Low-cost Groundwater Treatment System for Arsenic Removal:

experience with a full-scale field pilot

Lessons learned from operating a low-cost, low-tech arsenic treatment system in Guanajuato State, Mexico

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INTRODUCTION

Aquifers in the state of Guanajuato are facing dangerously high levels of over-exploitation, mainly driven by commercial agriculture. Because of the drop in the level of the water tables, fluoride and arsenic, among other elements, have begun to appear in sampled groundwater ([1]-[3]) . Fluoride and arsenic have been identified in the Alto Río Laja aquifer at concentrations up to 15 and 23 times the WHO recommendations for drinking water, respectively ([4]). These contaminants, which have become a problem not only locally in Guanajuato, but also in many places around the world, are known to have several detrimental effects. These health effects include dental fluorosis, skeletal fluorosis, kidney disease, developmental disabilities, skin lesions, organ failure, cancer among long-term consumers, and inhibited neural development in children ([5], [6]).

Caminos de Agua (henceforth "Caminos") has been promoting rainwater harvesting for years, which provides water which is naturally free of arsenic and fluoride and can be easily turned into a sustainable and well-accepted source of domestic water. However, the high initial investment cost and the slow pace of increasing the reach of such systems has led Caminos to simultaneously investigate alternative approaches, including the removal of arsenic and fluoride from groundwater.

Commercial options for arsenic and fluoride removal — such as activated alumina and reverse osmosis — are costly, often require reliable access to energy and spare parts, and are overall beyond the reach of low-income communities. Indeed, low-cost, effective and locally relevant solutions to groundwater treatment are not readily available in those contexts. In response, Caminos embarked on a mission to develop a system that could be locally made and quickly implemented.

The team's first hurdle was to find filtration media that remove arsenic and fluoride from water, taking into consideration the region's particular groundwater chemistry. To treat fluoride, the team settled on in-house production of a cow bone-based carbon, called "bone char" (see report available here). To remove arsenic, on the other hand, Caminos decided to leverage Bayoxide E33, a commercially-available iron oxide-based medium. Intensive laboratory testing, conducted primarily with groundwater sourced from around the region, confirmed the efficacy of these media. To assess their real world performance, Caminos built and operated two large-scale pilot systems, made from locally available components -- the first to remove arsenic, the second to remove both arsenic and fluoride. This report describes the design, construction, operation, maintenance, and performance of the first system, designed to remove arsenic from the source drinking water.

The report will go over the design of the pilot and the technologies that allow Caminos to remove arsenic from the water. Then, it will describe how the pilot was operated before presenting the technical and economic performances of the system. Detailed design information can be found in the appendixes at the end of this document.

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DESIGN AND TECHNOLOGY OF THE PILOT

General Information

The Pilot 1 treatment system, designed to remove arsenic from the source water, was installed at a local spirulina farm. The farm owner aims to limit the total amount of arsenic in his final product, in line with international recommendations and thus is motivated to grow his spirulina in water that has little or no arsenic present. This pilot site is nearby to the field site that Caminos owns and so this facilitated ease of access for monitoring and maintenance by the Caminos team. The system was designed to treat 2,300 liters per day, which matches the requirement of the farm's operations for water demand. If this system were to be used for drinking water, it would support 460 people (based on 5 L/person/day). The system was retrofitted into the farm's existing water supply. It was installed on the side of one of the concrete tanks holding water for the spirulina process.

The system was designed to be as easy to operate as possible, so that it only requires periodic monitoring and no continuous human-power when functioning normally. It is operated under gravity, except for the treated water which is transferred to a concrete storage tank via a small submersible pump. The treatment objective (TO) was set at 10 µg As/L (the World Health Organisation threshold for Arsenic in drinking water). The team chose a lead-lag design (two stationary bed Bayoxide contactors, in-series) to remove arsenic from the water. This setup has been shown to significantly decrease sorbent use [12]. The inlet water used for the system has an arsenic level ranging around 15-20 µg/L. This is more than the WHO recommendations and the Mexican norm for purified water (NOM-201-SSA1-2015) which are set at 10 µg/L, but way lower than the most affected sites studied by Caminos. In those cases, rainwater harvesting systems would probably be more appropriate for heavily contaminated areas or areas lacking groundwater access altogether. As in the case of this pilot, the focus of groundwater treatment systems will more likely be the, far more numerous, moderately contaminated sites, where it is expected that they would make more economic sense.

Figure 1: Pilot System for Arsenic Removal

Arsenic Removal Technology

Sorption Media - Bayoxide E33

In this system, arsenic removal is achieved using adsorption on a commercially available granular iron-oxide media, named Bayoxide E33. Bayoxide E33has been specifically engineered for arsenic removal, for which it has high affinity. Arsenic is removed from solution by bonding to the positively charged hydroxyl groups present on the surface of the iron-oxide. Arsenate[1] is hence more difficult to

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[1] Arsenic can exist in two major forms (oxidation states) in water: arsenic (III) also known as arsenate and arsenic (V), arsenite.

remove, because it exists as a neutral species below a pH of 9.2 (which is the case of most groundwater), as compared to Arsenite, which exists as a negatively charged ion in naturally occurring waters and is hence attracted toward the positively charged sorption sites.

Arsenic removal by Bayoxide E33 has been studied in several scientific articles. The Sandia National Laboratories have conducted a series of pilot scale experiments, measuring the adsorption capacity of the media under different conditions. This capacity, which is an essential indicator of the performance and viability of a sorption process, can be measured in terms of volume treated (often measured as bed volumes, BVs), or as mass of arsenic removed per mass of media (mg As/g) when a certain condition is met. In these studies, the capacity was measured between 1.4 and 4.2 mg As per gram of Bayoxide when breakthrough (10 µg As/l in the effluent) was reached ([7]-[9]). Note that a great variety of factors can affect the adsorption capacity:

Factor	**Considerations**
Contact time	The longer the contact time, the higher the sorption capacity of the media. 3-5 mins is recommended by the manufacturer.
pH of inlet water	For most iron-based sorbents, higher pH water leads to lower sorption capacity. A pH of 5.5-8.5 is recommended by the manufacturer, though it has been shown that the higher end of that range is associated with a reduction in sorption capacity [10].
Arsenic concentration in inlet water	In a seeming contradiction, higher arsenic concentration will lead to a higher capacity of the media due to the higher force driving sorption. However, it can also lead to an overall reduction in time-to-breakthrough.
Arsenic oxidation state	Under most conditions, iron oxides have a higher affinity for As(V) than As(III).
Competing species	The adsorption media will remove a variety of chemical species besides the target species. Bayoxide E33 has documented interferences with silicates, phosphate, and vanadium, among others. The presence of these species in the inlet water will decrease the media's capacity to bind arsenic. For example: silicates levels of 13.5 mg/l have been shown to reduce the sorption capacity by 70% at a pH of 8 [11].

Table 1: Factors Impacting Sorption Capacity

Background tests were performed on the well water prior to the building of the pilot (July 2018) to quantify interfering species. Silicates were measured at 42ppm (measured again in January 2019 at 143ppm), Vanadium was measured below the detection limit (50ppb), as was lead (5ppb), mercury (0.5ppb), and iron (0.1ppm). Total phosphorus was also below detection limit (5ppm), but no measurement was done for phosphate specifically. During the pilot run, pH was mostly fluctuating between 8 and 8.5, with some measurements in the range 7.5-8. Arsenic speciation was not measured during the experiment, but is assumed to be in a vast majority As(V), as is quite typical in the area.

Overall, these background conditions are rather adverse, and were expected to degrade the performances of virtually any arsenic sorbent. However, Bayoxide has been reported in various studies as being one of the least impacted by adverse background conditions. These challenging conditions allowed Caminos to prove the viability of Bayoxide E33 in a moderate-arsenic, adverse background context (which are to be expected in many sites in central Mexico), without pretreatment steps which would add complexity to the system.

Bayoxide Contactors

A key element of the system is the contactors which contain the Bayoxide and are where the adsorption process occurs. With the design size of the pilot, Caminos was able to use PVC columns as contactors (larger systems may require contactors utilizing larger plastic or concrete containers). As for the entire system, a point was made to only use locally available materials and pieces to increase the replicability and affordability of the project. The columns must be able to be opened to allow for media changeout and must be of a sufficient size to contain enough media to have a reasonable changeout frequency. The design characteristics are presented in Table 2.

Parameter	Pilot Design Value
Column diameter	4”
Column height	100 cm
Column volume	8.1 L
Bed volume	6.25 L
Volume for bed expansion (for backwash)	23% of total volume
Empty Bed Contact Time (recommended by manufacturer: 3-5mins)	3.9 min
Max flow (EBCT of 3 min)	3,000 L/day

Table 2: Column Specifications

Caminos spent a large amount of time developing such a column, and the ones used for the pilot are the 4th generation built by Caminos. Their design is shown on the diagram below and is based on 4" sanitary PVC. A complete list of parts can be found in Appendix 1.

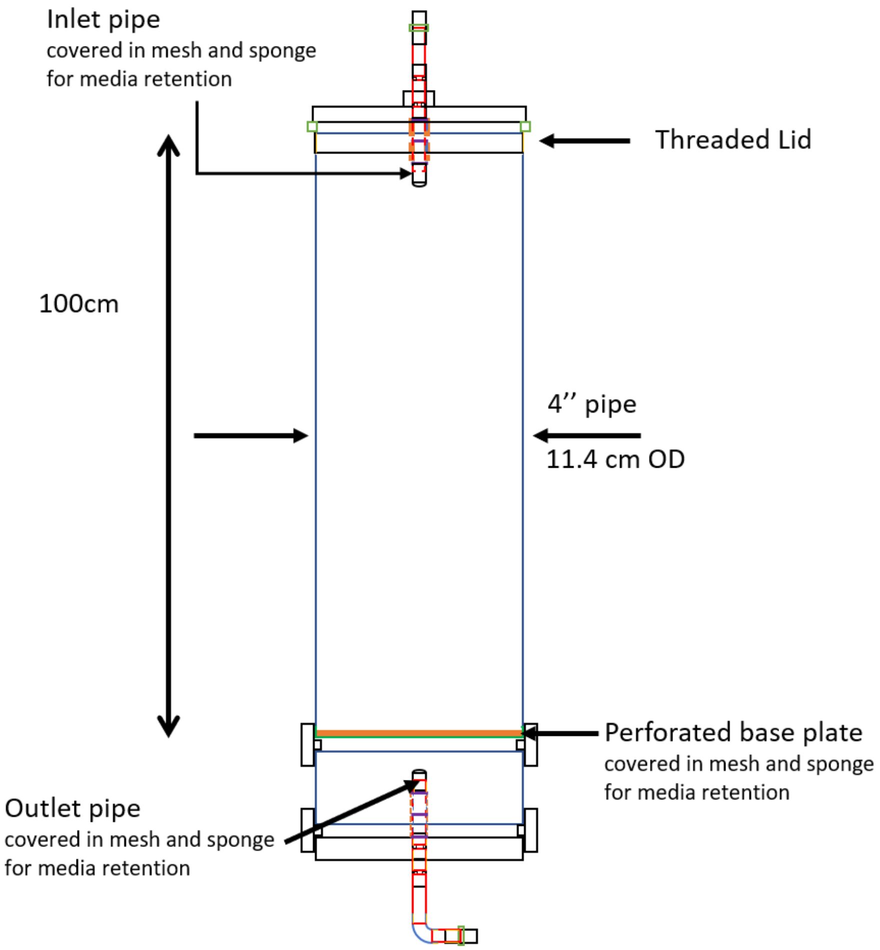


Figure 2: Bayoxide E33 Contactor Design

Figure 3: From left to right: top/inlet of the column; perforated base plate of the column

Lead-lag Configuration

The lead-lag configuration (two columns in series) used in this pilot is a strategy to optimize the use of sorption media in a water treatment system.

In a single column system, the contaminant is adsorbed through the column bed. Once the bed starts to become saturated, it will begin to pass through into the effluent water. The filter will need to be replaced once the contamination reaches an unacceptable level. However, saturation does not occur uniformly within the bed. The treatment objective can be reached in the effluent while part of the media still has some remaining sorption capacity. In a single column scenario, the column needs to be changed, and that remaining capacity is simply lost.

As illustrated in Figure 4 below, having a second column in series allows the system to make use of that capacity. When the first (lead) column reaches the treatment objective, the second (lag) maintains the effluent under the objective. By the time the second column finally reaches the treatment objective, the capacity of the first column that remained has been mostly used. The second column, which still has some capacity, is then placed in the lead position, and a fresh column is placed in the lag position.

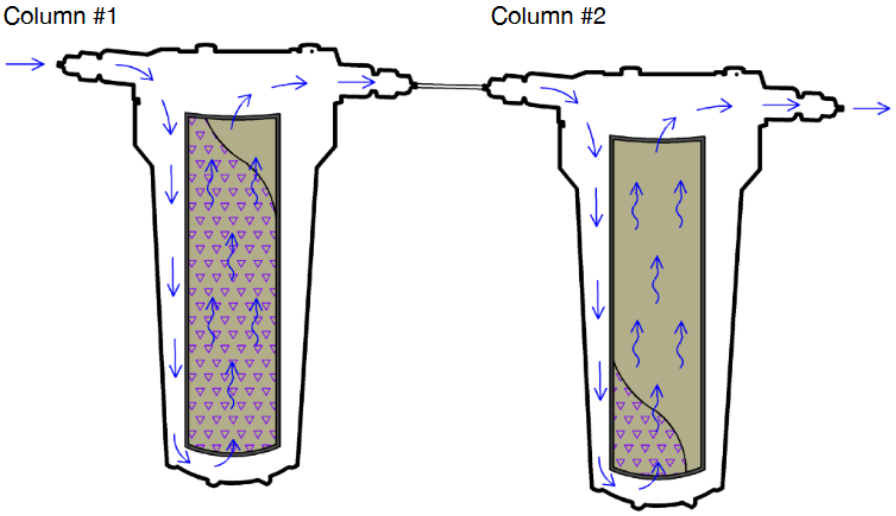


Figure 4: Lead-lag Concept (the purple pattern represents the saturated media)

Caminos has published a report about our experience working with lead-lag systems for fluoride removal, which can be read here.

Hydraulic Design

The whole treatment operation is driven by gravity, with only the treated water being pumped to an elevated concrete tank for later use. A process flow diagram is shown in Figure 5, and a more detailed layout can be seen in Appendix 2. The water comes from a well located about a 100m away from the system, and is untreated prior to entering the system. A large cistern (exact volume unknown, total capacity around 20m^3) located by the well, stores water prior to use. Water is first held in a 200L container, equipped with a float valve, to maintain constant available head in the system.

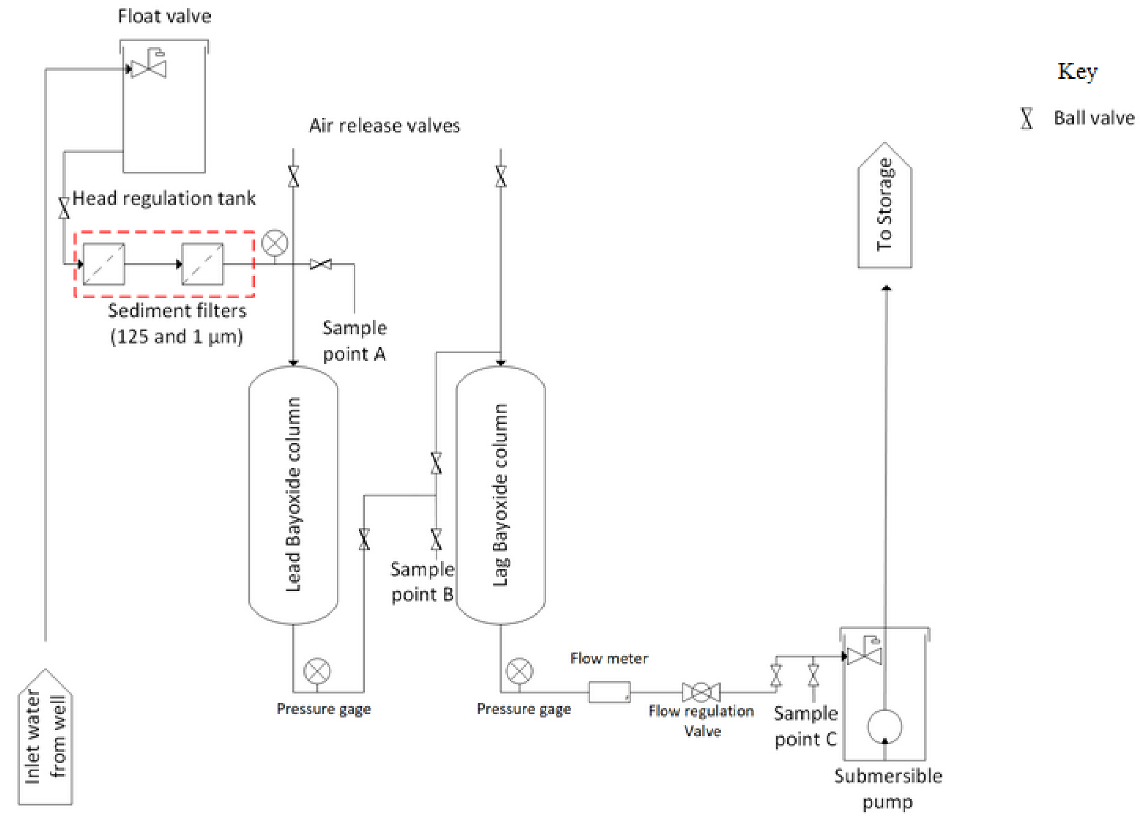


Figure 5 : System Schematic

The water first passes through a 125µm disk filter and a 1µm polypropylene filter to remove the sediment that would otherwise clog the Bayoxide columns. The washable disk filter was added during the experiment to reduce the replacement frequency of the 1µm filter. Sample ports allow sampling of the water at three points: inlet (after sediment filters), lead column outlet, and lag column outlet. The lead outlet sample valve was equipped with a globe valve to allow sampling at the normal operating flow of the column and prevent draining the lead column. Three pressure gages (transparent hoses) have also been installed to measure the pressure drop across the sediment filters and across each column. Both columns are equipped with an air release valve, as well as with backwash ports, which can be connected via flexible hoses. The backwash water is sourced from the system itself and is taken after having passed through the sediment filters (from the sample port A) and injected at the base of the column which requires backwash.

For flow measurement, a turbine flow meter is on the outlet of the system, as well as a globe valve for flow regulation. A 200L plastic tank collects the treated water and is equipped with a float valve to shut off the system when full and a submersible pump to transfer the water to a larger storage tank. An electrical float switch has been placed in the storage tank, shutting off the pump and closing the system when the tank is full, to avoid overflow.

Construction Cost

This section details the cost of construction for a similar system, by a team with previous experience, and in our context. It is based on the materials that were used for the pilot, but the construction of the pilot itself was longer and more expensive, due to the lack of experience of the team. Conversion between US dollars (noted as $) and Mexican pesos (MEX) was done with a 21 MEX/$ rate.

Such a system can be built for a cost of about $500-550, whose breakdown is shown below. This includes all the equipment necessary for the pilot (including pump, electrical connections, flow meters, plastic storage tanks, etc.) but does not include the existing infrastructure (well with pump, hydraulic lines to and from the system, large concrete storage tanks, etc.), nor does it include operating costs, such as the sorbent costs (see the cost analysis section under results for an estimation). Some elements included in the list might not be necessary for a system whose purpose is solely to treat water (as opposed to a pilot which needs some additional instrumentation), but this should only have a marginal effect. The construction labor cost includes two skilled workers for a day and a half, paid at $25/day, and an additional $25 to represent the cost of designing and planning the system (estimation). This may largely vary, depending on site details.

Three columns have been included in the cost: two for operations, and an extra one to be able to prepare the changeout in advance, or in case of a leak or other issue.

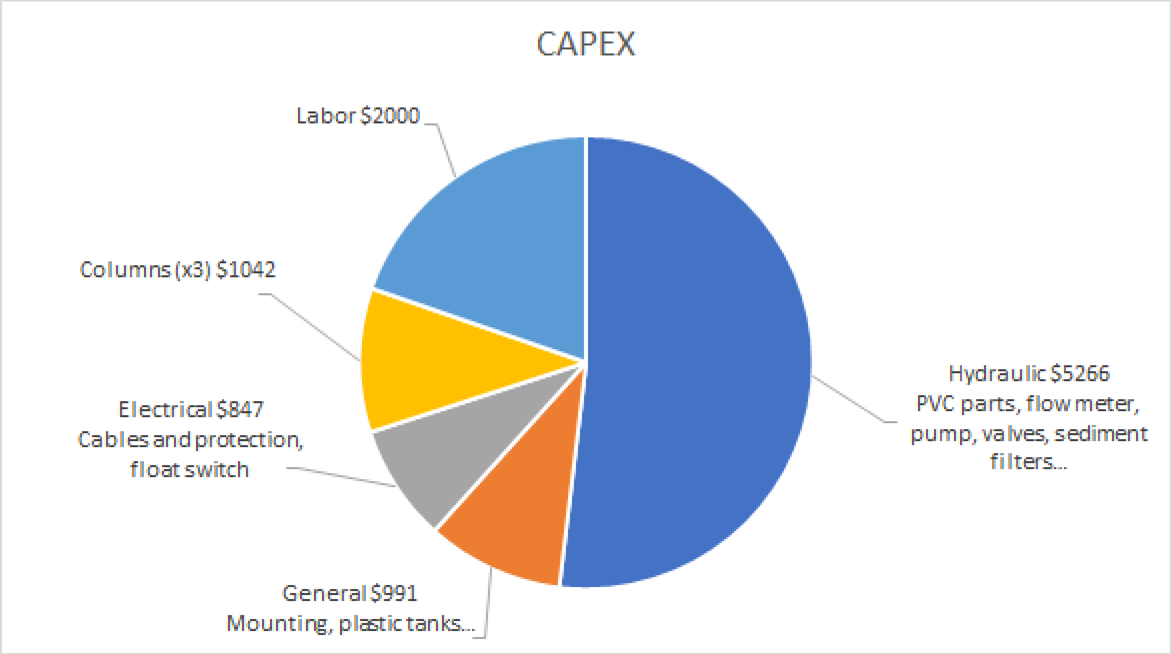


Figure 6: CAPEX Cost Breakdown (costs in pesos) – Total: MEX 10,611

The Bayoxide used in this system was obtained at a price of $15/kg. However, the commercial price is somewhat more expensive at around $20/kg (depending on the volume), excluding delivery cost. Adding 30% losses due to fines (conservative assumption) brings the cost up to $28.6/kg. With those assumptions, the Bayoxide cost of a single column with 3.5kg is $100. The price of the sediment filter cartridge is $2.90. Those costs, as mentioned above, were not included in the construction cost. They are discussed in greater detail below (see Cost Analysis Section) but, for a site with similar water quality, can be estimated at $1.20-1.50/1,000L (not including electricity).

PILOT OPERATION

Partnerships

Caminos recognizes that a major challenge for the first full-scale groundwater treatment pilot was developing how it was to be implemented and what the requirements for monitoring and testing would be. Caminos recognizes that community involvement and decision making from the beginning of a project are essential requirements to transform a technology into a proper solution. We are all agents of our own change and follow community decision making processes. Therefore, the goal of the pilot became not only to understand the technical performance of the treatment technology, but to run a full-scale operational system alongside end users. With this came the opportunity to observe user interaction and sampling and maintenance requirements.

The community that initially came to mind, as a place to implement this pilot, was a community with high levels of groundwater contamination, Pozo Ademado. Caminos approached the community about the option to work side by side on the project. After conversations regarding the details of the project, the community members unfortunately decided against involvement. The pilot would only serve a limited amount of the families and they were worried it would create conflict. In addition, due to the nature of it being a pilot, it would require more involvement than usual, to collect samples and take readings. In the end, they decided that this was not possible.

Luckily, another connection was made, and a partnership moved forward to install the first pilot on a spirulina algae farm, located near the land owned by Caminos. The owner of the farm, recognizing government regulation to have limited arsenic in his product, became interested in the project in order to treat the water he used to grow his spirulina.

Caminos is convinced that implementing these systems at any meaningful scale will require community involvement, in one form or another. Having the farm owner and his worker involved in the operation of the pilot was thus critical and they were trained for basic monitoring and maintenance of the system. They took over sampling, taking pressure readings, measuring and adjusting the flow of the system. Training materials were developed, and a training session was conducted. Caminos monitored the farm staff until they could perform these tasks autonomously.

Reading the flow meter proved to be somewhat challenging for the farm worker. That issue was solved by him taking pictures of the meter to keep track of the moment at which samples and measures were taken, to be sent to the farm owner for documentation, and by estimating the flow by measuring the time taken the red needle to complete a lap (0.1 US gallon).

Figure 7: Flow Meter Used in the System

The other monitoring tasks (sampling, pressure reading etc.) were performed appropriately. Most of the troubleshooting could be done either autonomously via the guide provided, or via over-the-phone support.

In April 2020, the system was handed over to the farm owner. The agreement that was reached was that the owner would be operating the system, and paying for the adsorption media and analysis costs. Caminos would be offering technical assistance in case of issues, as well as facilitating arsenic analysis, filtration media sourcing, and column preparation. The simplicity of the system, as well as its integration within the existing system and the experience of the owner in working with hydraulic systems all contributed to making the transition smooth.

Preparing the Pilot

This section details the operations that were performed before commissioning the pilot.

The Bayoxide columns were packed to the appropriate bed height in order to reach the adequate bed volume. They were manually shaken to compact the media, until no changes in height were observed. The media was pre-sieved by the manufacturer to a US standard #8-#30 size. However, a substantial amount of fine particles had been generated during transport, enough to clog the column and make it inoperable without additional sieving. The generated fines were found to make up about 20-30% of the weight. The media was sieved again using the same sieve sizes of #8 and #30 (dry and then wet sieving). A moisture test was done prior to packing the columns to calculate the dry amount of media from the volume packed as a reference. This was done because the moisture content of the media placed in the column might vary depending on how well it is dried prior to column packing. The first two columns ended up with a very similar mass of dry media (3,456 and 3,470g). However, the third column, put in place during the first change-out in September 2019, was packed with much drier media, which resulted in a greater total mass of (dry) Bayoxide being put in the column (3,784g, or about 9% more than in the first two columns). The column filling protocols were later adjusted to fill by mass rather than volume.

Backwashing of the columns after installation has sometimes been necessary to flush the column and reach the target flow. Though it was not necessary for this application, discarding the first few bed volumes might be necessary, as they tend to have some residual fine particles. The system is also prone to be impacted by air bubbles which interfere with its hydraulic behaviour. The media beds tend to retain air, and care should be taken to remove them prior to starting operation (by gently tapping the side or shaking the column).

Running the Pilot

The pilot system was run from January 23rd, 2019 to April 10th, 2020, at which point it was handed over to the farm owner. The pilot ran continuously over this period, except for short maintenance periods (pump work and disinfection of the system) or for periods during which the storage tank was full. The farmer had one episode in November 2019 during which his batch of spirulina died, leading to a very low consumption of water for about a week.

The treatment strategy for the pilot was to run water through the two Bayoxide columns until the second one reaches the treatment objective at 10 µg/L of arsenic, then perform a column change out (as described in the "lead-lag configuration" section). Then, once they are swapped out, run it until the treatment objective is achieved on the lag column for a second time. The first cycle is not representative of the long-term performance of the system, because both columns start with completely unsaturated media, which is not the case afterwards. However, the second cycle is much closer to the long-term behaviour of the system, which is why the pilot timeline included this cycle.

During the experiment, algae grew in the tubing of the system, disturbing the operation of the system by reducing its flow. On two occasions (May 14th, at 33,700 BV treated and August 13th, at 55,500 BV), the system was stopped and disinfected by passing a strong chlorine solution. The first time, the columns were free of algae and were simply taken out. On the second occasion however, they were also affected by algae growth. To try and prevent further disturbances, Caminos decided to disinfect the columns as well, taking out the Bayoxide from the columns to preserve it from the chlorine solution. Each column was packed again with its original content (after thorough rinsing), but the beds were to some extent disrupted by the process. Samples taken about an hour after restarting the system showed a huge increase in arsenic in both of the columns' effluent (with the lag column reaching breakthrough, and the lead reaching levels slightly higher than the inlet water), as compared to the pre-disinfection levels. As a breakthrough was expected soon regardless, and because of the risk of artificially overloading the lag column by extending the filtration cycle (there was at least a 2-week delay between when a sample was taken and when the results were received, due to the external laboratory delay), the team decided to run the system for another two weeks, and then change the column.

At this point, the first cycle ended, after about 7 months of operation (61,800 BV treated). The lag column was placed in lead position, and a fresh column was put in the lag position. The final analysis showed that the lag column had gone back under the treatment objective of 10ppb just before changeout (7.20ppb in the sample before changeout). It might be that the media still had some capacity, and that the initial high levels were just an artifact due to the repacking of the bed. On the other hand, the less-saturated media which used to be at the bottom of the column prior to the disinfection would tend to have been put back near the top of the column, where it would have had to be saturated before seeing a breakthrough, artificially increasing the duration of the cycle.

This provides some hard to quantify uncertainty on the performance during the first cycle, but is also representative of the real-life issues that can arise with such a system.

To protect the system from UV light and limit algae growth in the future, the team implemented two changes which for the rest of the pilot experiment, managed to prevent any further notable algae build up. The system has been covered with a tarp to provide some shade, and the pipes were painted with a white acrylic paint, to prevent most of the sunlight from entering the pipes.

During the second cycle, which gives an approximation of the long-term behavior of the system, initial breakthrough was achieved at 95,300 BV (33,500 BV in the cycle), after 4.5 months of operation. The outlet then went below 10ppb again, where it remained in the interim until the columns were changed again, at 108,700 BV (46,900 BV in the second cycle). As the systemhad reached breakthrough once (which, in a real world drinking water application, would be the indicator that you need to change your columns), and since the extensive monitoring of the pilot had significant cost,the team decided not to continue to monitor the experiment to see a more definitive breakthrough, and decided to end the second cycle, and the experiment, at this point. A discussion about the fluctuation of the outlet level and its implication in terms of media changeout strategy can be found in the result section.

Sample Collection and Analysis

During the run, a total of 169 arsenic analyses were conducted, which averages to a little less than one sample per week and per sample point. The system flow was measured and adjusted (if necessary) daily by either Caminos or local farm staff (except on weekends). Samples were taken 3-4 times a week and stored on-site, in case a problem arose with one of the samples sent to analysis.

Arsenic analysis was done by an external laboratory, using Atomic Absorption Spectrophotometry (AAS). There was a lag time of 2-3 weeks between sampling and access to the analysis results, which sometimes complicated decision making for the pilot (see results discussion). The detection limit was 1 ppb, and results below the detection limit were considered equal to 0.5 ppb for mass balance calculations. Mass balance calculations were done by linearly interpolating the breakthrough curve to get the point at which breakthrough occurred.

Measurements of pH were taken using a handheld meter, calibrated every week. Fluoride measurement was performed on the inlet water and in some outlet samples, using the SPADNS-2 method (with an Hach DR-850 colorimeter).

RESULTS

The following sections outline the results of the pilot experiment. Included are the technical performances and the cost analysis.

Technical Aspects

Hydraulic Performance

The pilot was meant to operate at a flow as constant as possible, to maintain the contact time in the columns consistent. Keeping track of all the periods during which the system was closed (especially when full of water) proved difficult, which makes the analysis of the average flow between two sample events impossible. However, the team measured and charted the instantaneous flow rate through the system, prior to sampling. Though efforts were made to regulate the flow, it naturally fluctuated, impacting the theoretical empty bed contact time (EBCT) of 4 min, as shown in Figure 8.

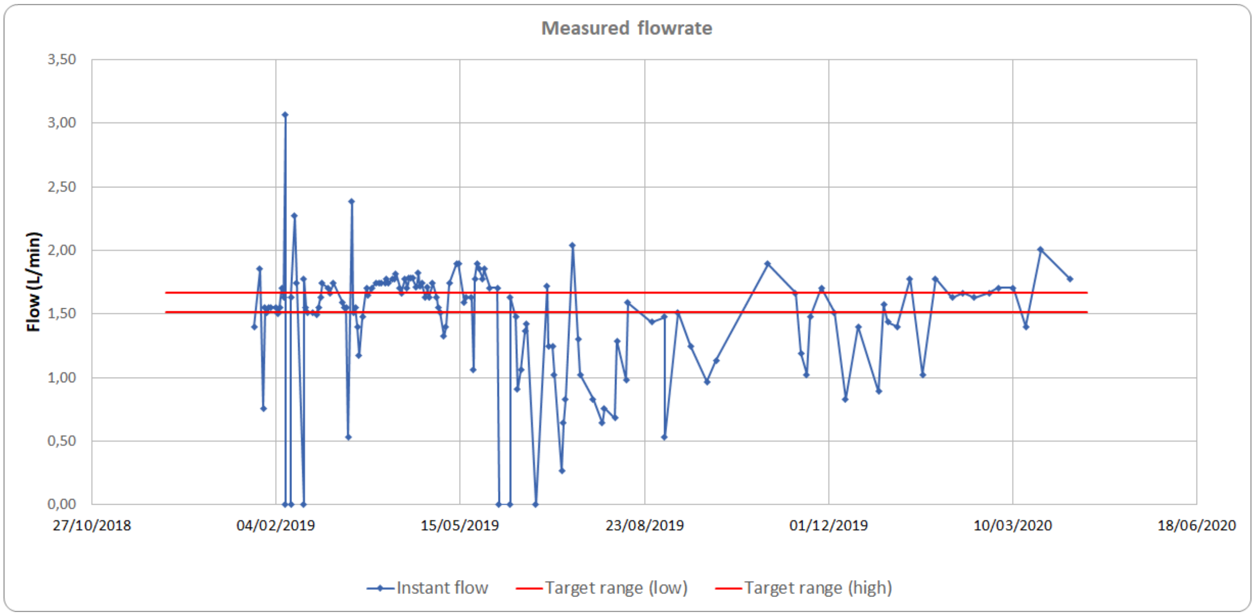


Figure 8: Instantaneous Flow Rate in the Pilot System, Prior to Adjustment
Red lines show the target range (2,180-2,400 L/d; 3.75- 4.13min EBCT).

Adsorption Performance

The breakthrough curve, the main technical output of the pilot experiment, is presented in Figure 8 below, and will be discussed and analyzed in the following paragraphs.

For calculations, the volume of a bed volume has been held constant at 6.25L, regardless of any compaction or extension that was actually happening in the bed throughout the run, or variation between columns.

The inlet arsenic level fluctuated between 8.0 and 19.9 ppb (average of 14.2 ppb). The fluctuations do not follow any clear seasonal trends, and their origin is unclear. The well cistern, which is enough to hold about a week's worth of water, and whose elevated inlet should provide some reasonable mixing, is expected to smooth to some degree the curve of the inlet arsenic level.

The outlet curves are following the trends of the inlet curve (a sudden spike in the inlet will result in a spike in both outlets), except for one event (which was linked to a maintenance event, as discussed above). When the system is approaching breakthrough, this might result in the outlet arsenic level going above and then back below the WHO thresholds. This has implications in terms of managing the media changeout. Depending on how acceptable it is to go slightly above the treatment objective (TO), a more or less conservative approach can be taken. This can have an important influence on the changeout frequency, and hence on treatment cost. When the TO is set at a strict regulatory level, a conservative approach must be taken, but if a more ambitious objective is chosen, or in a context which is not for human consumption, the media could be pushed further, at the expense of risking to briefly not meeting the TO.

Due to these variations, when analyzing the media performance, a conservative scenario will be defined as one which considers breakthrough as the first time a curve goes above the 10 ppb threshold and a best-case scenario as when the curve goes above the threshold and stays above it consistently.

The saturation of the lead column in the first cycle indicates the sorption capacity of a system operated in a non lead-lag configuration (single column). With a conservative approach, breakthrough was reached at 25,500 BV, with an adsorption of 0.40 mg of As per gram of media used. This translates to a sorbent usage rate of 21.9 mg of Bayoxide used to treat each liter of water. Under a best-case scenario, those numbers become respectively 32,800 BV, 0.47 mg of As per gram, and 17.0 mg of media per liter. See the breakthrough curve below.

In either scenario, those numbers are quite lower than those reported in other studies. This might be due to a number of factors as mentioned above (low As level in the inlet, adverse pH conditions, presence of competitive species, etc.).

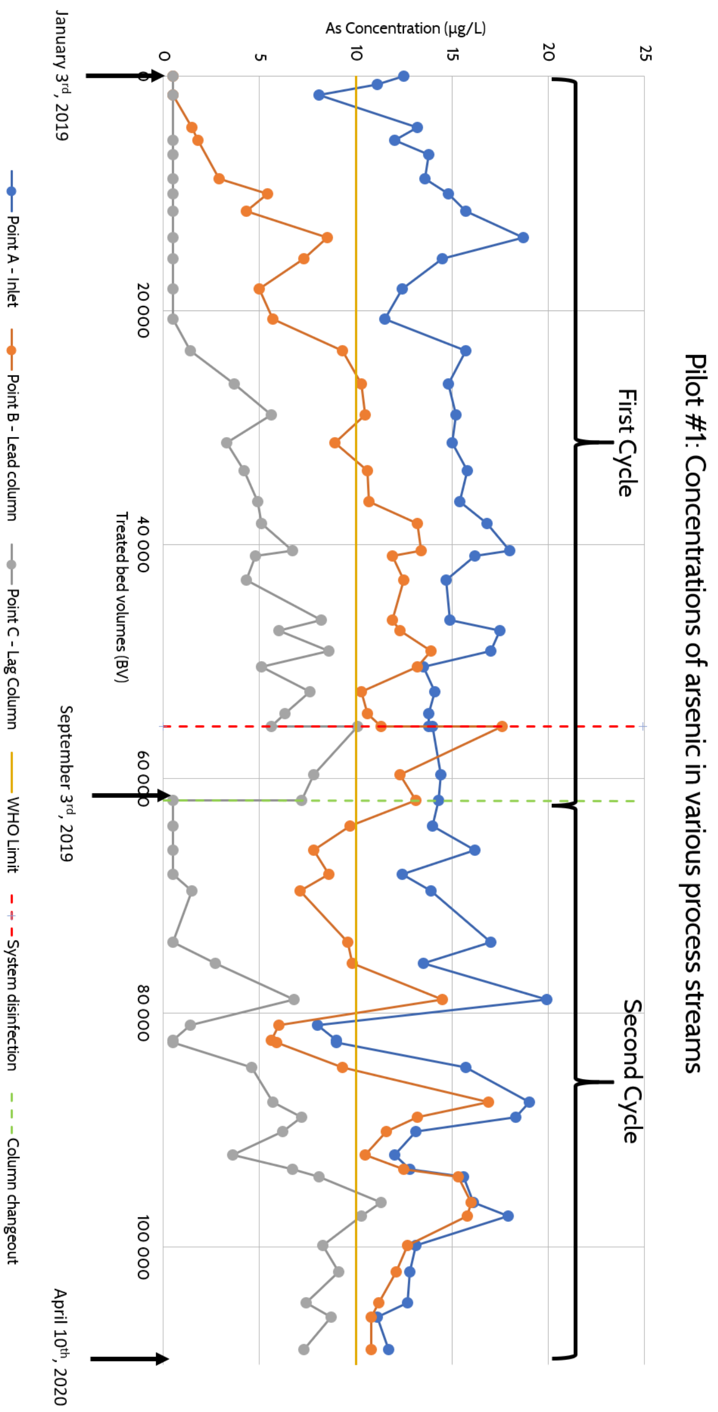


Figure 9: Arsenic Concentration at the Different Sampling Points

As mentioned above in the “Running the Pilot” section, the second cycle can be assumed to be fairly representative of the long term performance of the system (as opposed to the first cycle, which starts with two fresh columns). The system briefly reached breakthrough after 33,500 BV, before dropping below 10ppb up to at least 46,900 BV (at which point the system was handed over to the farm owner, and the columns were changed out). The lead column in the second cycle (previously acting as the lag column), over its life accumulated up to 0.723-0.789 mgAs/g. On average, this is a 74% increase as compared to the capacity using a single column (performance noted above).

By the end of the second cycle, the other column (lag) was essentially not participating in the arsenic removal. This shows that in that context, the media is almost completely saturated when it has to be changed, indicating that a 3-column set up (lead-middle-lag) to further increase sorbent use would have little to no effects. The increase of bed volume treated to treatment objective is a bit harder to analyze, because of the different mass of sorbent used in each column, and therefore was not analysed.

At the system’s nominal flow, and without interruptions, a column must be replaced every 93-130 days to maintain the effluent below the 10ppb objective. The average arsenic level in the effluent was 3.21-4.80 ppb (during the second cycle). However, these numbers are highly dependent on the local water chemistry, and would need to be adapted based on the system location.

Discarding Spent Media

The arsenic that is adsorbed by the Bayoxide is very strongly bonded to the media, making regeneration of the media impractical. Spent media must thus be discarded after use. How it can be discarded depends on its classification or not as a hazardous material. This is regulated in Mexico by the NOM-052-SEMARNAT-2005, which is very similar to the US federal requirements. To comply with this norm, spent Bayoxide E33 must be submitted to an extraction test called PECT (Procedimiento de Extracción de Constituyentes Tóxicos) during which the sample is submitted to strong acidic conditions. The extraction solution must contain less than 5 mg of As per liter after the test.

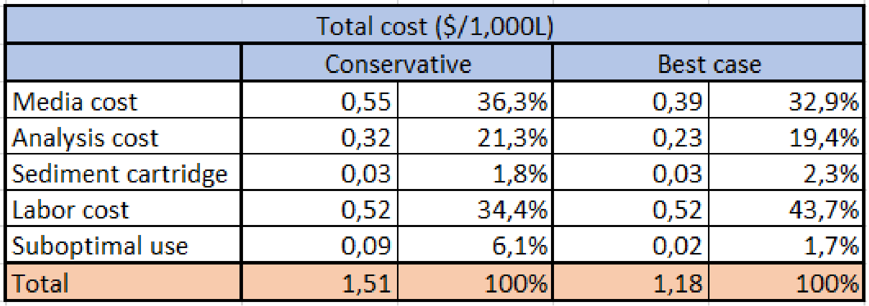
This test was done by an external lab in Queretaro on October 19, 2019 and showed no detectable arsenic in the extraction solution. This means that spent Bayoxide can be disposed of with regular trash, without the need to send it to a specific facility for hazardous waste.

Cost Analysis

Cost per Unit of Water

This section contains a discussion about the price per 1,000L of the water produced by the system operating in a ‘production’ mode (as opposed to the pilot mode, when analysis cost would be, by far, the greatest component of the total cost). Conversion between US dollars (noted as $) and Mexican pesos (MEX) was done with a 21 MEX/$ rate. For comparison, the price of bottled water (20L *garrafón)* is about 71 $/1,000L (30MEX/20L).

Five components are used to define the long-term cost of the water produced by the system, as described in the table below. The total cost comes out to $1.18-$1.51/1,000L, roughly 2% of the cost of bottled water. The following paragraphs discuss the specific components.



Total cost ($/1,000L)				
	Conservative		Best case	
Media cost	0,55	36,3%	0,39	32,9%
Analysis cost	0,32	21,3%	0,23	19,4%
Sediment cartridge	0,03	1,8%	0,03	2,3%
Labor cost	0,52	34,4%	0,52	43,7%
Suboptimal use	0,09	6,1%	0,02	1,7%
Total	1,51	100%	1,18	100%

Table 3: Long-Term Cost of Water Produced (construction cost not included)

Taking into account the construction cost (labor and materials) depends on the period of time considered and was not considered in the above estimate. The total cost of the water will decrease progressively, trending towards the long-term price described above.

Analysis Cost

Arsenic analysis costs with the external lab are 522MEX per analysis, plus a pickup cost (which is spread among all the samples being analyzed). The total cost of analysis was taken as 700MEX/analysis. With an estimation of the volume that can be treated, and sampling only the treated water (instead of at the three points tested during the pilot), it is reasonable to have the water tested 2 or 3 times per cycle (depending on how close to the treatment objective the latest result is, the operator might decide to keep going with the same media, or to proceed with a column change). With an average of 2.5 analysis/cycle, the cost is 0.29-0.40$/1,000L.

Media Cost and Associated 'Suboptimal Use' Factor

The price of Bayoxide has been rounded up to 30.0$/kg of useful media, to account for the cost associated with sourcing it and to account for losses. The media cost for the system was 0.39-0.55 $/1,000L (conservative or best-case scenario). However, whatever the chosen approach, it is to be noted that not all of the theoretical life of the media will be used. Limited number of analysis (for cost reason) and the delay between sampling and analysis results will likely result in a diminution of the effective lifetime of the media. This is especially true with a conservative approach, where overshooting the treatment objective is not acceptable. In such a case, operating procedures might specify to proceed to a changout when the first reading above 9 or 9.5ppb is obtained, in order to incorporate a factor of safety. In the cost prediction table, this was incorporated as a 15% diminution in the media lifetime for the conservative scenario, and 5% for the best-case scenario, labeled as 'suboptimal use', with an associated cost of 0.020-0.092$/1,000L.

Increasing the analysis frequency decreases that suboptimal use cost but drives the analysis cost up. When analyses are expensive (as it is the case with the external lab, the optimal strategy is heavily weighted toward a low-analysis, high-loss scenario).

As a side note, Caminos is working on a low cost analytical method for arsenic determination, based on electrochemistry. By reducing substantially analysis cost (and also by providing substantially faster results), one would be able to lower not only the analysis cost, but also reduce the suboptimal use of the media.

Sediment Filter Cartridges Cost

The sediment filter cartridges, after adding the washable 125µm filter, were changed about once every 45 days, which amounts to 0.028$/1,000L. Electricity cost (pumping) is not included, as this would be largely site dependent.

Labor Cost

Finally, there is some labor associated with the management of the system (monitoring of the system, sample taking, preparation and changeout of the columns, etc.). This was estimated at 1.5 days of a qualified worker's time per month of operation. This only does not include the construction of the system. With a local 500MEX/day rate, that amounts to 0.52$/1,000L. Labor requirements associated with the pilot were more intense than an average system, but this estimate is a reasonable expectation once experience with the operation of these systems is acquired.

Cost Comparison

For comparison, the cost of water produced by a domestic rainwater harvesting system (with ceramic filters to be replaced periodically) and the price of bottled water are shown in Figure 10. The water produced by the pilot is not treated to potable standards and not meant for human consumption, unlike the other two, but the comparison remains interesting. Assumptions include a 900$ construction cost per 12,000L cistern (typically enough for 7-8 people), which produces 120% of that capacity per year, with a ceramic filter that needs to be replaced every 3.5 years for 21.4$ (long-term cost of 1.49$/1,000L).

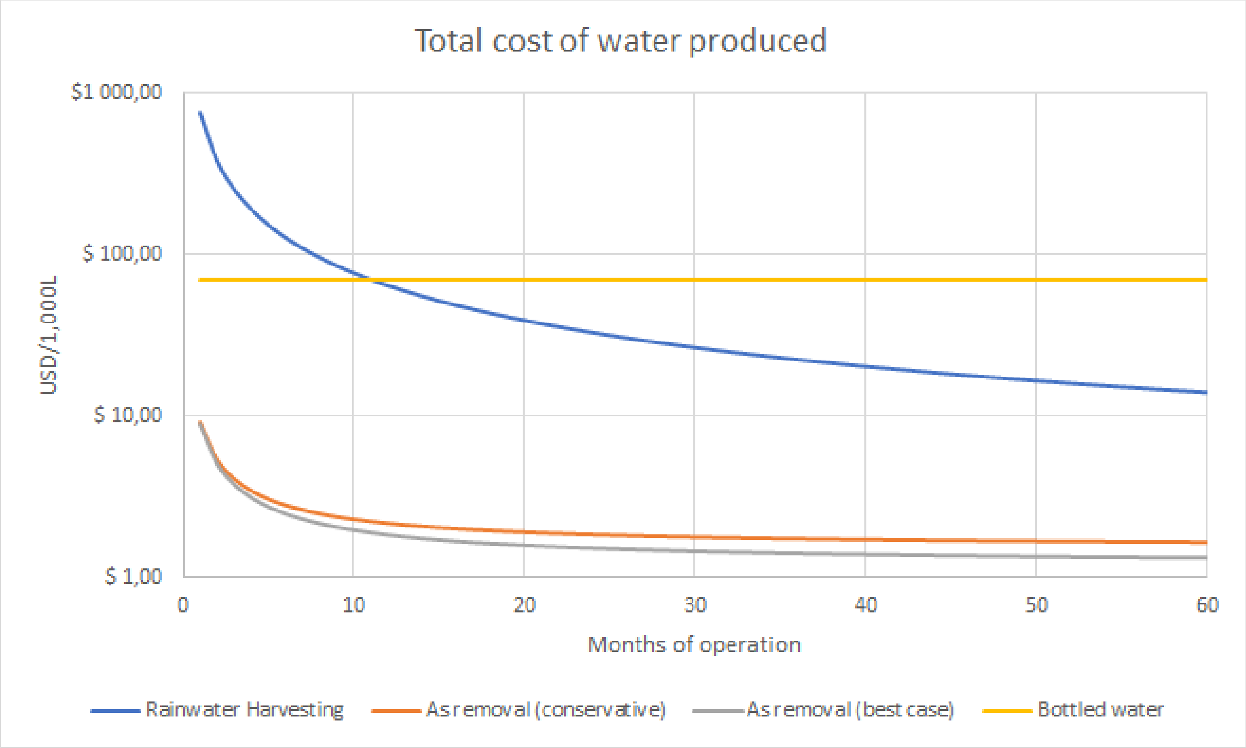


Figure 10: Cost of Water Produced, as a function of operation duration

The first conclusion is that domestic rainwater harvesting is globally more expensive than the arsenic removal system, even very long term. Short term, its cost per volume produced is much greater than the arsenic removal system, because of a higher initial cost and much lower production. It does not catch up with the conservative scenario over the lifetime of the cistern (which can be assumed to be 50-75 years). The scale of the groundwater treatment system also allows it to distribute its construction cost over the volume produced much more rapidly: it is within 20% of its long-term cost within 2 years, whereas that does not happen over the lifetime of the rainwater harvesting system.

The comparison is also a bit biased by the scale of the treatment system, which would be enough to produce water for 460 people (under the assumption that it is only used for drinking and cooking which requires 5L/day/person), which is probably on the large end of what Caminos would implement. In terms of cost however, rainwater harvesting systems at a domestic scale do not benefit from scaling-up (except maybe from buying the materials in large quantities).

Cost Reduction

For a given system and flow requirement, increasing the Bayoxide contactors volume could reduce the operational cost through three major expenses :

- Media cost: as mentioned above, increasing the contact time above the 4min of the system is likely to increase the sorption capacity, and hence reduce the overall media cost
- Analysis cost: in ‘operation’ mode, analyses are done when the unit is expected to reach breakthrough (unless there are regulatory monitoring requirements). Scaling the system would reduce the impact of the analysis cost. For example, doubling the volume of Bayoxide will at least double the cycle duration, and result in halving the analysis cost.
- Labor cost: less analysis and less frequent column changeouts will result in overall less labor requirements.

Increasing the volume of Bayoxide can be achieved by making the columns longer (which would only marginally increase the hardware cost), or by placing more columns in series. However, this might have some negative consequences in terms of the hydraulics of the system. The best approach would be to use a larger column (Caminos has been experimenting with columns with x4 the capacity, for about x3 the cost). This has the additional benefits of reducing the flow velocity within the column, making the column more resilient to fine particles. This would make the use of a larger size fraction possible, reducing or eliminating the loss due to the sieving, and thus reducing the media cost. Such a change could reasonably lower the price per 1,000L by at least 20%, which would pay the increase in column cost in about 3 or 4 months.

Even without changing the column size, some preliminary hydraulic tests show that intense backwashing (without additional sieving) might be enough to provide sufficient fine particles removal while having notably lower material losses. This approach would on its own reduce the media cost by a significant portion.

CONCLUSION

This pilot proved the very high potential of an adsorption system for arsenic removal to treat moderately contaminated groundwater in rural communities. The use of locally available materials makes the system easy to reproduce in other places, and keeps its initial cost to a reasonable level. In spite of non-optimal background conditions, resulting in an adsorption capacity in the range of 20-50% of what had been reported in other pilots, the system is able to treat arsenic for a total cost per liter of less than 5% of the price of bottled water, after only 4 months of operation and with a cost of about 2% of bottled water once construction costs have been absorbed. With appropriate training and support, community members can take care of basic operations and maintenance associated with a system such as this..

LESSONS LEARNED

- There are several design and operations improvements to be incorporated, especially regarding the necessity and ways to protect the system against outdoor conditions and algae growth.
- Even under reasonably challenging conditions, Bayoxide E33 can provide good arsenic adsorption on moderately-contaminated water. The adsorption capacity of about 40,000 BV allows for the treatment of large amounts of water with a very limited footprint, while maintaining a reasonably low changeout frequency (once per 4 months).
- Economically, the system compares very favorably with bottled water (5% of the cost within 4 months), and even with rainwater harvesting (20% of the cost after 10 years of operation), and can produce arsenic free water for a total cost of USD 1.5-1.8/1,000L (at two years of operation).
- The routine monitoring and operation can be performed by community members genuinely interested in the project, if provided with adequate training and support.

NEXT STEPS

Caminos is developing a new pilot which will provide a complete treatment train, including a fluoride removal step using Caminos' in-house manufactured cow bonechar, and produce potable water in compliance with Mexican regulations. This will prove much more challenging, both technically and from an economic point of view. The system will serve as a proof-of-concept of a groundwater treatment system on a small centralized scale. Implementation strategy, regulation requirements, and the viability of a regeneration process for the bonechar, which will be tested, will be significant towards project success.

Members of a community located by the spirulina farm, many of which are now familiar with the first pilot, have shown interest in being part of the second pilot project. They will be much more integrated in the project, not only supporting the operation, but also as end users of the system, being involved in the decision making processes. This work will be done in collaboration with Caminos' community outreach team, and will help the crafting of an implementation model which respects Caminos' core values of having community members being the main actors of the supported project. Finding ways to make groundwater treatment systems easily scalable, financially viable, and truly accepted by communities is the challenge Caminos aims to start tackling with the second pilot.

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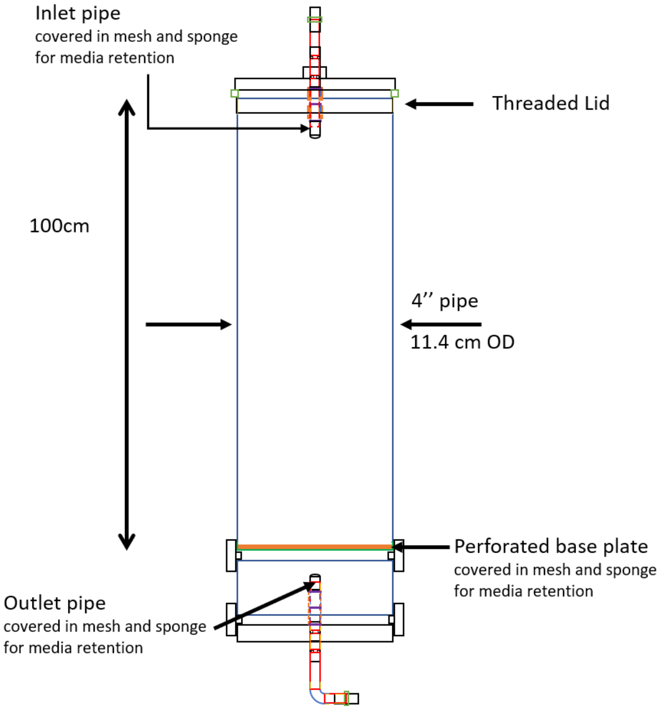
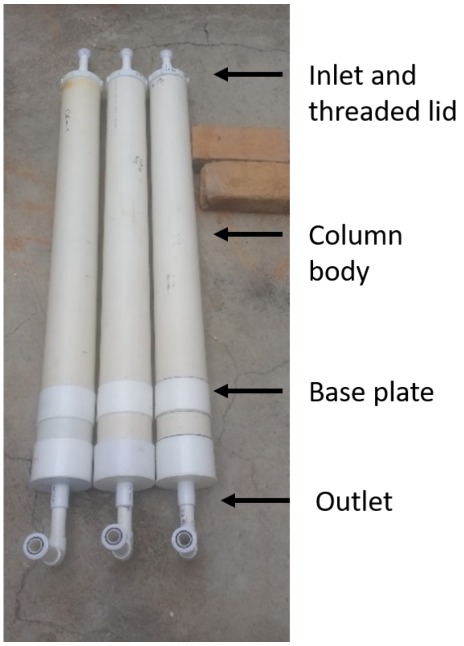
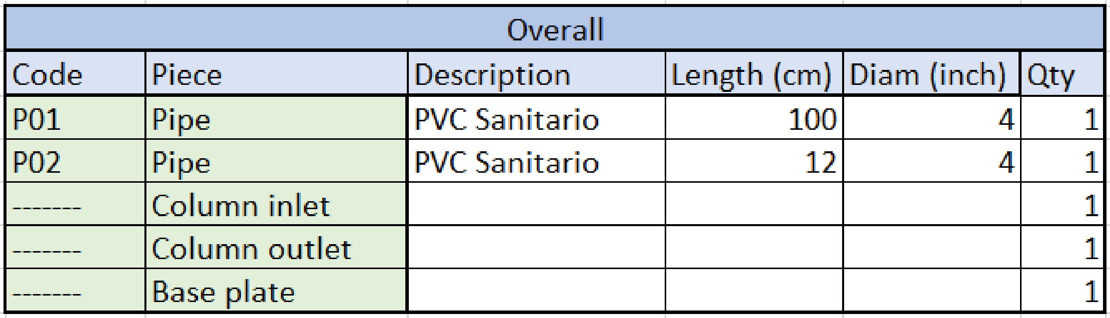
Appendix 1: Design of the Bayoxide Columns

The columns used in the pilot are made out of easily available PVC parts. They are made of an inlet which includes a threaded lid, a body of 4” sanitary PVC, a perforated base plate which acts as a support of the Bayoxide bed, and an outlet:

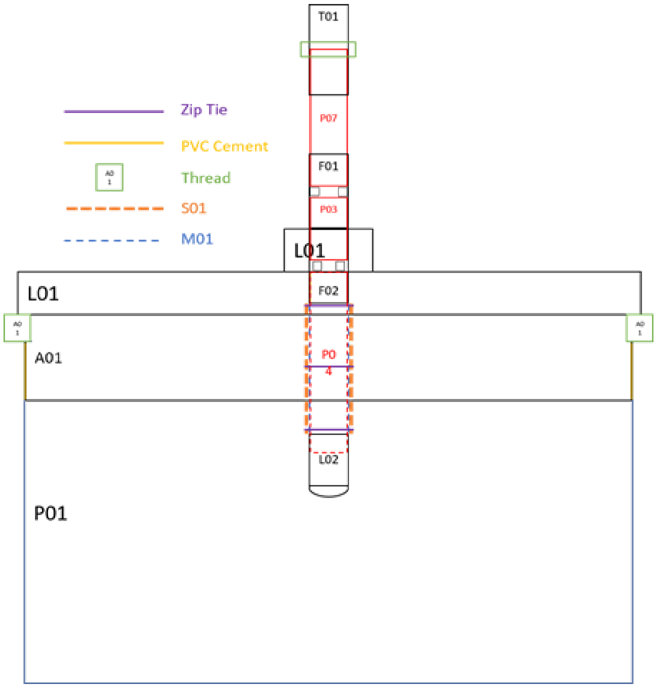






Overall					
Code	Piece	Description	Length (cm)	Diam (inch)	Qty
P01	Pipe	PVC Sanitario	100	4	1
P02	Pipe	PVC Sanitario	12	4	1
-------	Column inlet				1
-------	Column outlet				1
-------	Base plate				1

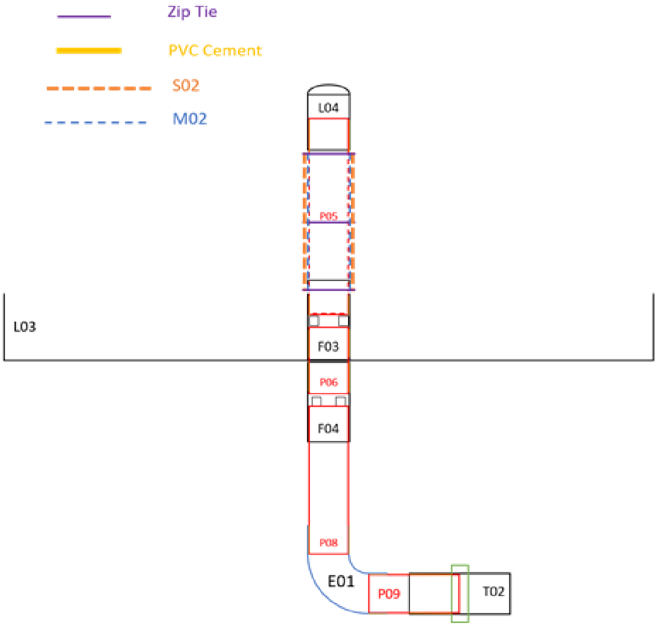
Column Inlet



Inlet					
Code	Piece	Description	Length (cm)	Diam (inch)	Qty
L01	Pipe threaded lid	PVC Sanitario (US)		4	1
A01	Female threaded adapt	PVC Sanitary (US)		4	1
F01, F02	Pipe fitting	PVC Sanitario		0,75	2
P03	Pipe	PVC Sanitario	4	0,75	1
P04	Pipe	PVC Sanitario	10,5	0,75	1
P07	Pipe	PVC Sanitario	7,5	0,75	1
L02	Pipe lid	PVC Sanitario		0,75	1
T01	Threaded join	PVC Sanitario		0,75	1
Z01, Z02, Z03	Zip Tie				3
M01	Glass fiber mesh		8*21		1
S01	Sponge (Pellon)		10*12		1

Parts List for Inlet

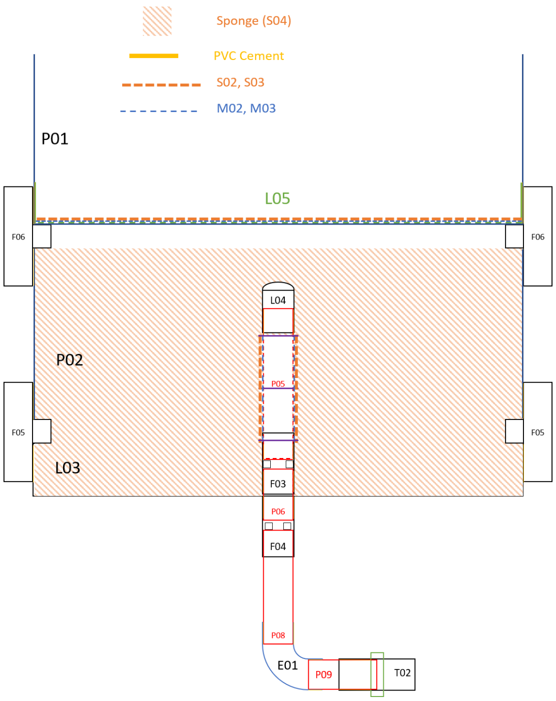
Column Outlet

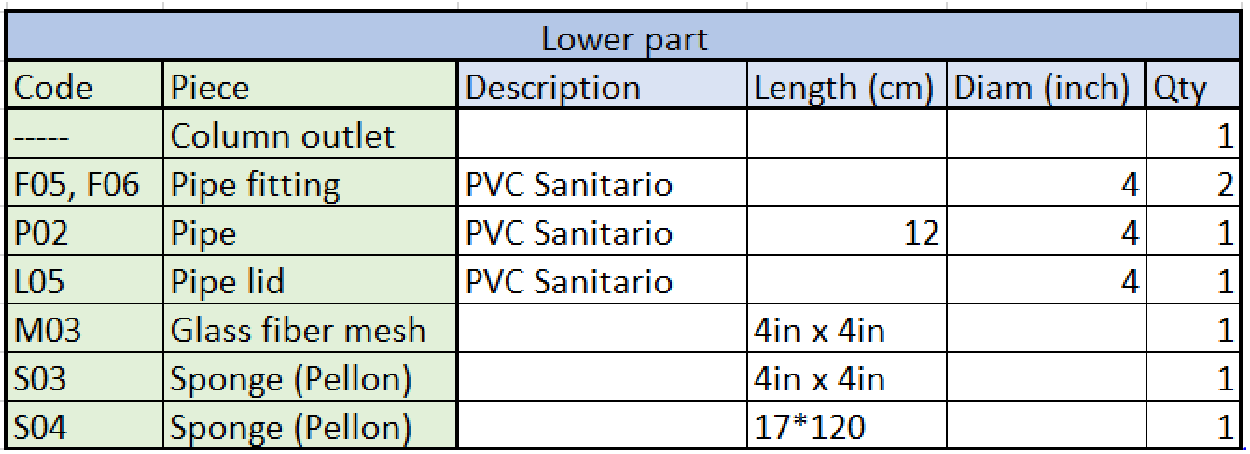


Outlet					
Code	Piece	Description	Length (cm)	Diam (inch)	Qty
L03	Pipe lid	PVC Sanitario		4	1
F03, F04	Pipe fitting	PVC Sanitario		0,75	2
P05	Pipe	PVC Sanitario	4	0,75	1
P06	Pipe	PVC Sanitario	10,5	0,75	1
P08	Pipe	PVC Sanitario	8	0,75	1
P09	Pipe	PVC Sanitario	10	0,75	1
E01	Elbow	PVC Sanitario		0,75	1
L04	Pipe lid	PVC Sanitario		0,75	1
T02	Threaded join	PVC Sanitario		0,75	1
Z04, Z05, Z06	Zip Tie				3
M02	Glass fiber mesh		8*21		1
S02	Sponge (Pellon)		10*12		1

Parts List for Outlet

Column Base Plate





Lower part					
Code	Piece	Description	Length (cm)	Diam (inch)	Qty
-----	Column outlet				1
F05, F06	Pipe fitting	PVC Sanitario		4	2
P02	Pipe	PVC Sanitario	12	4	1
L05	Pipe lid	PVC Sanitario		4	1
M03	Glass fiber mesh		4in x 4in		1
S03	Sponge (Pellon)		4in x 4in		1
S04	Sponge (Pellon)		17*120		1

Parts List Base Plate

Note: It appears that the sponge placed on top of the base plate is enough to keep the media in place. In that case, additional sponge layers S03 and S04, as well as several PVC pieces of the outlet would not be necessary.

Appendix 2: Layout of the System