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Hydraulic design to optimize the treatment capacity of Multi-Stage Filtration units

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ABSTRACT

Multi-Stage Filtration (MSF) can provide a robust treatment alternative for surface water sources of variable water quality in rural communities at low operation and maintenance costs. MSF is a combination of Slow Sand Filters (SSFs) and Pre-treatment systems. The general objective of this research was to optimize the treatment capacity of MSF. A pilot plant study was undertaken to meet this objective. The pilot plant was monitored for a continuous 98 days from commissioning till the end of the project. Three main stages of MSF namely: The Dynamic Gravel Filter (DGF), Horizontal-flow Roughing Filter (HRF) and SSF were identified, designed and built. The response of the respective MSF units in removal of selected parameters guiding drinking water quality such as microbiological (Faecal and Total coliform), Suspended Solids, Turbidity, PH, Temperature, Iron and Manganese was investigated. The benchmark was the Kenya Bureau (KEBS) and World Health Organization (WHO) Standards for drinking water quality. With respect to microbiological raw water quality improvement, MSF units achieved on average 98% Faecal and 96% Total coliform removal. Results obtained indicate that implementation of MSF in rural communities has the potential to increase access to portable water to the rural populace with a probable consequent decrease in waterborne diseases. With a reduced down time due to illness, more time would be spent in undertaking other economic activities.

1. Introduction

Access to treated water in Kenya is reported as 46% in rural areas and 89% for the urban populace. Rural areas in Kenya often rely on surface water (i.e. water drawn from rivers, streams, lakes, ponds and springs) for their drinking water, which more often than not is contaminated. As a result, numerous water-related outbreaks such as typhoid fever and cholera have led to a growing need for alternative but simple, reliable, and sustainable treatment technologies for use in such areas. Multi-Stage Filtration (MSF) is such technology which can provide a robust treatment alternative for surface water sources of variable water quality in rural communities at low operation and maintenance costs. MSF is a combination of Slow Sand Filters (SSFs) and Pre-treatment systems.

MSF was developed in the 1990s by researchers in Colombia where it is now being applied on a larger scale and some efforts are being made to support wider dissemination and further development particularly in Latin America. Worldwide experience with MSF shows the significant potential of this treatment concept in producing potable drinking water from polluted turbid water (Wegelin, 1996).

The Sustainable Development Goals (SDGs) require improved interventions in the water and sanitation sector. Using experience from other countries where this technology has been implemented, this research aimed to develop design data for MSF units. The general objective of this research was to optimize the treatment capacity of MSF. The research endeavored to optimize the treatment capacity of MSF units in Kenya with a view of applying the technology to further improve access to safe water by the population in Kenya in order to meet the SDGs on the subject of water.

2. Objectives

The general objective of this study was to design and construct a pilot plant of Multi-Stage Filtration (MSF) units and to optimize its

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treatment capacity. The specific objectives was to construct Laboratory model Multi-Stage Filtration (MSF) units, i.e. two Dynamic Gravel Filters (DGF) and three Horizontal-flow Roughing Filters (HRFs) connected in series with two Slow Sand Filter (SSF) units. The study also endeavoured to investigate the water quality improvement performance of Laboratory model units under varied raw water conditions particularly with respect to Coliform bacteria, Turbidity, Suspended Solids (SS), colour, Iron and Manganese while monitoring retention time/hydraulic loading, filtration rates, filter bed resistance and filter run period. Finally a comparison of the Overall performance of the MSF against the existing Conventional System (Moi University Water Treatment Works) with respect to microbiological water quality improvement was made.

3. 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°310N 35°170E.The County has a cool and temperate climate with mean annual rainfall 1100 to 1200 mm. Temperature during wet season drops to 18 °C and dry season records a temperature of 26 °C. There are four noticeable soil types in the district: red loam, red clay, brown clay and brown loam.

3.1. The Multi-Stage Filtration (MSF) pilot unit

To investigate the research objectives, a pilot plant was built at Moi University water treatment works in the year 2013. This site was a perfect location because of the readily available raw water and space to accommodate all the units. The topography of the site also offered convenient flow of water by gravity thus avoiding pumping equipment and associated costs.

The MSF pilot unit comprised of three raw water treatment stages: Dynamic Gravel Filters (DGFs), Horizontal-flow Roughing Filters (HRFs) and Slow Sand Filter units (SSF).

In this study, Dynamic Gravel Filters (DGFs) and Horizontal-flow Roughing Filters (HRFs) were selected as the pretreatment filters followed by Slow Sand Filters as the final filters. There was no disinfection of the filtrate. The raw water flow in this unit was by gravity. Flow control devices (valves) were provided at each stage not only to control the retention time/filtration rates of the MSF units but also were essential to give different operational possibilities for the MSF pilot system. To ensure continuous flow of raw water in the MSF System during maintenance of Filters and to increase the operational possibilities, an additional Slow Sand Filter and Horizontal-flow Roughing Filter were provided in the design.

3.2. Dynamic Gravel Filters (DGFs)

The first treatment option of raw water consisted of two Dynamic Gravel Filters (DGFs) in parallel and processing raw water from a constant head-feeder tank or Mixing Tank (MT). The main role of the DGF was to protect the treatment plant units from high Turbidity peaks. This is because high turbid surface water can easily clog filters, especially SSF units thus reducing the run time period and making it a tedious process to do frequent filter maintenance activities.

The design and sizing of the pilot-plant DGFs were guided by the Wegelin design criteria (Wegelin, 1996) based on the preliminary raw water quality data obtained prior to the commencement of the full pilot-plant study. The DGF require a smaller filter depth of about 40–60 cm. The Dimensions of the DGF and particularly those corresponding to the Surface area (Length L and Width W) are conditioned by the water flow available for washing the Surface. The horizontal flow velocity over the filter bed surface should be small (<0.3 ms^{-1}) or nonexistent. Filtration rate depends on the Local conditions. Values between 0.5 and 3 m/h have been applied in Colombia (Wegelin, 1996). For this Study, two parallel DGF units with total active area of 0.5 m^2 were used. These units operated at a filtration rate in the ranges of 0.5 to 1 m/h depending on the raw water quality.

Two parallel DGF units were connected in series with three HRF units and SSF units as shown in Fig. 1. The DGF consisted of a layer of fine gravel (3 to 5 mm) of 0.2 m height placed over a layer of coarse gravel (5–25 mm) of 0.4 m of height upon which water flowed vertically downwards. In the bottom layer perforated pipes were placed as drainage system. With the fine grains at the top, most of the Suspended Solids accumulated at this point in the system which facilitated the cleaning of the unit. The lower coarse gravel acted as filter support and allowed an even abstraction of the pre-filtered water through the perforated drainage pipes. The raw water infiltrated into the gravel bed to the drainage system from where it flowed to the HRF unit.

3.3. Horizontal-flow Roughing Filters (HRFs)

The second stage consisted of three lines of Horizontal-flow Roughing Filters (HRFs) in parallel. The design and sizing of the pilot-plant HRFs were guided by the Wegelin design criteria (Wegelin et al., 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 (3 mm thick). Each measured 5.4 m length, 0.5 m width and 1 m 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 main part of the HRF consisted of a filter bed 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 15–24 mm, medium material was in the range of 8–15 mm and the finest from 4 to 8 mm. These filter media packs were separated with perforated Mild Steel (MS) plates to avoid mixing. The filter bed was also 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 0.5 m/h. Fig. 2 shows the pilot-plant scale HRF unit used.

3.4. Slow Sand Filters (SSFs)

The final Stage consisted of two vertical Slow Sand Filters (SSFs) connected in parallel. The sizing of the pilot plant SSF units in this study was done in accordance with the set guidelines in design manuals (i.e. Wegelin, 1996; Galvis et al., 1998). The Slow Sand Filter (SSF) was the main treatment unit in the whole process. The basic composition of the SSF comprised of: a supernatant layer of raw water to provide storage capacity above the sand bed and the required head to drive the raw water through the bed of filter medium (fine sand); a system of under-drains in the filter medium to allow unobstructed passage of treated water; filter regulation/