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Experimental basis of an emergency filtration system treating river flood water for rural areas in developing countries

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ABSTRACT

The study was carried out with the primary objective of developing and testing a filtration system that could serve rural areas in developing countries under emergency conditions to satisfy the water needs without the risk of waterborne diseases. The goal was to propose a sustainable filtration system in terms of cost, size, energy consumption, maintenance and especially the use of cheap, locally accessible materials such as tree bark as filter media. Water from the River Pinn was used as the influent for the tests. The experiments were performed in two stages: in the first stage, four filters were constructed, all with different configurations in terms of filter materials; their performance was observed in terms of the removal of major pollutants. The filter materials used in the two filters with the best performance were selected for the second stage in which two new filters were manufactured, primarily using the same filter materials supplemented with cotton wool and cotton sheets. They were also subjected to similar tests and checked for their bacteriological performance. These filters manufactured from simple materials such as gravel, fine sand, tree bark and cotton were observed to reduce turbidity below 2.0 NTU, total suspended solids down to 1.0–3.0 mg L^{-1} and to secure complete removal of coliforms with simple and minimal chlorination. They yielded safe water for the daily requirements of 30–50 persons.

Keywords: Water filtration; Rural areas; Developing countries; Sustainability; Pathogens; Tree barks

1. Introduction

Rural low-income areas in developing countries are largely dependent on running surface waters for their water supply. Rivers and their tributaries often carry various pollutants of a natural and anthropogenic nature; they may receive untreated domestic and industrial discharges and runoffs from agricultural land, which are then transported to locations where they are used as the water source. The water quality in rivers exhibits high fluctuations to the extent that it becomes unfit for consumption, mainly due to microbiological agents involving a severe risk of disease. This risk becomes aggravated with the seasonal effects of climatic conditions, which often lead to flooding. Therefore, these rural areas need simple, cheap and yet effective measures to improve the quality of the water they use under emergency conditions [1].

The use of filtration to clarify water has been practiced for thousands of years. The most striking examples date back to the Romans, who constructed parallel channels to lakes to benefit from natural filtration through the soil when using these lakes as sources for water supply. This practice was first commercialized in France around 1750, and then in England and Scotland about 1800 using various filter media such as sponges, charcoal, wool, sand, crushed sandstone or gravel.

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The importance of filtration increased based on the observation that it prevented waterborne diseases [2]. Today, rapid sand filtration serves as the integral and indispensable component of modern water treatment plants that operate to treat surface waters. Its widespread implementation is ensured by extensive research on various aspects [3–8]. Currently, the use of rapid sand filtration includes many different configurations such as Monomedia; Deep bed Monomedia; Dual media (anthracite/sand) and Mixed media filters [9].

Initially, water filtration for consumptive uses was also developed as a slow sand filter. An excellent treatise on slow sand filtration was presented by Bellamy et al. [10] and Seelaus et al. [11]. This system uses layers of sand that are not uniform in size, and it does not require coagulation or backwashing; its filtration rate is 50–100 times lower in comparison with a rapid sand filter and consequently requires much more land [12].

The above alternatives are usually designed to serve urban communities; they are excessively complicated and expensive for low-income rural areas. In 2006, the United Nations International Children's Emergency Fund (UNICEF) and the World Health Organization (WHO) indicated that the most common cause of death among children is diarrhoea, which kills about 1.5 million children each year: it kills more children than AIDS, malaria and measles combined. The global waterborne disease rate is much higher than this value due to various other pathogens, which find their way into primitive water supply sources [13,14]. Disinfection methods such as UV disinfection and ozone treatments are relatively effective but costly and are not applicable on a small scale. Simple carbon-based filters are not effective in removing pathogens; the use of membrane filters capable of removing pathogens often becomes prohibitive due to the high costs and maintenance level they require. Therefore, there is a pressing need to develop simpler and cheaper filtration systems that require no technical maintenance, which would provide effective treatment and eliminate the risk of waterborne diseases under emergency conditions.

In this context, the ground breaking inspiration of Boutilier et al. [15] from nature, which used plant xylem obtained from the sapwood of trees as filtration material in simple pressure-driven systems proved to be quite promising. They reported that plant xylem, a porous material that conducts fluids in plants, was relatively effective in removing pathogens from water and could be a sustainable solution for providing pathogen-free consumption water for rural areas in developing countries under emergency conditions. The study pursued this general idea with the aim of developing a household-level water filtration system that can deliver microbiologically safe water, which would reduce the risk of waterborne diseases. The objective of the project was to propose and test a sustainable filtration system in terms of cost, size, energy consumption maintenance and especially the use of cheap, locally accessible materials as filter media.

2. Materials and methods

2.1. Experimental rationale and filter characteristics

The experimental plan for developing and testing a simple filtration system that would yield safe potable water under emergency conditions mainly involved two stages. In the first stage, four filters (F1, F2, F3 and F4) were structured with different configurations in terms of filter materials; their performance was observed for the removal rates achieved concerning major parameters. The filter materials of the two filters with the best performance were selected for the second stage; two new filters (F5 and F6) were manufactured, one (F5) with the same configuration as F3 supplemented with cotton sheets and the other with a new structure including cotton wool, as shown in Table 1. These two filters were subjected to similar tests and checked for their bacteriological performance to ensure that their effluent could be safely be used for consumptive purposes.

Filters were fabricated with necessary filter materials such as coarse gravel, pea gravel, fine sand, tree barks and cotton, which can easily be obtained and is largely available in the rural areas of developing countries. A total of six filters were designed, four for the preliminary tests and two for the final examinations, each with a different configuration, as summarized in Table 1.

The expected function of each filter component is briefly explained below:

Coarse gravel: 5–10 mm diameter coarse gravel used only in the design of the last filter to allow the passage of water through to the collection tank (reservoir), with materials large enough to protect pea gravel and fine sand from passing.

Pea gravel: 2–5 mm diameter gravel used in the design of all filters except the second filter, prevents fine sand from passing through the system to the reservoir and also avoids blockage of the filter by fine sand.

Fine sand: 0.5 mm diameter industrial fine sand used in filter design which facilitates mechanical filtration.

Table 1
Different filter configurations tested in the experiment

Filter	Material	Depth (cm)
Filter1 (F1)	Coarse gravel	6
	Pea gravel	6
	Fine sand	12
Filter2 (F2)	Tree barks	24
Filter3 (F3)	Pea gravel	6
	Fine sand	6
	Tree barks	12
Filter4 (F4)	Tree barks	12
	Pea gravel	6
	Fine sand	6
Filter5 (F5)	Pea gravel	6
	Fine sand	6
	Tree barks	12
	Cotton sheets	3 (approximately)
Filter6 (F6)	Coarse gravel	6
	Pea gravel	6
	Fine sand	12
	Tree barks	12
	Cotton wool	8 (approximately)

Tree barks: The material used in the replacement of GAC. Tree barks are the outer part of woody stems and branches; it anatomically includes all the plant tissues outside the cambium and is sometimes referred to as "blast."

Cotton sheets: Has low permeability similar to that of cotton wool, used to see how it can replace cotton wool in the filter design.

Cotton wool: Has low permeability, used in the design of filter 6, helps in effective filtration due to its small pore size and enhances good filtration due to its adsorption properties.

2.2. Experimental location

The study was conducted using River Pinn as the water source tested for filtration experiments. The River Pinn is a river located in West London/England, which originates around Pinner and flows into the Frays River, a distributary of the River Colne. It runs through Ickenham and onto Uxbridge, where it passes through RAF Uxbridge and Brunel University. Water samples from the river served as the influent for the laboratory-scale filtration experiments. Table 1 summarizes the quality of the samples from the River Pinn used in the tests:

2.3. Experimental setup

Transparent plastic containers were selected to serve as the filter shell. They represent similar containers of different sizes, which would be easily accessible in rural areas for the same purpose. The volume of the containers was approximately 1.8 m^3 with the following dimensions: 120 mm height, 150 mm length and 100 mm width. A 3.5 mm diameter drilling rig was used to make a template, for a 3 mm diameter hole in each container, except the bottom containers, which served as a reservoir for the collection of effluent water. The 3 mm diameter hole size was chosen to allow the free flow of water through the filter, and to prevent blockage of the holes by fine sand; it also served as a filter for debris in the influent water.

A plastic spigot is attached to the bottom plastic container, which serves as a reservoir for collecting the effluent. The plastic spigot is clamped with a washer from both inside and outside of the container to make it tight and avoid any leakages. A plastic plate of 2 cm height was made and inserted at the bottom of each container for collecting effluent (i.e., the effluent container) so that no water remained after draining the effluent to avoid contamination. The experimental setup used in the study is displayed in Fig. 1.

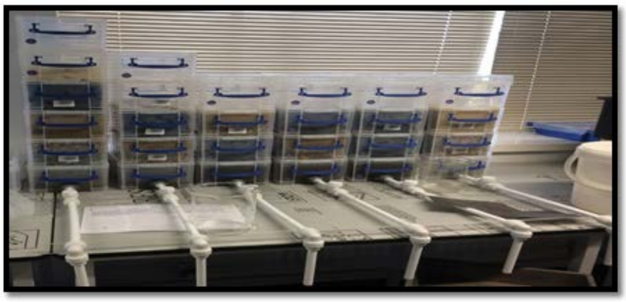

Fig. 1. Experimental setup used in the study.

2.5. Analytical measurements

Samples collected from the river were tested for their primary characteristics before they were used as the influent stream for the filter units; similarly, the effluents were tested for pH, dissolved oxygen, turbidity, COD, nitrate, total dissolved solids (TDS), total suspended solids (TSS) and faecal coliform counts, mainly to determine whether the water coming out of the filters satisfies the WHO standards [16] for drinking water. Routine measurements were performed as defined in Standard Methods [17]. COD is now the most recognized parameter used for assessing organic substrate in natural and engineered systems [18]. In the COD test, the organic matter in the sample is oxidized to CO_2 and H_2O by potassium dichromate in boiling concentrated sulphuric acid (150°C) and in the presence of a silver catalyst. In this study, COD measurements were performed as described by ISO 6060 [19,20]. The presence of coliforms in the water was tested as they are the primary indicators of water pollution. The presence of these microbes is associated with the presence of disease-causing microorganisms [21]. Analysis and risk assessment of microbial water quality is needed regularly in order to determine the likely means of contamination and its improvement [22]. The microbiological tests were conducted using an Oxfam DelAgua water testing kit and manual, which is a recognized water testing kit used in most emergency situations when treating water. This testing kit yielded the bacterial count present in water (thermotolerant or faecal coliform) with a unit of CFU/100 mL of water.

3. Experimental results

3.1. Preliminary filtration tests

Initially, four different filter configurations were tested to determine the final filter configuration with the optimum performance. After a week of start-up period, as shown in Table 2, the filter depth was always kept as 36 cm, while the filtration material was altered: The first filter (F1) was designed as dual-media composed of pea gravel and fine sand; the filter material of the second filter (F2) was tree bark; the third and fourth filters (F3 and F4) provided multi-media filtration with different configurations of pea gravel, fine sand and tree bark. The performance of the filters was observed for 10 consecutive runs, by measuring the turbidity, COD, dissolved oxygen, pH and nitrate in daily composite samples for both influent and filter effluent.

The turbidity removal achieved in the filters is summarized in Table 3. In the first five runs, no turbidity removal

Table 2
Characteristics of River Pinn water used in the experiments

Parameter	Average	Range
Turbidity, NTU	5.2	2.7–11.0
Total suspended solids (TSS), mg L^{-1}	5.6	3.0–8.0
Total dissolved solids (TDS), mg L^{-1}	276	269–290
COD, mg L^{-1}	21	11–57
Nitrate, mg N L^{-1}	0.9	0.6–1.4
Colony count, N/100 mL	58	52–64

Table 3
Performance of the filters regarding turbidity measurements

Test	Influent	Effluent from F1	Effluent from F2	Effluent from F3	Effluent from F4	%Removal F1	%Removal F2	%Removal F3	%Removal F4
5	3.12	NR*	NR	NR	NR	–	–	–	–
6	2.57	2.41	NR	2.17	NR	6.2	–	15.6	–
7	4.15	2.25	NR	3.07	NR	45.8	–	26.0	–
8	11.00	3.25	NR	6.07	NR	70.5	–	44.8	–
9	4.43	2.35	2.87	1.96	3.43	46.9	35.2	55.8	22.6
10	2.45	1.84	2.13	1.03	2.16	24.9	13.1	58.0	11.8

was observed, mostly due to washout of initially present impurities associated with the filter materials. After this period, the turbidity removal rate increased up to 70% in Filter 1 and to around 60% in Filter 3. The performance of the other two filters remained far below the satisfactory levels, as shown in Fig. 1.

The COD content of the river water remained in the range of 11–57 mg L^{-1}. Aside from Filter 1 (F1), no appreciable COD removal could be detected in the effluent of the other filters. In four different runs, F1 was able to remove 50%–76% of the influent COD (Table 4). It should also be noted that the influent COD was predominantly too low (<20 mg L^{-1}) to be able to obtain a precise and reliable measurement. Similarly, no reliable assessment could be made for nitrate removal since the influent nitrate level was always below 1.4 mg L^{-1} and at this level, there is no risk associated with water consumption. Moreover, filtration did not change the pH of the influent measured in the range of 7.2–7.5. Also, the dissolved oxygen content of ≥6.5mg L^{-1} in the river water did not appreciably change after filtration.

3.2. Final filtration tests

The results of the preliminary filtration experiments suggested that (i) the composition of the filters for the last filtration tests could be used as starting point filters F1 and F3 due to the positive performance-related top turbidity and COD removals; (ii) materials selected for the new filter configurations should initially be washed with the same water to be treated at least four to five cycles so as to clean the impurities present in all the selected components, in order not to impair the effluent quality.

Table 4
Performance of the filters in terms of COD measurements

Test	Influent	Effluent from F1	%Removal F1
2	57	53	7
4	19	NR	–
5	16	NR	–
6	17	4	76
7	20	10	50
8	12	NR	–
9	22	10	54
10	13	3.97	69

This study essentially uses the multimedia approach and selected sand and gravels as the most applicable materials in similar practice. Many studies in Northern Pakistan have demonstrated how household sand filters can reduce turbidity up to 67% and remove up to 97% of bacteria, which is also a prime water quality issue responsible for negative consequences [21,22]. In another similar research conducted by Chow et al. [23], a turbidity and colour removal rate of up to 60% was achieved using an NH_2–SAM sand filter, and it was suggested that this could be used in the drinking water treatment process. In this context, two new filters (F5 and F6) were designed as multi-media systems, using the same materials as in F1 and F3 in different configurations, which also included cotton sheets or cotton wool, to improve achievable filter performance. The primary motivation for the selection of cotton was to use a low-cost material that would be available locally in developing countries in the event of an emergency. The second experimental stage was carried out with the main objective of improving the filtration performance, which was also tested using additional parameters such as faecal coliform count, TDS and TSS.

The turbidity of the influent exhibited a slight variation between 2.5 and 11 NTU during the five consecutive runs. As shown in Fig. 2, both filters could achieve 65%–75% turbidity removal and reduce the effluent turbidity below 2.0 NTU, which is much lower than the target turbidity of 5.0 NTU, which is the standard value set by WHO for drinking water. The results may be attributed to the adsorption properties of tree barks and the small pore sized texture of both cotton sheets and cotton wool.

One of the main reasons for comparing the two filters was to check whether the cotton sheet will perform the same as cotton wool, a more expensive material that may not be available locally in developing countries. The results indicated that in emergency cases, cotton sheets can be used as effective filter materials before any assistance is provided from outside aid groups.

During this experimental phase, the river water had a TDS level of 269–290 mg L^{-1} and a very low TSS content below 6 mg L^{-1}. As expected, the TDS removal rate remained in the low range of 5%–15%, since physical mechanisms of particle entrapment cannot be effective in the soluble range (Table 5). F5 equipped with cotton sheets performed slightly better than F6 in reducing the TSS down to the 1–3 mg L^{-1} range (Table 5).

As in the preliminary tests, the COD of the river water remained in the low range of 11–26 mg L^{-1}. As shown

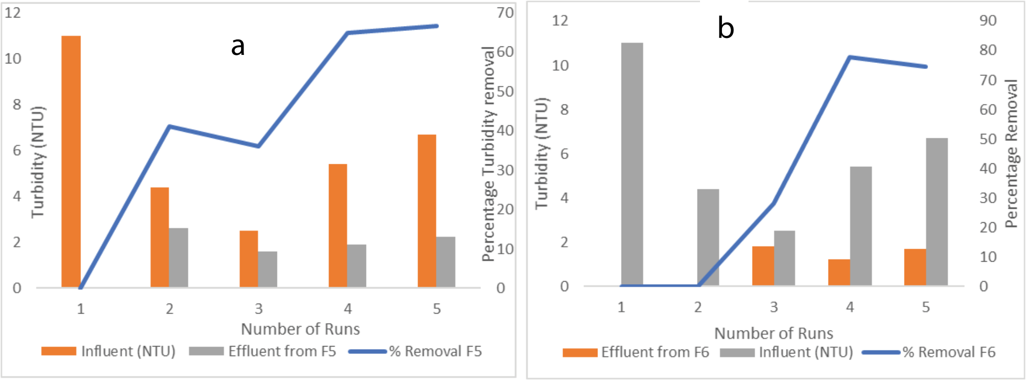

Fig. 2. Turbidity removal performance of (a) Filter 5 and (b) Filter 6.

Table 5
Performance of F5 and F6 with respect to TSS and TDS

Test	Influent (mg L^{-1})		Effluent F5 (mg L^{-1})		Effluent F6 (mg L^{-1})		%Removal F5		%Removal F6	
	TSS	TDS	TSS	TDS	TSS	TDS	TSS	TDS	TSS	TDS
1	6	269	3	254	4	262	50	5.6	30	2.6
2	3	269	1	249	2	260	60	7.4	33	3.34
3	8	290	3	242	5	273	63	16.5	38	5.86

in Table 6, the removal performance of both filters was quite small and stayed below 25% and 38% for F5 and F6, respectively, because they were limited with the particulate fraction of COD and the adsorption capacity of filter materials.

The most significant part of the experimental phase was the reduction in the faecal coliform count, which is directly related to the risk of disease when the effluent is used as the consumption water supply. The bacteriological quality of the influent was assessed as 52/100 mL and 64/100 mL above 50/100 mL faecal coliform counts in the two samples used for this purpose. Filtration through F5 was found to be more effective as it could reduce the faecal coliform counts down to 6–10/100 mL, the same count in the effluent of F6 remained in the range of 16–28/100 mL (Table 7). Additional disinfection of the filter effluents with 0.5 mL L^{-1} of sodium hypochlorite provided complete removal of coliform. This way, the filter effluents became free of bacteriological contaminants and qualified as a safe resource for consumptive use under emergency conditions.

Volumes of effluent flows were recorded for four consecutive days to yield an average accessible volume of 575 L d^{-1} for Filter 5 and 355 L d^{-1} for Filter 6. Based on the average water requirement for survival (per person) in the range between 7.5 and 15 L d^{-1}, according to Chatterton amd Rod [9], under emergency conditions, the average number of persons per day these filters can provide with safe drinking water may be calculated as more than 50 persons using Filter 5 and more than 30 persons with Filter 6.

Table 6
Performance of F5 and F6 concerning COD

Test	Influent COD	Effluent COD F5	Effluent COD F6	%Removal F5	%Removal F6
1	11.0	NR	NR	–	–
2	13	10	9.7	25.0	25.4
3	26	20	16	23.0	38.5

Table 7
Performance of F5 and F6 concerning coliform counts

Samples	CFU per 100 mL sample A	CFU count per 100 mL sample B
Influent water sample	64	52
Effluent water sample before chlorination Filter 5	10	6
Effluent water sample before chlorination Filter 6	28	16
Effluent water sample after chlorination with 0.5 mg L^{-1} sodium hypochlorite in Filter 5	1	0
Effluent water sample after chlorination with 0.5 mg L^{-1} sodium hypochlorite in Filter 6	1	0

4. Conclusion

Under emergency conditions, low-income rural areas that lack proper infrastructure are usually unable to find a suitable source of consumptive water that is free of microbiological agents and does not present a severe risk of disease. Different technologies prescribed in the literature are not applicable in this environment. The experimental results of this study satisfied this critical quest for safe water: Based on preliminary filtration experiments, which tested different configurations, filters manufactured from simple materials such as gravel, fine sand, tree bark and cotton were observed to reduce turbidity below 2.0 NTU, TSS down to 1.0–3.0 mg L^{-1} and secured the complete removal of coliforms with simple and minimal chlorination. They yielded safe water for the daily requirements of 30–50 persons.

Aside from the positive results, the study also illustrated that similar filters could be easily manufactured from locally available, cheap and straightforward materials and they could be operated manually without requiring any source of power or additional operation/maintenance expertise and skill.

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