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Civil Engineering Capstone Design Project

Design of a Water Treatment System for the Ryan Epps Home for Children in Haiti

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Department of Civil Engineering

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March 2015

March 16, 2015

Martin Bollo, PEng
Department of Civil Engineering
British Columbia Institute of Technology
3700 Willingdon Avenue, Burnaby, BC V5G 2N7

Dear Martin Bollo,

Submission of CIVL 7090 Capstone Design Project

We, the undersigned, are pleased to present this design report as per the course requirements for the CIVL 7090 course. For this project, we have developed the design for a full-scale water treatment system for the Ryan Epps Home for Children in Haiti. This design has been based on the construction and testing of a pilot scale ultrafiltration system built at the British Columbia Institute of Technology. Using existing site conditions in Haiti provided by our sponsor, and empirically obtained data from the pilot system, Optimus has developed a unique design solution.

As requested, the design solution presented by Optimus was developed with considerations made for alternative options and long term sustainability. The design report prepared outlines the project background, methodology, relevant design specifications, and recommendations. In addition to design recommendations, Optimus has included an implementation plan, a business plan, and an operating manual to accompany the full-scale system model. Estimated project costs, and potential areas for further project development and testing have also been identified.

The attached report is entirely original and has been completed solely by team Optimus. By signing this document, all parties agree to an equal evaluation and an equal grade for this report. We trust that this design report meets the expectations and deliverables as per the CIVL 7090 project criteria.

Sincerely,
Optimus Engineering Associates

David Lorenzi – Project Manager

Lindsey LeBlanc – Hydraulic Engineer

Meghan Matienzo – Environmental Engineer

Shane Haxton – Water Resource Engineer

Attachments: REHC Water Treatment System Design Report – Vol. 1
REHC Water Treatment System Appendices – Vol. 2

Disclaimer

The work represented in this Client Report is the result of a student project at the British Columbia Institute of Technology. Any analysis or solution presented in this report must be reviewed by a Professional Engineer before implementation. While the students' performance in the completion of this report may have been reviewed by a faculty advisor, such review and any advice obtained therefrom does not constitute professional certification of the work. This report is made available without any representation as to its use in any particular situation and on the strict understanding that each reader accepts full liability for the application of its contents.

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Team Optimus would like to acknowledge the following people for their technical advice, project support, and encouragement. Optimus recognizes that this project would not be possible without the contributions that each of these individuals provided. Their efforts and dedication to the project are greatly appreciated.

Syed "Zaki" Abdullah, PhD: Zaki is a civil and environmental engineer with the University of British Columbia. His technical expertise and advice regarding membrane filtration technology was invaluable to Optimus. Zaki encouraged the team to be innovative and helped develop the idea of utilizing a minimal energy gravity flow system. The tours of the UBC labs and the personal time and effort that he spent to get this project off to a good start is greatly appreciated.

Colleen Chan, PhD, PEng: Colleen is one of the faculty at the British Columbia Institute of Technology and acted as the technical advisor for this project. Her support in obtaining pertinent project details, ordering the membrane filters, and problem solving helped keep the team on track. Optimus would like to acknowledge and thank her for introducing the team to water quality engineering and inspiring the development of this project.

Mike Baumert, PhD, PEng: Mike is another faculty member at the British Columbia Institute of Technology. He is the lab coordinator for the civil department, and helped team Optimus gain access to the facilities and equipment that played a vital role in the pilot testing component of the project. In addition, Mike helped the team procure project materials. His advice and positive attitude kept the team in good spirits during the beginning of the project when the team encountered initial problems.

Sepideh Jankhah, PhD: Optimus would like to thank Sepideh for providing technical information and advice during the onset of the project. Her experience with water quality engineering and membrane filtration helped the team with their overall design.

AquaSolve Ventures: Sponsorship for this project was provided by AquaSolve Ventures. Their preliminary data, advice, and support inspired Optimus to take on this project. Optimus modelled this project from AquaSolve's previous project work in Haiti which helped with the development of project criteria and objectives. It was the goal of this project to create a design solution meeting the high level of standards that AquaSolve has set with their global achievements.

Team Optimus would also like to thank many others for their support and encouragement during the course of the project: Jay Kim for his playful humour in the lab and help with providing pretreated water, fellow colleagues in the civil engineering program for their input, and friends and family for their patience and understanding of all the long nights and weekends away.

Executive Summary

As per the course requirements of CIVL 7090: Capstone Design Project, Optimus Engineering Associates (Optimus) has developed a unique solution to an open ended engineering project. For this project, a water treatment system for the Ryan Epps Home for Children in Haiti (REHC) has been designed utilizing membrane filtration technology. Industry sponsorship was provided by AquaSolve Ventures (AquaSolve) and technical support has been provided from faculty at the British Columbia Institute of Technology (BCIT) and the University of British Columbia. The main objectives of this project included the development of a full system design and an implementation strategy incorporating social, economic, and environmental sustainability.

Haiti is a country in the Caribbean that has been devastated in the past by natural disasters and disease. This, combined with the poor geological conditions, has left much of the population without access to clean drinking water. Many of the water sources that are used by Haitians are contaminated with bacteria and other pathogens. As such, there is a need in Haiti for water treatment systems to help provide sufficient clean drinking water. REHC is a school and home for children located near Croix-de-Bouquets in central Haiti. This is home for 30 children year-round and accommodates 200 students during the school year. REHC has an existing well on site but has no water treatment or power facilities.

Ground water in Haiti is generally not very turbid, but can be contaminated by fecal bacteria which cause diseases such as cholera. As such, removal of these types of bacteria was the main focus of our treatment system. Haiti currently does not have its own water quality standards, so World Health Organization (WHO) drinking water guidelines were used for this project. As per WHO drinking water guidelines, standards for pathogen removal are as follows:

- 4-log removal for bacteria and viruses
- turbidity of less than 0.3 NTU
- zero E.coli per 100 mL sample

During the pilot model test, these water quality parameters were monitored.

In order to remove pathogens from water, there are several methods such as settlement and filtration. Based on the site constraints, direct filtration was best suited for this system. In a direct filtration system, there are three main stages: pre-treatment, filtration, and disinfection. Pretreatment is meant to remove large particles prior to filtration. Filtration is used to remove pathogens and can effectively

produce clean water. Disinfection is a precautionary step that protects the users in the case of a filtration breach.

Membrane filtration was selected as the filtration method over other methods such as sand filtration because of the much smaller footprint required. A gravity-fed membrane filtration system was chosen to suit the constraints of our location for the following reasons:

- Produces sufficient amounts of water
- Uses little energy
- Has low maintenance requirements

Membrane filtration is a fairly new technology which works by providing a barrier that prevents the passage of small particles called foulants. Flow through membranes decreases over time due to fouling, so periodic backwashing and chemical cleaning are used to restore the losses.

A pilot model was built and tested at BCIT to determine the performance characteristics of the gravity-fed membrane filtration water treatment system. This model was tested for approximately six weeks. During this trial, sand-filtered creek water was used to simulate the low turbidity and high bacteria groundwater conditions in Haiti. Turbidity, microbiological parameters, and flux were monitored over the course of the trial period. Optimus was able to successfully remove fecal bacteria from the creek water. As well, from the flux data collected, Optimus was able to determine an optimal backwash frequency for the REHC system.

Two membrane configurations with different surface areas were tested using the pilot model. From this trial, Optimus was able to confirm that the pilot model system could be scaled up directly based on membrane surface area. As such, the full-scale treatment system was designed with the same hydraulic characteristics as the pilot model, but with a much larger membrane surface area.

The REHC water treatment system was designed with the following components:

- A solar-powered well pump to extract the groundwater
- Pre-treatment storage tank with constant head tank
- Pre-screen unit
- Membrane filtration modules
- Post-filtration storage tank with disinfection

- Backwash water storage tank and backwash system

These components will be housed in a reinforced concrete support structure so that elevation is provided for the gravity feed system to work. This system has been designed to treat enough water for the REHC students and staff, with excess to be sold to the locals in the community.

To promote environmental and social sustainability, most materials and components for this system were sourced in Haiti. As well, local construction materials and labor are recommended to be used during the construction. The wastewater produced by backwashing will be discharged into an infiltration trench to further promote these sustainability considerations.

A sustainable implementation plan has been developed to ensure the treatment system is viable. As part of this plan, REHC officials and community members will be consulted prior to deploying the system. Deployment will take three months and involves the following steps: consultation, collecting materials, constructing the system, initializing the system, training system operators, and setting up a water selling business. After this, phone and email support will be provided for five years. The water treatment system implementation will be validated if the system is operational, producing clean drinking water, and is able to recover costs through selling water. After five years, Optimus will continue to provide support, however, responsibility for operating and maintaining the system will be passed on to REHC.

An operation and maintenance manual has been prepared for the water system operators at REHC. Within this manual are detailed descriptions of the system operation, backwashing, chemical cleaning, maintenance, and monitoring requirements. As well, a section in the manual is dedicated to educational considerations for training operators.

A WASH program was produced for the staff at REHC to promote sanitation and hygiene for students and the community. This program contains recommendations for REHC teachers to incorporate sanitation and hygiene into their curriculum. A child-friendly pamphlet has also been produced to make these recommendations clearer for the children at REHC.

A business plan has been developed to set up REHC Pure Water: a business that will sell excess treated water to members of the community. Proceeds for this business will go towards recovering system deployment costs, paying for system operating costs, and to fund future maintenance and upgrades to REHC. We anticipate that there is enough of a market within walking distance of REHC to make the business successful. Based on conservative estimates, Optimus believes that deployment costs can be recovered within five years.

Many alternative options were evaluated for the final product. Some of the alternative options that were considered include:

- Type of membrane filtration method used (microfiltration & ultrafiltration), and filters used (hollow fibre, sheet, hollow tube)
- Gravity system vs pumped system
- Manually operated backwash vs automatic backwash
- Options for dealing with wastewater
- Option for water delivery business
- Materials selection

Through analysis of the above alternatives, the most suitable options were chosen to fit the site conditions.

Although comprehensive analysis was done, there are still some aspects of the project that are outside of the scope and require more design and analysis. Some of these aspects are the structural design of the support system and storage tanks as well as a more thorough geotechnical analysis. As well, this project has been conducted based on limited research data. As such, actual site conditions must be confirmed as they could differ from what has been presented.

Optimus feels that this design project exceeds all of the design criteria considered, and meets all project requirements. Through completion of this project and report, it is Optimus' recommendation that the water treatment system for REHC be implemented as per this report.

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List of Symbols and Abbreviations

AquaSolve	AquaSolve Ventures
BCIT	British Columbia Institute of Technology
CDN	Canadian Dollar
Committee	Capstone Project Committee
DBP	disinfection by-products
DINEPA	National Directorate for Potable Water and Sanitation
EPA	United States Environmental Protection Agency
HTG	Haitian Gourde
kWh	kilo-Watt hour
Lmh	Litres per meter squared per hour
Lpm	Litres per minute
MF	Microfiltration
NTU	Nephelometric Turbidity Unit
Optimus	Optimus Engineering Associates
ppm	parts per million
PVC	Polyvinyl chloride
PVDF	Polyvinylidene fluoride
REHC	Ryan Epps Home for Children
TMP	Trans Membrane Pressure
UNICEF	United Nations Children's Fund
UF	Ultrafiltration
USD	United States dollar
UV	Ultraviolet
WASH	Water, Sanitation, & Hygiene
WHO	World Health Organization

1.0 Introduction

As per the course requirements of the CIVL 7090 Capstone Design course, Optimus Engineering Associates (Optimus) is pleased to present this report outlining the design and implementation of a water filtration system for the Ryan Epps Home for Children (REHC) in Haiti. This project follows from Optimus' proposal that was accepted by the Capstone Project Committee (Committee) during the CIVL 7089 Capstone Design Proposal course. As requested, Optimus has developed a design solution to an open-ended engineering project. The subsequent design takes into account alternative design options in addition to implications on sustainability and economy. This report details the project scope, methodology, pilot testing results, system design and alternatives, sustainability considerations, and estimated costs for the REHC water purification project.

1.1 Problem Statement

Optimus has been retained by the British Columbia Institute of Technology (BCIT) to develop a design for a water purification system to be implemented at REHC. This project includes the development and testing of a pilot model followed by a full-scale design based off existing and empirically determined design parameters. Industry sponsorship for this project has been provided by AquaSolve Ventures (AquaSolve), with additional technical support provided by faculty at BCIT and advisors from the University of British Columbia (UBC).

1.2 Project Scope

The scope for this project, as outlined in the project proposal, includes the following:

- Development of a pilot model water filtration system
- Testing and analysis of the pilot system
- Conceptual design of full-scale system for REHC based on pilot testing
- Creation of business plan, implementation plan, and operations manual
- Creation of design drawings for key system components
- Recommendations for project sustainability and economy

Sustainability is one of the primary considerations for successful implementation of a water treatment system in any developing nation. As such, this aspect of the project was emphasized in the project scope, where Optimus targeted social, economic, and environmental aspects.

Initially, structural and geotechnical considerations for individual system components and site conditions were to be included in the scope. However, due to Committee feedback, these items were removed from the project scope due to time limitations.

2.0 Background

Optimus identifies the importance of creating a well-rounded sustainable solution to improve the living conditions for the residents and students of REHC. Local environment and water quality characteristics in Haiti play key roles in the implementation of the proposed design solution. In addition, a strong understanding of the project site's history, project design criteria, and relevant standards help ensure the final design focuses on immediate and long-term actions necessary to ensure the filtration system is effective.

2.1 Haiti

Haiti is a country in the Caribbean which has a population of approximately 10 million people and occupies the western one-third of the island of Hispaniola. Deforestation since the early 1900's has left only 2% of the island forested, which when combined with the sloping geographical conditions, contributes to the erosion of fertile soils and decrease in groundwater recharge (Peter J. Wampler & Andrew J. Sisson, 2011). The primary economic activity is farming; however, dense population and soil erosion now limit farmers to very small parcels of land. The lack of economic and social opportunities for Haitians has led to widespread poverty and corruption. About two-thirds of the population are unemployed and three-quarters live in poverty (Columbia Electronic Encyclopedia, 6th Edidtion., 2013). As a result, many of the lower class families have little education and do not understand the importance of sanitation.

On January 12, 2010, a devastating 7.0-magnitude earthquake struck the nation, resulting in an estimated 316,000 fatalities and the displacement of over 1 million people (Fritz, Hermann et. al, 2013). The already poor conditions in Haiti were magnified in many aspects by this event. The epicenter of the earthquake was located 25 km off the coast of Port-au-Prince, the nation's capital. This area was one of the worst struck, destroying many of the political buildings and contributing to the political instability (Klarreich, 2012). Many of the wells and drinking water supply systems were also destroyed by the earthquake forcing many people to rely on contaminated water sources. This produced a dramatic increase in people, especially children, becoming sick as a result of waterborne diseases. Many people in Haiti still need help to access clean drinking water.

2.2 Support in Developing Countries

The need for external support is especially important in developing countries. These locations are often poor and unprepared for natural disasters which can lead to catastrophic results. As well, developing countries typically lack the infrastructure for proper sanitation and clean drinking water. When disaster strikes, these conditions tend to cause civil unrest and corruption resulting in the need for external support. Many relief programs have been created with the goal of re-establishing healthy living conditions. However, many of these programs have underperformed with regards to their long-term sustainability (Davis, 2014). With these in mind, Optimus' goal considered economic, social, and environmental aspects of long term sustainability as a top priority in the water treatment system design.

2.3 The Ryan Epps Home for Children

This project focused on supplying clean water for REHC, located in a suburb of Port-au-Prince. This children's home and school was founded in January 2007 and is a safe haven for orphaned boys and girls in Haiti. It currently houses approximately 30 children year-round and as many as 200 children, including others from the surrounding community, attending REHC during the school year.

Figure 1: Residents of the Ryan Epps Home for Children (Ryan Epps Home for Children, n.d.)

REHC has recently expanded their operation by building a community center nearby that offers classes to adults from the adjacent areas. The community center has been built to allow for future expansion including a second floor. Optimus believes that a sustainable water treatment system can contribute to these future expansions.

2.4 Design Criteria

The primary objective of this project is the development of a plan for water treatment to allow for drinking and sanitary purposes at REHC. The anticipated water demand for the orphanage was determined using several considerations. Optimus identified the general baseline usage for water to be approximately 6.1 L per person per day in Haiti (PCI, 2012). However, since the primary users at REHC are mainly of children, the quantity of treated water output will be increased. This increase is because hydration requirements are related to metabolism, and since children have higher metabolisms than adults, they are more susceptible to dehydration (Derbyshire). Moreover, children are more susceptible to waterborne diseases and should take extra precaution with sanitary practices. Additionally, water demands should be doubled in regions, such as Haiti, with hot climates (Ready, 2014). In lieu of these considerations, the following design criteria are used for design:

- 20 L/person – permanent children residents
- 15 L/person – school-time children
- 15 L/person – Adult staff members

The REHC site consists of a large school and church building, a kitchen, and a newly constructed home for the children. The water treatment system was designed to be installed on the square plot of land located to the west of the kitchen building as shown in Figure 2.

Figure 2: Plan view of the Ryan Epps Home for Children (Google 2015)

The area available for the water treatment facility is estimated to be approximately 550 m^2. Optimus has designed the system in this area since it is located beside the well, minimizing the quantity of piping required for installation. The opening in the fence shown in Figure 2 has since been gated off to provide security for REHC's investment. The total size of the system has been influenced by both the demand for treated water and the area allotted to construct it.

2.5 Water Contaminants for Treatment

One of the most important elements to consider with water treatment technologies is the type of contamination that needs to be remediated. Bacteria and viruses transmitted through fecal matter in water are responsible for millions of deaths every year in developing countries. Further considerations include organics, such as arsenic and mercury, and inorganic compounds, such as pesticides and fertilizers, both of which can also have negative effects in high enough concentrations (EPA, 2013). The type of contamination present in the water is highly dependent on the source of its supply. Different pathogens, minerals, and other substances may be picked up as the water flows along its course. For example, water from an underground supply may be relatively free of pathogens but may contain high levels of inorganic chemicals due to the dissolution of the minerals in the rock (LeBlanc et Lorenzi, 2014). These concerns need to be addressed to determine the most appropriate method to treat the water source.

The water source at REHC is an existing 100 mm diameter well with a depth of 40 m and a water table of 20 m. AquaSolve has advised that the maximum flow that can be drawn from the well is approximately 110 liters/minute (Lpm) (Wong, 2015). Due to the lack of water quality data available for this source, Optimus has based the water quality assumptions for contamination on a field study conducted in 2008 near Verrettes, Haiti. The findings from this study can be found in Appendix A. Figure 3 shows the location of Verrettes relative to Croix-des-Bouquets.

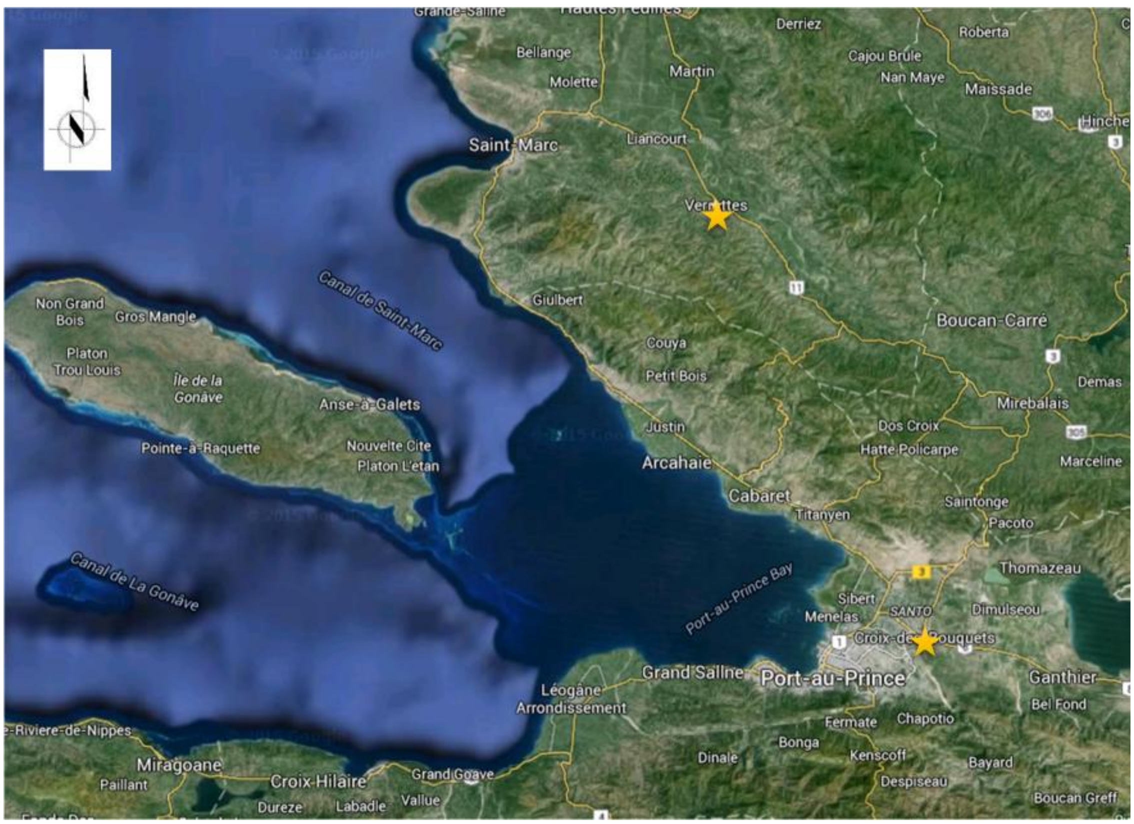

Figure 3: Locations of Verrettes and Croix-des-Bouquets, near REHC (Google 2015)

Optimus believes that the data for Verrettes should be representable of the conditions at REHC since both locations are surrounded by small farming communities and the capped springs studied in the article are very similar to the capped well at REHC. Deforestation and substantial erosion of soils has reduced the natural filtration of biological contaminants which is apparent in the testing data. Optimus has based the water quality assumptions for the designed system on the average turbidity, E. coli, and total coliform data for the capped springs shown.

Typically, ground water sources may also contain dissolved minerals and objectionable gases. Water hardness is a result of minerals such as calcium and magnesium and can create issues on water facilities through scale buildup on pipes and filter membranes. While there are no known health risks associated with the consumption of hard water, concerns for humans may include gray staining of washed clothes and reduced lathering of soaps. Optimus has been advised by AquaSolve that the water hardness levels in the source water at REHC are low and do not need to be considered for this project.

2.6 Relevant Design Standards & Guidelines

Historically, minimal standards or regulations for both water quality and sanitation are existing in Haiti. In 2009, the National Directorate for Potable Water and Sanitation (DINEPA) was formed by Haitian parliament. DINEPA's mission is the development and regulation of the potable water and sanitation sector in Haiti, and management of all actors within the sector (Joseph, 2015). However, no set standards have been implemented to date. Efforts to reform the existing water resource and sanitation practices have been ongoing since the 2010 earthquake.

Optimus' design for the REHC water treatment system incorporated standards set by the United States Environmental Protection Agency (EPA), the World Health Organization (WHO), and Health Canada. These regulating bodies produce local and international norms on water quality and human health guidelines. Standards set by these agencies meet or exceed acceptable health standards and will ensure that the design solution promotes ongoing conformance with future targets for Haiti. In addition, Optimus has followed the international Water, Sanitation and Hygiene (WASH) guidelines for sanitation and water system implementation, more specifically the guidelines from United Nations Children's Fund (UNICEF) and The Sphere Handbook (Centers for Disease Control and Prevention, 2013).

2.6.1 Contaminant Log Removal

Water industries have expressed the level of physical removal and inactivation of microorganisms in terms of log removal. Log removal is not a logarithmic process, but rather, it means that the percent removal found at a point in time can be mathematically represented by a log removal function. It is expressed as 90% or microorganisms inactivated for 1-log inactivation, 99% for 2-log inactivation, 99.9% for 3-log inactivation, and 99.99% for 4-log inactivation.

EPA specifies recommendations to improve drinking water quality and to provide additional protection from disease-causing microorganisms. The targeted requirement for drinking water sources is to achieve 4-log inactivation or removal of viruses.

The Canadian standards set in the Drinking Water Protection Act specify similar bacteriological water quality standards for potable water and the protection of human health. These standards have been based on WHO recommendations and contain treatment objective parameters for enteric viruses and pathogenic bacteria including the following:

- 4-log reduction or inactivation of viruses.
- 3-log reduction or inactivation of Giardia and Cryptosporidium.
- Two treatment processes for surface water.
- Less than or equal to (≤) one Nephelometric Turbidity Unit (NTU) of turbidity.
- No detectable E. coli, fecal coliform and total coliform (World Health Organization, 2011)

Based on table 7.8 from WHO's Guidelines for Drinking-water Quality (World Health Organization, 2011), the removal credits from the direct filtration method that is used for Optimus' REHC design are shown in Table 1.

Table 1: Log Removal for Optimus Direct Filtration System

System	Type	Log Removal	Cumulative Removal
Pre-treatment	None	0	0
Filtration	Ultrafiltration	3	3
Chemical Disinfection	Free Chlorine	3	6

*Note Table 7.8 can be seen in Appendix B. Baseline values were used by Optimus for a more conservative design.

An important design consideration made by Optimus was that a multi-barrier approach to log removal credits was incorporated. This staged approach helps to ensure that treatment requirements are met with a satisfactory level of safety in the event that one stage fails or performs below expected levels. Based on the assumption that the design treatment system achieves a full log credit for the individual systems, Optimus' solution for REHC aimed to achieve a reliable minimum 4-log contaminant removal or inactivation of viruses.

2.6.2 Turbidity Requirements for Drinking Water

Turbidity is the measure of the scatter of light through water caused by suspended or dissolved matter in water. These materials present in natural waters can be clay, silt, organic and inorganic fines, soluble colored organic compounds, and other microscopic organisms such as plankton and pathogen microorganisms. High turbidity measures indicate large amounts of suspended and dissolved material present in the water (BCIT Dept. Civil Engineering, 2014).

The WHO specifies a turbidity limit of 0.3 NTU for drinking water (World Health Organization, 2011). While there are no direct health implications associated with the turbidity of a water source, it provides an indicator of the overall water quality and the effectiveness of the filtration process. Optimus' water treatment system aims to achieve an effluent turbidity level less than 0.3 as specified by WHO.

2.6.3 Chemical Removal Requirements

According to EPA regulations, there are maximum water contaminant levels for chemicals and organic substances that can be hazardous to human health. Some of these contaminants include disinfectants and disinfection by-products (DBP) such as chloramines and trihalomethanes, inorganic chemicals such as arsenic and fluoride, and organic chemicals such as benzene. While DBP and other contaminant levels must be monitored to meet water quality standards set by EPA, they are not typically monitored in developing countries such as Haiti. Considerations for these contaminants are outside of the scope of this project but should be considered upon implementing a long-term sustainable solution.

3.0 Methodology

The methodology used for this project has been based upon relevant water quality standards and engineering principles. Optimus included both physical and chemical treatment processes in the design to ensure that system integrity and efficiency can be maintained for the lifespan of the project. The extent of both treatment processes is dependent on the quality of the source water; therefore, Optimus first identified which contaminants are likely to be present in the REHC well-water supply. Optimus then developed and tested a pilot model treatment system to simulate full-scale performance under these expected conditions. Finally, Optimus developed recommendations for the full-scale REHC system based on the given design criteria and empirical results obtained from the testing process.

3.1 Direct Filtration Water Treatment Principles

The methods of treatment required to make water suitable for drinking depend on the source of the water and exiting condition of the water. The true effectiveness and efficiency of a water treatment system depend on a number of factors, such as cost and ease of use. In some cases, it may be necessary to combine methods in order to create an effective program. Optimus' water treatment system design for REHC utilizes a direct filtration method powered by gravitational energy to produce safe drinking water. The process model for this system is shown in Figure 4.

Figure 4: Direct filtration process model

As can be seen in Figure 4, the direct filtration process used by Optimus involves three sequential steps. The first step of the process is pre-treatment, followed by filtration, and finally disinfection.

3.1.1 Preliminary Treatment

The main objective with preliminary treatment is to remove large particles, suspended solids, or other particulate that may lead to an increased rate of fouling or clogging of the subsequent filtering processes. This way, the performance of the main filtration components is optimized for its long-term usage. Methods for pre-treatment may include rough screening, while initial filtration methods may include microfiltration (MF). Other contaminants such as such as chemicals, gases, and dissolved minerals may also be target objectives for the preliminary treatment process. For hard water sources, processes such as lime or soda ash dosing and sedimentation may be required.

Design characteristics provided from AquaSolve indicated that groundwater extracted from the well at REHC has minimal turbidity and hardness levels. Therefore, Optimus' plan for preliminary treatment is focused on removing rough particulate only, leaving smaller particulate to be treated in the main filtration process.

3.1.2 Filtration

Many filtration methods have been successfully implemented in developing countries, including slow sand filters, household/point-of-use filters, and membrane filters. Optimus feels that a membrane filtration system is best fit for the constraints of the REHC location because it can produce a sufficient quantity of water with minimal energy consumption and maintenance requirements. Optimus feels that production rates for slow sand filters and biosand filters will not be high enough to meet the demands for

REHC. Household filters also do not provide a sustainable long-term solution and can be hazardous if the user is not educated about proper sanitation practices.

Membrane filtration is a relatively new technology that has become widely accepted for many applications around the world. MF and ultrafiltration (UF) are typically used to treat ground and surface water sources that are not saline. These systems have high production capacities but often require a large amount of energy to power the pumps and instrumentation. Several organizations have implemented these type of systems in developing countries, including AquaSolve. The membrane filtration system Optimus developed for REHC utilizes gravity feed system to minimize the power requirements while satisfying the demand for clean drinking water.

Materials filtered out of the water can be categorized as temporary fouling or permanent fouling. These small solid particles are either trapped in the pores or on the membrane surface. Most of these particles are temporary foulants, since they can be removed by backflushing the system with clean water. The bacteria removed by the membrane can adsorb to the surface and may not be effectively removed by backflushing. Periodic chemical cleaning is required to remove this permanent fouling and restore the membrane flux approximately back to its original state. The frequency of backflushing and chemical cleaning was determined based on the fouling rate in the pilot system.

3.1.3 Disinfection

A precautionary disinfection process takes place once the source water has been filtered. This is part of the multi barrier approach methodology which protects the consumers from harmful pathogens that can pass through the membrane fibres in the case of a breach. The system designed by Optimus will use chlorination since it is relatively cheap and familiar to Haitian residents. The dosage of chlorine must be sufficient to protect the consumers from pathogens while avoiding an objectionable taste and adverse health effects.

3.2 Representative Water Sample

To estimate and optimize the expected performance of the full-scale treatment system, Optimus attempted to create representative conditions for the pilot model trials. However, specific data for hydrologic and geotechnical conditions were not provided for REHC. Therefore, Optimus consulted relevant literature to determine in situ conditions. Based on a thorough water quality study for the nearby town of Verrettes, Optimus concluded that the groundwater source at REHC likely has significant total coliform, low turbidity, and low hardness (Sisson, 2010). Refer to Appendix A for groundwater analysis done during the referenced study.

Water representing the expected characteristics of REHC is not available at the testing facilities at BCIT; therefore, Optimus created a synthetic groundwater sample to represent these conditions. Optimus modified the properties of locally available surface water from Guichon Creek using a sand filter. Guichon Creek runs through the BCIT Burnaby campus and is known to have significant biological contamination and low hardness levels. The sand filter created an ideal sample by significantly reducing the turbidity levels but not the microbiological contaminants. Influent and effluent water quality data for pilot testing can be found in Appendix C.

3.3 Pilot Model

The design, testing, and optimization of the pilot-model water filtration system was done in accordance with the guidelines prescribed in the EPA Membrane Filtration Guidance Manual. The primary goal for developing a pilot model was to prove the effectiveness of Optimus' filtration modules and determine the operating parameters necessary to design a full-scale membrane filtration facility. The model was constructed using simple techniques and materials that are readily available in Haiti.

3.3.1 Schematic of Pilot Model

Optimus developed multiple pilot model schematics and considered alternative system components. The initial system was designed to include pumps for both feed and backwash flows as well as solenoid valves on an automated timing system to optimize the production. As the design of this system progressed, Optimus realized that these items introduced large costs which could create problems for the successful implementation of our system. This design was then refined to minimize the system energy requirements and specialized parts. The schematic used to construct our pilot model is shown in Appendix D.

3.3.2 Construction Methods & Materials

To imitate the full-scale system, the pilot model was constructed using materials that are readily available in Haiti, except for the membrane fibres. Table 2 shows a list of the materials used.

Table 2: Pilot Model Materials

Materials	Quantity
120 L Garbage Can	1
20 L Pail	2
Toilet Float Switch Valve	1
Manual ¾” PVC Ball Valve	4
¾” PVC Tee	2
¾” x 90 Degree PVC Elbow	6
¾” PVC Threaded Coupling	1
3” PVC Threaded Cap	1
5 psi Pressure Gauge	2
3” Acrylic Pipe	1 m
¾” PVC Pipe	3 m
Unreinforced PVDF hollow fibre membranes	Variable

The components were fabricated and assembled in the Civil Lab at BCIT using basic power tools. The connections were sealed using polyvinyl chloride (PVC) pipe glue, silicone, and epoxy putty. The silicone seals are not ideal as they are fairly delicate and not sustainable. Therefore, it is recommended that proper rubber gaskets are used for the construction of the full-scale system to completely prevent any leaks from occurring.

3.3.3 Hydraulic Conditions and Head Losses

As previously mentioned, the Optimus system utilizes gravity to provide the operating pressures for the feed water as well as the backwash system. Head losses are negligible in the pilot model system due to the extremely low flow rate. A preliminary design was conducted to determine the membrane properties under pilot model operating conditions. As this is typically done by the manufacturer, Optimus estimated the design parameters to determine the losses through the fibres using the pilot model empirical data.

The water flux density for specific operation parameters can be determined using the following equation:

$$J_w = K_{membrane} \times \frac{TMP}{\mu}$$

Where $K_{(membrane)} = membrane\ coefficient$
$TMP = transmembrane\ pressure$
$\mu = dynamic\ viscosity\ of\ water$

Optimus was able to use the flow and pressure measurements from the pilot test to determine the K coefficient for the membranes used. Since the transmembrane pressure (TMP) is kept constant in this system, it is K_m that decreases with fouling buildup. The pilot conditions helped provide a better understanding of the theoretical membrane design. See Appendix E for hand calculations outlining the pilot model design.

3.3.4 Scalability of Pilot System

The full-scale membrane modules were designed using the empirical properties from the pilot model. It is very important to note that the testing data obtained by our team is specific to the source water quality and lab operating conditions at BCIT and is subject to change at the REHC location. The fouling rate will be affected by the operating temperature and pressure; therefore, additional optimization with regards to these parameters is recommended once the system is in place.

Optimus fabricated two membrane modules containing different surface areas to confirm that the system flux is consistent. It was found that the module with double the surface area actually provided more than twice the flow. This increase in flux can be attributed to the more thorough wetting technique and priming by air pressure used during the second trial. To be conservative, the lower flux value was used to design the full-scale system. This is appropriate as access to proper equipment for wetting may be limited at REHC.

Since the actual operating conditions are not known, Optimus has assumed that the conditions used for pilot testing are consistent with the conditions at REHC. Given that the source water quality, viscosity, and TMP are the same, the system output should theoretically be proportional to the membrane surface area. By making this assumption, Optimus was able to determine the total output and appropriate backwash frequency for the full-scale system.

3.4 Pilot Testing

Various tests were performed on the pilot system during the course of this project. Integrity tests and challenge tests were performed to ensure efficiency and effectivity of the pilot model. As well, periodic monitoring, which includes system flow measurements, turbidity tests, and microbiological tests were performed in conjunction with the pilot model's operation.

3.4.1 Integrity Testing of Ultrafiltration Membranes

Direct integrity testing is a physical test applied to the membrane unit to identify and isolate any breaches. Both the reinforced and unreinforced membrane filters underwent direct integrity testing prior to installation and operation of the pilot model. The direct integrity testing is required for all membrane filtration processes to ensure and verify the removal efficiency of the membranes during operation and as a compliance to the EPA Guide. The testing procedure involved applying air pressure into the membranes while being submerged underwater to check for bubbling which would indicate holes on the membrane filters.

Since the pilot system operates with gravity, the system's operating pressure ranged around 1.5 psi or lower. Thus, the integrity tests were performed with air pressures around these ranges, and the points of breaches on the membranes fibers were isolated. Under relatively low pressures (1-1.5 psi), the test indicated breaches in the reinforced membranes, which may have been caused by poor quality manufacturing. Further increasing the applied pressure showed substantial increase in the amount of bubbling indicating the breaches in the membranes. Epoxy was then applied to these points to correct the breaches. Applying epoxy closes the holes, essentially negating the breach; however, it also decreases the amount of effective membrane area available for water filtration.

Similarly, the unreinforced membranes were tested for integrity breaches. During the tests, we determined that the unreinforced membranes were able to hold over 40 psi without any signs of breaches or bubbling. The extreme difference in pressure holding capacity was concluded to be caused by different pore sizes in the two membrane types. It is possible that the reinforced membranes were actually MF fibres, and therefore, they would not remove sufficient pathogens. Since the unreinforced membranes passed the direct integrity test with zero identified breaches, Optimus selected them for the REHC system.

3.4.2 Challenge Testing of Membrane Modules

Challenge testing is required by EPA to ensure the effectiveness of a membrane process, that is, the ability of a membrane filtration process to remove specific target organisms. Some common target organisms include E.coli and total coliform, but can also include pathogens such as bacteria, viruses, and other protozoa that have a known presence. Microbiological tests are performed by filtering the sample through a membrane filter and allowing the microorganisms to incubate in mColiblue-24 broth for 24 hours.

Samples were tested both before and after filtration to challenge the pilot model. These tests showed that the Guichon Creek water was contaminated with both E.coli and total coliform which satisfied the assumptions for the REHC source water quality. The filtered water samples showed 100% removal of the pathogens, satisfying EPA standards. See Appendix C for influent and effluent water quality data from pilot model testing.

3.4.3 Pilot Model Testing During Operation

EPA guidelines stipulate that a minimum period of three months should be used to test pilot models. However, due to project time constraints, the pilot model system was run for a period of six weeks. Over this period, permeate flow was monitored periodically to measure the flux through the module and determine the efficiency of the membranes. The standards and frequencies of the flow, turbidity and microbiological tests are summarized in Table 3.

Table 3: Pilot model Monitoring Parameters and Frequencies

Parameter	EPA Drinking Water Regulation	Frequency	Method
Membrane Flux	N/A	daily	The permeate output rate was measured and converted into a flux value depending on the surface area of membranes in the system.
Turbidity	never greater than 1 NTU; 95% of samples less than 0.3 NTU	once per week	Permeate water was tested using a HACH 2100Q turbidity meter.
Indicator Organisms	zero E.coli No more than one sample for total coliform can test positive per month.	once per week	Pre-filtered samples were tested to confirm presence of contamination for removal. Appropriate dilutions of filtered water samples were tested to confirm absence of contaminants per 100 mL.

Primary and ongoing testing of the pilot model was completed on a scheduled basis to ensure consistent system integrity.

3.4.4 Results from Pilot Tests

Overall, the turbidity tests did not satisfy the EPA requirements, however, the success of the microbiological tests suggests that the turbidity is below the maximum allowable. It was found that the turbidity meter was not precise at the lower levels as the measurements varied by +/- 0.1 NTU. The turbidity and microbiological testing results are summarized in Appendix C. The flux vs time data for the pilot testing is shown in Figure 5.

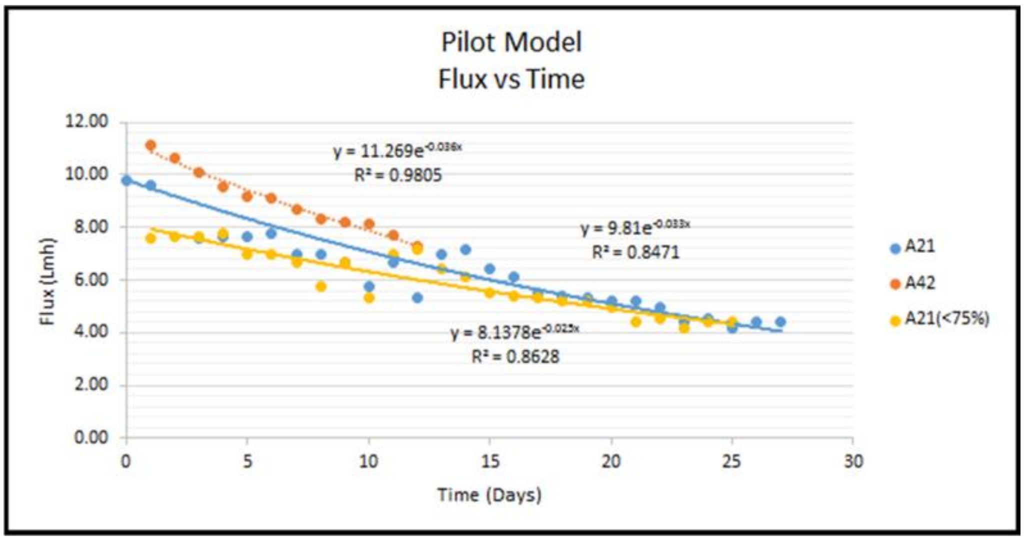

Figure 5: Flux vs time pilot model data

The three lines shown in the plot represent the A21 module with 21 membrane fibres, the A42 module with 42 membrane fibres, and the A21(<75%) which is modified from the A21 data to represent the fouling rate of a membrane that is not brand new. The data for the A21 module was used to design the full-scale system. Pilot system results for system flux are summarized in Appendix F.

The data shown in Figure 5 shows that after almost a month of testing the flux did not stabilize. Under low TMP conditions, there is a critical flux level at which the rate of fouling goes to zero. Optimus aimed to be below this flux level to minimize backwash requirements, however, the pilot system was operating above. This component can be further optimized.

3.5 Sustainability

One of the primary concerns when implementing a new treatment system in a developing country is to ensure that it is sustainable. There have been issues in the past with implementing long term water treatment systems. Optimus has targeted several areas concerned with sustainability to help ensure the overall success of the project. Considerations were made with regards to environmental, social, and economic impacts towards the community of Haiti. These sections are further discussed in Section 6.

3.5.1 Issues with Water System Implementation

In the past, a great deal of effort, money and time were put into implementing water treatment systems in developing countries; however, many of these water systems become inoperable a few years after implementation due to problems which local stakeholders are not equipped to deal with. Lack of proper training during implementation and lack of long term monitoring after implementation are the reasons why many of these water treatment systems become inoperable after a few years (Davis, 2014). Several lessons can be learned from these past water system failures, which are listed below:

- Collaborate with local stakeholders and governments upon implementation
- Define roles and responsibilities with local stakeholders
- Define handover and exit timeline with stakeholders, plan for follow-up monitoring
- Make lifecycle costs of system clear to stakeholders, and define who will pay for what over what time period (Davis, 2014)

Optimus has incorporated these lessons into the implementation of the REHC water treatment system.

3.5.2 Environmental Sustainability

In terms of environmental sustainability, Optimus focused on three key areas:

- power

- materials acquisition
- wastewater management

Optimus aimed to reduce the power input required to run system. By using gravity instead of pumps to provide head for the filtration process, the need for power is greatly reduced. As well, the membranes foul more slowly and last longer with the low pressure provided by the gravity system. The well pump is the only component that requires power.

Most materials are to be purchased in Haiti upon system implementation in order to reduce our carbon footprint through reducing shipping required. Most components are available at hardware stores nearby REHC. Some components, including the membrane filtration modules, solar power system, and well pump are to be ordered from other places and brought to Haiti.

Wastewater is produced as a result of the backwash cycle. This backwash water contains particulate matter which can harbor bacteria, and trace amounts of chlorine. While the water is not safe for human consumption, it can be used for irrigation or can be reprocessed through the system. Another use for this water is recharging the groundwater. Optimus feels that groundwater recharge is the best use for this water, through means of an infiltration trench, as pictured in Figure 6 below.

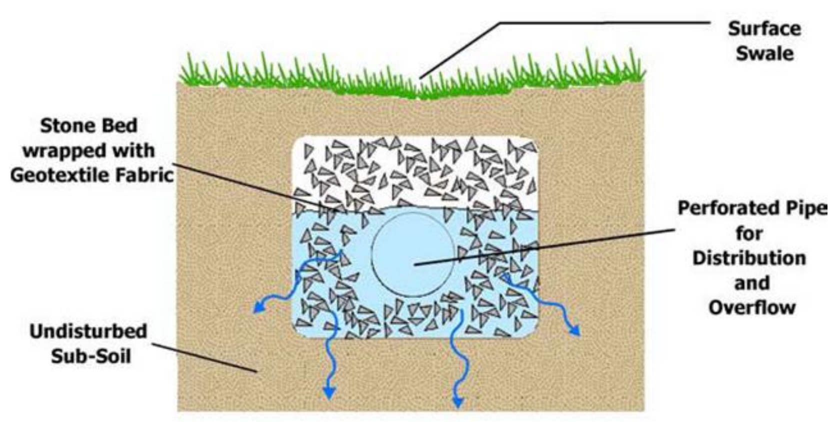

Figure 6: Concept drawing for a typical infiltration trench (Temple - Villanova Sustainable Stormwater Initiative, 2009)

As shown in Figure 6, the wastewater will seep back into the ground to replenish the water table, with the contaminants being filtered out in the soil.

3.5.3 Economic Sustainability

To make the water filtration system implementation economically sustainable, Optimus determined that the system would have to be inexpensive to build, inexpensive to operate, and able to earn money to cover the operation and maintenance costs.

The water filtration system has been designed with inexpensive, durable, and readily available components to ensure maintenance and repairs are done fast and cost effectively. For components not available in Haiti, supplier information has been included in the materials list found in Appendix G to make ordering any new components easier.

Because the grid power in Haiti is unreliable and expensive, Optimus has specified to use a better power system using solar panels, similar to what is shown in Figure 7.

Figure 7: Solar panels being installed (Solar Electric Light Fund, 2013)

Although the initial cost for this type of system is high, the overall cost will be cheaper than using grid power for the lifetime of the system. This would also benefit REHC as they will have access to additional power not required by the filtration system.

To cover maintenance, part replacement and upgrade costs for the water system and school, a plan to establish a small business at REHC has been established. The business is designed to be run by the school and is going to sell excess treated water to people in the community at a competitive price. See Appendix H for the REHC Pure Water business plan.

3.5.4 Social Sustainability

To ensure that the water treatment system is successful, Optimus has incorporated social sustainability into the system design and implementation. The key areas of social sustainability that have been identified are as follows:

- education on sanitation
- involvement of locals
- proper system implementation

A document has been produced which outlines proper sanitary practices, as well as information on how waterborne diseases are transmitted. This document is recommended to be incorporated into the educational curriculum at the school to help teach the children about sanitation and disease prevention. It is believed that if the children are introduced to these topics early, they will make a more lasting impact. This sanitation document would also be applicable to educating adults on sanitary practices also. See Appendix I for Optimus's WASH program.

Involving people is an integral part of the implementation for the water treatment system, as local people in the community, and at REHC, will be using and operating the system. Prior to construction of the filtration system, several local people (from both the community and the school) are to be selected to be involved in constructing the filtration system. Through the construction, these individuals will get a better sense of the how the system works. These same individuals will also be trained to maintain, operate, and repair the system. See Appendix J for the operation and maintenance manual. The skills learned to construct, operate, and maintain this system could then be used in constructing and implementing other similar systems in Haiti.

The business plan for REHC Pure Water was prepared to make the system self-sustaining. Prior to implementing this plan, officials at REHC and officials in the community will be consulted to determine how the system should be implemented, how to price the water, and how to distribute it. It is important to consult community leaders and convince them of the need and benefits of having treated water, in order to gain support from the community. The money raised by REHC Pure Water will go directly towards REHC's funds.

4.0 REHC Water Treatment System

Optimus developed the full-scale water treatment system for REHC based on the testing and analysis performed on the pilot model at BCIT. Using the design criteria provided by AquaSolve, and the anticipated water quality from the well water source, Optimus has established design recommendations for the various components of the full-scale system. Figure 8 below shows the component layout of the full-scale system.

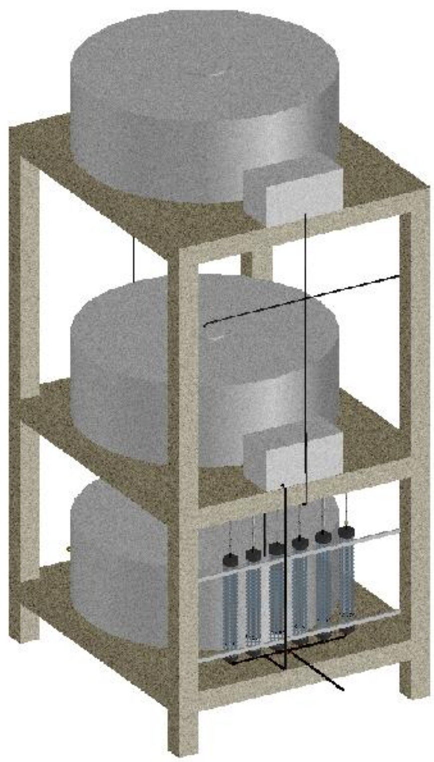

Figure 8: Isometric view of full-scale REHC treatment system

The final design for the system consists of six membrane modules and supporting components to produce a total output of over 4000 L/day. The following sections explain the design process and specifications for the REHC water filtration system.

4.1 Pump System from Well

The first component of Optimus' treatment system is the pumping system to extract water from the well at REHC. Several constraints were considered when developing this component including output capacity, power requirements, and reliability. As estimated by Optimus, the daily extraction volume is expected to be in excess of 4000 litres/day during yearly peak events. Using a hand pump to extract this volume of water was determined to be impractical on a consistent basis. The constant manpower required to achieve the target output capacity suggested that an electric pump would be better suited for REHC for long term sustainability.

Haiti's power grid is highly unreliable and costly, which makes it impractical for consideration. Electrical power from diesel generators was also considered; however, based on similar projects in Haiti, to operate the pump for a few hours a day using a generator would require approximately 5-10 litres of fuel (Kaiwen Sun et al., 2014). With the current price of diesel estimated at roughly $1 USD, this results in yearly costs between $1,500 and $3,500 USD. Optimus feels that this is not the best economical option.

A solar powered pump system was selected as the optimal design solution for REHC as this method can meet output requirements independent of the electric grid, providing a reliable and economically feasible solution. While the estimated cost for a complete solar powered system is $5000, this investment is the more economical long-term solution, and the costs are anticipated to be recoverable.

Three main components comprise the solar pumping system recommended for REHC; the solar panels and submersible deep well pump, a battery system to provide supplementary power during off-peak hours and during rare climate events with insufficient sunlight, and a charge controller to maintain the proper charging voltage on the battery bank and regulate operating power to the pump.

There are numerous pump manufacturers that provide complete solar powered systems that would be suitable for application at REHC. Optimus has selected a Grundfos SQFlex submersible solar well pump as potential option for the REHC system. This system can be adapted to run off either solar panels or wind turbines and creates a reliable water supply with low operating costs. Overall installation is fairly simple while ongoing operation is handled through an automated built in electronic system. The Grundfos specifications and pump curve can be seen in Appendix K.

4.2 Support Tower & Housing Structure

All system components of the REHC system will be supported and sheltered by a three-storey reinforced concrete structure. This structure has a small footprint on the REHC site as it measures 4 m in width by 4.5 m in length and covers 18.0 m^2. Each level of the structure houses the system components and provides the hydraulic head necessary to operate the system. The tower design is essential for the gravity-fed treatment system, as the treatment uses a sequential process. Structural design and soil bearing analysis for this tower are outside of the scope of this project.

The first floor of the tower structure provides space to store the post-treatment tank and the 6 filtration modules. It has been designed 0.5 m above ground level for ease of final water distribution and to provide hydraulic head for distribution. In addition, this elevation protects the post-treatment tank and filtration modules from surface flooding or small animals. Manual valves for backwash control and isolation of individual modules, dispensing faucets, and backwash manual pump are also located on this level.

The second level of the tower provides space for the pre-treatment storage tank and head tank required to drive the filtration process. Water pumped in from the well in a 50 mm PVC pipe and discharges through the pre-screen, and is then transported by 25 mm PVC pipes into the pre-treatment tank located at the level. After water leaves the pre-treatment tank, it flows through the constant head tank, and then down to the filtration modules on the first level.

The upper level of the tower provides the space for the backwashing storage tank and the backwashing constant head tank. This level is 2.6 m above the modules to provide a minimum 3 psi of hydraulic head required for the backwashing procedure. PVC piping for backwash water is also located on this level.

4.3 Pre-screen System

Water for REHC comes from the existing capped groundwater well located on site. As discussed in Section 2.6, turbidity and water hardness levels from the well source are anticipated to be relatively low. Since these parameters are not a major concern for REHC, preliminary filtration and hardness removal are not required for this system. However, Optimus recommends investigating the use of a preliminary filter such as a cartridge filter or MF membrane module if observed groundwater turbidity levels increase.

As a precautionary measure, the inlet to pre-treatment holding tank is outfitted with a fine mesh screen to prevent residual fine material from entering the treatment system. Optimus recommends the use of a screen with maximum nominal opening size of 0.074 mm (#200) for this application.

4.4 Pre Treatment Storage Tank

Design of the influent storage tank for REHC has been based on selecting a material with the greatest durability and low cost. Several types of storage tanks are readily available in Haiti including polyethylene, bolted steel, and ferrocement tanks. A comparison between these systems is shown in Table 4:

Table 4: Design Tank Options

	Polyethylene	**Bolted Steel**	**Ferrocement**
Expected Lifespan	12 yrs	25 - 30 yrs	25 - 30 yrs
Capacity	locally available in Haiti up to 1000 gal	locally available in Haiti up to 500,000 gal	customised to suit project need
Advantages	• lightweight • will not corrode or rust • seamless construction	• prefabricated components • fast assembly	• insulate water against temperature changes • negligible maintenance and repair needs

Disadvantages	• water affected by temperature • not biodegradable	• needs protection from rust and corrosion • rivet and weld locations subject to leaks • water affected by temperature	• heavier than other tank options • labour intensive • potential rust degradation of steel components
Cost	Moderate	Moderate	Low

Based on the criteria identified by Optimus, a ferrocement tank was selected for implementation at REHC. Ferrocement is similar to reinforced Portland cement structures, though it utilizes layers of woven or expanded steel mesh in addition to steel rebar as tension reinforcement. These types of tanks are reliable and effective for storing large quantities of water. The main advantages for using this material are the flexibility of tank size and the lowest cost compared to pre-manufactured polyethylene or steel. While these tanks are the heaviest of the options, they have a high expected lifespan and can easily be repaired if necessary. Ferrocement tanks are also lighter than traditional reinforced concrete tanks and have proven to perform very well during seismic events.

Structural design of the tanks is outside the scope of this project. Operational design stresses, construction monitoring, and quality control practices need to be confirmed by others. Such confirmation is needed to ensure tank integrity and mitigate effect of reinforcement degradation due to poor construction.

While ferrocement requires more labour than the other options, the hourly wages of construction workers in Haiti is fairly reasonable and will not substantially impact the overall project costs. Social benefits of using ferrocement come from community involvement during the construction of the project through utilizing local construction labour. This will also help locals become aware of REHC and its water treatment system and aid in the implementation of the system.

Figure 9: Community construction of a ferrocement water tank (Westra, 2010)

The pre-treatment tank is designed to hold over 6000 litres of water. Overall tank dimensions are as follows:

- 3000 mm inside diameter
- 1000 mm high
- 30 mm tank wall thickness

The top of the tank has a 500 mm opening to house the pre-screen, and a 600 mm removable lid to provide maintenance access. The base of the tank is connected via PVC to a smaller ferrocement tank to provide the constant head for the filtration process. Flow through the constant head tank is regulated by an internal float valve that allows for unrestricted flow until the target water height 400 mm is achieved. Water exiting the head tank flows through PVC piping and in to the filtration module, providing a total hydraulic head of 1.7 psi.

4.5 Filtration Module

The filtration component will utilize UF membranes. Optimus determined that the MF filtration component that was proposed was not necessary due to the low turbidity levels. The membrane component of a water treatment system is typically designed and fabricated by the manufacturing company. To save cost, Optimus developed a membrane potting method and sustainable module configuration. This module was designed to operate under low pressure conditions to reduce the energy requirements, and was tested for integrity and efficiency using the pilot model described in Section 3.4**.**

The UF component will use hollow fibre membranes in a shell feed (dirty water enters through the outside walls of the fibres and clean water is extracted through the inside of the tube) configuration. This configuration is sustainable since backwashing and chemical cleaning can effectively remove the fouling that builds up on the membranes. An MF module can be added to the system if the turbidity levels at REHC are determined to be higher than predicted.

Membrane filtration has proven to be effective and efficient given that the right techniques are used to manufacture the polymers. These techniques are often proprietary information since the manufacturing companies have invested so much time and money developing them. Typically, the manufacturing company will design and fabricate the membrane component to satisfy the system parameters provided to them. Polyvinylidene fluoride (PVDF) polymers are commonly used for UF membranes because of their durability and chemical resistance. Based on a number of case studies, Optimus chose to use the PVDF type membranes form an international manufacturer in the REHC treatment system.

Optimus designed and tested a custom UF membrane module configuration in the pilot model. The fibres are bundled in 6 mm plastic tubes which are potted in a plastic potting plate. The plate is mounted in the discharge cap which can be easily removed for maintenance or replacement. Figure 10 shows the configuration of the membrane fibres during potting.

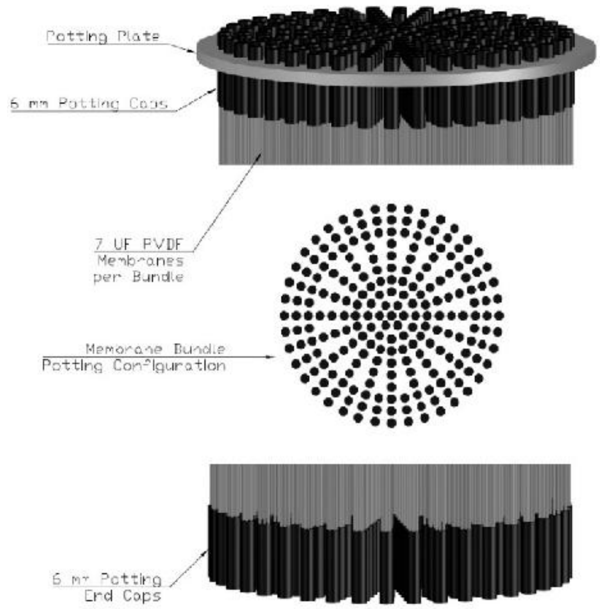

Figure 10: Membrane fibre potting configuration

A bottom to top flow configuration allows for some of the suspended matter to settle to the bottom of the module. This makes the backflushing process more effective as the settled particles are allowed to flow out through the bottom of the module. By developing an effective and efficient module configuration, Optimus was able to drastically reduce the overall cost or the system.

The membrane module was designed to operate with a gravity feed system under low pressure conditions. The low operating pressure allows for unreinforced PVDF membranes to be used. Reinforcement prevents the membranes from collapsing due to high TMP which is not a concern for gravity-fed systems. The unreinforced membranes have a smaller diameter meaning that more filter surface area can be achieved in the same size module. These UF membranes function by rejecting particles that are larger than the pores in the fibres. The rejected particles are known as foulants and their accumulation must be monitored regularly during operation. The low operating pressure of our system will reduce the fouling rate and the required frequency of backwashing.

The full-scale module is known as the Optimus A1 module, and has been designed based on the empirical data obtained from the pilot model. Each A1 module can house over 1550 of the 1.2 mm diameter unreinforced PVDF fibres for a total surface area of 5.8 m^2. Based on the pilot model testing, the average flux over the lifetime of the membranes is expected to be approximately 4.8 Lmh. This means that each module can produce 668 L of water per day. Therefore, to satisfy the 4015 L/day system requirement, the REHC system will consist of six Optimus A1 modules, as shown in Figure 11 below.

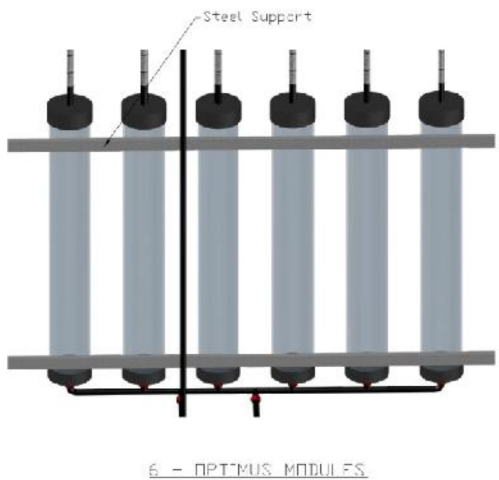

Figure 11: Optimus A1 module configuration

A Microsoft Excel calculator used for determining the number of modules has been developed by the Optimus team and can be found in Appendix L.

4.6 Treated Water Holding Tank

Similar to the influent storage tank, Optimus specifies the use of a 3000 mm diameter ferrocement tank to hold the treated water prior to distribution. A tank size of over 7000 litres will allow for a minimum three-day emergency supply when combined with the backwash storage. Distribution from the tank will be provided by a PVC pipe rail with several faucets. Treated water can either be bottled or transported via hose for distances below 500 mm in elevation using the available hydraulic head. Access for disinfection and maintenance is provided by a removal 600 mm lid, similar in specifications as the pre-treatment tank.

4.7 Disinfection System

Due to the time constraints for this project Optimus was not able to fully design a disinfection system. According to EPA, post-treatment disinfection is not always necessary for membrane filtration systems but is generally required by municipal regulations. Optimus feels that the REHC system should include a disinfection process to protect the consumers in the case of a membrane breach. Both chlorination and ultraviolet (UV) disinfection have been implemented in water treatment systems for developing countries. Chlorination is the most common for many reasons including cost, familiarity, and ease of use. UV disinfection is an effective post-treatment method that is gaining popularity due to its sustainability advantages.

Chlorination is a relatively simple and cheap method of disinfection that is accepted around the world. The advantages of this method for the REHC system are the availability, familiarity, low cost, and inactivation capability of pathogens such as E.coli. Some potential disadvantages of this method include the formation of disinfection by-products (DBPs) and the ineffectiveness for removing chlorine-resistant organisms such as Giardia and Cryptosporidium (EPA, 2013). Chlorine can react with natural organic matter to form DBPs, which may pose health risks. However, because the water is filtered prior to chlorination in Optimus's system, DBP formation should not be an issue. The groundwater source at REHC is not believed to contain pathogens that are highly resistant to traditional disinfection practices. Optimus recommends to manually add chlorine to the treated water storage tank in the form of chlorine tablets. The chlorine levels in the tank should be kept below 4 ppm to avoid irritating effects to the eyes, nose, and stomach. Inexpensive home drinking water test kits can be used to check and detect levels of chlorine (EPA, 2013).

The use of UV light to disinfect drinking water involves generating light with the desired germicidal properties and transmitting that light to the pathogens. Contrary to chemical disinfection, which typically destroys or damages the cellular structure, UV light inactivates microorganisms by damaging their nucleic acid, preventing them from replicating (EPA, 2006). Microorganisms that are incapable of replication cannot infect a host. After the discovery of DBPs, UV disinfection became more popular and much more reliable with increased development. Today, many UV disinfection products can be combined with solar power to create a sustainable solution. The major disadvantage of this method is the cost of purchasing the units and replacing the UV cartridges. Additionally, since this technology is not familiar to the Haitians, they might not trust that it is effective. However, Optimus recommends that UV disinfection be installed once the start-up costs have been recovered. By this point the consumers will be more confident in our system's performance and likely more accepting to our recommendations.

4.8 Piping System & Valves

All piping for the REHC filtration system will be composed of 25 mm PVC piping, which is readily available in Haiti. Valves for junction points and cleanout sections will use PVC manually operated ball valves. Flexible 25 mm hose is to be used at sections above the filtration modules to allow for module cap and membrane cartridge removal. Connection between the flex hose and the modules will consist of PVC threaded valve units. All elbows and tees will also be composed of PVC fittings.

4.9 Backwash System and Optimization

The REHC backwash system is designed using the same operating conditions as the pilot model. Similar to the rest of the REHC design, the true effectiveness of this component depends on how representable the pilot tests were compared to the conditions in Haiti. The full-scale system consists of three main components:

- Ferrocement water reservoir and constant head tank located on the upper level of the support tower
- Hand pump to transport water from the treated tank to the backwash reservoir
- PVC piping and valves

The ferrocement backwash reservoir also acts as an emergency storage tank for REHC.

The efficiency of the gravity feed backwash system was not fully optimized in this project due to time constraints. However, Optimus was able to estimate a backwash frequency for the pilot model using the system flux and initial backwash data from the pilot model. This estimate was determined using three main assumptions:

1. the first backwash is only 75% effective

2. all subsequent backwashes leave 5% additional permanent fouling
3. chemical cleaning restores membranes to 90% efficiency

The first assumption accounts for the high fouling rate which occurs when the membranes are new or have been chemically restored. The second assumption is to account for an estimated 5% permanent fouling that cannot be removed each time by backwashing. The chemical cleaning is only 90% efficient due to permanent fouling. However, since biofouling is the only expected form of permanent fouling, the chemical cleaning procedure is expected to be fairly consistent in effectiveness.

All backwash procedures are based on the backwash test that was performed on the A42 module. This backwash test was performed at a TMP of 3.1 psi, requiring a total of 13 L in a one-hour period. This backwash procedure restored the membranes to over 80% of the initial flux which agrees with the assumptions used for the backwash optimization. Figure 12 shows an optimal backwash and chemical cleaning schedule based on the assumptions aforementioned.

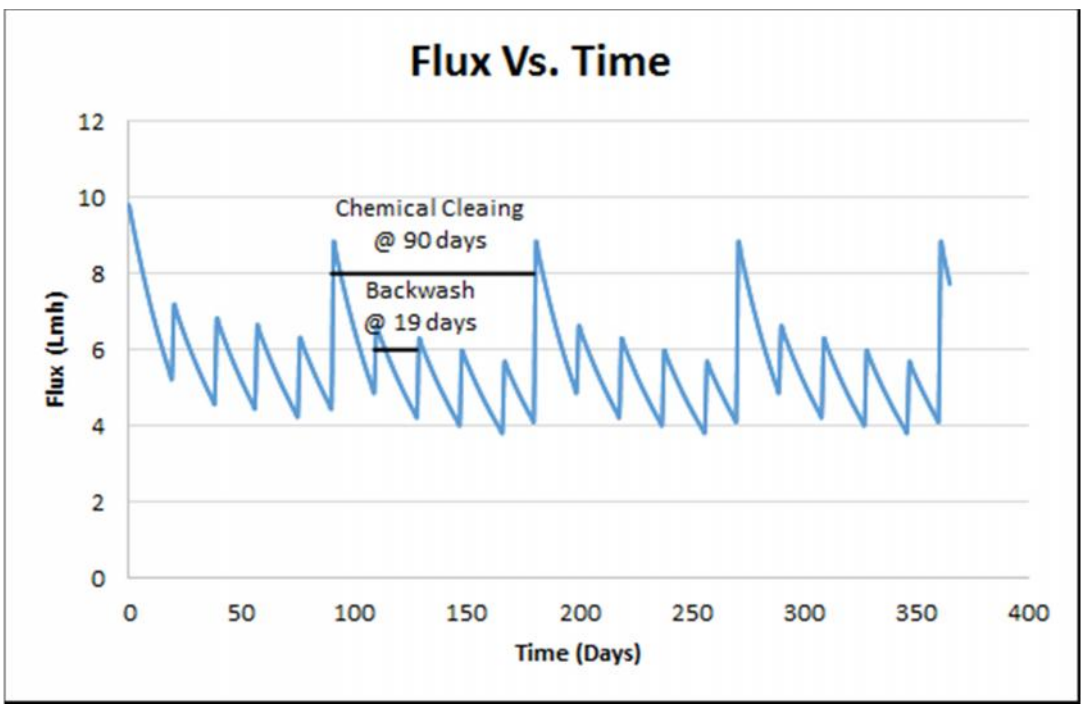

Figure 12: Optimized Backwash and Cleaning Cycle

The backwash frequency of 19 days produced optimal results based on the pilot model flux versus time data. This frequency was determined by calculating the total volume of water produced in one year of operation. There are two potential sources of error with the calculator which are:

- the total output volumes did not fully account for “down time” of maintenance
- more data is required to produce accurate estimates of long term performance

Additional volume was added to the volume of backwash water to account for lost production; however, the time needed for chemical cleaning was not accounted for. The backwash component of the project takes significant testing to fully optimize and could be improved.

4.10 REHC System Detailed Drawings

See Appendix M for detailed design drawings outlining Optimus’ system schematic, including system components, and sizing information.

5.0 Alternative Options

As per the project requirements, Optimus considered numerous alternatives throughout the design of the REHC water treatment system. Different types of filtration systems were identified and potential options for membrane selection were investigated. Alternative designs were developed to minimize the power requirements to operate the treatment system. The use of gravitational potential energy instead of electrical pumps to facilitate operating pressure was identified. In addition, the potential of using a manually operated backwash cleaning system versus an automated system was evaluated. Considerations were also made in order to create a solution with both minimal environmental impact and maximized economic value.

5.1 Filtration Module Type

The two types of filtration systems considered for REHC were MF and UF. Both systems operate by rejecting particles larger than the pores in the fibres. Optimus initially made conceptual designs that included both MF and UF modules. However, after further analysis of the groundwater conditions in Haiti, the conceptual designs were revised to accommodate UF systems alone. It was determined that UF systems would be sufficient to remove most of the turbidity and pathogens left from the pre-screened water.

5.2 Gravity Powered versus Pumped System

One of the most significant alternative options that was considered in the design was to use a gravity feed system. Membrane filtration typically requires minimum operating pressures around 15 psi that are generally provided through the use of powered pumping systems. These pressures are specified as requirements for the filtrate to permeate through the pores in the membranes at a reasonable flux. However, based on research conducted at UBC and technical advice provided to Optimus, it was determined that low pressure gravity systems can be compatible with membrane filtration at lower flux.

Several advantages were identified by Optimus through the use of a gravity-fed system including:

- lower power requirements
- lower operating costs
- reduced effects of fouling on membrane fibres
- minimal head losses at valves and fittings due to lower pressures

Due to the advantages listed, Optimus elected to pursue a gravity-fed option for the design choice of the REHC treatment system.

5.3 Membrane Selection

Several types of ultrafiltration membranes are currently available including hollow tube, hollow fibre, and flat sheet. Initially, Optimus considered using either hollow tube or sheet fibres for application at REHC. Figure 13 shows the various types of membranes available.

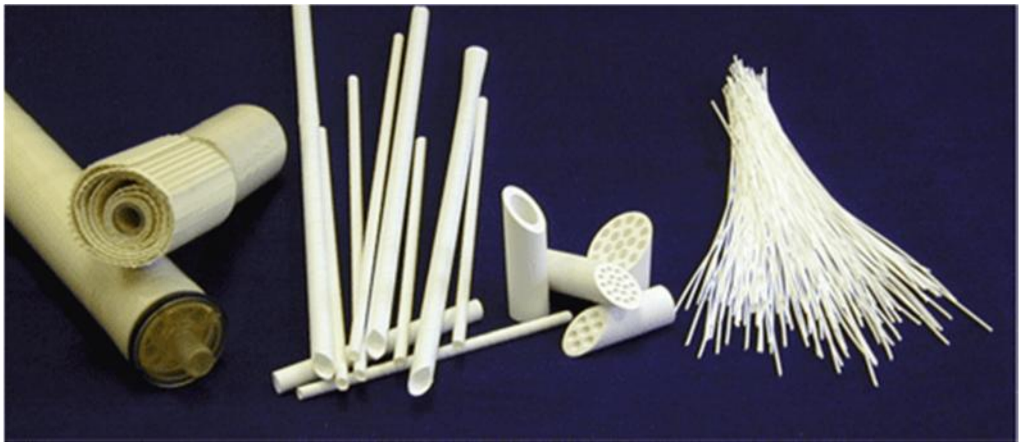

Figure 13: Types of membranes. Sheet, hollow tube, and hollow fibre (Membrane Specialists)

However due to availability, Optimus opted to utilize hollow fibers for the membrane filtration module as these membranes were provided by faculty advisors at BCIT. Two types of hollow fibre membranes were available for use including reinforced and unreinforced PVDF hollow tube fibres. Initially, Optimus planned to use the reinforced fibres as they were assumed to have a higher integrity and would be less likely to collapse due to pore water pressure when compared to the unreinforced fibres. However, after integrity testing of both fibres, Optimus determined that the unreinforced fibres performed better and had fewer manufacturing defects. The unreinforced PVDF hollow tube fibres were selected by Optimus for use in the full-scale REHC system.

5.4 Backwash System

The backwashing system in both the pilot model and full-scale REHC designs presented several alternatives. Similar to the forward treatment process, the backwash system can either be run through gravity-fed or through powered pumping systems. Optimus investigated the use of gravity for the backwash components with lower power requirements and lower maintenance. Due to lower pressures and resulting lowered fouling rate, Optimus decided to utilize a gravity-fed for its backwashing system. Optimization of the design backwashing cycle was then performed numerically based on pilot model testing data.

5.5 Manual Valve System versus Automated Valve System

In order to backwash the treatment system, the direction of flow through the system has to be reversed. To do this, shut-off valves are used to block normal operating flow and are opened to allow for backwash flow. These valve systems can be controlled and timed on an automatic system or can be operated manually.

During the pilot model testing program, Optimus had planned to develop an automated backwash system. However, it was determined that the cost to implement such a system would be outside of Optimus' project budget and would also dramatically inflate the costs for a final design solution for REHC. In addition, due to the low operating pressures from the gravity-fed design, and subsequent low fouling rate, it was determined that a manual valve system performs adequately for the anticipated backwashing frequency.

5.6 Options for Dealing with Wastewater from Backwash

As part of the backwashing process, wastewater is produced which contains pathogens and is not safe for human consumption; however it can be used for other purposes such as:

- recycling the water back through system
- irrigation use
- groundwater recharge via an infiltration trench

While the water could be recycled again through the system, it could lead to the membrane filters fouling more quickly; consequently, recycling the water through the system was not chosen as the method for dealing with the wastewater. Using the wastewater for irrigation is a viable option; however, REHC does not have an immediate need for irrigation water. As well, relatively small amounts of wastewater would be produced from backwashing which would be insignificant for irrigation.

Ultimately, groundwater recharge using an infiltration trench has been selected as the preferred option to deal with the backwash water. This method allows the water to make its way back to the groundwater source while filtering out particulate matter along the way.

5.7 Delivery Service for Water Sales

An option for the water selling business was to use motorcycle delivery to expand our market for selling water. While having a person delivering water via motorcycle or car would increase the amount of water REHC could sell, it would also increase the amount of water that needs to be produced. After analyzing a 1.25 km radius, a reasonable walking distance with a bucket of water, it was decided that there was enough of a market within walking distance and that the business would not have a delivery service. Unless the filtration system was expanded significantly the delivery service would not be feasible.

5.8 Alternative Materials Selection

Throughout the design process, Optimus assessed available materials in the efforts to develop a system with minimal costs and long term sustainability. Tank materials such as plastic, steel, and ferrocement and pipe/valve materials such as metal and PVC were selected from. Optimus ultimately selected ferrocement for the water tanks and PVC for all pipes and valves due to implementation costs, and overall adaptability into the sustainability program.

6.0 Sustainability

Sustainability was taken into consideration in every aspect of this design project. Because sustainability is such a broad and open-ended topic, we decided to narrow our focus to three aspects of sustainability as depicted in Figure 14.

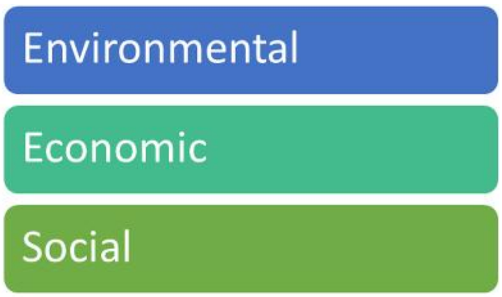

Figure 14: Sustainability Focus Areas

Environmental, economic, and social aspects are the main focus for sustainability in this project. For environmental considerations, the aim was to reduce the power requirements of the system, reduce the carbon footprint by sourcing local materials, and to recycle wastewater responsibly. In terms of economic considerations, the goal was to come up with a realistic cost estimate for the system and to set up a business to recover costs for the water filtration system. For social considerations, we aimed to prolong the operation of the system through proper system implementation and training for the system operators. As well, we planned on addressing social sustainability through educating residents of REHC and people in the community about sanitation and disease prevention. This section elaborates on the sustainability methodologies as discussed in Section 3.

6.1 Environmental

Optimus has focused on three main areas to make our design environmentally sustainable including: power required to run system, acquisition of materials and components, and managing wastewater from backwashing.

6.1.1 Reducing Power Required

Instead of using pumps, the entire filtration system is gravity-fed under constant elevation head. Because the backwashing cycle is infrequent, the cycle will be operated with manual ball valves. Water level in the backwashing head tank will be maintained via a hand pump, and will require no power for backwashing. The well pump is responsible for maintaining the water level inside the pre-treatment storage tank. The well pump comes with its own solar panels and system. The pump is expected to draw a maximum power of 1400 watts at 8.4 amps (Grundfos, 2015). This is the total anticipated power requirement for the system.

To provide capacity for the well pump and also the school, we have specified a Boka Power Systems 3000 watt off-grid solar system (Alibaba, 2015). The additional capacity will give REHC the ability to run electric lights and small appliances. This system includes the inverter, batteries, panels and racks and has a capacity of 40 amps, which is well below the filtration system requirements. Ten solar panels are included in the system at dimensions of 1580 mm x 808 mm x 35 mm (Alibaba, 2015). Installation costs for the system have been summarized in the economic sustainability section. See site plan in Appendix N for approximate solar panel layout. There is potential in the future to increase the capacity of the solar panel system if required. Figure 15 shows a typical installation for roof-mounted solar panels.

Figure 15: Typical solar panel installation on a sloped roof (Circelli, 2013)

Installation of solar panels can be time consuming and adds to the already high costs of the system. However, with a 25-year lifespan, the cost is $0.10 USD/kWh which is less than 5% of the cost for grid power. This number is based on the initial cost of the system, a $100 per year maintenance and replacement allowance, and only includes power required to run the filtration system. By also including the power used by the school, this number would decrease further. Grid power is only available for two hours in the early morning, and costs $3.50 USD/kWh (Wong, 2015).

6.1.2 Acquisition of Materials

To reduce the carbon footprint, materials should be sourced locally in Haiti. With the exception of the membrane modules, solar panel system, and pumps, most of the local materials will be acquired from MSC Trading. MSC Trading is a hardware store located about 11 km away from the REHC site, making it an ideal source for building the full-scale system. In addition, other hardware stores that have plumbing, electrical, and hardware supplies also exist within the area (Wong, 2015). See Appendix G for materials list and supplier list.

6.1.3 Site Geology / Wastewater Management

For managing wastewater from backwashing and sterilizing drinking water containers, we have decided to use groundwater recharge. An infiltration trench has been designed to temporarily store the water and allow it to recharge the groundwater from which we are drawing water from. A geological analysis of the watershed and surrounding geology has been done to determine the following:

- characteristics of the soils at the site
- characteristics of the aquifer that the well is drawing from
- adequacy of natural filtration through the native soil to remove any contaminants by the time the water reaches the water table.

The site is located in a valley, bounded by mountain ranges to the north and south, a bay to the west, and a large lake to the east. This also defines the watershed for the valley that feeds the aquifer as shown in Figure 16. The marker on the image denotes the location of REHC.

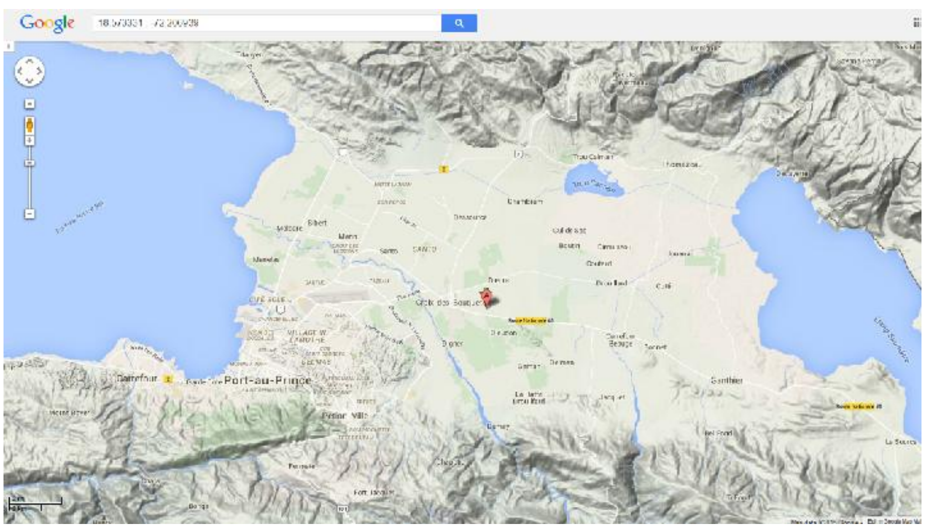

Figure 16: The watershed for the valley region near Port-au-Prince (Google 2015)

The soil in the valley is mostly made up of quaternary alluvium. The quaternary alluvium material is geologically young and composed mainly of unconsolidated, silty sand material. This layer is very permeable and extends to depths up to 60 m below the surface. It is underlain by another layer of consolidated gravel, sand, and limestone (Taylor & Lemoine, 1949). An approximate groundwater profile has been provided in Figure 17.

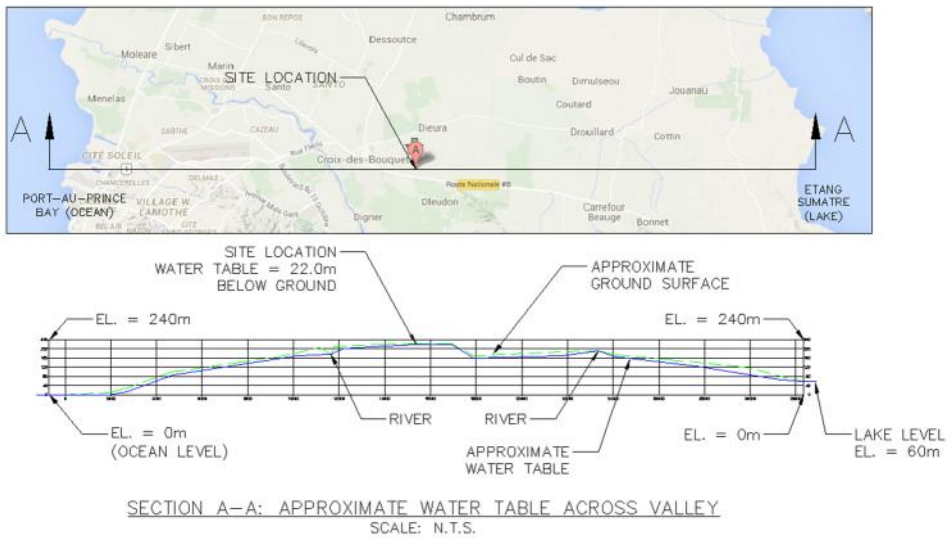

Figure 17: Approximate groundwater profile (Google 2015)

From the topography and observed water table in the region, we have determined that groundwater is recharged by the mountains to the north and south, and not from the lake to the east. Because of the pervious nature of the material, the natural filtration is sufficient to remove biological contaminants by the time the runoff reaches the water table. At the site, the groundwater elevation is approximately 22 m below the ground surface.

The maximum expected volume to be infiltrated is approximately 3000 L per backwash cycle plus 100 L/day for water jug cleaning. As such, the infiltration trench will see a peak rate of approximately 3100 L/day. The alluvium soil has an average expected infiltration rate of 0.84 cm/hr (California Department of Water Resources, 1999). To provide lots of capacity for wastewater, the infiltration trench has been sized at 0.75 m deep x 2.00 m wide x 6.00 m long, allowing the trench to infiltrate over 100 L/hr. The trench bed will consist of a 19 mm clean gravel layer with a porosity of 35% giving the trench a combined storage capacity (including storage and infiltration) of 3250 L. See Appendix N for site plan and infiltration trench details.

6.2 Economic

The system design incorporates a plan to ensure that the full-scale treatment system is economically self-sustaining throughout its lifespan. During the course of the project, Optimus has performed a cost analysis of the construction, deployment, and maintenance of the system. It is recommended to follow this business plan to recover initial construction costs, ongoing operation and maintenance costs, and to make future improvements financially feasible.

6.2.1 Economic Background in Haiti

The currency in Haiti is the Gourde, referred to as HTG. The exchange rate as of January, 2015 was $1 USD to 46 HTG (XE, 2015). Although the currency is fairly deflated, the cost of goods in Haiti is not that cheap. For example, a loaf of bread in Haiti costs $1.57 USD on average (Numbeo, 2015). This is expensive considering that on average, approximately 78% of people in Haiti live on less than $2 USD per day, and the gross net yearly income per capita is $810 USD (The World Bank, 2015).

The Haitian government only distributes water to one-third of the population, and this water is untreated. Because of this, clean water distribution is left up to private industries. These industries are usually centralized and usually use trucks to deliver water. Costs increase the farther the trucks have to travel. On average, these private companies sell water for about 5 HTG per gallon (DloHaiti).

6.2.2 Costs of Water Treatment System

Listed in Table 5 below is a summary of the deployment costs of system components required to construct the system.

Table 5: System Deployment Costs

Item	Cost
Local Components	$ 2,525.66
Non-local Components	$ 12,271.44
System Deployment (Construction & Operator Training)	$ 774.80

Included in the summary are materials purchased in and outside of Haiti, labour costs for construction, and costs for training of REHC staff and system operators. Non-local components of system, such as the membrane modules, solar panels, solar pump, and pre-filter screens, would have to be sourced outside of Haiti.

Periodic costs for keeping the system operating include maintenance, disinfection, system monitoring, power (cost of solar system over lifetime and power usage), component replacement, and backwashing. These costs are summarized in Table 6 below.

Table 6: Periodic Costs for System Operation

Item (Interval)	Description	Cost
Regular Maintenance (Monthly)	Maintenance Activities including leak inspection, well pump inspection, and repairs associated.	$780
Disinfection (Monthly)	This includes costs associated with testing for how much chlorine is present in the treated water tank, calculating the amount of chlorine needed to add to the treated water tank based on the volume, and adding the chlorine into the tank.	$1,560
Monitoring (Weekly)	This includes costs associated with monitoring flow through the system, checking pressure across the membrane, and visual inspection of membranes.	$780
Testing (Bi-weekly)	This includes costs associated with performing microbiological and turbidity tests on clean water to ensure that there are no breaches.	$2,925
Power Costs (Monthly)	This includes solar-powered system costs broken down over the projected lifetime of the system.	$252

System Backwash & Chemical Cleaning (Every 19 Days / Every 3 Months)	This includes costs associated with periodic backwash of the system (weekly), as well as removing the membranes and soaking them in chlorine overnight for chemical cleaning (every 3 months).	$3,900
Membrane Module Replacement (every 5 - 7 years)	This includes the costs of the membrane modules, potting new ones, and associated material needs.	$4,464

6.2.3 Business plan to recover costs

Optimus has developed a business called REHC Pure Water to sell treated water to the community. The complete business plan is contained in Appendix H.

Drinking water in Haiti is typically sold in gallons and as such, Optimus' treated drinking water will be priced at 4 HTG per gallon, lower than the typical price of 5 HTG per gallon in many areas in Haiti (DloHaiti). In addition, most people buy a 5 gallon container or a "bokit" of water (DloHaiti). Optimus has organized and implemented these methods of selling treated water to the community in order to keep our business socially and culturally appropriate.

A secure storefront will be constructed at REHC and will require one person to run the till for transactions. We anticipate that there will be enough interest in the local community to support the business. Figure 18 shows the 1.25 km radius around REHC, which was assumed to be a comfortable walking distance for customers.

Figure 18: Radius of marketability (Google 2015)

As shown in Figure 18, the radius was used to analyse how many customers may be expected to buy water on a given day. Several conservative assumptions were made to make the analysis as realistic as possible. The area of the radius was determined to be approximately 4.91 km^2. Optimus used the most current population density of Haiti, which is estimated at 374 persons per square kilometer as of 2014 (The World Bank, 2015). It is assumed that only 10% of the population within this area will purchase the water on a daily basis. Based on this, Optimus anticipates approximately 790 L/day of water sales during the school season. This corresponds to 25 customers (at 30 L per customer) on a school day.

To increase public awareness of the new business, a flyer has been produced for distribution around the local community. This flyer is contained in Appendix O as well as in Figure 19.

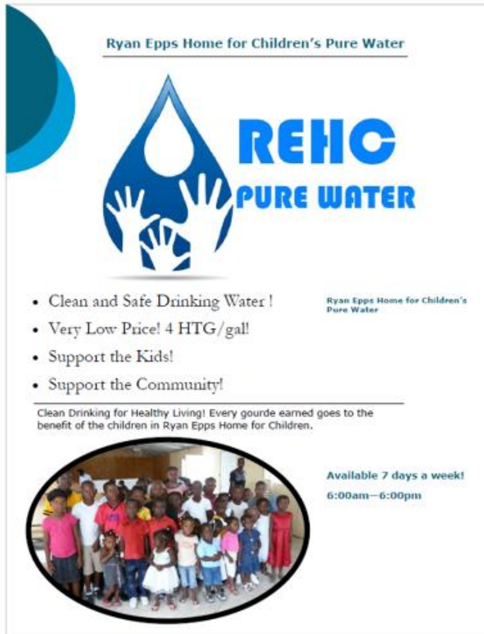

Figure 19: Snapshot of REHC Pure Water flyer

Optimus initially considered having a delivery service as part of the business in order to expand the market; however, it was determined that there would be sufficient demand within walking distance of REHC. Any increase in sales will require expansion of the water filtration system.

Sanitation and sterilization equipment will also be available on site for returning customers. To ensure quality disinfection is done, all cleaning of containers will be overseen by REHC staff. Extra treated water not sold for the day will be kept in sealed containers and bottles and will be kept clean and available for sale the next day.

6.3 Social

Providing clean drinking water alone will not prevent the spread of disease as people's habits and practices contribute to the transmission. Optimus believes that the REHC residents will benefit the most by incorporating a program on proper water, hygiene, and sanitation in conjunction with the implementation of the water filtration system. An organized implementation plan for the filtration system has been formulated by Optimus to involve leaders within the community. A simple and easy to understand operations manual for the filtration system was also created.

6.3.1 Social Background in Haiti

In Haiti, approximately 48% of the population lives without easy access to clean water (The World Bank, 2015). Using contaminated water leads to waterborne illnesses, which are responsible for half of the total deaths in Haiti per year (The World Bank, 2015). Figure 20 depicts the unsafe drinking water sources which many Haitians are forced to rely on.

Figure 20: Contaminated water supply in Haiti (White, 2009)

Surface water sources are more susceptible to being contaminated by pathogens. Cholera, a disease transmitted through contaminated water, is relatively new in Haiti and caused an outbreak about 10 months after the 2010 earthquake (Raedle, 2015). Since then, cholera has become a major issue for Haitians.

6.3.2 Promoting Education on Sanitation and Disease Transmission

Using contaminated water can lead to illnesses like typhoid, cholera, and diarrhea. These diseases are not only caused by drinking contaminated water, but also from unsanitary practices that are used by the Haitians. Therefore, in addition to providing clean drinking water, providing education on proper sanitation practices is necessary to minimize these diseases.

Water, Sanitation, and Hygiene (WASH) promotion standards aim to promote better hygiene, both personal and environmental, and to protect the health of individuals (The Sphere Project, n.d.). Through the water filtration system, we hope to address the water supply function of WASH. To address the sanitation and hygiene promotion functions of WASH, Optimus aimed to tackle this through education of the children at the school as well as local people. WASH recommendations, as presented in Appendix I have been prepared to cover the major components of promoting good health. These recommendations include:

- how diseases are transmitted
- different types of diseases
- tips on how to avoid getting sick
- sanitary practices

As well, a pamphlet was produced which summarizes the contents of the WASH recommendations. This was chosen as a simple but effective method of communicating the educational information to children. Figure 21 contains a snapshot of the pamphlet prepared.

Figure 21: Educational pamphlet snapshot

As shown in Figure 21, the pamphlet incorporates pictures in order to make the information very clear. The pamphlet is intended to be translated into Haitian Creole, the official national language, when brought into REHC. The full educational pamphlet can be found in Appendix P.

The WASH recommendations and pamphlet will be incorporated into an educational session for use by the teachers at REHC. By implementing sanitary practices in the school, this can help prevent the spread of diseases. In addition, the students from REHC can then spread the word to their own families and communities about how to keep themselves healthy and safe.

6.3.3 System Implementation

An implementation plan has been prepared and has been included in Appendix Q. This implementation plan is intended to ensure that the water filtration system is properly deployed and functional. It also ensures that the system is sustainable for the expected lifespan. Prior to going to Haiti, the following tasks have to be undertaken:

- consult community leaders and REHC regarding business
- select people who will be involved with building the system/business

Three stages of system implementation are summarized in Figure 22.

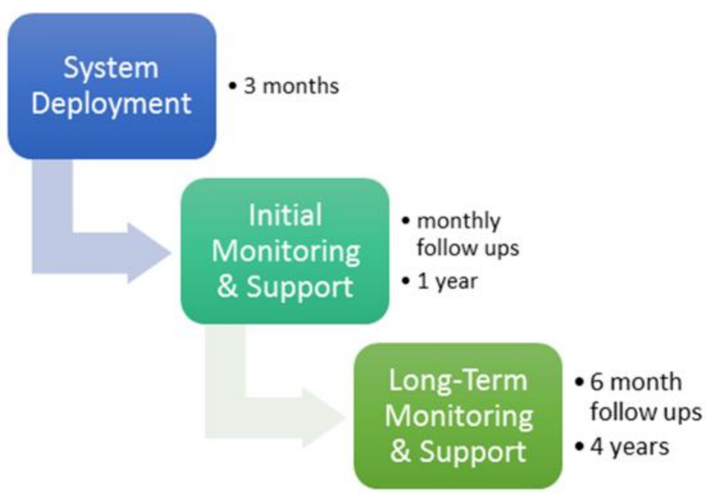

Figure 22: Implementation plan process chart

During the System Deployment stage, Optimus will be going to Haiti, constructing the system, and initiating operations. After this stage, the Initial Monitoring and Support stage is intended to answer any questions that operators may have and to ensure that the system continues to run effectively. In the Long-Term Monitoring and Support stage, less frequent follow-ups and support will be maintained to ensure that the system continues to run. After five years, Optimus will end support and officially hand the water filtration system over to REHC. At this stage, the operators should be comfortable with the system and its operation. Implementation of this system will be validated when the goals shown in Figure 23 are completed.

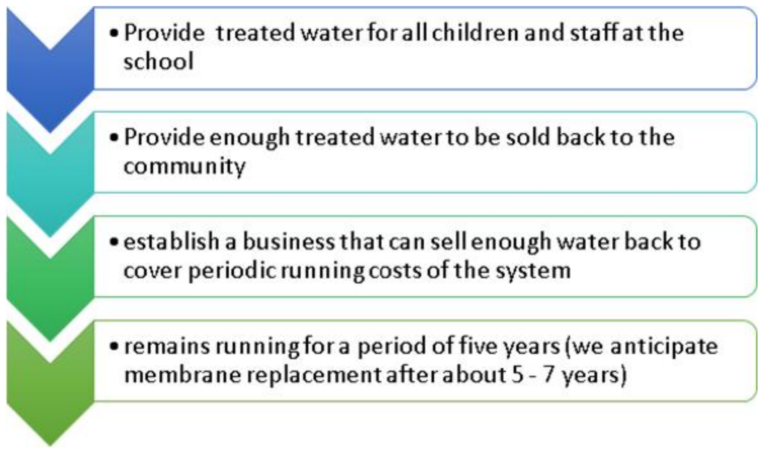

Figure 23: Implementation goals

Upon completion of these goals as presented in Figure 23, the system will have been successfully implemented.

6.3.4 Training Operators to Run System

Optimus has planned on training at least two operators to run the filtration system, perform monitoring and testing, and perform maintenance and repair work. These individuals will be selected in coordination with REHC. An integral part of the training is to be involved during the filtration system construction. The rest of the training will involve in-class seminars in order to learn how to keep the system running.

Table 7 contains the training duration recommendations based on the EPA guidelines.

Table 7: Approximate training durations

Time Period	Topic	Approximate Duration
Pre-construction	System Overview & Membrane Operation Principles	1 - 2 hrs
During Construction	System Construction	3 weeks
Comprehensive Training (Post-construction)	Pre-treatment Operation	0.5 hrs
	Post-treatment and Disinfection	1 hr
	Backwashing & Chemical Cleaning	1 hr
	Integrity testing / module repair	1 - 2 hrs
	Monitoring and Troubleshooting	1 - 2 hrs
Total In-Class Time (excluding system construction)		5.5 - 8.5 hrs

A section has been included in the Operation and Maintenance Manual briefly outlining the stages of training and educational material to be taught. The section is meant to guide the operators through the Operation and Maintenance Manual.

7.0 Estimated Project Costs

Based on the economic analysis performed by Optimus, the expected cost to implement the design solution for the full-scale treatment system at REHC is $36,280. This total cost includes required materials, construction, and ongoing maintenance activities for the system's lifespan of 25 years. The total project cost can be broken down into the initial start-up investment of $18,686, and an average yearly cost of $703 per year for 25 years.

8.0 Conclusion & Recommendations

Optimus Engineering Associates completed the design for the REHC water treatment system as well as all the supporting documents to ensure that the treatment system is implemented sustainably. Industry sponsorship was provided by AquaSolve Ventures for this project. The design is intended to benefit the residents of REHC in Haiti, a country that has limited access to clean drinking water. Several deliverables were produced for this project, which include the following:

- Full-scale water treatment system design based on a pilot-scale model
- Operations and Maintenance Manual for system including operator training program
- Implementation plan for system
- Business plan for a water selling business at REHC
- WASH program with educational information on sanitation and hygiene

Based on preliminary research during the proposal stage, we opted to use membrane filtration for the water treatment system. Optimus utilized a gravity-fed system as a sustainable option to operate the treatment system. The two water quality treatment criteria monitored were turbidity and microbiological contamination. From research, it was determined that turbidity in Haitian groundwater is relatively low, but microbiological bacteria can be an issue. Water containing fecal contamination from Guichon Creek, near BCIT, was filtered through sand filters in BCIT's hydraulics lab to reduce turbidity and simulate Haitian groundwater.

A pilot model of the full-scale treatment system was constructed in the lab at BCIT. This model was used to determine the scalability of the model and the flux-drop over time. During the pilot model testing, the pilot system was successful in filtering out fecal bacterial and reducing turbidity. It was also observed that the flux drop was relatively low over time meaning that backwashing is not frequently required. The second module configuration tested in the pilot model, which had twice the membrane surface area of the first module tested, was able to produce approximately twice the flow of the first module. This confirmed that our pilot model could be scaled up by increasing membrane surface area.

The full-scale was designed with the same hydraulic parameters of the pilot model. The full-scale design consists of the following components:

- solar-powered well pump
- pre-treatment storage tank with constant head tank
- pre-screen unit
- membrane filtration modules
- post-filtration storage tank with disinfection
- backwash water storage tank and backwash system

The treatment system incorporates mainly materials that are readily available in Haiti. Exceptions to the list are the solar power system, the well pump, the membrane modules, and the manual backwash pump. All of these materials will be outsourced.

Throughout the design process several alternative options were considered for various components, which include: Type of membrane filtration method used, gravity-fed system or pumped system, manual backwash or automatic backwash, wastewater options, option for water delivery, and materials selection. The most suitable options were chosen for the REHC system including:

- Ultrafiltration membrane filtration
- Gravity-fed treatment system
- Manually operated backwash
- Infiltration trench for wastewater
- No water delivery service for business
- Ferrocement tanks and PVC piping for full-scale design

Several documents were prepared to ensure the long term sustainability of the system. The first document is the implementation plan, which details the schedule for deployment, short term system support, and long term system support. The second document prepared was an operation and maintenance manual and a training program to keep the system operational. This document will act as a reference for the local operators who will run and maintain the system. The third document was a business plan for REHC Pure Water. This plan consists of a cost analysis for the system and a business set-up to sell excess water to members of the community. Profits from the business are expected to recover the cost of the water treatment system within five years. The WASH program is intended for use as a reference for teachers at REHC to incorporate sanitation and hygiene into their lesson plans.

Optimus recommends implementing the water treatment system at REHC as per the design and specifications laid out in the supporting documents. As designed, Optimus feels that the treatment system should be self-sustaining and require little maintenance over its projected life span. The project cost consists of an initial start-up investment of $18,686, and an average yearly cost of $703 per year for 25 years.

Several limitations for this project should be reviewed before any final implementation of Optimus' design. Structural analysis of all components should be performed by others. In addition, site conditions and geotechnical analysis should also be reviewed, while water quality characteristics should also to be confirmed. Optimus trusts that the developed water treatment system for REHC meets or exceeds all relevant standards and design criteria.

Epilogue

Upon completion of this project, Optimus has had the chance to reflect on all the hours put in to make this project a success. While the work may be complete, the potential for future revision, optimization, and alternate design considerations or improvements still exist. Optimus hopes that the lessons learned from the outcome of this project will inspire others to contribute to the ever changing world of water quality engineering. With more research and developed ideas, the current technology may become cheaper and more efficient. It is the intention of this project to be considered for future student testing and research at BCIT.

Options for Further Project Development

Some of the potential ideas that Optimus feels could be developed using the team's pilot model include the following:

- Optimize gravitational head to minimize fouling rate or determine subcritical flux rate where negligible fouling occurs
- Develop automated control system (valves, pump, timer) to allow for standalone backwashing cycle
- Conduct additional pilot testing trial experiments to optimize membrane configurations, backwash programs, chemical cleaning cycles, and other system components
- Design structural components for full-scale system
- Educate future classes through hands on demonstrations of membrane filtration technologies.

Skills and Knowledge Gained

Optimus is grateful for all the support that was given by everyone involved with this project. It provided the team with a unique engineering design experience and supplemented the knowledge obtained through studies at BCIT. We feel that this project helped solidify fundamental knowledge of hydraulics, water quality, business and project management, and environmental engineering. In addition, the team was able to further develop skills with computer aided drafting, report writing, and project presentation.

Challenges and Lessons Learned

One of the key lessons learned by the team was the importance of strong team planning, organization, documentation, and project tracking. Optimus feels that the success of this project can greatly be attributed the positive team dynamic that was established. Utilizing weekly meetings and progress reporting, the team was able to stay on track for the duration of the project and maintain a healthy balance with other classes and personal obligations. The team logbooks also ensured that allotted hours were adhered to and that pertinent information was not lost. By tracking progress along the way, the team was able to adapt to unforeseen issues, and develop mitigation strategies for areas of uncertainty. This project reinforced the roles that engineers face in addition to strictly technical skill sets.

Some of the challenges that Optimus faced were due to the open nature of Capstone design course and the relative inexperience of the team for projects of this magnitude. Membrane filtration technology is highly proprietary and often the scientific data regarding membranes are not shared publicly. Often the team had to seek advice and expertise outside of material that was introduced through engineering course work or provided in technical literature. This encouraged critical thinking since at times assumptions and engineering judgment had to be used in lieu of specific procedures or design standards. Optimus feels that challenges faced such as these provided a great benefit as often engineers face unforeseen issues and must be able to adapt and problem solve in a dynamic world. It is important to establish, develop, and fully understand all design methods employed.

Recommendations

Optimus has several recommendations for future students developing their Capstone design projects and for future iterations of the CIVL 7090 Capstone Design class. We feel that teams should not take for granted the magnitude of their projects and really spent a lot of time in the planning and development stages. The stronger you start in the beginning, and the more effort that you put into keeping the project on track, the easier it will be to put things together in the end. Never underestimate the time it takes to get things done and when in doubt, double or triple hours to mitigate the risks associated with uncertainty. As a rule of thumb, it always takes longer. Also never forget to ask for help if you need it. Many problems can be averted before they begin with the right guidance. As a suggestion to the Capstone Committee, Optimus also has the following recommendations:

- Defer review of draft report documents until later in the term to allow for more refined feedback on final deliverables (still highly encourage continuous report writing throughout project execution).
- Less time devoted to progress reporting and more time for actual project completion.
- Review project expectations as actual completion times for most Capstone projects seem to be greatly over the anticipated 140 hours.

Costs spent by Optimus to develop their pilot model system was approximately $500. Estimated consulting fees for Optimus based on burden rates and scheduled task hours were recorded at $109,468 CDN, with final project costs $148 CDN below the estimated budget. See Appendix R for a full breakdown of the task hours and consulting fees used by Optimus for the development of this project. Included is a list of project tasks, hours allocated and spent, Optimus burden rates, and a three line graph depicting the planned, earned, actual consulting fees.

Overall, Optimus feels that the experiences gained through the duration of this project have been positive. We feel that the objectives and ideas that were developed during the proposal stage were either met or exceeded. From the feedback provided after the proposal, the team was able to refine the scope and remove unnecessary components while ensuring the development of the key elements. The many good jokes shared in the lab, technical lessons learned, and experiences shared have helped to prepare us for our future engineering careers.

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