and intentional methods of removing phosphorus have been created through expanding our knowledge of phosphorus and an evolution of process technologies. While learning about how to remove phosphorus, humans have also come to discover how we are impacting the fragile balance of nutrients in nature. The eutrophication process and its impact on nature started to be investigated during the late 1940s. This research led to increasing the efficient phosphorus removal methods. During the 1960s, chemical precipitation was introduced to the treatment processes in Switzerland; this method involved adding chemicals to the influent before the primary clarifiers in traditional biological treatment plants. Similar methods of adding chemicals before the primary clarifiers or into the mixed liquor in the activated sludge tanks were used around the same time in Scandinavian countries.[29]

Phosphorus can be present in wastewater in many forms. Therefore it is necessary to have multiple methods of removing phosphorus including chemical precipitation, biological assimilation, and physical filtration. Chemical precipitation is where chemicals are added to the water which forms particles with the target elements. These particles then are allowed to settle out allowing the clean water and the particles containing the contaminants to separate. The settled particles, also known as waste or sludge, are combined with the rest of the sludge from the plant and is dewatered and disposed of. Chemical precipitation is useful for removing the metals, suspended solids, fats, oils, greases, phosphorus, fluoride, ferrocyanide, some organics and inorganics.[30] This method of removal can result in an increase of the volume of sludge produced which leads to an increase in disposal costs and sometimes the sludge has poor dewatering and settling characteristics. The pH of the effluent from the chemical removal process can be low which will necessitate the need for pH adjustment before the water can be released into the environment.[31]

Biological phosphorus removal involves "exposing the mixed liquor to an anaerobic/aerobic sequence in the biological reactor" to help select microorganisms that have the ability to "accumulate higher levels of intracellular phosphorus than other microorganisms." The phosphorus is consumed by the microorganisms and the biomass removed from the clean water

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[29] http://www.lwr.kth.se/forskningsprojekt/Polishproject/JPS3s121.pdf

[30] http://www.cleanh2o.com/ww/chemppt.html

[31] http://dnr.wi.gov/org/water/wm/ww/biophos/1intro.htm

by settling. The settled biomass can either be wasted or reused to help keep the microorganism population high. The positive side effects of using this method of removal is that the decreased amount of sludge produced, reduced oxygen requirements, less pH issues, and the sludge has good dewatering and settling characteristics.[32] Physical filtration makes use of various filters, including membranes and sand, to separate contaminants such as phosphorus from water. A positive aspect of this filtration method is it results in exceptional clean water that may be free of a majority of contaminants not just the target one.

7.0 Concord Wastewater Treatment Plant

The wastewater treatment plant for the town of Concord, Massachusetts is located off of Bedford Street in Concord. This WWTP handles an average daily flow 1.2 MGD and its outfall is located on the Concord River. Appendix C shows the flow diagram for the Concord Wastewater Treatment Plant. There are two force mains that bring the influent to the plant. The headworks consist of one fine screen followed by grit removal equipment. The water continues from the headworks to the two primary clarifiers and the effluent from these tanks gets transported via gravity through the two trickling filters. These filters make use of plastic medium on which the microorganisms grow on. The effluent from the trickling filters is pumped into the two secondary clarifiers. A portion of the effluent from these tanks is recycled back to the trickling filters and the rest is pumped to the CoMag™ for the removal of phosphorus and other contaminants. The polisher runs at the minimum level everyday in order to remove any magnetite and increase the quality of the effluent. Before the water is released through the outfalls into the Concord River, it is disinfected through ultraviolet light and any leftover

[32] http://dnr.wi.gov/org/water/wm/ww/biophos/1intro.htm

magnetite settles to the bottom of the UV tank where it is picked up with a magnet. The pH of the water is adjusted before entering the CoMag™ and before the outfalls if need be. The sludge from the secondary clarifiers and the tertiary treatment is combined and thicken before it is added to the sludge from the primary tanks. The sludge is trucked to the Upper Blackstone Wastewater Treatment Facility where the waste is incinerated.

8.0 Test Results

This section will describe BluePro™, CoMag™, and Actiflo® and analyze how each technology performed in a variety of performance and economic evaluations. In order to determine which technology is the best to use, one should look at the overview of the system to determine how much maintenance will be needed. Performance results show which chemical and dosage should be used, along with impact of the technology on the various metal concentrations, biochemical oxygen demand ($BOD_{5)}$, and total suspended solids (TSS) levels. Analysis of the economics of the technology allows one to determine which technology is economically viable for the community. All the results in the performance and economic evaluations are from the pilot study performed at the Westborough Wastewater Treatment Facility by Earth Tech along with Fay, Spofford & Thorndike, LLC. This study was presented on January 29, 2008 at the NEWEA 2008 Annual Conference.

8.1 Overview of BluePro™

BluePro™ is a continuous flow filtration system that makes use of a chemical addition to remove phosphorus to low levels. Ferric chloride is added to the influent then mixed into the influent in the Rapid Conditioning Zone™ before entering the reactive filtration system. The addition of ferric chloride renews the hydrous ferric oxide coating to the surface of the sand media. This coating allows the phosphorus to be absorbed from the water, allowing the effluent to have total phosphorus levels of lower than 0.010 mg/L. This system is continuous since there is no need to stop operations for backwashing or changing of the media. This is achieved through the use of the “continuous regeneration of reactive filter media within a moving bed filter.” [33]

Depending on the quality of the influent, BluePro™ can be run as a single pass system or a two pass system with a possible reject recycle. Using these different configurations, full scale systems have been able to reach lower than 0.010 mg/L phosphorus. The reject recycle is the process of returning process residuals to a previous point in the wastewater treatment plant. Recycling these process residuals leads to additional phosphorus removal during the secondary system since the “BluePro™ reject particulates contain significant adsorptive capacity” and the already absorbed phosphorus is not released from the reject during digestion and other processes. The waste from the BluePro™ system does not require alteration of the sludge handling system and the iron in the waste does help control odor. Figure 3 shows the flow of water throughout the BluePro™ system and Table 2 contains the flow rates with the corresponding footprints for different BluePro™ models.

Table 2: BluePro™ Sizing Chart[34]

BluePro™ Models	Flow Rate	Footprint
Skid Systems	5 – 100 gpm	8’x10’ and up
CF – 50 Fiberglass	0.25 MGD	7’x7’
CF – 50 Concrete	0.25 MGD	7’x7’

[33] www.blueh2o.net/Blue_PRO.ashx

[34] http://www.blueh2o.net/products/bluepro.html

Quad Concrete	1 MGD	15’x15’

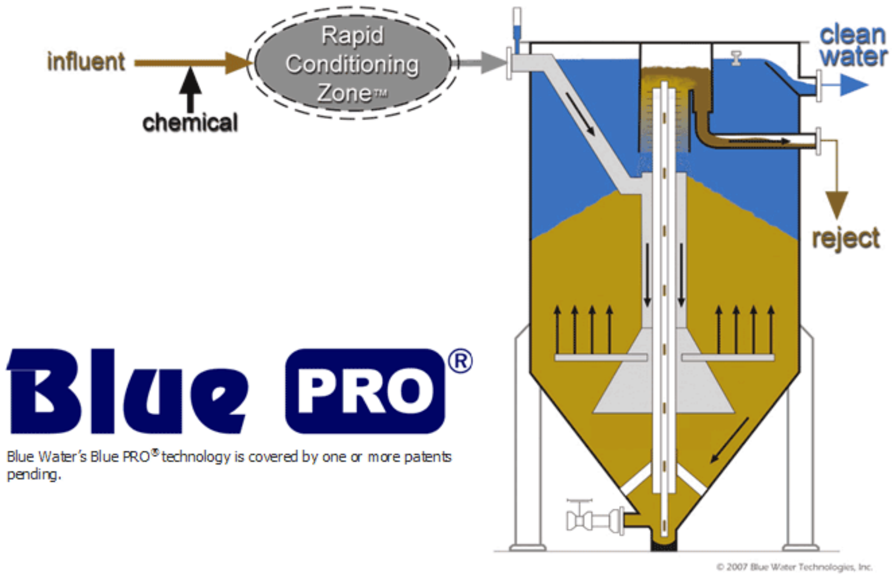

Figure 3: BluePro™ Diagram[35]

8.2 Overview of CoMag™

CoMag™ is a process based on “removing solutes from a fluid stream using magnetically conditioned coagulation.”[36] This technology uses magnetite, which is a fine iron powder, to help decrease the concentration of phosphorus and other containments from the water via chemical coagulation and flocculation.[37] Treatment plants can use a variety of coagulants with the CoMag™ technology, such as ferric chloride, aluminum sulfate, polyaluminum chloride, and ferric sulfate. Magnetite ballast is the chemical additive that allows the system work. The CoMag™ flocs settle faster than regular flocs that were chemical coagulated in the clarifying

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[35] www.blueh2o.net/Blue_PRO.ashx

[36] http://www.cambridgewatertech.com/content/about.html

[37] http://www.assumption.edu/users/hauri/Research/Pharms/Concord/setac2005e.pdf

system, which allows low hydraulic retention times. This low hydraulic retention time gives CoMag™ the advantage of smaller clarifiers and thus a smaller footprint. A small footprint is a plus for treatment plants that have limited land that is available for use. CoMag™ has a fast start up time of about 10 minutes, which allows the treatment plant to recover quickly from plant upsets and cold startups. Magnetic filtration is a useful step to maximize the total amount of phosphorus that is removed. This step is called the polishing step in the following test results.[38] Figure 4 shows the flow diagram for a CoMag™ unit.

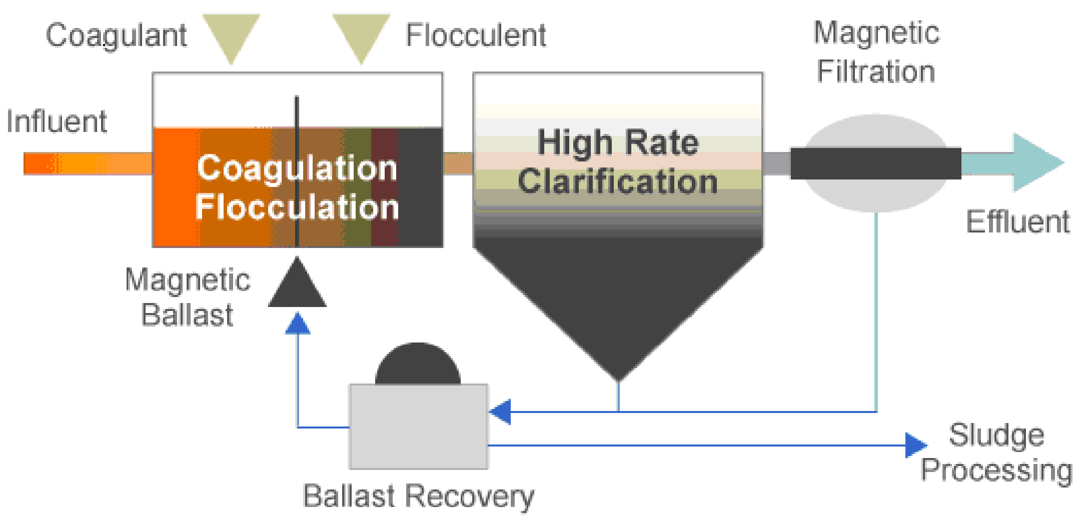

Figure 4: CoMag™ Diagram[39]

8.3 Overview of Actiflo®

Actiflo® is a traditional water clarification system that can be used in both wastewater and drinking water applications. This system makes use of a chemical coagulation process that uses microsand ballast (Actisand™) as a coagulant which produces flocs that settle rapidly due to the weight of the microsand. Due to the rapid clarifying time, the hydraulic retention time is

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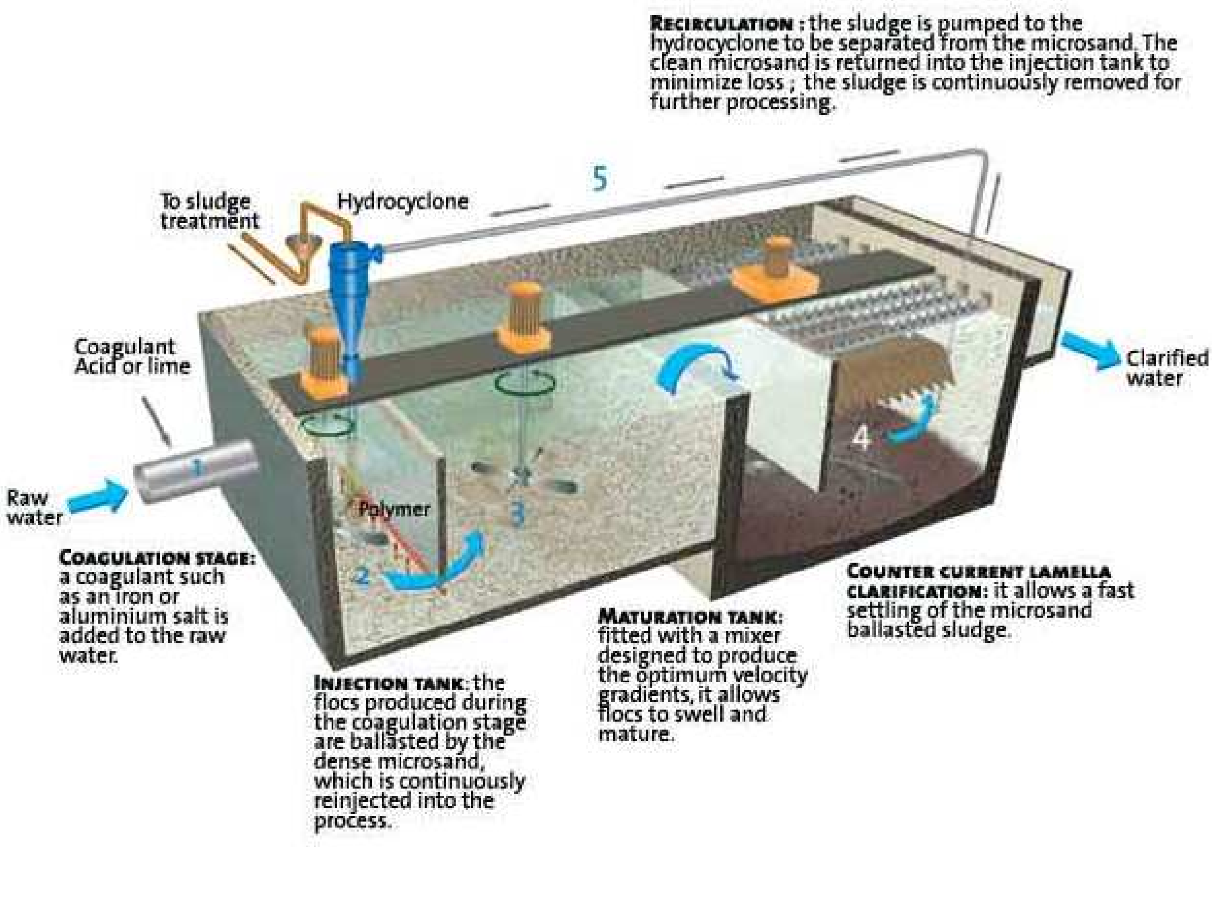
[38] http://www.cambridgewatertech.com/content/technologies.html

[39] http://www.cambridgewatertech.com/content/technologies.html

low and the clarifiers can be small which reduces the footprint to up to 20 times smaller than traditional clarification systems. The startup time for this technology is less than ten minutes, which allows treatment plants to recover quickly from any plant upsets.[40] Figure 5 shows a descriptive flow diagram of the Actiflo®. It is important to note that microsand ballast is removed from the sludge via the hydrocyclone, where the sludge is removed and added to the rest of the sludge that is produced throughout the entire treatment process of the plant. In the hydrocyclone, the microsand is cleaned before being reintroduced into the system where it is added to injection tank to help create heavier flocs. Throughout this tertiary process, only a chemical coagulant and the microsand ballast are added to the influent.



[40] http://www.veoliawaterst.com/processes/lib//pdfs/productbrochures/EA8B54VXw77k6B0CD1fv4od1.pdf

Figure 5: Actiflo® Diagram[41]

8.4 Performance Evaluations

The performance evaluations, chemical analysis tests, include the total phosphorus levels in comparison to dose level of ferric chloride, aluminum sulfate, and poly-aluminum chloride. The previously mentioned evaluations are important to determine the best chemical and dosage to use in order to achieve a final concentration for phosphorus of 0.01 mg/L. The impact of each phosphorus technology on the effluent can be determined by analyzing the difference between metal concentrations, BOD_5, and TSS levels in influent and effluent of each technology. It is important during the chemical analysis tests to determine which processes' final product will meet the effluent limitations set by the National Pollutant Discharge Elimination System, also known as NPDES, permit.

It was noted in presentation on the pilot study on the Westborough WWTP that under different loading conditions all three technologies consistently met the 0.1 mg/L total phosphorus limit while using ferric chloride. It was also mentioned that with using polishing or the second pass through the systems, the effluent would reach 0.05 mg/L total phosphorus with ferric chloride for all three systems.

Table 3: Impact of Phosphorus Reduction on Biochemical Oxygen Demand and Total Suspended Solids

Characteristic	Pilot Influent	Blue Pro™	CoMag™	Actiflo®	NPDES
BOD_5 (mg/L)	12.0	4.1	6.6	5.2	10*
TSS (mg/L)	11.6	1.3	2.9	2.5	15*

** Average monthly- April 1 to October 31*

[41] http://www.veoliawaterst.com/actiflo/en/

Both BOD_5 and TSS are good indicators of water quality and in high enough quantities can have a negative impact on the receiving water where the effluent is dumped. The wastewater treatment plant is allowed by the NPDES to have an average of 10 mg/L for BOD_5 and 15 mg/L for TSS in the effluent during the months of April to October. Since these numbers are only an average, it allows the plant some leeway for bad days where the treatment processes are not as effective in decreasing the BOD_5 and TSS. Even though the plant is allowed to once in a while have high numbers, it is still important to always have a target number below the allowed average.

All three technologies reduced the influent's BOD_5 and TSS to a final effluent concentration lower than the NPDES numbers. As can be seen in Table 3, the influent had 12.0 mg/L BOD_5 and 11.6 mg/L TSS. Blue Pro™ was the most successful in removing the BOD_5 and TSS with having a result of 4.1 mg/L and 1.3 mg/L respectively. CoMag™ has the highest results with 6.6 mg/L and 2.9 mg/L respectively.

Table 4: Impact of Phosphorus Reduction on Biochemical Oxygen Demand and Total Suspended Solids Following Polishing

Characteristic	Blue Pro™ Pass 2	CoMag™ Polisher	Actiflo® Filter 1	Actiflo® Filter 2	NPDES
BOD_5 (mg/L)	4.2	3.6	7.5	5.2	10*
TSS (mg/L)	1.5	1.1	1.3	1.3	15*

** Average monthly- April 1 to October 31*

Since it may take extra passes or cleaning to remove enough phosphorus or hit new allowable limits, it is important to measure the different characteristics of the water after the extra phosphorus removal process. Both the BOD_5 and TSS does not vary that much for Blue Pro™ with only an increase of 0.1 mg/L BOD_5 and 0.2 mg/L TSS as can be seen in Table 4.

CoMag™ had the most variation between the first cleaning and the polishing process with coming in at a difference of 3.0 mg/L BOD_5 and 1.8 mg/L TSS.

Table 5: Impact of Phosphorus Reduction on Metal Concentration

Characteristic (mg/L)	Pilot Influent	Blue Pro™	CoMag™	Actiflo®	NPDES
Iron	0.950	0.346	0.365	0.601	Report
Aluminum	0.005	---	0.052	0.057	Report
Copper	0.012	<0.009	<0.009	<0.009	0.009
Zinc	0.080	0.081	0.112	0.081	Report
Lead	<0.040	<0.040	<0.040	<0.040	Report

Out of the five trace metals that were tested for in the effluent, only copper has a maximum allowable limit of 0.009 mg/L under the NPDES permit. All technologies reduced the initial concentration of 0.012 mg/L to below 0.009 mg/L as can be seen in Table 5. The wastewater treatment plant is only required to report the levels of the other five trace metals that were tested for, which were aluminum, iron, zinc, and lead. The final concentration levels of zinc increased significantly only for CoMag™ in comparison to the influent concentrations due to the treatment of the water during the cleaning process; the zinc concentration increased from 0.080 mg/L to 0.112 mg/L. There was no reportable difference in the lead concentration for each technology.

As BluePro™ does not use aluminum during its process; it was the only technology that did not contribute to an increase in the aluminum concentration. While the initial concentration of aluminum was 0.005 mg/L, CoMag™ resulted in a final concentration of 0.052 mg/L and Actiflo® increased the final concentration by 0.052 mg/L. All three technologies, BluePro™, CoMag™, Actiflo®, decreased the iron concentration by 0.604 mg/L, 0.585 mg/L, and 0.349 mg/L respectively. Out of all the three processes, Actiflo® had the lowest decrease in iron concentration and increase in aluminum.

Table 6: Impact of Phosphorus Reduction on Metal Concentration Following Polishing

Characteristic (mg/L)	Blue Pro™ Pass 2	CoMag™ Polisher	Actiflo® Filter 1	Actiflo® Filter 2	NPDES
Iron	0.766	0.370	0.214	0.238	Report
Aluminum	0.085	0.036	0.027	0.014	Report
Copper	<0.009	<0.009	<0.009	<0.009	0.009
Zinc	0.083	0.222	0.110	0.097	Report
Lead	<0.040	<0.040	<0.040	<0.040	Report

During the secondary cleaning process, zinc levels increased by 0.110 mg/L for CoMag™**,** by an average of 0.023 mg/L between the two filters for Actiflo®, and only by 0.002 mg/L for BluePro™ as can be seen in Table 6. Both lead and copper stayed around the original final concentrations from Table 5 of lower than 0.009 mg/L and 0.040 mg/L respectively. Both aluminum and iron levels increased during the second cleaning for BluePro™ by 0.080 mg/L and 0.420 mg/L respectively. On the other hand, CoMag™ and Actiflo® saw a decrease or no decrease in their final concentrations in Table 6 compared to the concentrations in Table 5 for aluminum and iron. The use of CoMag™'s polishing process increased the concentration of iron by 0.005 mg/L and decreased aluminum concentration by 0.016 mg/L. Actiflo®'s two filters removed an average of 0.037 mg/L aluminum and an average of 0.375 mg/L iron.

8.5 Economic Evaluations

Evaluating the costs associated with each technology is an important part of the decision making process. Economic analysis complements performance analysis by allowing one to determine which process can achieve the intended results while still having low costs. The life cycle cost, the overall cost of a technology for usually twenty years, can be broken into two categories, capital cost and operation and maintenance costs. It is important to remember that some of the following costs are based on Westborough Wastewater Treatment Plant flows and data.

Table 7: Capital Costs for Two Trains

Technology	Capital Costs
Blue Pro™	$1.622 M
CoMag™	$2.275 M
Actiflo®	$1.871 M

Capital costs are a onetime cost at the beginning of the usage of the technology. This category is the cost of a full design which includes acquiring the equipment and installation and design fees. The information in Table 7 shows that in the beginning, costs of Blue Pro™ is lowest, while CoMag™ has the highest upfront cost.

Table 8: Chemical Use Analysis for Westborough Treatment Plant

Chemical		Blue Pro™	CoMag™	Actiflo®
Ferric Chloride	Dosage (mg/L)	40	30	30
	Daily Usage (gal)	653	490	490
Sodium Hydroxide	Dosage (mg/L)	35	25	25
	Daily Usage (gal)	373	267	267
Polymer	Dosage (mg/L)	---	3.0	0.3
	Daily Usage (gal)	---	200	20
Aluminum Sulfate	Dosage (mg/L)	---	50	80
	Daily Usage (gal)	---	622	995

Table 8 shows the best concentrations for the different chemicals used or can be used in each process. Each technology uses sodium hydroxide for pH control, which is necessary since both ferric chloride and aluminum sulfate lower the pH of the water. Blue Pro™ used the highest concentration of sodium hydroxide with 35 mg/L, while both CoMag™ and Actiflo® used 25 mg/L. Blue Pro™ only uses ferric chloride for coating the sand particles used to remove phosphorus. For treatment at the Westborough Treatment Plant, Blue Pro™ uses only 40 mg/L. CoMag™ and Actiflo® are more flexible since they both can use ferric chloride or aluminum sulfate. While both used a concentration of 30 mg/L ferric chloride, CoMag™ used less aluminum sulfate with a concentration of 50 mg/L and Actiflo® needed 80 mg/L. Both CoMag™ and Actiflo® used 3.0 mg/L polymer to treat the influent at the Westborough Treatment Plant.

Table 9: Operation and Maintenance Costs per Year

Description	Blue Pro™	CoMag™	Actiflo®
Ferric Chloride	$179,000	$134,000	$134,000
Sodium Hydroxide	$409,000	$292,000	$292,000
Polymer	---	$73,000	$7,000
Consumables	$3,000	$20,000	$1,000
Electrical	$19,000	$24,000	$30,000
Labor	$3,000	$14,000	$1,000
Total O&M Cost	$613,000	$557,000	$465,000

Operation and maintenance costs for tertiary treatment processes can be separated into the different chemicals needed, consumables, electricity costs, and labor costs. BluePro™ has the highest operation and maintenance costs between the three different technologies, while Actiflo® incurs the lowest cost with $465,000 per year according to Table 9. It is important to notice possible ways that the yearly costs may be change, such as increasing costs for electricity and changes in costs for different chemicals. While this data is based on each technology using ferric chloride, it is important to remember that CoMag™ and Actiflo® can also use aluminum sulfate which may reduce or increase the yearly costs. BluePro™ is limited to using ferric chloride and chemical costs are $45,000 higher than the other technologies for ferric chloride and $117,000 more for electricity.

Table 10: Life Cycle Costs

Description (in Millions of Dollars)	Blue Pro™	CoMag™	Actiflo®
Capital Cost	$1.622	$2.575	$1.871
Life Cycle O&M Cost	$9.808	$8.912	$7.440
Total Life Cycle Cost	$11.430	$11.487	$9.311

The initial or startup cost, also known as capital cost, along with 20 years (the typical years of usage of a technology is 20 years) of operation and maintenance costs is considered the life cycle cost. In Table 10, the life cycle cost along with the breakdown for the life cycle for each process is listed. Actiflo® has the overall lowest cost with $9.311 million. BluePro™ and CoMag™ cost about the same with the latter costing $57,000 more.

9.0 Design Phase

For the design portion of the project, a hypothetical wastewater treatment plant was designed. Although there is typically a peak and average flow, the overall assumed flow would be 3 MGD. For different units of the treatment process, a peak flow factor of three was used in accordance to the TR-16 guide that is put out in 1998 by the New England Interstate Water Pollution Control Commission. This plant would make use of three parallel trains, which is beneficial because two trains could still treat the wastewater in the case one train had to be shut down. The plant would be designed in a way that the three parallel trains that would hold 1 MGD each if all three were in use and 1.5 MGD if one train was taken out of commission. Appendix D shows the flow diagram for this hypothetical plant. Table 11 shows the final dimensions of each unit. The footprint of the three phosphorus removal technologies are calculated in order to help determine the amount of land each one would need if used. However, in an actual plant, only one type of phosphorus removal unit would be used.

Table 11: Final Dimensions of the Wastewater Treatment Plant with a Flow of 3 MGD

Unit	Dimensions
Mechanical Bar Screen	2ftx1ft w/ 1/8" bar @1" on center
Manual Bar Screen	3ftx1ft w/ 1/8" bar @1.5" on center
Aerated Grit Chamber	38' L x 9.5' W x 7' D
Parshall Flume	18" throat
Primary Clarifier	46 ft Diameter 12 ft Sidewall Depth
Aeration Tank	100' L x 25' W x 14' D
Secondary Clarifier	36 ft Diameter 12 ft Sidewall Depth
Phosphorus Removal	
BluePro™	900 sf
Actiflo®	200 sf
CoMag™	710 sf
Ultraviolent Disinfection	See section 9.8

9.1 Bar Screens

Based on the guidelines set by the TR-16, the velocity of the water between the bar screen should be between two and four ft/s for the mechanical cleared bar screen and between one to two ft/s for the manually cleared bar screen. The mechanical bar screen will have 1/8" bars that are 1" on scale. The manual bar screen, which is used as a backup for the mechanical, will be made up of 1/8" bars that are 1.5" on the center. The inflow velocity will be 4.65 ft/s and the dimensions of the mechanical bar screen will be 2ft by 1ft which will produce a 3.1 ft/s velocity if the screen is only 75% clear. The dimensions of the manual bar screen will be 3ft by 1 ft producing a 1.94 ft/s if the screen is only 80% cleared.

9.2 Aerated Grit Chamber

The minimum hydraulic detention time is three minutes at peak/hourly and since the peaking factor is 3, the minimum hydraulic detention time for average flow is 9 minutes.[42] The

[42] "TR-16 Guides for the Design of Wastewater Treatment Works," 1998 edition, New England Interstate Water Pollution Control Commission

depth should range from seven to sixteen feet and the length to width ratio should be 3:1 to 5:1 while the width to depth ratio should range from 1:1 to 5:1.[43] The final dimensions of the aerated grit chamber shall have a length of 38 feet, a width of 9.5 feet and a depth of 7 feet.

9.3 Parshall Flume

Since the peaking factor is three, the average flow will be 3 MGD or 4.5 ft^2/s and the peak flow will be 9 MGD or 13.95 ft^2/s. The final dimension of the Parshall flume will be 18" throat.[44]

9.4 Primary Clarifier

The activated sludge is wasted to primary tanks. A circular tank shall be used which dictates the diameter should not exceed 125 feet and the sidewater depth should range from eight feet to thirteen feet. Each tank will be sized for one third of the flow since the train setup of three tanks will be used. The average overflow rate should be limited from 600 to 800 gpd/sf and the peak hourly overflow rate should not exceed 1200 gpd/sf. The diameter for each primary clarifier shall be 46 feet and the sidewater depth will be 12 feet. This tank size will also work for a peak flow of 1,500,000 gpd per tank.

9.5 Conventional Aeration Tank

The hydraulic detention time for air should range from four to eight hours; six hours will be used for an average flow.[45] Each tank will be sized for one third of the flow since the train

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[43] "Theory and Practice of Water and Wastewater Treatment," Ronald Droste, pg.343

[44] http://www.wrightwater.com/wwe/Parshall%20Flume.pdf

setup of three tanks will be used. The depth of the tank will range from ten to twenty five feet according to TR-16. The length of each conventional aeration tank will be 100 feet, the width will be twenty five feet and the depth will be fourteen feet. This size tank has a hydraulic detention time of four hours for peak flow.

9.6 Secondary Clarifier

The activated sludge will be wasted to the primary tanks. No selectors will be used and each tank will only handle one third of the flow if all tanks are being used due to the train setup of three tanks. The overflow rate will be 1000 gpd/sf. The diameter of each secondary clarifier will be thirty six feet with a sidewater depth of twelve feet.

9.7 Phosphorus Removal Technology

The phosphorus removal units would be set up in two trains and a peak flow of 9 MGD would be used. Therefore, each train would have to handle 4.5 MGD and one train would be able to treat the average daily flow on its own. The loading rates from the Westborough Wastewater Treatment Facility pilot study test were used. The loading rate for BluePro™ was 3.5 gpm/sf, Actiflo® with 16.8 gpm/sf, and CoMag™ with 4.4 gpm/sf. The filters for BluePro™ require 50 sf per filter.

9.8 UV Disinfection

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[45] "Wastewater Treatment Plant Design," WPCF Manual of Practice No.8, ASCE Manual on Engineering Practice No.36, Water Pollution Control Federation, printed 1982

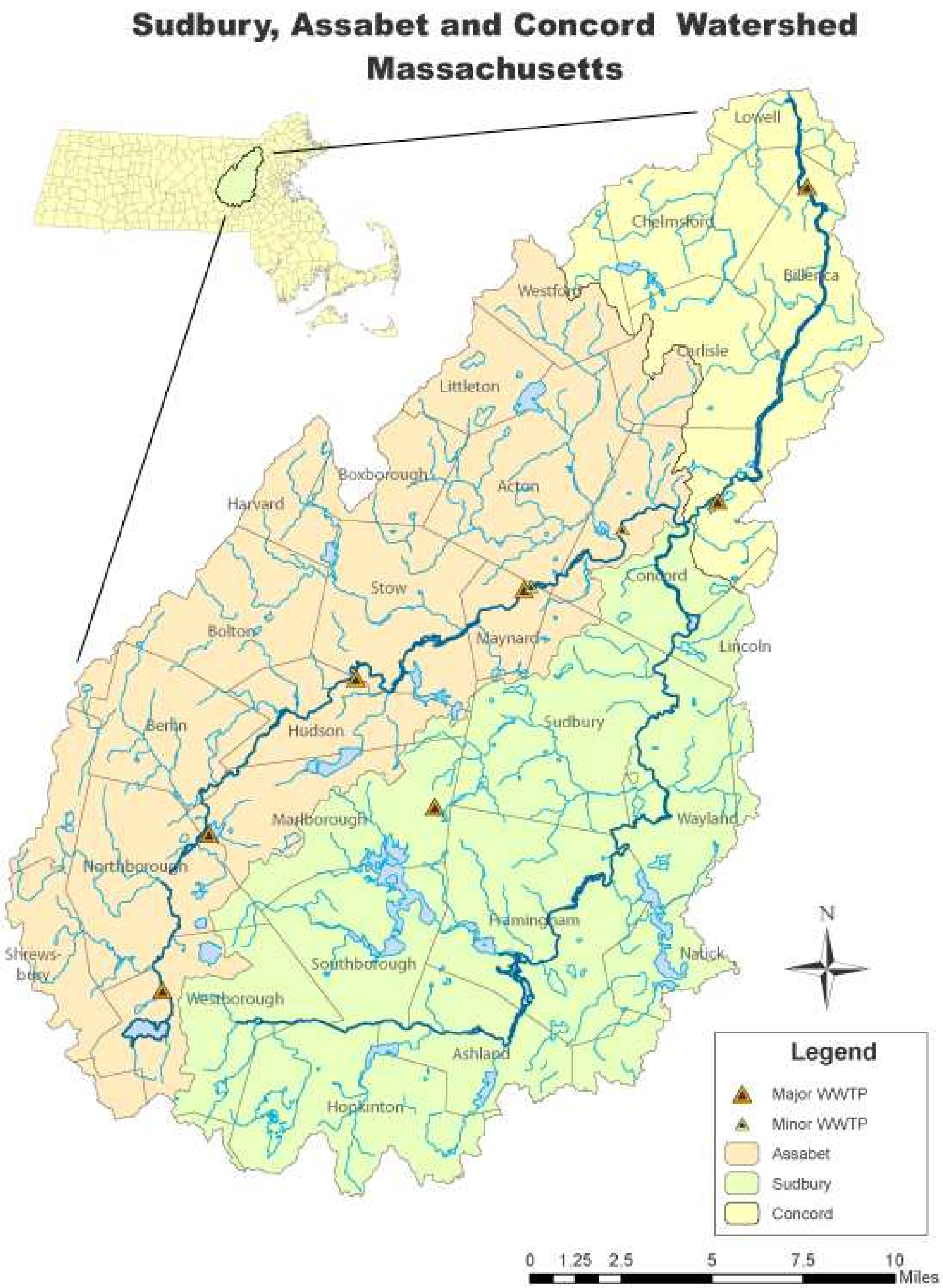
Trojan 300 plus, which is a mechanical-chemical wiping system, would be used for this hypothetical plant to disinfect the water before it reaches the outfall. Disinfection is a necessary step to prevent microorganisms, such as bacteria and viruses, from entering the ecosystem. To correctly size the ultraviolet system, or determine the number of lamps needed, one must consider the following factors: 50 to 100% redundancy depending on the client and state; end of lamp life factor which is typically 0.8 to 0.9; fouling factor which is 0.95 for this model; and a pilot test using the actual wastewater to determine the transitivity of the water, which is based on turbidity, suspended solids, and biochemical oxygen demand. A third party would need to validate after the UV system was installed that it was properly sized in order to properly disinfect the water.

10.0 Conclusion

Based on both the performance and economic evaluations, running two Actiflo® filters would be the most viable method of removing phosphorus. Not only does this method cost less overall than the other possible methods, it also allows flexibility in chemical additives, as seen in Table 8, that can be used, which can be helpful if one chemical becomes too expensive or the supply cannot keep up with the demand. By running two filters, the metal concentrations become quite low, as can be seen in Table 6, which is helpful for reducing the amount of pollution in the Assabet River. Since metal concentrations increase as one goes up the food chain, it is helpful for fish, humans, birds, and other wildlife for the metal concentrations in the effluent to be kept to a minimum. Although Actiflo® did not prove to be the best in decreasing the BOD_5 or TSS, it still made up for it by proving to be the most cost effective and space efficient method of not only meeting the limit of 0.1 mg/L Total Phosphorus but even 0.05 mg/L.

It was important that a phosphorus removal method not only met today's standards but also meet future limits in order to keep the WWTPs from having to upgrade their systems for the next possible limit. Since this paper is theoretical and pulls results from different sources, it would be recommended to perform a bench scale or pilot study for individual plants since each one has unique needs.

Appendix A: Sudbury, Assabet, and Concord Watersheds[46]



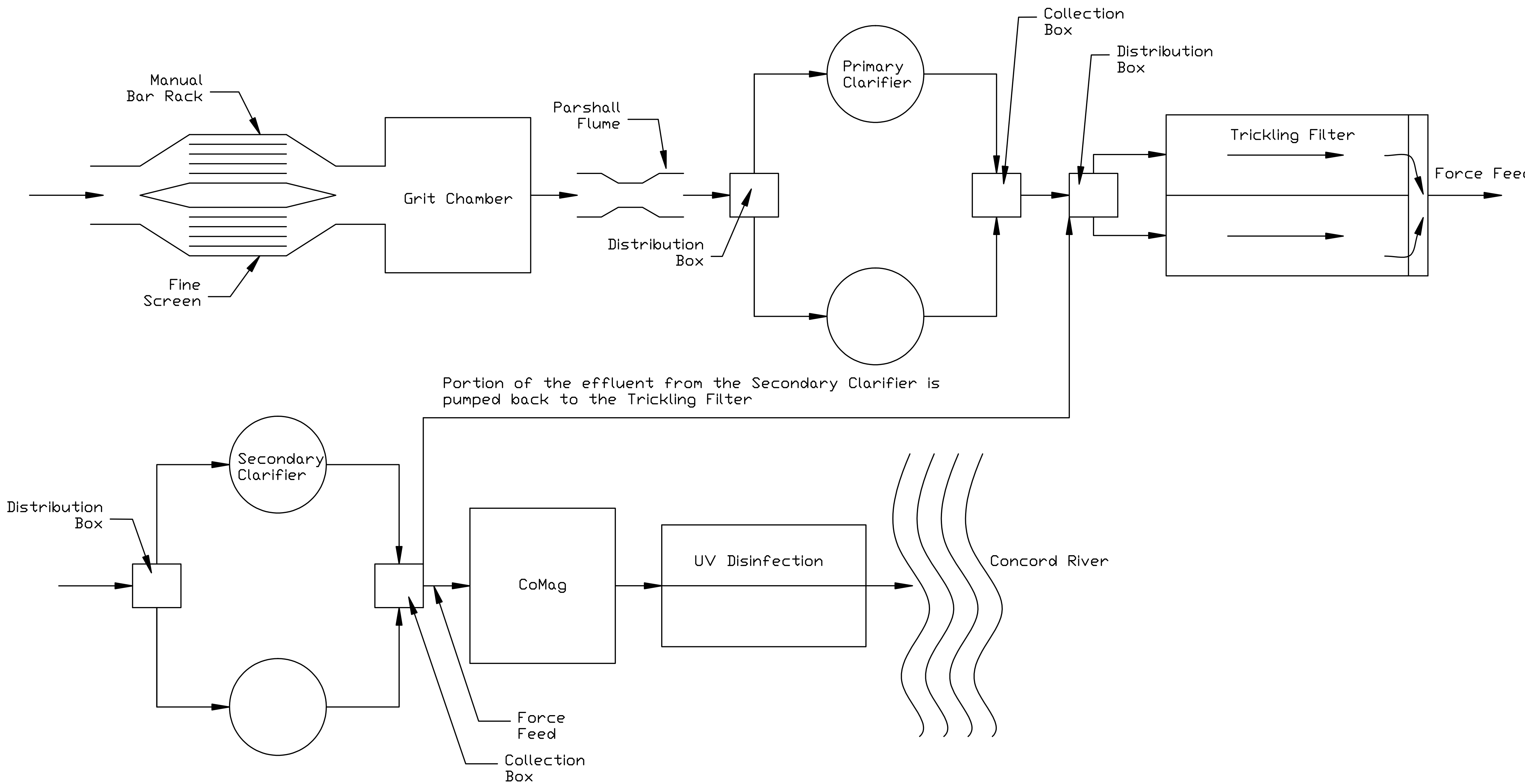
[46] http://www.assabetriver.org/map.html

Appendix B: 2002 Massachusetts Integrated Water Listing: Massachusetts Category 5 Waters From the Assabet River[47]

NAME	SEGMENT ID	DECSCRIPTION	SIZE	POLLUTANT NEEDING TMDL
Assabet River Reservoir (82004)	MA82004_2002	Westborough	333 acres	Metals; Noxious aquatic plants; Turbidity; (Exotic species)
Assabet River (8246775)	MA82B-01_2002	Outlet Flow Augmentation Pond to Westborough WWTP, Westborough. Miles 31.8-30.4	1.4 miles	Nutrients[1]; Organic enrichment/Low DO[1]; Pathogens
Assabet River (8246775)	MA82B-02_2002	Westborough WWTP, Westborough to Route 20 Dam, Northborough. Miles 30.4-26.7	3.7 miles	Metals; Nutrients[1]; Organic enrichment/Low DO[1]; Pathogens
Assabet River (8246775)	MA82B-03_2002	Route 20 Dam, Northborough to Marlborough West WWTP, Marlborough. Miles 26.7-24.3	2.4 miles	Nutrients[1]; Pathogens
Assabet River (8246775)	MA82B-04_2002	Marlborough West WWTP, Marlboro to Hudson WWTP, Hudson. Miles 24.3-16.4	7.9 miles	Cause Unknown; Metals; Nutrients[1]; Organic enrichment/Low DO[1]; Pathogens
Assabet River (8246775)	MA82B-05_2002	Hudson WWTP Hudson to Routes 27/62 at USGS Gage, Maynard. Miles 16.4-7.6	8.8 miles	Nutrients[1]; Organic enrichment/Low DO[1]; Pathogens
Assabet River (8246775)	MA82B-06_2002	Routes 27/62 at USGS Gage, Maynard to Powdermill Dam, Acton. Miles 7.6-6.4	1.2 miles	Priority organics; Metals; Nutrients[1]; Organic enrichment/Low DO[1]; Thermal modifications; Taste, odor and color; Suspended solids; Noxious aquatic plants[1]
Assabet River (8246775)	MA82B-07_2002	Powdermill Dam, Acton to confluence with Sudbury River, Concord. Miles 6.4-0.0	6.4 miles	Nutrients[1]; Organic enrichment/Low DO[1]; Pathogens

[1] being addressed in this TMDL via Total Phosphorus control

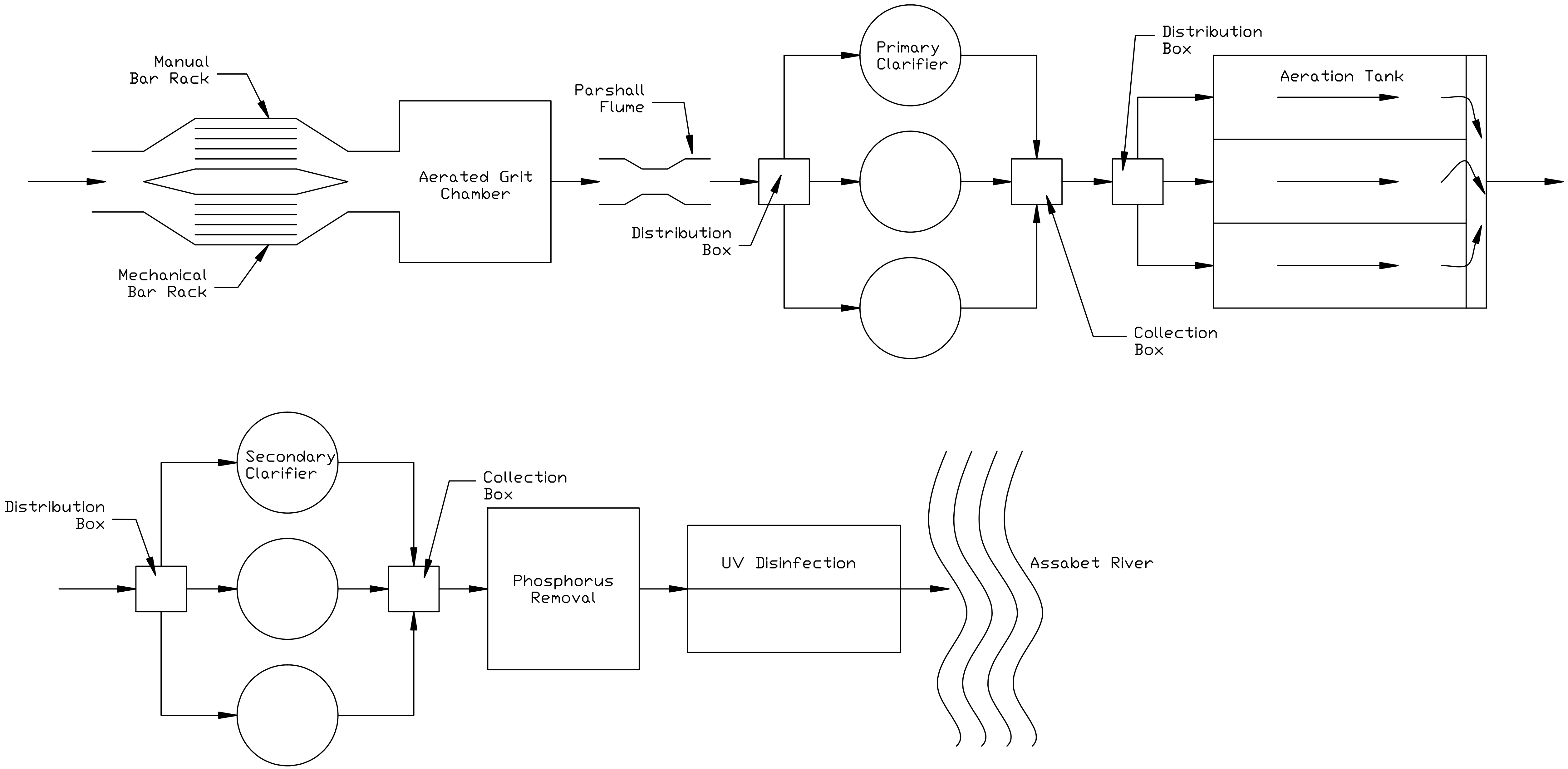
[47] "Assabet River Total Maximum Daily Load for Total Phosphorus," Massachusetts Department of Environmental Protection, Division of Watershed Management, 2002, CN: 201.0, Report Number: MA82B-01-2004-01



Flow Diagram for Concord Wastewater Treatment Plant

Appendix C

Assabet River and Phosphorus Removal Options



Wastewater Treatment Plan Flow Diagram

Appendix D

Assabet River and Phosphorus Removal Options