

Prefab 1 L/s, Spring 2016

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May 20, 2016

Abstract

The goal of the Prefabrication 1 L/s team was to research, test, and provide fabrication methods to be used when constructing the 1 L/s plant design in Honduras. The team worked on an approximate 1/10th flow rate scale model to design novel geometries for a low-flow flocculator and sedimentation tank while implementing known AguaClara fluid mechanic techniques. The cost per capita associated with these plants was calculated to be much lower than plants built using traditional construction methods. Recommendations on design and fabrication methods were relayed to future teams working on full-scale plant production.

Introduction

Traditional AguaClara water treatment plants have successfully served relatively large communities for the past decade. Comprised mainly of concrete, they required extensive excavation and on-site construction, resulting in high fixed costs of roughly \$100,000 per plant APP (2015). For plants operating at flows greater than 30 L/s, the total cost per L/s was relatively low, at a value of \$7,000 per L/s. As plant capacity decreased, the price per L/s increased non-linearly to over \$20,000 per L/s for a 5 L/s plant, and presumably even higher as the plants' flow rates continued to decrease. These amounts translated to an associated cost of \$30 per capita at 30 L/s and almost \$100 per capita at 5 L/s.

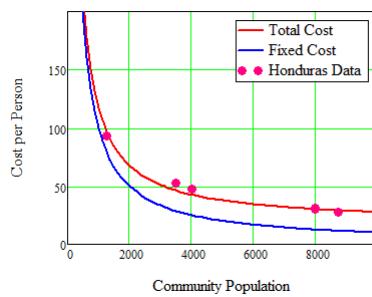


Figure 1: The plot of total cost per person vs population the plant served APP (2015). In large populations, the cost per person remained low, but in smaller plants the cost per person increased drastically.

Because of these high costs, traditional AguaClara designs were not viable options at flow rates below 5 L/s, preventing them from being implemented in small villages with populations ranging from one hundred to one thousand people. In order to serve this niche, a new design was required with additional constraints of portability, material availability, fabrication ease, and overall size limitations. A successful implementation of a prefabricated 1 L/s AguaClara plant design would allow small communities around the world to have access to safe and affordable drinking water.

Previous Work

This project was the first prototype attempt at integrating various low-flow process investigations. It built off of the work completed by previous CEE 4540 Capstone Design projects, past findings from AguaClara design teams, and existing AguaClara plant designs. No fluid dynamics design constraints used in existing plants were altered, as they were known to successfully treat water up to World Health Organization drinking water standards. All adjustments to the plant design were made to geometry, size, and material selection only.

Previous version of low flow flocculators have explored single pipe designs. A 5 cm (2 in) pipe geometry with constrictions in coiled flexible tubing was proven to work in the lab by William Pennock Pennock (2015). However, this geometry was only tested at a plant flow rate lower than the project's target of 1.0 L/s. Multiple flocculators could be run in parallel to achieve desired the flow rate, but cost and size would quickly become inhibitors. Another problem with this design was the complicated geometry and the high stress placed on the constricting pieces. The flexible tubing was also much less durable than rigid plastic and therefore required additional upkeep or regular replacement. A team in CEE 4540 FA 2015 designed another low-flow pipe flocculator Jiang et al. (2015). From their calculations, a straight rigid pipe approximately 160 m in length would provide the necessary collision potential, but that length was unreasonable for the prefabricated plant's portability constraint. However, by utilizing both mixing due to wall shear and expansions around many elbows in the pipe, a compact and rigid design was suggested for use with the 0.1 L/s sedimentation tank fabricated in the lab in Spring 2016.

Various low flow sedimentation tank designs have been considered by CEE 4540 teams. The intial design of the sedimentation tank was the capstone project by Buhl, DeVoe, and Erickson in Fall 2015 Buhl et al. (2015). In that project, it was proposed that the sedimentation tank be enclosed in a 0.6 m (2 ft) diameter PVC pipe inclined at 60°. While it was assumed that AguaClara technologies such as high flow rate sedimentation would be available, the basic design could be altered to meet traditional plant constraints. The base of the tank maintained 60° slopes, as established in the CEE 4540 curriculum in order to prohibit floc settling Weber-Shirk (2015). The entrance pipe was similarly designed with jet diffusers and a jet reverser to maintain fluidization of the floc blanket Weber-Shirk (2015). Plate settler surface areas and spacing reflected dimensions used in traditional full-scale AguaClara plants and the exit launder matched existing exit pipes.

Design Challenges

The bulk of the research on this project was focused on designing and testing construction methods for the plant's sedimentation tank. However, initial research was also directed towards finalizing the flocculator design. Design of both components entailed developing visual models, calculating compatible dimensions, and performing fluid mechanics derivations. This writeup outlines tested methods for constructing a sedimentation tank while keeping in mind the integration of all processes into a functioning, semi-portable treatment plant.

Flocculator

The flocculator design stemmed from the desire to utilize a single pipe geometry while minimizing the amount of space occupied. The initial proposed design was 2.1 m long, 1.2 m wide, and 0.4 m tall. It employed the use of 7.62 cm (3 in) diameter PVC pipes and elbows. In order to utilize space efficiently, the pipes were arranged vertically in a 6×6 array with connecting elbows on the top and bottom of the structure (see figure 2). Clear plastic tubing replaced regular opaque pipe at key locations to allow for the operator to visually analyze the flocs as they progress through the structure. This design was not fabricated because similar single pipe flocculators have been used effectively in the AguacClara research lab and it was determined that the sedimentation tank was the greater priority. Future teams should investigate flocculator designs to determine more detailed specs.

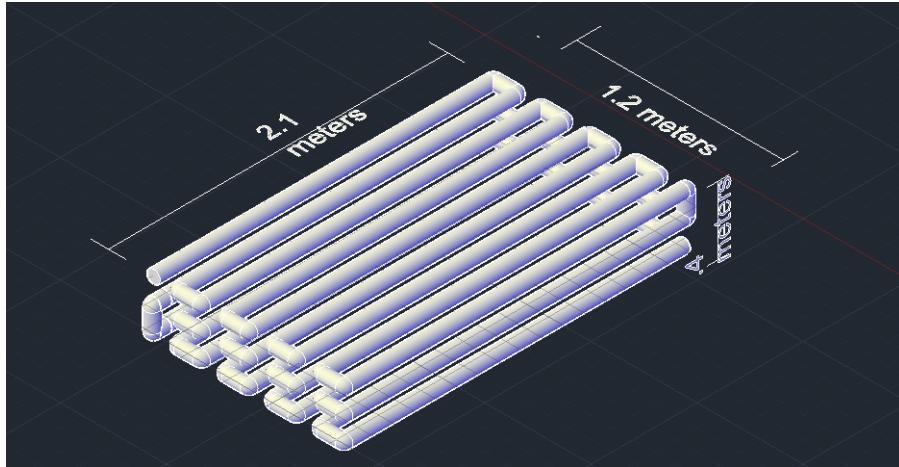


Figure 2: The flocculator is comprised of thirty straight pipe sections, each 2 meters in length, and connected by pairs of 90° elbows. The straight sections provide friction for major head loss, and the minor losses are due to expansions around the bends. This “packed” geometry allows the flocculator to meet the desired collision potential while minimizing the amount of space occupied.

Sedimentation Tank

The primary concern surrounding the sedimentation tank design was to eliminate the need for on-site construction, specifically concrete pours. Cylindrical corrugated HDPE pipe was selected for the tank due to its available sizes, standard use in agriculture and water systems, portability, and ability to retain shape when subjected to hydrostatic forces. A tank diameter of 0.91 m (36 in) was chosen for the 1 L/s plant based on the maximum upflow velocity constraint $V_{active} \leq 1.0 \text{ mm/s}$. This value is the standard design practice in traditional plants and is low enough to allow for the formation of a floc blanket, where suspended particles remain until they exit the pipe through the floc hopper. The cylindrical shape of the tank added new challenges that were not associated with the traditional rectangular tanks, but after various prototype ideas it was determined that working with a circular shape was more practical than scaling down a rectangular tank. By adding a 30° bend in a vertical pipe, the plate settler geometry was greatly simplified without adding unnecessary complications to the base geometry. In the small scale model, it was important that our pipe matched the geometry of the regular tank and was similarly corrugated.

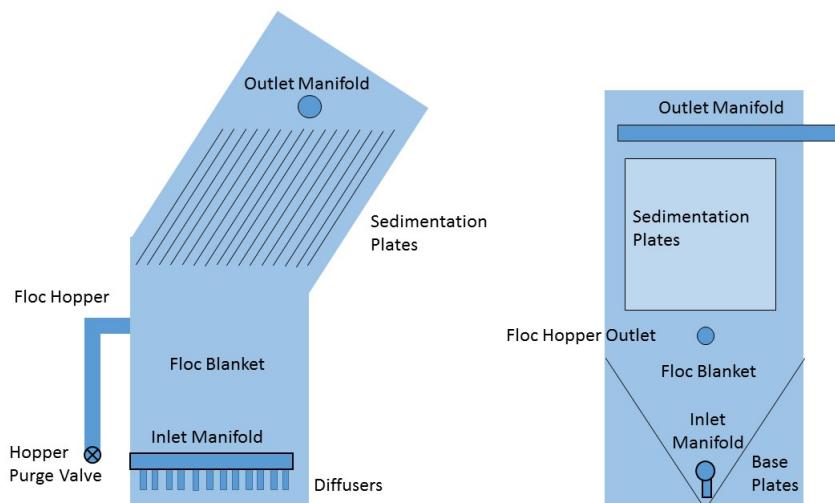


Figure 3: An overall schematic of the proposed sedimentation tank. Each tank component is present in traditional plants and geometry has been updated to fit the circular pipe geometry.

Fabrication of the sedimentation tank model was a multi-step process. First, the corrugated pipe was cut at a 15° angle into two 2-foot sections. This cut provided the seam for the 30° bend in the sedimentation tank. Next, the sloped base was welded into the bottom section of pipe. Holes were drilled for the inlet manifold and the floc hopper. The plate settlers and jet diffusers were put together concurrently with the prior step. Once the two corrugated pipe sections were welded back together, the plate settler module was inserted and secured in place. Finally, the outlet pipe with multiple orifices drilled along the crown

was installed just below the water surface level of the completed sedimentation tank.

Cutting the Corrugated Pipe

To create the 30° bend, the pipe was cut in half at a 15° angle, one section was rotated 180° , and then reattached by plastic welding. This cut was slightly difficult given the round surfaces and corrugations. A guide was created by calculating the ellipse formed by the outer pipe edge at 15° , tracing the shape onto a cardboard sheet, and cutting out and removing the inside ellipse. The remaining elliptical ring was placed around the outside of the pipe at the appropriate angle and a line was drawn on the pipe to be used as a guide.

The corrugations presented a physical challenge to drawing and cutting because the depth of the surface was continually changing . First the pipe was cut along the line using a handsaw to break through the outer and inner layers of plastic (the ribs caused by the corrugations were hollow). Next a sawzall was used to finish the cut. One person guided the sawzall while two other people braced and rotated the pipe. The handsaw was much less precise than the sawzall. While the final cut was satisfactory, the method could be improved with the correct tools such as creating a box jig to guide the saw and provide a more consistent cut.



Figure 4: The cut was made at a 15° angle. When pieced together with the other section of pipe, the two will form a 30° bend.

A minor concern was that the the outer diameter corrugations did not line up exactly after the section was replaced. This did not prove to be detrimental

to the functionality of the tank because the outer corrugations were only for structural support and were cut back from the connection for weld access. The priority was to have a solid weld along the inner diameter to ensure that the tank was watertight and structural support could be added once finished, if necessary.

Plastic Welding

When welding HDPE base plates, the temperature of the Leister plastic welder was set to 550°F. Tack welding was used in a few places along the weld line to hold the plastic in place. Next, the area surrounding the immediate contact points was heated using the closed tip and a side to side motion, and the plastic rod was melted into the pipe and base plastic. Finally, using the open tip position, HDPE welding rod was slowly fed into the weld seam. Between heat applications, the plastic was allowed to cool so it retained structural integrity. If heated too much, the hot air melted through the thin walls of the corrugated pipe, leaving a puncture. If not heated enough, the welding rod would not properly bond to the material.



Figure 5: The thin walls of the pipe make welding a delicate process. Too much heat or pressure can lead to a puncture in the tank.

Base Geometry and Jet Reverser

Initially, the plan for fabricating the base of the sedimentation tank was to use a two-step concrete pouring process. However, it was determined that this option did not comply with the ease-of-fabrication and portability constraints.

A variety of other materials including fiberglass were considered, but given available tools, flat HDPE sheeting was selected to form the base of the model. HDPE met the criteria of being light weight and durable while the congruity of material between base and pipe ensured a reliable bond to the smooth inner walls of the corrugated pipe. It is important to note that the full-size 1 L/s plants will use PVC for any and all HDPE-substituted materials in the model.

The base of the sedimentation tank consisted of two plastic half-ellipses, each 1/4-inch thick, angled at 60° from the horizontal that met at the bottom in a jet reverser to re-suspend the settled particles (see figure 6). The minor axis of the ellipse was set equal to the tank's radius (6 in) and the major axis was calculated at 12 in. The ellipse was then cut in half along the minor axis and welded into the triangular shape. To create a jet reverser for the HDPE scale model, 1/4" thick sheet of HDPE was heated with a plastic welder and bent around a 2-in diameter pipe. It should be noted that in a full scale sedimentation tank, half of a PVC pipe would be used as the jet reverser for simplification purposes.

In the model tank, the jet reverser was placed at the bottom 'V' of these plates and welded to both half ellipses. In the actual tank, it needs to be determined whether the jet reverser should be placed on top of the plates or if the ellipses should be trimmed on the flat end and welded flush with the plates. In the model tank, there was a ridge where the jet reverser met the ellipses on both sides which could result in floc buildup. However, this area could be insignificant and this may not be an issue. Lastly, the plate and jet reverser unit was inserted into the lower half of the corrugated pipe and the seam between these plates and the pipe was welded until watertight. When leaks still remained after multiple welding attempts, the entire seam was sealed with silicone and allowed to cure for 24 hours.

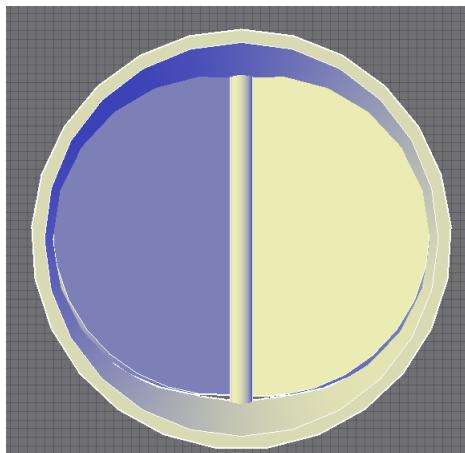


Figure 6: Top view of AutoCAD drawing. A jet reverser spans the diameter of the pipe and is welded along the flat edges of both semi-ellipses.



Figure 7: The base is comprised of two semi-ellipse pieces, welded together along their major axis. The slopes of these sheets measure 60° . The jet reverser is not present in the photo.

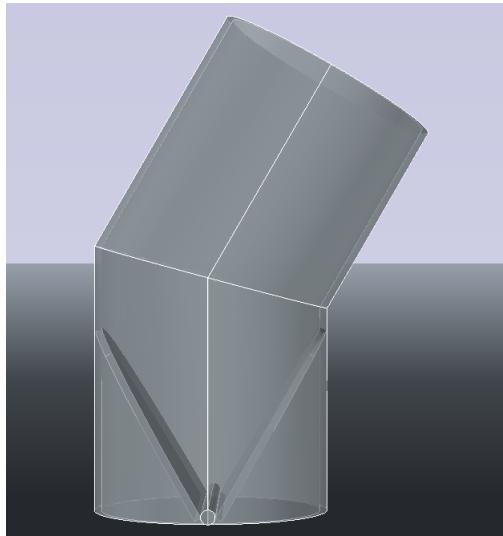


Figure 8: AutoCAD side view of the sedimentation tank. The sloped base and jet reverser are visible.

Plate Settlers

In order to maximize the total settled area within the sedimentation tank, plate settlers were installed at a 60° angle, parallel with the walls of the angled section of corrugated pipe.

The minimum plate-settler spacing required to prevent floc roll-up was a function of the diameter and density of the particles, the dynamic viscosity and density of water, and the upflow and capture velocity of the sedimentation tank. It can be defined by equation (1) below. Entering in the appropriate values for

each variable yielded a minimum plate spacing of 2.485 mm, which was well below the selected spacing of 1.5 cm.

$$S_{FlocRollup} = \frac{3V_{Active}}{\sin(\alpha)^2 \cdot V_{Capture}} \cdot D_{0Clay} \dots \\ \dots \cdot \frac{18 \cdot V_{Capture} \cdot \phi \cdot \nu_{water}}{g \times D_{0Clay}^2} \cdot \frac{\rho_{water}}{(\rho_{clay} - \rho_{water})^{\frac{1}{(D_{Fractal})-1}}} \quad (1)$$

A plate settler spacing of 1.5 cm was chosen to prevent floc roll-up at the scale model flow rate of 0.1 L/s and to allow relatively simple construction. Smaller plate spacing was decided against once ease of fabrication and material costs were considered. The closer together the plates, the more material and fabrication time would be required. The length of each plate in the model was set to 30.5 cm (12 in) because of the limited length that the corrugated pipe section allowed. It should be noted that in the larger prefabricated plants, the plate settler spacing will be increased to 2.5 cm, and the length of each plate will be 48.2 cm (1.582 ft). The thickness of each plate used in the model was 1.587 mm (1/16 in), which should remain constant for the full-sized prefabricated plant as well. Values for plate thickness, plate spacing, and the pipe diameter determined the number of plate settlers to be 19 as calculated in Mathcad. The two end plate settlers were discarded because they were deemed too thin to capture any settled particles, leaving 17 plate settlers total for the scale model sedimentation tank.

Table 1: Dimensions of each plate settler. Each HDPE plate was cut to the following specifications using a shear. Duplicates of each plate numbered 1-8 were made for the other half of the set, while there was only one plate number 0, positioned across the center of the pipe.

| Plate No. | Width (in) | Distance from center (in) |
|-----------|------------|---------------------------|
| 0 | 12 | 0 |
| 1 | 11.929 | 0.653 |
| 2 | 11.712 | 1.306 |
| 3 | 11.342 | 1.959 |
| 4 | 10.803 | 2.612 |
| 5 | 10.067 | 3.265 |
| 6 | 9.088 | 3.918 |
| 7 | 7.772 | 4.571 |
| 8 | 5.901 | 5.224 |



Figure 9: All 17 HDPE plate settlers before assembly into the bundle. Widths vary from 12" to 5.901".

Hole Spacing

The first step was to determine where the rods will intersect each plate. The plate settlers were designed to lie parallel to the 60° inclined section of the corrugated pipe. The rods used to secure the plate settlers run perpendicular to each plate. In order to achieve this geometry the rods intersect each plate at a lower point. The holes on each consecutive plate were cut at increasingly farther distances from their top edges so that each plate would be sloped at 60° with its bottom edges lying in the horizontal x-y plane.

The first step to determining the hole location for any plate size and length was to calculate the total change in parallel distance along the plate for the width of the sedimentation tank. If this distance was longer than the plate itself, multiple rods would be required to connect the unit. This distance can be calculated using equation 2.

$$(\text{Change in parallel distance}) = \tan(30) * (\text{Sedimentation tank diameter}) \quad (2)$$

The bottom hole must start at this distance plus a buffer space of at least 2cm above the bottom of the plate to minimize plate cracks and failure. The distance between the holes must be chosen to allow for buffer space between the edge of the plate and the holes. To find the location of the hole on the subsequent plate, the same geometrical relationship as the first calculation was used but the

inter-plate spacing replaced the tank diameter in the calculation. This ensured the plates remained inclined at 60 degrees. Each plate that followed had holes that were one increment lower. To ensure even horizontal spacing the center line was drawn onto each plate. The horizontal spacing of the upper rods was chosen to be evenly spaced between the edge and the center.

At 1.5 cm plate spacing, the additional distance increment for each plate was calculated as to be 0.87 cm (See Figure 10). Across the entire set of plates, the vertical change in distance along the plates was calculated using the 30.5 cm (12 in) inner diameter to be 17.5 cm (6.9 inches). This means the bottom hole needed to start more than 6.9 inches from the bottom of the plate so that the last hole was still located on the plate. The distance from the top edge of the first plate was arbitrarily chosen to be 2.5 cm, a distance that would provide buffer space between the edge of the plate and the first hole. The distance between the two vertical holes was chosen to be 8 cm to ensure that as the hole was placed lower on each consecutive plate the rods not run too close to the bottom of the last of the 17 plates. The horizontal spacing of the upper rods was chosen as 5cm from the center line since it was the approximate midpoint between the center line and the edge. This separation distance can be calculated using the Mathcad doc and plate separation calculations as described earlier.

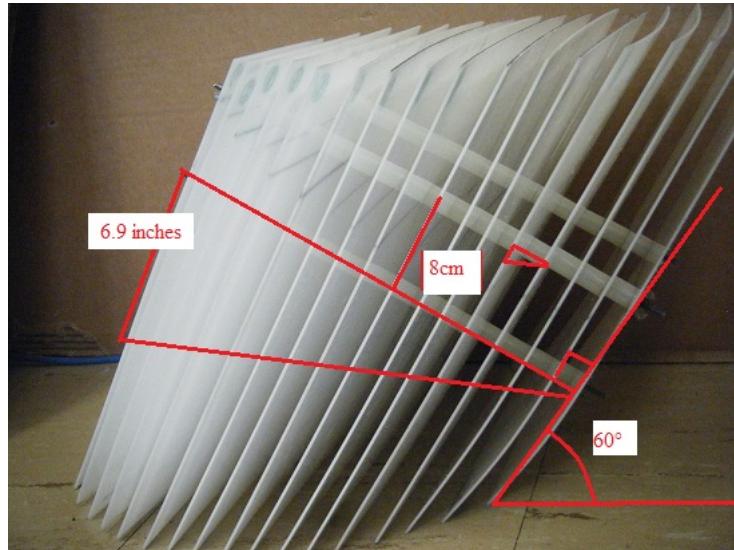


Figure 10: Plate Settler Unit: The small triangle shows the change in distance for each consecutive plate

Table 2: Detailed measurements for hole drilling. Three holes in each of the 17 plates will be used to secure them into a single unit.

| Plate Widths [in] | Dist. Top Hole to Top [cm] | Dist. Bottom Hole to Top [cm] |
|-------------------|----------------------------|-------------------------------|
| 5.901 | 2.50 | 10.50 |
| 7.772 | 3.37 | 11.37 |
| 9.088 | 4.24 | 12.24 |
| 10.067 | 5.11 | 13.11 |
| 10.803 | 5.98 | 13.11 |
| 11.342 | 6.85 | 14.85 |
| 11.712 | 7.72 | 15.72 |
| 11.929 | 8.59 | 16.59 |
| 12.000 | 9.46 | 5.224 |
| 11.929 | 10.33 | 18.33 |
| 11.712 | 11.20 | 19.20 |
| 11.342 | 12.07 | 20.07 |
| 10.803 | 12.94 | 20.94 |
| 10.067 | 13.81 | 21.81 |
| 9.088 | 14.68 | 22.68 |
| 7.772 | 15.55 | 23.55 |
| 5.901 | 16.42 | 24.42 |

The horizontal spacing of the top holes was 5 cm from the center line. This distance was chosen as the maximum distance reasonable for the smallest plate.

Three stainless steel threaded rods, each 0.3175 cm (0.125 in) in diameter and 30.48 cm (12 inches) in length were used to assemble plate settler bundle. Each plate was separated by plastic spacers with the desired length of 1.5 cm. This ensured consistent spacing, ease of fabrication, and uniformly parallel plates. Plates were secured at each end of the three rods using wingnuts. Note that the stainless steel rods used in the full-scale 1 L/s plant should be at least 0.635 cm (0.25 in) in diameter to ensure enough strength to resist bending of the rods and curvature of the plates.

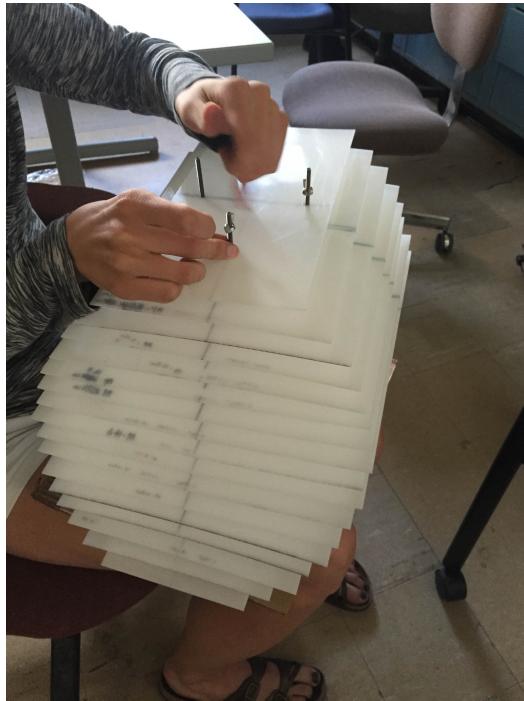


Figure 11: Finished plate settler bundle on the stainless steel rods.

Inlet Manifold and Jet Diffusers

The inlet manifold presented a number of challenges such as providing a resuspension velocity, creating a watertight connection and orienting the inlet pipe to optimize the floc re-suspension effects of the jet diffusers. While a 5.08 cm (2 in) diameter pipe had the advantage of minimizing the interference of the jet diffusers with the flow, calculations showed that the flow velocity was below the acceptable 0.15 m/s needed for re-suspension. To ensure a flow velocity high enough to prevent floc sedimentation, a smaller diameter of 3.81 cm (1 in) was chosen. The watertight connection is dependent on what material is used for the inlet manifold, which must also be able to bond with the jet diffusers. The materials must be readily available and low in cost, for these reasons a PVC pipe was chosen to form the inlet manifold. Since the pipe forming the model's sedimentation tank is made of HDPE, welding is not a possible option for sealing the connection. A bulk head fitting was chosen as the best available option due to its capacity to interface with different materials and the water tight seal it provides through the presence of an O ring. The last major challenge in the installation of the manifold was drilling through the curved corrugated surface of the sedimentation tank. Ideally the inlet manifold would be offset so that the jet stream flowing out of each diffuser hits the side of the reverser, resuspending the flocs by forcing them to follow the curvature of the reverser. Due to space limitations and the difficulty of drilling through the side of the tank it was decided to install the inlet manifold in the center then rotate it slightly so that the diffusers direct the influent toward the edge of the jet reverser rather than vertically down to the center.

The jet diffusers were fabricated in a similar manner as those in the full scale plants. The goal was to flatten the ends to decrease the width of the jet to between 0.15875 - 0.3175 cm (0.0625 - 0.125 in) with the idea of creating a two-dimensional jet. Half-inch diameter pipe was chosen due to its availability and its sufficiently small diameter, which minimized interference with flow through the inlet manifold. To fabricate the jet diffusers, 10.16 cm (4 in) sections of pipe were cut, the ends were heated using the heat gun and then the ends were pushed around a steel spreader to force the sides apart from inside the pipe. The spreader was a triangular piece of metal that was cut to fit inside the 0.5 inch pipe and provide a gradual angle. To minimize the thickness of jet the ends were also clamped in a vice grip. The result of both these spreading and compressing processes was a semi-uniform thickness between 0.15875 - 0.3175 cm (0.0625 - 0.125 in). In the full scale plant, the jet diffusers and the inlet manifold will be fabricated almost identically as in traditional plants, limiting many of these issues to only the 1/9 scale tank.



Figure 12: Molding the jet diffusers using the plastic welder and the metal mold.



Figure 13: Finished jet diffusers and diffuser on metal mold.



Figure 14: The diffusers were fastened to the inlet manifold with a coat of PVC primer and glue.

Welding the Corrugated Pipe at an Angle

When welding the two corrugated pipe sections back together at a 30° angle, it was helpful to first trim back the corrugations around the circumference of the seam to provide the welder with more room and visibility. The sections were held in place using duct tape along the inside, while the outside parameter was carefully tack welded. Additional strips of thin plastic cut directly from HDPE scrap were added to the seam as necessary during welding because the two sections did not provide a perfectly uniform connection when pieced together. Additional strips could be added perpendicular to the weld to aid in structural stability. After the weld was completed around the entire circular connection, the seam was inspected for holes by shining a flashlight through the tank from inside, and those locations were then patched with the plastic welder and additional plastic strips. Once welding was finished, a generous layer of silicone caulking was applied to both the inside and outside of the tank's seam

in order to ensure that it would remain watertight.

In the full scale tank, this welding might prove to be too difficult. In that case, it could be more efficient to purchase a pre-welded pipe at the correct angle. However, the problem with this system would be the length constraints of the pre-welded pipe. The dimensions of the pipe that extend from the pipe bend is approximately less than 2 feet. This length does not provide sufficient space for the base installation or the plate settlers and exit launder so an additional pipe connection could be necessary. This would increase costs and provide an additional failure mechanism where the tank could leak. Thus, ideally only a single weld connection would be necessary.

Sedimentation Tank Test Run

Once fabrication was complete, the tank was connected to a flocculator operating at 0.115 L/s, slightly above the target flow rate.



Figure 15: Turbid water was run through the tank at the target flow rate for 8 hours.

At a coagulant dose of 3 mg/L, flocs formed and were visible in both the sedimentation tank and coiled flocculator tubes. As the test run proceeded, the effluent turbidity gradually decreased as the floc hopper successfully captured the settled particles. Although the decreasing effluent NTU suggests the formation of a functional floc blanket, further testing is required to confirm that hypothesis.

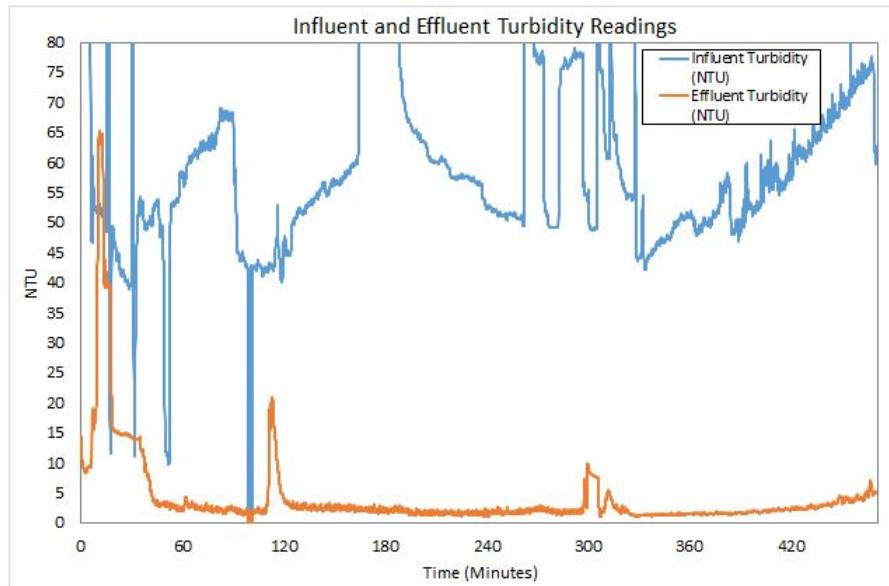


Figure 16: The effluent turbidity gradually decreased as the plant continued to run over the course of 8 hours. Even when the influent turbidity increased, the effluent turbidity consistently remained below the World Health Organization's Standard of 5 NTU.



Figure 17: After priming, the flocs captured by the floc hopper are visible.



Figure 18: Once flocs are large enough to settle, they slide down the sloped walls of the tank down to the floc blanket.

Conclusions

Traditional AguaClara flocculation, sedimentation, and filtration constraints can be applied on a smaller scale to meet the needs of small communities.

By maintaining fluid mechanics and design principles but changing materials and geometry, water treatment plants can be transported pre-fabricated and assembled on site, with minimal labor aside from the initial building construction. This advance in Aguacalara technology allows us to now reach many more communities that were once inhibited by cost. Sedimentation Tank ease of construction will be the limiting factor in plant construction. A circular corrugated plastic pipe, while the most structurally sound and light weight, does not allow for simple translation of traditional sedimentation tank construction techniques. Because of the 60° constraint on wall slope, multiple tank geometries were investigated. It was determined that a vertical pipe transitioning into an angled pipe was best because of base construction and tank support. However, the structural stability of a 0.9144 m (3 ft) diameter pipe still needs to be determined and will determine the proposed geometry of the tank. Additionally, weld strength of the base will also need to meet the minimum demand of water pressure.

Future Work

The next step in this design process will be to build a complete, full size treatment plant in Ithaca during Summer 2016 to determine the plant geometry and test full scale fabrication methods. Depending on further planning and funding, this step could be bypassed and a full scale model and test plant could be constructed in Honduras as early as Summer or Fall 2016. Constructing a plant will require additional troubleshooting and so a continuing Aguacalara team in Ithaca should be maintained to improve design and fabrication methods.

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Task Map

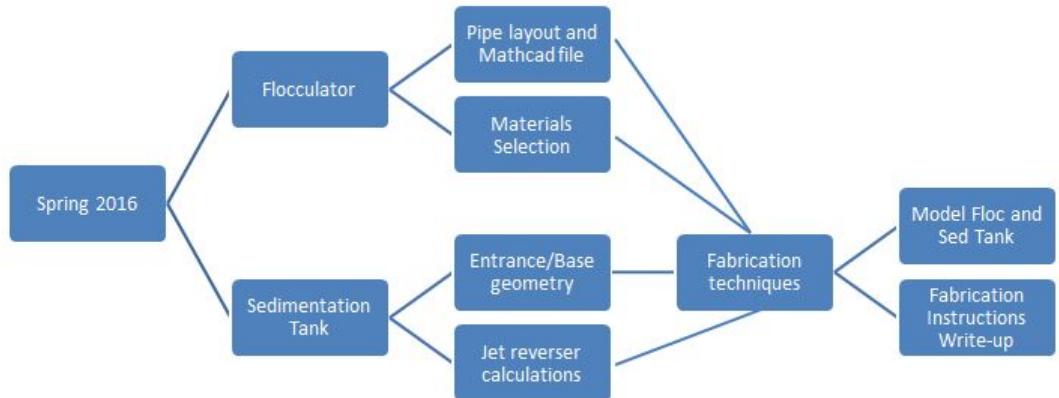


Figure 19: Spring 2016 Task Map