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Full Length Research Paper

A comparison of horizontal roughing filters and vertical roughing filters in wastewater treatment using gravel as a filter media

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Roughing filtration can be considered as a major pretreatment process for waste water, since the process efficiently separate fine solid particles over prolonged periods without addition of chemicals. Roughing filters mainly act as physical filters and reduce the solid mass. However, the large filter surface area available for sedimentation and relatively small filtration rates also supports adsorption as well as chemical and biological processes. Therefore besides solid matter separation, roughing filters also partly improve the bacteriological water quality and to a minor extent, change some other water quality parameters such as colour or amount of dissolved organic matter. This article evaluates modifications to roughing filtration technology, which may address these limitations without compromising the simplicity of the treatment process and also compare the efficiency of horizontal roughing filters and vertical roughing filters. Successful modifications include the design concept and process capabilities for roughing filter. Achieved results in this study shows that Horizontal roughing filters perform better than vertical roughing filters due to unlimited filter length, simple layout and less susceptible than vertical-flow filters to solid breakthroughs caused by flow rate changes in the filters.

Key words: Roughing filters, horizontal roughing filters, adsorption and vertical roughing filters.

INTRODUCTION

Water supplies continue to dwindle because of resource depletion and pollution, whilst demand is rising fast because of population growth, industrialisation, mechanisation and urbanisation (Falkenmark, 1994). This situation is particularly acute in the more arid regions of the world where water scarcity and associated increases in water pollution, limit social and economic development and are linked closely to the prevalence of poverty, hunger and disease (Falkenmark, 1994).

Water is essential to life on our planet. Over 70% of the water used in both rural and urban areas in South Africa is surface water drawn from rivers, streams, lakes, ponds and springs (DWAF, 2004). This fundamental resource is of such importance because no living organism can survive without water. Therefore there is a demand for clean, unpolluted water in substantial supply. This scenario thus calls for efficient and effective treatment of water from such sources before use, to avoid instances of water–borne and water related diseases such as typhoid fever and cholera. It has also been known that inadequate water supply both in terms of quantity and quality coupled with poor sanitation globally account for approximately 30, 000 deaths daily, many of them infants and 80% of such cases occur in rural areas (Ochieng and Otieno, 2006).

Roughing filtration

Filtration is one of the oldest and simplest methods of removing contaminants in surface water (Wegelin, 1996). Generally, filtration method includes slow sand filtration and roughing filtration. The slow sand filters constructed in rural communities show that many of these filters have short filter runs and produce turbidity in the excess of the WHO guideline values for drinking water (Jayalath, 1994). Reliable operation of sand filtration is possible when the raw water has low turbidity and low suspended solids (Graham, 1988). For this reason, when surface waters are highly turbid, ordinary sand filters could not be

Table 1. Different sizes of roughing filter media.

Media description	First compartment (mm)	Second compartment (mm)	Third compartment (mm)
Coarse	24 - 16	18 - 12	12 - 8
normal	18 - 12	12 - 8	8 - 4
Fine	12 - 8	8 - 4	4 - 2

used effectively. Therefore, the roughing filters are used as pretreatment systems prior to sand filtration (Jayalath, 1994). Furthermore, roughing filters could reduce organic matters from wastewater. Therefore, roughing filters can be used to polish wastewater such as mine water before it is discharged to the environment (Younger, 2001). Although roughing filtration technology is used as pre-treatment to remove turbidity and followed by slow sand filtration, it may be used without slow sand filtration if raw water originates from well protected catchment and if it is free from bacteriological contamination (Wegelin, 1996). Roughing filters use natural purification processes and no chemicals are necessary. Besides these, filters could be built from local materials and manpower. These filters will work a long time without maintenance (Wegelin, 1986). Therefore, roughing filters are appropriate and economical for rural water supply schemes. They are grouped into vertical roughing filters and Horizontal roughing filters.

Roughing filter design parameters

The basic roughing filter design parameters may be classified to include the following: (1) Filter media sizes (2) Filtration rate (3) Filter length.

Filter media size

Media types commonly used in roughing filtration are quartz sands and gravels but can be replaced by any clean, insoluble and mechanically resistant material (Graham, 1988). Previous work by Wegelin (1986) showed that the effect of surface porosity and roughness of filter media on particle removal efficiency in roughing filtration was insignificant compared to the size and shape of macro-pores in the filter. Rooklidge and Ketchum (2002) studied the removal efficiencies in calcite limestone, basaltic river rock and limestone-amended basalt horizontal roughing filters and found only marginally improved efficiency (7%) for calcite amended basalt filters over unaltered filters. Improved removal efficiencies are generally correlated to smaller media sizes (Collins, 1994; Wegelin, 1986).

The use of multiple grades of filter media in a roughing filter promotes the penetration of particles throughout the filter bed and takes advantage of the large storage capacities offered by larger media and high removal efficiencies offered by small media. The size of filter media decreases successively in the direction of water flow and ideally the uniformity of filter media fractions is maximised to increase filter pore space (storage capacity) and aid in filter cleaning (Boller, 1993). Common grades of media used in roughing filters are provided by Wegelin (1996) and shown in Table 1.

Filtration rate

Filtration rate also has a significant influence on the treatment removal. Good removal in roughing filters are best achieved with low filtration rates (Boller, 1993), because low filtration rates are critical to retain particles that are gravitationally deposited to the surface of the media. While as pretreatments used for removal of iron and manganese were able to operate at filtration rates of 1.5 - 3 m/h (Hatva, 1988). Researchers like (Jafari Dastanaie, 2007) reported that horizontal flow roughing filter is capable of removing metals like iron, manganese, turbidity and colour at a filtration rate of 1.8 m/h.

Wegelin (1986) found that at increased filtration rates (2 m/h), coarse particles penetrate deeper into the bed and these will cause decrease in filter efficiency. Whereas at 1 m/h there was a good distribution of solids loading throughout the bed. Hendricks (1991) also suggested that normal filtration rate of horizontal roughing filters is between 0.3 and 1.5 m/h.

Filter length

Improved cumulative removal efficiencies are typically correlated to longer filter lengths (Collins, 1994; Wegelin, 1986). However, incremental removal efficiencies tend to decrease with increasing filter length due to the preferential removal of larger particles early in the filter (Wegelin, 1996). The rate of decline is dependent on filter design variables and the size and nature of particles in suspension. The use of different media sizes may allow for treatment targets to be met by a shorter filter with multiple media sizes compared with long filter packed with one media size. This is shown in Figure 1.

Filter bed depth also affects efficiency of roughing filters. While particles deposits on the filter bed, pore spaces becomes smaller. As suspended particles,

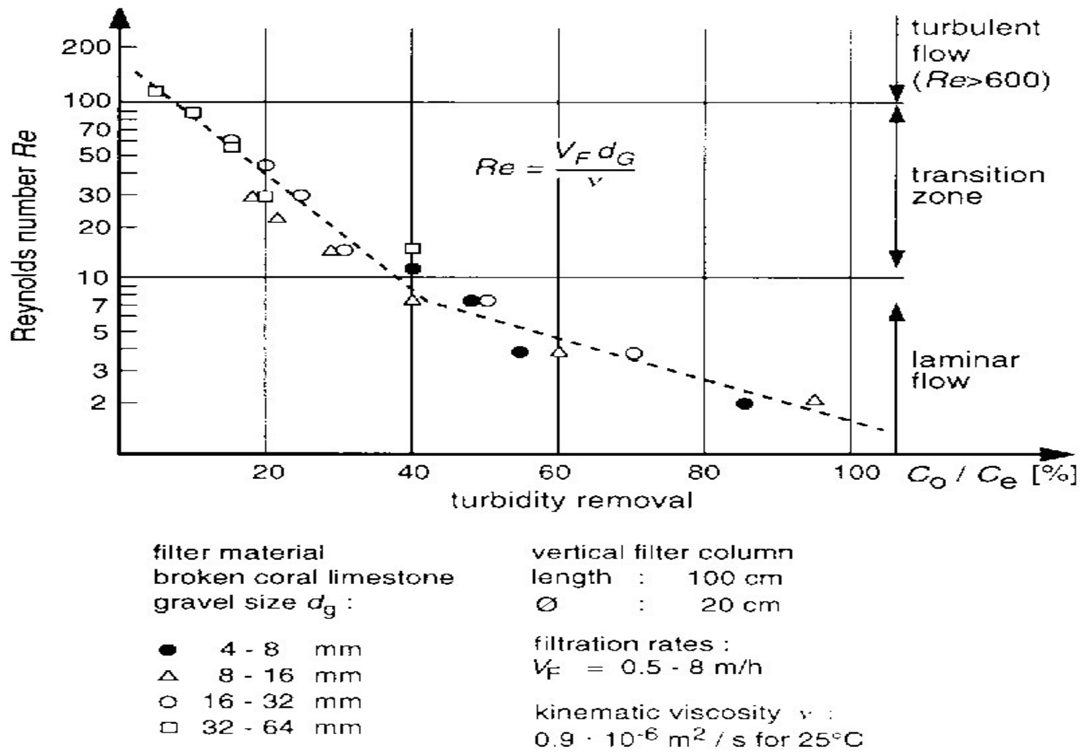

Figure 1. Roughing filter efficiency in correlation to flow conditions (Wegelin, 1996).

accumulate on the filter bed, the pressure drop through the filter and increased the efficiency of the system (Wegelin, 1996). Operating with high-pressure drop may increase the chance of detachment and penetration of detached solids will move deeper into the filter bed. Therefore, increasing filter bed's depth will improve overall performance and coliform removal. On the contrary, Reed and Kapranis (1998) described that there was no significant difference between two bed depths of 0.75 and 1.0 m. Although they did not discuss in detail, the reason might be that they used large size filter media in the experiment. Lee (2003) indicated that improved cumulative removal efficiencies are typically correlated to longer filter lengths at the expense of pressure drop. Without affecting the removal efficiency, the filter length and thus the pressure drop can be reduced with the use of multiple media sizes. Wegelin (1996) revealed that roughing filters were good for removal of major solid particles and for highly turbid waters. Clark et al., (1997) described filtration performance depends on the source of water quality (types and concentration of natural organic matter and suspended particles) and viscosity changes in raw water would affect filter's performance. Beside, the particle sizes and nature (organic and inorganic) also have a significant influence on its removal in roughing filter (Wegelin, 1996). (Wegener, 2003) strongly supported that suspended solid removal was less than 50% at the particle size of 5-10 µm and almost 100% at particle size of 50 - 100 µm in the trickling filter using low density plastic filter media. This is shown in Figure 2.

In summary, performance of roughing filter depends on influent solids concentration, particle size, filter media size, bed depth and filtration rate. Roughing filter design becomes more of an art than science when attempting to determine the optimal combination of media size and bed depth for particular source of water (Wegelin, 1996).

Media types commonly used in roughing filtration are quartz sands and gravels from river but can be replaced by any clean, insoluble and mechanically resistant material (Graham, 1988). Previous work by Wegelin (1986) showed that the effect of surface porosity and roughness of filter media on particle removal efficiency in roughing filtration was insignificant compared to the size and shape of macro-pores in the filter. Rooklidge and Ketchum (2002) studied the removal efficiencies in calcite limestone, basaltic river rock, and limestone-amended basalt horizontal roughing filters and found only marginally improved efficiency (7%) for calcite amended basalt filters over unaltered filters. Improved removal efficiencies are generally correlated to smaller media sizes (Collins, 1994; Wegelin, 1987).

The use of multiple grades of filter media in a roughing filter promotes the penetration of particles throughout the filter bed and takes advantage of the large storage capacities offered by larger media and high removal

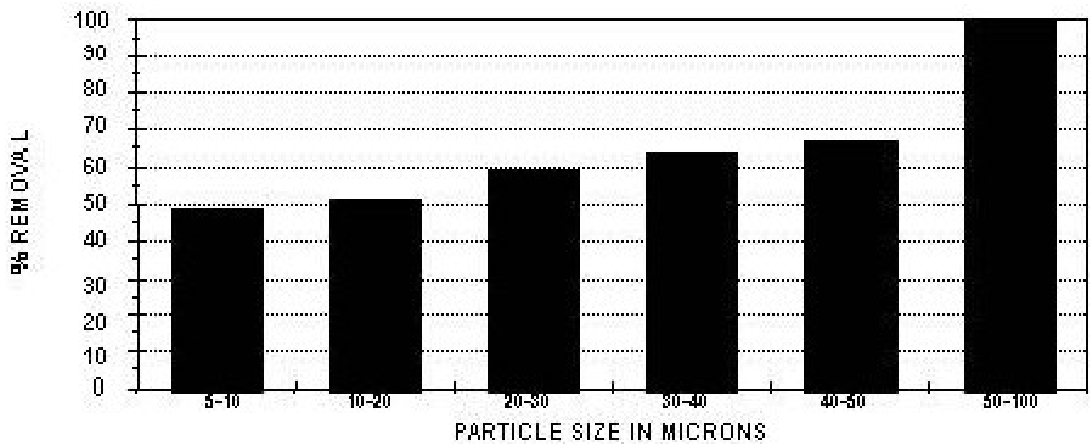

Figure 2. Percentage removal versus particle size (Wegener, 2003).

efficiencies offered by small media. The size of filter media decreases successively in the direction of water flow, and ideally the uniformity of filter media fractions is maximised to increase filter pore space (storage capacity) and aid in filter cleaning (Boller, 1993).

Factors affecting roughing filter performance

The disadvantage of roughing filters is low hydraulic load. The only way to provide sufficient treated water to meet a high drinking water demand would be to build a larger RF unit (Boller, 1993). The filtration rate (m/h) depends largely on the type of filter, the water characteristics, desired turbidity reduction, variations in the filter media (porosity), each filter medium's proportion, the number of filter fractions and height and width of filter bed. The most influential factor for turbidity removal efficiency in the raw water is particle sizes and distribution.

Filter efficiency depends on the concentration of suspended solids. The 1/3 and 2/3 Filter theory explains how each layer removes about 1/3 of the particles letting the other 2/3 flow to the next layer (Wegelin, 1996). This continues at each layer, because there is a greater concentration of particles at the first layer, more particles are removed than in latter layers. Intermittent flow operation can greatly decrease the particle removal efficiency because it is possible that the biofilm around the coarse media might have dried and lost its sticky properties (Galvis, 2006).

High sludge storage space can be advantageous in lengthening filter runs but becomes problematic when the filter finally needs to be cleaned. Its buffering capacity to manage fluctuating solid concentrations exists because the large pore spaces allow considerable amounts of solids to be stored at very low head loss (Boller, 1993). Periodic drainage through perforated or corrugated pipe may be able to improve the filter run time between cleanings and needs to be further developed (Boller, 1993). Scraping of the top layer of biofilm on a weekly basis could also improve the filter run time. Fully unpacking the media and cleaning it is one of the biggest drawbacks of the RF even when the media is readily accessible as it is in HRF (Horizontal roughing filter).

Vertical flow roughing filters

Vertical-flow roughing filters operate either as down flow or up flow filters. They are hence either supplied by inflowing water at the filter top or at the filter bottom. The vertical flow roughing filters incorporates a simple self cleaning mechanism and occupies minimal floor space when compared to horizontal flow roughing filters (Dastanaie, 2003).

The filter material of vertical-flow roughing filters is completely submerged. A water volume of about 10 cm depth usually covers the gravel and other local available materials such as charcoal, coconut fibre and broken burnt bricks. The top should be covered by a layer of coarse stones to shade the water and thus prevent algal growth often experienced in pretreated water exposed to the sun. Drainage facilities, consisting in perforated pipes or a false filter bottom system, are installed on the floor of the filter boxes. Finally, pipes or special inlet and outlet compartments are required to convey the water through the subsequent three filter units (Wegelin, 1996) and they are shown in Figure 3.

Horizontal flow roughing filters

As shown in Figure 3, unlimited filter length and simple layout are the main advantages of horizontal roughing filters (Wegelin, 1996). Horizontal roughing filters have a large silt storage capacity. Solids settle on top of the filter medium surface and grow to small heaps of loose aggregates with progressive filtration time. Part of the

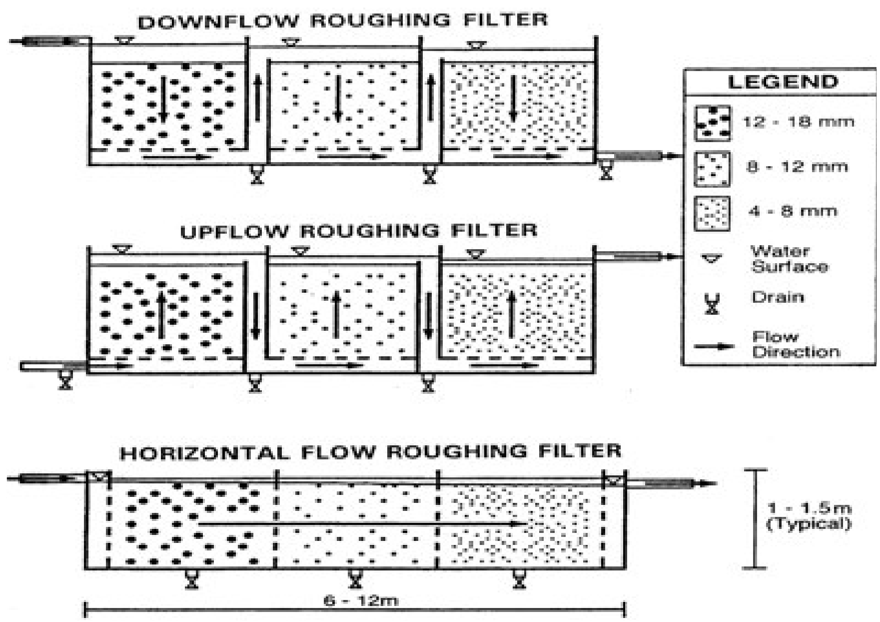

Figure 3. The diagram of horizontal and vertical roughing filters.

small heaps will drift towards the filter bottom as soon as they become unstable. This drift regenerates filter efficiency at the top, and slowly silts the filter from bottom to top (Wegelin, 1996).

Horizontal-flow roughing filters also react less sensitively to filtration rate changes, as clusters of suspended solids will drift towards the filter bottom or be retained by the subsequent filter layers. Horizontal-flow roughing filters are thus less susceptible than vertical-flow filters to solid breakthroughs caused by flow rate changes. However, they may react more sensitively to short circuits induced by a variable raw water temperature (Wegelin, 1996).

Practical experiences with vertical roughing filters

A Vertical flow pilot plant was designed and run by Dastanaie et al at the bank of Zayandehroud River near the village of Chamkhalifeh in 2003. In order to provide required head, the pilot was installed 2 m below the elevation of river bed. Water was conducted towards the filter via a man made conduit. The filter is comprised from three different parts which are separated with perforated baffles. Each compartment is filled with some local sand and gravel from nearby river considering a special decreasing size regime. In other words, the diameter of stuffs in the compartments is decreased from 25 - 15 mm in the first compartment to 15 - 8 mm in the second and 8 - 4 in the last one. The average height of materials in the filter is 2.5 m and water always undergoes a subsurface flow beneath the surface of the filter. In order to monitor the quality of outlet water, parameters like Total Suspended Solids (TSS), turbidity, color and fecal coliforms as well as ions like iron and manganese are being compared between inlet and outlet water. The comparison between the values of mentioned parameters in inlet and outlet water is illustrated in Table 2. As it is shown in the figures, the overall function of the filter in removing turbidity and TSS is acceptable. Additionally, iron, manganese and color removal are also been covered to some extent.

A pilot plant was constructed by Reed and Kapranis (1998). The filter model chosen for the research was the vertical upflow type using a single size aggregate. The vertical upflow type was chosen because it incorporates a simple self cleaning mechanism and occupies minimal floor space when compared to horizontal flow roughing filters. Two identical filters were set up to run in parallel in the laboratory, one with polystyrene media and the other with gravel of similar size. The manufactured water quality for turbidity was chosen to be within the indicative raw water quality limits for water treatment systems as reported by Galvis et al. (1993): turbidity 100 to 200 NTU. The filters ran for 40 days. The filtration rate was 0.75 m/h. Two 300 mm diameter PVC pipes were used to hold the media. The filter media depth was 1.0 m and the under drain was 0.5 m in depth. The filter achieved an average 42% turbidity reduction in the filter.

Practical experiences with horizontal roughing filters

Horizontal roughing filter was investigated by Ochieng and Otieno (2004) in a pilot plant built at Moi University in Kenya using broken burnt bricks and charcoal, as filter media for removal of suspended solids and turbidity. They noted that broken burnt bricks and improved agric-

Table 2. Removal efficiencies of the filter.

Parameter	Unit	Inlet	Outlet	Removal (%)
Turbidity	NTU	3.528	1.29	63.4
Colour	mg/l	0.8	0.6	20
Iron	mg/l	0.083	0.07	15.6
manganese	mg/l	0.0417	0.015	64
TSS	mg/l	18.93	1.95	89.7
Coliforms	MPN	112.6	6.74	94

cultural waste (charcoal Maize cobs), can also be effectively used as pretreatment media and therefore could serve as alternatives where natural gravel is not readily available. The design and sizing of the pilot plant was guided by wegelin design criteria and a constant filtration rate of 0.75 m/h was chosen for the HRF units. The filter recorded 90 and 95% respectively for suspended solid and turbidity removal in the plant.

Another pilot horizontal flow roughing filter was constructed and operated by Tamar and Losleben (2004) at Ghanasco Dam in Tamale, Northern region Ghana using three 7 m tubes filled with three sizes of granite gravel, local gravel and broken pieces of ceramic filters arranged by decreasing size. The pilot study was run for 52 days to test if HRF could reduce the high turbidity (305 NTU) to < 50 NTU to make SSF a viable option. There were a number of promising outcomes: the best performing media, the granite gravel, by removing an average 46% of the influent turbidity (filter coefficient ë = 0.002 min^{-1}), produced an average effluent turbidity of 51 NTU which almost achieved the goal of < 50 NTU. The granite gravel HRF removed twice as much turbidity (46%) as plain settling (25%). Overall, the granite gravel removed 76 and 84% of the influent turbidity according to the settling test and pilot HRF data respectively.

Another Horizontal roughing filter was constructed by Nkwonta and Ochieng (2009) at delmas coal using gravel for removal of magnesium and iron. The design and sizing of the pilot plant was guided by wegelin design criteria and a constant filtration rate of 1 m/h was chosen for the HRF units. The filter recorded 52 and 72% reduction of magnesium and iron in the filter. Some findings from other researchers are shown in Table 3.

DISCUSSION

A comparison of horizontal flow roughing filters with vertical flow roughing filters reveals the following:

(1) Direction of flow and sedimentation are obviously the first differences which might interfere or support solids settling on the filter material. Solid removal efficiency should consequently vary in the two filter types. Theoretically, horizontal filters should have a better performance than vertical filters as the solid particles are more likely to settle on top of the gravel surface in the direction of flow. However, practical field experience has shown a similar efficiency for both filters. In dead filter zones, where the water flow is reduced to a minimum, solids settle regardless whether the roughing filter is operated in horizontal or vertical direction. Hence, filter efficiency is similar in both filter types.

(2) The accumulation pattern of retained solids is another difference between horizontal and vertical filters. The bulk of the solids is deposited at the inlet of the filter; that is, for horizontal filters in the compartments of the filter and for vertical filters in the filter medium located next to the filter bottom. This, however, has a tremendous impact on hydraulic filter cleaning.

(3) Due to structural constraints, vertical-flow roughing filters have a relatively small filter depth of about 1 m. Total filter depth of the three filter units used in series is thus 3 m. This total length will affect its efficiency. It can generally and efficiently handle moderate raw water turbidities of 50 to 150 NTU, while horizontal-flow roughing filters can handle turbidity peaks of 500 to 1,000 NTU.

(4) Vertical-flow roughing filters are usually operated at 0.3 to 1.0 m/h filtration rates while filtration rate in horizontal-flow roughing filters ranges between 0.3 and 1.5 m/h. Vertical-flow roughing filters may be sensitive to hydraulic fluctuations, especially if loaded with large amounts of solids. Settled matter might be resuspended at increased filtration rates, causing solids to break through the filter. Filter operation at constant flow rates is, therefore, recommended.

(5) Horizontal-flow roughing filters have a large silt storage capacity than vertical roughing filters. Solids settle on top of the filter medium surface and grow to small heaps of loose aggregates with progressive filtration time. Part of the small heaps will drift towards the filter bottom as soon as they become unstable. This drift regenerates filter efficiency at the top and slowly silts the filter from bottom to top.

Conclusion

Roughing filtration is experiencing renewed interest as a result of its potential for application to small-scale systems. Significant advantages of horizontal roughing filters include simplicity of design, ease of operation and maintenance, cost effectiveness and reliability. Innovative

Table 3. Results from other researchers on HRF and VRF.

References	Filtration rates (m/h)	Mean percent removed (%)	Parameters	Roughing filter type
Pacini (2005)	1.20	85 and 95	Iron and manganese	HRF
Dome (2000)	0.3	95 and 90	Algae and turbidity	HRF
Mahvi (2004)	1.5	90	Turbidity	HRF
Ochieng and Otieno (2004)	0.75	90 and 95	Turbidity and algae	HRF
Dastanaie (2007)	1.8	63.4, 89 and 94	Turbidity, TSS and Coliforms	VRF
Jayalath (1994)	1.5	50and 60	colour and turbidity	VRF
Rabindra (2008)	1.0	95 and 95	TSS and turbidity	HRF
Mukhopadhay (2008)	0.75	75	Turbidity	HRF
Nkwonta and Ochieng (2009)	1	52 and 72	Magnesuim and Iron.	HRF
Reed and Kapranis (1998)	0.75	42	Turbidity	VRF

operational and maintenance techniques have made this system suitable for communities that have limited resources. Vertical and horizontal roughing filtration systems have proven to produce exceptional quality water despite operating in cold temperatures, encountering a variety of contaminants and in highly variable water condition with minimal maintenance making them a suitable alternative for poor communities. Achieved results in this study shows that horizontal roughing filters perform better than vertical roughing filters with the parameters that was put to test and also due to unlimited filter length, simple layout and less susceptible than vertical-flow filters to solid breakthroughs caused by flow rate changes in the filters

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REFERENCES

Boller M (1993). Filter mechanism in roughing filters. J. Water Supply Res. Technol. -Aqua, 42(3): 174.

Clarke BA, Lloyd BJ, Crompton JL, Major IP (1997). 'Cleaning of up flow gravel prefilters in Multi-stage filtration water treatment plants', in Advances in Slow Sand & Alternative Biological Filtration, ed. Graham, N and Collins, R 1996, Wiley and Sons, Chichester, England.

Collins MR, Cole JO, Paris DB (1994). Assessing roughing filtration design variables. Water Supply, 12: 1-2.

Dastanaie J (2007). Use of horizontal roughing filtration in drinking water treatment. Int. J. Sci. Technol., 4(3): 379-382.

Department of Water Affairs and Forestry (2004). Olifants Water Management Area: Internal Strategic Perspective. Report P WMA 04/0000/00/0304.Department of Water Affairs and Forestry, Pretoria.

Falkenmark M (1994). The dangerous spiral: near-future risks for water-related eco-conflicts. In: Proceedings of the ICRC Symposium "Water and War: Symposium on Water in Armed Conflicts", International Committee of the Red Cross, Montreux, Switzerland, 21-23 November 1994. 16 pp.

Galvis G, Visscher JT, Latorre J (2006). Multi-stage filtration and innovation water treatment technology. International reference centre for community water supply and sanitation, The Hague, Netherlands and Universidad del valle instituto CINARA, Cali, Colombia.

Graham N (Ed) (1988). Slow sand filtration, recent developments in water treatment technology. Elis Horwood limited/ Wiley and sons Chichester England.

Hatva T (1988). Treatment of groundwater with slow sand filtration. Water Sci. Technol., 20(3): 141-147.

Hendricks DW (1991). Manual of design for slow sand filtration. American water works association research foundation Denver. CO.

Jayalath J (1994). Algae removal by roughing filter. 20th WEDC conference 1994.Manual on Water Supply and Treatment. CPHEEO, Ministry of Urban Development, Government of India, New Delhi, 1991, p. 495.

Lee CH (2003). Assessment of contamination load on water, soil and sediment affected by the Kongjujeil mine drainage, Republic of Korea, Environ. Geol., 44: 501-515.

Nkwonta OI, Ochieng GM (2009). Roughing Filter for water pre-treatment Technology in developing countries. A review. Int. J. Phys. Sci., 4(9): 455-463.

Ochieng GM, Otieno FAO (2006). Verification of wegelin design criteria for horizontal flow roughing filters with alternative filter materials. Watersa vol 32 January.

Oryx Environmental and Jones and Wagener Consulting Engineers. (2003). The Grootvlei Proprietary Mines Limited Project to reduce and treat the volumes of water pumped from underground. Braamfontein: Oryx Environmental.

Pacini V (2005). Removal of iron and manganese using biological roughing up flow filtration technology. Water Res., 399: 4463-4475.

Rabindra NB (2008). Performance of HRF as a pretreatment unit before conventional water treatment system. Published inn HYPERLINK "mailto:engi@philica.com"engi@philica.com.

Reed R, Kapranis Y (1998). Roughing filtration with polystyrene beads. Proceedings of the 24th WEDC conference Islamabad Pakistan.

Rooklidge SJ, Ketchum KL (2002). Calcite amended horizontal roughing filtration for clay turbidity removal, J. Water Supply Res. Technol., 51(6): 333-342.

Tamar R, Losleben P (2004). Study of Horizontal Roughing Filtration in Northern Ghana as Pretreatment for Highly Turbid Dugout Water B.A. Environmental Science and Engineering, Rice University.

Wegelin M (1996). Surface water treatment by roughing filters. A design, construction and Operation manual, Swiss Federal Institute for Environmental Science and Technology (EAWAG) and Department Water and Sanitation in Developing Countries (SANDEC).

Wegelin M, Boller M, Schertenleib R (1986). Particle removal by horizontal flow roughing filtration. Aqua, 42(3): 174-185.

Younger PL (2001). Passive treatment of ferruginous minewater using high surface area media. Elsevier science Ltd.Great Britain.