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REVERSE BANK FILTRATION FOR CLEANING WATER IN A REMOTE VILLAGE IN SOUTH INDIA

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REVERSE BANK FILTRATION
FOR CLEANING WATER IN A
REMOTE VILLAGE IN SOUTH INDIA

BY
MILES SCHELLING

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
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MASTER THESIS
OF
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ABSTRACT

This study sought to remove *E.coli* and Total Coliform bacteria contamination from the village water supply in Nersa, Karnataka, India by using a reverse bank filter (BF). Reverse bank filtration uses natural processes to clean water, including filtration through layers of sand and gravel and a bioactive layer, known as collimation layer or Schmutzdecke, that forms on top of the filter. The origin of the village water supply is a mountain spring. After initial testing of water quality in the village and an exploration of alluvial deposits suitable for filter construction, two pilot filters were constructed in 300 L plastic tanks. The hydraulic properties of these experimental filters were tested by conducting a conservative tracer test and the using the method of moments to determine filter properties, such as pore volume and residence time. Additionally, the filters ability to remove bacteria and the benefit of adding granular activated carbon (GAC) were evaluated. The test results indicate that local alluvial deposits are suitable for filter construction and that bacteria removal is not improved by the addition of this type of GAC. A full-scale filter system was then constructed including a flow regulating tank, gravel ascending flow pre-filter, and BF filter (5 m by 7 m by 2 m). Although limited data exists, this system successfully reduced turbidity and *E.coli*. Replication of a BF filter technology in the larger study area requires locating other spring fed rivers. Precipitation and air temperature data combined with normalized distribution vegetation index (NDVI) was used in an exploratory analysis of spring locations in the context of a digital elevation model. This study showed that reverse bank filtration can be part of a clean and affordable water supply system for rural villages in mountainous terrain in India.

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INTRODUCTION

Study background:

Rural villages across India struggle to access clean water and villagers are forced to drink water that is detrimental to their health (Bandyopadhyay, 2016). 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*) (Naik, 2006). This includes the study location, a rural village called Nersa, Karnataka, which is one of many villages in this mountainous region of India that rely on polluted spring water for drinking and household use. The spring water in Nersa is polluted with *E.coli* bacteria which causes negative health effects for the villagers. Because these villages typically lack the financial and technical resources to improve their drinking water quality, research in sustainable and replicable water treatment options provides a framework for continued progress towards improving health in rural Indian villages.

In addition to water pollution, climate change will impact the region's water resources. It is predicted that the region's mean temperature will increase and that precipitation events will be more intense with more dry days in between (Pujari, 2013). In 20 years, about 60 percent of all of India's aquifers will be critically degraded (Schiermeir, 2014). It is therefore essential to investigate the use of springs as a water source that, unlike bore wells, will not deplete aquifer storage.

Understanding the response of springs to changing climate is essential in order to understand the long-term reliability of these resources. Besides its focus on water quality improvement, this project aims to develop a method for identifying untapped springs and contribute to understanding the reliability of springs in a changing climate.

Initiative for this project started in 2017, when I first visited the village of Nersa. It was apparent from talking with local villagers that water quality was negatively affecting their health and causing issues such as diarrhea, especially during the rainy season. The village of 300 people has tried solutions, such as a government supplied reverse osmosis (RO) plant, which quickly became inactive due to a lack of professional maintenance (Census Organization of India, 2011). Various defunct concrete dams and holding tanks can be found covered in vegetation surrounding the village. According to the locals, some of these structures date back to the British Colonial era.

One of the remediation measures that have been successfully applied for treating polluted water in South India is River Bank Filtration (RBF) (Boving, 2017). This process involves drilling one or more wells near a river and hydraulically pulling water through the alluvial bank sediments to attenuate contamination (Boving, 2018). As river water passes through the bank sediments it is naturally filtered (Unger, 2006). The RBF well pumps a mixture of river bank filtrate and groundwater (Unger, 2006). An important element of removing pollutants is the Schmutzdecke (collimation layer), a highly active biological layer that naturally forms at the bottom of rivers (Gutiérrez et al., 2017). Periodic scouring during flood events naturally regenerates the treatment activity of this layer (Gupta et al. 2009).

This project uses similar natural processes to clean the water but does so with a passive, gravity fed system that mimics the natural flow of water through alluvial sediments. As such, I refer to this treatment approach as a *Bank Filter* (BF). Similarly designed biosand filters are not a novel idea and have been used throughout the world to treat water from household to city scales (Basit, 1986). However, biosand or BF filters are new to Nersa

and present a novel water treatment technology to the residents. Besides installing the first BF filter, the originality of my proposed project is that it is the first study which systematically (1) investigates the current, pre-intervention water supply conditions (by water quantity and quality) and compares it to post-intervention research, (2) maps sources of local, alluvial sand and gravel deposits needed for filter construction, and (3) tests competing filter designs (with/without added layer of activated carbon) at the pilot scale before designing and constructing a full-sized filter. In addition, studies of climate change and its potential impact on natural springs in the Western Ghats are lacking. Addressing this knowledge gap, I have investigated if local spring occurrence can be identified from digital elevation models and vegetation indexes linked to analyzing long term precipitation records.

I hypothesize that a BF filter can be built at low cost using locally available materials and resources and that such a filter will reduce the levels of *E.coli* and Total Coliform bacteria in the village water supply by at least 99.9% (or 3 Log units). Two types of filters (with/without activated carbon layer) will be tested at the pilot scale before constructing the actual BF. The quantifiable measures for those outcomes will be water quality data obtained from (1) an U.S. EPA - approved method to quantify *E.coli* and Total Coliform bacteria, known as IDEXX and (2) periodic field-testing of turbidity as well as inorganic (e.g. major ions) and organic (e.g. pesticides) parameters. This project will add to the knowledge base of affordable water treatment techniques in developing nations. A well-documented scientific investigation of the hydrology, sedimentology, and water quality of a village scale sand filter will provide valuable information for future water development projects in this part of India.

Sand Filter History:

John Glibb is attributed with constructing the first sand filter in London in 1804, and in 1829, James Simpson built the first community scale sand filter (WHO, 1974). By 1852, the Metropolis Water Act required all water from the River Thames to be filtered (WHO, 1974). The industrial revolution brought about great advances in sand filter technology and use. In 1990, Dr. Eric Mantz at the University of Calgary, Canada developed an alteration of the slow sand filter used on the household scale, which he termed the biosand filter (Center for Affordable Water and Sanitation Technology [CAWST], 2009). With the introduction of the underdrain pipe, this design allowed for water to be treated in batches, instead of continuously flowing (Earwaker, 2006). Mantz also added a diffuser plate so that input water would not disturb the biolayer on top of the filter (Earwaker, 2006). The Center for Affordable Water and Sanitation Technology (CAWST) distributed this technology worldwide but the sand used as filter media often had to be imported because of either lacking local resources or insufficient information about locally available filter materials. By June 2009, CAWST implemented 200,000 biosand filters in over 70 countries (CAWST, 2009).

Slow sand filters have been shown to remove bacteria by 87.9% to 98.5% (Earwaker 2006; Duke & Baker 2005; Visscher 1990; Saravanan & Rivindran, 2015) and 99.5% removal of bacteria was reported in laboratory studies (Lee, 2001). Turbidity, an indicator of other contaminants, can be reduced by 95% (Saravanan & Rivindran, 2015) and to below 1 Nephelometric Turbidity Unit (NTU) (Visscher, 1990). The World Health Organization (WHO) has noted slow sand filtration to be an economic and successful drinking water treatment method for rural areas (WHO, 2002).

Sand Filter Mechanisms:

The mechanisms of sand filters are similar to those of RBF systems in that they rely on natural filtration processes as well as a Schmutzdecke (Unger, 2006). They act as a contained system and, unlike an RBF well, can be either pressure or gravity fed.

Rapid sand filters can filter water 20 to 100 times faster than slow sand filters and require less space but the maintenance needs are much higher with some needing to be cleaned every few hours (WHO, 1974; Howe, 2012). For this project, a slow, gravity fed system was a clear choice because of the availability of space and gravity fed water.

Slow sand filters remove contaminants through physical, biochemical, and biological means. Water enters the filter box from the top and is allowed to sit in a supernatant layer before percolating through layers of sand and gravel. The water then passes through an underdrain system of slotted pipes. Underdrains are ideally evenly spaced to ensure a relatively even percolation rate across the filter. A Schmutzdecke forms at the surface of the topmost sand layer and is a crucial element of the filtration process (Ranjan, 2018). A typical mature biolayer extends about 1.3 cm into the sand bed (Lynn, 2013). Upon exiting the filter, water passes over a weir before being sent to distribution. In my system instead of an outlet weir the outflow pipe simply rises to above the level of the sand and has an air valve rising from this location. An outlet water level control mechanism is necessary to preserve the biolayer and ensure the headwater does not drop below the topmost layers of sand (WHO, 1974; Ranjam & Prem, 2018). Such a mechanism also prevents a vacuum forming when water is draining away from the pores directly below the biolayer; a vacuum would suck the biofilm into the pores, thereby clogging the filter (WHO, 1974).

The sand bed of a slow sand filter is typically 0.6 to 1.2 m thick and the supernatant water is 1 to 1.15 m in depth. Typical flow rates through these filters range from 0.1 to 0.4 m³/m²/hr (WHO, 1974; Visscher, 1990). The sand comprising the majority of the filter media generally ranges from 0.15 to 0.30 mm in diameter (Visscher, 1990; Ranjam & Prem, 2018). The filter box is often made of concrete, but it is also possible to use natural earth berms, plastic or metal materials (Marrón, 1999). The inner walls of the filter box in the section containing the filtration bed must have a rough finish to prevent the formation of short-circuits where water will take a direct path (“preferential flow”) along the edge of the filter without percolating through the sand grains (Marrón, 1999). Sand filters can be augmented with layers of additional material, such as activated carbon, charcoal, zeolites, and silver nitrate impregnated materials that further enhance their performance (John et al., 2017; Saravanan & Rivindran, 2015).

The mechanisms of filtration in a sand filter extend beyond straining of particles too large (approximately 0.155 times the sand grain diameter WHO (1974)), to fit through the pore spaces (Howe, 2012). Straining occurs only in the topmost layers of sand and the biolayer and forms a caked layer at the very surface of the filter that can aid in filtration but will also create resistance and cause head loss (Howe, 2012). Particles much smaller than those caught by straining are attenuated through sedimentation, diffusion, sorption, electrostatic and electrokinetic interactions with the filter matrix (WHO, 1974).

The Schmutzdecke is an essential component of a slow sand filter. In slow rate sand filters most of the bacteria removal will occur in this biolayer (Unger, 2006), which is formed by microbes in the raw water (Ranjam & Prem, 2018). It takes an approximately two-week ripening period for this layer to form before optimal performance is achieved

(Elliot et al., 2008). Inside the biolayer, organic matter present in the raw water is gradually broken down and converted into water, CO₂ and relatively inoffensive inorganic salts, such as sulphates, nitrates, and phosphates (Ranjam & Prem, 2018). The bioactive microorganisms are benign but predate on harmful bacteria (Unger, 2006) and excrete toxins that kill other bacteria (Ranjam & Prem, 2018).

Sand Filter Operation:

The flow rate through a sand filter can either be controlled at the inlet or outlet. For outlet-controlled systems, clogging of the filter will increase resistance, continuously lowering the hydraulic conductivity and flow rate (Visscher, 1990). Because of this, an adjustable weir must be installed such that an operator can increase the flow rate daily (Visscher, 1990). I chose to use an inlet-controlled system which requires less operation tasks. For inlet-controlled systems, the headwater will raise due to clogging until it overflows, at which point the filter must be cleaned (Visscher, 1990).

Sand Filter Maintenance:

Filters must be maintained to remove the accumulated matter both caked on the top of the sand and dispersed throughout the pores. Buildup of suspended particles and biomass causes clogging in the filter which reduces the hydraulic conductivity. This reduction of hydraulic conductivity is most severe in the top 1 cm of sand where straining catches large particles. Clogging can cause a 95-99% reduction in hydraulic conductivity through the filter (Bouwer, 2000).

Filters are maintained either by scraping the top layer of sand, backwashing, or by systematically re-sanding, where sand is removed from the filter, thoroughly washed, and

returned to the filter (Cullen, 1985; Marrón, 1999; Visscher, 1990). Maintenance of smaller biosand filters, such as those distributed by CAWST, can be accomplished by agitating the biolayer and scooping the biofilm that becomes suspended in water (Kubare, 2010). Most filters in large treatment plants are rapid sand filters which are cleaned by backwashing every few hours or days.

For slow sand filters, scraping is performed every few months and re-sanding is only necessary every few years once the sand layer has been reduced to 0.5-0.6 m (Visscher, 1990). Scraping must be performed when a breakthrough occurs in turbidity due to particles that were attached to the filter media becoming detached and returning to the effluent water (Visscher, 1990). Clogging will increase the resistance and raise the supernatant water height to above the overflow level, often before a breakthrough in turbidity occurs (Visscher, 1990). Cleaning by scraping will destroy the Schmutzdecke and will require a few days to regenerate before optimal performance is resumed (Ranjam & Prem, 2018; Cullen, 1985). After re-sanding a longer regeneration period will be required (Cullen, 1985).

Sand filters are constructed such that the flow of water through the media is descending, ascending or flowing horizontally (Marrón, 1999). Ascending flow filters are easy to maintain because it is possible to backfill them with water gravity fed through the top of the filter (Marrón, 1999). Ascending flow designs will also reduce the threat of short circuiting (Marrón, 1999). Ascending flow filters cannot be cleaned by scraping and the Schmutzdecke is less effective because it will occur at the end of the filtration process. Also, effluent water on the surface must be protected from contamination.

I chose to use an ascending flow gravel pre-filter in order to reduce initial turbidity and

descending flow conditions for the main BF filter. A descending flow filter was chosen for the main filter because the filtered water can exit from the bottom and therefore has less chance of contamination. Because of the pre-filter, the main filter will require less maintenance.

Springs and Climate Change:

Both climate change and direct human impacts pose significant threats to water resources globally (Haddeland et al., 2013). In India, mean annual surface air temperatures have increased by 0.4 °C in the last century (Hingane et al., 1985). These increases in temperature will result in a redistribution of surface water due to changes in evapotranspiration and precipitation patterns (Waggoner, 1990). In the Western Ghats, climate change is predicted to increase mean temperatures and make precipitation more intense with more dry days in between (Pujari, 2013). Additionally, direct human impacts, such as land use change, may cause greater changes in water resources than changing climate (Taylor et al., 2012).

In the Western Ghats, termed “the water tower of peninsular India”, springs are the main discharge of groundwater (Pujari, 2013). Springs are an essential source of drinking and household water to many villages and is also used for irrigation (Naik, 1993). Further, springs serve important ecological roles, and often have spiritual significance (Buono et al., 2015; Naik, 1993). In the Western Ghats, which are known for their high biodiversity (Buono, 2015), these springs sustain the unique ecological system of the forest areas.

The Western Ghats feature many springs in the altitude range of 600 m to 1080 m (Naik, 1993). Most springs are on the eastern side of the mountain range, likely because the slope on the western side is too steep for proper infiltration - slopes of greater than 6%

are found to be unsuitable for spring locations (Naik, 1993). Springs typically occur when groundwater percolating through vesicular basalt encounters a compact basalt layer and is forced to move laterally until it emerges on the surface (Naik et al., 2002).

In the dense forests of the Western Ghats, springs are difficult to locate, access, and explore, and there is a distinct lack of direct field observations that can support a scientific assessment of their variability. Forests in the Western Ghats are highly susceptible to climate change impacts (Sukumar, 2008) and forest morphology has a strong impact on spring discharge (Hosseini et al., 2010). Springs interact in a symbiosis with the forests; they provide perennial sources of water to the plants and the plants in turn retain rainwater to replenish the springs. Therefore, I hypothesize that a change in spring flow will change the vegetation surrounding it. That change can be identified in remotely sensed data sets, such as natural vegetation index data (NVID).

Climate change and springs have been much less studied in the Western Ghats than in the nearby Himalaya mountains where climate impacts may be more immediate. In the Western Ghats, climate change is difficult to predict because of the thin geographic shape of the mountain range, stretching North/South along the Western coast, which makes this region hard to generalize with low-resolution predictions. Predictions from the 4X4 assessment of India for the 2030's indicate temperature in the Western Ghats is likely to rise by 1°C to 3°C (Pujari, 2013). While precipitation in the Western Ghats is projected to increase by between 4% to 25%, periods in between rain events are expected to become extended, causing more droughts (Pujari, 2013). Evapotranspiration is expected to decrease by up to 5%, likely because of increased runoff due to concentrated rain events (Pujari, 2013).

Springs in the Western Ghats are also at threat from anthropogenic factors, mostly direct impacts of deforestation but also erosion of topsoil, forest fires, and development activities (Buono et al., 2015; Naik 1993). Groundwater depletion due to irrigation can also decrease spring discharge (Giordano, 2009; Konikow, 2011). Seasonal springs have shown a particular susceptibility to human and climate disturbance (Agarwal et al., 2012).

Investigating the hydrology of a spring can lead to understanding the response of spring discharge to climate change (Cartwright & Johnson, 2018). *Figure 1* shows factors influencing the discharge of a spring. Based on Darcy's law, the spring discharge is determined by the change in the elevation of the water table. Precipitation will raise the water table, while increased temperature will cause more evapotranspiration and lower the water table. Changes in land use will also change the evapotranspiration rate and the rate of infiltration and therefore recharge. In some cases, springs may act as a refugia against climate variation, especially those originating from deep aquifers with long residence time (Tambe et al., 2012; Kresic & Bocconi, 2010).

Figure 1. Water budget of a springshed. After Hosseini et al. (2010).

The relation of spring discharge to precipitation patterns depends on several factors, including the travel time of water through the aquifer. In the Western Ghats, terrain physiography and orientation of basaltic flow units play a key role in dictating spring discharge (Naik, 2006). Depending upon the flow rate and size of the aquifer, spring discharge can follow year-long trends based on cumulative precipitation (Fiorillo et al., 2010). Springs with long aquifer residence time will show greater lag in discharge after rain events or cumulated average peaks (Solder et al., 2016). If the aquifer has a low gradient, even springs with long aquifer residence time will show variance due to changes in hydraulic head caused by droughts (Cartwright & Johnson, 2018). Variations in discharge can be influenced by even diurnal trends due to changes in evapotranspiration from daily temperature variation (Buono, 2015).

Geographic information system (GIS) examinations of the normalized difference vegetation index (NDVI), an indication of the amount of vegetation present, has been used to analyze spring locations by delineating surface moisture zones (SMZ) (Cartwright & Johnson, 2018). Springs will nurture a vegetated ecosystem directly downstream and the NDVI has been used to identify this, even when such observations are not possible with only a satellite image (Cartwright & Johnson, 2018).

My overall aim was to improve the village water supply and in doing so, improve the health and livelihood of the people living there. My detailed research and well-documented solution methodology will provide valuable structure and opportunity for other projects within the region and across the country.

METHODS

Study Area:

The study site is the village Nersa located in the Khanapur Taluk of Belgaum District, Karnataka (see *Figure 2*). The village is situated on the edge of the Bhimgad wildlife sanctuary in the Londa forest range. The village lies on the western edge of the Western Ghats mountain range which traverses north/south along the coast of India. The village is at an elevation of 700 m above sea level and has a mean annual rainfall of 1,859 mm of which is 72% occurring during the monsoon period from June to September (Government of India, 2007). Most of the springs in this region originate between massive and vesicular units of basalt (Naik, 1993).

Figure 2. Study site location. (Wikipedia)

The area around Nersa is classified as rugged terrain with bedrock of schist and basalt. The soil types are shallow to very deep black soils, red loamy soils, and lateritic soils (Government of India, Central Ground Water Board, 2007). Sugarcane is the dominant crop in Nersa although sorghum, maize, paddy, wheat, millet, grams, mustard, groundnut,

sunflower, cotton, and tobacco are also grown in this region (Government of India, Central Ground Water Board, 2007). The entire Khanapur taluk is within the Krishna river basin (Government of India, Central Ground Water Board, 2007). The major water bearing formations are gneiss, schists, limestones, sandstones, basalts and alluvium. In 2006 the depth to water level was 0.4 to 17.3 m before the monsoon and 0.3 to 17.3 m after the monsoon. Exploratory wells in the region yielded discharges from 0.02 to 7.58 L per second and drawdown ranged from 0.1 to 32.4 m with a transmissivity calculated as between 1 and 2,220 m²/day (Government of India, Central Ground Water Board, 2007).

Current Water Supply System:

The village's current water supply system originates at a makeshift dam blocking a small stream. This dam is constructed from sandbags placed behind wooden beams and metal poles that span the stream. The structure is roughly 10 m long and 1 m high, catching an approximate 30m³ of water. Each year this dam must be rebuilt after being destroyed by the monsoon. About 50 m above the dam are two rheocrine springs that feed the stream channel (Springer et al., 2008). The channel originates upstream past these springs but is dry during the pre-monsoon season. During the monsoon this channel is flooded, and it is therefore impossible to create a spring box to shelter and contain the springs.

Water caught behind the dam flows into an 8" (20.3 cm) PVC pipe which narrows to a 3" (7.6 cm) pipe after only 20 m. This pipe then 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* (pronounced "part" with the 'p' and 't' aspirated). 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* remains around 50 L/min with fluctuations caused by rain events and damages or repairs to the pipeline. Villagers complain that *Pharth* will often go dry during the months of April and May and they will have to gather water from agricultural open wells. Villagers gather to collect water mostly in the morning hours between 7am to 10am. This task is primarily completed by women. When collecting water for drinking they filter the water through a cotton cloth before collecting it in 12 L plastic buckets. This drinking water is stored in stainless steel 5 or 10-gallon holding tanks within each house. These tanks have stainless steel lids and stainless-steel cups are used to procure water for drinking. Some households boil water, especially during the monsoon or for elderly family members. A few families have household ceramic or charcoal filters. Water for other household uses, also collected from *Pharth*, is stored in plastic containers behind most houses.

Maintenance of the dam and pipeline are completed by volunteers within the village. If money is needed for small repairs, it is raised by the community with Ranjit Desai, the village leader, overseeing. The village municipality, the panchayat, takes no part in this water system but instead ensures that water is supplied to the village taps. Villagers choose to collect water from *Pharth* because of its religious significance, the cold temperature, the fact that it continuously flows (never held in a storage tank), and because they know it is cleaner than the tap water provided by the panchayat.

A reverse osmosis (RO) system was constructed in the village in 2005 by the panchayat. It was not maintained properly and quickly became inactive. While it was operational, villagers paid 2 rupees for 10 L of water. Only some families used the RO and many

complained that it had a bad, oily taste.

Initial Water Quality Testing:

Initial water testing on Feb 25th, 2019, included laboratory testing of water samples from various water sources including the main collection point *Pharth*, a tap located behind a randomly selected typical household of 5 people with water originating in a tank supplied with water pumped from a downstream location on the same stream which supplies *Pharth*. Other sampling locations included a low output spring, named *Nag Zhar*, located at lower elevation than the village and an agricultural bore well with water depth around 8 m (see *Figure 3*). While the spring and agricultural bore well do not represent legitimate drinking water sources within the village, they were included in my sampling to understand the local water quality from multiple sources. Samples were collected in 5 and 10 L plastic jugs and were sent to a commercial laboratory (VIMTA in Pune, Maharashtra) by car the same day. They were tested for parameters including major ions, heavy metals, parasites and pesticides (see SI for list of all parameters). Handheld devices were used to test for pH (Middons, digital pH meter), electrical conductivity/total dissolved solids (Sumgot, TDS meter), temperature as well as field test kits for nitrate, alkalinity, and phosphate (LaMotte, 2018). *E.coli* and Total Coliform samples were collected in 100 ml 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 (United States Environmental Protection Agency, 2010). The IDEXX method includes incubating samples with a nutrient indicator that will turn fluorescent in the presence of *E.coli* and Total Coliform bacteria. Samples are placed

in slotted trays and the occurrence of fluorescence is translated into bacteria counts.

Figure 3. Local Water Sources in Nersa. (Google Earth).

Local Alluvial Deposits:

In preparation for building the pilot scale and full-size filters, alluvial deposits were investigated and mapped. *Figure 4* shows sampling locations. These deposits could be a useful resource in creating sand filters within the region. Local knowledge was used to identify accessible areas along rivers nearby to Nersa including the Bandura, Malaprabha, and Mahadayi. Samples were taken from each location and analyzed using sieves. Samples were also analyzed for porosity by filling a 1 L container with sand and recording the volume of water needed to fill the pores in the container.

Figure 4. Sampling sites for alluvial deposits. Samples are numbered by sampling order. (Google Earth).

Pilot Filters:

Two experimental filters were constructed in 300 L plastic tanks, one containing a layer of granular activated carbon (GAC) and one without GAC. *Table 1* shows specifications of these filters. These filters were constructed with layers of locally sourced sand and gravel [see *Figure 5 (b)*] laid on top of a 0.25" (0.64 cm) slotted PVC pipe underdrain. *Table 2* shows the origins of these filter materials and *Figure 6* shows images of each material. The outflow pipe rose to a height 2" (2.5 cm) above the sand level to ensure the sand always remained submerged and the biolayer remained intact. The water flowing into and out of these tanks was periodically tested with the handheld devices and for bacteria.

Pilot Filter Specifications	
Total tank effective height (cm)	76
Circumference (cm)	223
Radius (cm)	35.5
Sectional area (cm)	3959
Volume (liters)	300
Drain height (cm)	4
Porosity	0.23

Table 1: Specifications of the pilot filters.

Figure 5 (a): Picture showing the two pilot filters. (b): Diagram showing the distribution of materials used for each of the pilot filters.

Material	Notes:
M-1	Crushed stone from construction site
M-2	From Bandura - sieved w/ large sieve and caught
M-3	From Bandura - sieved w/medium sieve and caught
M-4	From Bandura - sieved w/small sieve and caught
M-5	Sand from construction site
GAC	Granular activated carbon

Table 2: Notes on the origin of materials used for filters.

Figure 6: Sand and gravel materials used for filter construction.

A falling head test was performed to measure the hydraulic conductivity (K) of the filter. The test was carried out by blocking the tank outflow until the headwater rose 6 cm and then recording the time for the headwater to return to equilibrium 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 h_1 to h_2 .

A tracer test was conducted by adding a solution of table salt (sodium chloride, NaCl) to the filter and monitoring the effluent electrical conductivity (EC) for 7.5 hours afterward. The tracer stock solution was prepared by adding 500 g of sodium chloride to 4 L of water from Pharth. One liter of stock solution was added to the supernatant in each filter as a single dose. There was a 9 cm layer of water residing on top of the filter material. It was assumed that the tracer stock solution instantaneously mixed with the water inside the filter (approximately 35 liter), resulting in the dilution of the tracer stock solution to approximately 3,550 mg/L. The filters were running with a constant input of 300 ml/min during the tracer test and each maintained a constant head.

A standard curve was used to convert EC measurements to concentrations of NaCl . These concentrations were then converted to a non-dimensional (C/C_o) concentration. This non-dimensional concentration shows the effluent concentration as a ratio to the influent concentration and therefore permits a direct comparison of results from tests conducted at

different initial tracer concentrations. Time was also converted to a non-dimensional pore volume ($PV = Q t / A l n$) – the number of pore volumes that have been discharged through the filter – using the observed flow rate (Q), time (t), filter material bulk porosity (n) and the filter dimension area (A) and height (l). With these parameters, I was able to plot a breakthrough curve (BTC), i.e. a graph of (dimensionless) time versus concentration for each of the two filters. I calculated the zeroth temporal moment (the mass of tracer recovered during the test) using Eqn. 1:

$$M^0 = \int_0^t C dt$$

Eqn.1

where M^0 is the zeroth temporal moment and C is the non-dimensional concentration (Boving et al., 2017).

I calculated the first temporal moment (the time required to recover half of the tracer mass injected) using Eqn. 2:

$$M^1 = \frac{\int_0^t C Q t dt}{M^0}$$

Eqn.2

where M^1 is the first temporal moment, and Q is the flow rate at time t (Boving et al., 2017). Finally, I calculated the adjusted first temporal moment by subtracting half of the injection time (T_0) from the first temporal moment.

$$M_{adj}^1 = \frac{\int_0^t C Q t dt}{M^0} - \frac{1}{2} T_0$$

Eqn.3

The adjusted first temporal moment is also referred to as the travel time of the tracer. It can be related to retardation factor (R) of the tracer via Eqn. 4:

$$R = \frac{M_{adj}^1 Q}{n V} \quad \text{Eqn.4}$$

where n is the bulk porosity of the filter material and V is its volume. The R for a conservative tracer, such as NaCl, is expected to be 1.0. Any deviation from that value might indicate preferential flow through the filter ($R < 1.0$) or filter clogging issues when $R > 1.0$.

Bank Filter System:

The full-scale filter system consists of a flow regulating tank, a gravel ascending flow pre-filter, and a large BF filter (see *Figure 7*). In preparation of the tank construction, an excavator leveled the ground in a 100 m² area such that the regulating tank and pre-filter can sit 3" (7.6 cm) above the large filter tank.

Figure 7: Picture of filter system. A diagram was painted on the filter wall giving a simple explanation of the system in both English and Marathi, the local language.

The main BF filter consists of a 5 m by 7 m by 2 m reinforced concrete structure with an open top (see *Figure 8*). A 46 cm deep footing was dug by hand and large rocks were laid in the footing to prevent roots from damaging the structure. The filter was constructed with rebar and concrete and has 6” (15.2 cm) thick walls. A sealant was used to prevent leakage. The floor of the tank gently slopes to a 2.5” (6.4 cm) thick PVC drainpipe which exits the filter from the back side. A valve along this outflow pipe remains closed and is buried for tamper proofing. The underdrain system was constructed of 2” (5.1 cm) unplasticized polyvinyl chloride (UPVC) pipe with 10 mm holes drilled every 5.1 cm along the bottom of each pipe. The underdrain was placed on bricks 6.5 cm above the bottom of the tank. The top of the tank is covered by a plastic mesh supported by nylon ropes which span the structure.

Figure 8. The BF filter consists of a concrete structure of dimensions 5 m by 7 m by 2 m filled with layers of gravel and sand. Percent composition of material by volume is shown.

Sand and gravel used in constructing the filter was collected from a nearby alluvial deposit along a small river named Bandura. This source was determined a best fit during field investigations in 2019 where sieve tests and hydraulic conductivity were investigated. Raw alluvial medium was sieved using three sieves; see *Table 3* for sieve specifications. A sieve test was performed by taking 0.15 kg of each sample and shaking this sample vigorously through the sieves for 3 min. The volume retained on each sieve was recorded and the percent by weight was calculated assuming each material had roughly equivalent density.

Sieve Specifications			
	BSS NO.	ASTM No.	Microns
Sieve 1	5	6	3359
Sieve 2	25	30	600
Sieve 3	60	60	250

Table 3: Properties of the sieves used to analyze alluvial deposits.

The separated sand was then washed in the nearby river. Washing was accomplished by collecting the sand in a plastic fine mesh (holes less than 0.5 mm) with a laborer holding each end and then submerging the sand while vigorously shaking back and forth. Grass and other debris were allowed to float away while the shaking motion caused most of the fine dirt to be carried away by the flowing water. The cleaned sand was then loaded onto a tractor trailer and transported to the filter site. The sand was loaded by hand into the filter with the larger sized gravel going first and fully covering the underdrain. Care was taken not to damage the PVC underdrain pipes. Each layer was raked flat before adding the following layers.

Figure 9: Map of the filter area including a diagram of the flow diverter constructed from a 300 L tank. From that location, water flow is diverted to the Pharth (blue) and the BF filter system (orange). (From GoogleEarth)

A 1" (2.5 cm) filter pipeline supplies water to the filter system (see Figure 9). It originates 100 m uphill from a flow diverter tank (300 l). This plastic tank is fed by the

pre-existing 3" (7.6 cm) *main pipeline*. Any water not diverted to the BF system flows to Pharth. Preserving some flow of unfiltered water to the *Pharth* was considered important because of the spiritual significance of the traditional water systems. The *filter pipeline*, installed in 2020, is buried 0.5 m deep to protect it from damage by wild pigs or fire.

Figure 10. The filtration system consists of a flow regulator tank, ascending flow gravel pre-filter and descending flow BF filter. During normal operation, valve V1 is partially closed and valves V2, V3, and V4 remain fully closed. A1 and A2 represent airlocks.

Figure 10 shows a diagram of the filter system. Water first enters the 300 L *flow regulator tank*, which is placed on a 0.75 m concrete cylinder to enable gravity flow (total difference in head: 2 m). Inflow first passes through a plastic mesh screen to remove coarse debris, such as leaves. The top of the tank can be opened, and debris can be removed by hand. Water entering the tank is diverted to a flow to the BF system. Excess flow is returned to the Pharth. The overflow pipe level is located 8 cm above the outflow pipe thereby ensuring that the BF filter will preferentially receive water should water inflow diminish during parts of the year. Because the pipeline exiting the *flow*

regulator tank is only 1" (2.5 cm) in diameter, flow is limited and the head in the tank is maintained at a level of the main pipe during normal operation thus ensuring a constant flow rate.

Water from the *flow regulator* tank enters the gravel-filled pre-filter tank from the bottom through a 1" (2.5 cm) UPVC pipe with 5 mm holes drilled every inch, resulting in ascending flow conditions. Pre-filters or roughing filters have been shown to save the lifespan of the main filter and also will significantly contribute to bacteria removal during the ripening period before the biolayer forms on the main filter (Cleary, 2005).

Continuous and even flow through the filter is preferred because this will create a consistent environment for the biolayer to form (Visscher, 1990; Marrón, 1999). The flow rate is regulated by valve *V1* to ensure that head is maintained in the flow regulating tank (Figure 11). The pre-filter consists of a 1000 L plastic tank filled with medium sized gravel (Material M-4; *Table 4*). Water ascends through the filter media and then drains via a 1" (2.5 cm) UPVC pipe leading from the top of the pre-filter and into the large BF filter. While a biolayer does form at the top of the pre-filter, it is likely discontinuous due to the large gravel size. Airlock *A1* stops air from entering the pre-filter and disturbing the biolayer.

The pre-filter can be backwashed by opening valve *V2* along a 1.5" (3.8 cm) UPVC pipe allowing water to flow directly from the flow regulating tank into the top of the pre-filter. The 1.5" (3.8 cm) UPVC drain of the pre-filter can then be opened with valve *V3* to allow backwash water to flow away from the system. Valve *V4* can be opened to allow for sampling of the water filtered exclusively by the pre-filter.

Water is gravity fed from the pre-filter to the *BF filter*. Inflow to the BF passes through a diffuser consisting of a horizontal pipe with 5 mm holes drilled every inch. The diffuser reduces disturbances of the biolayer that forms on top of the BF. Water exits the system through the underdrain and then rises through a 1" (2.5 cm) UPVC pipe to a height 8 cm above the sand layer. This ensures that the sand in the tank is always submerged even if influent water were to be cut off. Because of the resistance of the filter, the water height in the tank during normal operation is always higher than this outflow pipe. As resistance builds due to clogging and development of the biolayer, the supernatant water height rises. When the supernatant water has risen such that it is flowing out of the overflow pipe, then the filter will need to be cleaned by scrapping. A dipstick can be used to measure the water height in the tank and will be checked periodically. Note that the effluent flow rate will remain constant throughout this process until the overflow height is reached. Airlock *A2* ensures the tank does not drain from suction. The filtered water exiting the system travels 10 m through a buried 1" (2.5 cm) UPVC pipe to the distribution point where it continuously flows from a concrete distribution point located adjacent to the pre-existing Pharth structure (see *Figure 11*). The system was running at 6.7 L/min during the entire testing period.

Figure 11: Photo of distribution point. The filtered water flows through a 1" (2.5 cm) pipe in the foreground. In the background, the two pipes of water known as Pharth remain intact for all water uses besides drinking.

Water samples were collected at valve V4, i.e. before entering the BF filter, and from the filter effluent. EC and turbidity were measured with handheld devices and *E.coli* samples were sent to TERI laboratories in Panjim, Goa. Sampling had to be suspended in March, 2020 due to the coronavirus pandemic and subsequent lockdown.

Remotely Sensed Data:

True color satellite images and normalized difference vegetation index (NDVI) maps were obtained from Sentinel-2 Earth observation mission. A digital elevation model (DEM) was obtained from the shuttle radar topology mission (SRTM). Climate data (precipitation, temperature) was obtained from NASA's Atmospheric Infrared Sounder (AIRS) and Special Sensor Microwave/Imager (SSM/I) using the GES-DISC Interactive Online Visualization ANd aNalysis Infrastructure (Giovanni). Standardized Precipitation Index (SPI) was calculated over a 19 year span. Anomalies in surface air temperature

were plotted for the dry season in an attempt to understand the variability of water availability in this region.

BF System Cost:

In order to compare the cost of water produced by the BF system (USD/liter) with that of competing systems, such as RO, water delivered by tanker truck or bottled water, the cost of constructing the BF filter system were tracked by categories (e.g. material, equipment, labor). Only the actual cost of constructing the BF system was accounted for, excluding the on-time cost of the pilot-scale filter study and my cost (travel, housing etc.).

RESULTS

Initial Water Quality Testing

All four water sources (the main collection point (Pharth), a tap located behind a typical household with water originating in a tank supplied with water pumped from a nearby stream, a low output spring (*Nag Zhar*) located at lower elevation than the village, and an agricultural bore well) tested below detection limit for pesticides including: Chlorpyrifos, Methyl Parathion, Monocrotophos, Phorate, Imidocloprid, Bromodiolone, Fipronil, Aldrin/Dieldrin, Endosulfan (sum of Alpha, Beta, and Sulfate), and DDT (O,P and P,p isomers of DDT, DDD, DDE). All four water sources tested absent for parasites including *Giardia Lamblia* and *Cryptosporidium* spp. and no other parasites were found in a microscopic examination by VIMTA laboratories. Results for heavy metals were all non-detects besides 0.03mg/L Magnesium found in Pharth, 0.003mg/L Lithium in the spring water, and 0.006mg/L Lithium and 0.002mg/L Chromium found in the bore well. All results were far below Indian standards BIS IS: 10500 requirements (see Supporting Information).

The results of major ions testing by VIMTA laboratories, Pune, Maharashtra, were deemed invalid because the ion balance failed my quality control criterion (5% deviation). That is, because Magnesium, Sodium, and Potassium cations were reported as below testing limits for all four samples, the ion balance was negative. The reported absence of these major ions in natural waters is highly unlikely and must be an artifact of the laboratory analysis. Unfortunately, this data quality issue prevented the evaluation of major ion data in a Piper Diagram (SI *Figure 1*) and the chemical classification of the different water sources.

Initial testing for *E.coli* and Total coliform in water from the same four sources was conducted on February 25th, 2019 at TERI laboratories, in Panjim Goa. Results are shown in Table 4. Because samples were not diluted during the initial test, results for total coliforms were all above the detection limit of 2419 Most Probable Number (MPN)/100 ml.

Sample Name	<i>E.coli</i> (MPN/100 ml)	Total Coliform (MPN/100 ml)
Tap Behind House	117.8	>2419
<i>Pharth</i>	45.7	>2419
Nag Zhar Spring	167.4	>2419
Agricultural Bore Well	<1.0	>2419

Table 4: *E.coli* and Total Coliform detected in a 100 ml sample, sampled on February 25th, 2019.

Pharth Time Series:

Electrical conductivity (EC) data was collected from *Pharth* during 2019 (Fig. 12). I collected data in Nersa from February 2019 to May 2019 and Miss. Shweta Hawaldar, a local volunteer, continued data collection into the summer. Two short rain events occurred in March and April and these corresponded with peaks in EC. Precipitation data was obtained from rain gauges at a field station in Belgaum, 40km from Nersa. The monsoon began in June 2019 and brought about a low period in EC. The pH of water collected at *Pharth* varied over a narrow range from 5.1 to 5.5 and the temperature varied from 21.4 to 26.0 degrees Celsius during this testing period.

Figure 12: Electrical conductivity measured at Pharth during 2019. Precipitation from rain gauges at Belgaum Samba field station is also shown (NOAA National Climatic Data Center).

E.coli and total coliform data from Pharth in 2019 to 2020 [Figures 13 (a) and (b)] show that concentrations of both contaminants dropped during the monsoon (June to August) but reached a maximum soon after the end of the monsoon (October). *E.coli* reached 1,509 MPN/100 ml and total coliforms reached 61,300 MPN/100 ml. The two rain events in March and April also corresponded with higher bacteria contamination.

Figure 13 (a): Time series of *E. coli* and (b) Total coliform concentration from water collected at Pharth. Precipitation from rain gauges at Belgaum Sambra field station (NOAA National Climatic Data Center).

Alluvial Deposits:

I investigated whether local alluvial deposits were available and if they could be used for the construction of a BF water filter. Hence, the mapping and geotechnical evaluation of alluvial deposits was a part of this research project. Samples of alluvial deposits were collected at nine locations (*Figure 3*) and analyzed by sieving and by porosity testing.

Results of the analysis are shown in *Table 5* and *Table 6* respectively.

Sieve test				
Material	Sieve 1 (3.4 mm) (%)	Sieve 2 (0.6 mm) (%)	Sieve 3 (0.25 mm) (%)	Plate (%)
S-1	18	58	22	2
S-2	50	40	8	2
S-3	66	24	6	4
S-4	55	36	8	1
S-5	4	56	30	10
S-6	66	22	10	2
S-7	36	40	16	8
S-8	4	42	46	8
S-9	58	40	2	0

Table 5: Sieve analysis of alluvial sands. Percent by weight retained on each sieve is shown.

Porosity	
Material	Porosity (%)
S-1	30
S-2	26
S-3	46
S-4	32
S-5	38
S-6	34
S-7	30
S-8	38
S-9	36

Table 6: Porosity of alluvial deposits.

Filter Sand Material:

Locally sourced commercial sand and gravel was used for the pilot filters and for the pre-filter, respectively. The material for the BF filter all originated from an alluvial deposit along the nearby river Bandura (S-5) (See *Figure 3*). *Table 7* shows the sieve analysis of each material used. Note that all particles in material M-1 and M-2 were larger than the diameter of sieve 1 (3.4 mm). The porosity of each material and 50-50 mixtures of materials is shown in *Table 8*.

Material	Sieve 1 (3.4 mm) (%)	Sieve 2 (0.6 mm) (%)	Sieve 3 (0.25 mm) (%)	Plate (%)
M-1	100	0	0	0
M-2	100	0	0	0
M-3	59	49	1	7
M-4	0	0	0	0
M-5	0	0	0	0

Table 7: Sieve analysis of materials used in filters as percentage by weight retained on each sieve.

Material	Porosity (%)
M-1	44
M-2	46
M-3	44
M-4	39
M-5	37
GAC	50
M-1 and M-2	40
M-2 and M-3	38
M-3 and M-4	36
M-4 and M-5	34
GAC and M-3	40
GAC and M-4	30

Table 8: Porosity of each material and 50-50 mixtures.

Pilot Filters:

Hydraulic conductivity (K) was calculated from a falling head data test and both filters had values of $K=0.12$ cm/s. The filters did not affect the pH which remained in the range of 5.2 to 6.7. The tracer breakthrough curves (BTC) of the two pilot filter tracer tests are shown in *Figure 14* and *Figure 15*. Time was converted to Pore Volume (dimensionless time) and tracer concentrations data was converted into dimensionless concentration (C/C_o). This permitted plotting both data sets side-by-side on the same graph.

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 the expected (i.e. between 0.4 and 0.6 PV). Finally, the retardation factor (R) of the NaCl tracer was found to be lower than ideal ($R=1.0$), indicating the possibility of preferential flow conditions, particularly in filter II.

Figure 14. Relative time, expressed as pore volume (PV), plotted against relative concentration (C/C_o) for the two pilot filters.

Figure 15. Cumulative mass of tracer recovered, calculated as a percent of the initial slug injection, plotted against PV for the two pilot filters.

While this test was not run to a sufficient length for recovering all of the injected tracer mass, I was still able to calculate a tracer mass recovery from the zeroth temporal moment (M^0) for the duration of the test (450 minutes; see SI for data). M^0 was 87 g for Filter 1 and 104 g for Filter 2 or equivalent to 70% and 83% of the injected 125 g NaCl, respectively. The first temporal moment (= center of mass) was $M^I=209$ min and $M^I=189$ min for filters I and II, respectively. These values represent the time necessary for half of the tracer mass to pass through the filters. The adjusted first temporal moment (M^I_{adj}) is the travel time of the tracer and ideally coincides with the location of the inflection point on the leading limb of the BTC. M^I_{adj} can be viewed as the residence time of water in the filter. M^I_{adj} was of 150 min for Filter 1 and 130 min for Filter 2 with consideration to a tracer injection time of 117 min. The retardation factor for Filter 1 was calculated as 0.83 and for Filter 2 it was 0.78.

E.coli and total coliform results comparing the two filters are shown in *Tables 9*. Because water that bypasses the pilot filters travels directly to Pharth, *E.coli* values from Pharth are used to illustrate the influent water quality. Filter 1 showed that the *E.coli* contamination was reduced between 97.1% and 100%. Accounting for the variable inflow concentration, the average *E.coli* removal was 98.3% or 1.78 log units. The performance of Filter 2 varied over time. Initially, the filter contributed *E.coli*, presumably washed off the layer of activated carbon unique to this filter. Based on these results, the filter was disinfected with 100 grams of sodium hypochlorite on May 4th. Bacterial concentrations dropped after this treatment. Similar results were observed in case of the Total Coliforms.

	<i>E.coli</i> (MPN/100ml)				
Sampling Date	Pharth	Filter 1		Filter 2	
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%

Table 9: E.coli and Total Coliform counts in a 100ml sample. Percentages indicate removal. Since the Filter 2 was disinfected in May, the April data were excluded from calculating the averages.

A time series of EC for the pilot filters and Pharth is shown in *Figure 16*. Filter 2, with GAC, had initial high EC values reaching 120 $\mu\text{S}/\text{cm}$ for the first month and then fell to mimic the levels of Pharth and Filter 1. Similarly, low EC levels were recorded during the monsoon season.

Figure 16: Electrical conductivity for the two pilot filters and Pharth. Precipitation from rain gauges at Belgaum Sambra field station is also shown (NOAA National Climatic Data Center).

Turbidity and EC results from the full-scale system are shown in *Figure 18* and *Figure 19*. The turbidity in the pre-filter water (*Figure 17*) remained consistently at detection limit, i.e. lower than the *Pharth* measurements, which were as high as 4.5 NTU on March 18th. Afterward, the turbidity in the *Pharth* water was undetectable. With regard to the BF, turbidity reached as high as 16.5 NTU during the initial period of testing. Only by April 29th did the BF filter turbidity reach the non-detect level. *Figure 18* shows that the EC of both the pre-filtered and the BF filter effluent mimicked the EC of *Pharth* and therefore the filters had little influence on EC.

Figure 17: Turbidity measurements after passage through the pre-filter (PF) and BF filter (BF) from the Pharth.

Figure 18: Electrical conductivity measurements after passage through the pre-filter (PF) and BF filter (BF) from the Pharth.

Table 10 shows the *E.coli* and Total Coliform data from the full-scale system. Only two measurements could be performed before I had to evacuate my field site because of COVID-19. The available data shows that the pre-filter had a highly variable effect on both parameters. The BF filter removed on average 90.2% of the *E.coli* but showed a

variable performance relative to the Total Coliforms. The porosity of the BF filter, calculated as a weighted average of the porosity of each material based on percent composition, and assuming a 5% by volume mixing area between each layer, was found to be 39%.

	<i>E.coli</i> (MPN/100ml)				
Sampling Date	Pharth	Pre-Filter		BF Filter	
24-Feb-20	1,012	14	98.6%	11	98.9%
11-Mar-20	10.8	22.2	-105.6	2	81.5%
Average			-3.5%		90.2%

	Total Coliforms (MPN/100ml)				
Sampling Date	Pharth	Pre-Filter		BF Filter	
24-Feb-20	17,812	6,592	63.0%	3,144	82.4%
11-Mar-20	1,778	4,363	-145.4%	2,773	-56.0%
Average			-41.2%		13.2%

Table 10: E.coli and Total Coliforms measured in Pharth and effluent water from the pre-filter and BF filter.

Remote Sensed Data:

The normalized difference vegetation index (NDVI) for the study region as well as a digital elevation map and satellite image are shown in *Figure 19*. In *Figure 20 (A)*, greener patches, indicating higher NDVI and a surface moisture zone (SMZ), can be seen directly downslope from the main spring and Kongla spring. A channel of higher NDVI originates at the main spring and continues down slope. A clear SMZ is not apparent adjacent to the *Nag Zhar* spring.

Figure 19. Summary of remote sensed data. (A) Normalized Difference Vegetation Index (NDVI), (B) digital elevation map, (C) satellite image. NDVI and Satellite images are from Sentinel-2 10 m bands taken 04/09/2020. The digital elevation map is from Shuttle Radar and Topography Mission (SRTM) 1-arc collected in 2000.

Yearly surface air temperature, shown as a yearly average and as standard deviations from the norm, from the dry season, January to April, is shown in Figure 20. No general trend is apparent, and no year showed an extreme high JJA temperature above 1.5 standard deviations. The mean monsoon precipitation, shown as yearly total and as standard deviations from the norm, from June to August, is shown in Figure 21. No general trend is apparent, and no year showed a drought in JJA average below 1.5 standard deviations. The NDVI, averaged over the Nersa region shown as a yearly average and as standard deviations for January through April is shown in Figure 22. A strong increasing trend in NDVI is apparent since the year 2000.

Figure 20: Surface air temperature shown as a yearly average and as standard deviations of the dry season (January to April) average for the study region. Data from MERRA-2 model.

Figure 21: Yearly rainfall and average precipitation for the Monsoon (June-August) from rain gauges shown as the standardized precipitation index (SPI) for the study region.

Data from AIRS_SSM.

Figure 22: Normalized Difference Vegetation Index (NDVI) for the dry season (January-April) from MODIS -TERRA for study region.

Cost Category	# items	Cost per item	Total Cost (USD)
1000 L plastic tank (Pre-filter)	1	60	60
PVC pipe	90	5	450
Valves	70	2	140
Purchased sand/gravel filter material	1 truck load	350	350
Concrete	150 bags	5	750
Steel rebar (6 mm and 10 mm)	250	1	250
Rental of construction machinery	2 days	150	300
Other construction material	NA	NA	200
Labor	350 days	6	2,100
Total			\$4,600

Table 11: BF Filter system costs in USD.

BF-filter cost:

The cost of constructing the BF filter system were tracked by category and are reported in *Table 11*. The total cost was \$4,600. Conversations with villagers indicate that the average daily amount of water used for drinking and cooking is 10 liters per person.

Assuming the filter runs for 10 years with all 300 villagers using it as their primary water source, this would provide 10,950,000 liters of drinking water. This indicates a cost of \$0.00042 per liter. When the RO was functional, villagers would have to pay 1 rupee for 10 liters (\$0.0013 per liter). Water supplied by a tanker truck would cost approximately \$0.004 per liter.

DISCUSSION

Initial Water Testing

All four water sources tested during this study were free of pesticides (see Table A1). The water from both the *Pharth* and the House Tap originated from a mountain stream that does not receive influents from any agricultural fields. The spring *Nag Zhar* however, is located downstream from an agricultural field and the bore well is surrounded by agricultural fields where pesticides are used. It is therefore noteworthy that pesticides have not found their way into these two water sources.

All four water sources also were free of parasites. It is somewhat surprising that parasites are not present in the large tank which feeds the village taps given that this tank stores a large volume of water and has an uncovered opening on top.

The water from the village taps showed higher *E.coli* contamination than *Pharth*. Because both originate from the same stream it is evident that the large tank which stores the tap water is contaminated with *E.coli*. Villagers often would refer to this tank as dirty and a source of contamination which they suspect makes them sick. These findings confirm the anecdotal evidence.

While the agricultural bore well had no *E.coli* contamination, it does not provide a legitimate water source because water can only be used for agricultural purposes. The spring *Nag Zhar* showed a high level of *E.coli* contamination perhaps due to the fact that it is downstream from an agricultural field used for animal grazing and may receive runoff.

Pharth Time Series:

The EC times series from the *Pharth* is characterized by spikes during rain events but consistently lower EC values during the monsoon. The data indicates that these short rain events outside the actual rainy season resulted in surface runoff and associated inflow of higher EC water to the Pharth. During the monsoon, dilution due to intense and prolonged precipitation resulted in overall lower EC measurement. In the Western Ghats, rivers with no upstream sewage pollution have comparatively low bacteria counts during the monsoon, as has been observed by others (Vincy, 2017). Similar results are reported for other monsoon-influenced areas in India (Boving, 2018; Laluraj, 2006; Javed, 2014).

Alluvial Deposits:

All 9 alluvial deposits offered suitable amounts of sand in the desired grain size ranges for filter material, i.e. from 0.25 mm to 3.5 mm. The porosity of these sands ranged from 26% to 46% which is also suitable for filter material. This investigation showed that local material for constructing sand filters is abundant and easily accessible in the study area.

Pilot Filters:

The measured hydraulic conductivity of the two filters was $K=0.12$ cm/s in both cases, a value in line with laboratory experiments with sands of similar grain size which exhibited K values ranging from 0.029 to 0.19 cm/s (Lynn, 2013; Rogers et al., 2004). The hydraulic conductivity for both pilot filters is close to the preferred range of 0.03 cm/s to 0.06cm/s (Lynn, 2013). The pilot filters were built with a comparable small fraction of

the finest sand material (M-5: 10%). It is therefore plausible that the hydraulic conductivity can be modulated should slower flow through the filter system be needed.

As expected, the moment analysis for both filters provided similar results. Overall, both filters have residence times exceeding 2 hrs (i.e. 190 min for Filter 1 and 140 min for Filter 2). This is above the 1hr minimum retention time required by the CAWST manual (CAWST, 2009). The retardation factor for both filters was less than unity. This observation is mirrored in the BTC, where tracer breakthrough occurred earlier than expected. Both observations suggest that preferential flowpaths are present or that the assumption of instantaneous mixing of the tracer slug with the water inside the filter was incorrect. In general, preferential flow inside a carefully packed filter is less likely than incomplete mixing. This statement is supported by the data from the tail end of the conservative tracer tests, which is the part of the experiment where the tracer concentrations decrease back to background levels. The observed prolonged tailing is more indicative for incomplete mixing than preferential flow. Under ideal flow conditions, the original tracer slug (representing 0.65 PV) should have eluted from each of the filters at approximately $1+0.65$ PV (not accounting for naturally occurring spreading). From *Figure 15*, it can be estimated that only 50% tracer mass had eluted at that point. Since tracer was still eluting from both filters when the experiment was terminated, the data suggest that the tracer infiltrated over a prolonged time (~117 min) rather than an ideal slug. Independent of this issue, the tracer test confirmed that both filters retained water long enough to improve the water quality.

Regarding the removal of bacteria, Filter 1 was 98% effective, especially after the 2-week ripening period of the biolayer. A non-detect was achieved on 18 June, 2019. Total

Coliforms were also reduced up to 2.1 log by Filter 1. With regard to Filter 2, *E.coli* and Total Coliform results indicate that GAC did not improve filtration. In fact, the GAC layer in Filter 2 likely was a source of contamination, requiring disinfection. This assessment is further supported by the EC measurements, which were initially higher than in the Filter 1 effluent, before decreasing. However, even after disinfection, that filter's performance did not surpass that of Filter 1 (no GAC). These results suggest that there is minimal value in adding this particular GAC material to the filter system.

BF Filter System:

The pre-filter, composed of larger gravel sizes, was rapidly filled and emptied many times before the actual testing period began. This rinsing removed much of the fine materials and resulted in subsequently low to non-detect turbidity measurements.

Because of time constraints, the larger BF filter was rinsed less thoroughly (three times) which explains why higher turbidity was present in the filter effluent initially. After fine grained sediment particles were flushed out of the BF filter during its first two months of use, a subsequent drop in turbidity was observed.

Because Pharth water showed zero turbidity during the latter part of the testing period, it was not possible to quantify the effect of the BF filter system on turbidity removal. With the predicted increase in turbidity at the beginning of the monsoon season in June, I anticipate to observe successful turbidity removal by the filter system. Lastly, it was not surprising that the filter system had little effect on EC because such a system is not intended for removal of dissolved solids and slow sand filters may even increase EC by 200% (Laghari et al., 2018).

The first testing (Feb. 24) for effluent water from both the pre-filter and BF filter indicated >98% (~1.9 Log units) removal of *E.coli* (Table 10). Between 63% and 82% of Total Coliform were also removed. The influent counts were >1000 *E.coli* and >17800 MPN/100 ml Total Coliform. During the second round of testing (March 11), the respective influent concentrations were significantly lower (10.8 and 1778 MPN/100 ml). Although *E.coli* removal by the BF filter was still high (81%), the pre-filter effluent was more contaminated with both *E.coli* and Total Coliform bacteria. This suggests that during low influent concentrations, bacteria might get rinsed off the pre-filter and washed into the BF filter. However, the BF treated the inflow from the pre-filter effectively. Since there was no measurable precipitation before these two sampling events (Table 9) and in the absence of any obvious disturbances in the water supply to the filter system, there are no direct reasons for these observed differences in bacteria influent concentrations.

Because of the COVID-19 pandemic, the laboratory at TERI closed and bus services were no longer running to transport water samples after the second sampling event in March 2020. Once this changes, I have made arrangements with a local and appropriately trained volunteer to continue testing for total coliforms and *E.coli*.

A tracer test for the full scale system was planned but could not be realized before the COVID-19 outbreak. Based on the tracer tests results from the two pilot-scale filters and taking into account the volume (40 m³), bulk porosity (39%), and design flow rate of the BF filter (6.7 L/min), I estimated the water residence time in the much larger BF filter to be 19 hrs. This time is within the range of other studies (WHO, 1974). The BF filter was

filled and drained only three times before testing began and it was then allowed to flow continuously.

A comparison of the cost of constructing and operating the BF filter system relative to other water treatment approaches used in the study area, i.e. RO, water supplied by tanker truck, showed our system was 3 to 10 times more cost efficient respectively, given that it supplies water for 10 years.

Remote Sensed Data

The NDVI map (*Figure 20*) shows some promise for locating springs based on NDVI patterns; greener patches indicating surface moisture zones (SMZ) could be observed downslope from springs in some instances. However, these SMZ's followed topographic features and in order to locate new springs it would be important to observe how springs create SMZ's that are not simply a result of topography (Cartwright and Johnson, 2018). While the NDVI has been used to locate springs in arid and semi-arid, my results cannot provide a definite answer if this technique could be used in the more dense forests of the Western Ghats.

The data for surface air temperature in the dry season, January to April, for the study area showed no general trends. The dry season data were observed because fluctuations could cause droughts and reduced spring flow. There were no dry years from 2000 to 2018 passing lower than 1.5 standard deviations. Similarly, I did not see a significant trend in monsoon precipitation patterns over the area, i.e. there were no years with greater than 1.5 standard deviations in precipitation from 2000 to 2018. This indicates a stability in variables influencing spring discharge in the region. A study of rainfall trends in the Belgaum region from 1980 to 2012 also showed no obvious long term patterns. It is noted

that, because of the skew of data, only minor dry periods are common (Rani, 2014). Finally, the NDVI time series averaged for the dry season shows a significant increasing trend with a correlation coefficient of 0.91. This is likely not a result of climate factors because I do not see similar trends in surface air temperature or precipitation. This trend is therefore likely due to land use change or development of new-growth forests within the area. However, these activities can directly and indirectly influence spring yields (Tambe et al., 2012). Overall, a more detailed analysis of remote sensed data must be conducted to fully develop a tool for remotely identifying spring locations in the forests of the Western Ghats.

CONCLUSION

My study focused on a cost-effective, sustainable, and replicable solution to the water quality issues facing the village Nersa. I also investigated the source of the village water supply, a mountain spring, and how NDVI patterns might be useful for remotely locating spring locations. After initial water quality testing and many conversations with local villagers I constructed two pilot filters. One of these filters contained GAC and after testing I concluded that the GAC material available in the study area did not significantly improve filtration in the pilot test. I constructed a bank filter (BF) system consisting of a flow divert tank, a flow regulating tank, gravel pre-filter, and large BF filter. My limited data set indicates that the filter system achieved 1.78 log removal of *E.coli*. While less than my initial goal of 3 log removal, this is a significant decrease in a critical contaminant which causes negative health effects in the village. While testing for this

system was cut short due to the COVID-19 pandemic, I expect it will provide clean water at comparably low cost to Nersa and reduce illness especially during the monsoon season.

An examination of remote sensed data showed that the NDVI has some promise in locating springs in the region. Climate factors influencing spring discharge such as seasonal precipitation and air temperature show little long-term variation and local springs will likely remain a viable source of water.

Besides returning to the test site and measuring the performance of the BF filter after sufficient maturing time, future research should also include continued examination of natural springs in the area as they provide a legitimate source of community water. This examination should include both a search for more springs which can be used to better understand NDVI patterns and also long-term discharge flow rate monitoring. Such a long-term dataset of spring discharge could be compared to climate data to better understand spring variability and how springs will react to climate change.

APPENDIX

Supporting Information:

Table A1

VIMTA Laboratory results from testing performed Feb 24, 2019.

Test Parameter	Units	Testing Limit	Tap	Pharta	Nag Zhar (spring)	Bore Well	Indian Standards BIS IS: 10500	
Testing name:			NS-1	NS-2	NS-3	NS-4	Requirement	Permissible Limit
Color	Hazen Units	1	-	-	-	-	5	15
Odour	NA	NA	Aggreable	Aggreable	Aggreable	Aggreable	Aggreable	Aggreable
Taste	NA	NA	Aggreable	Aggreable	Aggreable	Aggreable	Aggreable	Aggreable
Turbidity	NTU	1	-	-	-	-	1	5
Total dissolved	mg/L	1	21.00	14.00	34.00	79.00	500	2000
pH	NA	1	7.43	6.79	6.53	6.66	6.5-8.5	no relaxation
Boron B	mg/L	0.005	0.006	0.006	0.006	0.008	0.5	1.0
Bicarbonates	mg/L	10	19.80	9.90	19.80	89.10	NA	NA
Copper Cu	mg/L	0.001	-	-	-	-	0.05	1.5
Carbonates	mg/L	1	-	-	-	-	NA	NA
Nitrate NO3	mg/L	0.1	0.63	-	0.21	1.32	45	no relaxation
Nitrite NO2	mg/L	0.01	-	-	-	-	NA	NA
Flouride F	mg/L	0.1	0.25	-	-	0.16	1.0	1.5
Zinc Zn	mg/L	0.005	0.006	-	0.005		5	15
Silver Ag	mg/L	0.001	-	-	-	-	0.1	no relaxation
Total suspended	mg/L	10	-	0.002	0.002	0.002	NA	NA
Fixed solids	mg/L	10	-	0.002	0.002	0.002	NA	NA
Chloride Cl	mg/L	5	12.41	10.64	9.31	14.18	250	1000
Selenium Se	mg/L	0.005	-	-	-	-	0.01	no relaxation
Sulphate SO4	mg/L	0.1	0.96	0.29	1.00	0.77	200	400
Alkalinity to phe	mg/L	1	-	-	-	-	NA	NA
Calcium Ca	mg/L	1.0	3.23	10.50	5.56	13.73	75	200
Total alkalinity CaCO3	mg/L	1	19.80	9.90	9.80	89.10	200	600
Magnesium Mg	mg/L	5	-	-	-	-	30	100
Sodium Na	mg/L	1	-	-	-	-	NA	NA
Potassium K	mg/L	1	-	-	-	-	NA	NA
Residual free chloride	mg/L	0.1	-	-	-	-	NA	NA
Phenolic compounds	mg/L	0.001	-	-	-	-	0.001	0.002
Ammonical nitrogen	mg/L	1	-	-	-	-	NA	NA
Total hardness CaCO3	mg/L	1.0	8.08	28.28	18.18	36.36	200	600
Iron Fe	mg/L	0.005	0.018	-	-	-	0.3	no relaxation
Manganese Mn	mg/L	0.001	-	0.03	0.00	0.00	0.1	0.3

Cadmium Cd	mg/L	0.001	-	-	-	-	0.003	no relaxation
Lead Pb	mg/L	0.001	-	-	-	-	0.01	no relaxation
Mercury Hg	mg/L	0.0005	-	-	-	-	0.001	no relaxation
Molybdenum Mo	mg/L	0.001	-	-	-	-	0.07	no relaxation
Nickel Ni	mg/L	0.005	-	-	-	-	0.02	no relaxation
Arsenic As	mg/L	0.001	-	-	-	-	0.01	0.05
Chromium Cr	mg/L	0.001	-	-	-	0.002	0.05	no relaxation
Lithium Li	mg/L	0.001	-	-	0.003	0.006	NA	NA
Reactive silica	mg/L	0.05	-	-	-	-	NA	NA
Tin Sn	mg/L	0.001	-	-	-	-	NA	NA
Vanadium V	mg/L	0.001	-	-	-	-	NA	NA
Pesticides:	Units	Testing Limit	House (tap)	Pharta	Nag Zhar (spring)	(borewell)	Limit	
Chlorpyrifos	ug/L	0.01	-	-	-	-	30	
Methyl Parathion	ug/L	0.01	-	-	-	-	0.3	
Monocrotophos	ug/L	0.01	-	-	-	-	1	
Phorate	ug/L	0.01	-	-	-	-	2	
Imidacloprid	ug/L	0.01	-	-	-	-	NA	
Bromodiolone	ug/L	Qual	-	-	-	-	NA	
Fipronil	ug/L	0.01	-	-	-	-	NA	
Aldrin/Dieldrin	ug/L	0.01	-	-	-	-	0.03	
Endosulfan (sum of Ipha, Beta, and Sulfate)	ug/L	0.01	-	-	-	-	0.4	
DDT (O,P and P,p isomers of DDT, DDD, DDE)	ug/L	0.01	-	-	-	-	1	
COD	mg/L	3.0	20.00	70.00	40.00	30.00	NA	
BOD	mg/L	5.0	-	10.00	6.00	-	NA	
Handheld Results:			Subash House	Pharta	Nag Zhar (spring)	My Well (borewell)	Requirement	Permissible Limit
pH	-		6.62	5.24	5.22	5.76	6.5-8.5	no relaxation
TDS	ppm		21	21	28	54	500	2000
EC	us/cm		42	42	54	128	NA	NA
Temp	F		70.1	70.5	71.6	76.1	NA	NA

Table A2

Data collected with handheld devices:

Source	Date	Time	pH	TD S	EC	Temp	Temp	Nitrogen	Alkalinity	Turbidity
Filter 1	25-Apr-19	11:30 AM	5.32		68	30.0	86.0			5
Filter 1	27-Apr-19	10:00 AM	5.45		25	29.0				0
Filter 1	28-Apr-19	12:00 PM	5.68		60	29.0	84.2			0
Filter 1	29-Apr-19	12:00 PM	5.93		62	28.0	82.4			0
Filter 1	30-Apr-19	10:00 AM	6.00		86	27.0	80.6			0
Filter 1	01-May-19	12:00 PM	5.81		64	29.0	84.2			0
Filter 1	04-May-19	12:00 PM	6.07		47	29.0				5
Filter 1	05-May-19	12:00 PM	5.88		68	30.0				0
Filter 1	06-May-19	12:00 PM	6.01		66	30.0				0
Filter 1	07-May-19	11:00 AM	5.85		60	30.0				0
Filter 1	13-May-19		5.31		60	30.0				0
Filter 1	18-Jun-19		5.63		56	27.0				5
Filter 1	19-Jun-19		5.32		21	26.0				0
Filter 1	07-Jul-19		6.22		20	30.0				5
Filter 2	25-Apr-19	11:30 AM	5.19		3	27.0	80.6			5
Filter 2	27-Apr-19	10:00 AM	6.23		108	32.0	89.6			0
Filter 2	28-Apr-19	12:00 PM	6.20		118	29.0	84.2			0
Filter 2	29-Apr-19	12:00 PM	6.41		108	29.0	84.2			0
Filter 2	30-Apr-19	10:00 AM	6.53		120	27.0	80.6			5
Filter 2	01-May-19	12:00 PM	6.53		49	31.0	87.8			0
Filter 2	04-May-19	12:00 PM	6.70		67	30.0				5
Filter 2	05-May-19	12:00 PM	6.71		108	30.0				0
Filter 2	06-May-19	12:00 PM	6.77		108	31.0				0
Filter 2	07-May-19	11:00 AM	6.72		106	27.0				0
Filter 2	13-May-19		5.68		41	30.0				0
Filter 2	18-Jun-19		5.77		33	29.0				5
Filter 2	19-Jun-19		5.59		30	26.0				0
Filter 2	07-Jul-19		5.43		17	28.0				5
Bore well	15-Feb-19	1:00 PM	6.74	29	60	24.7	76.4			
Bore well	25-Feb-19	12:00 PM	5.76	54	128	24.5	76.1			
Nag Zhar	03-May-19									
Nag Zhar (spring)	15-Feb-19	5:00 PM	5.25	33	76	24.2	75.5			

Nag Zhar (spring)	25-Feb-19	11:00 AM	5.22	28	54	22.0	71.6			
Pharta	15-Feb-19	1:30 PM	5.24	20	40	25.0	77.0			
Pharta	17-Feb-19	11:30 AM	5.45	24	48	-2.6	27.3			
Pharta	18-Feb-19	1:30 AM	5.45	17	34	25.0	77.0	0.0	15	0
Pharta	25-Feb-19	10:00 AM	5.24	21	42	21.4	70.5			
Pharta	26-Mar-19	12:00 PM	5.10	32	68	27.0	80.6	1.0	20	20
Pharta	27-Mar-19	12:00 PM	5.15	28	58	28.0	82.4	0.0	12	5
Pharta	11-Apr-19	11:00 AM	5.48	15	30	29.0	84.2	0.0	10	0
Pharta	21-Apr-19	11:00 AM	5.28		32	27.0				
Pharta	23-Apr-19	12:00 PM	5.23		50	29.0				5
Pharta	24-Apr-19	11:00 AM	5.23		31	26.0				5
Pharta	27-Apr-19	10:00 AM	5.26		20	26.0				0
Pharta	28-Apr-19	12:00 PM	5.18		40	27.0	80.6			5
Pharta	29-Apr-19	12:00 PM	5.19		40	27.0	80.6			5
Pharta	30-Apr-19	10:00 AM	5.22		38	26.0	78.8			0
Pharta	01-May-19	12:00 PM	5.32		38	27.0	80.6			5
Pharta	03-May-19	12:00 PM	5.34		38	25.6	78.0			0
Pharta	04-May-19	12:00 PM	5.38		19	26.0				0
Pharta	05-May-19	12:00 PM	5.39		36	27.0				5
Pharta	06-May-19							0.0	10	
Pharta	06-May-19	12:00 PM	5.25		34	29.0				5
Pharta	07-May-19	11:00 AM	5.38		40	26.0				5
Pharta	13-May-19		5.99		36	28.0				5
Pharta	18-Jun-19		5.57		25	26.0				5
Pharta	19-Jun-19		5.44		21	25.0				5
Pharta	07-Jul-19		6.36		17	24.7				0
Point Source	04-May-19		4.81		38	28.0				
Point Source	06-May-19							0.0	15	
Subash House (tap)	25-Feb-19	9:00 AM	6.62	21	42		70.1			
	Units	-	-	ppm	us/cm	Celcius	degrees F	ppm	ppm	JTU

Piper-Hill diagram showing major ions.

Electrical conductivity from the two pilot filters with a tracer solution added at $t = 0$ plotted against time.

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