Construction and testing of a point-of-use drinking water disinfection and filtration system for developing nations

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***Abstract* – Point of Use (POU) drinking water treatment shows potential to save the lives of thousands who die every day from preventable waterborne illnesses. Most POU treatment focuses on either household scale filtration or community-level disinfection, but there remains a need for a low-cost batch treatment system incorporating both filtration and disinfection. Consequently, a drinking water treatment system including sand filtration and locally-generated chemical disinfection was constructed from inexpensive and accessible materials. The prototype consisted of two barrels and a circulation pump, with water cycling through a gravity sand filter before being injected with chlorine produced through saline electrolysis. The treatment efficacy of the prototype was determined by turbidity reduction and disinfection effectiveness. Ninety gallons of surface water displayed a 70% reduction in turbidity after ninety minutes of operation, and no coliform bacteria were detected in the system upon completion of treatment. The purchase cost of the system components was less than \$900 (2017) and the total project displays an estimated net present value of (\$4,100) over 10 years. The system is safe, simple, and reliable, and could be foundational to the development and implementation of chemical disinfection in batch filtration processes for POU water treatment.**

***Index Terms* – gravity sand filtration, locally-generated chlorine disinfection, point-of-use water treatment, saline electrolysis**

INTRODUCTION

Water is essential to life; however, as of 2014, 748 million people worldwide lacked access to “improved drinking water”¹. Five thousand individuals, primarily children under the age of 5, die every day from preventable diseases originating in untreated water². As such, the National Academy of Engineering has identified providing access to clean water as one of the pressing engineering challenges of the 21st Century³.

Solving the world’s water crisis requires overcoming two challenges. Foremost is the challenge of providing water to areas with limited supply, which is typically addressed by diverting surface water, pumping water to arid locations, or tapping local aquifers. The second challenge is in treating the available water to make it safe for human consumption. One strategy for providing water treatment to remote or impoverished regions is through point-of-use (POU) water treatment, in which water is purified at the location of consumption⁴. It has been estimated that 94% of diarrheal cases in developing nations can be eliminated by POU water treatment^{5,6}. Research in this area has sought to increase local access to water treatment to reduce susceptibility to waterborne diseases.

POU water treatment faces several obstacles. Over 700 million people live on less than \$1.90 per day, the World Bank’s standard for extreme poverty⁷. This means that POU water treatment must improve water quality while not being a financial burden to the beneficiaries. Additionally, drinking water supplies in developing nations are frequently contaminated with wastewater⁸, which requires that treatment systems must be designed to treat low strength wastewater. Consistent access to materials and power may also be impossible in locations requiring POU treatment⁹. Finally, POU water treatment is reliant upon the consumer, and long-term adoption rates are typically below 50%^{10,11}. Consequently, these hurdles to implementation provide design parameters for POU water treatment systems.

One approach to POU water treatment utilizes filters capable of treating water for one family, which is considered to be 20L daily for a family of five¹². This strategy places the responsibility for water acquisition and filter maintenance on each household. Furthermore, family-scale filtration systems can operate at flow rates as low as 5L/h¹³ and incur minimal capital and operating costs, which has been correlated to improved adoption rates¹⁴. The most widely utilized of these designs is the biosand filter (BSF)¹⁵. BSFs are typically concrete, metal, or plastic structures containing layers of sand and gravel for filtration¹⁶. Water poured in the top of the structure provides head to drive flow through the filter media. Reduction of viruses, bacteria, parasites, and cysts is accomplished through the biological layer that develops over weeks of use¹⁷. Pathogen are adsorbed onto the sand and oxidized by the microorganisms in the biological layer¹⁸. This system provides up to 4 log₁₀ removal of *E. coli* and 95% removal of bacteriophages, and is estimated to be in over 80,000 homes and utilized by over 500,000 individuals worldwide¹⁹. BSFs do not require any reagents, making them nearly immune to economic fluctuations once installed. They are remarkably easy to use, require little training and no external intervention, and are cheap and simple to set up^{20,21}.

Though BSFs have been successful both in the field and in the laboratory, there are challenges associated with their use. Typical BSFs can filter and disinfect between fifteen and twenty gallons per day²², but treatment rates cannot be increased much beyond this due to insufficient contact time with the active biological layer²³. In addition, biological treatment can be inconsistent. Performance has been shown to vary based on influent water composition, with central measures

of bacterial reduction varying between 74% and 84-88% in Nicaragua and the Dominican Republic respectively^{24,25}. On occasion, BSFs have shown greater coliform concentrations in the effluent than in the influent^{26,27,28,29}. Though rare, this highlights the challenges of applying biological treatment to drinking water.

In contrast to providing household water treatment, other designs have sought to produce drinking water on a small community scale through either UV light or chemical disinfectants. UV radiation acts to disrupt the nucleic acids of bacteria and viruses, rendering them unable to replicate³⁰, whereas chemical disinfectants such as ozone or the halogens are highly oxidative and work by chemically disrupting biological structures³¹. This strategy exhibits alternative benefits to household filters; a disinfection system located at a school can provide the students and staff with drinking water for lower cost than the equivalent capacity of household POU filters. In addition, the responsibility for water disinfection is placed on fewer individuals, reducing the requirement for widespread education on system operation³². In addition to the initial chemical disinfection, residual chlorine remains in solution to protect against future contamination. These systems can be scaled to the application based on availability, source, and quality of water and the number of people being served³³.

As with the household BSFs, there are drawbacks to the community-scale disinfection approach. UV treatment can suffer from fouling on quartz sleeves in contact with the water and from inconsistent delivery of power required for disinfection^{34,35}. Moreover, since pure disinfection lacks the turbidity reduction and solids removal of filtration, the treated water appears identical to raw water. Both UV irradiation and chemical disinfection have reduced efficacy in turbid water, and are thus limited in their use when not combined with mechanical filtration³⁶. Unfiltered water can also have high total organic carbon (TOC) content, which reacts with free chlorine to form trihalomethanes (THMs) and haloacetic acids (HAAs), both of which are known carcinogens^{37,38}. Some systems utilize prefiltration mechanisms in an attempt to reduce turbidity and solids content, but this tends to counteract the benefits of the large-scale batch approach by making filtration the rate-limiting step³⁹.

The water treatment system described in this paper seeks to combine the turbidity reduction of sand filtration with locally-generated chlorine disinfection. The design requirements for the system were determined by analyzing the current challenges associated with implementing POU drinking water treatment for 75 people per day. As such, the system was designed to treat over 300 L per day while being safe, reliable, simple to use and operate, and highly cost-efficient. Furthermore, the lack of consistent power supply in impoverished areas was addressed through supplying all required energy from a 12V lead-acid battery. Once designed, a system prototype was tested to determine its effectivity at turbidity reduction and disinfection on a sample of surface water, and a cost analysis of the system was undertaken to determine its economic impacts. Finally, implications of system installment and operation were considered and suggestions for design improvements were documented.

METHODS

System Design

The water treatment system was designed as a recycle loop between a storage barrel and a filter barrel. Water flowed from the storage barrel through a pipe to the filter barrel, where it trickled through a gravity sand filter. Water was pumped from the bottom of the filter through a venturi

injector where locally-generated chlorine was absorbed in the water returning to the bottom of the storage barrel. The system was designed to operate continuously until turbidity reduction and disinfection had occurred. Figure 1 is a diagram of the system and Appendix I provides the components required for construction. As the system was constructed from locally available materials in Stillwater, Oklahoma, the nominal material sizes and measurements are given in English engineering units.

Safety for the users and reliability of the system were vital considerations in the design phase of the project. Consequently, the system eliminated contact between electrical components and the water, and the saline electrolysis unit was designed to lose shut off when the pump was disconnected from the power supply. The longevity of materials was also a concern in the design phase. The electrodes utilized in the saline electrolysis unit were made from carbon fiber due to the material's common application as an inert electrode as well as its reduced cost in comparison to inert metals. The other materials at high risk of wear included the pump and battery, each of which will require replacement over the estimated 10-year lifetime of the system. The battery can be replaced by any similar 12V DC deep-cycle battery that can be acquired with relative ease worldwide. Though the pump was a specific model, the use of 3/4" threading and hoses to connect the pump to the system allows the pump to be replaced by a variety of similar makes and models. While the pump was one of the more expensive system components, the pump selected was relatively inexpensive and is designed to work with raw surface water and runoff. Furthermore, normal system operation dictates that the pump will only be pumping water after it has traveled through the sand filter, which will prevent damage to the impeller by suspended solids. Finally, system design incorporates the pump such that the direction of flow can be easily reversed for filter backwash.

FIGURE 1

DIAGRAM OF WATER TREATMENT SYSTEM PROTOTYPE INCORPORATING GRAVITY SAND FILTRATION AND LOCALLY-GENERATED CHLORINE DISINFECTION

Additionally, materials were selected not only for their high global availability and low cost, but also for their safety in drinking water applications. Polyvinyl chloride (PVC) pipe and fittings were utilized for most connections due to its low cost, ubiquity, and resistance to chemical

breakdown. While PVC has been known to leach vinyl chloride, PVC pipe manufactured since 1997 display much reduced leaching characteristics⁴⁰. More recent leaching issues in PVC pipe is from plasticizers such as phthalic anhydride esters, which are known carcinogens⁴¹. Despite these drawbacks, the cost and functionality benefits of PVC and the low contact area between the water and PVC in the treatment system was enough to outweigh the potential of PVC leaching. In contrast to the PVC fittings, the storage and filter barrels were made of food grade high density polyethylene (HDPE) manufactured for water storage.

Construction of hydraulic components

The detailed construction process is provided in Appendix II. The filter barrel was modified from a 55-gallon HDPE drum. The lid was removed and a 2" diameter bulkhead fitting was installed near the bottom in the barrel wall. Similarly, a 3/4" diameter bulkhead fitting was installed in the barrel wall near the top of the barrel (Figure 2).

FIGURE 2

ASSEMBLY AND PRESSURE TESTING OF THE HYDRAULIC COMPONENTS OF THE WATER TREATMENT SYSTEM.

PVC bushings and threaded adapters were used to reduce the 2" diameter outlet to 1" diameter, and a PVC ball valve was cemented to the outlet to allow pump isolation. A 3/4" diameter male threaded adapter was installed for hydraulic connection to the pump inlet using a standard garden hose. An additional 1" diameter PVC globe valve was connected to the interior of the upper bulkhead fitting. The water collection sieve (Figure 2) was connected to the interior of the 2" diameter bulkhead fitting. The sieve was constructed from 2" diameter PVC pipe that had been capped, perforated to allow water infiltration, and covered with polypropylene landscape fabric. A 2" diameter PVC union was used to connect the collection sieve to the PVC adapter that was installed in the interior of the 2" diameter bulkhead fitting. The storage barrel was constructed from an available HDPE rainwater collection drum that had previously been fitted with an outlet spigot. A 3/4" diameter bulkhead fitting was installed in the wall of the storage barrel at an

elevation matching that of the upper bulkhead fitting in the filtration barrel. A 1" PVC ball valve was installed on the interior of the storage barrel, and a 2-foot length of 1" diameter PVC pipe was used to connect the filtration barrel to the storage barrel between the 3/4" bulkhead fittings.

The pump utilized for the system was a Wayne PC1 12-Volt Metal Transfer Pump (WAYNE Water Systems, a Scott Fetzer Company, Harrison, OH). This pump was selected because it advertised a flow rate of 310 GPH at 10 feet of head and included 3/4" diameter threaded garden hose connections at the inlet and discharge. In addition, it operated on a 12V DC power supply that can simultaneously power the electrolytic chlorine cell. A 12V lead-acid battery (ValuePower Group Size 35, Johnson Controls, Joseph, MO) was acquired to run the pump. The pump was connected to the outlet of the filter barrel using a standard 5/8" diameter garden hose. Two additional hoses were used to connect the pump discharge to the chlorine injector inlet and to carry the water from the chlorine injector to the bottom of the storage barrel. The disinfectant injector was constructed from 1/2" diameter PVC pipe and allowed control of the suction pressure by adjusting the 1/2" diameter ball valve (Figure 3). The injector itself was a Mazzei 484-PP 1/2" MNPT Injector (Mazzei Injector Company, LLC, Bakersfield, CA) that had a 1/4" diameter hose barb connector at the suction port. The inlet and outlet of the disinfectant injector assembly had 3/4" diameter male threading for hose connection.

FIGURE 3
ASSEMBLY OF THE CHLORINE INJECTOR.

Construction of the saline electrolysis unit

The saline electrolysis unit (Figure 4) was constructed of four identical electrolytic cells wired in parallel. Each cell was made from an outer 2" diameter PVC shell and an inner 1" diameter PVC shell. The caps for the outer shells were modified with offset holes in the end for the installation of a carbon electrode and the 1" diameter PVC shell. The cap on the 1" diameter PVC shell was modified with a slit for an electrode on the top and a threaded 1/2" diameter hole on the side for removal of generated chlorine. A 1/2" NPT to 1/4" diameter hose barb fitting was installed into each of the four 1" shells and were each connected to a 4" length of vinyl tubing. The four vinyl tubes were wrapped together in duct tape and inserted into the end of a 3/4" 90° PVC fitting. To

the opposing side of the elbow was fixed with duct tape a 1/4" polyethylene tube that was connected to the inlet on the venturi injector.

Eight carbon rectangular electrodes were acquired from *graphitestore.com* (Northbrook, IL) (though any carbon fiber of similar geometry will do), cut into 12" lengths and modified with a 3/8" holes in one end to facilitate connection with ring terminals. Each ring terminal was connected to a 12" length of coated 12-gauge wire, and groups of four electrodes were connected together and attached to a 10' length of either black or red 10-gauge wire. All exposed connections were coated in electrical tape. The 2" diameter capped PVC shells were placed into a wooden frame, and each shell was filled halfway with a 30 wt% saline solution. The inner shells were fitted into the large holes offset on top of the 2" diameter caps and held in place with duct tape. The electrodes for the red 10-gauge wire were set into the slits on the top of the 1" diameter PVC caps, while the electrodes connected to the black wire were fit into the slits on the top of the 2" diameter cap.

FIGURE 4

PARTS AND ASSEMBLY OF THE SALINE ELECTROLYSIS UNIT. THE SYSTEM CONSISTED OF FOUR ELECTROLYTIC CELLS WIRED IN PARALLEL. CARBON FIBER ELECTRODES TRANSFERRED CURRENT FROM A 12V LEAD-ACID BATTERY TO A 30 WT% SALINE SOLUTION AND THE GENERATED CHLORINE WAS USED FOR DRINKING WATER DISINFECTION.

Testing of the water treatment system

The hydraulic components were pressure tested to determine the presence of leaks and confirm system operation. All threaded connections were sealed with Teflon tape. The filter barrel and storage barrel were connected by 1" diameter PVC pipe, and the suction side of the pump was connected to the discharge of the filter barrel. The gas injector was removed from the system and the pump discharge hose was fed into the storage barrel to complete the recycle loop. Both barrels were filled with surface water. All valves were placed in the fully open position and the pump was connected to the 12V lead-acid battery. The pump was switched on and the system was allowed to cycle for ten minutes. No leaks were detected.

Upon completion of pressure testing, the system was relocated for filtration and disinfection testing. The filter barrel was filled with 50 pounds of washed pea gravel to support the water collection sieve. Directly on top of this, 180 pounds of QUIKRETE pool filter sand (20/40 gradation, or 0.420 mm to 0.841 mm nominal sieve opening) was thoroughly rinsed and leveled to make a uniform filter surface. The venturi injector was connected to the discharge of the pump and the outlet hose of the gas injector was fed to the bottom of the storage barrel. Ninety gallons of surface water from the USDA-ARS Hydraulic Engineering Research Unit near Stillwater, OK was then mixed to resuspend any settled solids and transferred to the system. Turbidity was measured using a Hach 2100AN Laboratory Turbidimeter (HACH, Loveland, CO). Initial turbidity measurements were taken at the surface of the filter barrel, the surface of the storage barrel, and the storage barrel outlet. During system operation, turbidity measurements were also recorded from the discharge of the hose exiting the chlorine injector. Turbidity measurements were taken every 5 minutes at each of these sample points during testing.

Coliform bacteria concentrations were detected using 3M High-Sensitivity Petrifilm (3M Inc. St. Paul, MN). Water samples (4 mL each) were taken at the surface of the filter barrel and the tap outlet initially and every 30 minutes throughout testing. Samples were incubated for 24 hours at 35°C and colony forming unit (CFU) concentrations were determined by visual inspection. The rate of chlorine generated was determined from the current draw from the battery as measured by using a standard multimeter (Tasharina Corp, Mountain View, CA). Disinfectant concentrations were measured using AquaChek Free Chlorine Test Strips (HACH, Loveland, CO). The strips change color when exposed to free chlorine, allowing visual inspection of concentrations between 0.1 ppm and 10 ppm. Free chlorine concentration was measured at the surface of the filter barrel, the surface of the storage barrel, the tap outlet, and the injector outlet hose discharge. Measurements were taken initially and every 5 minutes throughout testing.

The circulation rate of the system was measured using a stopwatch and a bucket. The pump leads were connected to the battery terminals while the saline electrolysis unit was in operation. The chlorine injector outlet hose was rerouted into a 5-gallon bucket and the time required to fill the bucket was measured (Figure 5). Once determined, this flow rate was utilized to calculate the number of total volume cycles through the filter had been accomplished at each time point.

The cost and benefits of the POU water treatment system were analyzed according to the guide for small systems issued by the United States Environmental Protection Agency (EPA). Relevant categories that affect capital costs are purchase costs and installation costs along with engineering analysis, pilot testing, and public education. Operations and maintenance (O&M) costs are affected by the frequency of maintenance, emergency maintenance, monitoring frequency, residual disposal, and public education⁴². For this application, power costs were separated from annual

maintenance costs, which were estimated based on system wear and replacement of the saline solution for electrolysis. Emergency maintenance was estimated to account for replacing major system components, such as the pump, battery, electrolytic cell, or a water barrel. Additional factors that may impact the cost of a system that were deemed irrelevant to the design parameters, such as number of taps treated, permitting and legal costs, and insurance costs, were assumed to be negligible for this study.

FIGURE 5
COMPLETE WATER TREATMENT SYSTEM TESTING SETUP.

DATA AND ANALYSIS

Results for turbidity and disinfection are displayed in Figure 6. Initial turbidity varied throughout the system. The initial turbidity of each sample point was greater than 20 NTU, with surface of the filter barrel displaying a system maximum of 30.7 NTU. The initial turbidity measured at the outlet of the storage barrel was 25.8 NTU whereas the surface of the storage barrel displayed turbidity of 22.7 NTU, suggesting that settling within the storage barrel resulted in spacial turbidity variation. These values can be considered reasonable for what may be encountered in developing nations, as one study measured the turbidity of surface water in Haiti between 27 and 39 NTU⁴³. Before testing, bacterial concentrations were measured from the tap on the storage barrel and the surface of the filter barrel were 65 CFU/mL and 50 CFU/mL respectively. Before the pump was turned on, the saline electrolysis unit was connected to the battery and the current draw was measured. The current draw corresponded to 0.20 grams per minute of locally-generated chlorine to be available for injection to the system.

FIGURE 6. RESULTS OF COMPLETE SYSTEM TESTING.

A) PLOT OF TURBIDITY VS. TIME FOR FOUR LOCATIONS IN THE WATER TREATMENT SYSTEM. PHOTOS SHOW THE SURFACE OF THE FILTER BARREL AT THIRTY MINUTE INTERVALS. B) CHART OF TURBIDITY REDUCTION VS. TOTAL VOLUME CYCLES. THE DIFFERENCE IN TURBIDITY BETWEEN THE FILTER BARREL AND FILTER OUTLET SHOWS DECREASING TURBIDITY REDUCTION WITH INCREASED CIRCULATION. C) COLIFORM CONCENTRATION VS TIME AT TWO SAMPLE POINTS IN THE SYSTEM. NO COLIFORM BACTERIA WERE DETECTED AFTER NINETY MINUTES.

Once the initial measurements had been collected, the pump was turned on to start circulation at 4.35 gallons per minute through the filter media and to initiate chlorine absorption into the filtered water stream. Throughout the first thirty minutes of operation, turbidity measurements at each sample point excluding the outlet of the filter decreased and approached the turbidity of the water exiting the filter. As the turbidity of the water exiting the filter was measured consistently around 11 NTU for the first thirty minutes, the filter outlet turbidity appeared to be independent of the turbidity of the filter feed. After the first half hour, however, the turbidity of each of the sample points converged and decreased throughout the course of the experiment, showing the decreasing turbidity reduction for each additional pass through the filter (Figure 6B). The largest differences in turbidity were observed within the first two total volume cycles (the amount of time it takes to circulate the entire batch of water through the filter), with decreasing returns observed afterwards.

Water disinfection was measured with High-Sensitivity Petrifilm (Figure 6C). The initial concentration of coliform bacteria was counted as 65 CFU/mL at the tap outlet of the storage barrel, whereas the filter barrel surface displayed a concentration of 50 CFU/mL. After thirty minutes of filtration and injection of locally-generated chlorine, the detectible bacteria concentration had decreased to 7.5 CFU/mL at the surface of the filter barrel and 1.0 at the tap. These values are in accordance with the expected bacterial concentrations based on the system operation. The tap is located adjacent to the outlet of the filter and chlorine injector, which would suggest that the tap would show reduced bacterial concentrations in comparison to water being fed to the filter. After an hour of system operation, no bacterial colonies were detectible at the tap outlet of the system, and only 0.3 CFU/mL was detected at the surface of the filter barrel. By the end of ninety minutes, no coliform bacterial colonies were detectible at any point in the system.

Table I displays the initial and final turbidity and coliform bacteria concentrations in the water at the surface of the filter barrel and the tap outlet of the storage barrel. The system displayed a 70% reduction in turbidity and no coliform bacteria were detected after ninety minutes of testing. The despite these results, turbidity at the outlet of the surface barrel did not meet WHO standards for POU water treatment systems after the 3.9 total volume cycles through the filter achieved in ninety minutes. Consequently, the system was operated until the tap outlet turbidity measured less than 5 NTU, which was achieved after 5.8 total volume cycles through the filter, confirming that the prototype could comply with WHO turbidity standards with extended operation.

TABLE I
INITIAL AND FINAL TURBIDITY AND COLIFORM BACTERIA CONCENTRATIONS FOR SYSTEM
PROTOTYPE TESTING.

	Turbidity	Coliform Bacteria Concentration
Filter Barrel Initial	30.7 NTU	50 CFU/mL
Filter Barrel Final	8.54 NTU	0 CFU/mL
Tap Outlet Initial	25.8 NTU	65 CFU/mL
Tap Outlet Final	10 NTU*	0 CFU/mL
WHO Standards ⁴⁴	5 NTU	0 CFU/mL

*Turbidity measured after ninety minutes and 3.9 total volume cycles through the filter. Turbidity was measured below 5 NTU after 5.8 total volume cycles through the filter.

The concentration of free chlorine in the water was tested using a colorimetric assay designed for use with household swimming pools. Though the detection system could detect free chlorine in concentrations down to 0.1 ppm, no free chlorine was detected throughout the system at any point during testing. It had been confirmed through benchtop testing that the concentration of chlorine followed a trend with the free chlorine concentration growth rate increasing with time⁴⁵. Furthermore, current draw by the chlorine unit and benchtop testing confirmed that the saline electrolysis unit was operational. Consequently, it is likely that the free chlorine concentration never increased to the range of detection due to rapid reaction with organic materials and evaporation from the system.

Based on the evidence observed, however, it is impossible to state whether the observed disinfection was a result of the chemical disinfectant or the filtration media. Even so, the sand filter did not have sufficient time to develop a biological layer to provide biological disinfection as with a BSF, and chlorine would also detrimentally impact the active biological layer on the sand surface. As there was no sample point between the outlet of the filter and the inlet of the chlorine injector, no conclusion can be made about the effectivity of the chlorine in relation to the filter. Despite this shortcoming, the evidence of disinfection suggests that the combination of chemical disinfection with sand filtration is effective at reducing bacterial concentrations in surface water for drinking applications.

Though it was desired to confirm the replicability of the water treatment prototype test results, time and logistical constraints prevented its occurrence. Nevertheless, benchtop and small batch testing of system components suggested that the well-established principles of gravity sand filtration and chlorine disinfection are sufficient to infer that results similar to those reported should be expected in a replication study⁴⁶. Nonetheless, the documented water treatment system displayed the capacity to reduce the turbidity and disinfect 340 L of water in ninety minutes, which is equivalent to 46 times the treatment rate of a BSF.

Prototype testing revealed several practical implications of the system. Based on the standard of 4 L per person per day, the prototype was able to treat drinking water for 85 people, making it practical for use at a small school. Several limitations to the system were discovered, however, the foremost being that a single battery was quickly exhausted by the power requirements of the pump and chlorine unit. For extended circulation, one or more additional batteries would be necessary for continuous operation. Furthermore, the prototype did not account for battery recharge, and thus the equipment required to charge the batteries would increase the purchase cost of the system. This should not present a challenge, however, as low-cost 12V solar chargers are available in all but the most remote locations worldwide.

The sand utilized in this study was selected because it was readily available and represented an ideal case to determine the upper limits of filtration capabilities. Sand acquired remote locations may require hand screening and may lack the homogeneity of the filter sand in this experiment. This may result in lower filtration capabilities than those observed in this study. While this may result in variations in filtration, sand as a filter medium is excellent for POU applications. Not only is it available worldwide, but it also retains its filtration effectiveness up to 5 years, exhibits high chemical resistance, and allows for simple backwash⁴⁷. As such, sand is among the best materials for POU water treatment.

The most common maintenance procedure required for the system would be replacement of the saline solution in the electrolysis unit. Electrolysis produces sodium hydroxide, and thus the

solution remaining in the electrolytic cells is a strong base that can be the basis for soap⁴⁸ and recycling the spent saline can further improve sanitation in the community. With extended use, the battery and pump will be the first to break down, with standard sealed lead-acid batteries designed to last between 200 and 300 charge cycles but only with small depths of discharge (DOD). Wet cell deep cycle batteries, on the other hand, are designed to operate above 75% DOD but require occasional water addition to make up for that lost in gassing⁴⁹. With both battery types, longevity is increased with reduced DOD, and thus practical implementation of the prototype would benefit from several batteries operating at reduced DOD rather than a single battery operating at high DOD⁵⁰. As such, it is recommended that additional batteries are purchased and utilized up front rather than using them sequentially.

The cost of the unit was analyzed upon completion of testing. Table II displays the capital costs and O&M costs associated with the system. The purchase cost for each component was determined by the incurred costs of building one system at retail price in Stillwater, OK in 2017. Though expenditures will vary with time and location, the total purchase cost to build the water treatment system was below \$900.00. Additional capital costs and O&M costs were estimated relative to the purchase cost of the system and are reported to determine the net present value (NPV) of the system. These estimates were rough and should be reevaluated for each circumstance. The NPV for the project was calculated based on a discount rate of 5% and a 10-year project lifetime and found to be (\$4,100.00), which is quite reasonable for a water treatment system designed for use in remote developing regions.

TABLE II
CAPITAL COSTS AND O&M COSTS (2017) FOR BUILDING THE POU WATER TREATMENT SYSTEM

Capital Costs		
Item	Quantity	Cost
5 gpm 12V DC pump	1	\$90.00
12V car or marine deep-cycle battery	1	\$100.00
55-gallon drums	1	\$138.00
Sand	1	\$28.00
Pipe, fittings, and hardware for filter	1	\$115.00
Hoses and venturi injector*	1	\$78.00
Carbon electrodes*	1	\$88.00
Pipe, fittings, and hardware for chlorine cell	1	\$125.00
Subtotal		\$762.00
15% Contingency	15%	\$114.30
Total Purchase Costs, Rounded		\$900.00
Installation Cost	38%	\$337.50
Engineering analysis	20%	\$180.00
Pilot Testing	15%	\$135.00
Public Education	20%	\$180.00
Total Capital Costs, Rounded		\$1,733.00

Estimated Annual O&M Costs		
Power	10%	\$90.00
Annual Maintenance	5%	\$45.00
Emergency Maintenance	12%	\$108.00
Residual Disposal	2%	\$18.00
Public Education	5%	\$45.00
Annual O&M Costs		\$306.00

**May be difficult to acquire or show wide price variations in low-income areas*

CONCLUDING REMARKS AND FUTURE PERSPECTIVE

A drinking water treatment system utilizing sand filtration and locally-generated chlorine disinfection was constructed from readily available and low cost materials. All materials were acquired for less than \$900 (2017) and were selected for their widespread availability and utility. The combination of locally generated chlorine with gravity driven sand filtration utilized in a batch process treated drinking water for 85 people per day. When used to treat 340 L of surface water, system operation displayed a 70% reduction in turbidity and no detectible bacterial colonies after ninety minutes of operation. Based on an estimated annual O&M cost of \$306.00, the net present value of the system was calculated as (\$4,100.00) over a 10-year project lifetime with a discount rate of 5%. This result suggests that disinfection and filtration may be utilized in tandem to treat water on a community scale through batch processes.

Despite the efficacy of the aforementioned water treatment system, there remain several questions in regard to the operation of the system. While turbidity was effectively reduced using commercial filter-grade sand, the hand-screened sand that may be more readily available worldwide could display different turbidity reduction profiles than what was observed in this study. Furthermore, the relative contribution of chemical disinfection and mechanical filtration to the reduction of detectible coliform bacteria colonies in the water is yet unknown. Finally, scaling factors and parameters for initial water quality should be investigated when considering implementation in a real-world setting. Though these challenges seem daunting, the treatment of drinking water at the point of use is central to alleviating suffering in families and communities worldwide. As such, the combination of locally-generated chemical disinfectants with gravity sand filtration shows promise to fill the gap between household filtration and community disinfection in the application of POU drinking water treatment.

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APPENDIX I: WATER TREATMENT SYSTEM LIST OF PARTS

TABLE III

ADHESIVES, FASTENERS AND CONNECTORS REQUIRED FOR WATER SYSTEM CONSTRUCTION

Part	Quantity
8" nylon multipurpose cable ties	24
1/4" diameter ring terminals	10
1/4" diameter x 1/5" length machine screws and matching hex nuts	8
Electrical tape	1
Teflon tape	1
Duct tape	1
PVC cement and primer	1

TABLE IV

PVC COMPONENTS OF WATER TREATMENT SYSTEM

Part	Quantity
2" diameter slip PVC end cap	11
2" diameter schedule 40 PVC pipe, 10 feet	1
2" diameter male threaded to 2" diameter slip PVC adapter	1
2" diameter to 1" diameter slip PVC reducer	1
2" diameter slip PVC cross junction	1
2" diameter slip PVC union	1
2" diameter male threaded to 2" female slip PVC adapter	1
1" diameter slip PVC end caps	4
1" diameter slip PVC ball valve	3
1" diameter schedule 40 PVC pipe, 10 feet	1
1" diameter slip PVC union	1
1" diameter 90° slip PVC corner	1
3/4" diameter male threaded to 1" diameter slip PVC adapter	5
3/4" diameter female threaded to 1/2" diameter slip PVC adapter	2
3/4" diameter male threaded to 1/2" diameter slip PVC adapter	2
1/2" diameter slip PVC T-junction	2
1/2" diameter slip 90° PVC corner	2
1/2" diameter schedule 40 PVC pipe, 5 feet	1
1/2" diameter slip PVC ball valve	1

TABLE V
NON-PVC COMPONENTS OF WATER TREATMENT SYSTEM

Part	Quantity
0.2" x 0.787" x 12" carbon fiber electrode	8
12-gauge wire, white plastic coated, 1 foot	8
3/4" diameter female threaded garden hose mender	6
1/2" diameter NPT threaded to 1/4" diameter hose barb brass fitting*	4
5/8" diameter garden hose, 5 feet	3
3/4" diameter threaded bulkhead fitting	2
55-gallon plastic drum	2
2" diameter threaded bulkhead fitting	1
Polypropylene landscape fabric, 10 square feet	1
1/4" diameter flexible polypropylene tubing, 5 feet**	1
1/4" diameter flexible vinyl tubing, 5 feet**	1
10-gauge wire, black plastic coated, 10 feet	1
10-gauge wire, red plastic coated, 10 feet	1
Wayne 12V DC metal transfer pump	1
3/4" diameter threaded brass spigot	1
12V DC deep cycle lead-acid battery	1

**If possible, use other material such as PVC with better resistance to extended chlorine exposure*

*** Replace with flexible PVC tubing for extended material lifespan*

APPENDIX II: DETAILS OF SYSTEM CONSTRUCTION

Filter Barrel Construction

The filter barrel was modified from a standard 55-gallon industrial plastic drum. The lid portion was removed by drilling an entry hole on the top of the drum and cutting around the perimeter to provide access to the interior of the drum. A 3-3/16" diameter hole was cut 4" from the bottom in the side of the barrel and was sealed with a plastic 2" diameter threaded bulkhead fitting. Directly above that, a 1-5/8" diameter hole was drilled 4" below the rim of the barrel and was sealed with a plastic 3/4" bulkhead fitting (Figure 2).

The exterior of the 2" diameter bulkhead fitting was fitted with a 2" diameter male threaded to 2" diameter slip adapter. This was cemented to a PVC 2" diameter to 1" diameter slip reducer using PVC purple primer and PVC cement (Oatey, Cleveland, OH). A 1" diameter PVC ball valve with slip connectors was fitted with 2" length pieces of pipe on either end and cemented in the reducers to allow for pump isolation. The outlet of the valve was fitted with a 1" diameter slip to male 3/4" diameter threaded connector, which allows for standard garden hose fittings to connect the pump to the system.

The interior top of the filter barrel was also fitted with a valve to allow each barrel to be isolated. A 1" diameter slip PVC ball valve was fitted on one side with a 2" length of 1" diameter PVC pipe. A 1" diameter slip to 3/4" diameter male threaded adapter was cemented onto this pipe and the valve assembly was threaded into the interior side of the 3/4" diameter bulkhead fitting.

The water collection sieve (Figure 3) was connected to the interior of the 2" diameter bulkhead fitting. The sieve was constructed from three 2" diameter PVC end caps, one 2" diameter PVC cross fitting, one 2" diameter PVC union, one 2" diameter slip to male threaded adapter, three 8" lengths of 2" diameter PVC pipe and two 3" lengths of 2" diameter PVC pipe. The three 8" lengths of PVC were perforated in rows with a 1/2" diameter drill bit to ensure high water flux while maintaining the structural integrity of the water collection sieve. Each perforated pipe was fitted securely, but not cemented, into one of the four outlets of the 2" diameter cross connector, and the ends of the pipes were capped with the three 2" diameter PVC caps. Each of the perforated pipes was wrapped in one layer of untreated polypropylene landscape fabric and secured with multipurpose nylon cable ties.

One 3" length piece of PVC pipe was fitted securely, but not cemented, into the remaining outlet of the 2" diameter PVC cross connector. One end of the 2" diameter PVC union (separated) was connected to the other end of this piece, and another 3" length of 2" diameter pipe was connected to the other half of the union. The far end of this pipe was fitted with the 2" diameter slip to male threaded adapter, which was seated securely in the interior portion of the 2" diameter bulkhead fitting of the filtration barrel. The perforated and covered portion of the sieve was placed in the bottom of the filter barrel and connected to the assembly via the 2" diameter union joint.

Storage Barrel Construction

The storage barrel was constructed from a rainwater collection drum that was easily accessible and available. It was already fitted with a spigot 6 inches from the bottom of the barrel; if this was not the case, another tap would have been installed as the primary outlet for the system. A 1-5/8" diameter hole was drilled 90° away from the tap and 32 inches raised from the bottom of the barrel. This hole was sealed with a 3/4" diameter bulkhead fitting (Figure 4).

A 1" diameter slip PVC ball valve was cemented to a 2" length of 1" diameter pipe, and the other end of this pipe was fitted with a 1" diameter slip to 3/4" diameter male threaded PVC adapter. This 3/4" diameter male threaded adapter was fitted into the interior of the 3/4" diameter bulkhead fitting to allow for storage barrel isolation. The filtration barrel and storage barrel were hydraulically connected with a 24" length of 1" diameter PVC pipe. One end of the 24" length pipe was cemented to a 3/4" diameter male threaded to 1" diameter slip adapter, and the other end was connected to a 1" diameter PVC union. The other half of the union was cemented to a 2" length of 1" diameter PVC pipe, and that was glued to another 1" diameter slip to 3/4" diameter threaded adapter. The 3/4" diameter threaded adapter on the 24" length of 1" diameter pipe was screwed into the 3/4" diameter bulkhead fitting on the outside of the filter barrel, while the 3/4" diameter threaded adapter on the 2" length of pipe was screwed into the 3/4" diameter bulkhead fitting on the storage barrel. The two barrels were then oriented such that the 1" diameter union halves met, and the union was joined as seen in Figure 4.

Circulation and Injection System Construction

The pump utilized for the system was a Wayne PC1 12-Volt Metal Transfer Pump (WAYNE Water Systems, a Scott Fetzer Company. Harrison, OH). This pump was selected because it advertised a flow rate of 310 GPH at 10 feet of head and included 3/4" diameter threaded garden

hose connections at inlet and discharge. In addition, it received power from a 12V lead-acid battery, the type of which are readily accessible in remote regions and can simultaneously power the electrolytic chlorine cell. A standard 12V lead-acid battery (ValuePower Group Size 35, Johnson Controls, Joseph, MO) was acquired to run the pump.

Three separate 5' lengths of 5/8" diameter garden hose were modified on each end by attaching 5/8" to 3/4" female hose menders. One hose was connected to the pump discharge while another hose was connected to the pump suction. The opposite end of the suction hose was attached to the 3/4" diameter male threaded outlet at the bottom of the filter barrel, while the hose on the pump discharge was later screwed onto the 3/4" male inlet of the disinfectant injector (Figure 5).

The disinfectant injector was designed to allow for bypass flow control to control the vacuum pressure on the inlet line. The injector itself was a Mazzei 484-PP 1/2" MNPT Injector (Mazzei Injector Company, LLC, Bakersfield, CA) with 1/2" diameter male threaded inlet and outlet and 1/4" diameter hose barb for the suction port. 1/2" diameter PVC female threaded to slip adapters were connected to both the outlet and the inlet of the injector and a 2" length of 1/2" diameter PVC pipe was cemented on the outlet side. A standard 90° 1/2" diameter PVC elbow was fitted on the outlet pipe facing 180° away from the barb of the injector and cemented in place.

One 2" length of 1/2" diameter PVC was fitted with a 1/2" diameter slip to 3/4" diameter male threaded adapter. The free end of this pipe was placed into one end of the longitudinal axis of a 1/2" diameter T connector. The opposite side of the T connector was fitted with a 4" length of 1/2" diameter PVC pipe. This process was repeated to create a second T connector with a 3/4" diameter male threaded adapter on one end and a 4" length of 1/2" diameter pipe on the opposite. A 1/2" diameter slip PVC ball valve was cemented between these two 4" lengths. The perpendicular joints were fitted with 2" lengths of 1/2" diameter PVC pipe, and one was fitted with a 90° 1/2" diameter PVC elbow oriented parallel to the ball valve. The 1/2" diameter elbow connected to the outlet of the venturi was then connected to the remaining T connector line. The venturi and the opposite elbow were lined up and the required pipe length to connect the two was measured and cut. This length was placed in the system and all remaining connections were cemented in place. The end closest to the venturi inlet was connected to the pump discharge hose, while the outlet was connected to the third garden hose used to carry water to the bottom of the storage barrel.

Saline Electrolysis Unit Construction

The chlorine unit (Figure 7) was constructed of four identical electrolytic cells wired in parallel. Each cell was made by cementing a 2" diameter cap on the bottom of an 8" long shell of 2" diameter PVC pipe. Another 2" diameter PVC cap was modified with a 1-3/8" diameter hole drilled into it such that the outside edge of this hole aligns with the inside edge of a 2" diameter Sch. 40 PVC pipe fitted into the cap, or 0.35 inches off center. On the other half of the cap, a slit 1/4" by 7/8" was cut as shown in Figure 6.

A 10" length of 1" diameter PVC pipe was capped on one end with a 1" diameter slip cap. This cap was modified by cutting a 1/4" by 7/8" slit in its center. Once the cap was fitted on the pipe, a 1/2" diameter hole was drilled through the cap and pipe perpendicular to the longitudinal axis of the top slit. This hole was threaded and fitted with a 1/2" diameter NPT to 1/4" hose barb brass fitting, though nylon would be preferable. A 4" length of 1/4" diameter vinyl tubing was connected to the hose barb. The vinyl tubes were brought together and placed in the end of a 90° 3/4" diameter

PVC fitting and held in place using duct tape. A 10' portion of ¼" diameter polyethylene tubing was fed into the other end of the 90° fitting and held in place with duct tape.

The electrodes were constructed from 4' lengths of 0.196"x 0.787" rectangular carbon fiber rods acquired from *graphitestore.com* (Northbrook, IL), though other available carbon fiber may be a functional, chemically inert electrode. The electrodes were cut into 12" lengths and a 3/8" hole was drilled 1/2" from one end of each electrode. ¼" diameter machine screws and nuts were fitted with washers and used to connect ¼" diameter ring terminals to each electrode. Each electrode was wrapped in electrical tape directly below the ring terminals to prevent them from falling through the slots on the chlorine generator. Each ring terminal was crimped onto a 12" length of white coated 12-gauge wire that had its ends stripped using a manual stripping and crimping tool. Groups of four electrodes were wrapped around a ¼" diameter ring connector and were wrapped with electrical tape to hold them in place and insulate them from the environment. One ring connector attached to an electrode bundle was then crimped onto the stripped end of a 10' length of black coated 10-gauge wire, while the other ring connector with an electrode bundle was crimped onto the stripped end of a 10' length of red coated 10-gauge wire.

A wooden frame was constructed from 1" x 4" boards to hold the four chlorine cells vertically in a square formation while allowing for modification of individual cells and flexibility in design iterations. The 2" diameter capped PVC "shells" were placed into the frame and were held together in the center of the frame with rubber bands. Each shell was filled halfway with a 30% by weight saline solution, mixed from tap water and iodine-free table salt. The 1" diameter pipes were fitted into the 1-5/8" diameter holes offset on the top of the 2" diameter caps and lightly held in place by duct tape. The electrodes connected to the red 10-gauge wire were then set into the slit on the top of the 1" diameter PVC caps, while the electrodes connected to the black wire were fit into the slits on the top of the 2" diameter cap. All exposed electrodes and bare metal were covered using electrical tape to reduce the possibility of an inadvertent shock when the system was powered.

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