Journal of Global Resources Volume 2 January 2016 Page 136-144
ISSN: 2395-3160 (Print), 2455-2445 (Online)

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PERFORMANCE OF HORIZONTAL-FLOW ROUGHING FILTER UNITS (HRF) UNDER VARIED RAW WATER CONDITIONS IN KENYA

C.N. Mushila*[b], G.M.M. Ochieng[a], F.A.O. Otieno[c], S.M. Shitote[b] and **C.W. Sitters[b]**
[a] Faculty of Engineering, Vaal University of Technology, South Africa
[b] School of Engineering, Moi University, Eldoret, Kenya
[c] Masinde Muliro University of Science and Technology, Kakamega, Kenya
*Email: collymush@gmail.com

Abstract: *Horizontal flow Roughing filter units (HRF) have been found to be the most effective and appropriate pre-treatment method used before slow sand filters (SSF) for application in developing countries. The main advantage of HRF being its simplicity in design, have low capital cost, ability to separate fine solids particles over prolonged periods (high solids retention capacity) without addition of chemicals. Most research on HRF has concentrated on turbidity (solids removal) whereas its role in removal of other parameters of concern such as microbiological (Faecal and Total coliform), colour, dissolved iron and manganese has received little attention. The general objective of this research was to evaluate the performance of HRF units by way of their removal efficiencies for the various water quality parameters under varied raw water conditions. In order to meet this objective a pilot plant unit was designed and run. The pilot plant was monitored between the months of January to June 2013. The response of the respective HRF units in removal of selected parameters guiding drinking water quality such as microbiological (Faecal and Total coliform), Turbidity, Suspended Solids (SS), dissolved iron and Manganese was investigated. With respect to microbiological raw water quality improvement, HRF units reduced Faecal coliforms load by 36 percent and Total coliforms load by 38 percent respectively*

Keywords: Horizontal-flow Roughing Filter, pre-treatment of drinking water, slow filtration

Introduction

In the year 2000 access to safe drinking water in Kenya was 58 percent (UNFPA report, 2003). In this report, access to improved water source for Kenya is reported as 46 percent for the Rural and 89 percent for the urban populace. The 2008 population estimates for Kenya are 38,765,312 (WB 2010). It is clear that a significant number of people in Kenya, particularly in the rural areas, do not have access to safe drinking water leading to numerous water-related outbreaks such as typhoid fever and cholera. A simple low cost water treatment system is required in Kenya in order to alleviate the problem of in accessibility of the potable water to the rural community. Slow Sand Filtration (SSF) has been recognized as an appropriate technology for drinking water treatment in rural areas, and is recognized as a suitable filtration technology for removing waterborne pathogens *(Galvis, G. 2006).* 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 and viruses. In fact, Wegelin (1988) states, “no other single water treatment process can improve the physical, chemical, and bacteriological water quality of surface water better than Slow Sand Filtration”. In addition, the USEPA (1997) states, “when used with a source water of appropriate quality, Slow Sand Filtration may be the most suitable filtration technology for small systems”. These two statements elucidate the important role of Slow Sand Filtration for treating surface water in small systems.

The main drawback of Slow Sand Filtration is its inability to treat high turbidity surface water without the rapid development of head-loss and frequent clogging of the filter. Ellis (1985). A proven treatment method to cope with many of the limitations of Slow Sand Filtration is Multi-Stage Filtration (MSF). MSF is a robust, multi-barrier treatment method, which consists of pre-treatment with roughing filtration followed by Slow Sand Filtration. The MSF technology is still unknown in many countries including Kenya and hence the need to research on its adaptability in such countries (Ochieng, 2001). Horizontal flow Roughing filter units (HRF) have been found to be the most effective and appropriate pre-treatment method used before slow sand filters (SSF) for application in developing countries. This research endeavoured to investigate the water quality improvement performance of HRF units beyond its normal role of protecting the operational conditions of SSF against high turgidities and Suspended Solid (SS). Implementation of this technology as a pre-treatment to SSF will mean increased accessibility to potable water in Kenya.

Objectives

The general objective of this research was to evaluate the performance of HRF units by way of their removal efficiencies for the various water quality parameters under varied raw water conditions.

The specific objectives involved designing and constructing Laboratory model Horizontal-flow Roughing Filters (HRF). The effect of varying HRF gravel pack ratios and Series connection of two HRF units was also investigated. The parameters of interest were Coliform bacteria, colour, dissolved iron and Manganese.

Study area

The pilot plant was set up at Moi University Water Treatment Works in Kesses Division, which is about 36 kilometres South East of Eldoret town in Kenya. Eldoret falls within Uasin Gishu County. Uasin Gishu County lies on coordinates: 0^{o}310N 35^{o}170E.The County has a cool and temperate climate with mean annual rainfall 1100 to 1200mm. Temperature during wet season drops to 18^{0}C and dry season records a temperature of 26^{0}C. There are four noticeable soil types in the district: red loam, red clay, brown clay and brown loam.

Horizontal-flow Roughing Filter (HRF)

A Horizontal-flow Roughing Filter (HRF) consists of a horizontal filter box with 3 or 4 compartments of decreasing length separated by baffles, in which water flows horizontally. Each compartment is filled with gravel, with the coarsest media in the first compartment and the finest media in the last compartment. The advantage of HRF is its extended bed lengths and solids storage capacity, resulting in less cleaning frequency than up-flow Roughing Filters (Collins et al., 1994a). It is also more suitable for treating very high Suspended Solids concentrations. The disadvantage of the HRF is its large space requirements. The horizontal flow roughing filter (HRF) is commonly applied with SSF especially in the developing countries (e.g. Jayalath and Padmasiri, 1996; Mesfin, 1999; Torabian and Fazeli, 2004). To date, the most comprehensive model applied in HRF design is based on Wegelin design criteria founded on the “1/3 – 2/3” filter theory (Wegelin, 1986; 1996).

Wegelin design criteria

Wegelin design criteria is founded on the “1/3-2/3” filter theory and is still to date the most comprehensive model applied in design of Roughing Filters (Wegelin, 1986; 1996). The filter theory is based on Suspended Solids (SS) reduction. The “1/3-2/3” filter theory is classified as conceptual. The investigations of Wegelin et al (1996) describe this theory as follows; by logic or experience, a particle in water can bypass a gravel grain either on the left or right or settle on its surface. Hence the chance to fall on the grain is 1/3. However, the process continues, as there is a second, third and many other gravel grains to settle on. This theory has been used to formulate models, which give a simple elucidation of the removal kinetics of the Roughing Filters and hence further used to describe the filter efficiencies in the design of Horizontal-flow Roughing Filters. According to the mathematical exercise description of this theory, it clearly proves that solid matter separation by filtration can be described by an exponential equation. Based on Fick's law and other established filter theories, the filter efficiency can be expressed by the filter coefficient *λ*.

$$\frac{dc}{dx} = -\lambda c \qquad \text{..} \quad (1)$$

where;

c = solids concentration.

x = filter depth.

λ = Coefficient of proportionality also known as filter coefficient.

Equation (1) states that the removal of suspended particles is proportional to the concentration of the particles present in water. Assuming the total filter length as a multi-tore reactor consisting of a series of smaller filter cells, the performance of an HRF can be calculated on the basis of the filter cell test results. Neglecting straining mechanisms and further assuming surface chemical conditions to be constant, the total suspended solids (SS) concentration after an element *Δx* can be estimated by the following expression;

$$C_{out} = \sum C_{i(in)} e^{-\lambda_i \Delta x} \qquad \text{..} \quad (2)$$

where;

c_i = concentration of particles of size d_{pi}

Δx = the length of the experimental filter cell.

λ_i = filter coefficient for each filter cell.

Equation (2) shows that in knowing the inlet SS concentration, the filter coefficient, and the filter depth (length), the outlet SS concentration can be easily predicted and consequently the filter performance efficiency. This aids in filter design. According to Wegelin (1986; 1996), the effluent quality for an *n* number of compartments is given by the following expression;

$$c_e = c_o \times E_1 \times E_2 \times ..... \times E_n \qquad \text{...} \quad (3)$$

where;

c_o = concentration in the HRF influent.

c_e = concentration in the HRF effluent.

E_i = are the filtration "efficiencies" for i=1,2......n compartments respectively.

The basic expression for the above relationship is;

$$c_e = c_o e^{-\lambda L} \qquad \text{..} \quad (4)$$

where;

L = is the length of filter.

λ = is the coefficient of filtration (also known as filter coefficient).

Where;

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The filter efficiency is given by:

$$E = \frac{c_e}{c_o} = e^{-\lambda L} \qquad (5)$$

$$\therefore c_e = c_o \times E \qquad (6)$$

The values of E_i *(i = 1, 2… n)* are obtained either from tables or graphical nomograms as developed by Wegelin (see mentioned reference for further details).

The HRF pilot unit

To investigate the performance of the HRF units under varied raw water conditions, a pilot plant was built at Moi university water treatment works in the year 2013. This site was convenient because of the readily available raw water. The topography of the site allowed the flow of water by gravity thus avoiding pumping equipment and associated costs. The pilot unit comprised of a Constant head feeder tank supplying raw water to three Horizontal roughing filters. There was no addition of chemicals to the raw water.

Constant Head Feeder Tank

The constant head feeder tank or the Mixing Tank (MT) maintained a constant water head for the units and acted as the first sampling point of raw water. It also served as a unit where the chosen raw water parameters were varied to different levels and the response of the HRF unit investigated. The MT was positioned adjacent to the intake of the raw water at a lower head so as to allow flow of raw water by gravity from the point of abstraction to the SSF unit. The MT unit measured 1.2 m Length, 0.8 m width and 1 m height. The unit was fabricated using Mild Steel (MS) plates (3mm thick).

Horizontal-flow Roughing Filters (HRFs)

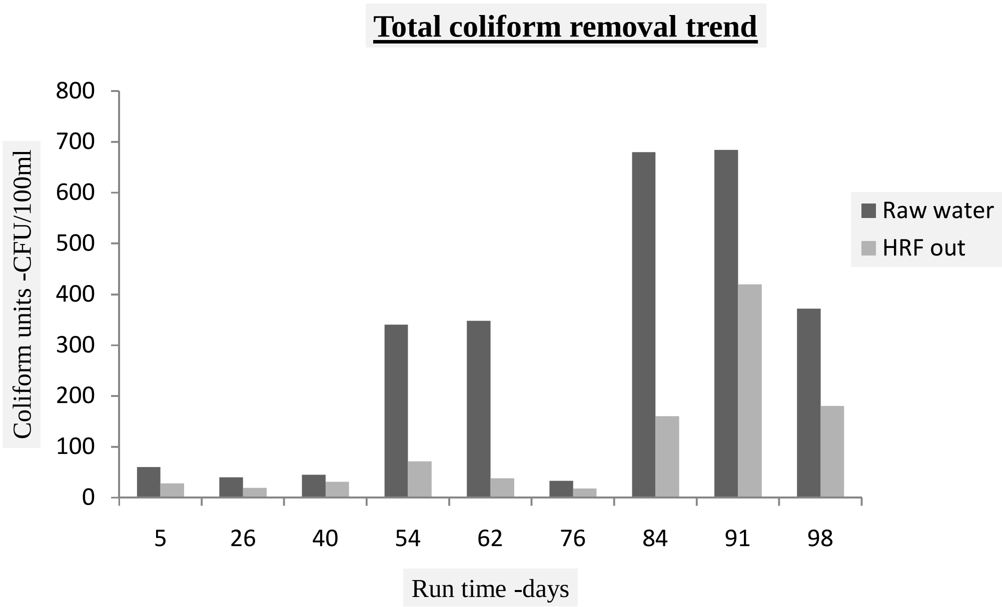
The pilot unit consisted of three lines of Horizontal-flow Roughing Filters (HRFs) (refer figure 1) processing raw water from the MT.The design and sizing of the pilot-plant HRFs were guided by the Wegelin design criteria (Wegelin, 1986) based on the preliminary raw water quality data obtained prior to the commencement of the full pilot-plant study.The units had the same design specifications and were fabricated using Mild Steel (MS) plates (3mm thick). Each measured 5.4m length, 0.5m width and 1m height. The designed HRF unit had three compartments with different sizes of gravel separated with perforated steel plates. Sampling points were identified along the length of each of the HRF unit and also at both inlet and outlet points to monitor the raw water quality improvement. HRF consisted of three parts: the inlet structure, the filter bed and the outlet structure. Inlet and outlet structures had flow control installations (valves). This was meant to maintain the designed flow velocity and water level along the filter bed. An "Equal distribution chamber" was provided at both the inlet and outlet to establish an even flow distribution along and across the filter. The filter bed was composed of 3 gravel packs of different sizes. The filter material was arranged from coarse to fine in the direction of water flow. The coarsest material diameter was in the range 15-24mm, medium material was in the range of 8-15mm and the finest from 4-8mm. These filter media packs were separated with perforated Mild Steel (MS) plates to avoid mixing. The filter bed was provided with under drainage system to enable hydraulic sludge extraction to be carried out after a certain running period. The HRF unit was operated at a constant filtration velocity of 0.5m/h.

RESULTS AND DISCUSSIONS

Bacteriological quality improvement

The HRF unit played a significant role in both Faecal and Total coliform reduction. On average, the HRF unit reduced Faecal coliform load of SSF influent by 36 percent and Total coliforms load by 38 percent respectively. Figure 1 shows Total Coliform removal trend in HRF units. It is important to note that efficiencies may be somewhat site specific as there is some variation in the findings from several authors.

Figure 1 Total Coliform removal trend in HRF units.



Removal of Iron and Manganese

It was noted that HRF units also played a critical role in both Iron and Manganese reduction. On average, HRF units reduced dissolved Iron load of SSF influent by 42 percent and Manganese by 57 percent. Figure 2 and 3 show the Manganese and dissolved Iron removal trends.

Figure 2 Manganese removal trend

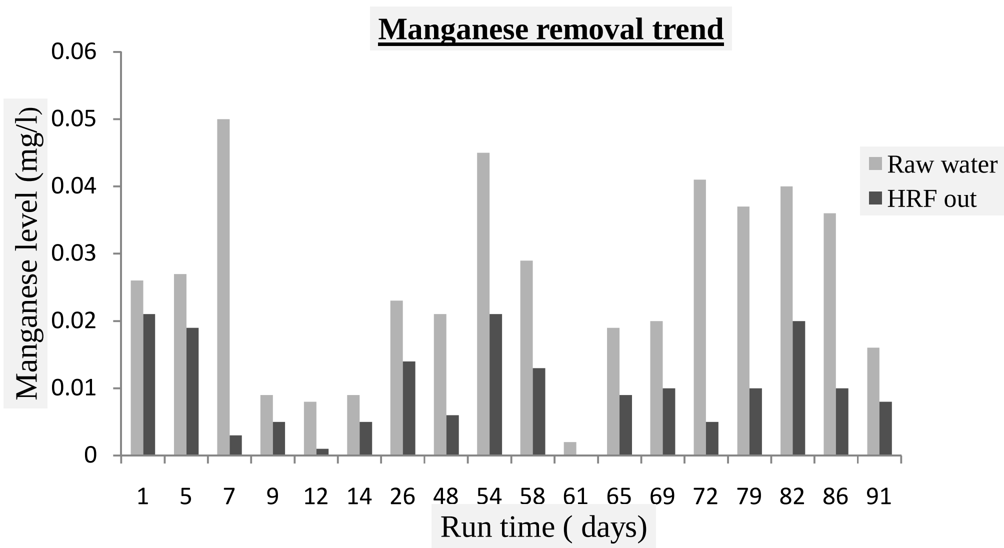
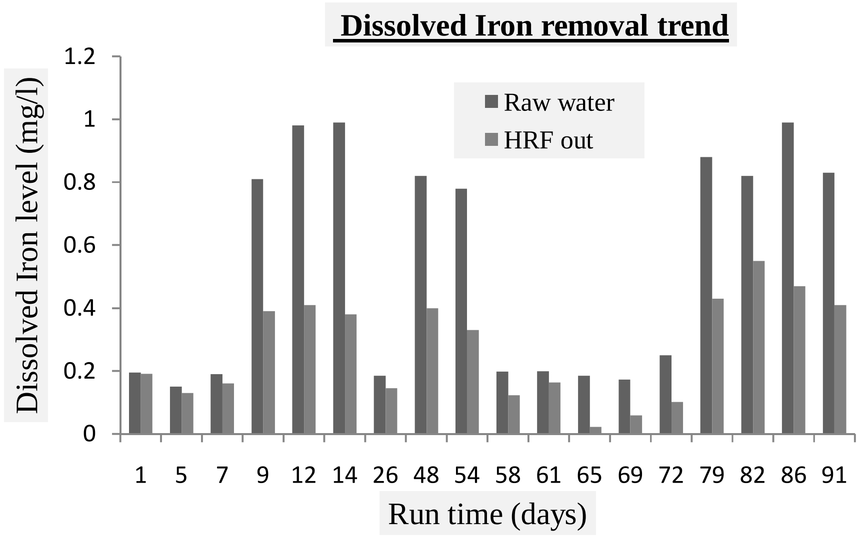


Figure 3 Dissolved Iron removal trend



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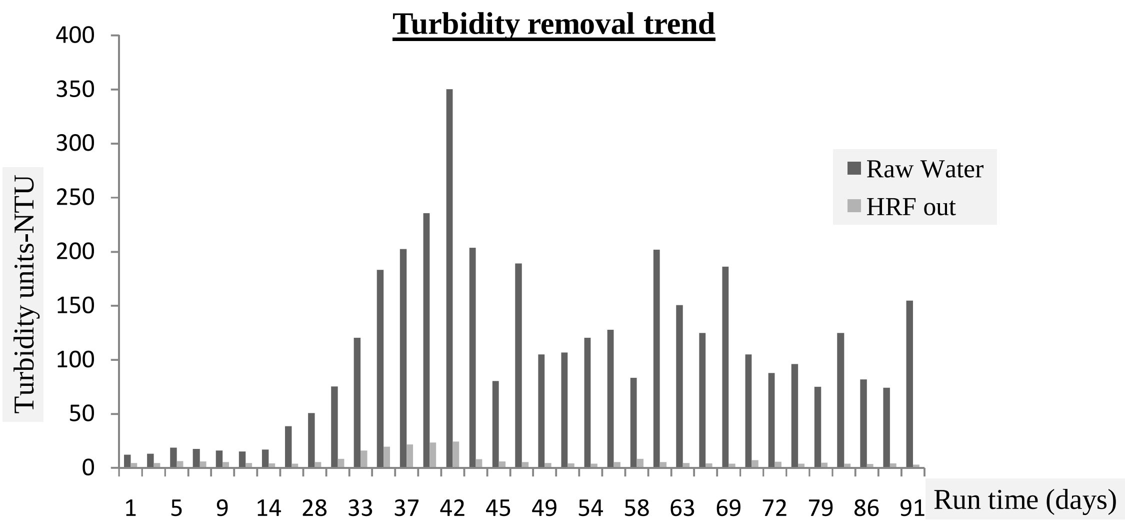
Removal of Turbidity

From the field data, it was observed that on average, the HRF unit registered 86 percent Turbidity and 85 percent SS removal. Figure 4shows the Turbidity removal trends by HRF units. The average Turbidity of water flowing from HRF unit was 8.28 NTU. According to most research findings in the field of Slow Sand Filtration, Turbidity levels to the Slow Sand Filters should be less than 10 NTU, hence the average Turbidity values from HRF units was within acceptable standards.

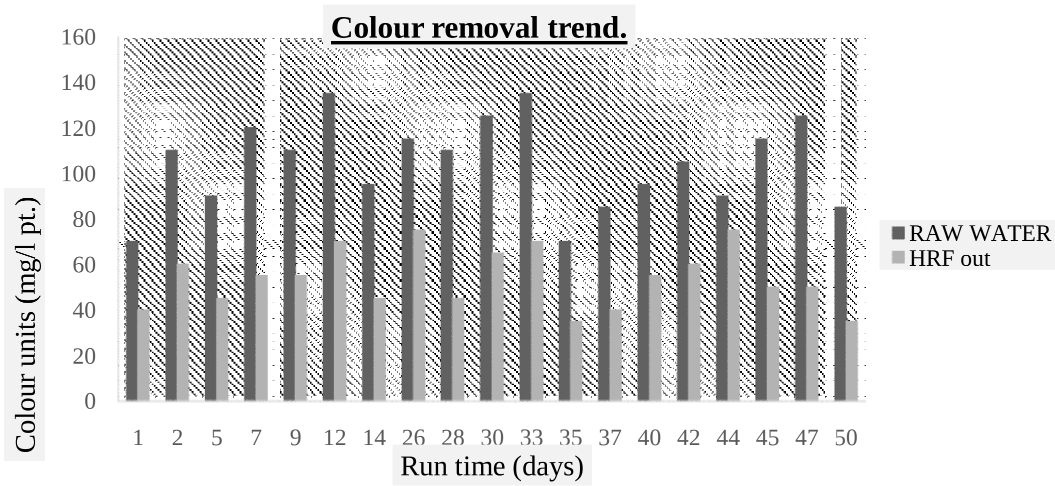
Figure 4 Turbidity removal trend by HRF units



Colour removal trend by HRF

The colour removal trend in the three HRF units proved that they are not as efficient in colour removal relative to values gotten for turbidity and SS respectively. Figure 5 shows colour removal trend in HRF units. The HRF units achieved an average of 50 percent colour removal.

Figure 5 Colour removal trend by HRF units



Varying Horizontal Roughing .Filter (HRF) gravel pack ratio.

Gravel was used as the filter media in the HRF unit, the unit had three chambers holding different sized Gravel material (Gravel packs) as discussed earlier. In order to achieve the objective of this research, the HRF was designed to allow variation of the ratios of the gravel packs. This was meant to examine its impact on raw water quality improvement. Sampling points were identified at the inlet, along the filter media and outlet of each HRF unit to examine raw water quality improvement. The following gravel pack ratios were analysed in this research;

1) 2:2:1 {*i.e. 2 metres (dg 15 -24mm), 2 metres (dg 8-15mm), 1 metre (dg4-8mm).*}
2) 1:2:2{*i.e. 1 metre (dg 15 -24mm), 2 metres (dg 8-15mm), 2 metre (dg4-8mm).*}
3) 1.5:1.5:2 {*i.e. 1.5 metres (dg 15 -24mm), 1.5 metres (dg 8-15mm), 2metre (dg4-8mm).*}

During the first month of this study, the HRF units operated at the same ratio of 2:2:1. Water tests done on HRF effluent showed similar trends with respect to Turbidity and suspended solid removal. A constant minimal filtration rate of 0.5 m/h was maintained in the three HRF units to give optimal results. After the first month, each HRF units were set at a different ratios and the impact on overall raw water quality improvement noted.

Table 1: HRF units Percentage removal (different ratios)

HRF UNITS	"Gravel pack" ratio	Percentage removal. Turbidity	Percentage removal. SS
HRF 1	2:2:1	88	87
HRF2	1:2:2	89	88
HRF 3	1.5:1.5:2	88	88

Source: Field data

Table 1 shows the average percentage removal of Turbidity and SS by the three HRF units. It was noted that there wasn't great variation with respect to percentage Turbidity and Suspended Solids removal by the units. HRF 2 gave the best performance with 89 percent removal of turbidity and 88 percent removal of Suspended solids. This was attributed to the fact that this unit provided a large length or surface area of fine filter media material, hence it was possible for this unit to intercept fine suspended matter that escaped through the first chamber thus resulting into better water effluent. However, it was noted that HRF2 experienced frequent clogging relative to the other two HRF units- especially during heavy rain events, hence a short filter run period. This necessitated frequent hydraulic cleaning in this unit whenever the raw water had high turbidity and SS levels. It was on these grounds that it was concluded that although HRF 2 gave good results, it is not advisable to operate such gravel pack ratio combination in high turbid waters since it would result in short filter runs and tedious cleaning and maintenance activities. This would compromise the sustainability of such a system. On the other hand, HRF1 was considered as the best alternative in high turbid water. This was because it gave the longest filter run period of about 2 to 3 weeks depending on the raw water quality.

Connecting two HRF units in series

The HRF was connected in series when the raw water turbidity levels were higher than 120 NTU. This was because, it was realized from field analysis that whenever Turbidity levels were higher than 120 NTU, HRF effluents recorded high values of more than 10 NTU. By connecting the HRF in series it was possible to minimize the Turbidity level to less than 10 NTU and achieve high efficiencies in removal of SS. Two HRF units connected in series achieved very high efficiency levels, recording an average of 95 percent in terms of turbidity removal and an average of 98.4 percent with respect to Suspended solids removal. The high efficiency with respect to turbidity removal was attributed to a high surface area of filter media provided by connecting the two units in series

CONCLUSIONS AND RECCOMMENDATIONS

- **Performance of HRF**

✓ HRF unit registered 86 percent turbidity and 85 percent Suspended Solids removal. HRF units apart from being used as a pre-treatment of turbidity and Suspended Solids it also played a significant role in both Faecal and Total coliform reduction. On average, HRF units reduced Faecal coliforms load by 36 percent and Total coliforms load by 38 percent respectively. It was also noted that HRF units also played a crucial role in both Iron and manganese reduction. On average HRF, units reduced dissolved iron load of SSF influent by 42 percent and manganese by 57 percent.

✓ The HRF operated in the range 1 to 3 weeks depending on the raw water quality. The main pointer to this observation is because Horizontal Roughing Filter (HRF) this unit had very large surface area which allowed storage of high volume of Suspended Solid or Sludge before hydraulic cleaning.

✓ Connecting the HRF units in series yielded very high efficiencies in terms of Turbidity and SS solids removal recording levels as high as 98 percent with respect to SS and turbidity.

Recommendations

✓ Research to examine the impact of media size and hydraulic loading rate on the removal of colloidal matter in HRF filters should be carried out.

✓ Further research targeting the optimization of HRF units should be conducted.

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