2018-2019

FINAL REPORT

UniverCity Year

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The Village of Monticello wastewater treatment facility: Evaluation of the environmental, economic and social impacts of compliance alternatives

CIVIL ENGINEERING 421: ENVIRONMENTAL SUSTAINABILITY ENGINEERING

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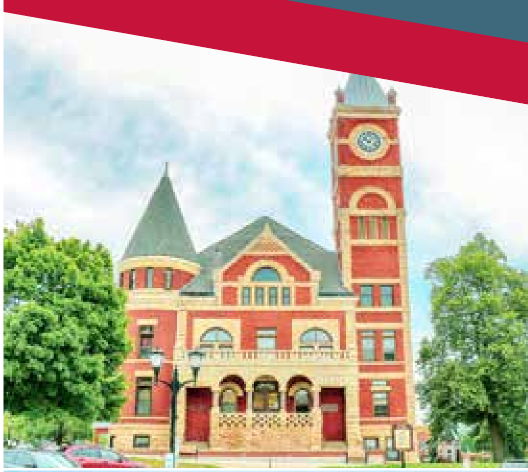

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LIST OF ABBREVIATIONS

A	Ampere
ABNR	Advanced Biological Nutrient Recovery
Al^{3+}	Aluminum ion
AP	Acidification Potential
ATP	Adenosine triphosphate
Ca^{2+}	Calcium ion
Ce_2O_3	Cerium oxide
CFC-11	Trichlorofluoromethane
CO_2	Carbon dioxide
CSEAO	County Sanitary Engineers Association of Ohio
CTUe	Comparative toxic unit for aquatic ecotoxicity
CTUh	Comparative toxic unit for human toxicity
d	day
DNR	Department of Natural Resources
EcoP	Ecotoxicity Potential
EP	Eutrophication Potential
EPA	Environmental Protection Agency
Fe^{2+}	Ferrous
Fe^{3+}	Ferric
FFP	Fossil Fuel Depletion Potential
gal	gallons
GEMMA	Group of Environmental Engineering and Microbiology
GWP	Global Warming Potential
HHAP	Respiratory effects
HTCP	Carcinogenics
HTNCP	Non carcinogenics
ISO	International Organization for Standardization
kg	kilogram
kW	kilowatt
kWh	kilowatt hour
L	liter

La_2O_3	Lanthanum oxide
lb	pound
LCA	Life Cycle Assessment
LCCA	Life Cycle Cost Analysis
m^3	Cubic meters
mg	milligram
MGD	Million gallons per day
ML	Megaliter
N	Nitrogen
NEWEA	New England Water Environment Association
NO_3^-	Nitrate
O_2	Oxygen
O_3	Ozone
ODP	Ozone Depletion Potential
P	Phosphorus
PAOs	Phosphorus Accumulating Organisms
PM2.5	Particulate matter with a diameter of less than 2.5 micrometers
PP	Priority Pollutant
RAS	Recycled Activated Sludge
SCP	Smog Potential
SDGs	Sustainable Development Goals
SO_2	Sulfur dioxide
TRACI	Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts
UN	United Nations
US	United States
V	Voltage
WAS	Waste Activated Sludge
WI	Wisconsin
WPDES	Wisconsin Pollutant Discharge Elimination System
WWOA	Wisconsin Wastewater Operators' Association
WWTF	Wastewater Treatment Facility
yr	year

EXECUTIVE SUMMARY

Wastewater treatment is the process of removing contaminants and creating an effluent that can be returned to the water cycle with minimal impacts. Municipal wastewater treatment includes streams from household sewage and sometimes industrial wastewater. Physical, chemical, and biological processes can be used to remove contaminants, including excessive nutrients, to produce an effluent that is safe enough to be released to the environment.

Excessive nutrients (e.g. phosphorus, nitrogen) in the water causes algae to grow faster than ecosystems can handle, which is called eutrophication. Significant increases in algae harm water quality, food resources, and ecosystems by decreasing the oxygen that fish and other aquatic life need to survive. Large growths of algae are called algal blooms; algal blooms can completely eliminate oxygen availability in the water, which leads to decreases in biodiversity and increases in water toxicity. Elevated toxin levels can be harmful to humans by direct contact or through indirect pathways, such as the consumption of tainted fish or contaminated water. Therefore, it is crucial to control nutrient levels, particularly limiting nutrients (e.g. phosphorus), to ensure the well-being of the environment and society.

The effectiveness of phosphorus removal can vary, depending on the available equipment and the treatment methods used. At the Monticello WWTF, phosphorus removal to the desired levels (1 mg/L) is accomplished by alum addition. However, currently employed techniques are not fulfilling the future phosphorus emission DNR limitations (0.075 mg/L). To meet the new phosphorus effluent standards, two alternatives are analyzed in this report. The first alternative is SorbX-100, which is a chemical treatment approach and uses a rare earth metal chloride solution for phosphorus removal in municipal and industrial wastewater streams. The other alternative is the CLEARAS ABNR System, which uses algae and other biological organisms to recover excess phosphorus, nitrogen and other high-profile contaminants in wastewater. SorbX-100 and CLEARAS ABNR systems have previously been tested in the Monticello WWTF as pilot systems to evaluate their performance with respect to phosphorus removal. The system boundaries are set to include input and output flows of material and energy resources for the operation of the systems over a 20-year period.

The goal of this study is to assess and make a recommendation on the most appropriate phosphorus removal strategy based on the three paradigm of sustainability (environmental, economic, and social impacts). This goal is achieved by quantitatively modeling and evaluating the environmental life cycle assessments, as well as social and economic assessments of the two

phosphorus removal strategies applied at the Monticello WWTF (SorbX-100 and CLEARAS ABNR). In this work, a comprehensive LCA, considering multiple impact categories, is performed using SimaPro 8.5.2 Software and TRACI 2.1 Impact Assessment Methodology. Regarding the environmental impacts, CLEARAS ABNR System is found to have less overall impact compared to SorbX-100 (<7%). With respect to economic assessment, SorbX-100 is found to have less total present cost compared to CLEARAS ABNR System (~23%). Considering social aspects, both options proposes relatively comparable results.

A weighting matrix is used to compare the two phosphorus removal options using the three paradigm of sustainability. The weights assigned to each paradigm were based on discussions with stakeholders of the Monticello WWTF. Environmental impacts are given a weight of one, economic impacts are given a weight of three, and social impacts are given a weight of one. Each of these weights were multiplied by the relative impact in comparison to the other option. Based on weighting matrix, the recommended option from this analysis is SorbX-100, which received a total sustainability score of 2.68 in comparison to CLEARAS ABNR which received 4.07. Even though the environmental impacts of CLEARAS ABNR were less significant than SorbX-100, the final recommendation is driven by the differences in economic impacts, which are more critical in this analysis.

1. INTRODUCTION

The Village of Monticello is located in north central Green County, Wisconsin, approximately 20 miles north of the Wisconsin-Illinois border. The village has a population of 1,224 residents and is nearly 70 square miles in size. An aerial map of the village was retrieved from Google Maps and can be seen in Figure 1.

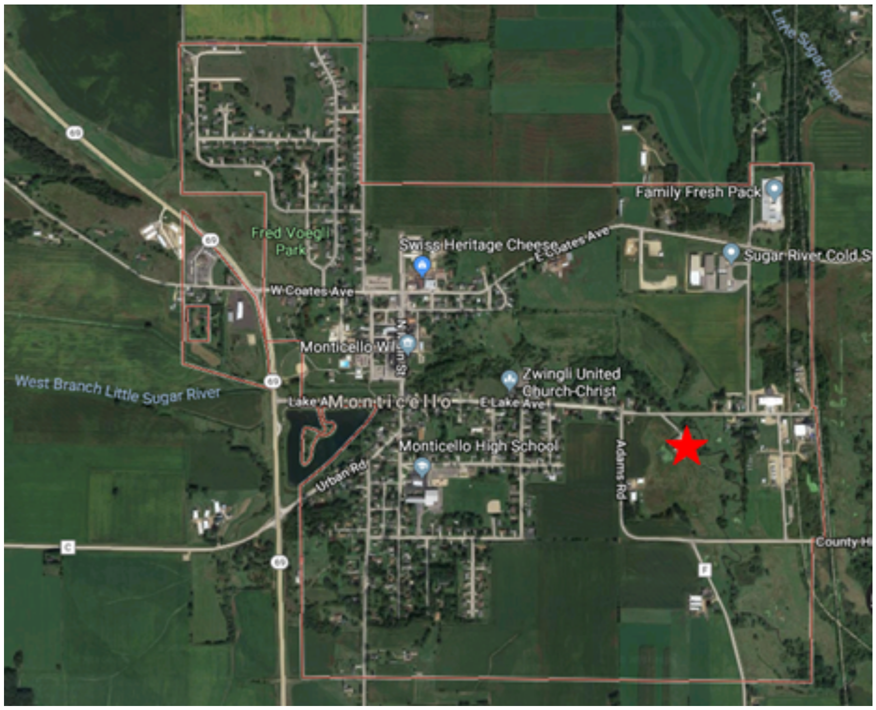


Figure 1. Satellite map showing the extent the Village of Monticello (outlined in red), which is located along Wisconsin State Highway 69 and the Little Sugar River. The Village's wastewater treatment facility is denoted on the map by the red star (Google Maps, 2018).

Monticello currently owns and operates a Wastewater Treatment Facility (WWTF) that utilizes an activated sludge oxidation ditch treatment process with a design flow of 0.421 million gallons per day (MGD). According to a 2014 Public Service Commission annual report, this WWTF serves 454 residential customers (i.e. 1,170 persons) with no industrial waste entering treatment system. The WWTF operates with an activated sludge system, which has preliminary screening, grit removal, oxidation ditch, final clarifiers, and ultraviolet light disinfection processes. Alum is currently being added for phosphorus control before the wastewater reaches the final clarifier. Additionally, a portion of the clarifier sludge is pumped to an aerobic digester where it is stabilized and stored in an on-site tank, and ultimately used in an agricultural biosolids land application program. The remainder is recycled to the oxidation ditch and added back into the wastewater stream. Figure 2 is an original schematic representation of the Monticello WWTF.

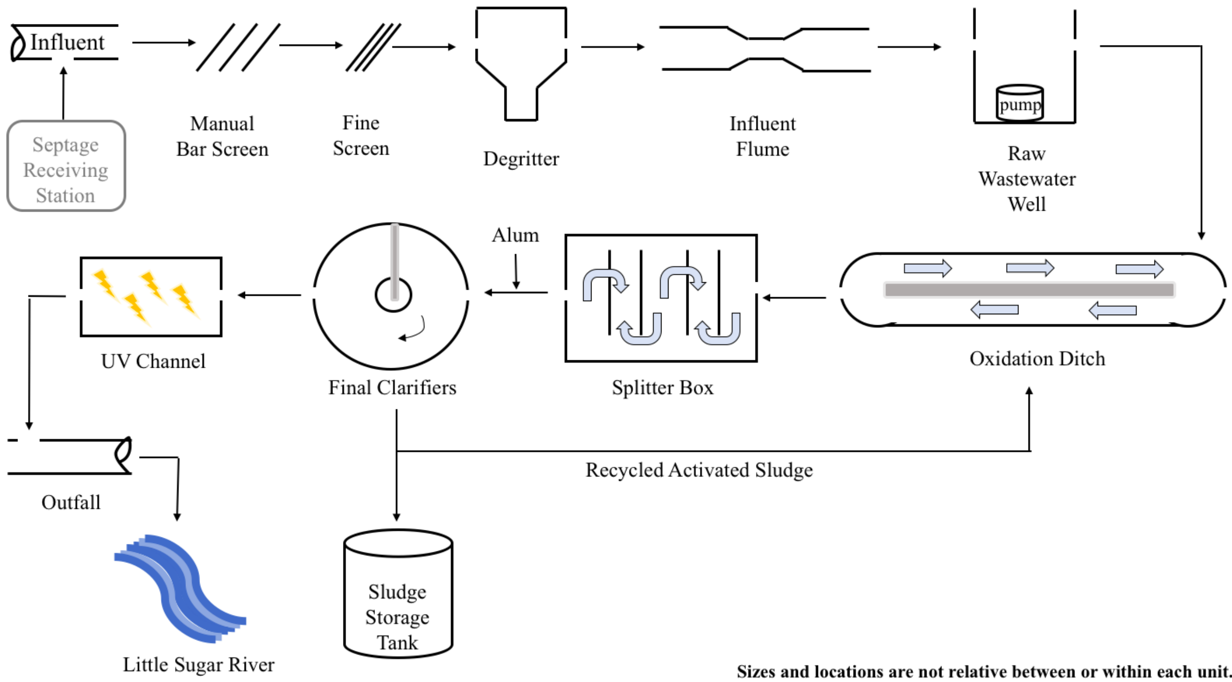


Figure 2. Monticello WWTF schematic representation not drawn to scale (original content).

The wastewater first passes through a vertical screen for removal of inorganic materials and small debris, then passes through a grit chamber for removal of grit. The raw wastewater then enters a wet well with pumps, which sends the wastewater to an oxidation ditch for treatment. For phosphorus removal, an alum chemical feed system is utilized, which injects alum into the splitter box which follows the oxidation ditch. After the splitter box, wastewater enters the final clarifiers, which separates the effluent from the solid activated sludge. The solid activated sludge is split into two different streams; one is recycled (recycled activated sludge or RAS) back into the oxidation ditch, and the other is wasted (waste activated sludge or WAS) and stored in the sludge storage tank for later agricultural application. Effluent from the final clarifiers is sent to an ultraviolet light disinfection channel for final treatment before being discharged to the West Branch of the Little Sugar River.

A primary focus for the Monticello WWTF is the control of phosphorus discharge. The monthly average effluent total phosphorus levels at the Monticello WWTF are 0.38 mg/L and the current interim limit set by the Wisconsin Pollutant Discharge Elimination System (WPDES) is 1.0 mg/L. While the facility is meeting the current interim limit, the WPDES permit indicates that the effluent total phosphorus limits will become an annual six-month average limit of 0.075 mg/L and a monthly average limit of 0.225 mg/L effective in 2022. To meet these new effluent total phosphorus limits, the Village of Monticello is considering a number of alternatives. These alternatives include the substitution of alum with SorbX-100, the CLEARAS ABNR System, and an Effluent Filter System.

In order to make a well-informed decision for which system is best-suited for meeting the effluent phosphorus requirements, it is crucial to consider the three paradigm of sustainability, which include environmental, economic, and social impacts. This report describes the assessment of the three sustainability paradigm associated with each phosphorus removal option.

2. BACKGROUND AND LITERATURE REVIEW

A review of the background information regarding phosphorus removal, as well as a literature review of previously performed life cycle assessments (LCA) are presented in this section. These case studies served as a guide throughout the evaluation of the Monticello WWTF.

2.1. Significance of Phosphorus Removal

Nitrogen (organic nitrogen, ammonia and nitrate) and phosphorus (organic phosphorus, polyphosphate, orthophosphate) act as fertilizers that promote algae growth in water bodies. This can lead to eutrophication, which is harmful for aquatic life. When nitrogen and/or phosphate reach water bodies, an increase in nutrient concentrations in the water are often observed. With these nutrients, algae grow and reproduces quickly and may form a green layer on the surface of the water. This algal bloom will then absorb sunlight, and the sunlight will not be able to reach the bottom of the water body. Plants that need this light to photosynthesize will eventually die. The algae will also eventually die once they consume all of the available nutrients (e.g. when they exceed the carrying capacity). Next, bacteria will start to break down the dead plants and algae, which releases more nutrients back into the water, continuing the algal bloom cycle. The bacteria with a continuing supply of food may reproduce in greater quantity, consuming oxygen when they grow. This will create an anoxic environment in the water, which leads to death of all non-bacterial organisms, including fish (NOAA, 2018). In order to prevent algal blooms, controlling the amount of phosphorus compounds that enter surface waters (from domestic/industrial waste discharges or natural runoff) is crucial, because this is typically the limiting reactant in this biochemical process. According to Metcalf and Eddy (2003), municipal wastewater may contain approximately 4-16 mg/L of phosphorus.

Phosphorus that comes from a wastewater treatment facility is generally 70% soluble or dissolved, and about 30% in particulate form containing organic molecules. The main idea of phosphorus removal is converting nearly 100% of the soluble phosphorus to particulate form, so that it can be settled or filtered out of the water. This can be done either chemically or biologically.

In the chemical phosphorus removal method, the goal is to precipitate dissolved phosphorus by adding a metal ion to the wastewater, which will form an insoluble metal phosphate. It should be noted that metal added to form metal phosphate will also be captured by the hardness (carbonate) and form metal hydroxide. This is not a problem for process removal efficiency, however, more metal would be needed because some of it will be reacting with the hardness in the water, rather than forming metal phosphates. Some metals used for this purpose include Ca^{2+} (i.e. lime), Al^{3+} (i.e. alum, sodium aluminate), Fe^{3+} (i.e. ferric chloride, ferric sulfate), Fe^{2+} (i.e. ferrous sulfate), and rare earth metals. Chemical methods may remove phosphorus up to 0.05 mg/L (Wright, 2015).

The biological phosphorus removal method is accomplished by using microorganisms called Phosphorus Accumulating Organisms (PAOs), which can use a phosphorus compound (ATP) as an energy source. These organisms release phosphorus from the ATP in anaerobic (i.e. absence of free oxygen, such as dissolved O_2, NO_3^-, etc.) conditions and absorb phosphorus into their cells in aerobic conditions. Repeatedly cycling these organisms through these two zones can lead to absorbing excess phosphorus and removing the phosphorus within the system by wasting those bacteria out of the system. This is only possible in an activated sludge process. Biological methods may remove phosphorus up to 1 mg/L (Wright, 2015).

2.2. Department of Natural Resources (DNR) Phosphorus Level Reduction

Phosphorus has been recognized as the controlling factor in plant and algae growth in Wisconsin lakes and streams. Small increases in phosphorus can fuel substantial increases in aquatic plant and algae growth, which in turn can reduce recreational use, property values, and public health.

Phosphorus entering Wisconsin lakes and streams comes from "point sources" - piped wastes such as municipal and industrial wastewater treatment facilities that release liquid effluent to lakes and rivers or spread biosolids on fields; and from natural sources, including past phosphorus loads that build up in lake bottom sediments. Phosphorus also comes from "nonpoint" or "runoff" pollution. Such pollution occurs when heavy rains and melting snow wash over farm fields and feedlots and carry fertilizer, manure and soil into lakes and streams, or carry phosphorus-containing contaminants from urban streets and parking lots.

In order to protect human health and welfare, revisions to Wisconsin's Phosphorus Water Quality Standards for surface waters were adopted on December 1, 2010. These revisions include (Wisconsin Department of Natural Resources, 2017):

- Creating water quality standards for phosphorus in surface waters. These standards set maximum thresholds for phosphorus in Wisconsin's surface waters.
- Setting procedures to implement these phosphorus standards in WPDES permits issued to point sources discharging to surface waters of the state.

- Helping to curb nonpoint sources of excess phosphorus by tightening agricultural performance standards.

Based on the previous DNR limits, phosphorus in the wastewater facilities effluent needed to be lower than 1 mg/L. However, according to the updated DNR limit enforced by WPDES, the WWTF's effluent phosphorus concentration is required to be less than 0.075 mg/L on an annual six-month average basis.

In the Monticello WWTF, the total annual phosphorus concentration of 0.38 mg/L is achieved by already implemented technologies (including alum addition). Despite this effluent concentration meeting the previous requirements ($C<1$ mg/L), it fails to meet the updated DNR limits ($C<0.075$ mg/L). Therefore, managers of the Monticello WWTF are seeking methods to meet the new regulations, while achieving the maximum efficiency in terms of the environmental, economic, and social impacts. In the following sections, different phosphorus removal options are compared based on the three sustainability paradigms.

2.3. Life Cycle Assessments Performed on Wastewater Treatment Facilities (WWTFs)

Several life cycle assessment (LCA) case studies were reviewed to help guide the framework of the evaluation performed for the Monticello WWTF. This literature review is important to validate the methodology and assumptions used in this evaluation.

2.3.1. LCA of WWTP in Catalonia, Spain (Garfi et al., 2017)

An LCA of wastewater treatment systems for small communities was performed by the GEMMA (Group of Environmental Engineering and Microbiology) at the Universitat Politecnica de Catalunya-Barcelona. The LCA compared a conventional wastewater treatment plant (e.g. activated sludge system) with two nature-based wastewater treatment technologies: hybrid constructed wetland and high rate algal pond system. The aim of the paper was to evaluate the environmental and economic impacts associated with natural and conventional wastewater treatment technologies in small agglomerations.

The evaluated activated sludge system is located in Catalonia, Spain, while the constructed wetland and algal pond systems were hypothetical plants designed by an engineering firm. The system boundaries were set to be comprised of input and output flows of material and energy resources for the construction and operation of the systems over a 20-year period. Potential environmental impacts were calculated using SimaPro and the ReCipe midpoint method, and background data was obtained using the EcoInvent database. The most pressing environmental issues of the area were evaluated, which included metal depletion, fossil depletion, climate change, ozone depletion, terrestrial acidification, freshwater eutrophication, and marine eutrophication. The economic analysis was performed using capital, operation, and maintenance costs of each treatment method. Data was gathered using price points provided by local engineering firms. Capital costs included cost for earthwork, construction materials, and electrical works. Operation and maintenance costs were the costs associated with labor, electricity, purchase of chemicals, disposal, and ordinary and extraordinary maintenance.

The results of the analysis showed that the environmental impacts of the conventional wastewater system were two to five times higher than that of the nature-based technologies. This can mainly be attributed to the high electricity and chemical consumption for the operation of the conventional wastewater treatment plant. The results also indicated that the smaller the community, the more appropriate the nature-based solutions are. With regards to the economic assessment, the algal pond system had the lowest capital costs, followed by the constructed wetland, and conventional systems the most expensive. Overall, the conventional system showed to be between two and three times more expensive than the nature-based alternatives. The paper indicates that approximately 45 kg CO2eq/p.e./year could be saved by implementing nature-based treatment systems over conventional systems. However, conventional systems have significantly lower land footprint than the nature-based technologies.

2.3.2. LCA Applied to Different WWTFs (Corominas et al., 2013)

In the pursuit of developing more sustainable wastewater treatment systems, it is clear that LCA is a valuable tool to elucidate the broader environmental impacts of design and operation decisions. In this work, a comprehensive review of 45 papers dealing with LCA and wastewater treatment is performed in order to review what has been achieved and describe the challenges for the future. Among those references, variety of definitions for functional unit, system boundaries, selected impact assessment methodologies and the interpretation procedures were reported. Therefore, it is necessary to have a stricter adherence to ISO methodological standards to ensure transparency and quality (need for better integration and communication with decision-makers).

As discussed by Corominas et al. (2018), one of the main challenges of LCA application in wastewater treatment is a paradigm shift from pollutant removal to resource recovery. Given the long-term needs for ecological sustainability, the goals for wastewater treatment systems need to move beyond the protection of human health and surface waters to also minimizing the loss of resources, minimizing energy and water use, reducing waste generation, and enabling the recycling of nutrients. This challenge can be properly addressed by performing an LCA.

Another challenge is adaptation of LCA methodologies to new targeted compounds. The developments in toxicity-related impact categories mainly relate to heavy metals and priority pollutants (a set of chemical pollutants EPA regulates). Moreover, organic micropollutants are also included in the most recent studies. Holistic LCA studies on assessing the fate of micropollutants in wastewater and excess sludge would contribute to better understand their environmental implications. The third challenge is the development of regional factors. It is necessary to understand what impact the WWTF effluent will have on the receiving environment. Location-specific factors are critical, especially for the eutrophication potential. The challenge here is to provide a set of accepted characterization factors that can be applied at regional scale.

2.3.3. Collection LCA Inventories for Alternative WWTFs (Foley et al., 2010)

Requirements for nutrient removal practices for WWTFs has been changing with the increasing environmental protection needs since the 20th century. There are several treatment designs which may vary by regional requirements and development level of a country. Foley et al., (2010) compiled cradle-to-gate LCA inventories for ten different scenarios including resource consumption and emissions generation per process. Their goal was to quantify, model and evaluate different scenario configurations. These include no treatment, basic primary sedimentation with anaerobic digestion, primary treatment with basic activated sludge system, primary treatment with nitrification added activated sludge system, primary treatment with anoxic-aerobic modified system, and advanced nutrient removal system. System boundaries included in this work were direct atmospheric emissions resulting from the operation of WWTF and the effluent discharges. Also, indirect inputs were included such as the purchased electricity generation, manufacturing of raw materials etc. Authors compiled the LCA inventories based on the same functional unit which was selected as treatment of 10 ML/d of raw domestic wastewater over 20 years.

Overall interpretation was that, with the increased nutrient removal efforts, the infrastructure resources, operational energy, direct greenhouse gas emissions and chemical consumption increase proportionally. However, especially for the phosphorus case, increasing phosphorus removal in WWTFs may be considered as an opportunity, since the recovery of biosolids may be applied to agricultural lands as fertilizers. Cradle-to-grave LCA is needed to assess the system holistically.

3. EXPLANATION OF MONTICELLO WASTEWATER TREATMENT FACILITY ALTERNATIVES

The Monticello WWTF is considering three phosphorus removal alternatives: SorbX-100 (previous pilot study), CLEARAS ABNR System (performed last year), and an Effluent Filter System (prospective method to be performed in future). In this section, summaries on the aforementioned systems are presented. Further analysis would be performed on SorbX-100 and CLEARAS ABNR System alternatives, as there is not a sufficient amount of information available regarding system design and properties for the Effluent Filter System for the Monticello WWTF.

3.1.SorbX-100 System

To date, there has only been a limited selection of chemical coagulants for the removal of phosphorus in wastewater. SorbX-100 is a proprietary mixed rare earth chloride solution for phosphorus removal in municipal and industrial wastewater streams. It is anticipated to offer wastewater treatment operators a cost-effective option to reduce phosphorus discharges, other chemicals usage, and sludge volumes, while improving environmental compliance (Univar Inc., 2013).

The Monticello WWTF is considering SorbX-100 as a potential method to for meeting the new WI DNR phosphorus limits. It is determined that it is not feasible to use alum for meeting the new phosphorus effluent standards, therefore a pilot study testing the addition of SorbX-100 in place of alum was completed in February and March 2016. In summary, this method of phosphorus removal is completed by the addition of the chemical solution SorbX-100 which causes phosphorus to precipitate out of the wastewater stream to be removed with the activated sludge in the final clarifiers.

3.2.CLEARAS ABNR System

CLEARAS Advanced Biological Nutrient Recovery (ABNR) system is a controlled and continuous flow environment that leverages a facility's existing microbiology – algae and other biological organisms – to recover excess phosphorus, nitrogen and other high-profile contaminants in wastewater. It is reported that, by implementing the CLEARAS ABNR System, 94% additional phosphorus reduction can be achieved, which results to a phosphorus concentration of 0.032 mg/L in the effluent (CLEARAS, 2016). The ABNR Solution is an advanced non-chemical treatment, which prevents the addition of disinfection by-products, and achieves best-in-class performance with phosphorus and nitrogen recovery to near non-detect levels, while reducing other harmful contaminants in wastewater. Although it minimizes the use of extra chemicals, the CLEARAS ABNR System is subject to additional construction and maintenance considerations to the WWTF.

3.3. Effluent Filter System

In order to meet the proposed effluent total phosphorus limits, the WWTF can be equipped with an additional effluent filter system. Effluent from the final clarifier would enter a coagulation/flocculation tank, in which additional coagulant for phosphorus removal would be added, possibly along with suspended polymeric beds, to aid in flocculation, manipulating their porous properties. Afterwards, the effluent from coagulation/flocculation tank could enter a disk filter (or similar technology) to remove precipitated solids. Since there is no pilot study performed by Monticello WWTF utilizing such a system based on WWTF configurations, the facility had no data obtained regarding this system. However, it is considered one of the prospective alternatives in addition to the two aforementioned systems.

4. ENVIRONMENTAL LIFE CYCLE ASSESSMENT

In the following sections, the four stages of the environmental life cycle assessment are defined and explained. These stages include goal and scope definition, inventory analysis, impact assessment, and interpretation.

4.1. Goal and Scope Definition

Because of the lowered effluent phosphorus limits set by DNR and WPDES, the Village of Monticello WWTF is considering a number of alternatives to assist in meeting the proposed effluent total phosphorus limits. The goal of this study is to quantitatively model and evaluate the environmental life cycle assessments of two different phosphorus removal strategies applied in Monticello WWTF.

Environmental impacts for each phosphorus removal process includes a boundary control volume for processes at the WWTF. By defining a control volume, the inputs are clearly defined, and the outputs can be objectively compared. The control volume of the phosphorus removal process at the Monticello WWTF will vary between the two methods under inspection, but in general begins directly after leaving the oxidation ditch and continue through the remainder of the treatment process until the effluent is discharged to the Little Sugar River. Neither boundaries will include the solid activated sludge flow from the two final clarifiers or any energy inputs required for pumping or turning the skimmer. The general input for each phosphorus removal option is the mixed liquor leaving the oxidation ditch. Figure 3 defines the scope of the current study split by the life cycle stages, which only covers utilization of different phosphorus removal systems (SorbX-100 and CLEARAS ABNR) along with their emissions to the environment. The specific system boundaries for SorbX-100 and CLEARAS ABNR are presented in Sections 4.2.1 and 4.2.2 respectively.

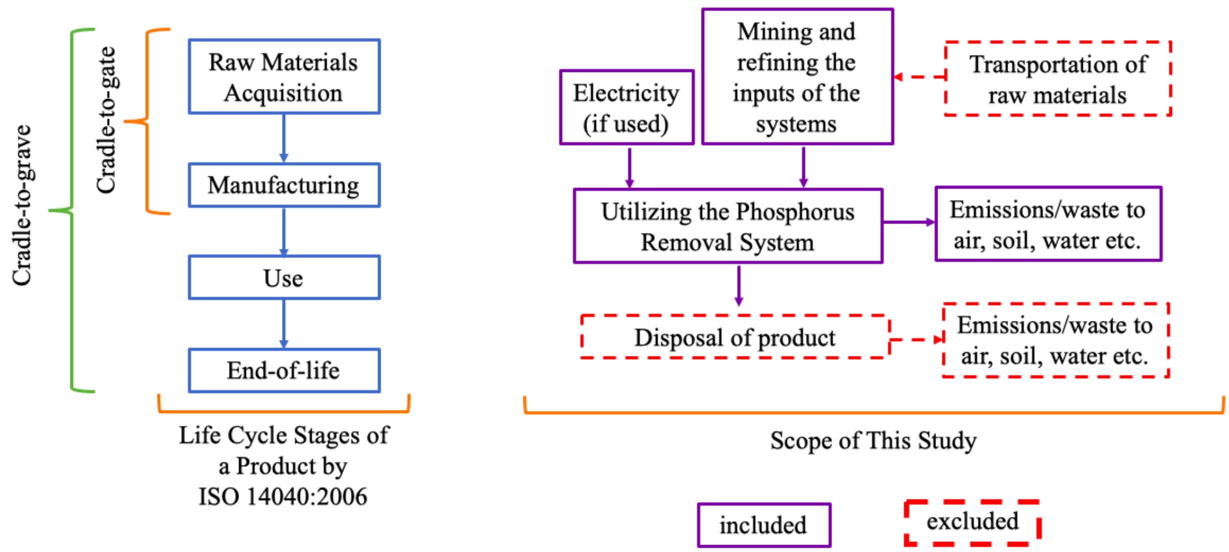


Figure 3. Scope of this study.

The functional unit for this study is selected as 1,000 gallons of wastewater. Results can be scaled up according to daily or design flow rates of Monticello WWTF. In addition, the influent phosphorus concentration will be assumed to be 3.81 mg/L, which is based on the average of measurements presented in the Monticello WWTF Report (Delta 3 Engineering Inc., 2016). Effluent phosphorus concentrations will be set as 0.075 mg/L, which is the new WI DNR six-month average limit.

4.2. Inventory Analysis and Necessary Assumptions

In inventory analysis stage the list of resources, inputs and outputs, and emissions (to air, water and land associated with the product) are collected and calculated according to the functional unit. This stage involves data collection and necessary assumptions to quantify relevant inputs and outputs including products, by-products and emissions. In this section of the report, inventory analysis and necessary assumptions are listed for both SorbX-100 and CLEARAS.

4.2.1. SorbX-100 System

As previously described in Section 3.2.1, SorbX-100 is a coagulant that is used to precipitate dissolved phosphorus out of the wastewater. The addition of this solution allows for phosphorus to be deposited through sedimentation processes in the final clarifiers, thereby removing it from the effluent. The in-place chemical feed system (currently being used for alum) feeds into the splitter box, which is where SorbX-100 will be assumed to be added into the wastewater treatment flow before proceeding into the final clarifiers. The pump for the chemical feed system has a maximum flow rate of 13.9 gallons per hour, but pumping rates will be on average less than one gallon per hour. Therefore, the power to run the chemical feed system will be assumed to have negligible environmental impacts. In addition, the power required to pump the activated sludge turn the skimmer in the final clarifiers will be assumed to be unaffected by the addition of SorbX-100, and therefore, will be considered outside of the boundaries for this analysis. Upstream treatment processes of the splitter box will also be outside of the boundaries for this environmental life cycle assessment. A visualization of the system boundaries for this is shown in Figure 4.

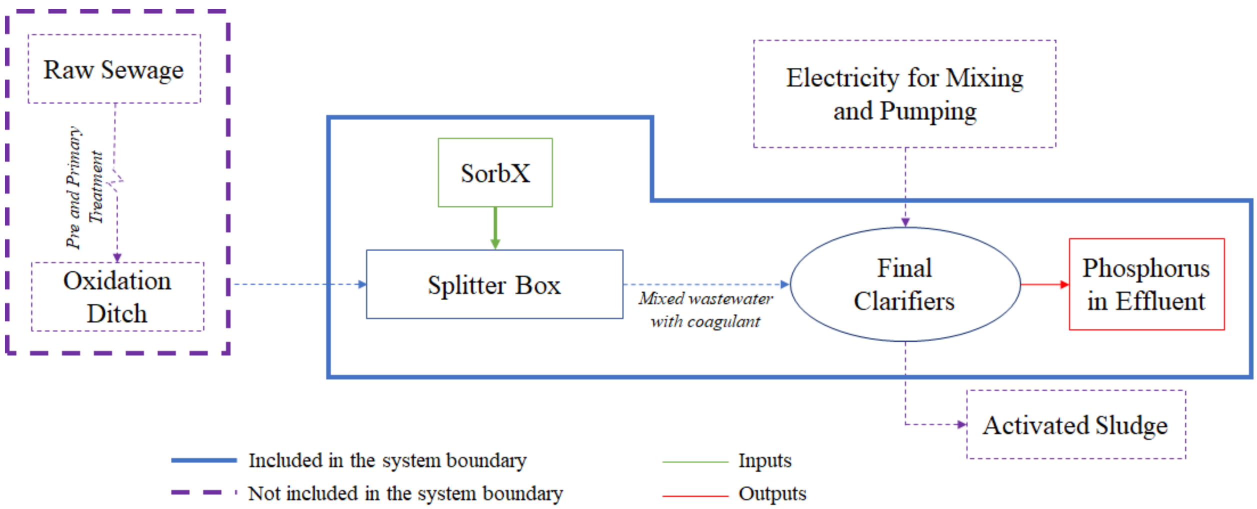


Figure 4. The system boundaries and input-output information for SorbX-100 System.

Based on the functional unit of 1,000 gallons and the assumed phosphorus concentration of 3.81 mg/L there will be 14,430 mg of phosphorus in the inflow. As a general rule, it will be assumed that 1 gallon of SorbX-100 solution will be able to remove 0.5 lbs of phosphorus (Lupo, 2017). Under these assumptions, 0.0636 gallons of SorbX-100 is required to treat 1,000 gallons of wastewater. To translate to units available in SimaPro, it was assumed SorbX-100 has a density of 1.42 g/mL (Neo Chemicals and Oxides, 2017). It is understood that SorbX-100 is made of rare earth metals (Cerium, Lanthanum, and others) to complex phosphorus (WWOA, 2017). As the mining and materials acquisition for these elements are similar, it is assumed that SorbX-100 is primarily made from Cerium oxide and Lanthanum oxide (databases available in SimaPro) with the mass ratio of 31.5:68.5 (Gonzales, 2015). Finally, in the SimaPro Software, the phosphorus in the influent is quantified as “phosphorus in water” and phosphorus in the effluent is qualified as "emissions to water/river". Table 1 shows all input and output data used in life cycle assessment study per each phase.

Table 1. Input and output data for SorbX-100 System.

INPUTS (functional unit 1,000 gallons per day)			
Phase	**Flow**	**Amount**	**Reference**
Mixing Chamber	Phosphorus (influent)	4,430 mg	Monticello WWTF
	SorbX-100 [1, 2]	107.56 g Ce_2O_3 (Cerium Oxide)	SorbX-100, 2014; Gonzales, 2015
	Phosphorus (influent)	233.92 g La_2O_3 (Lanthanum Oxide)	SorbX-100, 2014; Gonzales 2015
OUTPUTS			
Phase	**Flow**	**Amount**	**Reference**
Final Clarifiers	Phosphorus (effluent)	283 mg	Monticello WWTF

Although not within the scope of this analysis, several crucial SorbX-100 considerations were noted during the literature review and are included in the footnotes.

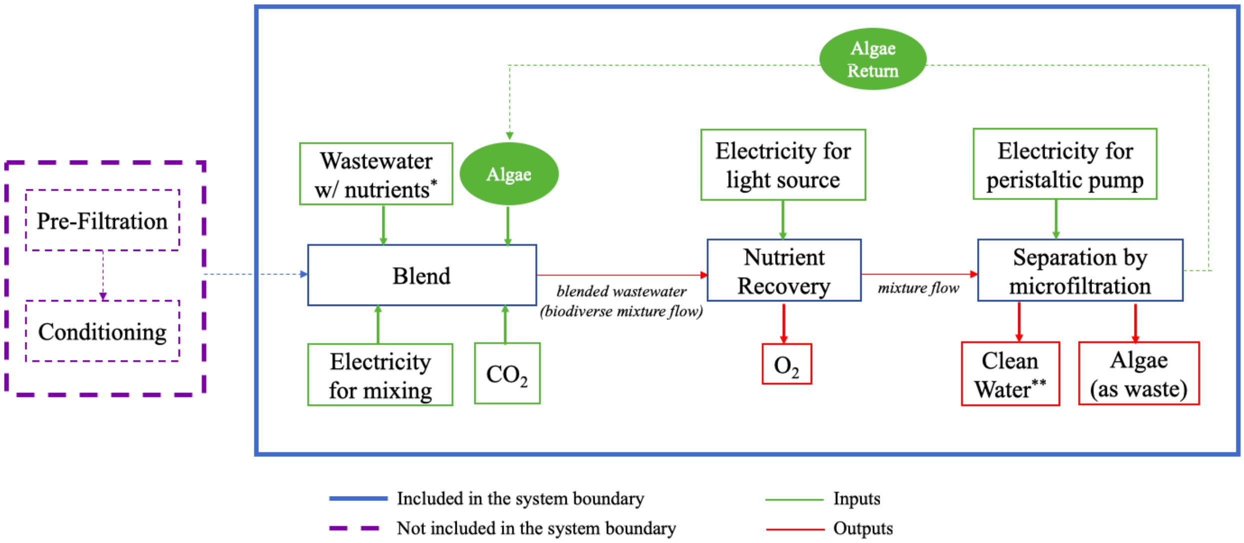
4.2.2. CLEARAS ABNR System

As mentioned in Section 3.2.2, the CLEARAS ABNR System may be used to recover excess phosphorus, nitrogen, and other high-profile contaminants in wastewater. It is closed loop, modular, scalable and highly flexible platform with automated instrumentation and controls. It consists of five steps, which are pre-filtration, conditioning, blend, nutrient recovery and separation. However, the first two stages (pre-filtration and conditioning) are not required for every application (Johnson, 2013). Since Monticello WWTF has relatively low influent rate, pre-

[1] SorbX-100 is incompatible with Ultrafiltration processes, which can be considered for downstream drinking water treatment plants (Fond du Lac WWTP, 2016).

[2] SorbX-100 is ineffective at pH > 8.3. Highest removal efficiency is obtained at pH~4 (NEWEA, 2017).

filtration and conditioning stages are excluded from this evaluation. It is assumed that wastewater, which leaves the oxidation ditch, directly connected to the blend phase of the CLEARAS ABNR System. Figure 5 shows the system boundaries and input-output information for aforementioned practice.



* Includes 14,430 mg phosphorus (P) in the influent per functional unit (1,000 gallons/day)

** Includes 285 mg phosphorus (P) in the effluent per functional unit (1,000 gallons/day)

Figure 5. The system boundaries and input-output information for CLEARAS ABNR System.

The breakdown of the ABNR system is explained in a report by Endress+Hauser Inc. (2018). According to this report, in blend phase, wastewater (with nutrients) and carbon dioxide are mixed with a blend of algae to create a biodiverse mixture flow. Nutrient recovery phase follows the blend phase, where greenhouse structure and light source provide light for 24/7 nutrient recovery in a vertical pond system. This is the step where algae perform photosynthesis and biologically cleans the water by metabolizing nutrients (nitrogen and phosphorus) and releasing oxygen. Finally, in the separation phase, advanced microfiltration technology is used to separate the mixture flow into the recycle and the clean water streams. The recycle stream returns the healthy algae back to the blend tank to be reused. Consequently, the clean water stream has allowable amounts of nutrients and may be released to the receiving bodies. Table 2 shows all input and output data used in life cycle assessment study per each phase.

Table 2. Input and output data for CLEARAS ABNR System.

INPUTS (functional unit 1,000 gallons per day)			
Phase	**Flow**	**Amount**	**Reference**
Blend phase at blend tank	Algae	0.182 kg	CLEARAS, 2017
	CO_2[3]	0.4 kg	CSEAO, 2015
	Electricity (for mixing)[4]	0.325 kWh	Singh et al., 2012
	Phosphorus (influent)	14,430 mg	Monticello WWTF
Nutrient recovery at vertical plastic pond	Light source for 550-675 nm (electricity)[5]	0.0288 kWh	Edmund Optics Inc., 2018
Separation (by microfiltration)	Electricity (for peristaltic pump)[6]	0.138 kWh	Robinson et al., 2012 and Cole-Parmer, 2018
OUTPUTS			
Phase	**Flow**	**Amount**	**Reference**
Nutrient recovery at vertical pond	O_2[7]	0.3 kg	CSEAO, 2015
Separation (by microfiltration)	Algae (as waste)	0.091 kg	Abdel-Raouf et al. 2012
	Phosphorus (effluent)	285 mg	Monticello WWTF

[3] 5 MGD facility consumes more than 1,600,000 pounds / CO_2 per year → [1,000 gal/day * 1,600,000 lb/CO_2.yr / 365] / 5 MGD = 0.4 kg

[4] 0.086 kWh/m^3

[5] (24V * 15A)/1000=0.36 kW and 300,000 gal/day in total → (0.36*24)/300=0.0288 kWh

[6] (115V * 15A)/1000= 1.725 kW and 300,000 gal/day in total → (1.725*24)/300=0.138 kWh

[7] 5 MGD facility emits more than 1,200,000 pounds / O_2 per year → [1,000 gal/day * 1,200,000 lb/CO_2.yr / 365) / 5 MGD = 0.3 kg

Data is collected from different studies, journal articles and industrial reports, and referenced accordingly. Several calculations were performed in order to convert data per the functional units selected, and each of them were shared in footnotes.

4.3.Impact Assessment

To complete the environmental impact assessment, SimaPro 8.5.2 Software is used. The potential environmental impact categories are assessed by using TRACI 2.1 Impact Assessment Methodology (Bare et al., 2012). Among other impact assessment methodologies (i.e. CML, USETox, BEES, ReCipe etc.), TRACI 2.1 is selected for this research, since it uses the amount of the chemical emission or resource used and the estimated potency of the stressor by focusing on the US average characterization factors (Bare et al., 2012).

As per ISO 14040:2006, life cycle impact assessment has both mandatory (selection of impact categories, classification and characterization) and optional elements (normalization, grouping, weighting and data quality analysis). The current study considers only the mandatory elements. Selected potential environmental impact categories, along with their units and abbreviations based on TRACI 2.1 impact assessment methodology are listed in Table 3.

Table 3. Impact categories on TRACI 2.1 impact assessment methodology.

Potential Environmental Impact Category	**Unit**	**Abbreviation**
Ozone depletion	kg CFC-11 eq.	ODP
Global warming	kg CO_2 eq.	GWP
Smog	kg O_3 eq.	SCP
Acidification	kg SO_2 eq.	AP
Eutrophication	kg N eq.	EP
Carcinogens	CTUh	HTCP
Non carcinogens	CTUh	HTNCP
Respiratory effects	kg PM2.5 eq.	HHAP
Ecotoxicity	CTUe	EcoP
Fossil fuel depletion	MJ surplus	FFP

4.3.1. SorbX System

The first alternative was SorbX-100, which is added to the wastewater to complex with phosphorus-containing substances and make them precipitate. Table 4 shows the environmental impacts resulting from the SorbX-100 system per functional unit (1,000 gallons per day).

Table 4. Environmental impacts of SorbX-100 System with materials contributions.

Impact	Total	Treated Effluent	SorbX-100, Cerium Content	SorbX-100, Lanthanum Content
ODP (kg CFC-11 eq.)	1.37E-06	0.00E+00	1.80E-07	1.20E-06
GWP (kg CO_2 eq.)	4.43E+00	0.00E+00	5.79E-01	3.85E+00
SCP (kg O_3 eq.)	2.32E-01	0.00E+00	3.03E-02	2.02E-01
AP (kg SO_2 eq.)	2.65E-02	0.00E+00	3.47E-03	2.31E-02
EP (kg N eq.)	1.79E-02	9.03E-04	2.23E-03	1.48E-02
HTCP (CTUh)	4.20E-07	0.00E+00	5.50E-08	3.66E-07
HTNCP (CTUh)	2.20E-06	0.00E+00	2.87E-07	1.91E-06
HHAP (kg PM 2.5 eq.)	6.19E-03	0.00E+00	8.10E-04	5.39E-03
EcoP (CTUe)	7.02E+01	0.00E+00	9.17E+00	6.10E+01
FFP (MJ surplus)	1.17E+01	0.00E+00	1.53E+00	1.02E+01

Rare earth metals (Cerium and Lanthanum) are found to be the biggest contributors in all investigated environmental impact categories (>94%). The high impacts for rare earth metals are resulting from their acquisition including mining, production and processing, and can be attributed to the treatment and disposal of the tailings (Oko-Institut e.V., 2011). The tailings typically contain high-surface-area particles, wastewater, and process chemicals. These particles have a high potential to contaminate air, soil, and groundwater when emitted to the environment (Webber, 2012). Additionally, energy inputs for mechanical processing stages are subject to have additional associated environmental impacts. In Figure 6, material based relative contributions are schemed and total environmental impacts are presented for the SorbX-100.

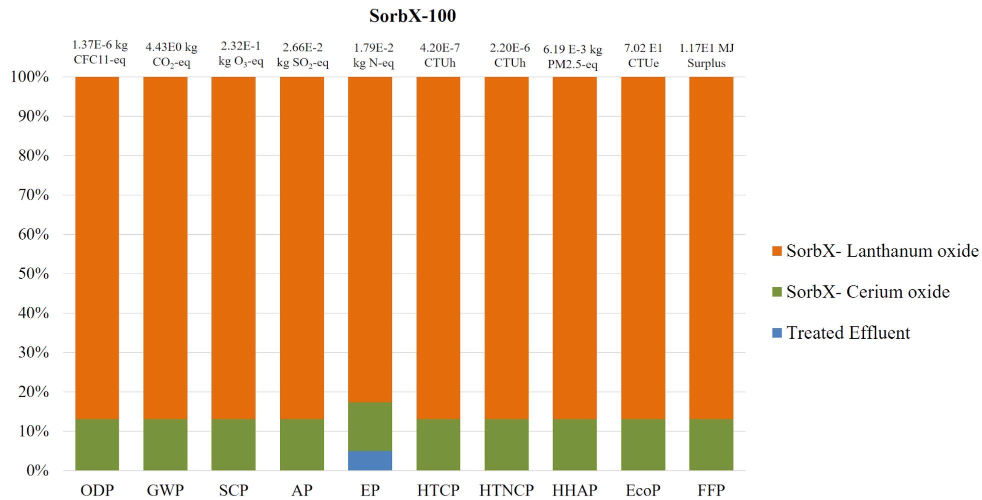


Figure 6. Process based LCA results for SorbX-100 System.

4.3.2. CLEARAS ABNR System

The second alternative is the CLEARAS ABNR System, which is a non-chemical treatment system and recovers phosphorus, nitrogen and other harmful contaminants in water by using biological organism such as algae. Table 5 shows the environmental impacts resulting from the CLEARAS ABNR System per functional unit (1,000 gallons per day).

Table 5. Environmental impacts of the CLEARAS ABNR System with process contributions.

Impact	Total	Treated Effluent	Algae	Electricity
ODP (kg CFC-11 eq.)	7.47E-08	0.00E+00	1.76E-09	7.30E-08
GWP (kg CO_2 eq.)	2.85E-01	0.00E+00	1.03E-02	2.75E-01
SCP (kg O_3 eq.)	8.74E-03	0.00E+00	4.70E-04	8.27E-03
AP (kg SO_2 eq.)	1.93E-03	0.00E+00	5.31E-05	1.87E-03
EP (kg N eq.)	1.00E-03	9.09E-04	6.46E-05	2.77E-05
HTCP (CTUh)	1.93E-09	0.00E+00	1.71E-09	2.22E-10
HTNCP (CTUh)	2.12E-08	0.00E+00	1.32E-08	8.03E-09
HHAP (kg PM 2.5 eq.)	1.54E-04	0.00E+00	1.20E-05	1.42E-04
EcoP (CTUe)	5.17E-01	0.00E+00	5.01E-01	1.65E-02
FFP (MJ surplus)	2.07E-01	0.00E+00	1.62E-02	1.90E-01

Electricity (used for mixing, lighting and peristaltic pump) is found to be the biggest contributor for six out of ten impact categories, including ODP, GWP, SCP, AP, HHAP and FFP. Use of algae (including algae production) contributes mostly to the HTCP, HTNCP and EcoP impact categories. Finally, as expected, treated effluent, which has allowed amount of phosphorus concentration, is found to be the biggest contributor for EP. In Figure 7, process based relative contributions are schemed and total environmental impacts are presented for the CLEARAS System.

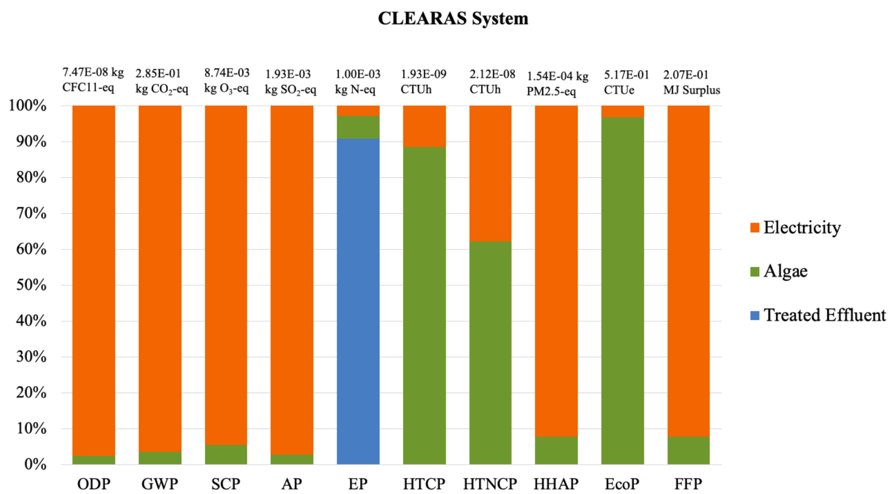


Figure 7. Process based LCA results for the CLEARAS ABNR System.

4.4. Interpretation

Relative environmental impacts of the two systems are presented in the Figure 8. According to this graph, use phase (operation) of the CLEARAS ABNR System is found to be a better practice for phosphorus removal. Its maximum contribution is from the AP, which is approximately 7% and can be neglected over the impact of SorbX-100.

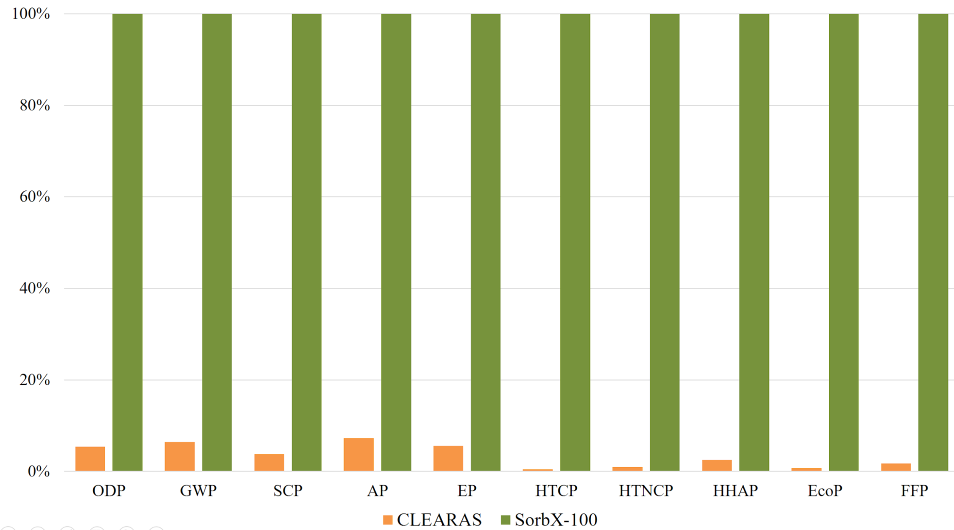


Figure 8. Comparison for environmental impacts of CLEARAS ABNR and SorbX-100 Systems.

According to the LCA results, SorbX-100 emits 4.43 kg CO_2-eq. greenhouse gases, and the CLEARAS ABNR System emits 0.285 kg and CO_2-eq. greenhouse gases both per the functional unit. Switching from the SorbX-100 to CLEARAS ABNR System would save 4.68 kg CO_2-eq., per 1,000 gallons of wastewater treated. If this amount is calculated for the daily design flow of Monticello WWTF (which is 421,000 gallons/day), approximately 1,800 kg CO_2-eq. would be saved per day. In order to exemplify these numbers with industrial analogies, dairy industry is selected. According to Gerber et al. (2010), greenhouse gas emissions per 1 kg of milk production is 2.4±0.26 kg CO_2-eq. Regarding phosphorus removal technologies mentioned herein, 1,800 kg CO_2-eq. saving is equivalent to the emissions generated from 750 kg of milk production.

5. ECONOMIC IMPACT ASSESSMENT

In general, this economic impact assessment aims to evaluate the costs associated with each of the two phosphorus removal methods to determine which method has the best economic value. To complete the economic impact assessment, a deterministic approach to the life-cycle cost analysis (LCCA) is used.

5.1. Scope and Assumptions

This LCCA includes initial costs, recurring costs, and recurring benefits. A time period of 20 years, similar to Garfi et al. (2017) and Foley et al. (2010), is chosen for evaluating each phosphorus removal option. Wastewater treatment technology is continuing to advance, and regulations associated with wastewater treatment are becoming more stringent. This 20-year period should be appropriate given the lifespan of wastewater treatment equipment and the life-cycle of wastewater treatment technology. According to the U.S. Bureau of Labor Statistics (2018) the average inflation rate from 2008-Present is 1.8%, which will be used in this LCCA. Additionally, costs will be compared in U.S. dollars ($). Costs used for this impact assessment will be investigated through a literature review, unless the information is already available in the previously completed WWTF Report (Delta 3 Engineering Inc., 2016). It should be assumed for this LCCA that all alternatives being analyzed have similar phosphorus removal results.

5.2. Cost Inventory and Literature Review

This section will define the specific initial costs, recurring costs, and recurring benefits of the SorbX-100 and CLEARAS ABNR System options.

5.2.1. SorbX-100 System

An initial cost of the $5,450 will be used for the SorbX-100 option. According to the WWTF Report (Delta 3 Engineering Inc., 2016) the chemical feed system at the Village of Monticello WWTF, which is currently being used for Alum, has been well maintained and does not require significant updates. Overall, the capacity of the tank (2,232 gallons) and pumps (up to 13.9 gallons per hour) would be robust enough to handle a switch from alum to SorbX-100. The only initial costs involve the replacement of insulation and heat tracing systems on the in-place chemical feed piping.

A recurring annual cost of approximately $33,840 will be used to assess this chemical phosphorus removal option. This estimate will yield more conservative results in comparison to that calculated in the WWTF Report (Delta 3 Engineering Inc., 2016), which estimated a cost of $26,010 per year. This WWTF Report (Delta 3 Engineering Inc., 2016) assumed an average daily SorbX-100 consumption of 15 gallons, although they noted this volume may need to be increased to a larger value around 25 gallons per day. They assumed this value of 15 gallons per day based on the pilot study results, which took place during a period with lower than average mean daily influent flow rates (about 0.220 MGD). The calculated recurring cost that will be used in this assessment is based on the average flow rate of 0.300 MGD and the average phosphorus concentration of 3.81 mg/L. To lower effluent phosphorus concentrations to the new WI DNR limits it is determined that an average of about 19.1 gallons per day of SorbX-100 will be required; this flow rate is calculated based on a general rule of thumb that SorbX-100 can remove 0.5 lbs of phosphorus per gallon of solution (Lupo, 2014). According to the WWTF Report (Delta 3 Engineering, 2018) the municipality can purchase SorbX-100 for $4.86 per gallon of solution. This results in a daily cost of $92.72 and an annually recurring cost of $33,840. There were no recurring benefits associated with using this chemical addition phosphorus removal option.

5.2.2. CLEARAS ABNR System

Although the CLEARAS ABNR System would require the construction of new structures and mechanical systems, these costs will not be incorporated into this LCCA as an initial cost. Instead of including the construction costs as a lump sum initial cost, it is more realistic to assume these costs will be financed through a loan. Therefore, construction costs will be accounted for as a recurring annual cost. Regardless, the total cost of the construction of a CLEARAS ABNR System is estimated to be $2.61 million. This value was estimated based on the estimated capital costs associated with the construction of CLEARAS ABNR Systems for the Village of Roberts, WI and the City of Beaver Dam, WI. A graphical display of these results is shown in Figure 9.

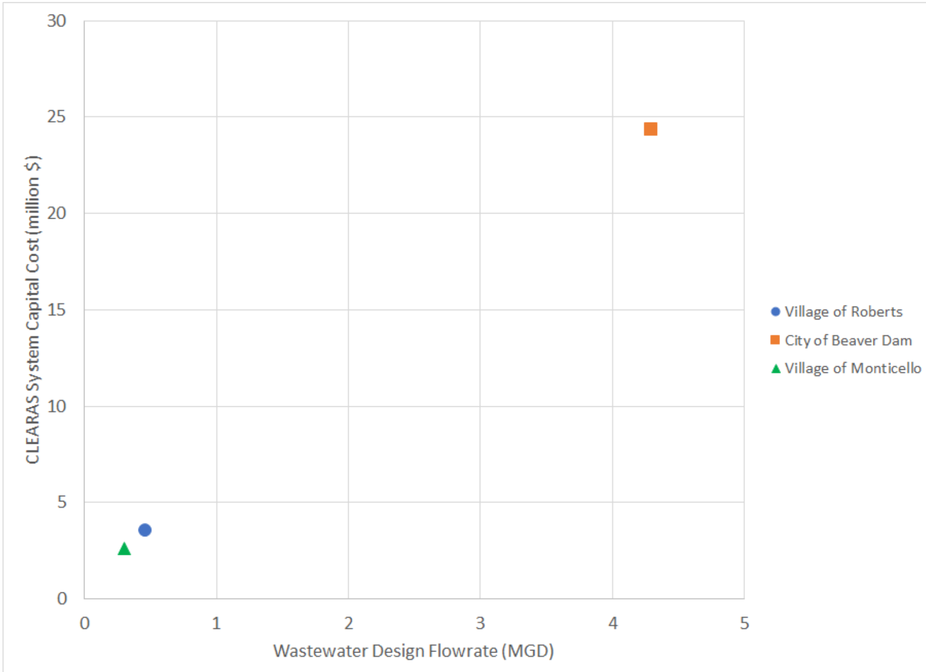


Figure 9. Projected CLEARAS ABNR System construction estimated by linear extrapolation.

The system for the WWTF in the Village of Roberts, WI is estimated to cost around $3.5 million (Lindfors, 2017) and has an average flow of 0.465 MGD ("WI DNR: WPDES PERMIT," 2006); the system for the WWTF in the City of Beaver Dam is estimated to cost up to $24.3 million (Rueter, 2017) and has an average flow of 4.3 MGD ("Wastewater Treatment Facility," 2018). These two case studies are used to linearly extrapolate a construction cost respective to the Village of Monticello WWTF's design flow of 0.3 MGD.

A recurring annual cost of $175,105 will be used to assess this biological phosphorus removal option. It is assumed that the estimated construction cost previously mentioned will be financed over the entire duration of the LCCA through a 20-year loan. Similar to the WWTF Report (Delta 3 Engineering Inc., 2016) an interest rate of 3% is assumed appropriate for this assessment. To calculate a fixed-rate payment the following Equation 1 is used.

$$R = (I/(1-(1+I)^{-N})) * LOAN \quad (1)$$

In Equation 1, R is the fixed-rate payment, I is the interest rate (0.03), N is the number of payment periods (20), and $LOAN$ is the total loan amount ($2.61 million). This results in an annually recurring fixed-rate cost of $175,105.

A recurring annual benefit of approximately $24,055 will be included in the economic impact assessment of this ABNR system. As shown in Table xx of section 4.2.2 there is 0.091 kg of algae wasted per 1,000 gallons of wastewater treated. Based on the average daily flow rate of 0.3 MGD there will be an average of 60.2 and 21,968 lbs of algae wasted daily and annually, respectively. Biomass buyers offered the Village of Roberts WWTF between $0.70 and $1.49 per dry lb of algae (Lindfors, 2017). For the purpose of this assessment it is assumed an average price of $1.10 per dry lb of algae would be appropriate. At this price of dry algae, the Village of Monticello WWTF would on average benefit $60.19 daily and $24,055 annually. The recurring benefit will be subtracted from the recurring fixed-rate cost to define the actual annual recurring cost, which is $151,050.

5.3.LCCA Results and Synthesis

To compare the two phosphorus removal options all future costs were translated into present costs. This calculation utilizes the following Equation 2.

$$P = (F/(1+i)^n) \tag{2}$$

In Equation 2, *P* is the present cost, *i* is the annual rate of inflation of 1.8% (0.018), *n* is the year that is being translated, and *F* is the future cost of the year under inspection. The present cost is calculated for every year of this LCCA and then summed as a total present cost. Any initial costs are defined in the zeroth year as they should already defined as a present cost. A summary of all future costs, present cost, and the total present cost for the two phosphorus removal options is shown in Table 6.

Table 6. Future costs and the total present cost of the SorbX-100 and CLEARAS ABNR phosphorus removal options.

***N* (Year)**	**SorbX**		**CLEARAS ABNR**	
	***F* ($)**	***P* ($)**	***F* ($)**	***P* ($)**
0	5,450	5,450	0	0
1	33,840	33,242	151,050	148,379
2	33,840	32,654	151,050	145,756
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
20	33,840	23,685	151,050	105,722
Total Present Cost	**$569,610**		**$2,518,225**	

Based on the previously defined assumptions the total present cost of the SorbX-100 and CLEARAS ABNR options are $0.57 million and $2.52 million, respectively.

6. SOCIAL IMPACT ASSESSMENT

Social impacts can have a cascading effect, and therefore it is a subjective task to define definitive boundaries. For this analysis, social impacts will be limited to the surrounding community (e.g. residents, small-business owners, local farmers) and workers at the Monticello WWTF. A framework similar to that used in Padilla-Rivera et al. (2016) is used to evaluate the social impacts of each phosphorus removal process. This methodology includes factors separated based on two critical stakeholders: the community and WWTF employees.

Impacts to the community should be evaluated through gauging social acceptance, safe and healthy living conditions, local employment, and contribution to economic development. Social acceptance is investigated through public outreach and meetings with the community, and the opinion of the public should be prioritized, as the WWTF will be serving the community. Common complaints from the public regarding wastewater treatment facilities include foul odor, poor aesthetics, and reliability. The location of the Monticello WWTF assists with its impact on the public, as it is relatively removed from the city center, meaning that it can go unnoticed by many of the city's residents. In addition to the aesthetics of the facility, members of the public are focused on the facility's ability to provide them with clean and reliable water. As long as the system is performing properly, the public's overall opinion of the facility should be positive.

Impacts to workers are evaluated through gauging working hours, health and safety, training, and monitoring programs. Working hours are evaluated based on projected changes from the current operation associated with each phosphorus removal process. Health and safety at the facility is analyzed based on operator's exposure to unhealthy and unsafe conditions. After discussion with current Monticello WWTF employees, it appears that there is not much variation in opinion across phosphorus removal alternatives, and the highest priority is selecting a system that is most efficient at meeting the standards set by the DNR and WPDES. Because pilot studies of the alternative have already been performed, Monticello WWTF employees will not need any additional extensive training for the proposed alternatives, meaning that there will be little disruption to their day-to-day activities.

Beyond direct impacts to the community and WWTF employees, the concept of resilience should be evaluated in order to understand how outside stressors could potentially lead to a system or component failure. Resilience is defined as a system's capacity to recover quickly from difficulties. This is especially important for a publicly relied upon entity such as a wastewater treatment facility, as a system failure could lead to the city's constituents without clean water.

Wastewater treatment practices have historically been designed around supporting human health and environmental protection, however there is now an additional challenge of preparing for the extremes of climate change. This means that the system needs to have both engineering-resilience as well as ecological resilience, as human impact is a significant contributor to the value of a system (P. Juan-Garcia, et al., 2017).

An engineered system is a combination of components that work in synergy to collectively perform a useful function. Such a system can be represented as a set of variables, with a particular structure and relationship. Figure 10 illustrates the conceptual representation of an engineered system within a resilience assessment framework. There are four elements that need to be defined in order to understand how resilience is understood within engineered systems: stressors, properties, metrics and interventions.

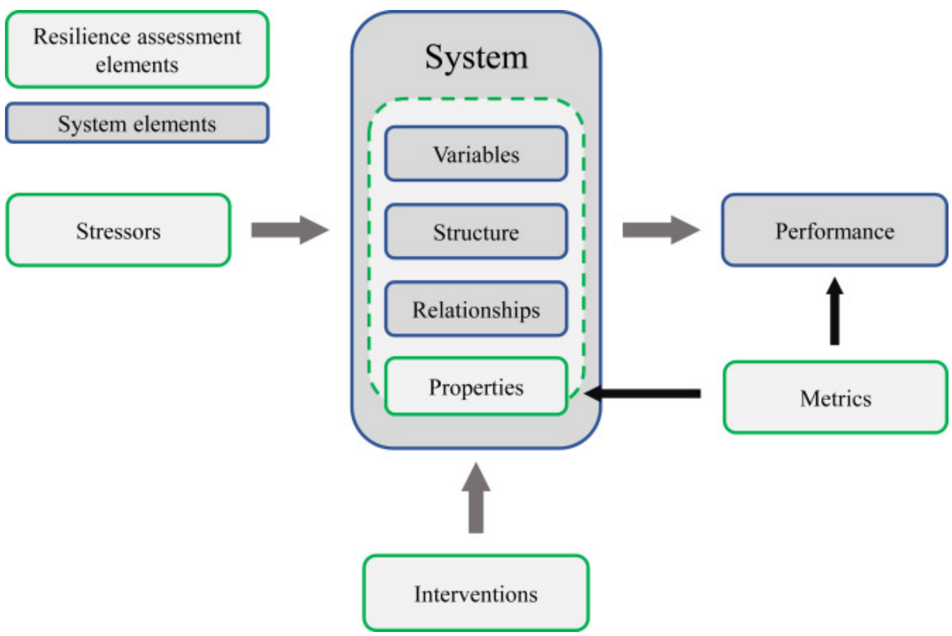


Figure 10. Schematic showing the conceptual components of resilience within an engineered system (Juan-Garcia, et al., 2017).

Stressors of the Monticello WWTF include quality of incoming water, effects of climate change (increased rainfall, colder winters, warmer summers, etc.), and stakeholder opinion. Properties would include the inner workings of the wastewater treatment method. Metrics of the Monticello WWTF would include factors such as effluent phosphorus levels and perceived water quality. As mentioned above, the main factor that could cause the public's opinion of the WWTF to shift would be if there was a failure of the system that left the community without water. The

Monticello WWTF has very little interventions in place that contribute to its resilience given a failure. Beyond a backup generator, a small amount of supplemental storage space in the sludge tank and dikes surrounding the perimeter of the plant to prevent overflow, the treatment plant does not have many built-in components that add to the resiliency of the system. Because of this, a few potential interventions have been proposed, which are summarized in Table 7.

Table 7. Summary table of proposed interventions to increase resilience (Juan-Garcia, et al., 2017).

Intervention	Risk Type	Description
Buffering stormwater tanks	Natural risks	The facility should incorporate additional stormwater tanks to reduce instances of flooding in Sugar River and surrounding areas.
Spare replacement equipment and backup	Mechanical failures	When implementing a new system of maintaining the current system, the facility should ensure that all equipment can be replaced in a reasonable time frame.
Active asset management	Preventative maintenance	Each step of the WWTF process should have sensors and monitors that are able to detect potential system failures.
Increased repair strategy	Mechanical failures	There should be a set strategy in place that predicts potential failures and educates employees on the steps taken to repair said failures.

As seen in the environmental assessment of the two treatment alternatives, the CLEARAS ABNR system has more system inputs that have the potential for failure. The SorbX-100 system is mainly operated by chemical addition, whereas the CLEARAS ABNR system requires new and/or additional equipment on site. Because of this, the suggested interventions in the table above should be more heavily considered if the CLEARAS ABNR system is selected.

Moving forward, there are a number of measures that the Monticello WWTF can take to ensure that the stakeholders are being considered. Any changes to the system should be reviewed with both the employees and the community, supplements to the facility should be made to consider the resiliency of the system, and management should be transparent throughout the lifetime of the facility.

7. CONCLUSIONS

The amount of phosphorus compounds that enter surface waters need to be controlled in order to prevent potential eutrophication issues. Phosphorus may enter the wastewater from domestic or industrial waste discharges or natural runoff, and excess amounts can result in algal blooms which reduces the availability of oxygen for other forms of aquatic life. Currently, DNR and WPDES set lowered effluent phosphorus limits and the Village of Monticello WWTF is piloting a number of alternatives to assist in meeting the forthcoming effluent total phosphorus limits. In this report, the different phosphorus removal strategies that have been applied in the Monticello WWTF are evaluated in terms of environmental, economic and social paradigm of sustainability. The system boundaries are set to include input and output flows of material and energy resources for the operation of the systems over a 20-year period.

The first alternative is SorbX-100 is a chemical treatment approach and uses a rare earth metal chloride solution for phosphorus removal in municipal and industrial wastewater streams. The other alternative is the CLEARAS ABNR System, which uses algae and other biological organisms to recover excess phosphorus, nitrogen and other high-profile contaminants in wastewater.

In terms of environmental paradigm of sustainability, LCA on operations of aforementioned systems are conducted using SimaPro 8.5.2 Software and TRACI 2.1 Impact Assessment Methodology. Results indicate that CLEARAS ABNR System is a better alternative than SorbX-100. If the overall contribution from SorbX-100 is set to 100%, CLEARAS ABNR System shows only 7% of the environmental impacts. Since SorbX-100 uses rare earth metals (Ce and La) for phosphorus treatment, the most impactful phase is resulting from the raw materials acquisition phase.

Regarding economic paradigm of sustainability, both Monticello WWTF resources and assumptions based on previously applied case studies are used. For the overall life cycle costs any initial costs, recurring annual costs, and recurring annual benefits are considered. Based on these values of future costs the total present costs of the two systems is calculated assuming an average inflation rate of 1.8%. The total present cost of the SorbX-100 is found to be \$0.57 million. It should be noted that there were no recurring benefits associated with using this chemical addition phosphorus removal option. Additionally, even though CLEARAS ABNR system has a recurring benefit coming from selling the algae used (\$1.10 per dry lb of algae), the cost of the overall system is found to be \$2.52 million.

With regards to the social analysis, the SorbX-100 and CLEARAS ABNR system have similar overall impacts. Differences between the alternatives are primarily technical, with day-to-day activities varying based on the treatment method. There are no significant differences in impacts that have been noticed by the WWTF employees, and the general opinion of the surrounding community appears to be similar for both treatment alternatives. When considering resilience, the SorbX-100 system has less components that could contribute to failure, meaning that it is likely the more resilient of the two alternatives. In discussions regarding selections of a final treatment alternative, the primary focus of the team's contact at the facility was meeting effluent phosphorus standards, meaning that social impacts were not much of a concern amongst the main stakeholders.

In 2015, the United Nations agreed to implement UN Sustainable Development Goals (SDGs) until the year 2030. There are 17 SDGs related with economy, environment and social dimensions of sustainability, which include human rights, gender equality and empowerment of all women and girls (Figure 11). Generally, Post-2015 agenda is a plan of critical areas that are of importance to humanity and the planet, including action for people, planet, prosperity, universal peace and partnership. These goals and accompanied 169 targets are the signs of the importance of this new universal evolvement.

Figure 11. UN Sustainable Development Goals (United Nations, 2015).

Global goals, especially SDGs 6, 12 and 14 are addressed in this project as well. Both SorbX-100 and CLEARAS ABNR systems improve resource management by encouraging water reuse and recycling which contributes to "*Clean water and sanitati*on (SDG6)[8]" goal. Further, especially CLEARAS ABNR System contributes safe management of chemicals and waste streams, and helps companies to comply with the environmental regulations, which contributes to *"Responsible consumption and production* (SDG12)[9]" goal. Finally, since both SorbX-100 and CLEARAS effectively remove excess nutrients from wastewaters, they help protecting marine ecosystems by controlling nutrient contamination, which is related with *"Life below water* (SDG14)[10]" goal (Sustania, 2018).

A weighting matrix is used to compare the two phosphorus removal options using all three paradigm of sustainability. The weights assigned to each paradigm was based on discussions with stakeholders of the Monticello WWTF. Environmental impacts are given a weight of one, economic impacts are given a weight of three, and social impacts are given a weight of one. Each of these weights were multiplied by the relative impact in comparison to the other option. For example, the economic impact score assigned to the CLEARAS option is 1.00 because it had the highest impact, while the score assigned to the SorbX-100 option is 0.23 as the total cost of this option is 23% of the CLEARAS option's total cost (i.e. \$0.57 million/\$2.52 million = 0.23). Environmental impact scores are a direct calculation as shown in Section 4.4 and the social impact scores are determined to be the same because there were no perceived differences in the two alternatives. These values were multiplied by the respective impact assessment weight and summed. Therefore, in a worst case scenario if an option had the highest impact in all three impact categories the total summed score would be five. The individual impact scores and the total sustainability scores are shown below in Table 8.

[8] *SDG 6: Ensure availability and sustainable management of water and sanitation for all*
[9] *SDG 12: Ensure sustainable consumption and production patterns*
[10] *SDG 14: Conserve and sustainably use the oceans, seas and marine resources for sustainable development*

Table 8. Assessment matrix with sustainability scores.

Impact Assessment (weight)	SorbX-100	CLEARAS
Environmental (1)	1.00	0.07
Economic (3)	0.23	1.00
Social (1)	1.00	1.00
Total (5)	**2.68**	**4.07**

Based on the results shown in Table 8, the recommended option from this analysis is SorbX-100, which received a total sustainability score of 2.68 in comparison to CLEARAS ABNR which received 4.07. Even though the environmental impacts of CLEARAS ABNR were less significant than SorbX-100 the final recommendation is driven by the differences in economic impacts, which are more critical in this analysis.

Future work and considerations for this analysis could include a poll of public opinion on each of the phosphorus removal strategies. This may include gaging the public's value of each of the three paradigms of sustainability. For instance, it is important to see if the community values environmental impacts over economic impacts that may affect their billing rates. This could also include polls on on societal impacts, such as if community members are impacts by odors or noise from the WWTF. Overall, this could be used to help guide the municipality's decision of which phosphorus removal technique they would like to pursue.

PROJECT CONTRIBUTIONS OF TEAM MEMBERS

Project planning methodology of the team was broad, with each member working on the section where they felt they could contribute their best work. In order to ensure that each section of the report was completed, the team worked with the Table 9.

Table 9. Team member tasks and contributions.

General Tasks and Sections	Necessary Work	Contributor(s)
Introduction	Provide information regarding project	*Redacted*
Background and Literature Review	Explain background using previously published works	
Explanation of Monticello WWTF Alternatives	SorbX-100	
	CLEARAS ABNR	
	Effluent Filter	
Environmental Life Cycle Assessment	SorbX Inputs/Outputs	
	CLEARAS Inputs/Outputs	
	Utilization of SimaPro for SorbX and CLEARAS	
	Interpretation	
Economic Impact Assessment	Cost inventory, results, synthesis	
Social Impact Assessment	Considered impacts, resilience analysis	
Conclusions	Conclusions with respect to three paradigm of sustainability	
	Final recommendation using decision matrix	

ACKNOWLEDGEMENTS

The project team would like to thank Mr. Kevin Komprood for his guidance throughout this project, sharing his experiences, and making the technical trip to the Monticello Wastewater Treatment Facility a possibility. Sincere appreciations also go to Prof. Andrea Hicks for her invaluable comments and devoted time to providing her feedback to this project. Lastly, the project team owes a great thanks to Madeline Sena for providing additional resources and materials that helped with the research.

REFERENCES

Abdel-Raouf, N., Al-Homaidan, A.A., Ibraheem, I.B.M. (2012). Microalgae and wastewater treatment. *Saudi Journal of Biological Sciences, 19*(3), 257-275. DOI 10.1016/j.sjbs.2012.04.005

Aluminum Sulfate Anhydrous (Rep.). (2005). Retrieved November 30, 2018, from Open Chemistry Database: https://pubchem.ncbi.nlm.nih.gov/compound/Aluminium_sulfate#section=Top

Bare, J., Young, D., QAM, S., Hopton, M., Chief, S.A.B. (2012). "Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI)", US Environmental Protection Agency.

Bowen, A., Neville, M., Grotton, E., Sangrey, K. (2017, January 25). *Selecting the Optimal Coagulant to Achieve Low-Level Phosphorus and Metal Limits*. NEWEA - 2017 Annual Conference and Exhibit, Boston, MA. Retrieved from http://www.newea.org/wp-content/uploads/2017/02/NEWEA17_Session25_ABowen.pdf

CLEARAS (2016, September 20). CLEARAS' Advanced Algae Filtration Technology Produces Unprecedented Results at Fond du Lac. Retrieved from http://clearaswater.com/press-release/clearas-advanced-algae-filtration-technology-produces-unprecedented-results-fond-du

CLEARAS. (2017, November 22). *Final Report: Flue Gas CO_2 Recycling at Upper Blackstone Water District.* Report for Massachusetts Clean Energy Technology Center (MassCEC), Report No: FY2017-WIP-WTTP-ITPI Retrieved from http://files.masscec.com/FlueGas_Blackstone_Final%20Program%20Report_Final.pdf

Cole-Parmer. (2018). *Cole-Parmer Peristaltic Injector Pump, Variable Speed 95.1 GPD, 115 VAC.* Retrieved from https://www.coleparmer.com/i/cole-parmer-peristaltic-injector-pump-variable-speed-95-1-gpd-115-vac/7420140?PubID=UX&persist=true&ip=no&gclid=EAIaIQobChMIof_Wm5zF3gIVSNbACh2u3A75EAQYBCABEgJrefD_BwE

Corominas, L., Foley, J., Guest, J.S., Hospido, A., Larsen, H.F., Morera, S., Shaw, A. (2013). Life cycle assessment applied to wastewater treatment: State of the art. *Water Research, 47*(15), 5480-5492.

CSEAO (County Sanitary Engineers Association of Ohio). (December, 2015). *Advanced Biological Nutrient Recovery (ABNR™)*. Retrieved from https://www.cseao.org/images/2015-winter-conferences-presentations/clearas-water-recovery.pdf

Delta 3 Engineering Inc. (2016, March 24). P*reliminary Compliance Alternatives Plan and Evaluation - Wastewater Treatment Facility: Village of Monticello, Green County, Wisconsin.* WPDES Permit No. WI-0024830-08-0.

Edmund Optics Inc. (2018). *Advanced Illumination High Intensity Linear Axial Diffuse LED Illuminators.* Retrieved from https://www.edmundoptics.com/f/Advanced-Illumination-High-Intensity-Linear-Axial-Diffuse-LED-Illuminators/14028/

Endress+Hauser Inc. (2018). *Effective water recovery simplified through committed partnership.* Retrieved from https://www.us.endress.com/_storage/asset/2262477/storage/master/file/10777953/download/Clearas%20Case%20Study%2008.29.2016.pdf

Foley, J., de Haas, D., Hartley, K., Lant, P. (2010). Comprehensive life cycle inventories of alternative wastewater treatment systems. *Water Research*, 44, 1654-1666. doi:10.1016/j.watres.2009.11.031

Fond du Lac Low Level Phosphorus Efforts & SNRP Overview (Rep.). (2016). Retrieved November 30, 2018, from CSWEA Resource Recovery Seminar: http://cswea.org/wp-content/uploads/2017/09/0900-0945_Low-Level-P-Pilots-and-Analysis-Fond-du-Lac.pdf

Garfi, M., Flores, L., Ferrer, I. (2017). Life Cycle Assessment of wastewater treatment systems for small communities: Activated sludge, constructed wetlands and high rate algal ponds. *Journal of Cleaner Production*, 161, 211-219. doi:10.1016/j.jclepro.2017.05.116

Gerber, P., Vellinga, T., Opio, C., Henderson, B., Steinfeld, H. (2010). Greenhouse Gas Emissions from the Dairy Sector: A Life Cycle Assessment. *Food and Agriculture Organization of the United Nations*, pp 36.

Gonzales, J. M. (2015). Fluoride and Phosphate Removal From Industrial and Domestic Wastewaters Using Cerium Chloride.

Google Maps (2018). Retrieved from https://www.google.com/maps

ISO 14040 (2006). Environmental Management – Life Cycle Assessment – Principles and Framework, Geneva, Switzerland.

Johnson, R. (2013, August 14). *Advanced Biological Nutrient Recovery: Clearas Water Recovery.* Retrieved from http://www.emcenter.org/wp-content/uploads/2014/03/Clearas-Water-Recovery-Presentation.pdf

Johnson, R. (2016, April 19). *Nutrient Reduction Through Use of an Advanced Biological Nutrient Recovery Process.* Retrieved from http://clearaswater.com/sites/default/files/resource-attachments/Influents%20Article_19apr16.pdf

Juan-Garcia, P. et al, (2017, May 15). Resilience Theory Incorporated into Urban Wastewater Systems Management. *Water Research.* https://doi.org/10.1016/j.watres.2017.02.047

Lindfors, T. (2017, February 3). Village moves closer to phosphorus solution. *River Towns*. Retrieved from http://www.rivertowns.net/news/government-and-politics/4210548-village-moves-closer-phosphorus-solution

Lupo, J. (2014, August 27). *New and Innovative Rare Earth Technology for Low-Level Phosphorus Removal.* Ohio One Water 2014, Columbus, OH. Retrieved from https://www.onewaterohio.org/docs/1055_new_and_innovative_rare_earth_technology_for_phosphorus_removal.pdf

Metcalf & Eddy, I. (2003). Wastewater engineering: treatment and reuse. Fourth edition / revised by George Tchobanoglous, Franklin L. Burton, H. David Stensel. Boston: McGraw-Hill, [2003] ©2003.

Neo Chemicals and Oxides (2017). *RE100 Product Data Sheet.* Retrieved from https://neowatertreatment.com/wp-content/uploads/2017/04/RE100_Product_Data_Sheet_March-2017.pdf

NOAA (2018). *What is eutrophication?*. National Oceanic and Atmospheric Administration. Retrieved from https://oceanservice.noaa.gov/facts/eutrophication.html

Oko-Institut e.V. (2011). Environmental aspects of rare earth mining and processing. In Study on Rare Earths and Their Recycling.

Padilla-Rivera, A., Morgan-Sagastume, J. M., Noyola, A., GüerecaPadilla-Rivera, L.P. (2016). Addressing social aspects associated with wastewater treatment facilities, *Environmental Impact Assessment Review*, 57, 101–113. http://dx.doi.org/10.1016/j.eiar.2015.11.007

Phosphorus Treatment and Removal Technologies (Rep.). (2006). Retrieved from https://www.pca.state.mn.us/sites/default/files/wq-wwtp9-02.pdf.

RE-100 and RE-300 can result in high bias of Arsenic and potentially other metals in biosolids. (Rep.). (2017). Retrieved November 30, 2018, from https://www.wwoa.org/files/2017/RE-100 notice.pdf

Reuter, B. (2017, November 13). Beaver Dam settles with DNR and moves forward with facility plan. *Daily Citizen*. Retrieved from https://www.wiscnews.com/bdc/news/local/beaver-dam-settles-with-dnr-and-moves-forward-with-facility/article_a02f7f92-5e0d-5251-b2e6-f88cf24c3e84.html

Robinson, T.S., McGraw, K.S., Sylvester, J.W., Weidow, J.D. (2012, January 24). *United States Patent: Advanced Biologic Water Treatment Using Algae*. Patent No.: US #8101080 B2.

Singh, P., Carliell-Marquet, C., Kansal, A. (2012). Energy pattern analysis of a wastewater treatment plant. *Applied Water Science, 2*, 221–226. DOI 10.1007/s13201-012-0040-7

Sustania (2018, November 16). Biological Nutrient Recovery From Wastewater Streams. Retrieved from https://goexplorer.org/biological-nutrient-recovery-from-wastewater-streams/

United Nations (UN). (2015). *Sustainable Development Goals*. Retrieved from https://sustainabledevelopment.un.org/?menu=1300

Univar Inc. (2013, March 4). Univar Announces Exclusive North American Distribution Agreement with Molycorp Advanced Water Technologies. Retrieved from https://investor.univar.com/investors/investor-news/investor-news-details/2013/Univar-Announces-Exclusive-North-American-Distribution-Agreement-with-Molycorp-Advanced-Water-Technologies/default.aspx

U.S. Bureau of Labor Statistics (2018). All items less food and energy in U.S. city average, all urban consumers, not seasonally adjusted. Retrieved from https://data.bls.gov/timeseries/CUUR0000SA0L1E?output_view=pct_12mths

Wastewater Treatment Facility. (2018). Retrieved from https://www.cityofbeaverdam.com/department/division.php?structureid=149

Weber, R. J., & Reisman, D. J. (2012). Rare earth elements: A review of production, processing, recycling, and associated environmental issues. *US EPA Region*.

Wisconsin Department of Natural Resources (2017). "Guidance for Implementing Wisconsin's Phosphorus Water Quality Standards for Point Source Discharges". Guidance Number: 3400-2011-02, 2nd Edition.

Wisconsin Department of Natural Resources. (2017, February 13). Wisconsin's phosphorus rule. Retrieved from https://dnr.wi.gov/topic/surfacewater/phosphorus/.

WI DNR: WPDES PERMIT - Village of Roberts Wastewater Treatment Facility. (2006, July 6). *Hudson Star-Observer*. Retrieved from http://www.hudsonstarobserver.com/news/948162-wi-dnr-wpdes-permit-village-roberts-wastewater-treatment-facility

Wright, R. (2015, January 23). *An Overview of the Activated Sludge and Nutrient Removal Process,* Blacoh University Engineer Series. Retrieved from https://www.youtube.com/watch?v=sb_heMM5vzs

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