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Induced Bank Filtration: Hydraulic Testing of Pilot Filters

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Abstract: Hydraulic tests were performed on two pilot scale filters as part of a water treatment project in the village of Nersa, Karnataka, India. The filters use locally sourced alluvial material to filter *E.coli* contamination using natural processes that mimic those in Riverbank Filtration (RBF). Two pilot scale filters were tested, one containing locally sourced granular activated carbon (GAC) and one without. A falling head test and tracer test were performed, and breakthrough curves were used to analyze the hydraulic performance. *E.coli* data were also collected, and percent removal was calculated to determine the effectiveness of the filters. Relative to the influent water, the *E.coli* removal percentage of Filter 1 (no GAC) was consistently high and ranged between 97.1% and 100% *E.coli*. The addition of GAC did not improve performance in this study. Overall, the effectiveness in bacteria removal observed in the non GAC filter warranted construction of a full-scale system.

1. Introduction

Rural villages across India, like in many other developing communities around the globe, struggle to access clean water and all too often, villagers are forced to drink water that is detrimental to their health [1]. A study of community water systems in the Western Ghats, India, showed that 80% of spring-fed water systems tested positive for *Escherichia coli* (*E.coli*) [2], i.e., bacteria known to cause diarrhea and other gastro-intestinal diseases. Because villages like the one studied herein typically lack the financial and technical resources to improve their drinking water quality, research in sustainable and replicable water treatment options can provide a framework for continued progress towards improving health in rural Indian villages.

One sustainable and replicable water treatment option that has been successfully applied for treating polluted water in South India and other places worldwide is Riverbank Filtration (RBF)[3]. This technology involves drilling one or more wells near a river or other surface water bodies, such as lakes or ponds, and then hydraulically pulling water through the alluvial or lacustrine bank sediments to attenuate contamination [4]. As polluted river water passes through these sediments, it is cleaned by a number of naturally occurring biological, physical, and chemical processes, such a predation of bacteria in a collimation layer at the contact of the river water and the sediment [5], as well as straining process [6] or chemical transformation reactions that take place during the passage of the water toward the RBF well(s) [7].



1.1 Induced Bank Filtration

The naturally occurring water filtration processes that make conventional RBF systems function were recreated in this project, but the flow was reversed. That is, surface water enters the alluvial sediments and flows through the layers forced by gravity instead of pumping. As such, we refer to this treatment approach as an *Induced Bank Filtration* (IBF). Similarly designed slow sand filters are not a novel idea and have been used throughout the world to treat water from household to city scales [8]. However, unlike most slow sand filters, the design of an IBF system is guided by the alluvial sedimentology of the local riverbanks. That is, in constructing an IBF, locally sourced alluvial material is used and layered to mimic local riverbank sedimentology as close as possible. The promise of this approach is three-fold: (1) the filter material can be inexpensively sourced locally in most locations, (2) the geologic composition of the filter material is identical to that of material coming in contact with local surface and groundwater, which ensures that the olfactory properties of the filtrate are very similar to traditional water sources. Specifically, the taste of water is an important consideration when supplying treated water to communities in India [9]. Finally, (3) beneficial bacterial communities that make up the culmination layer on top of the IBF are likely indifferent from those present in local rivers, i.e. the interplay of filter material mineralogy and water chemistry will not change to a great degree as it may happen when allochthonous material is used for filter construction. This property of IBF to support bacteria adapted to local conditions should ensure that naturally occurring biological filtration processes are as effective and sustainable as possible. We therefore hypothesize that these characteristics of IBF permit the construction of a comparatively inexpensive water treatment system that will produce water, which is acceptable, by taste, to the local community and which meets local drinking water standards.

2. Materials and Methods

2.1 Study Area

The study site is the village Nersa (population 300) located in southwestern India; specifically, the Khanapur Taluk of Belgaum District, Karnataka ($15^{\circ}36'00.26''\text{N}$, $74^{\circ}25'39.92''\text{E}$) [10]. The village lies on the eastern edge of the Western Ghats Mountain range which traverses north/south along the coast of India. Its elevation is about 700 m above sea level. The entire area is within the Krishna River basin. The climate is sub-tropical. The mean annual rainfall is 1,859 mm of which 72% occurs during the monsoon from June to September [11].

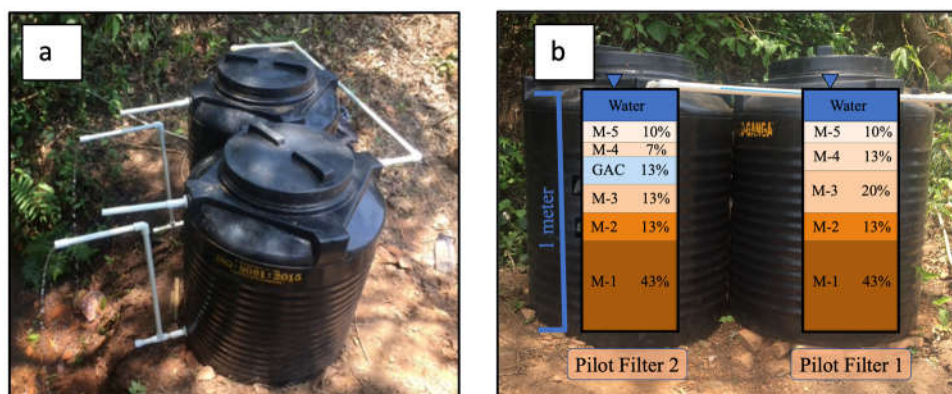


Figure 1. (a) Picture showing the two pilot filters constructed from 300 liter plastic water storage tanks. (b) Diagram showing the distribution of materials used for each of the filters. Materials ranged in particle size from gravel M-1) to fine sand (M-5).

The village's current water supply originates at a makeshift dam catching water from two rheocrine springs. The dam is roughly 10 m long and 1 m high, holding approximately 30 m³ of water. Each year this dam must be rebuilt after being destroyed by the monsoon floods. Spring water caught behind the dam flows into a 3" (7.6 cm) pipe which travels 3.5 km, with an elevation change of 30 m, to the village of Nersa where it terminates in an open channel of a few meters length before entering the main collection point named *Pharth*. This area holds significant spiritual significance for the villagers; certain customs and regulations govern the space. For example, shoes are to be removed upon approaching and while gathering water. During the dry season the flow at *Pharth* is around 50 L/min with fluctuations caused by rain events and damages or repairs to the pipeline.

2.2 Pilot Filter Testing

Two experimental pilot-scale IBF filters were constructed using 300 L plastic tanks: one containing a layer of locally sourced granular activated carbon (GAC) and one without GAC. The GAC was embedded between a layer of locally sourced fine sand on top and medium to coarse sand and gravel below. A 0.25" (0.64 cm) slotted PVC pipe served as underdrain. The outflow pipe rose to a height 2" (2.5 cm) above the topmost sand level to ensure that the filter material was permanently submerged and to support the formation of the biolayer on top of the sand layers. The filter was then connected to the village water supply.

In addition to periodic testing of the EC, pH, and temperature of the water flowing in and out of the proto-type IBF, a falling head test was performed to measure the filter's hydraulic conductivity (K). The test was carried out by blocking the tank outflow until the headwater rose 6 cm above the top sand layer. Then, the time was recorded for the headwater to return to the filter's normal operating water level while stopping all inflow. Hydraulic conductivity was calculated by using the formula $K=L/t * \ln(h_1/h_2)$ where L was the tank height, t was the time for the water to drop from height h₁ to h₂.

Further, a tracer test was conducted by adding a solution of table salt (sodium chloride, NaCl) to the filter and monitoring the effluent EC for 7.5 hours afterward. The tracer solution was prepared by mixing 125 g of sodium chloride and 1 L of water and adding that solution to the supernatant (approx. 35 liter) in each filter as a single dose. The effective initial concentration of the tracer solution was 3,550 mg/L. During the tracer test, the amount of water percolating through the filter was held constant at 300 ml/min, maintaining a constant head at all times. The tracer effluent concentrations were determined from a linear equation that related the EC to the salt concentration. The absolute salt concentrations were converted to a non-dimensional (C/C₀) concentration, where C₀ is the initial salt concentration and C is the concentration measure at a given time. Time was converted to a non-dimensional pore volume ($PV = Q t / A l n$) using the observed flow rate (Q), time (t), filter material bulk porosity (n) and the filter dimension area (A) and height (l). The mass of tracer recovered during the test (zeroth temporal moment, M⁰) was calculated from Eqn. 1 [12].

$$M^0 = \int_0^t C dt \quad (1)$$

Where C is the non-dimensional concentration. The travel time of the tracer was calculated from the adjusted first temporal moment (M_{adj}^1) [12].

$$M_{adj}^1 = \frac{\int_0^x Ct dt}{M_t^0} - \frac{1}{2} T_0 \quad (2)$$

Where T₀ is the injection time (here: 117 min). M_{adj}¹ is related to retardation factor (R) of the tracer via Eqn. 3:

$$R = \frac{M_{adj}^1 Q}{nV} \dots\dots\dots(3)$$

Where n is the bulk porosity of the filter material and V is its volume. The retardation factor for a conservative tracer, such as NaCl used herein, is expected to be $R=1.0$. Any deviation from that value indicates filter clogging issues when $R>1.0$ or preferential flow through the filter if $R<1.0$.

E.coli and Total Coliform samples were collected in 100 ml sterile plastic vials and stored in an ice cooled freezer box while being transported to Panjim, Goa, and analyzed by The Energy and Resources Institute (TERI) laboratory, a partner in this project. These samples were analyzed using the IDEXX method within 8 hours of collection [13].

3. Results and Discussions

Two proto-type IBF filters were constructed: one with a layer of granular activated carbon (GAC) added to the sand/gravel layers (Filter 2) and one without (Filter 1). The hydraulic conductivity (K) of both filters was similar ($K=0.12$ cm/s). The addition of GAC did not affect the pH which remained in the range of 5.2 to 6.7. However, Filter 2, with GAC, had initial EC values that exceed the natural background, reaching 120 μ S/cm for the first month. EC then decreased to the levels of *Pharth* and Filter 1. The tracer breakthrough curves (BTC) of the two pilot filters tracer tests are shown in *Figures 2 and 3*. Inspection of both BTCs reveals that the tracer was first detected at approximately 0.23 *PV* into the test and that full breakthrough occurred earlier than expected (i.e. between 0.4 and 0.6 *PV*). The cumulative NaCl tracer mass recovery (M^0) for Filters I and II were 70% and 83%, respectively. The travel time of the tracer (M^1_{adj}) was of 150 min for Filter 1 and 130 min for Filter 2. Finally, the retardation factor for Filters 1 and 2 were 0.83 and 0.78, respectively. These R values were lower than ideal ($R=1.0$), indicating the possibility of preferential flow conditions, particularly in Filter 2. However, this could also be due to incomplete mixing of the tracer slug with the supernatant water inside the filter, as indicated by the observed prolong tailing.

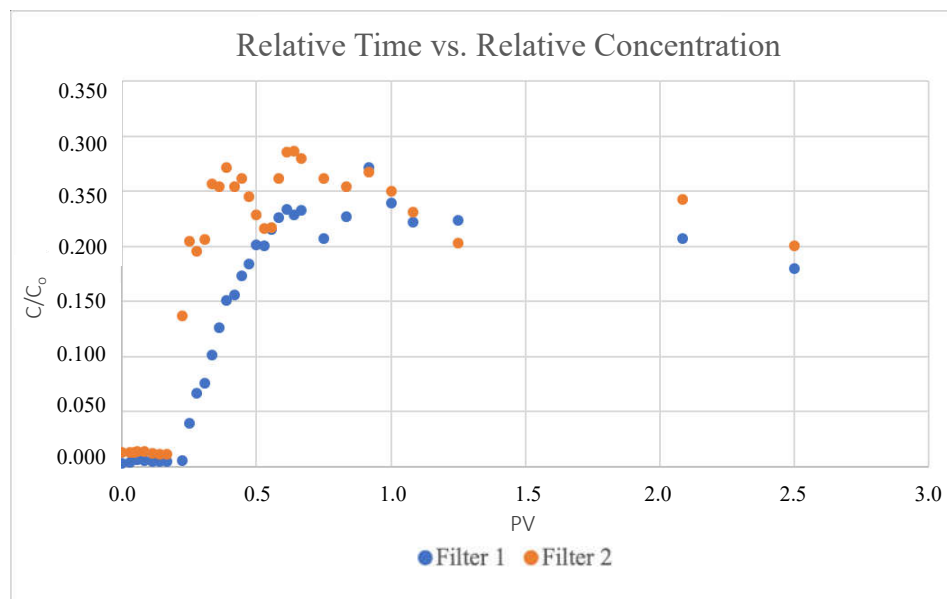


Figure 2. Relative time, expressed as pore volume (PV), plotted against relative concentration (C/C_0) for the two pilot filters.

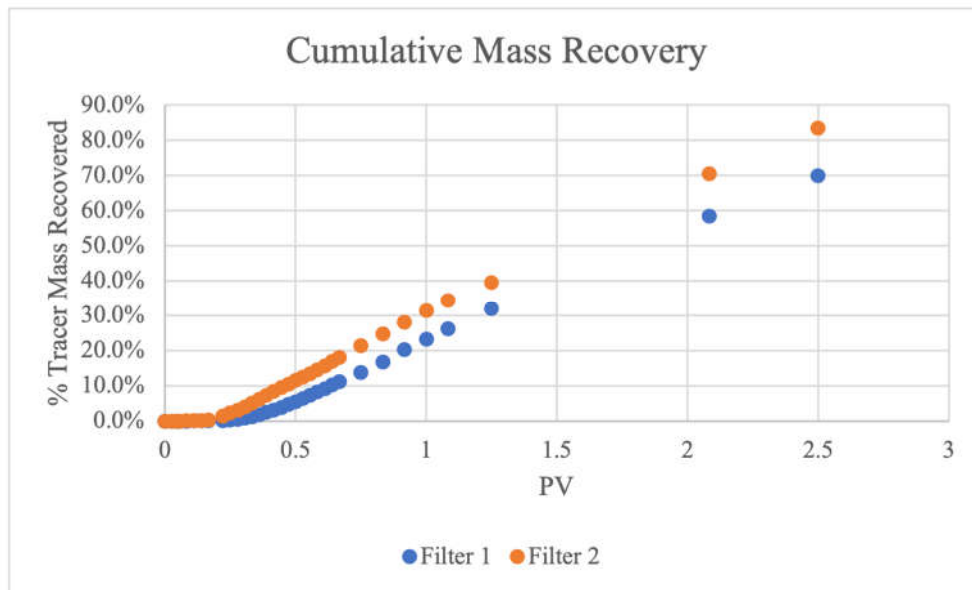


Figure 3. Cumulative mass of tracer recovered, calculated as a percent of the initial slug injection, plotted against *PV* for the two pilot filters.

Table 1: *E.coli* and Total Coliform counts in a 100ml sample. Both filters became active April 25th, 2019. Percentages indicate removal. Since the Filter 2 was disinfected on May 4th, the April data were excluded from calculating the averages.

		<i>E.coli</i> (MPN/100ml)			
Sampling Date	Pharth	Filter 1 (no GAC)		Filter 2 (with GAC)	
25-Apr-19	306.6	7.6	97.5%	516.6	-68.5%
29-Apr-19	765.2	9.9	98.7%	146.1	80.9%
18-Jun-19	40.9	0.0	100%	1.0	97.6%
25-Jul-19	68.4	2.0	97.1%	27.9	59.2%
Average			98.3%		78.4%
		Total Coliforms (MPN/100ml)			
Sampling Date	Pharth	Filter 1		Filter 2	
25-Apr-19	2185.5	2805.5	-28.3%	86640	-3864%
29-Apr-19	28510	4734	83.4%	34480	-20.9%
18-Jun-19	1119.5	8.8	99.2%	124.7	88.9%
25-Jul-19	355.7	12	96.6%	32.7	90.8%
Average			98.0%		89.8%

Relative to the influent water, the *E.coli* removal percentage of Filter 1 (no GAC) was consistently high and ranged between 97.1% and 100% *E.coli* (average removal was 98.3% or 1.78 log units; Table 1). Filter 1 appeared to be immediately effective, even without a fully matured biolayer. The performance

of Filter 2 (with GAC) varied over time, however. Initially, the filter contributed additional *E.coli*, presumably washed off the layer of activated carbon unique to this filter. Based on these results, Filter 2 was disinfected with sodium hypochlorite solution. After this treatment, the *E.coli* removal increased to 97.6% but then decreased again in subsequent measurements. Similar results were observed for Total Coliforms. The limited bacterial removal by the GAC may be due to its grain size which was much larger than the corresponding sand layer.

4. Conclusion

The hydraulics of both filters in terms of their hydraulic conductivity ($K=0.12$ cm/s) was close to the preferred range of 0.03 cm/s to 0.06cm/s [14] and in line with laboratory experiments described by others [15]. The moment analysis for both filters resulted in residence times exceeding 2 hrs (i.e. 190 min for Filter 1 and 140 min for Filter 2). This is comfortably above the suggested 1 hr minimum retention time for slow sand filters [16]. The inspection of both BTCs revealed that full NaCl tracer breakthrough occurred earlier than the expected, i.e. R ranged from 0.78 to 0.83, indicating possible preferential flow conditions. More importantly, the filter with no GAC (Filter 1) proved more effective in removing bacteria than the one with a GAC layer sandwiched between the sand/gravel filter material (Filter 2). In fact, the GAC layer in Filter 2 likely was a source of bacteria contamination, requiring disinfection. This assessment is further supported by the EC measurements, which were initially higher than in the influent, indicating that the activated carbon likely leached solutes into the water. Together, the results suggest that there is no apparent value in adding this particular, locally sourced GAC material to the filter system. A full-scale system was therefore constructed, without GAC, and modeled off of the design of Filter 1. The results of this field test are analyzed currently.

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