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Woodchip denitrification bioreactor for reducing nitrate in contaminated well water for St. Francis Retreat Center

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SANTA CLARA UNIVERSITY
Department of Civil Engineering

I hereby recommend that the
SENIOR DESIGN PROJECT REPORT
prepared under my supervision by

ANDREW HIGHLANDER
&
PATRICK JOHNSON

entitled

WOODCHIP DENITRIFICATION BIOREACTOR FOR REDUCING NITRATE IN CONTAMINATED WELL WATER FOR ST. FRANCIS RETREAT CENTER

by accepted in partial fulfillment of the requirements for the degree of

BACHELOR OF SCIENCE IN CIVIL ENGINEERING

Edwin Maurer 6/14/17
Advisor Date

6-14-2017
Chairman of Department Date
fr Mark Aschheim

WOODCHIP DENITRIFICATION BIOREACTOR FOR REDUCING NITRATE IN CONTAMINATED WELL WATER FOR ST. FRANCIS RETREAT CENTER

by

Andrew Highlander
&
Patrick Johnson

SENIOR DESIGN PROJECT REPORT

submitted to
the Department of Civil Engineering

of

SANTA CLARA UNIVERSITY

in partial fulfillment of the requirements
for the degree of
Bachelor of Science in Civil Engineering

Santa Clara, California

Spring 2017

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The team of Patrick Johnson and Drew Highlander would like to thank Keith Warner OFM and Edward DeGroot of the St. Francis Retreat Center for bringing this problem to our attention and being very helpful during our site visits. We would also like to thank Dr. Maurer and Dr. Chiesa for their help and guidance throughout this project. The team owes Dr. Kenneth Williamson of Clean Water Services (Oregon) much gratitude for providing the team with much needed insight on the construction of similar denitrification bioreactors he worked on in 2014.

WOODCHIP DENITRIFICATION BIOREACTOR FOR REDUCING NITRATE IN CONTAMINATED WELL WATER FOR ST. FRANCIS RETREAT CENTER

Andrew Highlander and Patrick Johnson

Department of Civil Engineering
Santa Clara University, Spring 2017

ABSTRACT

The St. Francis Retreat Center, which serves over 7000 people each year, has had issues with the health of Flint Lake, located on their property, during the drought season. By utilizing a nearby water well, the retreat center looks to recharge the lake and sustain its water levels, essentially restoring its natural ecosystem. The issue is that the well water is contaminated with high amounts of nitrates, which is not only an issue for the lake's health, but also is very unsafe for human consumption. In order to design a water treatment system that is eco-friendly, sustainable, and cost-efficient, the team looked to construct and test the effectiveness of a denitrifying woodchip bioreactor. This design will serve as a prototype for a much larger implementable system that will be able to handle the flow rates from the water being pumped from the contaminated well. To run the tests, a 300 gallon steel tank served as the bioreactor apparatus that facilitated the process of denitrification using heterotrophic bacteria which consumes the nitrates in the water and synthesizes them into nitrogen gas. The prototype demonstrated that denitrifying bacteria, using the woodchips as a growth source, effectively reduce nitrate levels to meet government-mandated standards, and can be implemented on a larger scale.

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Introduction

This project was introduced to the team in July of 2016 by Keith Warner OFM of the St. Francis Retreat Center, located within the foothills of the Gabilan Range in San Juan Bautista, California. Throughout the year, nearly 7000 people come to the Franciscan retreat house to escape their busy lives and attend numerous different retreats. In the middle of the retreat grounds, there is a small two acre lake called Flint Lake, that provides the drinking water for the retreat center.

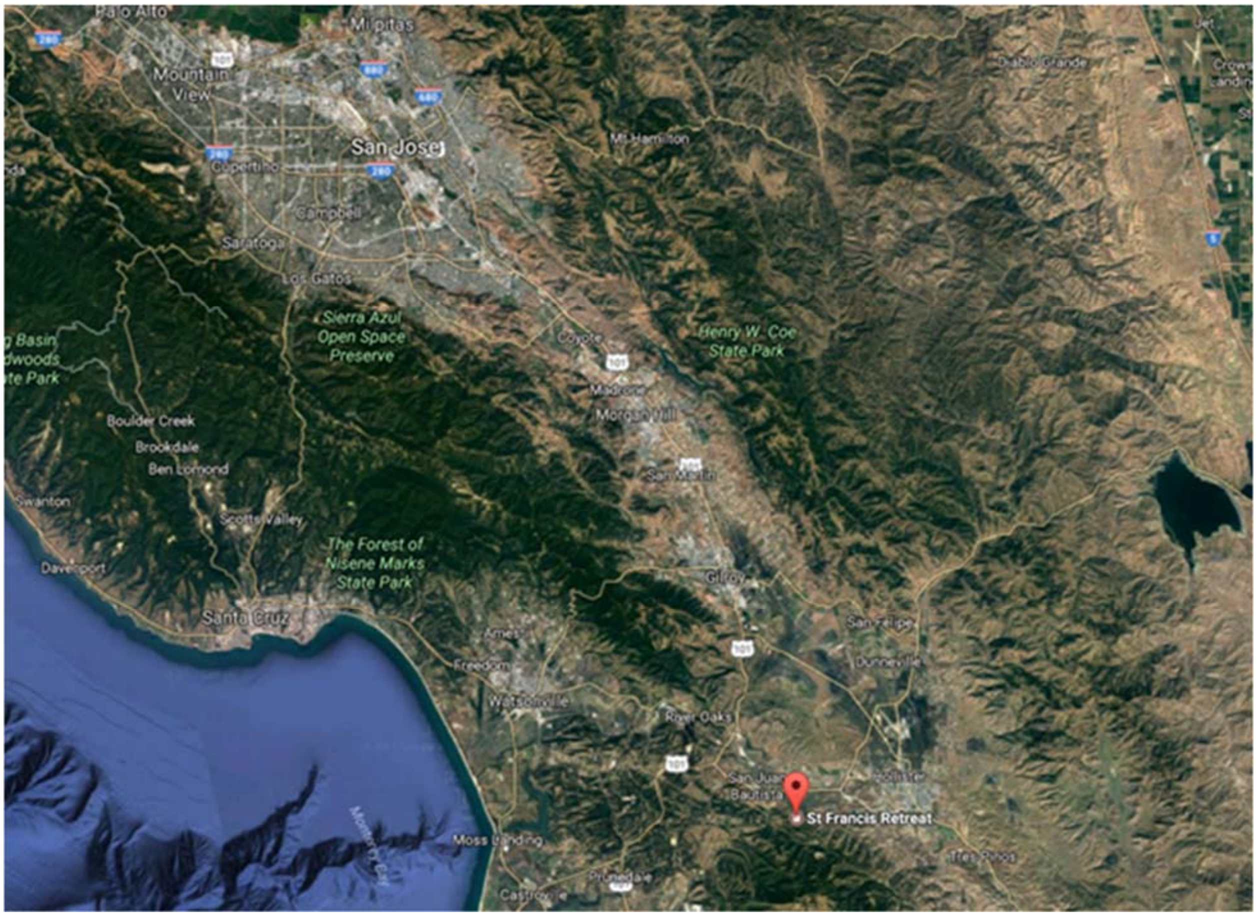


Figure 1: Map of St. Francis Retreat Center. This shows the centers location relative to San Jose.

Additionally, the health of the lake is imperative in adding a certain serenity that helps to generate greater meditation and reflection. During the drought years or dry months, however, the pond tends to dry up, leaving a dusty, sandy lakebed.

Figure 2: Photograph of Flint Lake at the St. Francis Retreat Center. This photo was taken on March 22, 2017.

The team of Patrick Johnson and Drew Highlander, combined with the team of Cathy Cantoni and Melene Agakanian, hoped to design a system that would utilize a nearby water well to recharge the pond in an eco-friendly and sustainable way. Unfortunately, the water well contains water that is high in nitrates due to the pesticides from the agricultural farmlands in the area. Located directly next to the lake is a pumping station that utilizes the lake's water for the retreat center's drinking water. To make matters worse, California water regulations have also been disrupting the flow of other nearby wells on the property to serve its retreatants. While Cathy and Melene designed the transportation system from the well to the pond, the main priority for this half of the project was to create a cost-effective, sustainable way to not only remove the high amounts of nitrates in the well water before it enters the lake, but also recharge the water table. This would allow the center's pumping station, located near the lake, to produce water with the lowest possible nitrate levels.

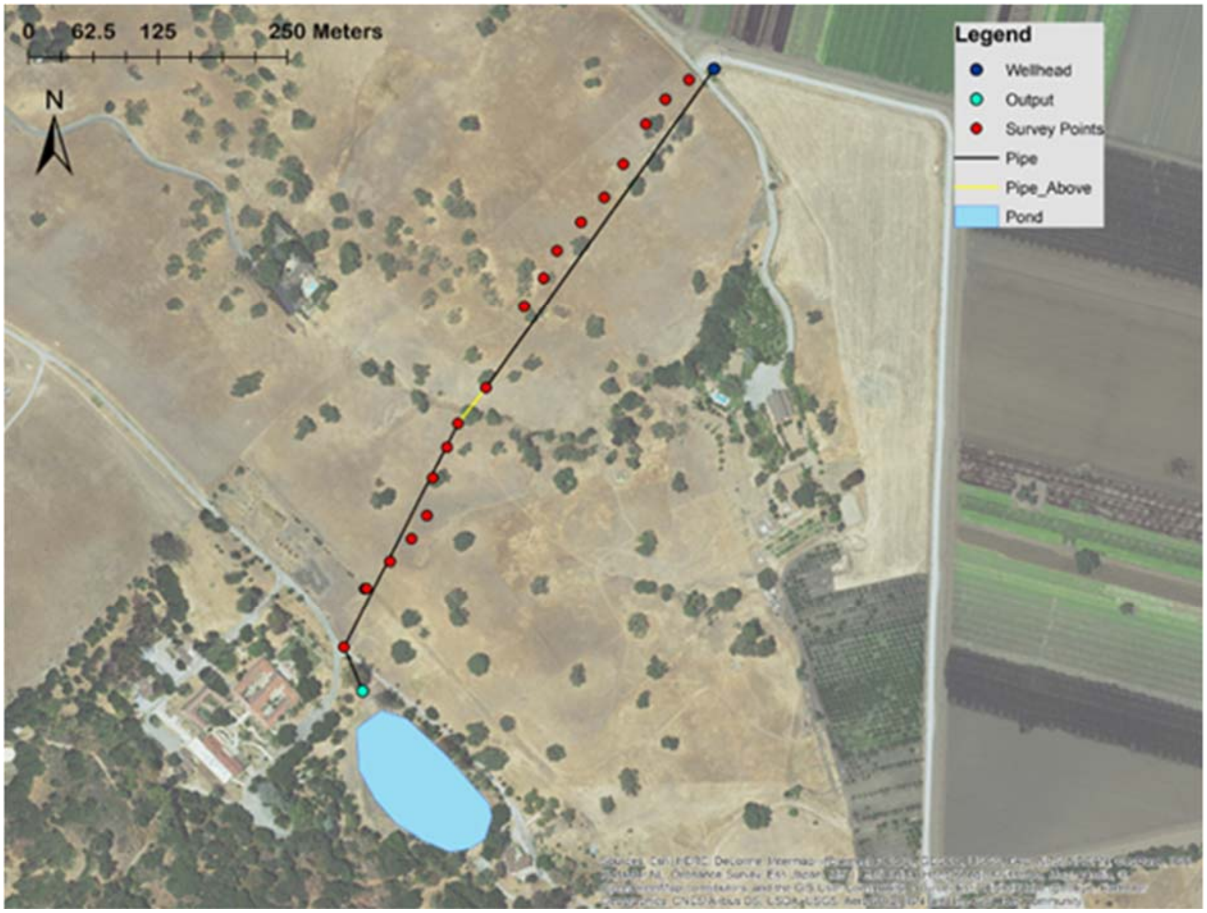


Figure 3: Diagram of the proposed pipe system that would transport water from the contaminated well to Flint Lake.

The well is located in the heart of farming land. Because plants need nitrogen to use as food to grow, nitrogen-rich fertilizers and animal manure are being used all across the world, including the lands surrounding San Juan Bautista, which have severely increased the amount of nitrates in rivers and groundwater. While the nitrogen cycle converts nitrogen into various chemical forms within terrestrial, atmospheric, and marine ecosystems, the natural denitrification performed by bacteria is not enough to combat the fertilizer runoff in the groundwater in agricultural areas. Consequently, the excess nitrates in surface water such as ponds, streams, or lakes are a direct cause of eutrophication, or algal blooms. While algae form the base of the food web of which nearly all marine organisms depend on, an excess of nitrate can lead to mechanical damage to organisms (such as the disruption of the epithelial gill tissues in fish), oxygen depletion from bacterial degradation, and even mass mortality events from the high production of neurotoxins. Furthermore, the high densities of algae on the water's surface blocks sunlight from reaching the plants and algae below, which will decay and create an environment too low in oxygen for aquatic insects and fish ("Nutrient Pollution"). High nitrate levels also have hazardous effects on people as well, especially with pregnant women and young children. It interferes with the body's red blood cells' ability to transport oxygen, a life threatening condition known as "blue-baby syndrome", or methemoglobinemia, in infants (Knobeloch).

Based off recent measurements (see Appendix A), the center's well has a contamination level of 98 milligrams per liter (mg/L) nitrate (NO_3^-), or 22 mg/L nitrate-nitrogen (NO_3^--N). The measurement of "mg/L nitrate (NO_3^-)" is the concentration of just the nitrate ion in the water, whereas the measurement of "mg/L nitrate-nitrogen (NO_3^- -N)" is the measurement of nitrate as nitrogen, or the amount of nitrogen in the nitrate ion. The California State Water Resources Control Board - Division of Drinking Water (SWRCB-DDW) requires that drinking water may not exceed concentration levels of 45 mg/L nitrate and 10 mg/L nitrate-nitrogen. This minimum represents the safe level of nitrates for drinking water, but the prevention of eutrophication requires the lowest nitrate levels possible (State Water Resources Control Board Division of Water Quality). This requirement made the goal for the design to reduce nitrate levels well below 10 mg/L nitrate-nitrogen at less than two mg/L.

The team applied for $1500 of funding through the School of Engineering, based on initial budgeting and cost estimates. The school granted $1000 to the team to complete this project. Despite this reduced funding, the team was able to design the project under the budget. More details on the budget are provided in the Cost section.

Figure 4: Contaminated well on-site at St. Francis Retreat Center.

Comparative Alternative Analysis

A few potential solutions that were considered included a rock media bioreactor or denitrifying plants. A rock media bioreactor would essentially be a system that facilitates the process of denitrification, or the reaction of turning nitrates into nitrogen gas, essentially reducing the nitrates in the water down to low levels. A tank would serve as the apparatus to facilitate an environment that would allow denitrifying bacteria to effectively remove nitrate from the contaminated water. These bacteria, which are heterotrophic (meaning they rely on a carbon source to stay alive), feed on nitrates in the water and are released as nitrogen gas. Since the rock media only acts as a home for the bacteria to form biofilms on, a carbon source in the form of methanol with glycerol would have to be added to support the bacteria in order for them to be added (*Clean Water Services Denitrification Pilot Reactors)*. Methanol and glycerol, although adequate carbon sources for such a bacterial environment, present numerous environmental problems for implementing the system within the pond. Methanol in particular is volatile, and can result in the death of aquatic life, plants, and birds (Australian Department of the Environment and Energy). The cost of such a system would be reasonable; practically the same as the cost of the chosen design (refer to Cost Estimate Section for further information), but the usage of a chemical carbon source would be an unnecessary risk for the lake's environment. Taking this into account, the feasibility of such a design would be impeded by the fact that the large-scale implementation of the bioreactor would need to prevent any chemicals from leaking into the lake's water. An entire filtration system would need to be added onto the bioreactor in order for this idea to work. The difficulty of such a task would increase both the complexity of the design and the cost of the system to create an eco-friendly and efficient bioreactor, thus demonstrating the rock media bioreactor's overall impracticality.

Another consideration was to utilize denitrifying plants within a bioremediation system that reduce nitrate to nitrogen gas, similar to denitrifying bacteria. The idea was to place the plants in a channel, ditch, or swale circling the lake, or at least in the effluent zone of the water well's pipes, before entering the lake. While the use of plants or fungi in large-scale bioremediation projects has been found to be successful (Christianson), these plants, such as hornwort or Amazon sword grass, require anoxic environments (Behrends). Creating such an environment for the plants near the pond’s surface would mean they would need to be submerged throughout the year to survive, something that would have been difficult to guarantee with the fluctuating weather, influent flow from the well, and possibility of drought.

Figure 5: Photograph of the denitrifying plant Ceratophyllum demersum, more commonly referred to as a Hornwort (Seymour).

Although the maintenance and environmental impact of such plants is extremely low, the high cost of the denitrifying plants was another reason this idea was not feasible. The placement of the plants would require construction to install them within a large area in the lake, and the implementation process would be even more complicated considering the fact that they would need to be kept submerged in water. Because the plants are not natural to San Juan Bautista, there would have been an increased cost in transporting the plants as well as greater maintenance costs should the pond drain in a drought. Overall, the cost of the plants alone would be upwards of tens of thousands of dollars, so this idea was not sustainable, cost effective, or feasible.

Design Criteria and Standards

There were many aspects of this design that had to work within the site specific constraints and government-mandated standards. The implementation of a system that would be eco-friendly and effective was not a simple task. This project would have required another one to two more years to figure out the planning, construction, and maintenance requirements for both the transportation system for the well-water and the denitrification system for significantly reducing the nitrates. Because of this fact, this design by Andrew and Patrick needed to put to test a smaller constructed denitrification prototype that acted as a small-scale version of what will actually be implemented in the field. This bioreactor prototype, however, had to consider both the small-scale factors and the large-scale factors that affect the design of an effective bioreactor system. The design and testing of the prototype helped the determination of implementing a feasible bioreactor.

First and foremost, the retreat center was looking for a system that was environmentally friendly and sustainable. Meeting the eco-friendly demands would likely mean no moving parts, sustainable and local materials, and minimizing the concentration of nitrates to the point that it would not affect the lake's ecology.

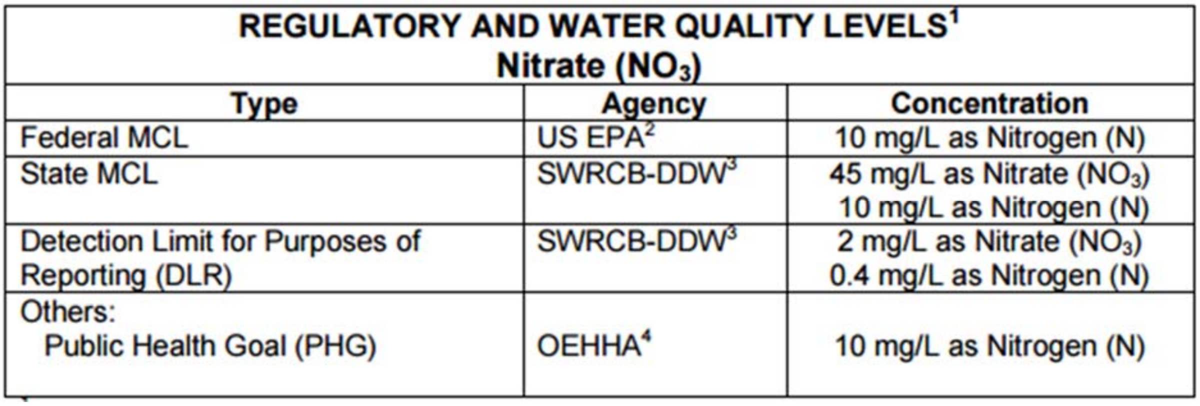
Secondly, the retreat center cannot afford an expensive water treatment system. The cost entirely depends on a multitude of factors, including materials, construction, size, maintenance, and service life. In order to meet the feasibility and environmental demands, the team was looking to design a prototype that would have the potential to be the lowest cost bioreactor system for the retreat center. Realistically, this meant the system would cost no more than $10,000, based on similar projects (Christianson).

Another constraint of the system was the sizing. The relation between volumetric size, flow rate, and detention time are the three main factors affecting how affect nitrate removal will be in the system. Given the small size of the prototype, these three factors are different, and this must be accounted for in determining if the bioreactor is implementable on site. For hydraulic tanks, the detention time is found by dividing volume by flow rate. Given the fact that the detention time remained relatively similar in the prototype and the large-scale bioreactor in order for the denitrification to be carried out, the main factor that determined the increase in size of the large-scale bioreactor was the flow rate. The transportation system will design the flow rate to be 23 gpm (gallons per minute), which will be used to determine the volume of the large-scale system given a detention time that works.

Due to volume restrictions, the team assumed a detention time of four days. Most of the other bioreactors researched had a detention time of two to three days, so four days would go above and beyond the state requirements for removing nitrates. This time was also chosen due to the volume of both the bioreactor and the 50-gallon barrel that was available to feed the bioreactor the nitrate-enriched water. Another assumption was that the well has a concentration of 98 mg/L NO_3^- based off of previous well records. With this, the team calculated that 20 grams of solid sodium nitrate had to be dissolved into 40 gallons of water every day that the barrel was refilled.

The performance of the bioreactor was constrained by government mandate standards set by the United States Environmental Protection Agency (EPA) for Maximum Contaminant Levels in drinking water. The Maximum Contaminant Level is the legal threshold limit on the amount of a certain substance allowed in public water systems set by the Safe Drinking Water Act. These standards, shown in Table 1, gave the team an idea for the rate of performance for the denitrification system. The bioreactor had to at least remove enough nitrate as nitrogen levels down to 10 mg/L, or below 45 mg/L only as nitrogen.

Table 1: This table illustrates the concentrations allowed for each separate category (State Water Resources Control Board Division of Water Quality).



REGULATORY AND WATER QUALITY LEVELS[1]
Nitrate (NO_3)

Type	Agency	Concentration
Federal MCL	US EPA[2]	10 mg/L as Nitrogen (N)
State MCL	SWRCB-DDW[3]	45 mg/L as Nitrate (NO_3) 10 mg/L as Nitrogen (N)
Detection Limit for Purposes of Reporting (DLR)	SWRCB-DDW[3]	2 mg/L as Nitrate (NO_3) 0.4 mg/L as Nitrogen (N)
Others: Public Health Goal (PHG)	OEHHA[4]	10 mg/L as Nitrogen (N)

The site location impacted the implementation of the bioreactor as well. The area around the lake is not particularly large, so the bioreactor may have to be placed across the street from the lake, which would also require the moving of a leech field. Also, due to the relatively high water table, the bioreactor could not be dug too deep into the ground.

An important factor for the cost was the materials available to build the large-scale bioreactor on site. More will be discussed on the materials that were included in the project and how using local products can drastically decrease the overall cost.

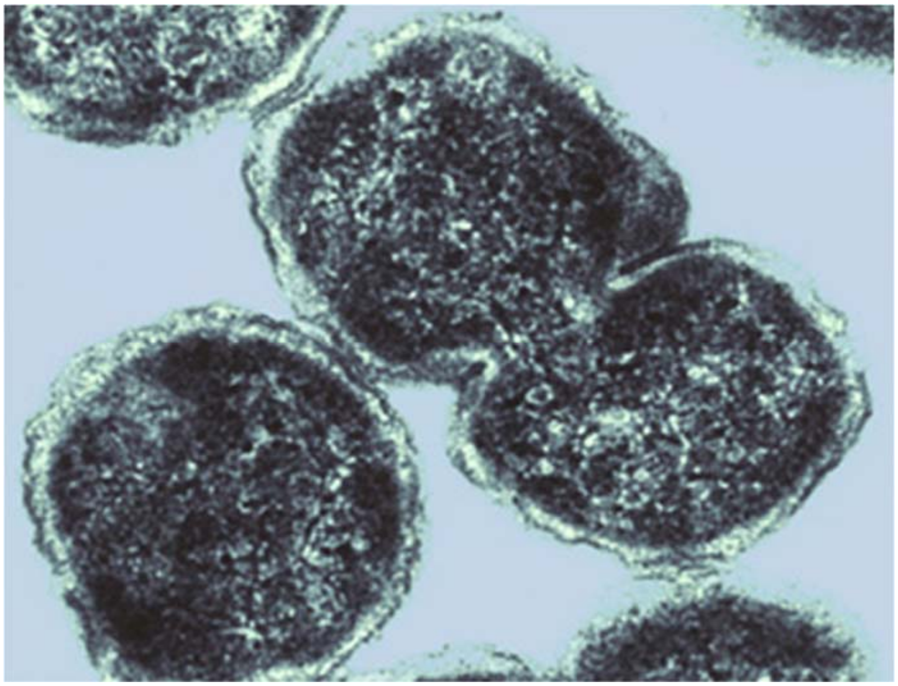


Figure 6: Photograph of the denitrifying bacteria Paracoccus denitrificans. This is one of many types of bacteria used during this project ("Paracoccus denitrificans").

Maintenance also played a large role in the feasibility of the large bioreactor; how can the retreat center implement the system without having to spend more money on maintaining it or fixing technical problems year after year? Much of this concern had to do with the lifespan of the materials used in the system. The bacteria are susceptible to dying off if exposed to sunlight, extremely low temperatures, or if not completely submerged in water where they can reproduce and stay alive (Davies). Without the presence of the bacteria, then the system is rendered useless, and major renovation costs would need to replace the bacteria, and allow them to repopulate back to the size that best allows the system to be effective in reducing nitrate levels. In the preliminary design for the prototype, and for the large-scale bioreactor system, keeping the bacteria in a safe environment was a priority.

Another problem that arose was the effluent control. When the system was first installed, the hose was used released water at a rate much higher than the desired rate, so the tank would essentially drain. To remedy this, the team obtained an adjustable valve and attached it to the end of the effluent tube. The valve was then adjusted so that water flowed out at the desired rate; the same as the influent flow.

$$Q = \frac{V}{t} = \frac{170\ gal}{4\ days} \approx 40\ gal/day \quad \text{. . . . . (1)}$$

Figure 7: Photograph of the pump used during this project. This pump was responsible for pumping 40 gallons per day into the system.

To get the desired flow rate (Q), the detention time (t) equation used the volume (V) of the water. This was the volume of the void space of the middle portion of the tank, as the amount of water that would submerge the woodchips. Using the four day detention time was not only similar to other bioreactor projects (*Clean Water Services Denitrification Pilot Reactors*), but gave the team the easiest pump rate to work with. The barrel containing the “contaminated” nitrate water was only 50 gal, so any flow rate above 50 gpd (gallons per day) would mean the team would have fill up the barrel multiple times each day.

Figure 8: Photograph of the valve system used to control the effluent flow. This was responsible for releasing 40 gallons per day.

The next goal was to determine a way to enrich the water being pumped into the bioreactor prototype in order to simulate the contaminated nitrate levels seen on site. The goal was to create water with 98 mg/L nitrate, or 22 mg/L nitrate-nitrogen. For enriching the tap water to fill up the barrel, the team purchased solid sodium nitrate which had similar properties to nitrate fertilizer. Using the amount of water in the barrel, the amount of sodium nitrate that had to be added could be calculated.

Figure 9: Photograph of containers used to hold 20 grams of sodium nitrate.

$$40\frac{gal}{d}\ x\ 3.785\frac{L}{gal}x\ 98\frac{mg}{L}\ NO_3\ x\frac{85\ NaNO_3}{62\ NO_3}\frac{g}{mol}=\mathbf{20}\frac{\boldsymbol{grams}}{\boldsymbol{day}}\ \boldsymbol{NaNO_3\ per\ 40\ gal} \qquad \text{. . . . .(2)}$$

With some conversion rates, the chosen flow rate, the contamination levels in the water well, and the ratio of molar masses for sodium nitrate and nitrate, the mass of sodium nitrate that needed to be added to the filled barrel was 20 grams each day. This made the process of contaminating the water to 22 mg/L nitrate-nitrogen easily simulated. At the beginning of each day, the barrel was simply filled up with a garden hose, and the 20 grams of sodium nitrate were added. Using this process, the team could analyze how effective the bioreactor prototype was in decreasing the nitrate-nitrogen levels from 22 mg/L to well below 10 mg/L.

Description of Designed Facilities

The solution required a system that had to be sustainable, environmentally friendly, and a design that proved resilient with the changes in weather and flow. Ultimately, what was chosen was a woodchip bioreactor design (see Appendix B). This bioreactor was built using an eight-foot steel tub, to serve as a prototype for a much larger bioreactor system on the site. Just like the rock media bioreactor, the system would utilize denitrifying bacteria. Instead of the addition of methanol, however, the woodchips provide an organic carbon source to host the bacteria in order for them to grow and live. The team was presented with the benefits of such organic material through contact with an outside professional at Clean Water Services. While they tested river rock media as a successful denitrification material, the use of woodchips does not rely on a carbon source to set off the reaction between the denitrifying bacteria and the nitrate contaminated water. Clean Water Services had conducted experiments with such woodchip denitrification reactors in 2014, and had found that the organic material was successful in leaching carbon into the water, providing an environment in which heterotrophic denitrifying bacteria could convert nitrate from water to nitrogen gas (*Clean Water Services Denitrification Pilot Reactors)*. The woodchip denitrification reactor would be a suitable design for the nitrate contaminated water to enter before flowing into the pond.

Figure 10: Photograph of a denitrification bioreactor experiment executed by Clean Water Services in Hillsboro, Oregon (Clean Water Services Denitrification Pilot Reactors).

The system involved the use of 170 gallons of dry redwood tree woodchips, 30 gallons of large rock media, small pea pebbles, baffle walls made of plastic, a 300 gallon galvanized steel tank, and two gallons of activated sludge. The activated sludge, obtained from the Palo Alto Water Treatment Plant, contains the heterotrophic bacteria needed for the denitrification reaction to take place (Prakasam). The rocks and baffle walls help to normalize flow throughout the woodchips. The bacteria in the activated sludge attaches to the woodchips and begins to use the carbon to synthesize the nitrates into nitrogen gas.

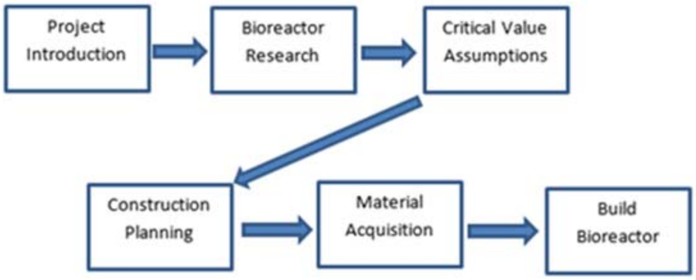


Figure 11: Flow chart of the team's design process.

This project was special because, unlike most civil engineering projects, it was a living project. While designing the bioreactor, the team realized that the success was mostly up to microscopic, living bacteria which could potentially leave a great deal of room for error. The team dealt with problems that most teams would not have to deal with, such as protecting the bacteria from light and ensuring the outside temperature was warm enough for the bacteria to be effective.

Figure 12: Photograph of the location of the wood chips used in the denitrification bioreactor.

For the construction process, the plastic panels were first drilled with holes, spaced a half of an inch apart on the upper half of the plastic. Using brackets and bolts in drilled holes, the panels were fit to the inside of the tank to act as baffle walls that separate the influent/effluent sides from the middle portion full of woodchips. Two pair of panels were installed six feet apart, with a five-inch gap in between the panel pair. The influent side panels had the holes on the top half, while the effluent side had the holes on the bottom half, to ensure a controlled flow through the tank. A hole was drilled in the effluent side of the tank, one foot from the bottom, to install the exit valve.

Figure 13: Beginning stages of construction. This photograph was taken after the baffle walls were installed and the wood chips and pea pebbles were added.

Next, the woodchips were added to the middle portion. Pebbles were added in between the pair of panels, and finally larger rocks were placed in the influent and effluent sections of the tank. A tube attachment with a valve on the end was connected to the effluent hole, and finally caulk was placed around all of the drilled portions of the tank to prevent leaking.

Once completely set up, the tank was fully filled to the top with water and two gallons of sludge containing the bacteria were added to the woodchips. The bacteria were given a week to grow and reproduce within the fully submerged woodchip section. A tarp covering the tank was put down to protect the bacteria from the sun. Then, the nitrate-enriched water was pumped in at the desired rate, with the effluent valve releasing water at the same rate.

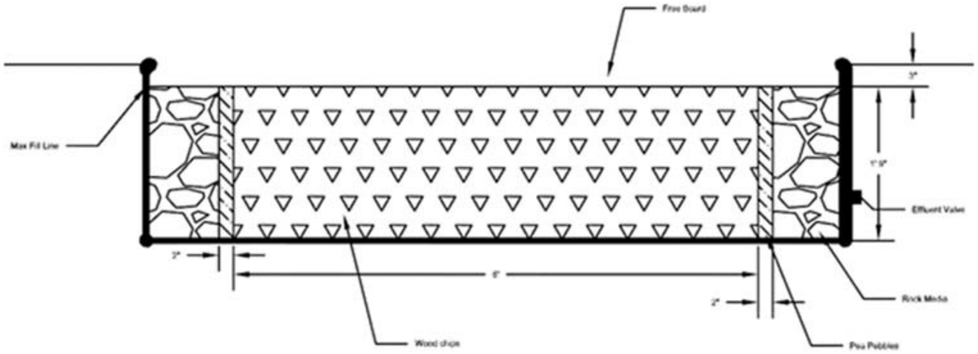


Figure 14: AutoCAD Drawing illustrating the basic layout of the system.

Finally, the measurement of the effectiveness of the bacteria in the tank proceeded by using nitrate testing strips. These testing strips were obtained from Hach; they are color based, and measure the concentration of nitrate-nitrogen in a sample, which was used to compare with the EPA's federal/state Maximum Contaminant Level (MCL) standard of 10 mg/L nitrate as nitrogen.

Figure 15: Late stage of construction. This photograph illustrates the bioreactor with the larger rock media and the mesh that holds the woodchips below the water surface.

Figure 16: Photograph of completed site setup.

Cost Estimate

While the bioreactor prototype itself turned out to cost approximately $800, the main concern was determining a cost estimate for the large-scale system. The main cost came from the lumber used for the woodchips, so if the retreat center uses soft wood trees locally sourced without having to purchase the wood for the large-scale system, half of the cost could be cut down.

Table 2: Cost breakdown for the entire project.

Material	**Cost**
300 Gallon Galvanized Steel Tank	$ 259
Redwood Woodchips	Obtained for no cost
Plastic Baffle Walls	$ 144
Large and small rock media	$ 150
Sodium Nitrate	$ 25
Nuts, Bolts, and Washers	$ 50
Wire mesh, 2x tarp, plastic fitting and tubing	$ 58
Pool Test Kit	$ 15
Wood crate, caulk, and bricks	$ 30
PVC Valve and hose	$ 20
Nitrate Test Strips	$ 20
Chlorine and heavy metal neutralize	$ 20
Poster and pens	$ 26
Total	**$ 817**

Figure 17: Photograph of completed denitrification bioreactor.

In Figure 18, the prototype can be seen in comparison to the large-scale system. The increase in size obviously would result in a major cost increase for the project, with the amount of woodchips needing to cover 450 square yards, in order to handle the flow rate on site of 23 gpm. Similar size projects completed by Iowa State have had a cost of approximately $10,000, again, with much of the cost coming from the woodchips rather than the installation. Fortunately, maintenance for bioreactor systems is minimal if the woodchips are kept submerged. Since the pump from the water well would only operate from April to October, however, the submersion of the woodchips in water would rely heavily on the rain during the winter months. It is also important to note that the woodchips will be covered with turf rolled over the top, adding to the overall cost. This is better not only for integrating the system within the surrounding environment, but also for blocking out sunlight which kills the bacteria. Construction will also add onto the cost in order to build the ditch to fill, which will then form the system boundaries. In the ditch, an impermeable layer or tarp would be placed first and the woodchips would be placed on top of that.

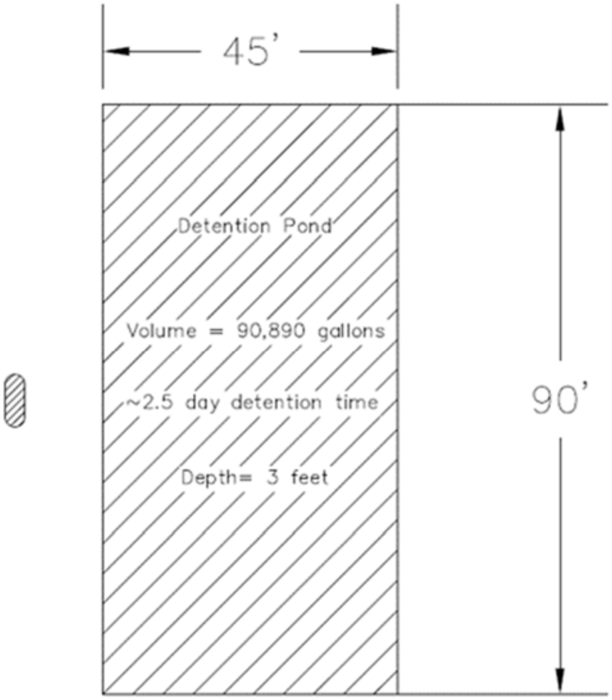


Figure 18: This illustrates the size difference between this project (on the left) and the size that would be needed to denitrify the required volume from the well (on the right).

Results

The final design and testing of the prototype bioreactor proved to be successful in reducing nitrate levels down to nearly zero. The testing period commenced in early April, and continued through to early May. As the nitrate-enriched water was pumped through the tank, a testing strip was used to measure the nitrate concentration each day. At first, the results did not show a noticeable decrease in nitrate levels, but on the third day, the concentration of nitrate-nitrogen began to decrease exponentially. By the fourth day, the bioreactor had decreased nitrate-nitrogen concentration to approximately 2 mg/L. Not only did the tank prove to reduce nitrate-nitrogen down to desired levels within four days, but it maintained low levels of nitrate-nitrogen concentration for the rest of the testing period. During this time, the nitrate removal was relatively slow, only causing incremental changes in the effluent. By day five, the effluent nitrate concentration had dropped to well below the three mg/L NO_3^--N maximum concentration set by the federal drinking water standards. The team continued to pump 40 gallons of water with a NO_3^- concentration of 98 mg/L (or 22 mg/L NO_3^--N) every day for the next 25 days. During this time period, the effluent nitrate concentration never rose above two mg/L NO_3^--N. Considering the state and federal concentration maximums for NO_3^--N is 10 mg/L, this project was successful.

Figure 19: Photographs of testing strips used to measure nitrates in the effluent. The top photograph shows Day One with a high nitrate concentration. The middle photo shows Day Three with a reduced nitrate concentration. The bottom photo shows the results we received from Day Five until we stopped testing.

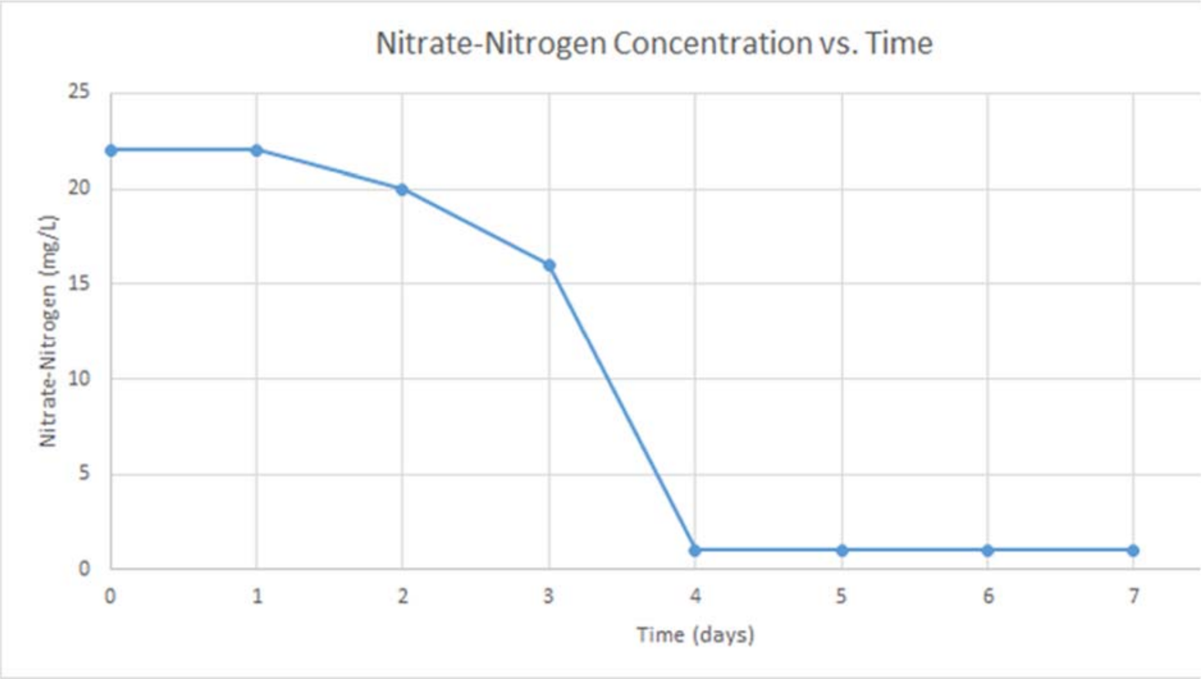


Figure 20: Graph illustrating the concentration of nitrates in the water starting from Day One up to Day Seven. This graph stops at Day Seven because the results were the same from that point onwards.

Analysis of Results and Implementation

The results not only demonstrated that a denitrification bioreactor is able reduce the nitrate contaminant levels on-site down to negligible levels, but it was also able to keep the concentration levels reduced for the remainder of the testing period of two weeks. These results gave the team confidence that the system would be able to handle the contaminated well water being pumped into the larger system to be implemented. Next, the feasibility of implementing this larger bioreactor must be explored, which includes looking into the issues of the new design: shape, location, cost, performance, maintenance, environmental safety, and sustainability.

In similar studies, the most effective design shape for large bioreactor systems has proven to be rectangular shapes of lengthy channels with not too much width or depth. Studies have shown that these shapes allow for a lower detention time since the contaminated water flows through a smaller wetted perimeter and cross-sectional area (SOURCE). Construction costs will be minimized with a lower depth, but it is the location of the system that is the primary constraint of the shape.

The best location for the bioreactor is as near as possible to the lake, where an effluent channel already exists (see Figure 21). This not only avoids building around the leech field on the other side, but it keeps the bioreactor in an area that is wet but not completely submerged within the lake's surface.

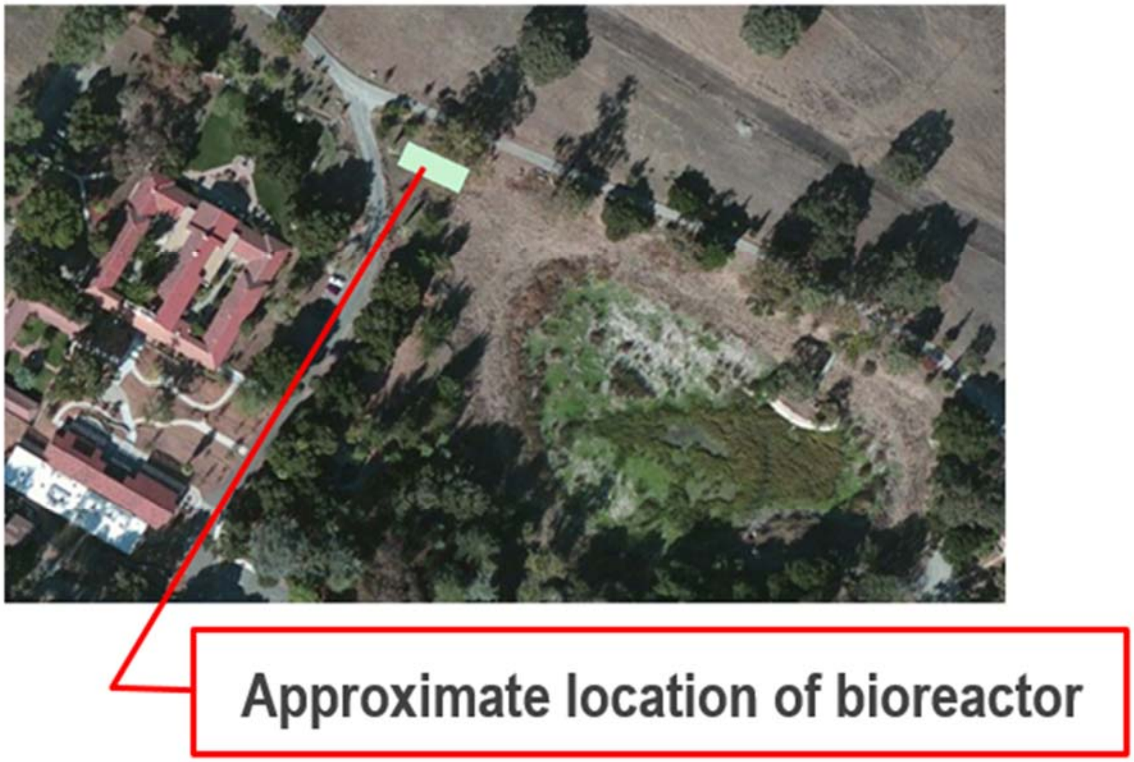


Figure 21: Approximate location of where the large-scale bioreactor would be placed on the St. Francis Retreat Center site.

This wet environment is vital to the survival and growth of the denitrifying bacteria, the key component of the system's effectiveness (Alefounder). The bioreactor would be best implemented underground, since this will help keep steady temperatures during the hot summers and the cold winters, which is another factor that will benefit the health of the bacteria (Christianson). This area, seen in Figure 21 will provide an easy transition point for the effluent pipes that the transportation team is designing for. As long as the contaminated water exiting the pipes will enter only the bioreactor inlet, then the system would provide sufficiently clean water for the lake and for the pumping station located nearby.

The bioreactor performance depends on a multitude of design options: shape, type of woodchip, and, most importantly, the assumed detention time, design volume and flow rate. Again, the shape that results in the most effective performance of the denitrification process is a smaller cross-sectional area for the bacteria to remove the nitrates. As previously discussed, the type of tree the woodchip comes from also matters to the performance of the bacteria. Softwood trees from areas with wet climates and dense vegetation provide the most carbon. This is because these types of trees sequester carbon from the atmosphere better, and they naturally grow in carbon rich environments. On the contrary, woodchips coming from hardwood trees in arid environments do not provide as much organic carbon (United States Department of Agriculture Forest Services). This will hinder the growth of the bacteria and the effectiveness of the system overall, while significantly reducing its lifespan. Once the trees are cut down, they lose their ability to sequester carbon but still store the carbon in the wood fibers long after harvested. Fortunately, buried or submerged woodchips retain carbon much better than woodchips directly exposed to the air, assuring a long-lasting carbon source for the bioreactor (Zeng).

When it comes to the detention time, the small-scale prototype had an assumed value of four days. This turned out to be a sufficient amount of time for the bacteria to reduce the nitrate in the water down to desired levels. For the large-scale bioreactor, an assumed detention time of two and a half (2.5) days was chosen. According to similar sized bioreactors, the detention time observed in the field was two to three days. The resulting volume of the large system, given a 23 gpm flow and a two and a half day detention time, was 450 cubic yards, using Equation 1. This volume bioreactor has been successfully implemented previously in nitrate contaminated, large agricultural drainage areas, while capably handling flows of over 300 gpm (Christianson). It must be noted, however, that bioreactors experiencing fluctuating flow rates have a decreased nitrate removal performance compared to those bioreactors with steady state flow (Greenan). Considering the change in precipitation throughout the seasons, the peak flow rate can change each month. Fortunately, since the water well pump is only in operation during the drier summer months, the bioreactor would not see too much fluctuation in flow due to precipitation.

Figure 22: Photograph of the area surrounding Flint Lake. Taken on March 22, 2017.

One of the biggest considerations for this project will be cost. The project size and location will be factors that affect the construction cost for the larger bioreactor. For this reason, excavation could prove to be difficult and somewhat costly, given what the design calls for. Since it is in a wet area, excavation would commence in the dry summer months for ease of installing the bioreactor. Aside from construction, the majority of similar bioreactor projects' cost come from woodchips. If the retreat center is able to save the money on purchasing the 450 cubic yards of woodchips needed, either by receiving donated woodchips (getchipdrop.com) or using a chipper with ideal local trees, the cost for the project decreases almost by half. In an effort to be as cost effective as possible, design adjustments and material acquisition are the two primary concerns for the implementation of the larger bioreactor system, but once construction is complete, maintenance costs would be relatively low, making this a retreat-friendly system to install.

Proper installation and management of the construction will likely mean minimal maintenance for the bioreactor over its long lifespan. One particular concern when it comes to maintaining such a system is making sure the bacteria are alive and are efficiently denitrifying the contaminated water at a solid rate. As previously mentioned, a dry environment or extreme temperatures could severely affect the bacteria, and even eradicate the colonies. If this does happen, the turf covering the system will need to be removed for the “reseeding” of the bacteria. Fortunately, the cost and time for such maintenance will not be very much. Bioremediation systems such as this, with no moving parts or complex structures, will not require technical repairs, and bacterial communities have been shown to be quite resilient over long periods of time (Enwall).

Figure 23: Recommended location for the future full-scale bioreactor. Taken on March 22, 2017.

One of the biggest aspects of this project is to be eco-friendly. Given the usage of organic materials, there will be very little, if at all, damage to the environment. Even large-scale bioreactors have been shown to integrate very easily into the surrounding environment without polluting or negatively affecting the natural habitat they serve (Greenan). In Figure 23, the proposed location for the bioreactor poses very little threat to the surrounding environment since it avoids the leech field on the other side of the road and already contains an outlet channel flowing into the existing riparian zone.

Figure 24: Construction of a large-scale denitrification bioreactor in Iowa (Christianson).

Finally, sustainability is at the forefront of a project like this, since it is in the best interest of the retreat center to have a bioreactor system that remains effective for a long period of time. Multiple bioreactors constructed by Iowa State for farms have been working effectively for over 10 years, with some reducing nitrate levels up to 80% as much as first observed 15 years before (Christianson). What makes this denitrification bioreactor different from others is that it will only be in operation for seven months out of the year. The lifespan of the bioreactor will be affected by this, but it remains to be seen as to how long it can continue to effectively denitrify the water. Regular testing will be needed to ensure the performance of the system does not diminish too quickly, and it will help determine how the five months of rest will affect it. Ideally, the wet, underground environment during those winter months will be adequate enough to keep the bacteria alive. Eventually, however, the woodchips will lose too much carbon and the bacteria's capacity for denitrification will diminish. Replacement woodchips and bacteria will have to be added at this point, and the disposal process will commence. Regardless, the reusability of bioreactor system give the team no reason to think that it wouldn’t be able to serve its purpose at the retreat center.

Conclusion

Regardless of the design chosen, this design project was to build a small prototype to prove to the St. Francis Retreat Center that this type of system could work, and be feasible in both cost and efficiency. The transformation of the bioreactor prototype into a large-estscale system will be very much achievable, and should demonstrate the effectiveness of such systems over a long period of time, even with the changing periods of operation. The retreat center should find that the denitrification system can successfully clean the water pumped in from the well. This will allow Flint Lake’s ecosystem to flourish during the dry months by providing an adequate amount of water for recharge, as well as giving the residents clean water to pump from the lake.

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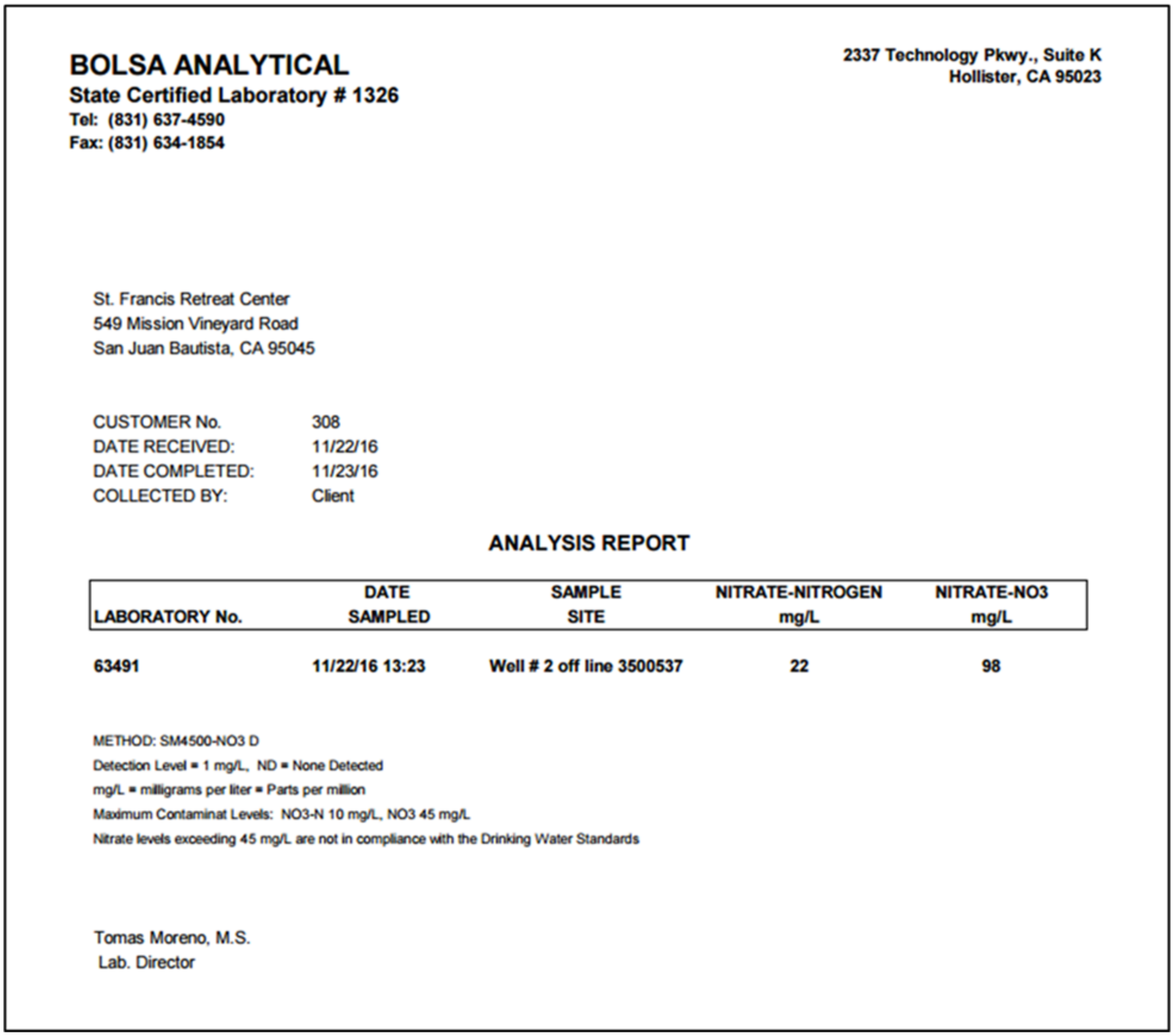
Appendix A

Contaminated Well Water Data



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Hollister, CA 95023

St. Francis Retreat Center
549 Mission Vineyard Road
San Juan Bautista, CA 95045

CUSTOMER No.	308
DATE RECEIVED:	11/22/16
DATE COMPLETED:	11/23/16
COLLECTED BY:	Client

ANALYSIS REPORT

LABORATORY No.	DATE SAMPLED	SAMPLE SITE	NITRATE-NITROGEN mg/L	NITRATE-NO3 mg/L
63491	**11/22/16 13:23**	**Well # 2 off line 3500537**	**22**	**98**

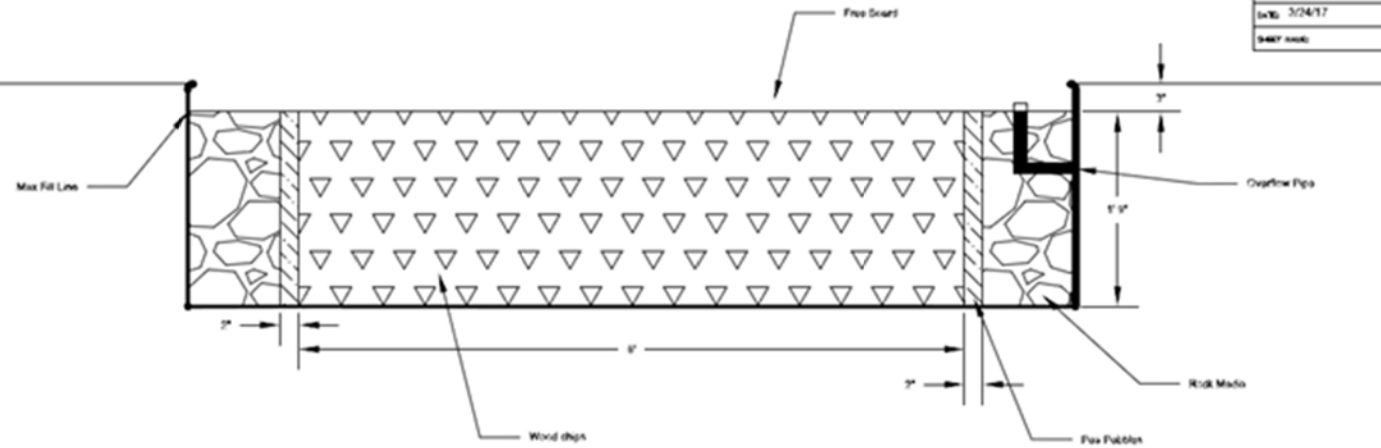
METHOD: SM4500-NO3 D
Detection Level = 1 mg/L, ND = None Detected
mg/L = milligrams per liter = Parts per million
Maximum Contaminat Levels: NO3-N 10 mg/L, NO3 45 mg/L
Nitrate levels exceeding 45 mg/L are not in compliance with the Drinking Water Standards

Tomas Moreno, M.S.
Lab. Director

Appendix B

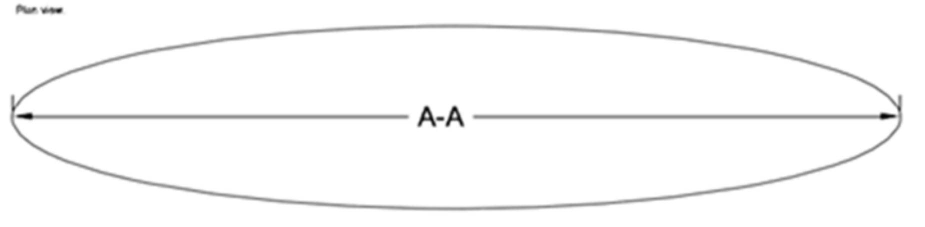
Detailed Drawings

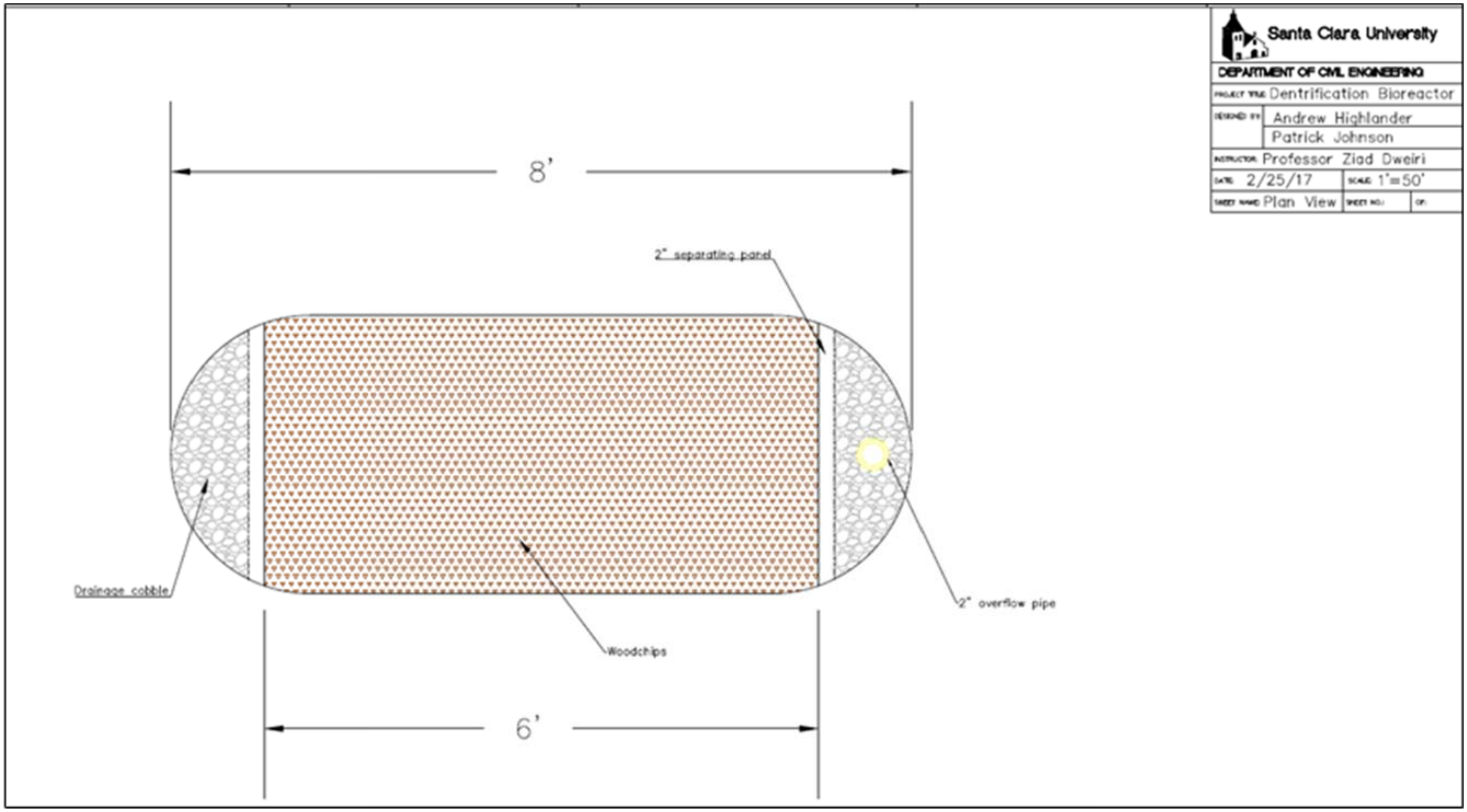
Santa Clara University
DEPARTMENT OF CIVIL ENGINEERING
PROJECT TITLE: Denitrification Bioreactor Section View
DESIGNED BY: Andrew Hightacker
Patrick Johnson
INSTRUCTOR: Professor Zied Dwein
DATE: 3/24/17
SCALE:
SHEET NAME:
SHEET NO.:
OF:



Section A-A

Notes: 1. Top of Section A-A to be flush with ground level of site location
2. Model will have a 1" slope. This is so gravity can help it flow to the effluent side
3. Woodchips will be home to denitrification bacteria. They will use the Carbon to start the denitrification process





Santa Clara University

DEPARTMENT OF CIVIL ENGINEERING

PROJECT TITLE	Dentrification Bioreactor		
DESIGNED BY	Andrew Highlander Patrick Johnson		
INSTRUCTOR	Professor Ziad Dweiri		
DATE	2/25/17	SCALE	1"=50'
SHEET NAME	Plan View	SHEET NO.	OF