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Project-Based Learning in the Developing World: Design of a Modular Water Collection and Treatment System

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Abstract

Project-based learning can be particularly effective in the field of engineering, in that students can apply what they have learned in the classroom to create a tangible product. Such experiences are especially engaging for students when their work is contributing directly to the solution of a real-world problem. The lack of potable water in the developing world offers numerous opportunities for such projects. A group of faculty and students designed a modular water collection and treatment system that engineering students of multiple disciplines can adapt to a variety of different locations where surface water is plentiful, but other sources such as wells and rainwater harvesting systems are infeasible or inadequate. This system draws water from a lake or river using an off-the-shelf turbine-driven river pump, then stores the water in a cistern for later treatment using a demand-operated slow sand filter. The system requires no external power and is modular, enabling students to modify it to meet a variety of different water demand requirements or site constraints. In addition, it is reasonably low-cost, and can be assembled and maintained by students and local labor with minimal training.

This system can be integrated into a course project or independent study for undergraduate engineering students from multiple disciplines; the students can modify the design for a specific location and requirement using skills learned in the classroom, then help to build it later on as a form of project-based or service-learning. Projects such as this are valuable in that they pique the interest of engineering students, and enable them to apply skills learned in the classroom to real-world applications. Bringing such projects through successful construction and customer handoff relies upon (1) having a good partnership with a local non-governmental organization; (2) including local labor and materials in the construction; and (3) getting support from local leaders on emplacement, operation, and maintenance of the system.

(1) Introduction

Engineering education presents many opportunities for project-based learning, since students can readily apply classroom knowledge to the creation of a tangible product. A project-based learning approach to engineering education has several advantages. For example, "inductive learning" methods such as this have been found to be generally more effective than traditional teaching methods for achieving learning goals.[1] In addition, such an approach is effective in enhancing critical thinking, teamwork, communication, and project management skills.[2] Finally, such experiences are especially engaging for students when their work is contributing directly to the solution of a real-world problem, and the excitement associated with such an endeavor can provide significant motivation for learning.

The lack of potable water in the developing world offers numerous opportunities for project-based learning. One such endeavor began in summer 2014 for the Kasiisi Project, a nonprofit organization in Uganda whose mission is "to conserve Kibale National Park through programs that support education, health, and care for the environment."[3] A group of four students and a faculty member traveled to Uganda to construct rainwater harvesting systems for some of the primary schools supported by the Kasiisi Project, and to investigate other potential solutions for the provision of adequate clean water. While rainwater harvesting systems can create a useful source of potable water, they may not be adequate for locations with higher demand, or those with prolonged dry seasons.

One such case is the Kasiisi project's farm, which supports some of the local primary schools with produce and eggs. Rainwater harvesting was proving inadequate for the farm in the dry season, which requires roughly 2700 liters per day (L/d) water for its 11 pigs and ~1100 chickens, as well as for general facility cleaning and limited crop irrigation. An additional 500 L/d water would be required for consumption and use by the projected work force of 20 farm employees.

While on the 2014 trip, the group was able to conduct a preliminary site survey of the farm, and to discuss system requirements with stakeholders. A well would be one potential solution; however, even if a suitable site could be found, it would be costly and require significant pumping with perhaps an external power source. Another option would be the use of surface water, since a small stream runs through the lower portion of the farm. However, surface water tends to be susceptible to contamination from sediment and pathogens; thus, this source would require pretreatment prior to disinfection and use by humans, though it would be fine for irrigation and use by the pigs and chickens.

To provide additional water for the farm, the group designed a water collection and treatment system that draws water from the river using an off-the-shelf turbine-driven river pump, then stores it in a cistern for later treatment using demand-operated slow-sand filters. The system requires no external power and is modular, enabling it to be modified to meet a variety of different water demand requirements or site constraints. In addition, it is reasonably low-cost, and can be assembled and maintained by students and local labor with minimal training.

This system presents a superb project-based learning opportunity for students of a variety of engineering disciplines. This system can be integrated into a course project or independent study for undergraduate engineering students from multiple disciplines; the students can modify the design for a specific location and requirement using skills learned in the classroom, then help to build it later on as a form of project-based or service-learning. In addition, instructors can use such a project to assess design-related learning outcomes, particularly those related to ensuring that solutions fulfill social, environmental, and economic criteria. Projects such as this are valuable in that they pique the interest of engineering students, introduce them to the engineering design process, and enable them to apply skills learned in the classroom to real-world applications.

(2) Methods

The design consists of three major components: the pump(s), the storage and distribution network, and the slow sand filter(s). Each of these can be scaled up or down to fit the particular needs of the site; the process of modifying the design to make it "site-specific" presents an excellent opportunity for engineering students to accomplish a limited amount of design work.

"River pumps" harness the energy of the flowing water to pump the water out of the river. One such example is the Rife RP-300 (Rife Hydraulic Engine Manufacturing Co., Nanticoke, PA USA), which could supply 2500-4000 L/d to the elevation required at Kasiisi (Table 1). Additional pumps or different models could be used to meet other needs.

Table 1. Comparison of RP-300 requirements to Kasiisi farm/stream characteristics

Specification/Requirement	Rife River Pump Model RP-300	Kasiisi Farm/stream
Min river depth [m]	0.45	0.6
Min river velocity [m/sec]	0.45	0.6
Max head [m]	25	20

Cisterns enable storage of the water to meet variable demand. In this case, the Kasiisi farm already had a variety of cisterns next to building roofs for rainwater harvesting. The group proposed one additional 10,000 L cistern on the highest portion of the farm, which the river pump would supply. This highest cistern would be connected to three of the existing cisterns, which would be replenished via gravity flow (Figure 1).

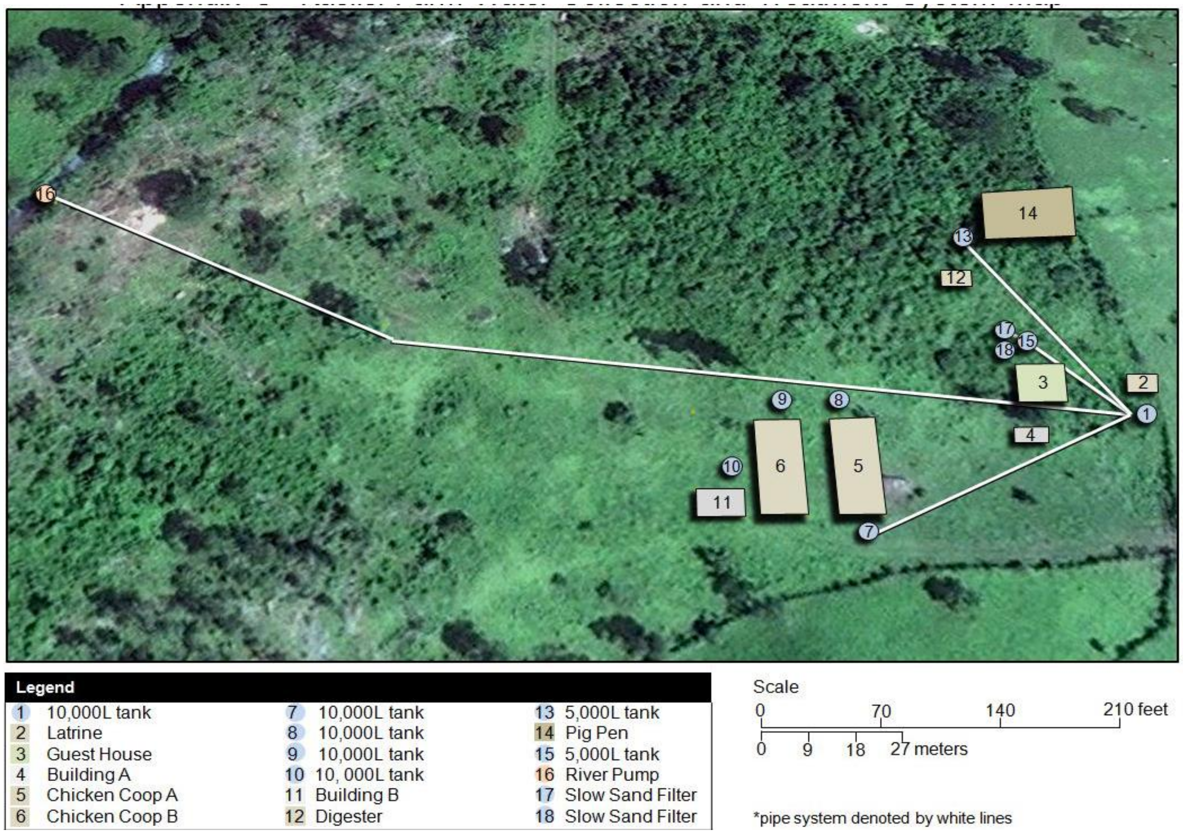
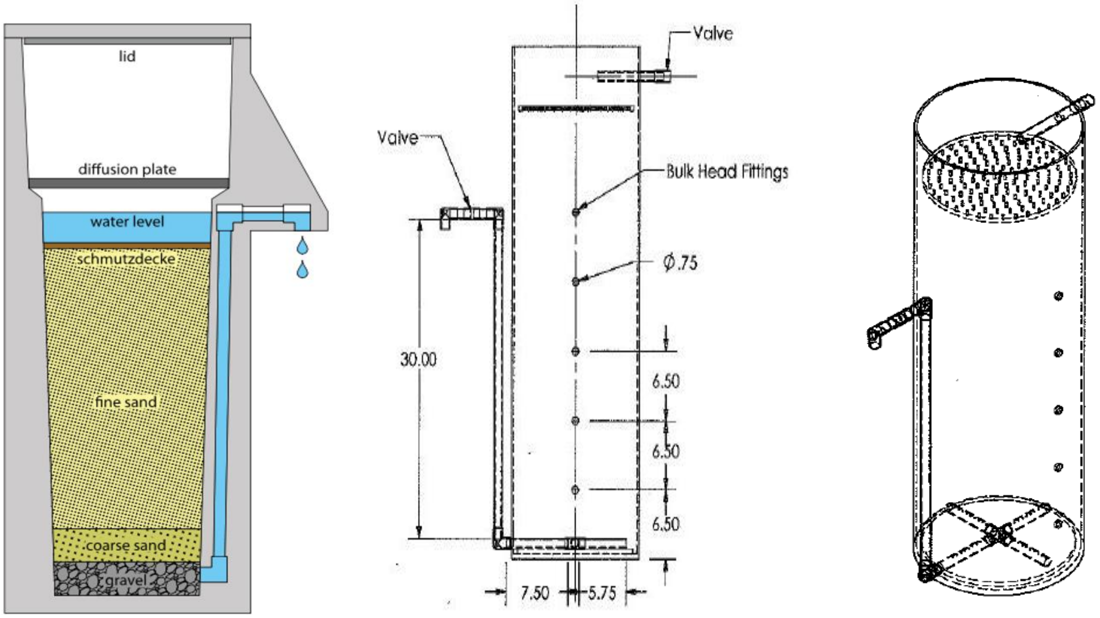


Figure 1. Imagery of the Kasiisi Farm, Uganda. The water source is located at far left (#16). Water would be pumped up to the 10,000L cistern at #1, then flow by gravity downward to cisterns at #7, #15, and #13. Slow sand filters would be located adjacent to cistern #15.

Using the energy equation and a Darcy-Weisbach approach to account for headloss,[4] the group designed the PVC pipes connecting the cisterns. Since the calculations are relatively straightforward, undergraduate engineering students could easily design a similar system to meet the needs of their particular project.

To treat the 500 L/d required for consumption by the farm workers, the group employed demand-operated slow sand filtration. Such filters would be located next to one of the cisterns to treat a portion of the water from that cistern. Slow sand filters are able to effectively treat surface water by reducing turbidity, and removing many pathogens through physical and biological processes in a biofilm or “schmutzdecke” that forms near the surface.[5,6] While disinfection via chlorination, boiling, or other methods would still be required to make the water completely safe for human consumption, the turbidity and limited pathogen removal by the slow sand filters would reduce the disinfectant requirement. Without the particles in the water shielding pathogens from the disinfectant, lower doses could be added (or a shorter boiling time employed), thus improving taste and odor and reducing the formation of harmful disinfection byproducts in some cases.

In a demand-operated slow sand filter, water flows over a diffuser plate downward through the sand filter medium into an underdrain system on the bottom that is connected to a spigot on the side with a valve (Figure 2a).[7] The water level is maintained a few centimeters above the surface when the filter is not in use, keeping the biofilm alive and thus enabling the filter to be operated only when the need arises (instead of constantly as required with traditional slow sand filtration).[6] Slow sand filters have typical loading rates of 3-8 m^3/m^2-day.[8] In this case, the filters could be filled via a spigot and hose directly from the cistern; alternatively, workers could drain water from the cistern into jerry cans to pour into the top of the filter. The treated water could then be put into additional "clean" jerry cans for subsequent disinfection.



(a) (b) (c)

Figure 2. (a) Conceptual image of a demand-operated slow sand filter.[7] (b & c) This group's design. Dimensions are in inches, and complete drawings are at appendix A.

Assuming a conservative filter loading rate of 3 m^3/m^2-day, the group determined that a filter 38 cm (15") in diameter would provide a minimum of 340 L/day. Thus, two filters of this size would meet the demand and provide flexibility in operation in case one needed to be shut down for maintenance for a short period during the day. The rest of the filter dimensions were based on parameters from previous studies;[5,6] figure 2b and 2c show the filter design with dimensions, and complete drawings are at appendix A.

The group had two full-scale prototypes of the filters constructed in order to test the design. The filter body was a plastic tank 122 cm high purchased off-the-shelf, which was then modified to fit the design. The rest of the materials consisted of PVC pipe and hardware fittings which were purchased at a local hardware store.

Since the group was uncertain of the type of sand that could be obtained in Uganda, they investigated the impact of different sands on filter performance. They looked for types of sand that might be commonly available for different construction needs, and thus would be available in the developing world. Specifically, they obtained a fine "mortar sand" as well as an "all-purpose concrete sand" from a local supplier. Sieve analyses of the sands obtained from the supplier indicated that they had the following characteristics:

Table 2. Sieve analysis results for filter sand

Sand Type	d_{10} [mm]	d_{60} [mm]	Uniformity Coefficient
mortar	0.21	0.39	1.9
all purpose concrete	0.19	0.90	4.7

Ideally, the medium of a slow sand filter should have an effective size (d_{10}) of 0.15mm – 0.35mm, with a uniformity coefficient of less than 2.0.[9] While both sands had suitable effective size (d_{10}), the all-purpose sand was much less uniform, thus falling outside the bounds of what is typically used in a slow sand filter. Nevertheless, the group decided to investigate its use to see if the filter would still be functional without an ideal medium, just in case a less uniform sand was the best that could be found in-country. Thus, the group filled one filter with the mortar sand, and one with the all-purpose sand. Sand was filled to a depth of 70 cm above an 11 cm pea gravel layer at the base; this gravel layer was used to support the sand bed and to prevent it from clogging the underdrain system. Sand was poured in while the tank was filled with water to prevent air binding, which would slow or eliminate flow.

As an addition unique to the lab prototypes, the group installed five piezometers to measure headloss throughout the depth of the filter bed. The intent of the headloss measurement was to investigate how it changed with time, so that the required frequency of cleaning the filter bed surface could be determined.

Using water from a local river, the group tested both filters over a period of several days, measuring turbidity (influent and effluent), flow rate, and headloss. They poured a total of 100L of river water through each filter, in 20L batches. There was no set time between trials, in order to mirror how the filter might be used on the Kasiisi Farm. The local river's turbidity was much higher than that of the stream in Uganda – average of 43 Nephelometric Turbidity Units (NTUs) vs. 6 – 7 NTU as measured in the Kasiisi stream. However, this was considered a "worst case" scenario that would enable a check of the true efficacy of the filters.

(3) Results

Results of the distribution system design are in table 3. The group found that 2.54 cm (1”) PVC would provide adequate gravity flow between the cisterns. Total length for all three pipes was 156m.

Table 3. Water collection system parameters

Cistern	Flow Rate [L/hr]	Pipe Diameter [cm]	Pipe Length [m]	Elevation Change [m]
1 to 13	2395	2.5	60.5	4.8
1 to 15	2641	2.5	31.8	3.0
1 to 7	2656	2.5	64.0	6.1

Both the mortar and all-purpose concrete sand filters were able to meet the EPA standard of 0.3 NTU for drinking water,[10] though the mortar sand provided a better average effluent turbidity of 0.13 NTU (Table 4). However, the mortar sand filter never breached 0.3 NTUs while the all purpose sand filter had two measurements above the standard within the first few hours of operation; this may have been the result of filter ripening (as the biofilm began to form), or some other anomaly (Figure 3).

Table 4. Summary of turbidity measurements

Sand Type	Max Turbidity [NTU]	Average Turbidity [NTU]
mortar	0.21	0.13
all purpose concrete	1.06	0.30

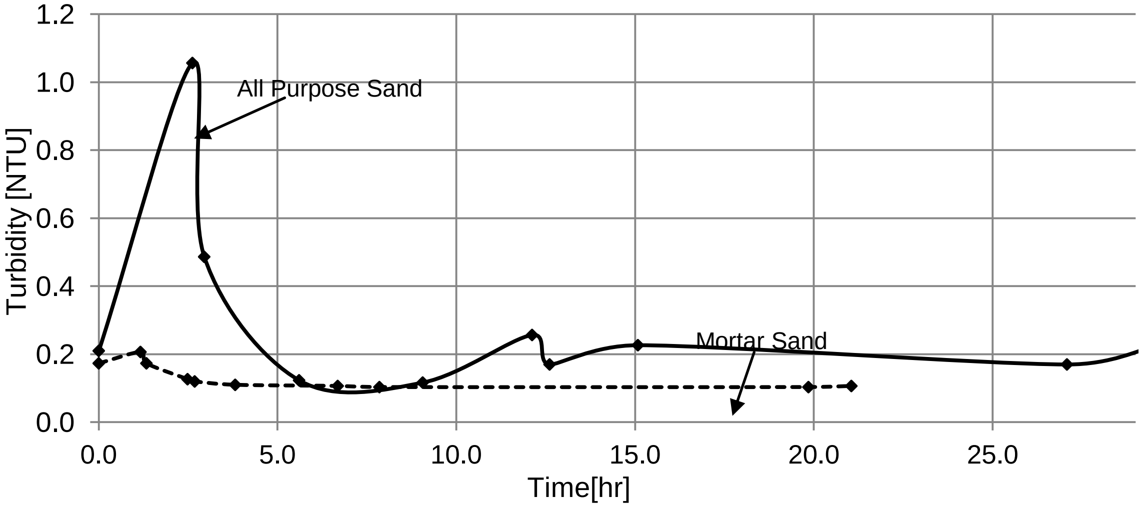


Figure 3. Effluent turbidity measurements [NTU] for slow sand filters. The x-axis indicates total elapsed time of filter operation.

Table 5 summarizes the maximum and average flow rates in both filters at the maximum head of 25 cm (a full 20L in the filter), as well as the corresponding loading rate. The mortar sand filter yielded a higher flowrate overall, and flowrate did not change significantly throughout the 100L tested.

Table 5. Summary of measured flow rates at head of 25 cm

Sand Type	Average Flow Rate [L/hr]	filter loading rate [m^3/m^2-d]
mortar	27.6	5.8
all purpose concrete	13.2	2.8

At these flowrates, two mortar sand filters will treat 1330 L/d, which is over twice the 500 L/d required for the farm. This implies that if one filter had to be taken off-line for a period for maintenance, demand would still be met. Two all purpose concrete sand filters will treat 640 L/d, adequate to meet demand; however, a third may be required to provide for redundancy should one filter require extended maintenance or repair.

Headloss was measured throughout the filter at two points during the experiment: when the head was at the maximum of 25cm above the top of the sand (total head of 106 cm from the base), and at the minimum head of 7cm above the sand (head of 88 cm above the filter base). This was done by measuring the difference in height between the water level in the first piezometer (at the filter bed surface) and the last piezometer (16.5 cm from the base of the filter). The data gathered from the piezometers during the experiment indicates no significant trends in head loss, which implies that the filter was not tested long enough for the pores to be clogged and require cleaning by scraping of the filter bed surface.[6] Graphs of head loss at both head heights are shown in Figure 4.

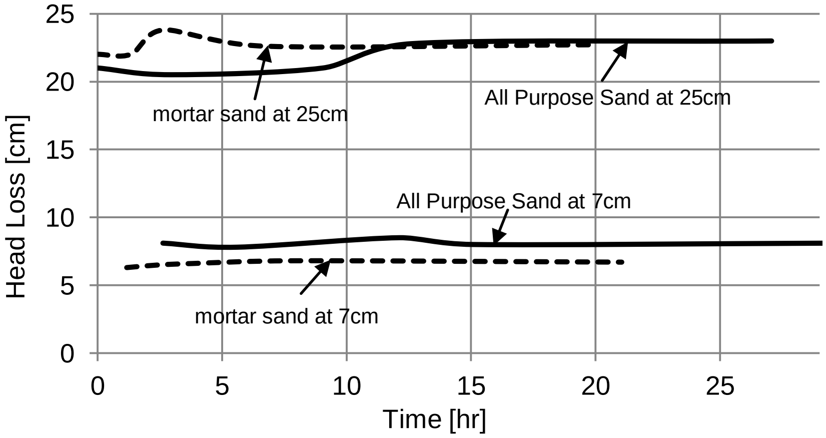


Figure 4. Head loss through the filter medium at differing head values. The x-axis represents total elapsed time of filter operation.

(4) Discussion

The “mortar” sand filter outperformed the all purpose concrete sand filter with regard to turbidity removal and loading rate. It has a lower and more consistent average effluent turbidity at 0.13 NTU (99.7% removal), compared to the all purpose concrete sand filter at 0.30 NTU (99.3% removal); however, both did meet the EPA standard of 0.3 NTU. In addition, the fine sand filter outperforms the all purpose sand filter in regards to filter loading rate (5.8 m^3/m^2-day vs. 2.8 m^3/m^2-day). This is compared to typical slow sand filter loading rates of 3-8 m^3/m^2-day.[8] Thus, the more uniform mortar sand should be used if at all possible; however, if the less uniform all-purpose concrete sand is the best that can be found, it will still perform adequately, but may require the installation of an additional filters to meet demand and redundancy requirements.

Materials cost of the system will depend greatly upon the specific requirements of the site – the number of filters and cisterns required, length of piping, etc. The total materials cost of the system for the Kasiisi Farm would be approximately $4000 USD, not including materials to construct a cistern foundation. Significant contributors to that cost include the filters ($700 per filter) and the one cistern ($1200). Labor to construct the filters and install the system will increase the overall cost considerably; while some of the construction and installation could be accomplished by the students themselves, it is likely that their efforts would need to be augmented by labor from a local contractor to conduct tasks such as building a secure foundation for the cistern(s). In addition, the cost of international travel for students to get to the site would increase the total expense significantly.

The modularity of this system makes it practical for use with undergraduates as a project-based learning opportunity. Given site location/elevation data (obtainable via GPS), demand data, and stream characteristics, students could modify the design to meet the specific requirement. For example, they could design the pump component based on head required and stream depth and velocity. They could also employ multiple pumps if necessary to meet the demand requirement. In addition, the cistern and pipe distribution component can be easily scaled up and down, depending on daily demand data. The system may require only one large cistern, or multiple ones scattered throughout the site, as shown here. Finally, students can select a number of filters (minimum of two for redundancy) to meet the daily demand for potable water in accordance with the applicable loading rate based on their sand type, described above in the results section.

The value of such a project lies in its accessibility to undergraduate engineering students. It gives them the opportunity to become familiar with all aspects of the design process – from problem definition and stakeholder analysis to construction and handoff - without becoming overwhelmed by the intricacies of the project itself. The “kit” presented here will enable them to conduct some detailed analysis and design (for example, in the sizing of the pipes for the distribution system), but also to integrate some components where that level of analysis and pilot testing has already been completed (for example, the river pump and the slow sand filters).

This "simplification" of some aspects of the design could give the students an opportunity to actually build and hand off the system, in addition to designing it, within the time constraints of an academic schedule. For example, they could design the system and construct portions throughout a semester-length independent study project, then spend a week or two on-site during the summer with a contractor installing the system and handing it off.

The final phase – construction and handoff – is the most challenging. If not done correctly, the project will not be sustainable over the long term. The group's experience with similar projects indicates that success in this area depends heavily upon (1) having a good partnership with a local non-governmental organization, which can assist with providing the appropriate contacts in the community; (2) including local labor and materials in the construction, so they are invested in it; and (3) getting support from local leaders on emplacement, operation, and maintenance of the system. Such local support enables students to utilize local networks and relationships, and allows "buy-in" by the customers so that the project is actually used and maintained by the locals, instead of sitting idle merely as a monument to western largesse.

While projects such as these are useful in their ability to excite students about engineering and demonstrate concepts in practice, they may be most valuable in that they require the students to work within real-world constraints to meet the needs of a specific customer throughout the entirety of the design process. Rather than being focused merely on engineering calculations, they must also consider the "triple bottom line" of economic, social, and environmental factors that will ultimately determine project success or failure. If they fail to adequately consider their customer's unique needs, or cannot work within their budget, their endeavor will fail as would any other engineering project. For the same reasons, this type of project also enables instructors to assess design-related learning outcomes, particularly those related to the solution's ability to fulfill social, environmental, and economic requirements.

(5) Conclusion

This paper has presented a modular water collection and treatment system that engineering students of multiple disciplines can adapt to a variety of different locations where surface water is plentiful, but other sources such as wells and rainwater harvesting systems are infeasible or inadequate. Its modularity gives students an opportunity to accomplish some design, without having to start completely from scratch. In addition, its simplicity and reasonable cost enables students to possibly install the system with help from local contractors and laborers.

Further research on this system could include an investigation into the pathogen removal achieved by the filters, as well as longer filter run times to observe changes in filter headloss that would help to determine an operation and cleaning routine. In addition, it would be worthwhile to look into ways to protect the plastic filter body from damage while in use; for example, a concrete foundation with a sleeve into which the filter base fits would stabilize it and prevent damage.

Projects such as this are valuable in that they pique the interest of engineering students, introduce them to the design process, and enable them to apply skills learned in the classroom to real-world applications. Such project-based learning can give engineering students the experience they need to further succeed in the classroom and beyond.

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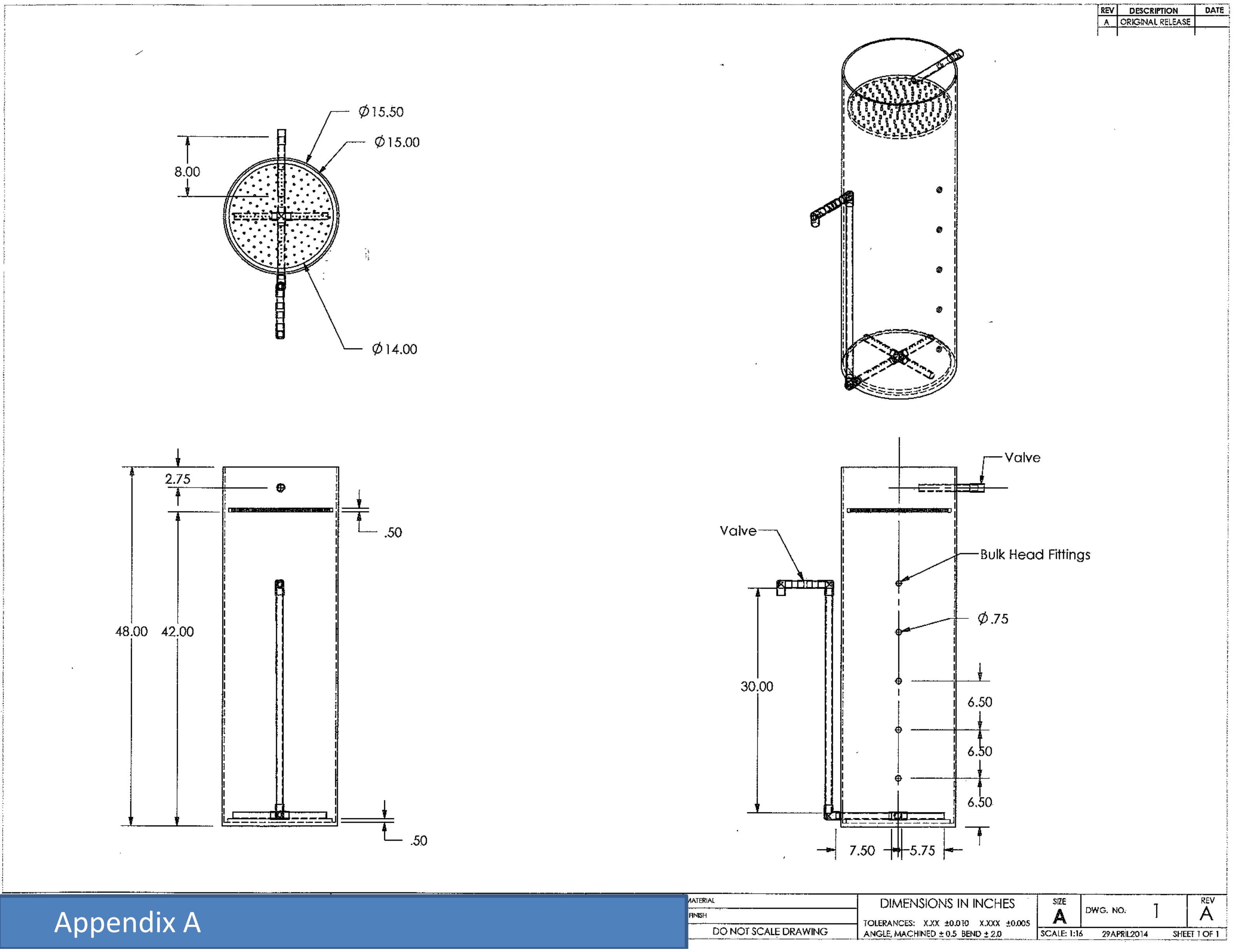
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Appendix A