# Design and Evaluation of Household Horizontal Slow Sand Filter

**Abstract**

Slow sand filtration has been recognized as an appropriate technology for drinking water treatment in rural areas, and is recognized as a suitable filtration technology in reducing turbidity and coliform concentrations. It is capable of improving the physical, chemical, and microbiological quality of water in a single treatment process without the addition of chemicals, and can produce an effluent low in turbidity and free of bacteria. The objective of this study was thus to develop a household-scale HSSF with a low-cost treatment process, which can be operated and maintained by a member of the families. It therefore involves obtaining different grain sizes of sand as a filter media and water quality data from laboratory after filtering the water in different slopes of the HSSF tool. So, the primary product of this project was the developed recommendations and design criterias for the use of HSSF technology to improve water quality. Accordingly, the developed tool was found to produce remarkable results in removing turbidity and coliform concentrations in water. The average percent removal of coliforms was found to be 100% with effect from the $9^{th}$ day; while, turbidity had become within the permissible limit in the first day of filtration.

**Key Words**

Slow sand filter; Water Quality; Microbiological Analysis; Physico-Chemical Analysis

## 1. Introduction

Water is not only a basic need but also human rights [1, 2]. According to different literatures [3, 4], approximately one billion people worldwide lack access to adequate amounts, and clean and safe water; while, 2.2 million people die of water born diseases, such as diarrhea [5].

Whilst attempts have traditionally focused on providing centralized systems for water treatment and distribution, there are millions of people who already have abundant access to water but depend on rivers, streams and other unsafe water sources [3, 6]. The implementation of municipal water treatment systems can be impractical and costly due to dispersed populations and poor transport infrastructures in many rural areas. Therefore, low cost community water treatment systems are reasonable alternatives [4].

Interest in household water treatment has grown significantly over recent years as studies have concluded that these simple low-cost household interventions may be as effective at preventing diarrhea as other environmental approaches such as improved sanitation, hygiene and improved water supply [7-9]. The increasing importance of such systems is also highlighted through the creation by the WHO of the International Network to Promote Household Water Treatment and Safe Water Storage to support study and dissemination of both existing and developing technologies.

The slow sand filter (SSF), one of such technologies, developed by Dr. Eric Mantz at the University of Calgary, in 1976, Canada, has been successfully introduced to many countries of the world. The technology demands little maintenance, is primarily managed at the household level and has been demonstrated to significantly reduce the potential for diarrheal disease. For the first few years after introduction, most studies of the filter have been limited to the laboratory and very little research exists which explores their long-term performance and suitability. Years later, slow sand filtration was proved to be the first water treatment process introduced to improve the quality of surface water and soon also proved to provide protection against to waterborne diseases. Thus, it has remained a suitable treatment technology throughout the world and is recognized as particularly appropriate for application in developing countries due to the simplicity of its design and construction and the ease of operation and maintenance.

However, the widely used type of slow sand filter is the vertical slow sand filter; while, it is known that the flow in vertical slow sand filter is relatively faster than that of the horizontal slow sand filter, for the head of water added at the top of the filter has its own pressure [10]. Moreover, the faster the flow within the filter results less quality of filtered water. Thus, a tool that slows the flow of water within the filter and increases the filtration capacity is very important in such a case. The objective of this study was therefore to develop a horizontal slow sand filtration technology with a relatively better filtration capacity, and which is a low-cost water treatment process that can be operated and maintained by a member of the families. More specifically, the project was aimed to:

- ❖ Develop affordable, socially acceptable and effective horizontal slow sand filter (HSSF).
- ❖ Evaluate the efficiency of HSSF in reducing turbidity and microbiological concentrations of drinking water during lab analysis.
- ❖ Evaluate the long term performance of the HSSF.
- ❖ Determine what practices and water sources could be used during the filtration process.
- ❖ Recommend adequate maintenance procedures that could be used by communities.
- ❖ Suggest any additional program components, which might aid the long term sustainability of the filtration process.

## 2. Materials and Methods

### 2.1. Design of HSSF Tool

The design of the HSSF sections was made using AutoCAD, version 2007. As shown in figure 1, the design of the sand filter has five sections, i.e., sections for the storage, gravel, coarse sand, medium sand and very coarse sand. The storage section is laid above the gravel container. Therefore, when the turbid water comes from the top to the gravel storage, the gravels help to disperse the water and to filter some of the large size dirt. Then, once water got dispersed by the gravel, pathogens are expected to be removed from the water through the filtration process and the coarse sand starts the serious filtration process. Finally, the turbid water passes through the medium sand section (filter media) and gets filtered well. At the end, very coarse sand section is used to prevent the clogging of the outlet by the medium sand.

#### 2.1.1. Filter Components

The dimensions of the filter components used in this study are purely experimental with the objective to design the filtration system of household horizontal slow sand filter. The essential components of the filter unit have 100 cm tire leg from the ground, and also it has sieves dividing the grains from each other (Fig.1). The tank filter as a whole is divided into four places by 40 cm width, 20 cm height and 22 cm length each (Fig.1). Moreover, the sizes of the sieves that are dividing the sections from each other are selected based on the grain sizes. For instance, the sieve size that is dividing the gravel and coarse sand is 1 mm in diameter. Therefore, the sieve protects the coarse sand from coming back to the gravel section.

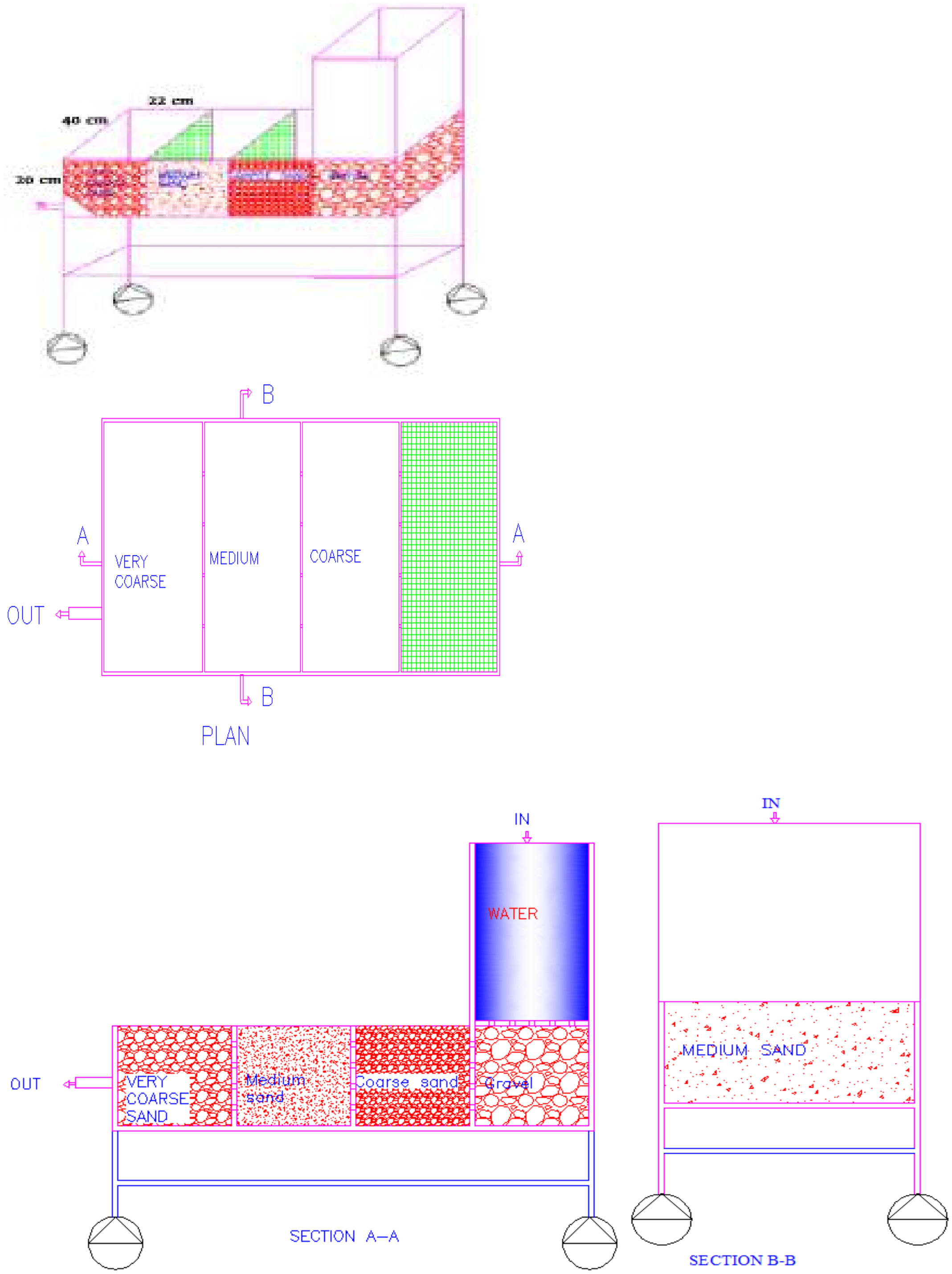


**Figure 1: Horizontal slow sand filtration tool sections/views**

### 2.1.2. Flow Rate

Filter flow rates were measured in different grades/slopes of the HSSF. Flow rates were measured by filling the filter to a level approximately 10 centimeters into storage at the inlet part. Discharged water was collected in a half-liter plastic bottle. The time required for 500 ml of water to flow through the filter was thus recorded, and the rate was determined for each grades. The rates were therefore calculated using the following equation:

$$Q = \frac{V}{t}$$

Where, Q is flow rate in L/s, V is volume in L and t is time in second

## 2.2.Sand and Gravel

A sample of sand taken from a source will not consist of uniformly sized grains but contains a range of grain sizes. Sand was taken from a source (gully sand bank), then washed by agitating it in running water to remove excessively fine grains and organic materials before shaking. The sand was dried thoroughly before testing. As RedR recommended "sand used in slow sand filters should have an effective size of 0.15 – 0.35 mm and a uniformity coefficient of 1.5 – 3; however, < 2 is desirable. Preferably, the sand should have rounded, rather than jagged grains and be free from clay. Hence, sand from streams and rivers is normally better suited to slow sand filters than sand from pits.

The sand was then sieved to obtain sand grains that could be used as filter media. A mesh with very small openings was used to prevent the sand clogging, the opening through which the water passes from one media to another sand media and the gate valve. Gravel, in two different sizes, was obtained by sieving the sample. Particle size of sand was known after sieving, and the range of particle size distribution was classified based on USDA sand classification system (Table 1).

**Table 1: USDA sand classification system**

| Types of sand sample | Particle size range (mm) |
|---|---|
| **Gravel** | 2 – 4 |
| **Very coarse sand** | 1 – 2 |
| **Coarse sand** | 0.5 – 1 |
| **Medium sand** | 0.25 – 0.5 |
| **Fine sand** | 0.1 – 0.25 |
| **Very fine sand** | 0.05 – 0.1 |

## 2.3.Characterizing Sand Samples

Sieve analysis was used to characterize the sand samples. Advantages of the sieve analysis include easy handling, low investment costs, precise and reproducible results in a comparably short time and the possibility to separate the particle size fractions. Therefore, this method is an accepted alternative than analysis methods using laser light or image processing.

To guarantee a high degree of reproducibility and reliability, sieve shakers and accessories have to fulfill the requirements of national and international standards. This means that test sieves, sieve shakers and all other measurement instruments which are used for the characterization of particle distributions have to be calibrated and subjected to test agent monitoring as part of the quality management system. Apart from that, it is necessary to carry out the sample preparation with great care. Only then is it possible to achieve sieving results which allow a reliable characterization of a product. Two quantities are needed to characterize a sand sample:

- Effective particle size – this is the particle diameter such that 10% (by weight) of the grains in the sample are smaller than it and 90% of grains are larger than it. The effective particle size is therefore referred to as $D_{10}$.
- Uniformity coefficient – this is a method of expressing the size differences between the largest and smallest grains in the sample (also known as the particle size distribution). The uniformity coefficient is defined as the ratio of $D_{60}/D_{10}$. Like $D_{10}$, $D_{60}$ is the particle size whereby 60% of the samples grains are smaller and 40% are larger.

Thus, the standard sieve analysis procedures and apparatuses were used in this analysis (Fig. 2).


**Figure 2: Grain Size Analysis**

### 2.4. Water Sampling Procedures and Analysis

The water samples were analyzed for various parameters in the laboratory. Various physical and chemical parameters like Temperature, pH, Turbidity, TDS and EC have been measured from the filtered water of different grades/slopes of filtration instrument. Moreover, samples were also analyzed microbiologically.

Plastic bottles of 2.0 liter capacity were used for collecting samples. Each bottle was washed with distilled water. The bottles were then preserved in a clean place. The bottles were filled leaving no air space, and then sealed to prevent any leakage. Each container was clearly marked with the name and date of sampling.


**Figure 3: (A) sampling site (B) water samples filtered with different slopes of the sand filter**

### 2.4.1. Drinking Water Quality Standards

The results of the analyzed parameters of filtered water of the different grades of HSSF were compared with the related standards for drinking water [11, 12]. The drinking water standards are given in the table 2.

**Table 2: Drinking Water Standards (WHO 2006)**

| S/No. | Parameters | Permissible value |
|---|---|---|
| **1** | Color | Unobjectionable |
| **2** | Taste | Agreeable |
| **3** | pH | 6.5-7.5 |
| **4** | Turbidity(Max NTU) | 5 |
| **5** | TDS | 500 |
| **6** | TSS | 5 |
| **7** | BOD | Nil to 5 |
| **8** | DO | 4.0-6.0 |
| **9** | Total hardness | 300 |
| **10** | Chloride | 250 |
| **11** | Alkalinity | 120 |
| **12** | Residual chlorine | 0.2 |

NB: Except pH and turbidity other parameters are in mg/l.

### 2.4.2. Methodology for the Measurement of Temperature

#### *2.4.2.1.Procedure*

a) Temperature was measured with the thermometer immersed directly in the water sample, after a period of time sufficient to permit constant readings.

b) Reading was therefore taken from the sample bottles after sufficient time has elapsed to allow the thermometer to come to the exact temperature of the water.

### 2.4.3. Methodology for the Measurement of Turbidity

#### *2.4.3.1.Principle*

It is based on comparison of the intensity of light scattered by the sample under defined conditions with the intensity of light scattered by a standard reference suspension under the same conditions.

#### 2.4.3.2.***Procedure***

Turbidimeter Calibration follows the manufacturer's operating instructions. Measure the standards on turbidimeter covering the range of interest. If the instrument is already calibrated in standard turbidity units, this procedure will check the accuracy of calibration.

For turbidity values less than 40 units, shake the sample to disperse the solids. Wait until air bubbles disappear. Pour sample into turbidimeter tube and read turbidity directly from the instrument scale or from calibration curve.

**Figure 4: Measurement of turbidity meter**

### 2.4.4. Methodology for the Measurement of pH Value (Electrometric Methods)

#### *2.4.4.1.Procedure*

After required warm-tip period, the instrument was standardized with a buffer solution of pH near that of the sample and electrodes were checked against at least one additional buffer of different pH value. The temperature of the water was measured. Electrodes were rinsed and gently wiped with solution. The sample pH and temperature were thus noted and recorded.

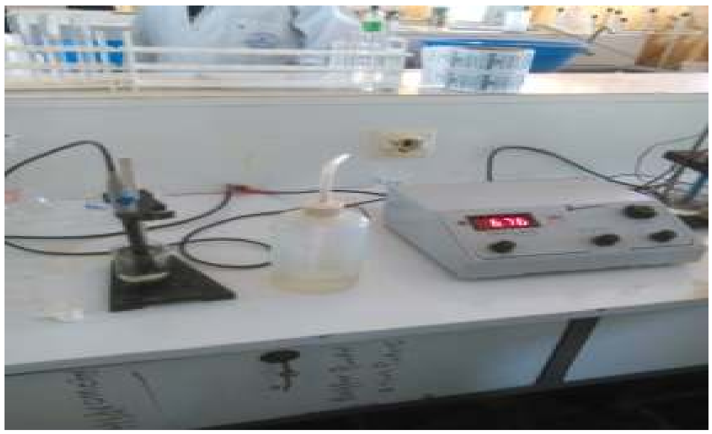

**Figure 5: Measurement of pH**

### 2.4.5. Methodology for the Measurement of Electrical Conductivity

#### *2.4.5.1.Procedure*

For testing the given water sample, first the reagents were prepared. Then the conductivity meter was calibrated. Then:

1. The electrode was thoroughly rinsed with deionised water and carefully wiped with a tissue paper.
2. 200 ml of water sample was measured and transferred to a beaker and placed it on the magnetic tube stirrer.

The electrode was dipped into the sample solution taken in a beaker and a steady reading was taken. Make sure that the instrument is giving stable reading. And the reading was recorded in micro Siemens per centimeter. Finally, the electrical conductivity was calculated as follows: $EC_{calcu} = (EC_{read} \times K) / (1+0.0191(T -25))$, where, K = cell constant with the value of 0.97, T = Temperature & EC = electrical conductivity.

**Figure 6: Measurement of electrical conductivity**

### 2.4.6. Methodology for the Measurement of Total Dissolved Solids

Electrical conductivity of water is directly related to the concentration of dissolved ionized solids in the water. Ions from the dissolved solids in water create the ability for that water to conduct an electric current, which can be measured using a conventional conductivity meter or TDS meter. When correlated with laboratory TDS measurements, conductivity provides an approximate value for the TDS concentration, usually to within ten-percent accuracy. The relationship of TDS and specific conductance of water can be approximated by the following equation:

$$TDS = Ke \times EC$$

Where: TDS is expressed in mg/L

EC is the electrical conductivity in microsiemens per centimeter at 25 °C and

The correlation factor Ke varies between 0.55 and 0.8. An average of Ke=0.67 was taken in this calculation. Therefore, the TDS values of the samples were calculated based on the above equation.

### 2.4.7. **Microbiological Test**

A filtered sample from the filter with a 5% slope and the pre-filtered sample were taken to the microbial test. The 70188 Violet Red Bile Agar (VRB-Agar) and Peptone Bacteriological reagents were used in the laboratory tests. In our case, 9.625 mg of VRB-Agar and 3.75 mg of Peptone were weighed first in an electrical balance. Then, they were added to separate glasses and mixed with 250 ml of distilled water each. The VRB-Agar was thus boiled at a 100 $^{o}$C; while, the Peptone mixture was autoclaved at a 121 $^{o}$C in an autoclave machine. So, 1 ml of sample from each of the 3 samples were taken and placed to separate tubes and diluted to a $10^{-1}$ and $10^{-2}$ dilution with a 9 ml each of the Peptone mixture. The analysis was in a duplicate analysis type. Finally, 1 ml of each of the diluted and original samples was taken to a plate where the microbes can grow and 10-15 ml of the VRB-Agar was added to each of the plates. The plates were then placed to an incubator with a 32 $^{o}$C temperature. Counting was finally conducted after 48 hours of period.

Result and Discussion

**2.5.Grain Size Analysis**

**Sieve Analysis:**

(1) The mass of sand retained on each sieve was obtained by subtracting the weight of the empty sieve from the mass of the sieve + retained sand, and this mass was recorded as the weight retained on the data sheet. The sum of these retained masses should approximately be equals the initial mass of the sand sample. A loss of more than two percent was considered as unsatisfactory.

(2) The percent retained on each sieve, by dividing the weight retained on each sieve by the original sample mass, was therefore calculated.

(3) The percent passing (or percent finer) was finally calculated by starting with 100 percent and subtracting the percent retained on each sieve as a cumulative procedure. The overall calculation results are shown in table 3. A semi logarithmic plot of grain size vs. percent finer was finally prepared as shown in figure 7.

**Table 3: Grain size analysis**

| Sieve Number | Diameter (mm) | Mass of Empty Sieve (g) | Mass of Sieve + Sand Retained (g) | Sand Retained (g) | Percent Retained | Percent Passing |
|---|---|---|---|---|---|---|
| **5** | 4 | 604.36 | 619.74 | 15.38 | 2.25 | 97.75 |
| **10** | 2 | 560.46 | 714.85 | 154.39 | 22.61 | 75.14 |
| **20** | 0.85 | 503.63 | 787.63 | 284 | 41.62 | 33.52 |
| **30** | 0.6 | 496.51 | 548.03 | 76.52 | 11.21 | 22.31 |
| **60** | 0.25 | 448.97 | 486.22 | 62.25 | 9.12 | 13.19 |
| **140** | 0.106 | 429.80 | 441.83 | 37.03 | 5.43 | 7.76 |
| **230** | 0.063 | 347.23 | 360.27 | 38.04 | 5.58 | 2.18 |
| **Pan** | - | 578.13 | 592.9 | 14.77 | 2.18 | 0.00 |

*Percent passing=100-cumulative percent retained.

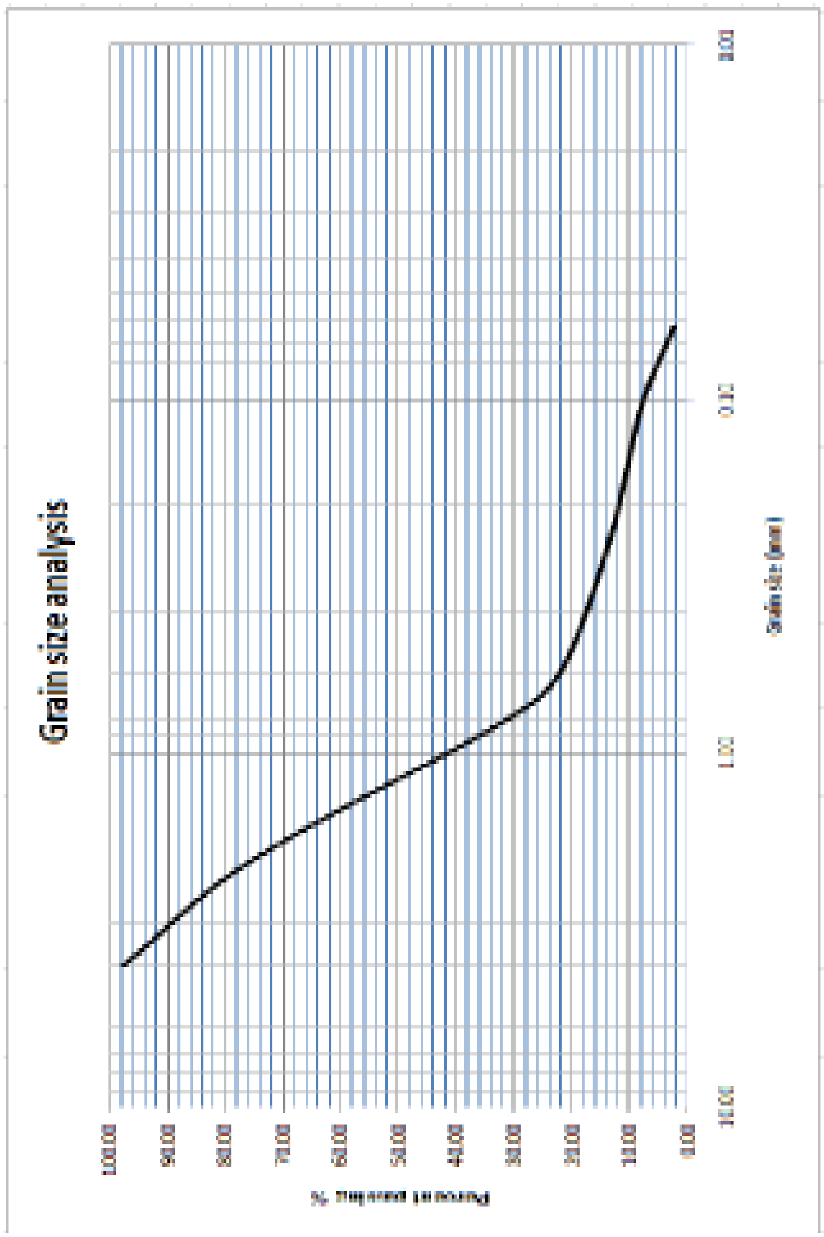


**Figure 7: The semi-logarithmic graph of grain size vs. percent finer**

(4) Cc and Cu for the sand were also computed as:

$C_U = D_{60}/D_{10}$ = 1.5/ 0.17 = <u>8.82</u>

$C_C = D_{30}^2/ D_{60}*D_{10}$ = $0.8^2$/ 0.17*1.5= <u>2.51</u>

- The sand we used as a filter media in this HSSF has an effective size of 0.17 mm and a uniformity coefficient of 8.82.

### 2.6. Flow Rates Analysis

Flow rates were found to increase with the increase in grade/slope. The highest flow rate was found at 30% grade with an average rate of 0.022 L/s. In contrary, the lowest flow rate was found at a 5% grade, averagely 0.011 L/s. The average flow rates of the filter tested using all grades are shown in Table 4.

**Table 4: flow rates with different grades of HSSF**

| S/No | Grades/slope (%) | Flow rates (L/s) |
|---|---|---|
| **1** | 5 | 0.011 |
| **2** | 10 | 0.013 |
| **3** | 20 | 0.015 |
| **4** | 30 | 0.022 |

### 2.7. Water Quality Analysis

#### 2.7.1. Temperature

The temperature values of the filtered water samples were found to be within the permissible limits (Table 5).

#### 2.7.2. Turbidity

Measurement of Turbidity reflects the transparency in water. It is caused by the substances present in suspension in water. In natural water, it is caused by clay, silt, organic matter and other microscopic organisms. In our case, turbidity was found to range from 3.93 to 75 NTU. However, the prescribed limit of turbidity for drinking water is 5 NTU [11, 13]. Turbidity was not found within the permissible limit in the filtered water samples with the grade/slope value greater than 10% (Table 5). It is also obvious that the filtration capacity of a sand filter increases with the increase in filtration days, for the filtered dirt will increase the filtration capacity of tool. However, in our case, the turbidity value of the sample had become within the permissible limits in the first day of experiment. So, we didn't continue testing for turbidity up to the 10$^{th}$ day of experimentation.

#### 2.7.3. The pH Value

The pH is a measure of the intensity of acidity or alkalinity and measures the concentration of hydrogen ions in water. It has no direct adverse effect on health; however, a low value, below 4.0 will produce sour taste and higher value above 8.5 shows alkaline taste. A pH range of 6.5 – 8.5 is normally acceptable as per the guidelines suggested by different organizations

[11]. In this study, the fluctuation of pH in the samples was found to range from 6.80 to 7.06, which is within the standard.

### 2.7.4. Total Dissolved Solids (TDS)

TDS may be considered as a salinity indicator for the classification of water samples. The TDS in water is due to the presence of Calcium, Magnesium, Sodium, Potassium, Bicarbonate, Chloride and Sulphate ions. The TDS of the filtered water, in our case, was found to vary from 190 to 464 mg/l and that of unfiltered water was 500. While, the prescribed limit of TDS for drinking water is 500 mg/l, all the water samples had TDS concentrations below the prescribed limit.

**Table 5: Laboratory results of filtered water parameters with different grades of HSSF**

| S/No. | Grades | | | Parameters | | |
|---|---|---|---|---|---|---|
| | | T$^{o}$ ($^{o}$c) | Turbidity (NTU) | pH | EC (µs) | TDS (mg/l) |
| **1** | 5% | 22.1 | 3.93 | 7.06 | 283.00 | 190.00 |
| **2** | 10% | 21.7 | 4.90 | 6.92 | 314.00 | 210.00 |
| **3** | 20% | 21.6 | 49.00 | 6.85 | 382.00 | 256.00 |
| **4** | 30% | 21.5 | 55.50 | 6.82 | 692.00 | 464.00 |
| **5** | Pre-filtration | 21.0 | 75.00 | 6.80 | 745.00 | 500.00 |

Finally, HSSF was found to be very effective in removing total turbidity, and able to decrease EC and TDS of water. Filtration using HSSF with 5% and 10% grades showed safe values for drinking purposes; while, filtering at 5% slope is very effective.

### 2.7.5. Microbiological Analysis

HSSF is a highly biologically active unit; therefore, the filter has to be operated for several days to develop a biological film (schmutzdecke) on the grain of the filter until the purifying bacteria become well established and plays an important role in the treatment process [14-16]. According to Bellamy et al. [17], the biological conditions governing the effectiveness of the slow sand filter are:

(i) The degree of scum formation and

(ii) The microbiological maturity of the sand bed

In this study, the microbial quality was monitored for 10 consecutive days, and samples had been collected both from the influent and effluent. It was observed that the qualities were improved and potable water was achieved after the 9$^{th}$ day of experimentation. The HSSF, in this experiment, was provided with a 5% slope. This was made purposely to increase the flow rate from the filter. The microbial analysis results are therefore presented in the table below and fig. 8. According to the results shown in table 6 and figure 8, HSSF was found to be effective in removing coliform bacteria as well.

Table 6: Coliform test results

| Day | Influent Conc.(Average) - cfu/100mL | Effluent Conc. (Average) - cfu/100mL |
|---|---|---|
| **1** | Unable to count (more than 300) | 177 |
| **2** | Unable to count (more than 300) | 70 |
| **3** | Unable to count (more than 300) | 49 |
| **4** | Unable to count (more than 300) | 36 |
| **5** | Unable to count (more than 300) | 28 |
| **6** | Unable to count (more than 300) | 15 |
| **7** | Unable to count (more than 300) | 08 |
| **8** | Unable to count (more than 300) | 02 |
| **9** | Unable to count (more than 300) | 0.0 |
| **10** | Unable to count (more than 300) | 0.0 |

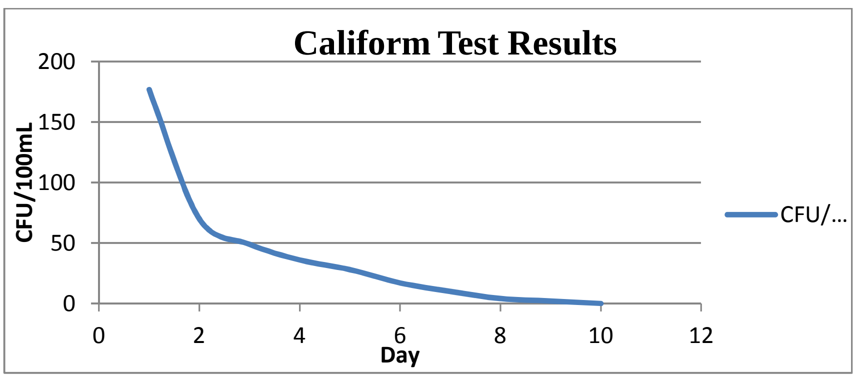


Figure 8: Coliform Test Results

In general, HSSF was found to be very effective in removing turbidity and coliforms. The average percent removal of coliforms was found to be 100% with effect from the 9$^{th}$ day. This is therefore in agreement with the findings of Ellis and Bellamy et al. [14, 17]. Therefore, developing a household HSSF would help in protecting the people from waterborne diseases.

## 3. Conclusions and Recommendations

In conclusion, slow sand filtration has been recognized as an appropriate technology for drinking water treatment in rural areas, and is recognized as a suitable filtration technology in reducing turbidity and coliform concentrations. It is capable of improving the physical, chemical, and microbiological quality of water in a single treatment process without the addition of chemicals, and can produce an effluent low in turbidity and free of bacteria.

In this study, the efficiencies of the HSSF at laboratory level in removing total turbidity and coliform bacteria were evaluated. Water analyses from the influent using HSSF with 5% and 10% grades showed that it is safe for drinking purpose, from turbidity and flow rate required to satisfy family need points of views. Moreover, the filter was able to remove coliforms 100% at the 9$^{th}$ day of analysis and monitoring. Thus, the baseline information generated from this study may contribute to develop a household-scale HSSF with a low cost water treatment process which can be operated and maintained by a member of the families.

Based on the findings, the following recommendations can be formulated:

- On the basis of this research, HSSF is an attractive option for supplying water treatment to family units in rural areas of developing countries.
- Decreasing the size of filter media from medium sand to fine sand and increasing the length of the filter are suggested to improve the filtration capacity.
- Education about waterborne diseases, sanitation and hygiene should accompany during the installation of the filter.
- Any shortcomings of the HSSF are likely best addressed by user education about the operation, maintenance and proper monitoring of the filter media preparation and installation, and of fundamental hygiene practices, but the basic principles of the technology are sound.

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