HYDRAULIC DESIGN TO OPTIMISE TREATMENT CAPACITY OF MULTI-STAGE FILTRATION UNITS:

A PILOT PLANT STUDY AT MOI UNIVERSITY WATER TREATMENT WORKS, ELDORET, KENYA

BY

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Research Thesis submitted to the Department of Civil and Structural Engineering, Moi University in partial fulfilment of the requirements for the award of the degree of MASTER OF SCIENCE IN WATER ENGINEERING

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NOVEMBER, 2016

DECLARATION

DECLARATION BY CANDIDATE

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In memory of my loving and inspirational father Eng. Charles Mushila Nabwayo.

ABSTRACT

Access to potable water in Kenya is reported as 46% in rural areas and 89% for the urban areas. Rural areas in Kenya often rely on surface water for their drinking water, which more often than not is contaminated. As a result, numerous water-related outbreaks have led to a growing need for alternative but simple, reliable, and sustainable treatment technologies for use in such areas. 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 (SSF) and Pre-treatment systems. The general objective of this research was to optimize the treatment capacity of MSF. Three main stages of MSF namely: The Dynamic Gravel Filter (DyGF), 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 Faecal and Total coliform, Suspended Solids, Turbidity, pH, Temperature, Iron and Manganese was investigated. The bench mark was KEBS and WHO standards for drinking water. The performance of the MSF unit was measured against the existing Conventional System (Moi University Water Treatment) with respect to microbiological water quality improvement. On average, DyGF achieved 59% Turbidity removal and 63% Suspended Solids (SS) removal. HRF unit registered 86% Turbidity removal and 85% SS removal. With respect to microbiological raw water quality improvement, MSF units achieved on average 98% Faecal and 96% Total coliform removal in comparison with the conventional system which registered average values of 75% Faecal and 78% Total coliform removal before chlorination. MSF units registered an average value of 70% removal of Iron and 64% removal of Manganese respectively. The pilot plant study results obtained indicate that implementation of MSF in rural communities has the potential to increase access to potable 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. Further research is recommended targeting development of a design manual for a population size as a function of raw water quality.

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LIST OF ABBREVIATIONS

A_{DyGF}	Active cross-sectional area of Dynamic Gravel Filter
A_{HRF}	Active cross-sectional area of Horizontal-flow Roughing Filter
A_{SSF}	Active cross-sectional area of Slow Sand Filter
BOC	Biodegradable organic carbon
C	Solids concentration
CGF	Coarse Gravel Filtration
CFU	Colony Forming Units
CMF	Coarse Material Filtration
DyGF	Dynamic Gravel Filter
DO	Dissolved Oxygen
E.Coli	Faecal coliforms
EB	Equalization Basin
ELDOWAS	Eldoret Water and Sewerage Company
GOSS	Government of South Sudan
HRF	Horizontal-flow Roughing Filter
IRC	International Water Supply and Sanitation Centre
KEBS	Kenya Bureau of Standards
MDGs	Millennium Development Goals
MSF	Multi-Stage Filter/Filtration
MT	Mixing Tank
NGO	Non-Governmental Organisation
NOM	Natural Organic Matter
NTU	Nephelometric Turbidity Units
O&M	Operation and Maintenance
PCU	Platinum Cobalt Units
PRSP	Poverty Reduction Strategy Paper
Q_{DyGF}	DyGF capacity
Q_{HRF}	HRF capacity
Q_{SSF}	SSF capacity
RSF	Rapid Sand Filtration/Filter.
TGCMSSF	Technical Guidelines for the Construction and Management of Slow Sand Filters
UNICEF	United Nations Children Fund
URFS	Up-flow Roughing Filter in Series
URFL	Up-flow Roughing Filter in Layers
V_f	Filtration rate
WB	World Bank
WHO	World Health organization

LIST OF SYMBOLS

c	Solids concentration
^{o}C	Degree Celsius
e	Exponential
λ	Filter coefficient
π	Constant pi
μ	Absolute Viscosity
x	Filter depth
ρ	Water mass density
η	Efficiency

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CHAPTER ONE

1.0 INTRODUCTION

1.1 General information

This research presents part of work under Kenya - South Africa research partnership project on Multi-Stage Filtration (MSF). The project was funded by the National Council of Science and Technology (NCST) of Kenya and National Research Foundation (NRF) of South African Government through a Joint Research Grant.The overall objective of the research partnership project was to develop a design, construction and operation manual for MSF for application in rural and developing areas in Kenya and South Africa. This study aimed at solving part of the research problem i.e. it involved design, construction and testing performance of pilot MSF units in the Kenyan context.

1.2 Background

It is estimated that Kenya has a population of approximately forty (40) million people of which about seventeen (17) million do not have access to potable water (Marshall, 2011). According to UNFPA report of 2003, access to potable water in Kenya is reported as 89% for the urban populace and 46% in rural areas. This is attributed to Kenyan government over dependent on using Conventional water treatment systems which are very expensive and demanding in terms of labour, energy and maintenance requirements considering rural or remote areas (Ochieng, 2004). The consequences has been numerous death cases due to water related diseases e.g Cholera, Typhoid and Dysentery (Marshall, 2011). This calls for a sustainable solution to water treatment in these areas. Multi-Stage Filtration (MSF) is one such system which if well designed will prove valuable in addressing this problem. MSF involves the combination of pre-treatment Systems (e.g gravel filters) with Slow Sand Filter in raw water treatment. The MSF technology was developed in Colombia in the mid - 1990s and studies have shown that it has a great potential of providing a solution to the afore-mentioned water problem in developing and remote or rural areas. Using experience from other countries where this technology has been implemented, this research aimed to design and test the response of MSF units with a view of applying the technology to further improve access to safe water to the population in Kenya in order to meet the Sustainable Development Goals (SDGs) on the subject of water.

1.3 Statement of the problem

A significant number of people in Kenya, particularly in the rural areas, do not have access to safe drinking water (as discussed in section 1.2). This situation can be alleviated through the use of Multi-Stage Filtration (MSF) in provision of water that meet drinking water quality standards in such areas. However, MSF is still not well known in Kenya hence there was an apparent need to design a pilot MSF system and investigate its response to variations in raw water quality.

1.4 Objectives

1.4.1 Main objective

The main objective of this research was to design and construct a pilot plant of Multi-Stage Filtration (MSF) units and to optimize its treatment capacity.

1.4.2 Specific Objective.

1. To investigate the raw water quality improvement performance of MSF pilot units particularly with respect to Coliform bacteria, Turbidity, Suspended Solids (SS), colour, Ammonia, Nitrite and Nitrate removal, Iron and Manganese while

monitoring retention time / hydraulic loading, filtration rates, filter bed resistance and filter run period.

2. To determine the significance of the HRF in pathogen removal, beyond its normal role of protecting the operational conditions of SSF against High turbidities and Suspended Solid (SS) load. Also, investigate the effect of Series connection of two HRF units.
3. Compare the Overall performance of the MSF against the existing Conventional System (Moi University Water Treatment Works) with respect to the Suspended Solids (SS), Turbidity, colour and microbiological improvement of water.

1.5 Justification

A simple but sustainable and affordable water treatment system such as Multi Stage Filtration (MSF) is essential to alleviate the problem of inaccessibility of potable water in Kenyan rural areas. Previous studies on MSF has shown it to be an appropriate and sustainable technology for use in rural and developing areas (Galvis et al., 1999). The MSF system is able to improve water quality to acceptable standards without the addition of chemicals. This system can be constructed from locally available materials, doesn’t require sophisticated equipment to operate, and is less labour intensive relative to a Conventional System (CS). Also, it operates under gravity flow conditions thus eliminating energy intensive backwashing (Ochieng, 2004). The MSF technology has been successful in Colombia where there are over 50 full scale systems in operation since 1980s (S´anchez et al., 2006b). Recently, this technology has gained research interest across the world and has shown success in other countries such as Latin and North America (Shawn, 2005). From the research findings it is evident that the MSF technology can contribute immensely to SDGs Goal 6 if well executed (i.e. by increasing access to potable water in rural and developing areas) hence there was an apparent need to research on its adaptability in Kenya.

CHAPTER TWO

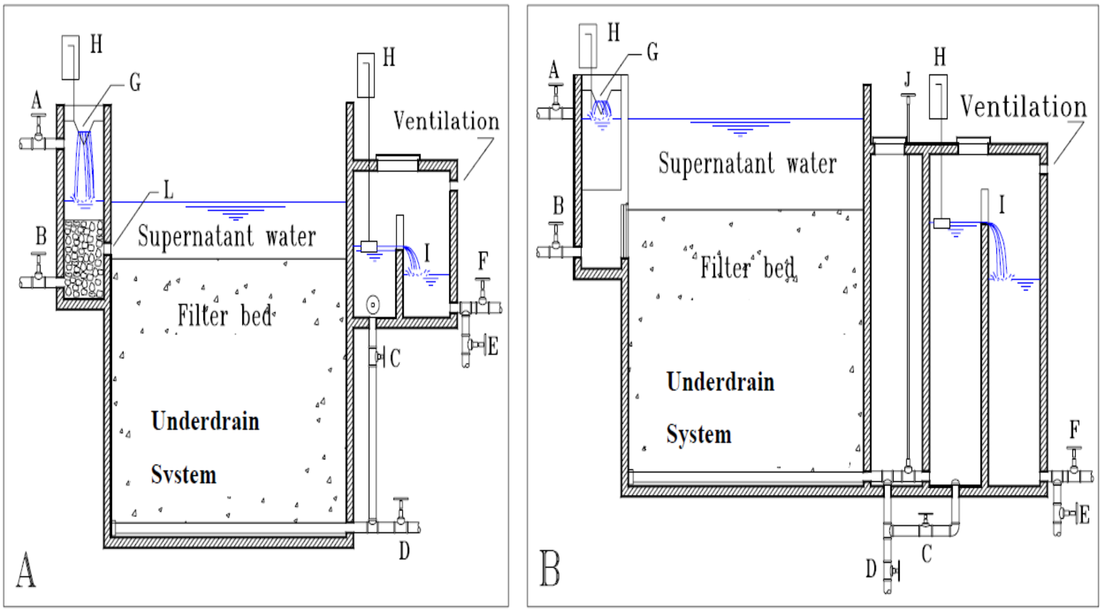
2.0 LITERATURE REVIEW.

2.1 Introduction

Although there has been notable progress in the Kenyan water sector since the enactment of the water act (2002), a lot still need to be done for Kenya to meet the SDGs i.e Goal 6 which targets sustainable access to water and sanitation for everyone (Derek, 2015). Rural areas in Kenya are the most affected relative to the urban areas in terms of potable water availability as discussed in section 1.2. As a result, there has been a number of death cases reported in Kenya mostly in rural and remote areas because of water related epidemics such as Cholera, Typhoid and Dysentery (Marshall, 2011). Implementation of CS in these areas might prove expensive and unsustainable considering technical, energy and maintenance costs involved (Ochieng et al., 2004). To address this problem, Kenya needs to welcome sustainable raw water treatment systems in rural areas. One of the methods which can be adopted is the Multi-Stage Filtration (MSF) system. This System was discovered in Colombia in 1990s where it has proved valuable in making potable water accessible to the rural populace (S´anchez et al., 2006b). This chapter presents the different MSF units including their operation and performance. Case studies on MSF are given at the end of the chapter.

2.2 Slow Sand Filtration (SSF)

A Slow Sand Filter (SSF) is an inexpensive water treatment method recommended for use in remote locations (Jason et. al., 2012). It consists of a structure with a supernatant water layer, a filter bed, drainage systems and water flow control or regulation devices (Huisman, 1977). The filter bed material is mainly sand which has met the recommended design specification as given by Huisman, 1977. The SSF unit is discussed in more detail in section 3.3.1 of this report. Figure 2.1 shows the basic components of a SSF.



A:Filtration rate regulation valve
B: Supernatant drain valve.
C: SSF unit backfilling Valve
D: Filter bed drain valve
E: Filtered water waste valve
F: Valve to contact tank or water storage
G: Inlet weir
H: Calibrated flow indicator
I: Outlet weir
J: Outlet control valve

Figure 2.1 Basic components of Slow Sand Filter units with inlet (A) and outlet (B) flow control (S´anchez et al., 2006b)

2.2.1 Brief historical background of Slow Sand Filters (SSF)

Slow Sand Filtration (SSF) is an ancient raw water treatment technology that is reported as early as 1804 in Paisley, Scotland when John Gibb designed and built a pilot SSF unit. The surplus water from the unit was sold to the Public (Baker, 1949). Later in 1829, the first SSF public supply system was implemented at the Chelsea Water Company, London, by James Simpson (Baker, 1949). The SSF technology then spread and was adopted in Europe in cities like. Paris, Hamburg and Amsterdam. However, in early 20th century, this system lost its popularity to Rapid Sand Filters (RSF) due to filter clogging which dramatically reduced run times when treating high turbidity surface water. However, recent advances such as the MSF technology which addresses the limitations of the SSF has stirred a renewed interest in Slow Sand Filters. The MSF technology was designed and tested in Colombia in 1980 – 1990s where it gave positive results. The success case of MSF technology in Colombia gave forth a rebirth and renewed interest in the use of SSF. Ever since, studies on MSF systems have been reported in many countries across the world such as Ghana, South Sudan, Kenya, Bangladesh, Latin and North America. (Refer to section 2.6 of this report for case studies).

2.2.2 The Design and Operating Specifications for the Slow Sand Filter

Sand is typically the most economical and readily available material used for Slow Sand Filter bed (TGCMSSF, 2009). Sand: effective size of 0.15 - 0.45mm, uniformity coefficient ≤ 5 and filter bed depths of 0.8 - 1.4 m is normally used (Huisman and Wood 1974, Visscher et al., 1987, Galvis et al., 1998, and Logsdon, 1991). New sand should be added when repeated scrapping and removal have reduced the depth to between 0.5 - 0.8m. The filtration rate or approach velocity varies from as low as 0.08 to as high as $0.4m^3/m^2$ /h (Huisman and Wood, 1974). Table 2.1 gives a comparison of design guidelines of SSF by different authors.

2.2.3 Performance of Slow Sand Filters

Studies on Slow Sand Filtration (SSF) have shown that they are efficient in bacteriological water quality improvement and removal of viruses with values of 95 - 100 percent removal (TGCMSSF, 2009). Logsdon, 1991 reported that total coliform removals greater than 99 percent are possible with mature SSF. Bellamy et al (1985a) demonstrated that removal of Giardia cysts was about 99.9 percent by use of SSF pilot filters operating at filtration rates of 0.04 - 0.4m/h.

Table 2.1 Design guidelines for Slow Sand Filtration (S´anchez et al., 2006b)

Design criteria	**TGCMSSF (2009)**	**Ten States Standards USA (1987)**	**Huisman and Wood (1974)**	**Visscher et al. (1987)**	**Galvis et al (1998)**
Design period (years)	10 - 15	Not stated	Not states	10 - 15	8 – 12
Period of operation (h/d)	24	24	24	24	24
Filtration rate (m/h)	0.1 – 0.2	0.08 – 0.24	0.1 – 0.4	0.1 – 0.2	0.1 – 0.3
Sand bed: *Initial height (m)* *Minimum height (m)* *Effective size (mm)*	 0.8 - 0.9 0.5 - 0.6 0.15 - 0.30	 0.8 Not stated 0.30 – 0.45	 1.2 0.7 0.15 – 0.35	 0.9 0.5 0.15 – 0.30	 0.8 0.5 0.15 – 0.30
Uniformity coefficient: *Acceptable* *Preferred*	 < 5 < 3	 Not stated ≤ 2.5	 < 3 < 2	 < 5	 < 4
Support bed height including drainage (m)	0.3 - 0.5	0.4 – 0.6	Not stated	0.3 – 0.5	0.25
Supernatant max H (m)	1	0.9	1 - 1.5	1	0.75
Freeboard (m)	0.5	Not stated	0.2 - 0.3	0.1	0.1
Max surface area (m^2)	Not stated	Not stated	Not stated	<200	<100

2.2.4 Advantages of Slow Sand Filtration (SSF)

There are several comparative advantages of SSF relative to Rapid Sand Filtration (RSF) in the context of rural areas in developing countries. They include:

i) **Simplified system design** – Slow Sand Filters (SSFs) have a simplified system design in terms of construction that requires minimum equipment. This system can be easily handled by local operators with minimum formal education. Also, Unlike RSF, SSF is not back-washed which means minimal energy requirements.

ii) **High effluent quality** - SSF provide a high quality of effluent without the need for chemical treatment as in the case of RSF which utilize a lot of chemicals in their operation e.g Coagulants, Flocculants and Chlorine which increases the cost of operation.

iii) **Absence of chemical treatment** – Absence of chemical treatment means local operators can, with minimum of training, learn to carry out simple routine maintenance procedures. In addition, the use of chlorine has become a more recent health concern i.e it produces disinfection by products e.g haloacetic acids and trihalomethanes which exhibit carcinogenic behavior in humans (Li et al., 2011, Wang et al., 2012).

iv) **Low cost** – Costs are minimised in execution of SSF project through means such as; use of locally available materials in construction, community involvement in construction, operation and maintenance .

v) Economical use of water – By considering arid areas, water is saved through not having to dislodge sedimentation tanks and avoiding backwashing as in the case of Rapid Sand Filters (Ochieng, 2004)

2.2.5 Cleaning of Slow Sand Filters (SSFs)

Cleaning is normally done at the end of a filter run, when the head-loss across the filter bed has reached its maximum. The most common method of cleaning SSFs involves scraping off 1 or 2cm of the top layer of the sand media after draining the water level down to just below the sand surface (Ellis, 1985). Another method of cleaning is known as "harrowing". It involves raking the sand by a comb harrow, which penetrates about 30cm into the sand bed to detach particulate debris. This debris is then washed away by continuously flowing water across the top of the filter bed (Eighmy and Collins, 1988). Cleaning agents and other chemicals are discouraged from use in case of SSFs. This is because they may interfere with the biological action of the filter bed (Jason et al., 2012).

2.2.6 Demerits of Slow Sand Filters (SSFs)

Some of the factors that have limited the application of SSFs in rural areas in developing countries include:

i. Inability to treat high turbid surface waters. It is suggested that Slow Sand Filters operates optimally with turbidity levels of < 20 NTU (TGCMSSF, 2009).

ii. Slow Sand Filters are sensitive to sudden changes in raw water quality, such as increases in solid loadings (Huisman and Wood, 1974)

iii. Limited ability to treat stable suspensions of fine colloidal matter (Montgometry, 1985)

iv. Slow Sand Filters are poor in removing colour (Lambart and Graham, 1995)

v. Reduced treatment efficiency at low temperatures (Huisman and Wood 1974)

vi. The performance of SSFs can be limited by inadequate nutrient loads in raw water such as dissolved oxygen and organics (Visscher et al.,1987)

2.2.7 Advances in Slow Sand Filtration

Several advances have been made in the recent years to address the limitation of SSF. These include use of pre-ozonation and granular activated carbon (GAC) with Slow Sand Filters. Pre-ozonation and GAC filters were used to address the problem of Organics. This was because it was discovered that SSF is not very efficient in organic removal (Shawn, 2005). Another proven method of coping with the limitations of SSF is Multi stage filtration (MSF). According to S´anchez et al (2006), MSF is suitable for rural and developing areas.

2.3 Multi-Stage Filtration (MSF)

Multi-Stage Filtration is the combination of pre-treatment systems e.g Gravel Filters (GFs) and Slow Sand Filters (SSF) to treat raw water. This technology can reliably provide effluent water quality that surpasses the capabilities and limitations of SSF.

MSF is a robust, sustainable and reliable treatment with simple maintenance procedures. Operators with low levels of formal education can operate the MSF system (Ochieng, 2004). Figure 2.2 shows the general layout of an MSF system with a terminal disinfection safety barrier.

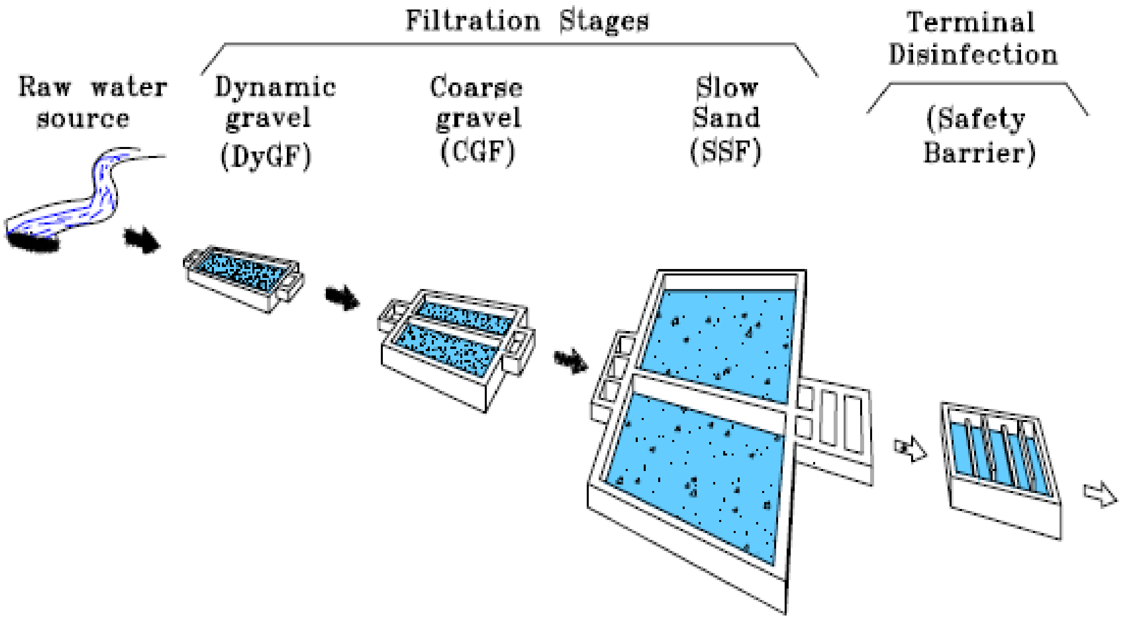


Figure 2.2 General layout of a Multi-Stage Filtration treatment plant (S´anchez et al., 2006b)

2.4 Coarse Gravel Filters

There are various pre-treatment alternatives for SSF, the most common being the Coarse Gravel Filters (CGFs) using gravel as the filter medium. The criteria used for classification of CGFs is the main application purpose and the flow direction. The most common CGFs include: Dynamic Gravel Filters (DyGF) and respectively Up-flow, Down-flow and Horizontal-flow Gravel Filters. (Galvis and Visscher, 1987).Figure 2.3 shows the common CGFs used before the SSF units.

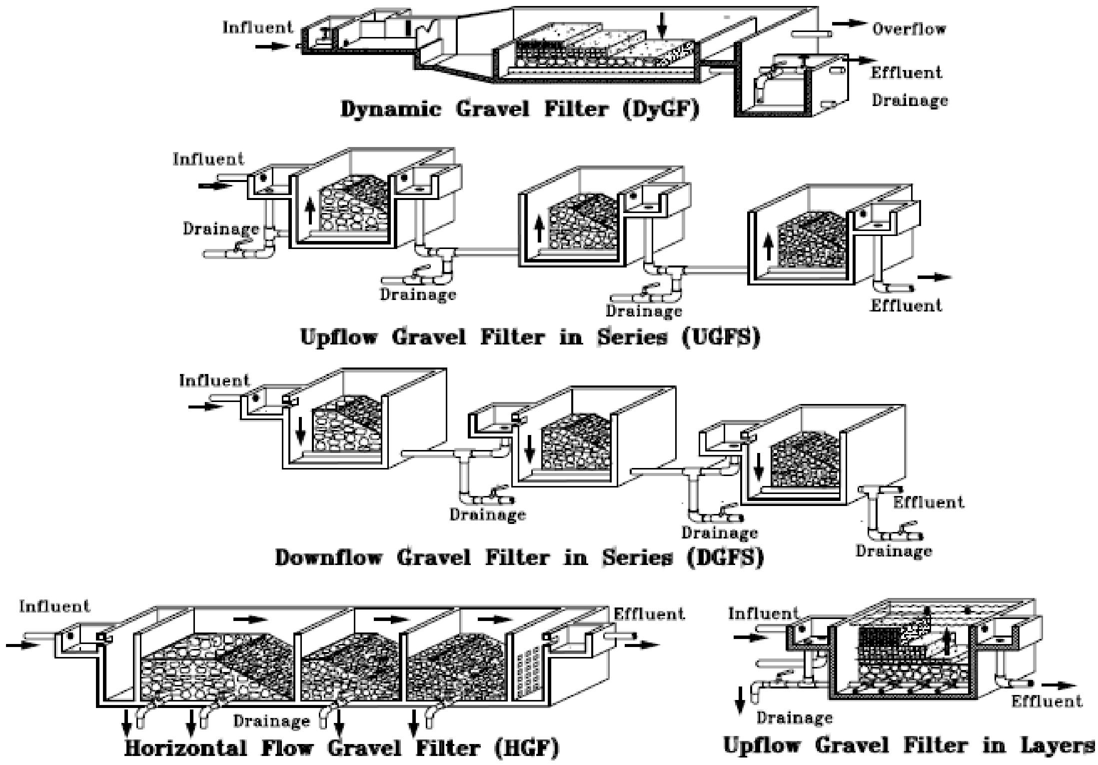


Figure 2.3 General views of different Coarse Gravel Filters (Galvis and Visscher, 1987)

2.4.1 Dynamic gravel filter (DyGF)

A DyGF is usually used to protect the subsequent units against high solid concentration shock loads. It is usually useful during seasons or periods of very high raw water turbidity peaks i.e. it may interrupt flow during such periods to minimise the work of filter cleaning (Wegelin, 1992). This Filter is normally comprised of a minimum of two parallel units filled with three layers of gravel material ranging from coarse at the bottom to fine at the top. Figure 2.4 shows the main components of a DyGF

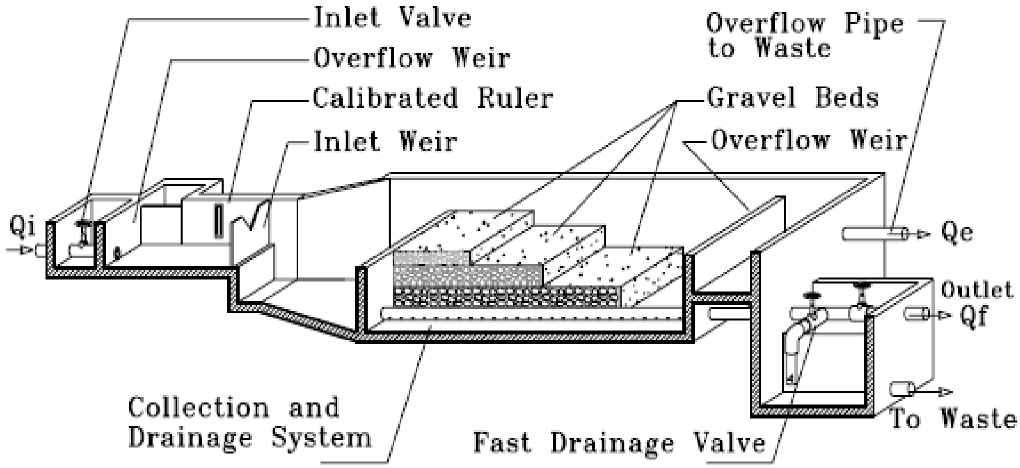


Figure 2.4 Layout of a Dynamic Gravel Filter (S´anchez et al., 2006b)

The filter height ranges from 0.6 - 0.8 m. Filtration rates depend on the desired purpose e.g if the purpose is to improve water quality a range of between 0.5 to 2 m/h may be used (Wegelin, 1996). The design guidelines for DyGF are displayed in Table 2.2.

Table 2.2 Design guidelines for Dynamic Gravel Filters (Wegelin, 1996).

Parameter	**Main treatment objective**	
	Improve water quality	**Reduce impact of peak of Suspended Solids (SS)**
Filtration velocity (mh^{-1})	0.5-2.0	>5
Filter bed layer: Upper (thickness in m and size in mm) Middle (thickness in m and size in mm) Lower(thickness in m and size in mm)	 0.20, and 3-5 0.20, and 5-15 0.20, and 15-25	 0.2-0.3,and1.5-3 0.10 and 3-5 0.10 and 5-15
Surface operating velocity (ms^{-1})	Nil or 0.1-0.3	Nil or <0.05
Surface washing velocity (mh^{-1})	0.2-0.4	0.2-0.3

2.4.2 Roughing Filters (RFs)

Roughing filters (RFs) are the main pre-treatment unit used for treating highly turbid surface water or reducing solid matter to acceptable levels for sound SSF operation. A SS concentration of 2 - 5mg/l or Turbidity level of < 20 NTU is generally considered an acceptable pre-treatment water standard for SSF (Wegelin, 1996). Roughing Filters (RFs) are classified based on the direction of flow (up-flow, down-flow, or horizontal flow) and the depth of media layers in the direction of flow. (Galvis et al., 1993). . Figure 2.5 shows the various types of RFs.

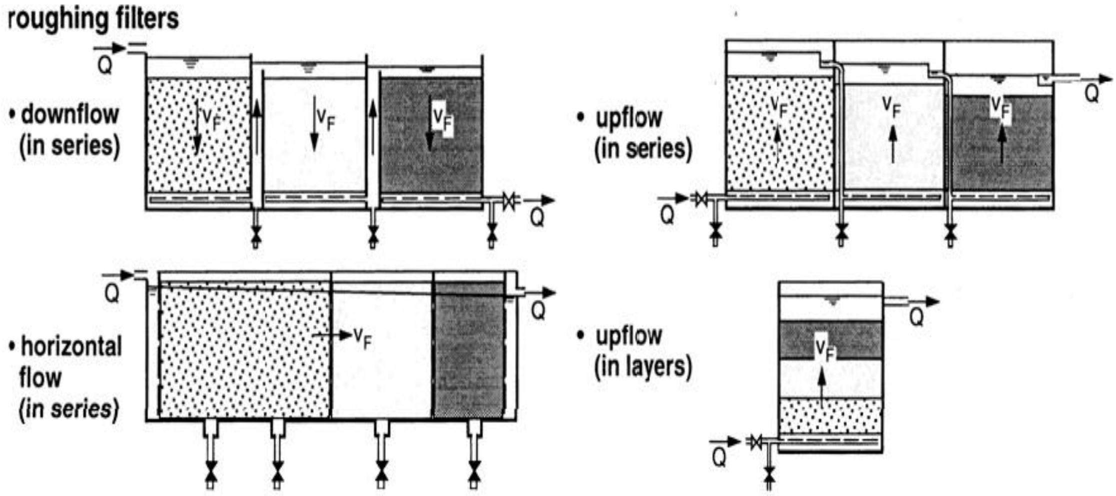


Figure 2.5 Types of Roughing Filters (Wegelin, 1996**).**

i. Horizontal-flow Roughing Filter (HRF).

A Horizontal-flow Roughing Filter (HRF) consists of a horizontal filter box with three or four sections or compartments of decreasing length separated by baffles, in which water flows horizontally. Each section is filled with gravel as filter media. The media with large diameter is placed in the first compartment and the smallest in the last compartment respectively (Wegelin, 1996). The major advantage of HRF is its extended bed lengths and solids storage capacity making it more suitable for treating very high SS concentrations. (Collins et al., 1994a). A diagram of a HRF and its design guidelines are shown in Figure 2.6.

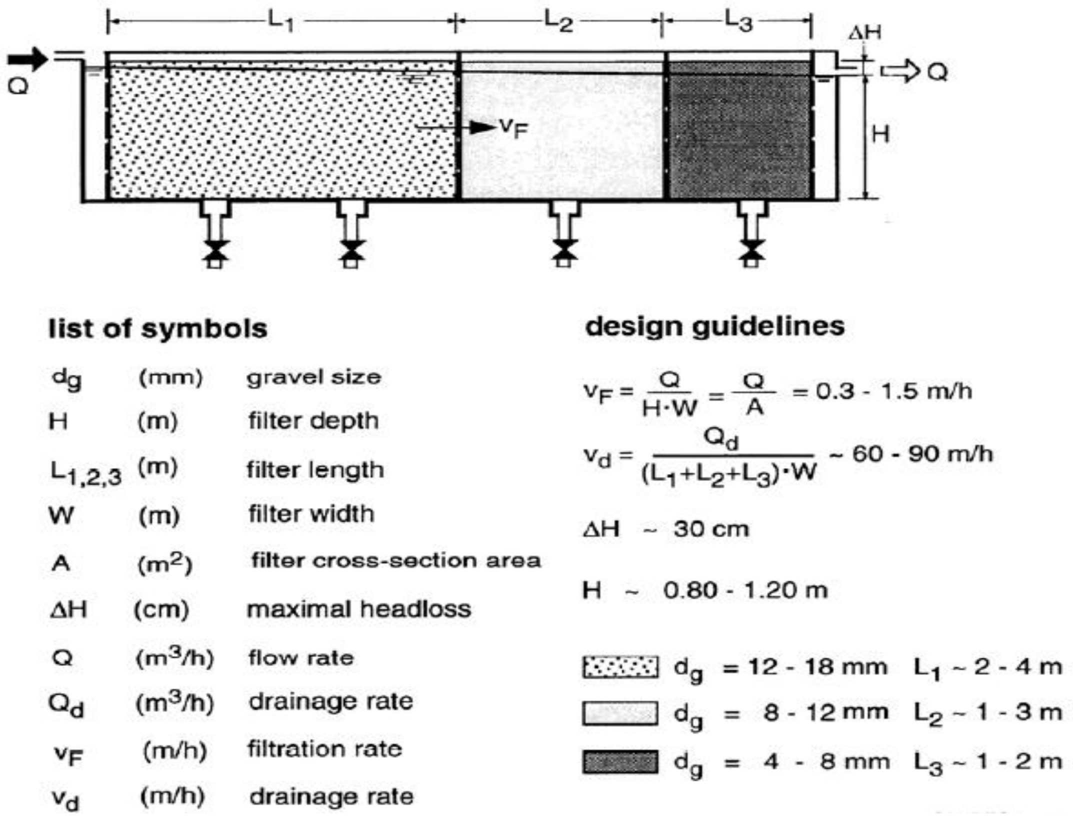


Figure 2.6 Horizontal-flow Roughing Filter (HRF) and its design guidelines (Wegelin, 1996).

ii. Down-flow Roughing Filter in series (DRFS).

A Down-flow Roughing Filter in series (DRFS) consists of three or four individual filter compartments or sections, each with gravel as filter media. The media with large diameter is placed in the first compartment and the smallest in the last compartment respectively. Water flow is downward through each media section. (wegelin, 1996). These sections are hydraulically independent and work in series. They all operate with the same filtration rate of around 0.3 - 1.2 mh^{-1} (Galvis, 1999). Figure 2.7 shows diagrammatic representation of the DRFS and its design guidelines.

iii. Up-flow Roughing Filter in series (URFS).

An Up-flow Roughing Filter in series (URFS) is similar to the DRFS except that water flows upward through each media compartment. The main advantage of URFS over

DRFS is that cleaning is much more efficient since most SS accumulation occurs in the bottom of the filter near the drainage pipes. (Wegelin, 1996). A diagrammatic representation of the URFS and its guideline design parameters are shown in Figure 2.7.

iv. Up-flow Roughing Filter in layers (URFL).

An Up-flow Roughing Filter in layers (URFL) consists of one filter compartment, with many layers of filter media, ranging from media with the largest diameter at the bottom to media with smallest diameter at the top. The major merit of the URFL is its low space and capital requirements compared to HRF or URFS. However, research has shown the URFL to be efficient with water sources of low to medium Suspended Solids concentrations (<150mg/l) (Galvis et al., 1993). This is due to its smaller solids storage capacity and smaller bed depth than the HRF or URFS. A diagram of the URFL and its guideline design parameters are shown in Figure 2.7.

2.4.3 Benefits of Coarse Gravel Filters

Some of the benefits of using Coarse Gravel Filters are:

i. Have proved efficient to in pre-treating high Turbidity and SS water prior to Slow Sand Filtration (Collins et al., 1994b)

ii. Roughing Filters do not require complicated mechanical equipment or the use of chemicals (Wegelin and Schertenleib, 1993)

iii. They are a sustainable method of pre-treatment in rural areas. (Ochieng, 2004)

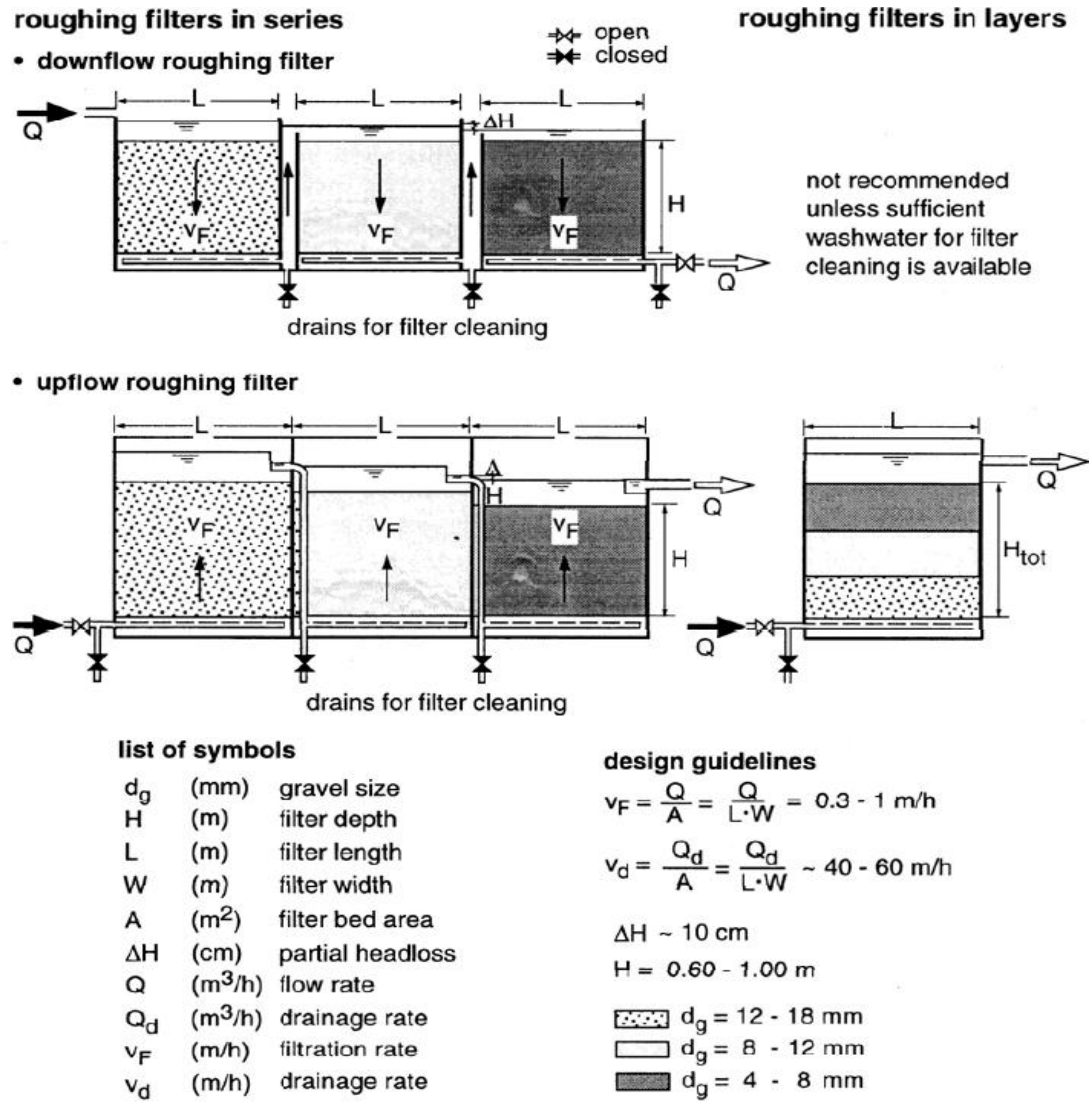


Figure 2.7 Typical design parameters of DRFS, URFS, and URFL (Wegelin, SKAT, 1996).

2.4.4 Performance of Roughing Filters (RFs)

This section presents a brief discussion of performance of Roughing Filters (RFs) from various studies. The main parameters discussed are Turbidity, colour, Suspended Solids, metals, algae and bacteria.

i) Removal of Turbidity, Colour and Suspended Solids

Roughing Filters are capable of excellent removals of Turbidity. For instance, Mukhopadhay (2008) reports mean Turbidity removal of 75% by the RFs. Tamar

(2008) found documents that the best performing RFs achieved on average 84% removal of the turbidity. Wegelin (1998) reports that Up-flow Roughing Filters can achieve removals of 50 - 90%. According to most research findings, the effluent that is produced by RFs is well within the limitations of Slow Sand Filtration. For instance, Barrett et al. (1991) found that RFs reduced the Turbidity from 150 NTU down to 15 NTU.

Rajapakse and Ives (1990) found that RFs can reduce SS concentrations to below 25mg/l. Wegelin et al. (1998) reports SS removals of 90% with influent concentrations of 50-200mg/l, and 50 - 90% with influent concentrations of 5-50mg/l. Ochieng et al. (2004) reports an average SS removal of 94 - 95% with influent concentrations of 9 - 116 mg/l. Rabindra (2008) reports mean TSS and turbidity removal of 95% by RFs. Wegelin et al. (1998) reports true colour removals of 20 - 50%.

ii) Removal of Metals

Research findings across the world show a varied response by RFs with respect to Metal removal. For instance, Pacini (2005) reports mean Iron and manganese removal of 85 and 95% respectively. Bernardo (1988) found significant reductions of Iron and Manganese in RFs. Wegelin et al. (1998) on the other hand reports average removal efficiency by RFs i.e 50% removal of Iron and Manganese. In another research, Wegelin and Schertenleib (1993) report 50% removal of heavy metals in RFs.

iii) Removal of Bacteria and Algae

Most research finding show good efficiencies with respect to Bacteria and Algae removal by Roughing Filters (RFs). Dastanaie (2007) reports mean Coliform removal of 94%. Clarke et al. (1996b) found that RFs achieved faecal coliform removal in the range of 80 - 90%. Wegelin and Schertenleib (1993) report bacteria removals of 90 -

99%. Dome (2000) reports average Algae removal of 95%. Barrett et al. (1991) documents values of 30 - 80% with respect to Algae removal.

2.4.5 Factors affecting removal in Roughing Filters (RFs)

The principal design parameters affecting removal in RFs are bed depth, filtration rate, and media size (Collins et al.,1994a). Treatment efficiency is enhanced with decreasing media diameter, increasing surface area, decreasing filtration rate, and increasing bed depth. Bed depth is the most influential design variable (Collins et al., 1994b).This means, it is vital to maximize the bed depth to capture particles that penetrate deeper into the filter.

2.4.6 Cleaning of Roughing Filters (RFs)

Cleaning is essential in RFs to remove accumulated SS and replenish the solids storage capacity of the filter. This is accomplished by opening a drain valve and allowing the filter to drain freely under gravity, thereby flushing solids from the media (Collins et al., 1994b). Wegelin (1996) recommends a drainage velocity of 30 m/h (preferably 60 - 90m/h) to induce turbulent flow conditions in the media pores, thus dislodging solid deposits from the media.

2.5 Wegelin design criteria

Wegelin design criteria is the most common model which is applied in design of Roughing Filters (Wegelin et al., 1996). It is based on the “1/3-2/3” conceptual filter theory which gives a simple explanation of the working of the Roughing Filter (RF) in SS removal or reduction. Wegelin et al (1996) describes it by considering a particle in water which can bypass a gravel of the RF either on the right or left or settle on its surface. This simply means that the probability of success of removal by the gravel grain is 1/3 and failure is 2/3. Mathematically this process can be as well be illustrated by an exponential equation in accordance with Fick's law .

$$\frac{dc}{dx} = -\lambda c \tag{2.1}$$

where:

c is solids concentration.

x is filter depth.

λ is the filter coefficient.

By assuming the total filter length as series of smaller and numerous filter cells, the total SS concentration after a length of Δx is expressed by the equation.

$$c_{out} = \sum c_{i(in)} e^{-\lambda_i \Delta x} \tag{2.2}$$

where:

c_i is concentration of particles of size d_{pi}

Δx is the length of the experimental filter cell.

λ_i is filter coefficient for each filter cell.

Equation (2.2) shows that if the inlet solid concentration, filter coefficient and depth are known the filter efficiency can be predicted. Wegelin (1996) gives the concentration of HRF effluent of n compartments by the following expression:

$$c_e = c_o \times E_1 \times E_2 \times ..... \times E_n \tag{2.3}$$

where:

c_o is concentration in the HRF influent.

c_e is 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:

$$c_e = c_o e^{-\lambda L} \tag{2.4}$$

where:

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

L is the length of filter.

The filter efficiency E is expressed by the equation:

$$E = \frac{c_e}{c_o} = e^{-\lambda L} \tag{2.5}$$

$$\therefore c_e = c_o \times E \tag{2.6}$$

The values of E_i (i = 1, 2… n) are obtained from table 2.3 developed by Wegelin.

Table 2.3.E-values for HRF design (Wegelin, 1989).

Gravel Size d_g (mm)	**Filtration rate V_f (m/h)**	**$E = c_e/c_o = e^{-\lambda L}$ (%)**				
		Filter Length L_f (m)				
		1	2	3	4	5
5	0.5	15.2	2.3	0.4	0.1	0.0
	0.75	28.3	8.0	2.3	0.6	0.2
	1	39.9	15.9	6.4	2.5	1.0
	1.5	59.0	34.8	20.5	12.1	7.2
	2	74.7	55.7	41.6	31.1	23.2
10	0.5	35.6	12.7	4.5	1.6	0.6
	0.75	50.7	25.7	13.0	6.7	3.3
	1	61.7	38.1	23.5	14.5	9.0
	1.5	77.7	60.3	46.9	36.4	28.3
	2	89.5	80.2	71.8	64.3	57.6
15	0.5	48.4	23.5	11.4	6.5	2.7
	0.75	62.4	39.0	24.3	15.2	9.5
	1	72.1	51.9	37.4	27.0	19.4
	1.5	85.4	72.9	62.2	53.1	45.3
	2	95.0	90.2	85.6	81.3	77.2
20	0.5	56.9	32.4	18.4	10.5	6.0
	0.75	69.6	48.5	33.7	23.5	16.4
	1	78.1	61.0	47.6	37.2	29.0
	1.5	89.6	80.1	71.7	64.2	57.5
	2	97.7	95.4	93.2	91.0	88.9

2.5.1 Horizontal-flow Roughing Filter (HRF) design guidelines.

Wegelin (1989) developed a criteria based on SS concentration in the raw water to guide the design of the Horizontal - flow Roughing Filter (HRF) as swon in Table 2.4.

Table 2.4 Design criteria for Horizontal-flow Roughing Filter (Wegelin, 1989).

Parameter	Suspended Solids (SS) concentration in raw water c_o (mg/l)		
	<100 Low	**300-100 Medium**	**>300 High**
Filtration rate V_f (m/h)	1 - 1.5	0.75 - 1	0.5
Filter length for (d_g) L_i (m)			
20mm	3	3	3 - 5
15mm	3	2 - 4	2 - 5
10mm	2	2 - 3	2 - 4
5mm	1	1 - 2	1 - 2
Total length (m)	8 - 9	8 - 9	8 - 16

2.5 Case studies on Multi-Stage Filtration (MSF).

2.5.1 Success of Multi-Stage Filtration in Colombia

The Multi stage Filtration (MSF) technology originated in Colombia in 1980 - 1990s. Comprehensive research on MSF pilot units in Colombia was done between this periods. Research findings show that Colombia has had a successful experience with this technology (Galvis , 1999). The results from the pilot units yielded positive results which necessitated the installation of full scale systems in different regions of Colombia. Galvis and Visscher (1999) document that there are about 50 full scale systems in operation since the 1980s. Recently, the Design and installation of bench-scale SSF units to treat drinking water for students in rural communities surrounding Barbosa, Colombia has been reported by Jason et al. (2012).

2.5.2 Performance of Horizontal-flow Roughing Filter (HRF) in Ghana

A pilot unit of HRF was installed and tested in Ghana to investigate its response in Turbidity removal. HRF performance in Ghana Showed positive results with an average turbidity removal of 84% with reduction from about 305 to 50 NTU was achieved (Tamar, 2008).

2.5.3 Success of Multi-Stage Filtration (MSF) in North America

Studies on Multi-Stage Filtration (MSF) have been reported in North America. Shawn (2005) demonstrated the reliability of MSF for small communities in northern climates. He reports that complete removal of coliform bacteria was achieved with turbidity values of <1NTU being attained by the MSF system. LeCraw et al. (2004) reports that MSF has proven to be a reliable treatment technology in a number of onsite pilot studies and full-scale plants throughout North America.

2.5.4 MSF performance in Bangladesh

In Bangladesh, MSF units were installed and tested for efficiency in removal of Turbidity and Microbiological raw water improvement. The units showed positive results, achieving around 99% Turbidity removal with turbidity reduction from 85 NTU to 0.75 NTU. With respect to Total coliform and *E. coli* the units achieved very high efficiencies recording around 99.97% and 100% respectively (Faroque, 2006).

2.5.5 Success of Multi-Stage Filtration (MSF) Pilot studies in Kenya

A pilot unit was first installed in Kenya in the year 2001 and an evaluation of its performance versus the Conventional System made. From the Pilot results, the MSF system performance was better than the Conventional System (CS) under similar raw water and environmental conditions achieving > 98% and 99% *E. coli* and Total coliforms removal respectively (Ochieng et al., 2004).

2.6.6 Slow Sand Filtration in South Sudan

Having recognized the significance of SSF in provision of potable water in remote areas, the Government of South Sudan (GOSS) in conjunction with UNICEF has recently developed a design manual to guide the implementation of SSF in South Sudan (TGCMSSF, 2009).

2.6.7 Multi - Stage Filtration (MSF) in other countries

Studies on MSF technology have also been reported in other Countries such as South Africa (Nkwonta and Ochieng, 2009), Burkina Faso (Sylvain et al., 2006) and England (Rachwal et al., 1998). All this studies gave positive results, thus enhancing the fact that MSF technology has a great potential of improving accessibility to potable water in rural and developing areas.

2.6.8 General conclusion on Multi - Stage Filtration (MSF)

From the success stories of MSF technology in other Countries, a general conclusion can be drawn that this technology has a high capability of enabling a developing Country such as Kenya attain the SDGs (on the subject of water) by improving accessibility to potable water in rural and developing areas if well executed.

CHAPTER THREE

3.0 MATERIALS AND METHODS

General information

This research was conducted in two stages. Phase one commenced in September 2011 and it involved an in-depth literature review, design and fabrication of the pilot MSF unit. It also entailed identification, surveying of the proposed site to establish a suitable field profile for gravity flow. The second phase commenced in February 2013. It involved on-site pilot plant set up and commissioning, filter bed maturation period, monitoring, sampling, field and laboratory tests. This phase lasted for a period of four months. The delay in the commencement of the second phase was due to logistical problems.

3.1 Study area

The pilot plant was set up at Moi University next to Moi University Water Treatment Works in Kesses Division, which is about 36 kilometres by road South East of Eldoret, Uasin Gishu County in Western part of Kenya. Eldoret is located It lies between longitudes $34^0$50' east and $35^0$37' West and latitudes 0^0 03' South and $0\ ^0$ 55' North. It borders Nandi-North, Nandi-South, Kericho, Koibatek, Marakwet, Transnzoia and Lugari. It covers a total area of about 3,300 Sq. Km. with a population of about 894,179. (Uasin Gishu, 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 eliminating pumping costs.

3.1.1 Topography

The area lies within a highland plateau with altitudes falling gently from about 2,700 to 1,500 metres above sea level (Uasin Gishu, 2013)

3.1.2 Climate

The area has a cool and temperate climate with mean annual rainfall of between 600 to 1,600 mm with two distinct peaks in May and August. The dry season is felt between the month of November and February. The temperatures ranges between 7 - 29 ^{o}C (Uasin Gishu, 2013).

3.1.3 Economic activity

The main economic activity in the area is livestock keeping and crop farming (Uasin Gishu, 2013)

3.1.4 Soils

There are four noticeable soil types in the area: red clay, red loam, brown loam and brown clay (Uasin Gishu, 2013).

3.1.5 Water resources

The area lies within the Lake Victoria catchment with most of its rivers draining into the Lake. The main water catchment are:

- Cengalo catchment, which provides water to Bargeyo area of the county.
- Timboroa catchment which is the source of river Daragwa
- Nabkoi area, the source of Kerita, Nderuguti and Kipkurere streams (Uasin Gishu, 2013)

Figure 3.1 shows the Location of study area

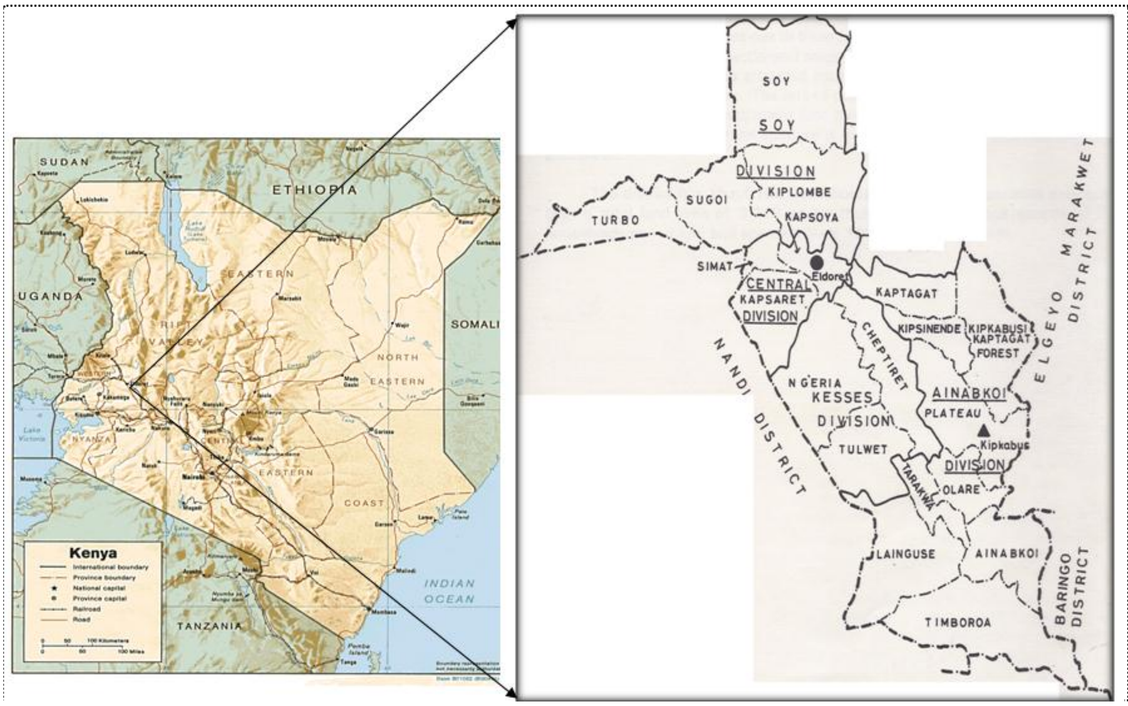


Figure 3.1 Location of study area.

3.2 General Layout of the Multi-Stage Filtration pilot units

The MSF pilot unit comprised of three raw water treatment stages. The layout is as shown in figure 3.2. The first stage consisted of two Dynamic Gravel Filters (DyGFs) in parallel and being supplied with raw water from a constant head tank or Mixing Tank (MT). The second stage consisted of three lines of Horizontal-flow Roughing Filters (HRF) in parallel. The final Stage was two Slow Sand Filters (SSF) connected in parallel.

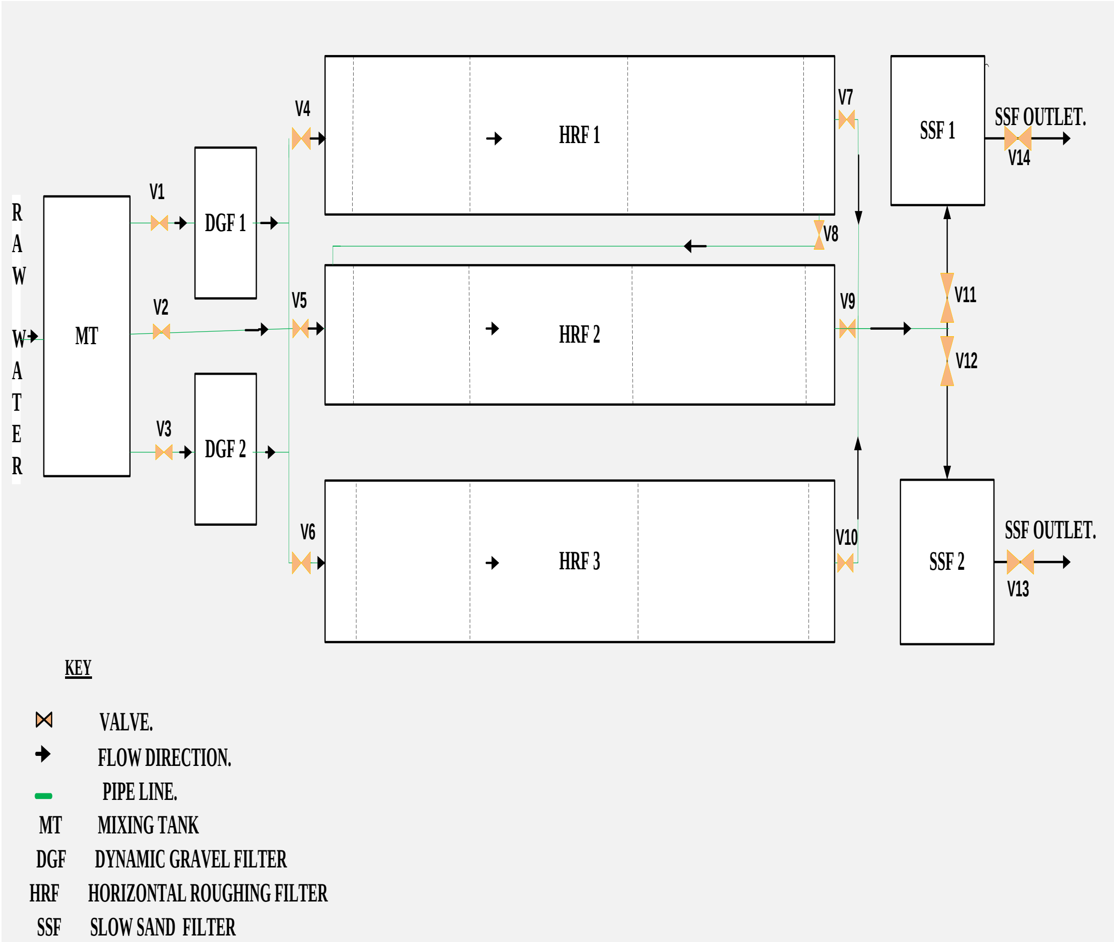


Figure 3.2 General layout of the Multi-Stage Filtration pilot unit.

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, an additional Slow Sand Filter and Horizontal-flow Roughing Filter were provided in the design.

The following section gives a description of the different MSF units used in this Study and their functions.

3.2.1 Mixing Tank (MT)

The Mixing Tank (MT) maintained a constant water head for the MSF units and acted as the first sampling point of raw water. The MT was positioned adjacent to the intake of the raw water at a lower head so as to enable gravity flow of raw water from the point of abstraction to the SSF unit. The MT unit measured 1.2m Length, 0.8m width and 1m height. The unit was fabricated using Mild Steel (MS) plates (3mm thick). Figure 3.3 shows the Mixing Tank unit used for this research.

Figure 3.3 Mixing Tank (MT)

3.2.2 Dynamic Gravel Filter (DyGF)

The main role of a Dynamic Gravel Filter (DyGF) was to protect treatment plant units from high Turbidity and Suspended Solid (SS) loads. This is because high turbidity result in clogging of filters, especially Slow Sand Filter (SSF) units thus reducing the run time period and making it a tedious process to do frequent filter maintenance activities. The water quality is also compromised in such cases. Hence DyGF units were incorporated in this Study. The DyGF units were the first treatment option of raw water. Two parallel DyGF units were connected in series with three HRF units and SSF units as shown in figure 3.2. The response of the designed DyGF units to different raw water quality parameters was investigated in this research. This was aimed at providing information on the contribution of DyGF unit in the overall water treatment process of MSF units. Sampling points were identified at both inlet and outlet to monitor raw water quality improvement. Figure 3.4 shows the Dynamic Gravel Filter (DyGF) units used for this research. The units were fabricated using Mild Steel (MS) plates (3mm thick) and measured 0.5m length, 0.5m width and 1m height.

Figure 3.4 Two Dynamic Gravel Filters (DyGFs)

The DyGF consisted of a layer of fine gravel (3 to 5mm) of 0.2m height placed over a layer of coarse gravel (5-25mm) of 0.4m 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 will accumulate at this point in the system which very much facilitates the cleaning of the unit. The coarse gravel acts as filter support and allows an even abstraction of the pre-filtered water through the drainage pipes. These units operated at a filtration rate in the ranges of 0.5 to 1m/h depending on the raw water quality. The raw water infiltrated into the gravel bed to the drainage system and then flowed to the HRF unit

3.2.3 Horizontal-flow Roughing Filter (HRF)

The role of HRF is treating Surface water of high Turbidity and SS over prolonged periods. Three HRF units with same design specifications were fabricated for this Study using Mild Steel (MS) plates (3mm thick). Each measured 5.4m length, 0.5m width and

1m depth. 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 at the centre of each compartment and also at both inlet and outlet points to monitor the raw water quality improvement. Three HRF units in parallel were connected to the Mixing Tank (MT), Dynamic Gravel Filter (DyGF) and Slow Sand Filter (SSF) units as shown in figure 3.2. Figure 3.5 show the Horizontal-flow Roughing Filter (HRF) units used for this research.

Figure 3.5 Three Horizontal-flow Roughing Filters (HRFs)

The HRF consisted of three sections: the inlet chamber, the filter media and the outlet chamber. The inlet and outlet chambers helped to maintain an even flow distribution along and across the filter. Valves were installed at both the inlet and outlet of the system to maintain the designed flow velocity and water level along the filter bed. The filter bed was composed of filter material 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 had an under drainage system to enable hydraulic sludge extraction to be carried out for easy cleaning and maintenance. The unit operated at a constant filtration velocity of 0.5m/h.

3.2.4 Slow Sand Filter (SSF)

The SSF was the main treatment unit in the whole process. An additional SSF unit was designed to ensure a continuous water supply whenever the SSF initially in operation was under maintenance (see figure 3.2). The SSF units were filled with sand as treatment media. The grain size was chosen according to SSF design guidelines as documented in chapter 2. Sieve analysis was carried out on the SSF media to obtain the required grain size distribution and the respective uniformity coefficients. Sampling points were identified at both the inlet and outlet to monitor the removal efficiency of the SSF unit.Additional five sampling points were identified along the SSF units to monitor raw water quality improvement along the filter media column.The SSF units were fabricated using Mild Steel (MS) plates (3mm thick) and measured 0.8m long, 0.8m wide and 3m high. Figure 3.6 shows the SSF units used in this research.

Figure 3.6 Two Slow Sand Filter (SSF) units

3.3 Design criteria used for Multi-Stage Filtration (MSF) units

3.3.1. Design criteria for Slow Sand Filter (SSF) unit.

i) Pilot plant capacity

The design considered four families of five people each (a population of 20 people). A small population was chosen for the pilot unit to minimise on costs

The average per/capita water demand in high potential rural areas is 60 l/capita/day *(*practice manual for water supply in Kenya, 2005*)*

Using the above information, the pilot plant capacity *(Q)* was determined by multiplying the population (20 people) by the average per/capita water demand {60l/capita/day} to get Q as $1.2\text{m}^3/\text{day}$ or $0.05\text{m}^3/\text{h}$.

ii) Active cross sectional area of SSF

The minimum design guideline filtration rate is 0.08m/h (TSS, 1987). Thus, active cross-sectional area *(A)* was given by dividing volume flow rate Q (m^3/h) by the minimum filtration rate V_f (m/h).

$$A_{\text{SSF}}(\text{m}^2) = Q_{\text{SSF}}(\text{m}^3/\text{h}) / V_{f\,\text{SSF}}(\text{m/h}) \quad (3.1)$$

$$A_{\text{SSF}}(\text{m}^2) = (0.05/0.08) = 0.625\text{m}^2 \quad (3.2)$$

A square Tank of sides 0.8m with an active area of 0.64m^2 was considered for this study. The new or adjusted filtration rate was found by dividing the volume flow rate Q (m^3/h) by the new active cross-sectional area (m^2).

$$V_{f\,\text{SSF}}(\text{m/h}) = Q_{\text{SSF}}(\text{m}^3/\text{h}) / A_{\text{SSF}}(\text{m}^2) \quad (3.3)$$

$$V_{f\,\text{SSF}}(\text{m/h}) = 0.05/0.64 = 0.078\text{m/h} \quad (3.4)$$

Two SSF units were made of sides 0.8m and height 3m with an active area of 0.64m^2.

iii) Period of operation of SSF

Research from various countries across the world has shown that intermittent operation tends to interrupt with the biological activity within the filter media (Shawn, 2005) For this research, twenty four hour operation period (24h/d) was considered to achieve optimal results.

iv) Height of filter bed of SSF

Research has shown that for the biological activity within the filter bed depth, the various strains of bacteria responsible for the various degradation processes in the filter colonise different depths depending on their nutritional needs and survival climates (Huisman, 1974). From literature, the recommended filter bed depths are 0.5-1.5m. Having a bed depth greater than 1.5m becomes uneconomical and below 0.5m compromises quality (Ochieng, 2001).

A filter bed depth of less 0.3 - 0.4m has been considered undesirable when targeting optimal results with respect to water quality (Huisman, 1974). In this Study, a filter bed depth of 1.2m was chosen to allow for 0.7m scrapping layer before re-sanding. This would give the filter a minimum of 23 filter runs before re-sanding.

v) Filtration rate of SSF

According to research findings on SSF across the world, low filtration rates of between 0.08-0.4m/h give optimal results (Visscher et al., 2006). This is attributed to the fact that low filtration rates give a longer retention time for efficient biological activity within the filter media. Therefore, low filtration rates of between 0.08 - 0.4m/h were maintained in this research.

vi) Specification of filter bed Material of SSF

Sand was used as the filter bed material in the SSF units. Sand is typically the most economical and readily available material used (Manz, 2005). The grain size of the filter media is a crucial factor for the filter efficiency. A smaller grain size improves the efficiency of the treatment process, although it will increase the initial head-loss (Huisman, 1974). The grain size was determined by carrying out sieve analysis. Relatively fine sand is recommended with an effective diameter between 0.15 - 0.3mm and U_c of preferably < 3 (Visscher, 1987). For this Study the Sieve analysis results of the sand used were as follows: d_{10}=0.3mm, d_{60}=0.7mm and U_c=2.33. These values fell within the acceptable ranges.

vii) Support bed height including drainage (m) of SSF

The under-drains serve to support the filter material and provide an outlet for the water passing through the Filter. The under-drains also allowed treated water flow out of the Filter for uniform abstraction. The recommended depth from literature is between 0.4 - 0.6m (TSS, 1987). In order to support a filter bed depth of 1.2m, 0.46m of graded Gravel was considered sufficient for the SSF pilot unit used in this study.

viii) Supernatant water maximum height (m) of SSF

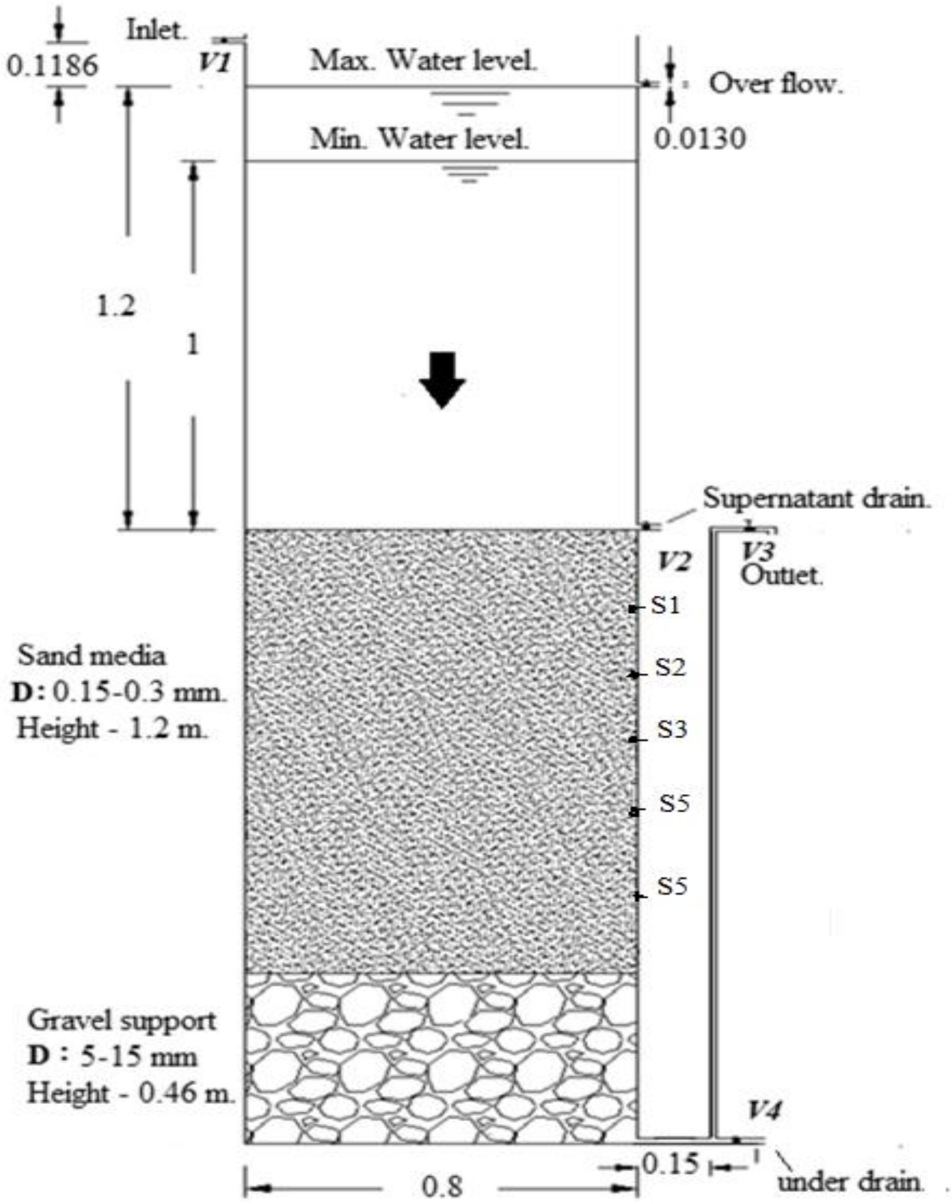
The Supernatant depth that must be applied depends on the maximum allowable head-loss. The maximum level ranges between 1 - 1.5m depending on total length of the filter (Huisman,1974). The maximum allowable head-loss for this research was 1m, hence a supernatant height of 1m was considered sufficient.

ix) Free board of SSF

During certain occasions, the filter can be operated beyond its required filter run length or the filtration rate might be reduced below the design rate thus increasing the supernatant height above the set level. To cater for these situations, a free board is normally included. The recommended ranges are 0.1 - 0.3m (Huisman, 1974). A Freeboard of 0.2m was considered sufficient in this Study.

x) Filter bed material cleaning

The sand was washed by use of clean water before placement in the SSF units to ensure that the required Sludge content is attained i.e. not greater than one percent by volume prior to placement (Huisman, 1974)



KEY

V	Valve
D	Diameter
⬇	Flow direction
S1, S2, S3, S4, S5	Sampling points

N/B All dimensions are in metres
Distance between sampling points is 0.2 m

Figure 3.7 Cross-sectional view of Slow Sand Filter (SSF) unit

3.3.2 Design criteria for Horizontal-flow Roughing Filter units.

i) Filtration rate

According to Wegelin (1996) design criteria, filtration rates of between 0.5 - 1.5m/h are recommended for the HRF unit, but for optimal results lower filtration rates are .A constant filtration rate of 0.5m/h was maintained for the HRF unit in this Study. This was achieved by daily monitoring of the inlet and outlet valve to ensure that the HRF unit operated within the designed flow.

ii) Height , width and length

In this Study, height, Width and Length was guided by required capacity of the system and the configuration of the construction material. The width depended on the required capacity of the treatment plant. Rectangular shaped cross-section was used with 1m height and 0.5m width for each HRF unit. This was because of the following reasons:

- Ease fabrication of the HRF units such as putting the separation MS plates for different compartment.
- Ease monitoring of the Filter like checking water level below or above Filter media.
- Ease initial media replacement: Removal and returning of the media in the event of manual cleaning.

According to Wegelin (1996), overall length normally lies within 5 and 7m. The length is. A filter length of 5.4m was considered appropriate in this case.

iii) Flow and head-loss control

The designed HRF units were operated at a constant filtration rate of 0.5m/h. This was because research has shown that low filtration rates give optimal results (Wegelin, 1996).Valves were installed both at the inlet and outlet of the HRF unit (as shown in figure 3.8) to maintain the designed flow conditions.

iv) Active cross sectional area

In order to calculate the active area for the Horizontal Roughing Filter (HRF) unit used in this study, it was important to ensure that the HRF unit was able to serve one SSF unit under maximum operation condition. The maximum filtration rate allowed in the SSF unit for this study was 0.4m/h hence by multiplying the new SSF active area ($0.64m^2$) with the maximum SSF filtration rate (0.4m/h) the design flow rate in the HRF unit (Q_{HRF}) was found as 0.256 m^3/h.

Referring to Table 2.4, the minimum design guideline filtration rate V_f for high turbid waters is 0.5m/h. Thus, HRF active cross-sectional area *(A_{HRF})* was found by dividing Volume flow rate Q (m^3/h) by the minimum filtration rate V_f (m/h).

$$A_{\mathrm{HRF}}(\mathrm{m}^2) = Q_{\mathrm{HRF}}(\mathrm{m}^3/\mathrm{h}) / V_{f\,\mathrm{HRF}}(\mathrm{m/h}) \tag{3.5}$$

$$\therefore\ A_{\mathrm{HRF}}(\mathrm{m}^2) = 0.256\mathrm{m}^3/\mathrm{h} / 0.5\mathrm{m/h} = 0.512\mathrm{m}^2 \tag{3.6}$$

For this Study, an active area of $0.5m^2$ was selected. The new or adjusted filtration rate was found by dividing the volume flow rate Q (m^3/h) by the new active cross-sectional area (m^2)

$$V_{f\,\mathrm{HRF}} = 0.256\mathrm{m}^3/\mathrm{h} / 0.5\mathrm{m}^2 = 0.512\mathrm{m/h} \tag{3.7}$$

For this research, three HRF units were made of 0.5m width by 1 m height with an active area of $0.5m^2$ and a length of 5.4m. An extra HRF unit was essential to ensure continuous flow of water in the SSF units when the other units are under maintenance.

v) Filter cleaning.

Drainage velocity of between 60 - 90m/h is advised (Wegelin, 1996).For this research, the drainage velocity was kept within the recommended ranges by maintaining a constant rate of 60 m/h.

vi) Filter material

In this Study, Gravel was chosen because it's easily available in the region and meets the above criteria. The Gravel was graded using sieves of the ranges 5 - 25mm. After grading, the material was thoroughly washed until the resulting water was clean and placed in their respective compartments. Figure 3.8 shows cross-sectional view of Horizontal-flow Roughing Filter pilot unit used in this Study.

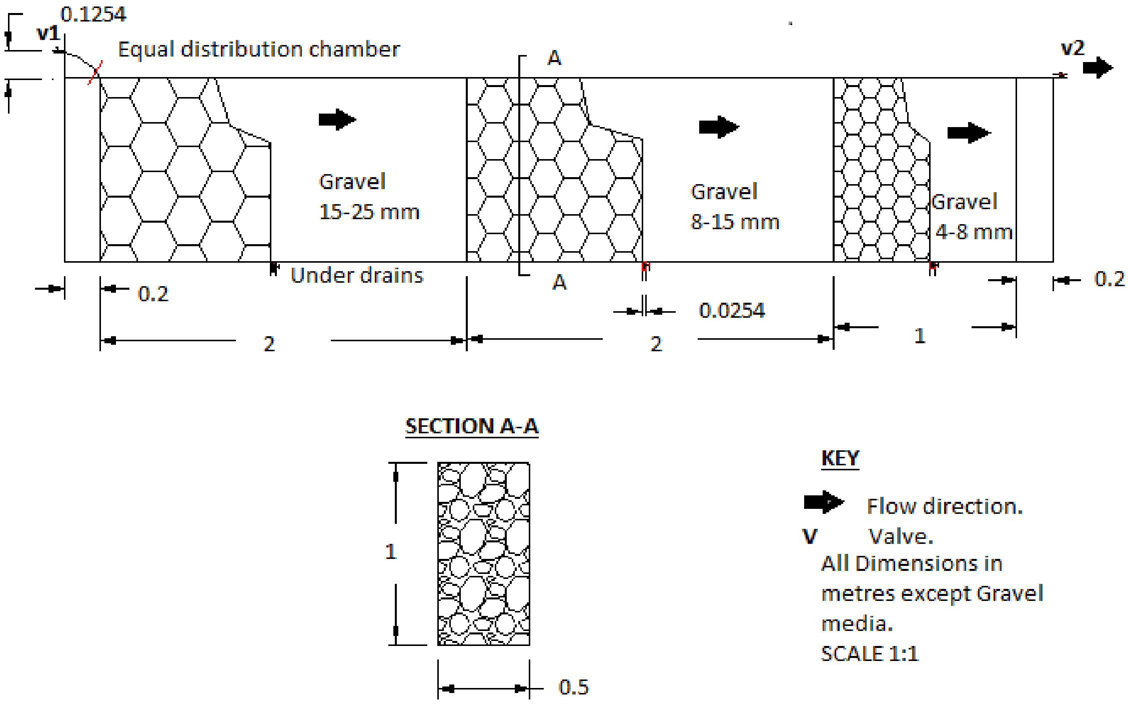


Figure 3.8 Cross-sectional view of Horizontal-flow Roughing Filter (HRF) unit

3.3.3 Design criteria for Dynamic Gravel Filter (DyGF) units

i) Active cross sectional area

For this Study, the design volume flow rate Q (m^3/h) in the DyGF unit (Q_{DyGF}) was taken equal to Q_{HRF} to minimise on overflows. Thus for this research Q_{DyGF} was taken as $0.256\ m^3/h$. The horizontal flow velocity was considered non-existent in this case to minimise the risk of fine filter media being carried away during filter operation.

Referring to Table 2.2, the minimum design guideline filtration rate for water quality improvement for DyGF unit is given as 0.5m/h. Thus, active cross-sectional area (*A*) is given by dividing Volume flow rate *Q* (m^3/h) by the minimum filtration rate V_f (m/h),

$$A_{\text{DGF}}(\text{m}^2) = Q_{\text{DyGF}}(\text{m}^3/\text{h}) / V_{f\,\text{DyGF}}(\text{m/h}) \tag{3.8}$$

$$A_{\text{DyGF}} = 0.256\text{m}^3/\text{h} / 0.5\text{m/h} = 0.512\text{m}^2 \tag{3.9}$$

For this Study, two parallel DyGF units with total active area of 0.5m^2 were used (see figure 3.1). Each unit measured 0.5m by 0.5m with a total height of 1m.

The DyGF design provided two operational scenarios:

Scenario 1: Two DyGF units working simultaneously in parallel with a filtration velocity of 0.5m/h.

The total active area for this case was 0.5m^2. The new or adjusted filtration rate was found by dividing the volume flow rate *Q* (m^3/h) by the total active cross-sectional area *A* (m^2).

$$V_{f\,\text{DyGF}}(\text{m/h}) = Q_{\text{DyGF}}(\text{m}^3/\text{h}) / A_{\text{DyGF}}(\text{m}^2) \tag{3.10}$$

$$V_{f\,\text{DyGF}}(\text{m/h}) = 0.256\text{m}^3/\text{h} / 0.5\text{m}^2 = 0.512\text{m/h} \tag{3.11}$$

Scenario 2*:* One DyGF unit in operation with a filtration velocity of 1m/h.

The total active area for this case was 0.25m^2. By referring to equation 3.10, the new or adjusted filtration rate was found by dividing the volume flow rate *Q* (0.256m^3/h) by the total active cross-sectional area *A* (0.25m^2) to get $V_{f\,\text{DyGF}}$ as 1.024m/h.

These research addressed Scenario 2 i.e. One DyGF unit was operated at a filtration rate of 1 m/h. The additional unit ensured a continuous water supply whenever the DyGF initially in operation was under maintenance.

ii) Dimensions of DyGF unit

The Dimensions of the DyGF and particularly those corresponding to the Surface area (Length and Width) are conditioned by the water flow available for washing the Surface. DyGF require filter depth of about 40-60cm (Galvis, Fernandez,1991). According to Wegelin (1996 the horizontal flow velocity over the filter bed surface should be small (< $0.3ms^{-1}$) or nonexistent In this Study DyGF unit of 0.5m Length and 0.5m width with a Filter depth of 0.6m was used. The horizontal flow velocity was considered non-existent.

iii) Filtration rate and Head-loss

Filtration rate depends on the Local conditions. Values between 0.5 and 3m/h have been applied in Colombia (Wegelin, 1996). The filtration rate for the DyGF units were was maintained in the range of 0.5-1m/h for this study depending on the raw water quality. Outlet valves were adjusted daily to ensure that total output of the System was kept within designed values by compensating for the gradual increase of the resistance in the Gravel layer. For this research a maximum head-loss of 20cm was allowed in the DyGF units. This value fell within the recommended ranges from literature of 20 - 40cm (Visscher, 1987).

iv) Cleaning

During washing the flow velocity has to guarantee that the re-Suspended Solids will be carried away from the Filter. The surface washing velocity has to fall in the ranges of 0.2 - $0.4mh^{-1}$ to avoid the risk of the fine filter media being carried away during filter washing. Cleaning was accomplished by raking the surface which provoked the re-suspension of the retained material which was easily carried away by overflowing water. This was meant to restore the Filtration Capacity.

3.4 Experimental design

The objective of the experimental design was to test the efficiency of the pilot Multi Stage Filter (MSF) in raw water treatment. The major experimental factors/parameters and levels or ranges investigated in this study were:

- Faecal coliforms (20 to 372 CFU/100ml)
- Total coliforms (33 to 684 CFU/100ml)
- Colour (70 to 165 mg/l pt.)
- Suspended solids (9.6 to 262.5 mg/l)
- Turbidity (5 to 400 NTU)

There were a total of nine scheduled tests in this study. The testing schedule and objective of each test is shown in Table 3.1. During each test, treatment performance was analyzed by collecting water samples from the various sampling points of the MSF pilot system. The list of the water quality parameters that were monitored in this study, including the frequency and sampling location of each parameter, is given in Table 3.2.

Water samples were analyzed either onsite or at Moi University water laboratory, or at ELDOWAS water Laboratory.

Table 3.1 Testing Schedule

No.	Objective/s	Dates	Remarks
1.	Determine the performance of pilot MSF system in removal of Turbidity, Colour and Suspended solids	Feb14 to June14	Monitored during entire test run period
2.	Determine the performance of pilot MSF system in removal of Total and Faecal coliforms	Feb14 to June14	Monitored during entire test run period
3.	Determine the performance of pilot MSF system in removal of Ammonia Nitrogen	Feb14 to April 12	Monitored during first two months to determine SSF maturation period.
4.	Determine the performance of pilot MSF system in removal of Nitrite Nitrogen and Nitrate Nitrogen	Feb14 to April 12	Monitored during first two months to determine SSF maturation period.
5.	Determine the performance of pilot MSF system in removal of Iron and Manganese	Feb14 to June14	Monitored during entire test run period
6.	Monitor Temperature and PH levels in MSF units	Feb14 to June14	Monitored during entire test run period
7.	Monitor Dissolved Oxygen (DO) levels in MSF units	Feb14 to June14	Monitored during entire test run period
8.	Determine the performance of the DyGF unit	March 14 to June14	Monitored after onset of rains i.e. during high turbidities and SS raw water levels
9.	Determine the effect of connecting two HRF units in series and effect of varying HRF gravel pack ratios.	March 14 to June 14	Monitored after onset of rains i.e. during high turbidities and SS raw water levels
10.	Comparison of MSF units with CS	Feb 14 to June 14	Monitored during entire test run period

Table 3.2 Summary of water quality parameters

No.	Water parameter/s	Units	Frequency	Sampling location
1.	Turbidity	NTU	Daily	R, D_I, D_O, H_I, H1, H2, H3, H_O, S_I, S1, S2, S3, S4, S5, S_O
2.	Suspended Solids	mg/l	Daily	R, D_I, D_O, H_I, H1, H2, H3, H_O, S_I, S1, S2, S3, S4, S5, S_O
3.	Colour	mg/l pt.	Daily	R, D_I, D_O, H_I, H1, H2, H3, H_O, S_I, S1, S2, S3, S4, S5, S_O
4.	E.Coli , T. Coli	CFU/100ml	Weekly	R, H_I, H_O, S_I, S_O
5.	pH		Daily	R, H_I, H1, H2, H3, H_O, S_I, S1, S2, S3, S4, S5, S_O
6.	Temperature	^oC	Daily	R, H_I, H_O,S_I, S_O
7.	Iron ,Manganese	mg/l	Weekly	R, ,H_I, ,H_O, S_I, S_O
8.	Dissolved oxygen	mg/l	Daily	R, H_I, H_O, S_I, S_O
9.	Filtration rate	m/h	Daily	R, D_I, D_O, H_I, H_O, S_I, S_O
10.	Nitrite Nitrogen	mg/l	3 times/week	R, H_I, H_O, S_I, S_O
11.	Nitrate Nitrogen	mg/l	3 times/week	R,H_I,H_O,S_I,S_O

Key:

R – Raw water

D_I, D_O –. DyGF influent and effluent

H_I, H_O – HRF influent and effluent

S_I, S_O – SSF influent and effluent

S1, S2, S3, S4, S5 – SSF sampling point

H1, H2, H3 – HRF sampling point

3.5 Analytical methods and quality control

3.5.1 Water Sampling Collection Method

Before sampling enough sampling bottles were identified i.e each for a sampling point and labelled to avoid confusion. The bottles were washed with a detergent and rinsed with pure water before any sampling exercise. Water samples were obtained starting at sampling points with the cleanest water i.e. SSF unit to upstream sampling ports throughout the pilot system. This was done to avoid sampling error due to potential disruption of flow caused by sampling. Samples that were analyzed onsite were collected in a clean flask or beaker. Samples meant for transport to the University or a commercial laboratory were collected in clean sampling bottles and safely sealed before transportation.

i) **Suspended Solids (SS)**: Gravimetric method was used (Standard Methods, 1995) An Oven *4870AJ Etten-leur* was used to dry filtered residue of a well-mixed sample at 103 to 105 ^{o}C. The increase in weight of the standard glass fibre filter represented the total Suspended Solids. Analytical balance *AB204* was used to measure the weight.

ii) **Turbidity**: An electronic Turbidimeter *HACH 2100Q* was used in which samples to be tested were put in 5 ml cell tubes inserted in the meter and readings taken directly.

iii) **Faecal coliforms and Total coliforms**: Membrane filtration method was used (Standard Methods, 1995). In this method, known volumes of the water (in this case 100ml) sample were filtered through a membrane filter that retains the bacteria on its surface. A selective medium was added to stimulate the growth of the coliform bacteria and the membrane incubated at 44.5^{o}C for a period of 24 hours i.e an Incubator *4870AJ Etten-leur* was used. On the membrane surface, each bacterium develops as a colony, which was easily counted under magnification.

iv) **Manganese**: Palintest photometer *7100* was used to determine Manganese levels.

v) **Ammonia:** Palintest photometer *7100* was used to determine Ammonia levels.

vi) **Colour**: Palintest photometer *7100* was used to determine colour.

vii) **Iron**: Palintest photometer *7100* was used to determine dissolved Iron levels.

viii) **Nitrite Nitrogen and Nitrate Nitrogen**: Palintest photometer *7100* was used.

ix) **Dissolved oxygen:** Dissolved Oxygen (DO) meter *970DO$_2$ Jenway* was used .

x) **Temperature**: Normal accurate mercury-filled Celsius thermometer was used.

xi) **pH:** A pH meter *370pH/mV Jenway* was used.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

General information

This chapter presents the findings of the research in terms of performance of the Multi-Stage Filter (MSF) units considered in this study i.e Dynamic Gravel Filter (DyGF), Horizontal-flow Roughing Filter (HRF) and Slow Sand Filter (SSF) by way of their removal efficiencies for the various water quality parameters. Operation and maintenance procedures of the MSF units are presented at the end of the chapter.

4.1 Raw water Quality

The selected water quality parameters were monitored from the months of January to June 2013. During this period an experience of both dry and rainy seasons was attained. Dry spells were experienced in the months of January to the end of February. Rains commenced in the month of March to June. From the tests done, it was realized that high levels of selected water parameters were achieved during the rainy period. For instance, high Turbidity level of up to 400 NTU and Suspended Solids (SS) value of 262.5mg/l was realized. A maximum value of 684 C.F.U/100ml Total coliform and a value of 372 CFU/100ml was recorded for Faecal coliform during high peaks.

Low peaks were realized during dry season with a minimum value of Turbidity of 5 NTU and Suspended Solids (SS) value of 9.6mg/l. However in the case of Iron and Manganese both seasons recorded very low traces (less than 1mg/l).

The observed trend was attributed to the fact that during dry seasons, flow velocities are low and hence minimal interference from the turbid runoffs. The water does not carry a lot of suspended matter since no runoffs are experienced during the dry season. In the rainy season, high levels of Suspended Solids concentration are experienced because of high flow velocities and runoff interference. In these two seasons, there occurs a great difference in terms of the particle size distribution and the colloidal stability of the suspension. A summary of recorded values for various raw water quality parameters is as shown in the Table 4.1.

Table 4.1 Range of raw water quality parameters

Parameter	Maximum	Minimum
Turbidity (NTU)	400	5
Suspended Solids (SS) (mg/l)	262.5	9.6
Colour	165	70
E.Coli (CFU/100ml)	372	20
T. Coli (CFU/100ml)	684	33
pH	8.98	6.5
Temperature(^{o}C)	26	18
Iron (mg/l)	0.99	0.15
Manganese (mg/l)	0.05	0.002

4.2 Dynamic Gravel Filter (DyGF) performance.

4.2.1 Removal of Ammonia Nitrogen

Ammonia Nitrogen level in SSF unit was monitored in the first two months (Mid-February to Mid-April) i.e was used as an indicator of SSF maturation (The main indicator was bacteriological water quality improvement as discussed in section 4.3.3). Normally, no traces of Ammonia Nitrogen in SSF effluent indicate full SSF maturation (Ochieng, 2001).

It was noted that at commissioning stage (0 to 10 days) low ammonia nitrogen removal was observed (i.e in the range of 10 to 34%) as shown in Table 4.2. The main pointer could be the filter bed was not yet mature. However from day 10 to 50, there was notable improvement in Ammonia nitrogen removal (i.e. in ranges of 82 to 100%) from the raw water. The main reason for such an observation was because of the development of the biological layer which enhanced efficiency of the filter media. Table 4.2 shows Ammonia Nitrogen levels percentage removal in SSF

Table 4.2 Ammonia Nitrogen levels percentage removal in SSF

Run time (days)	Ammonia Nitrogen(mg/l)		% Removal
	SSF in	SSF out	
1	0.19	0.17	10.53
2	0.2	0.16	20
5	0.16	0.14	12.5
7	0.35	0.23	34
9	0.55	0.095	82.73
12	0.72	0.008	98.89
14	0.31	0.005	98.39
15-25*	Nil	Nil	-
26	0.92	0	100
27-47*	Nil	Nil	-
48	0.81	0	100
50	0.85	Nil	100

* No traces of Ammonia Nitrogen in SSF influent within this period

For this Study, 26 days was considered as the maturation period for the SSF. This was because from day 26 onwards, good removal efficiency was not only realized for Ammonia Nitrogen but also for other parameters of concern e.g bacteriological water quality improvement as discussed in section 4.33. Table 4.3 shows descriptive statistics for Ammonia Nitrogen in SSF unit. A mean value of 0.54 mg/l Ammonia Nitrogen (standard deviation 0.296) for SSF influent was realized within this period. The SSF unit achieved average effluent values of 0.072 mg/l (Standard deviation 0.089mg/l).

Table 4.3 descriptive statistics for Ammonia Nitrogen in SSF unit

Descriptive statistics	SSF in	SSF out
	Ammonia Nitrogen (mg/l)	
Mean	0.54	0.072
Standard Deviation	0.296	0.089
Kurtosis	-1.91	-0.979
Skewness	-0.041	0.795
Minimum	0.16	0
Maximum	0.92	0.23
Data (N)	9	9

Figure 4.1 shows Ammonia Nitrogen levels in the inlet and outlet of the SSF unit as recorded between the commissioning stage up to a run time period of 50 days.

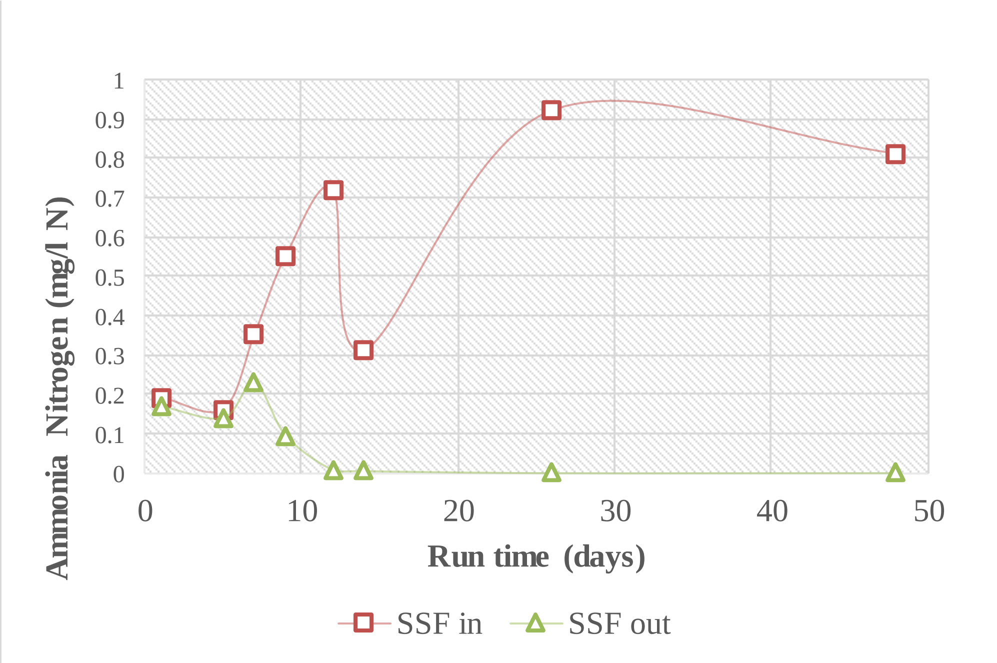


Figure 4.1 Ammonia Nitrogen Level in SSF inflow and SSF effluent.

The recommended KEBS and WHO standards for Ammonia nitrogen is <5mg/l. Values obtained for both raw water and SSF effluent showed that Ammonia nitrogen value was below threshold, hence it was not considered a major parameter of concern.

4.2.1 Removal of Turbidity, Colour and Suspended Solids

Dynamic Gravel Filter (DyGF) was incorporated in the design to protect the subsequent MSF units from high solid loads and Turbidity peaks. In this study, high solid loads and turbidity peaks were experienced during the rainy season (in the months of March to June) as discussed in section 4.1. The DyGF unit performance was investigated during this season (i.e from March 14 to June 14).

Table 4.4 shows descriptive statistics for Turbidity, Colour and Suspended Solids in the DyGF unit during this period. The average raw water Turbidity value within this period was 321 NTU with a standard deviation of 65.6 NTU. The average Turbidity value of DyGF effluent was136.9 NTU with a standard deviation of 65.7 NTU. On average, 59% Turbidity removal was achieved by the DyGF unit.

The average raw water Suspended Solids value within this period was 256.76 mg/l (standard deviation 7.72 mg/l). The DyGF average SS effluent value was 96.71 mg/l (standard deviation 34.53 mg/l). On average, 63% SS removal was achieved by DyGF units during the experimental run. With respect to Colour the average raw water value was 146.1 mg/lpt. (Standard deviation 11.71 mg/l pt.). The DGF unit recorded an average effluent Colour value of 97.04 mg/lpt. (Standard deviation 22.11 mg/lpt.) It was observed that the DyGF unit achieved low efficiency in colour removal recording an average value of 33%.

The results showed that even though the DyGF unit played a significant role in Turbidity, Colour and Suspended solids removal during heavy turbidity and SS loads, it was necessary to have subsequent pre-treatment units to improve the raw water quality further before reaching SSF during this period. For instance the average DyGF effluent Turbidity value of 136.9 NTU fell beyond the acceptable limits (< 10 NTU) of operation of SSF unit. However, the found values related well with documented literature, SS have been reported to be reduced by 23% to 77% by DyGF units (Galvis and Fernandez, 1991). Farooque (2006) reports DyGF average turbidity removal of

58%. Galvis (1999) reports Colour removal efficiencies of between 11 to 16 % in the DyGF units.

Table 4.4 Descriptive statistics of Turbidity, Colour and Suspended Solids in the DyGF unit

Descriptive statistics	Raw water	DyGF out	Raw water	DyGF out	Raw water	DyGF out
	Turbidity (NTU)		Colour (mg/l pt.)		SS (mg/l)	
Mean	321	136.9	146.1	97.04	256.76	96.71
Std Dev	65.63	65.7	11.71	22.11	7.72	34.53
Minimum	187.8	50.78	120	55	233	31.7
Maximum	400	350.52	165	135	263	162.5
Data (N)	27	27	27	27	27	27

4.3 Horizontal-flow Roughing Filter (HRF) and Slow Sand Filter (SSF) performance

4.3.1 Removal of Turbidity, Colour and Suspended Solids

The main role of HRF was treating Surface water of high Turbidity and SS over prolonged periods and thus protecting the SSF from frequent clogging and tedious maintenance practises. The SSF unit was the main treatment unit.

In this study, the HRF and SSF unit performance was investigated between the Months of February to June. In this period an experience of both dry and rainy seasons was experienced and hence a variation of raw water quality was attained. Descriptive statistics for Turbidity, Colour and Suspended Solids in HRF and SSF units (influents and effluents) are given in Table 4.5

Table 4.5 Descriptive statistics for Turbidity, Colour and Suspended Solids in HRF and SSF units

Descriptive statistics	HRF in	HRF out	SSF out	HRF in	HRF out	SSF out	HRF in	HRF out	SSF out
	Turbidity (NTU)			Colour (mg/l pt.)			SS (mg/l)		
Mean	110.8	7.4	0.97	105	50	5	77.6	6.21	0.68
Std Dev	75.8	5.7	0.755	17.78	12.5	7.9	44.5	3	0.573
Kurtosis	1.147	3.648	0.494	-0.52	-0.924	6.0	-1.2	-0.94	-1
Skewness	0.863	2.181	0.922	-0.34	0.262	2.2	-0.1	0.37	0.42
Minimum	12.5	3.03	0	70	35	0	9.6	1.98	0
Maximum	350.5	24.53	2.73	135	75	35	162.5	12.98	1.8
Data (N)	35	35	35	27	27	27	35	35	35

The average HRF influent Turbidity value within this period was 110.8 NTU with a standard deviation of 75.8 NTU. It was observed that on average, the HRF unit registered 86% Turbidity removal, achieving average effluent value of 7.4 NTU with a standard deviation of 5.7 NTU. The SSF unit attained on average 80% removal efficiency with an average effluent turbidity value of 0.97 NTU (Standard deviation of 0.755 NTU, skewness 0.922, kurtosis 0.494). The SSF average effluent value was slightly skewed from the recommended ranges (-0.5 to +0.5 for skewness, -1 to +1for Kurtosis) for a normal distribution. The obtained results in this case can be interpreted to mean that even though the MSF system showed efficient results with respect to Turbidity removal terminal disinfection with chlorine is advisable. The obtained result for turbidity compared well with other researchers, for instance, Farooque (2006) reports similar results with average SSF effluent turbidity values of 0.75 NTU compared to the set nil value. Figure 4.2 shows the Turbidity removal trends by HRF and SSF units.

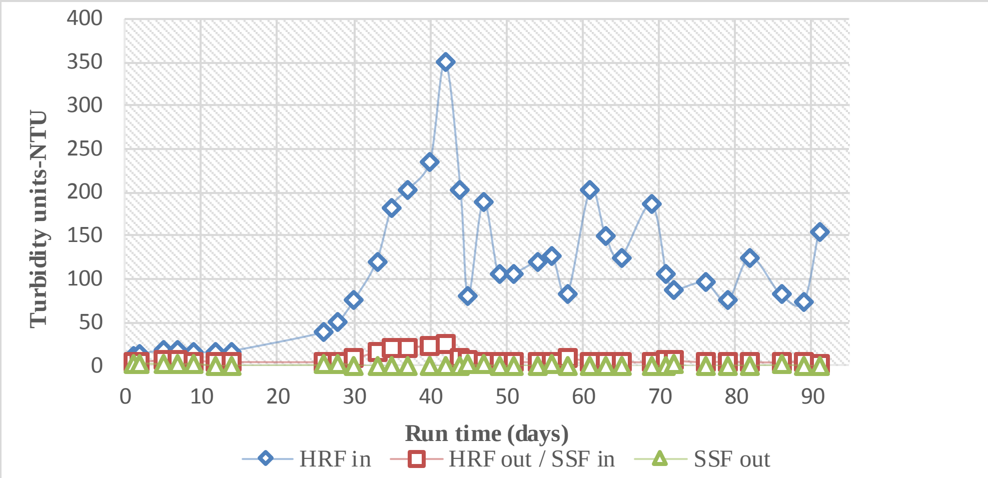


Figure 4.2 Turbidity removal trend by HRF and SSF units.

The average HRF influent Suspended Solids (SS) value was 77.6 mg/l with a standard deviation of 44.51 mg/l. On average, the HRF unit registered 85% SS removal, achieving average effluent value of 6.21 mg/l (standard deviation of 3 mg/l). The SSF unit attained on average 69 % SS removal efficiency with an average effluent value of 0.68 mg/l (Standard deviation of 0.57 mg/l). For SS, the SSF average effluent value was within the recommended ranges of (-0.5 to + 0.5 for skewness and -1 to +1 Kurtosis) for a normal distribution.

The average HRF influent Colour value was 105 mg/l pt (Standard deviation 17.8 mg/l pt). The HRF unit achieved an average of 50% colour removal with an average effluent value of 50 mg/l pt (Standard deviation 12.5 mg/l pt). Overall, the MSF unit achieved an average value of 87% colour removal. Figure 4.3 shows colour removal trend in HRF and SSF units.

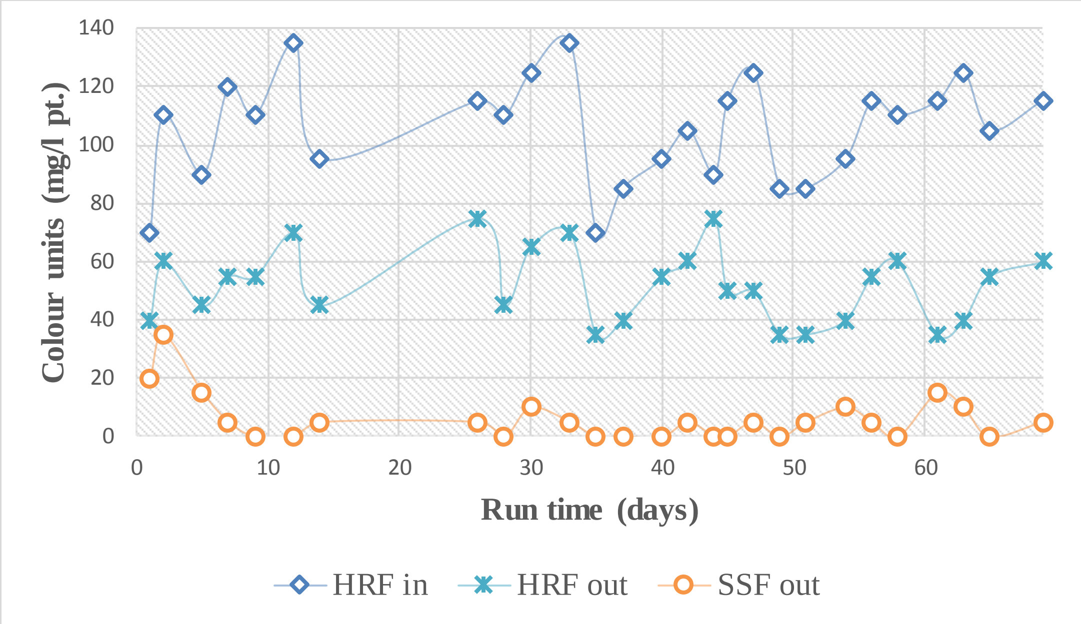


Figure 4.3 Colour removal trend by HRF and SSF units.

The final SSF average colour value was 5mg/l pt (standard deviation 7.97, skewness 2.2, kurtosis 6). The found values showed that the SSF effluent value did not fit the recommended ranges for a normal distribution (-0.5 to + 0.5 for Skewness and -1 to +1 Kurtosis). The main pointer to this observation could be the fact that from literature, SSF have been found to be inefficient in colour removal (Wolter et al, 1989, Barret et al, 1991, Farooque 2006), also the small data sample of 27 could be another factor. This means that other treatment means such as pre-ozonation are welcome before the SSF unit to improve efficiency with respect to colour removal. It remains to be seen if the MSF unit performance with respect to colour will tend towards normal distribution with a larger sample of data.

4.3.2 Removal of Turbidity, Colour and SS at HRF and SSF sampling points.

Turbidity, SS and Colour removal efficiencies showed improvement at the SSF sampling points as the bed depth increased (Refer to Appendix 1 Table A 1.6, Table A 1.7 and Table A 1.8). This could be attributed to an increase in sand bed depth causes a gain in total surface area of the sand grains thus total adsorption capacity is increased which improves the water quality (Muhammed et al, 1996). Figures 4.4, 4.5 and 4.6 shows turbidity, SS and Colour removal trend at SSF sampling points.

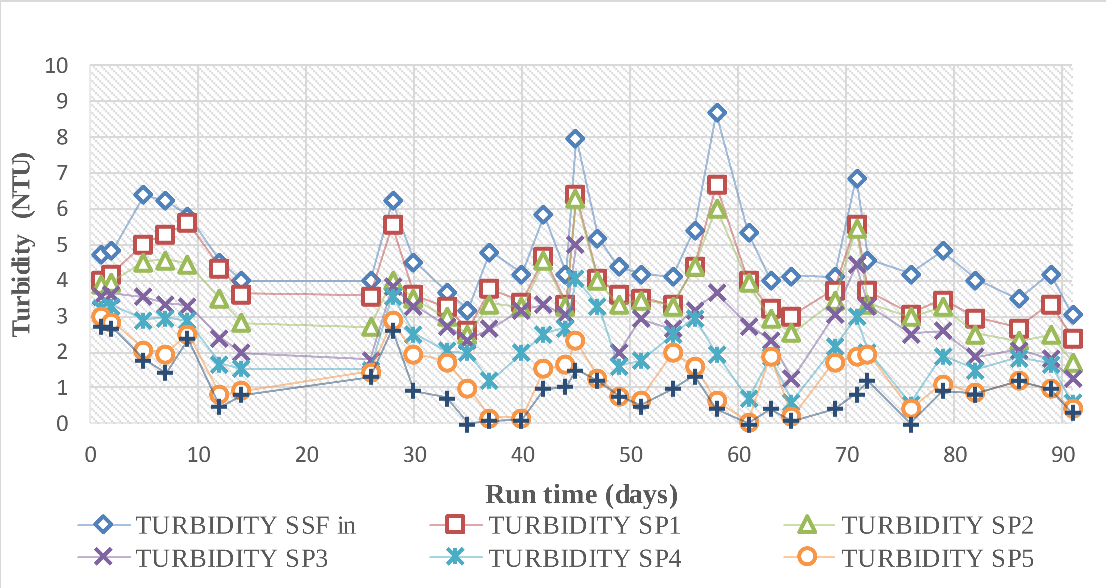


Figure 4.4 Turbidity removal trend at SSF sampling points

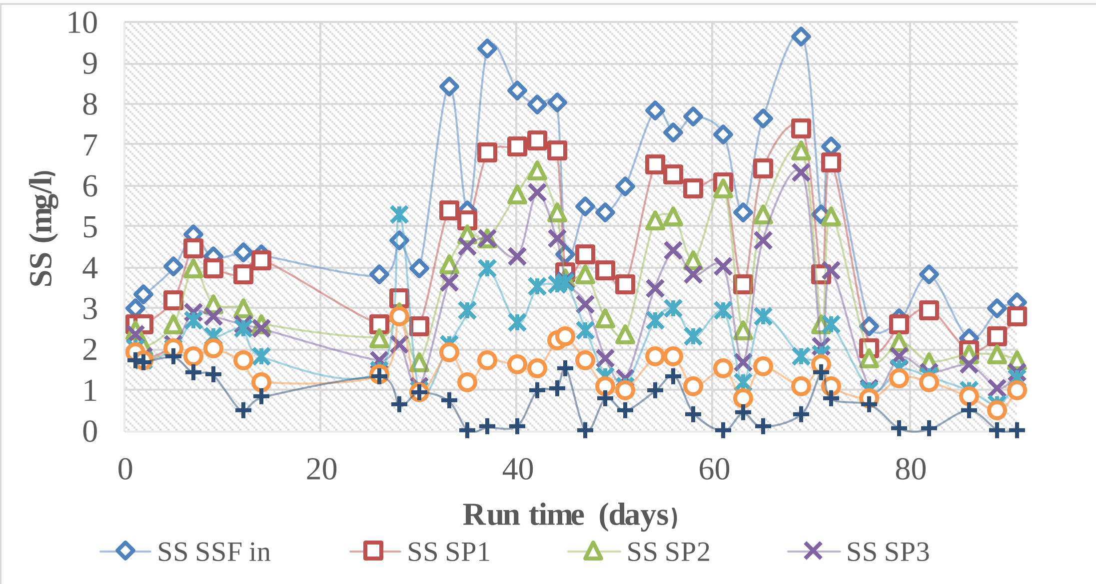


Figure 4.5 Suspended Solids (SS) removal trend at SSF sampling points

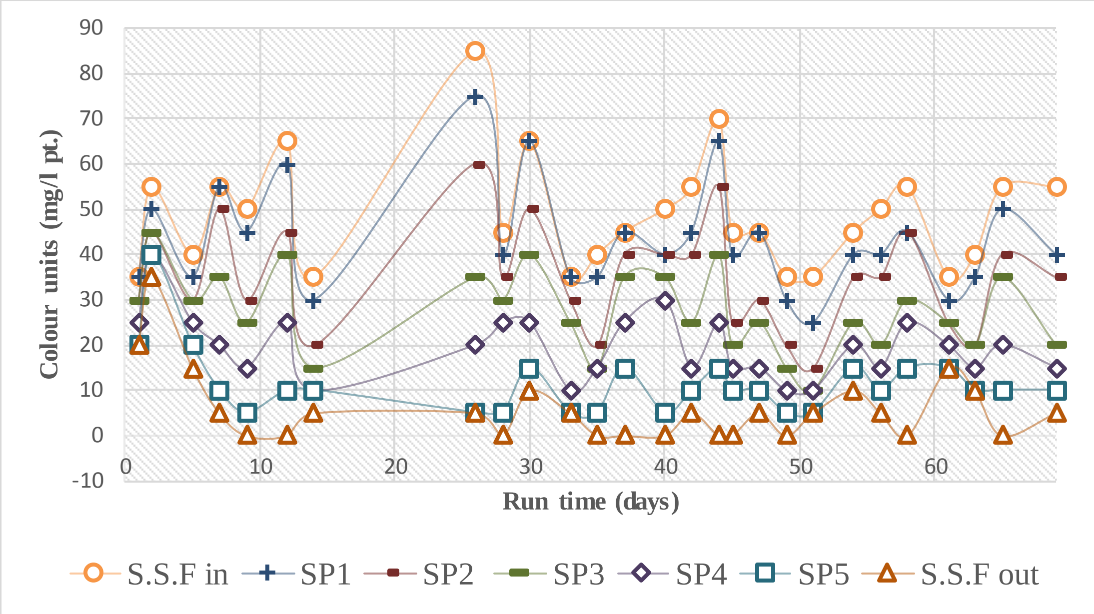


Figure 4.6 Colour removal trend at SSF sampling points

Turbidity, SS and Colour removal were found to improve at the HRF sampling points as the bed length increased. This could be attributed to an increase in bed length which causes a gain in total surface area of the gravel grains and ultimately total adsorption capacity is increased which improves the water quality.

Figures 4.7, 4.8 and 4.9 shows turbidity, SS and Colour removal trend at HRF sampling point

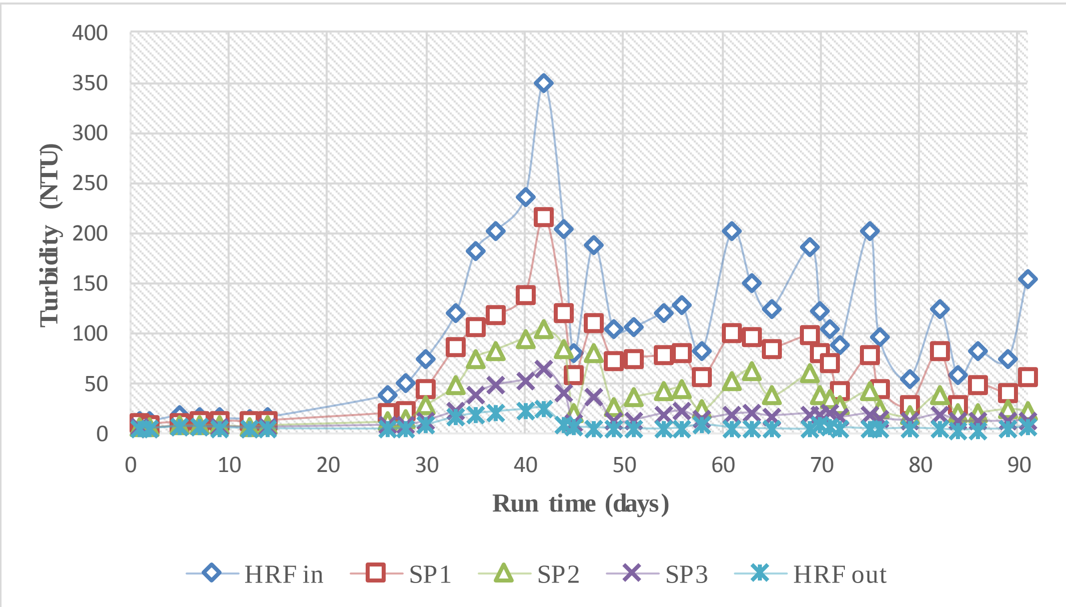


Figure 4.7 Turbidity removal trend at HRF sampling points.

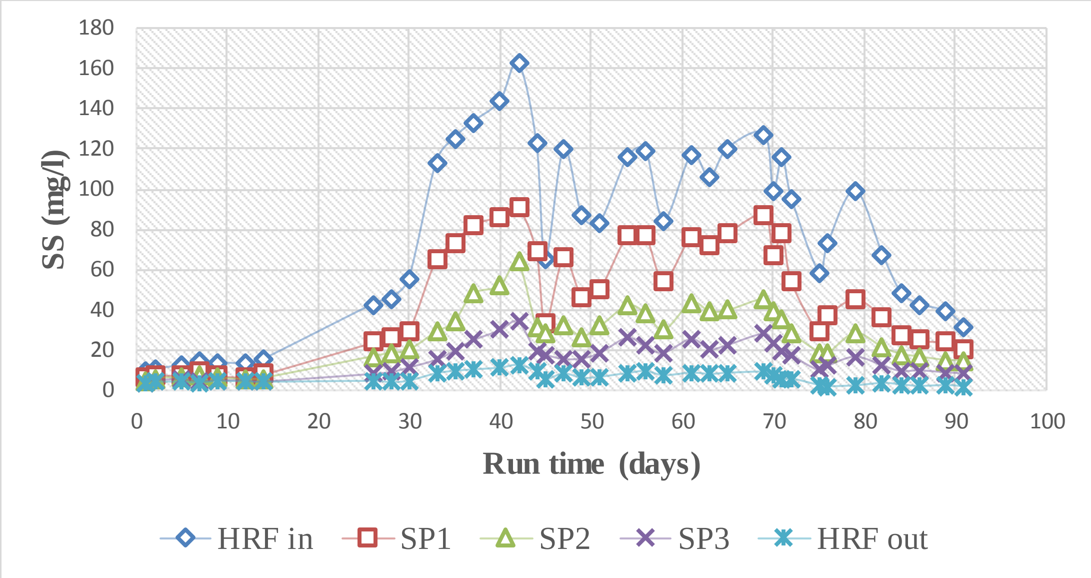


Figure 4.8 SS removal trend at HRF sampling points

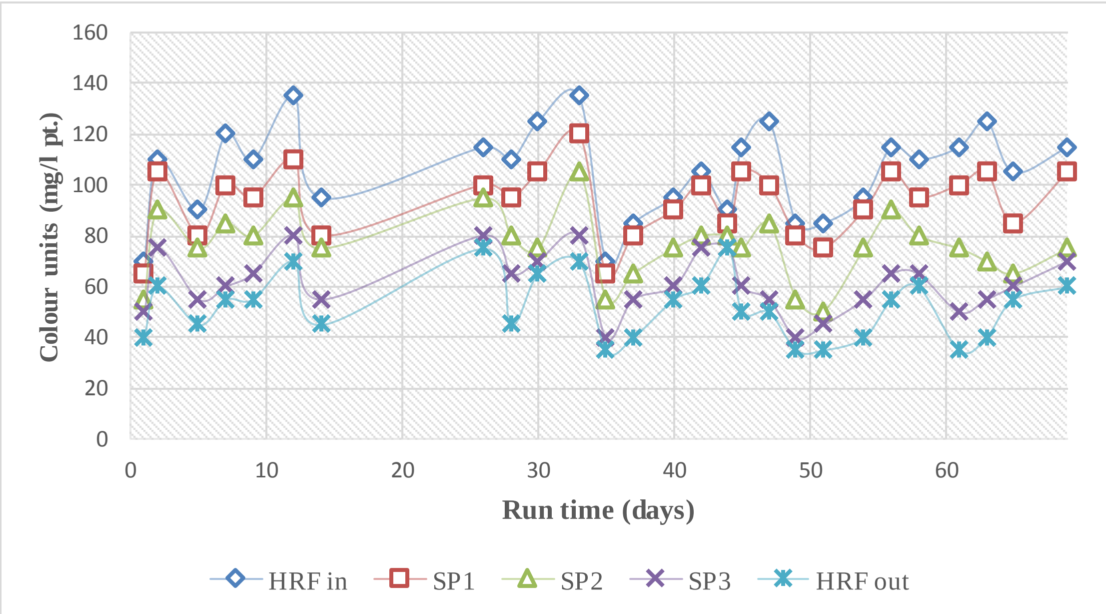


Figure 4.9 Colour removal trend at HRF sampling points.

4.3.3 Removal of Total and Faecal coliforms (E. coli.)

The pilot unit was monitored for its efficiency in Total and E-coli removal during maturation period (Mid-February to Mid-March) and after maturation (Mid-March to Mid-June). Low levels of Faecal and Total coliforms were observed in the raw water i.e from pilot plant commissioning to day 40. This observation was attributed to the dry season. However from day 40 onwards a significant increase in both the Total and

Faecal coliforms was observed attributed to the onset of rains. This is because during rainy period, the surface run-off carrying both organic and inorganic matter normally increases the pollution load of the raw water.

It was observed that removal efficiency for both Total and faecal coliforms was low before day 26 (i.e 20 - 57%). However, after day 26, a significant increase in removal efficiency was experienced (i.e. 75 - 100%) as shown in Table 4.6 and 4.7 respectively. Hence 26 days was considered to be the maturation period in this case. This value fell within the expected range as documented in literature i.e a ripening period of 14 - 35 days is expected. Ochieng (2004) reports a maturation period of 28 days. Galvis (1999) documents that it took about a month for the SSF effluents to produce water low in microbiological sanitary risk. Haarhooff and Cleasby (1991) reports ripening period of about 35 days in SSF units.

Tables 4.6 and 4.7 show a summary Total and Faecal coliform removal in HRF and SSF units.

Table 4.6 Faecal Coliform removal in HRF and SSF units

FAECAL COLIFORMS (CFU /100 ml)									
Run time (Days)	**HRF in**	**HRF out**	**HRF % Rvl**	**SSF in**	**SSF out**	**SSF % Rvl**	**MSF % Rvl**	**CS out**	**CS % Rvl**
5	23	18	22	16	9	44	61	9	60.9
12	22	20	9	20	12	40	45.45	8	63.6
19	25	23	8	23	10	57	60	10	60
26	20	18	10	16	4	75	80	7	65
33	24	20	17	21	2	90	91.67	8	66.7
40	27	17	37	19	1	95	96.3	6	77.8
47	26	17	35	17	0	100	100	5	80.8
54	38	21	45	19	0	100	100	7	81.6
62	44	23	48	22	1	95	97.7	9	79.5
69	57	31	46	28	0	100	100	10	82.5
76	22	10	55	8	0	100	100	6	72.7
84	240	129	46	8	0	100	100	17	92.9
91	104	56	46	110	3	97	97.1	20	80.8
98	372	120	68	360	10	97	97.3	17	95.4

Table 4.7 Total coliform removal in HRF and SSF units.

TOTAL COLIFORMS (CFU /100 ml)									
Run time (days)	**Raw water**	**HRF out**	**HRF % Rvl**	**SSF in**	**SSF out**	**SSF % Rvl**	**MSF % Rvl**	**CS out**	**CS % Rvl.**
5	60	28	53	20	16	20	73.3	19	68.33
12	58	55	5	26	18	31	68.97	12	79.31
19	62	59	5	28	17	39	72.58	26	58.064
26	40	19	53	18	2	89	95	16	60
33	48	45	6	22	9	91	81.25	11	77.08
40	45	38	16	30	5	97	88.88	15	66.67
47	128	118	8	30	3	93	97.65	23	82.03
54	340	72	79	38	2	95	99.41	32	90.6
62	348	38	89	72	2	97	99.43	38	89.08
69	340	302	11	28	4	96	98.82	36	89.41
76	33	18	45	13	0	100	100	13	60.61
84	680	160	76	160	3	98	99.56	45	93.38
91	684	420	39	422	7	98	98.98	53	92.25
98	372	180	52	184	5	97	98.66	43	88.4

The average HRF influent value for Total coliform was 231.3 CFU/100ml (standard deviation 233) and for E.coli 74.57 cfu/100ml (standard deviation 103.8 CFU/100ml). Table 4.8 shows descriptive statistics for Total and Faecal coliforms in HRF and SSF units.

Table 4.8 Descriptive statistics for Total and Faecal coliforms in HRF and SSF units

Descriptive statistics	**HRF in**	**HRF out**	**SSF out**	**HRF in**	**HRF out**	**SSF out**
	Total coliforms (CFU/100ml)			**E.coli (CFU/100ml)**		
Mean	231.3	78.7	5	74.57	37.143	3.7
Std Dev.	233.08	111.098	6.4	103.8	38.57	4.5
Kurtosis	-0.055	7.238	0.1	5.258	2.8	-0.94
Skewness	1.038	2.61	1.3	2.38	1.997	0.9
Minimum	33	18	0	20	10	0
Maximum	684	420	18	372	129	12
Data (N)	14	14	14	14	14	14

The HRF unit apart from being used as a pre-treatment of Turbidity and Suspended Solids (SS) also played a significant role in Faecal and Total coliform reduction. On average, the HRF unit reduced E.coli load by 36% with an average effluent value of 37.14 CFU/100 ml (standard deviation 38.57). The unit reduced Total coliforms load by 38% with an average effluent value of 78.7 CFU/100 ml (standard deviation of 111 CFU/100ml). The SSF units registered 98% Faecal coliform and 96% Total coliform removal after maturation (i.e after day 26).The average SSF effluent values for Total and Faecal coliforms were 5 CFU/100ml (standard deviation 6.4 CFU/100ml, skewness 1.3, kurtosis 0.1) and 3.7 CFU/100ml (standard deviation 4.7 CFU/100ml, skewness 0.9, Kurtosis - 0.94) respectively as shown in Table 4.8. The SSF average effluent for both Faecal and Total coliforms was slightly right skewed from the recommended ranges (i.e of - 0.5 to + 0.5 for skewness, - 1 to + 1 for Kurtosis) for a normal distribution. The main pointer to such an observation could be the small number of data sample used (i.e 14) in this case.

According to Kothari (2004), the sampling distribution tends quite closer to the normal distribution if the number of sample is large. A minimum of about 30 is recommended. However, in this study, a larger sample was not employed because of cost and time limitations. Nevertheless, the obtained values could be interpreted to mean that although the MSF proved efficient with respect to bacteriological water quality improvement. Terminal disinfection (e.g with Chlorine) is necessary to safeguard the system against pathogen breakthrough. However in this case a low dosage of Chemicals is expected. Good removal efficiencies achieved in this research was attributed to the filter bed maturation. The slow filtration rates of 0.08 - 0.4m/h in SSF also contributed significantly to the high efficiencies. Low filtration rate meant a long detention time of the water within the bed and thus better removal efficiency. The average value for this Study was within the range of values found by other researchers. For instance most research findings showed that SSF achieved 95 - 99.9% of pathogenic bacteria removal

(Huisman 1974, Farooque et al. 2006, Ochieng et al. 2004, Galvis 2006). Figure 4.10 and 4.11 shows the removal trend of Total and Faecal coliform in HRF and SSF units.

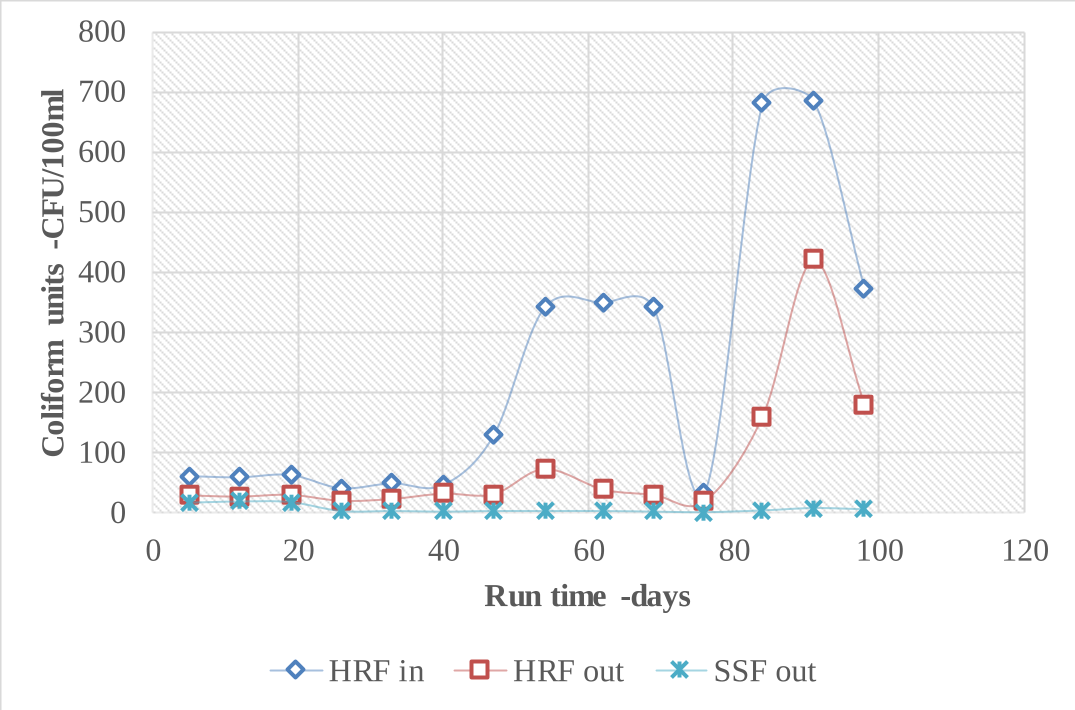


Figure 4.10 Total Coliform removal trend in HRF and SSF units.

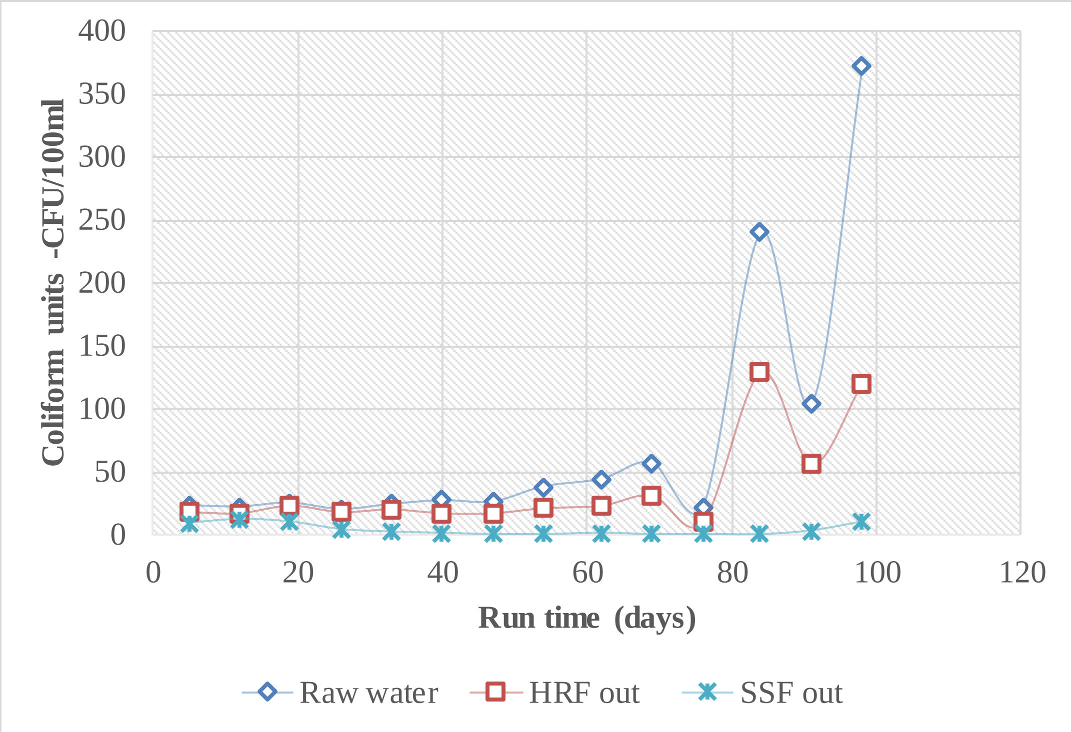


Figure 4.11 Faecal Coliform removal trend in HRF and SSF units

4.3.5 Removal of Nitrite Nitrogen and Nitrate Nitrogen.

Nitrite Nitrogen and Nitrate Nitrogen level in SSF unit was monitored in the first two months (Mid-February to Mid-April). Low removal efficiency was realized by the SSF unit at the commissioning stage (i.e. 25% removal efficiency for Nitrite Nitrogen and 26% removal for Nitrate Nitrogen.) as shown in Table 4.9. The SSF unit's efficiency improved from day 12 onwards for both Nitrite Nitrogen and Nitrate Nitrogen recording values ranging between 83 to 100%. This could be attributed to the SSF maturation. Table 4.9 shows the Nitrite Nitrogen levels in the raw water, HRF and SSF effluents from the commissioning stage up to a run time period of 50 days

Table 4.9 Nitrate and Nitrite levels in MT, HRF and SSF effluent.

Run Time (days)	Raw water		HRF out		SSF out			
	Nitrite N (mg/l)	Nitrate N (mg/l)	Nitrite N (mg/l)	Nitrate N (mg/l)	Nitrite N (mg/l)	Nitrate N (mg/l)	Nitrite N % Rvl	Nitrate N % Rvl
1	0.42	1.95	0.16	0.31	0.12	0.23	25	26
5	0.53	1.98	0.18	0.3	0.16	0.15	11	50
7	0.33	1.61	0.11	0.32	0.008	0.09	93	72
9	0.48	0.93	0.21	0.73	0.15	0.23	29	68
12	0.43	0.95	0.13	0.81	0.009	0.008	93	99
14	0.2	0.134	0.006	0.012	0.001	0.002	98	83
26	0.23	0.191	0.004	0.02	Nil	Nil	100	100
26-47	Nil	Nil	Nil	Nil	Nil	Nil	Nil	-
48	0.17	0.185	0.001	0.023	Nil	0.0	100	96
50	0.19	0.21	0.05	0.02	Nil	0.0	100	100

A mean value of 0.349 mg/l Nitrite Nitrogen (standard deviation 0.136 mg/l) HRF influent was realized within this period. The HRF unit achieved average Nitrite Nitrogen effluent values of 0.1 mg/l (Standard deviation 0.085mg/l). The SSF unit achieved an average Nitrite Nitrogen effluent value of 0.056 mg/l (standard deviation 0.073 mg/l). The HRF unit achieved average Nitrate Nitrogen effluent values of 0.32 mg/l (Standard deviation 0.312 mg/l). With respect to Nitrate Nitrogen, a mean value of 0.99 mg/l (standard deviation 0.785 mg/l) HRF influent was realized. The SSF unit achieved an average Nitrate Nitrogen effluent value of 0.089 mg/l (standard deviation 0.102 mg/l). Table 4.10 shows descriptive statistics for Nitrite Nitrogen and Nitrate Nitrogen in HRF and SSF units.

Table 4.10 Descriptive statistics for Nitrite Nitrogen and Nitrate Nitrogen in HRF and SSF

Descriptive statistics	HRF in	HRF out	SSF out	HRF in	HRF out	SSF out
	Nitrite Nitrogen (mg/l)			Nitrate Nitrogen (mg/l)		
Mean	0.349	0.1	0.056	0.99	0.32	0.089
Std Dev.	0.136	0.085	0.073	0.785	0.312	0.102
Kurtosis	-1.778	-1.92	-1.91	-1.898	-0.825	-1.681
Skewness	-0.1178	-0.189	0.72	0.165	0.709	0.584
Minimum	0.17	0.001	0	0.134	0.012	0
Maximum	0.53	0.21	0.16	1.98	0.81	0.23
Data (N)	8	8	8	8	8	8

4.3.6 Removal of Iron and Manganese.

Iron and Manganese removal in HRF and SSF removal was monitored from Mid-February to Mid-June. Both dry and rainy season's recorded low traces of Iron and Manganese i.e < 1mg/l. HRF influent had an average value of 0.535 mg/l Iron (standard deviation 0.358 mg/l) was realized within this period. The recommended KEBS and WHO standards for Iron (is < 3mg/l) and Manganese (is < 0.1 mg/l). Values obtained for both raw water and SSF Manganese effluent showed that it was below threshold, hence it was not considered a major parameter of concern in this case. Table 4.11 shows descriptive statistics for Iron and Manganese in HRF and SSF units

Table 4.11 Descriptive statistics for Iron and Manganese in HRF and SSF units

Descriptive statistics	HRF in	HRF out	SSF out	HRF in	HRF out	SSF out
	Iron (mg/l)			Manganese (mg/l)		
Mean	0.535	0.27	0.056	0.025	0.01	0.003
Std Dev	0.358	0.163	0.05	0.014	0.007	0.005
Kurtosis	-2.1	-1.5	1.1	-0.92	-1.0138	5.13
Skewness	0.08	0.068	1.193	0.085	0.47	2.41
Minimum	0.15	0.023	0.001	0.002	0	0
Maximum	0.99	0.55	0.18	0.05	0.021	0.018
Data (N)	18	18	18	18	18	18

The HRF unit achieved average Iron effluent values of 0.27 mg/l (Standard deviation 0.163 mg/l). The SSF unit achieved an average Iron effluent value of 0.056 mg/l (standard deviation 0.056 mg/l). Manganese average value of 0.025 mg/l (Standard deviation 0.014 mg/l) and 0.01mg/l (standard deviation 0.007) was registered in the HRF influent and effluent respectively. The SSF average effluent manganese value was 0.003 mg/l (standard deviation 0.003). Removal percentage of both Iron and Manganese was low before maturation of the SSF unit (Iron - 21% and Manganese - 10%). However, after maturation, the SSF unit registered on average 70% removal of Iron, and an average of 64% removal of Manganese. It was also noted that HRF units played a role in both Iron and Manganese reduction. On average, HRF units reduced dissolved Iron load of SSF influent by 42% and Manganese by 57%. The removal efficiencies achieved in this research was attributed to the filter bed maturation and low filtration rate of < 0.5m/h for the SSF and HRF unit respectively. The found values related well with documented literature. For instance, Wegelin et al. (1998) reports 50% removal of Iron and Manganese in Roughing Filters (RFs). Figure 4.12 and 4.13 show the Manganese and dissolved Iron trends.

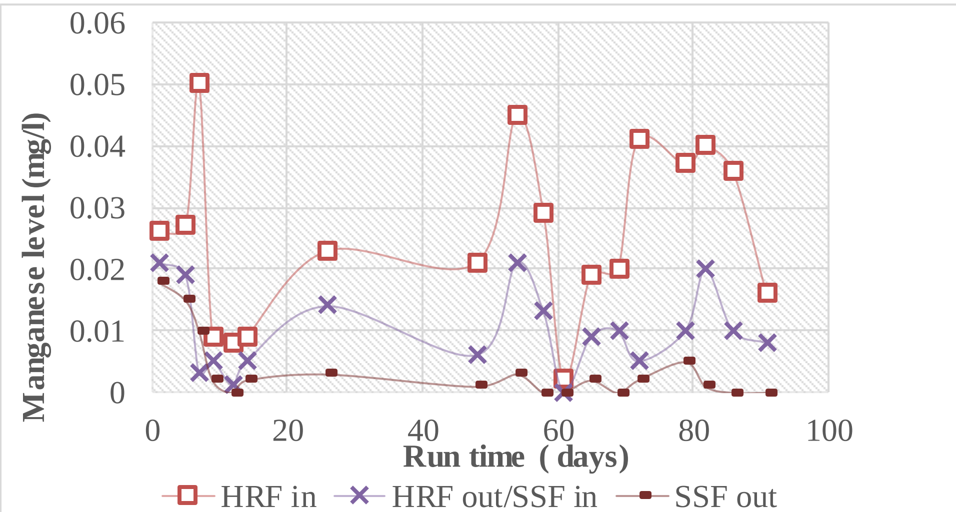


Figure 4.12 Manganese removal trend in HRF and SSF

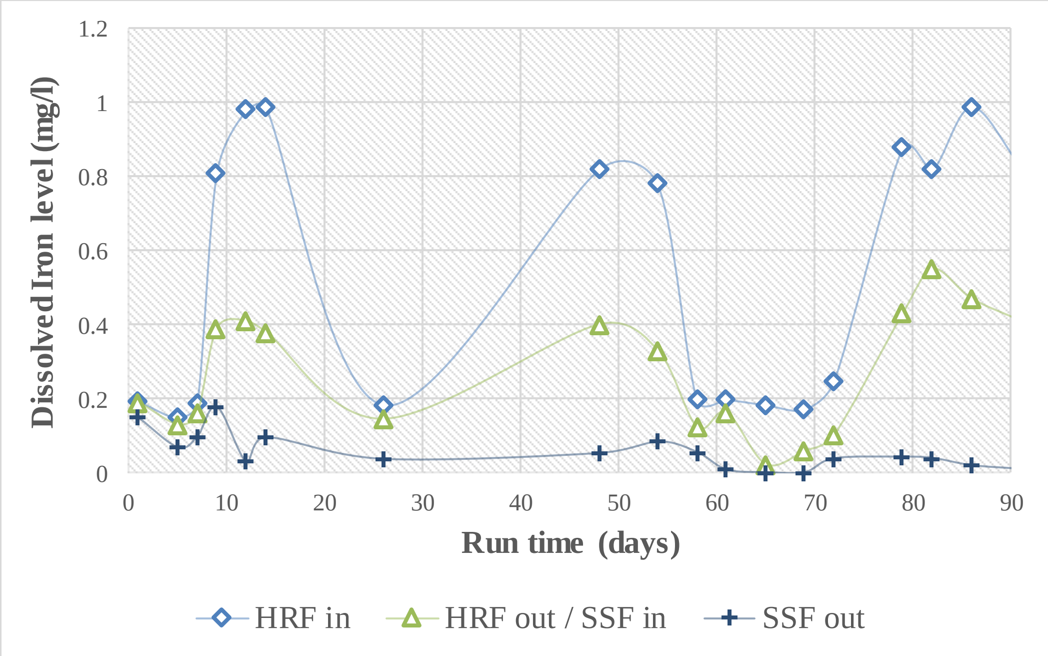


Figure 4.13 Dissolved Iron removal trend in HRF and SSF

4.3.7 Temperature and pH in Multi-Stage Filtration (MSF) units

Temperature and PH was monitored for the entire test period (Mid-February to Mid-June). During the test period it was noticed that the temperature condition of the raw water varied from 18 - 26°C. The pH values varied in the ranges of 6.5 - 9. The SSF effluent pH value was within the acceptable WHO and KEBS Standards (6.5 - 7.5). Table 4.12 shows descriptive statistics for Temperature, DO and PH in HRF and SSF units

Table 4.12 Descriptive statistics for Temperature, DO and PH in HRF and SSF units

Descriptive statistics	Raw water	HRF out	SSF out	Raw water	HRF out	SSF out	Raw water	HRF out	SSF out
	Temperature (°C)			Dissolved Oxygen (mg/l)			PH		
Mean	22.84	23.02	20.1	8.64	6.36	4.77	7.92	7.8	7.26
Std Dev.	1.24	1.51	0.61	1.46	0.76	0.98	0.33	0.32	0.254
Kurtosis	0.7	0.49	-0.6	3.02	0.85	-0.9	-0.75	-0.51	-1
Skewness	0.97	1.09	0.21	1.51	0.27	0.47	0.31	0.127	0.05
Minimum	21	21	19	6.42	4.3	3.43	7.29	7.17	6.87
Maximum	26.3	26.7	21.3	13.1	8.02	6.83	8.65	8.47	7.73
Count	40	40	40	40	40	40	40	40	40

Mean temperature and PH values of 20.1 ^{o}C and 7.8 respectively were realized by the SSF effluent. Generally, as observed from field data, it can be said that the pH conditions and temperature values could not be an inhibitor to the bacteriological activity in the MSF unit.

4.3.8 Dissolved Oxygen (DO) levels in Multi Stage Filtration (MSF) units

The DO levels were monitored at each treatment stage during the entire test period. The values varied from 2.98 - 13.1mg/l. It was observed that there was a slight decrease of DO concentration from the raw water to the final SSF effluent as shown in figure 4.14. The main reason was attributed to low filtration rates in the MSF units of < 5 mg/l which meant longer retention of raw water in the filter media and therefore a greater depletion of oxygen by the biological system. The average DO value in the SSF effluents was 5.3mg/l. This value is acceptable for drinking water by both WHO and KEBS. Figure 4.14 shows Dissolved Oxygen (DO) concentrations in HRF_{in}, HRF_{out} and SSF units.

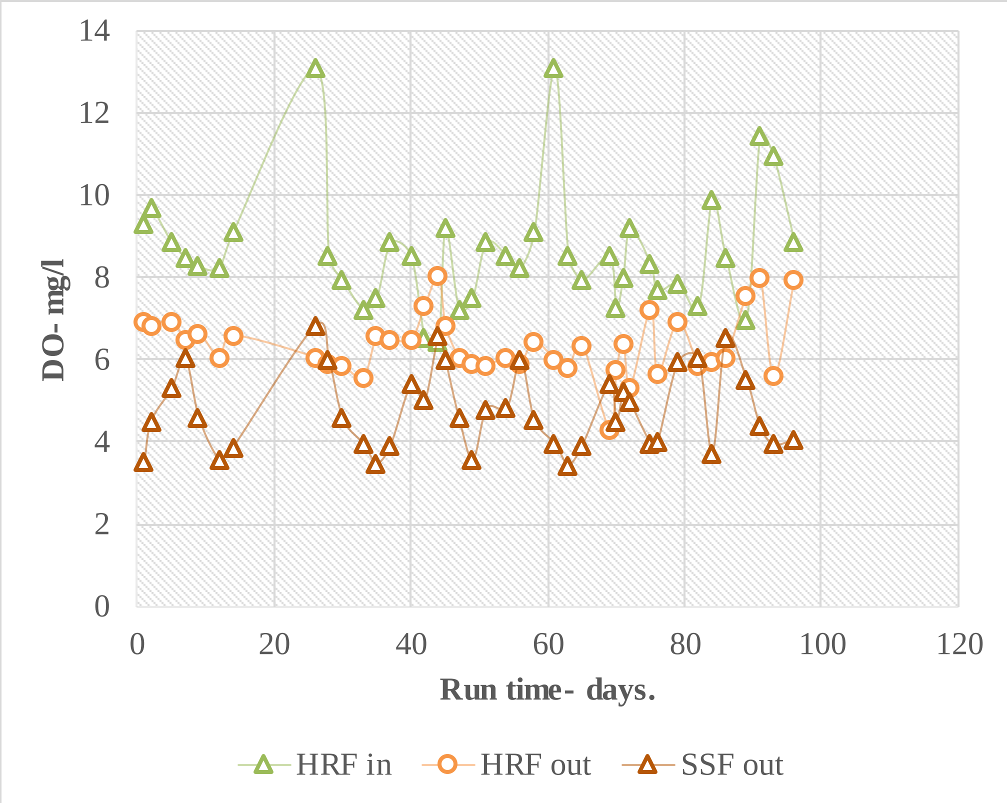


Figure 4.14 Dissolved Oxygen (DO) concentrations in HRF and SSF units.

4.3.9 Connecting two Horizontal-flow Roughing Filter (HRF) units in series.

The impact of connecting Two HRF units in series was investigated during the rainy season (From Mid-March to Mid-June). This was because during this period high turbidity were anticipated which could surpass the operation capacity of one HRF unit and thus resulting in short SSF runs. It was noted that by connecting the two HRF units in series high efficiency levels were achieved with respect to Turbidity and SS removal. The HRF units recorded 95% Turbidity and 98% SS removal respectively. The high efficiency achieved was attributed to a longer length of filter media provided by connecting the two units in series. This length gave ideal conditions for interception of SS thus resulting in improvement of overall raw water quality. This was in line with Wegelin "1/3-2/3" filter theory as discussed in section 2.4

4.3.10 Varied Horizontal roughing filter (HRF) gravel pack ratio.

The HRF unit had three Chambers holding different sized Gravel material (Gravel packs) as discussed earlier (refer to section 3.3.2). In order to achieve the objective of this research, HRF was designed to allow variation of ratios of Gravel packs. The following gravel pack ratios were analysed during the research period (d_g is the Gravel diameter):

1) 2:2:1 {i.e. 2 metres (d_g 15 -24mm), 2 metres (d_g 8-15mm), 1 metre (d_g 4-8mm).}
2) 1:2:2{i.e. 1 metre (d_g 15 -24mm), 2 metres (d_g 8-15mm), 2 metre (d_g 4-8mm).}
3) 1.5:1.5:2 {i.e. 1.5 metres (d_g 15 -24mm), 1.5 metres (d_g 8-15mm), 2metre (d_g 4-8mm).}

Table 4.13 shows the average percentage removal of Turbidity and SS by HRF unit under different ratios.

Table 4.13 Percentage removal of Turbidity and SS by HRF unit under different ratios.

HRF Units	"Gravel pack" ratio	Percentage (%) removal	
		Turbidity	Suspended Solids
HRF 1	2:2:1	88.33	87.2
HRF 2	1:2:2	88.98	88.01
HRF 3	1.5:1.5:2	88.67	87.63

It was noted that there wasn't great variation with respect to percentage Turbidity and Suspended Solids removal by varying the unit ratios. HRF 2 (i.e with ratio 1:2:2) gave the best performance with 88.98% removal of Turbidity and 88.01% removal of Suspended Solids. This was attributed to the large surface area of fine filter media material offered by this unit relative to the others, hence the interception of fine suspended matter thus resulting in better water effluent. However, it was noted that HRF 2 experienced frequent clogging relative to the other two HRF units, hence a short filter run period. This necessitated frequent hydraulic cleaning in this unit. It was on these grounds that a conclusion was made that although HRF 2 gave good results, it is not advisable to operate such gravel pack ratio combination in high turbid waters (> 120 NTU in this case) since it would mean short filter runs and tedious cleaning and maintenance activities. This would compromise the sustainability of such a system. On the other hand, HRF 1 was considered as the best alternative. This was because it gave the longest filter run period of about 2 to 3 weeks depending on the raw water quality. Figure 4.15 shows the Turbidity removal trend by the HRF units set at different ratios during the research period.

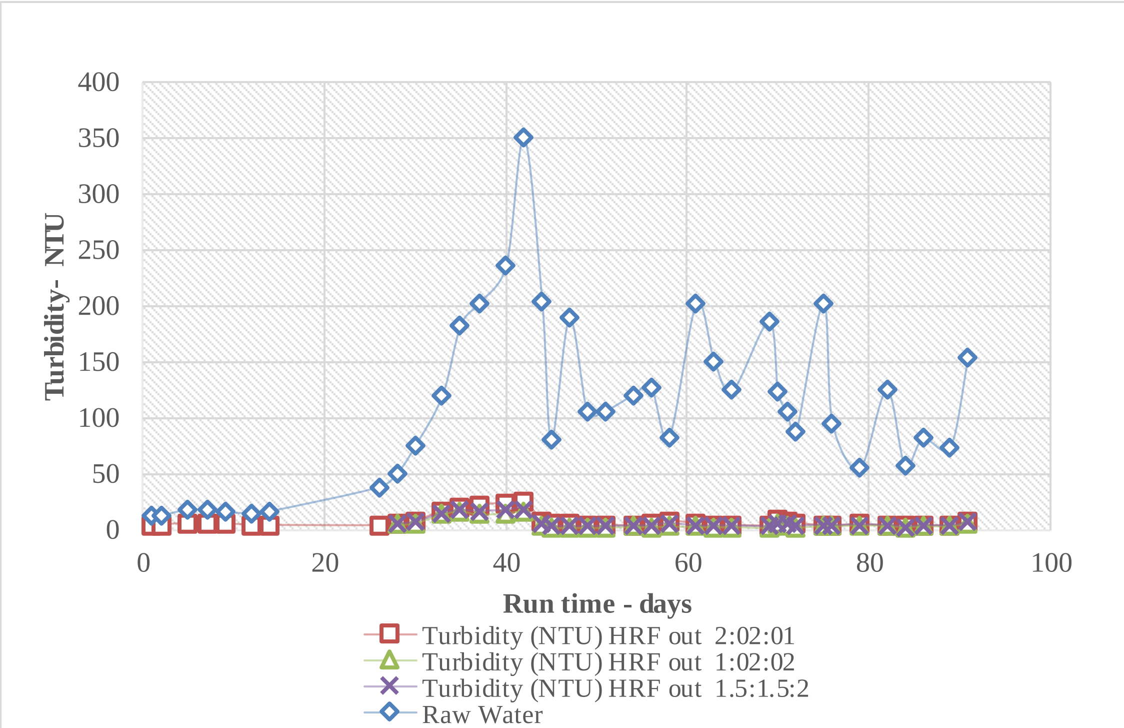


Figure 4.15 Turbidity removal trend by the HRF unit set at different ratios

4.4 Multi Stage Filtration (MSF) effluent quality versus KEBS and WHO standards

The final water effluent from the MSF units was compared with the KEBS and WHO guideline quality standards. It was observed that with respect to Turbidity, MSF met the general minimum set WHO and KEBS standard for drinking water of 5 NTU by registering an average Turbidity value of 0.97 NTU. For the case of SS, it was observed that the MSF unit had an average value of 0.69mg/l against the set nil value. With respect to E.Coli, the MSF unit registered average value of 3.7 CFU/100ml (with raw water going upto peaks of 372 CFU/100 ml and minimum of 20 CFU/100ml) as compared to the set KEBS Nil value. The MSF unit registered an average value of 5 CFU/100ml (with raw water going upto peaks of 684 CFU/100 ml and minimum values of 20 CFU/100ml) with respect to T.Coli removal against the set nil standard for drinking water. For Iron and Manganese the MSF unit met the KEBS by registering very low traces in the final effluent (< 0.06 mg/l). For colour the MSF unit met the set standard (< 15 mg/l pt.) as shown in the Table 4.14. This results can be interpreted to mean that although the MSF unit proved efficient in microbiological water improvement, chlorination should act as a final buffer to guide against pathogen breakthrough. However, in this case dosing will be minimal relative to Conventional System.

Table 4.14 Comparison of MSF effluents with KEBS and WHO standards.

Parameter	**MSF**	**WHO**	**KEBS**
Turbidity (NTU)	0.97	< 5	5 but < 1 effective disinfection
SS (mg/l)	0 - 0.69	Nil	Nil
E.coli (CFU/100ml)	0 - 1	Nil	Nil
T.Coli (CFU/100ml)	0 - 2	Nil	Nil
pH	6.5 - 8	7.5 +1	7.5 +1
Iron (mg/l)	0.06	< 0.3	< 0.1
Manganese (mg/l)	0.004	< 0.1	< 0.05
Ammonia (mg/l)	Nil	< 0.5	< 0.5
Nitrate as NO3 (mg/l)	Nil	< 50	< 10
Colour (mg/l pt)	5	< 15	< 15

4.5 Comparison of Multi-Stage Filtration (MSF) units with Conventional system

The results showed that the MSF unit performed better than the CS with respect to most of the selected parameters (refer to Appendix 1). It was observed that the MSF unit recorded an average efficiency of 98% for Faecal coliform and 96% for Total coliform removal. Table 4.15 shows the performance of both the CS and MSF unit.

Table 4.15 Comparison between Conventional System (CS) and Multi-Stage Filtration unit

parameter	**Percentage removal**	
	MSF	**CS**
Faecal coliform	98%	75.69%
Total coliform	96.2%	78.2%
Turbidity	95.33%	93.8%
Suspended Solids	98.2%	97.6%
Colour	93.8%	93.3%

With respect to Colour, Suspended Solids and Turbidity, Table 4.15 shows that the difference in performance between the CS and MSF systems was not very significant. It is important to note that the values given in the above table are for the overall removal efficiency in the MSF unit (i.e. combined pre-treatment and SSF unit) and the treated water from the Conventional System (CS) which was sampled before chlorination.

The observed values was attributed to the fact that MSF removal processes are majorly physical and biological. The low filtration rates in the SSF unit (0.08 - 0.4m/h) allowed for a longer retention time of the water within the filter bed. This facilitated the biological water quality improvement function. The finer Sand media used in SSF unit was also important in retaining colloidal matter on the surface thus improving the SSF effluents with respect to SS, Turbidity and colour improvement. The CS on the other hand, is majorly a physical and chemical process with high filtration rates in the Rapid Filters. High filtration rates limit the retention time of water within the filter bed, this condition is unsuitable for biological activity thus resulting in the low efficiency.

4.6 Head-loss development

Head loss development was monitored in the SSF unit throughout the entire experimental run period. The development of head-loss increased gradually during this period. The maximum recommended head-loss is 1 metre (Ochieng, 2001). It was observed that after a run period of 91 days the maximum head-loss had not yet been achieved. This implied that the SSF filter run given the operating conditions could run longer than 91 days before filter cleaning. Ochieng (2004) observed a similar trend i.e by the end of 82 days the SSF unit had not hit the maximum head-loss of 1 metre. The observed trend was attributed to the good efficiencies by the pre-treatment units with respect to Turbidity and SS removal. Figure 4.16 show the head-loss development in the SSF unit during the run period.

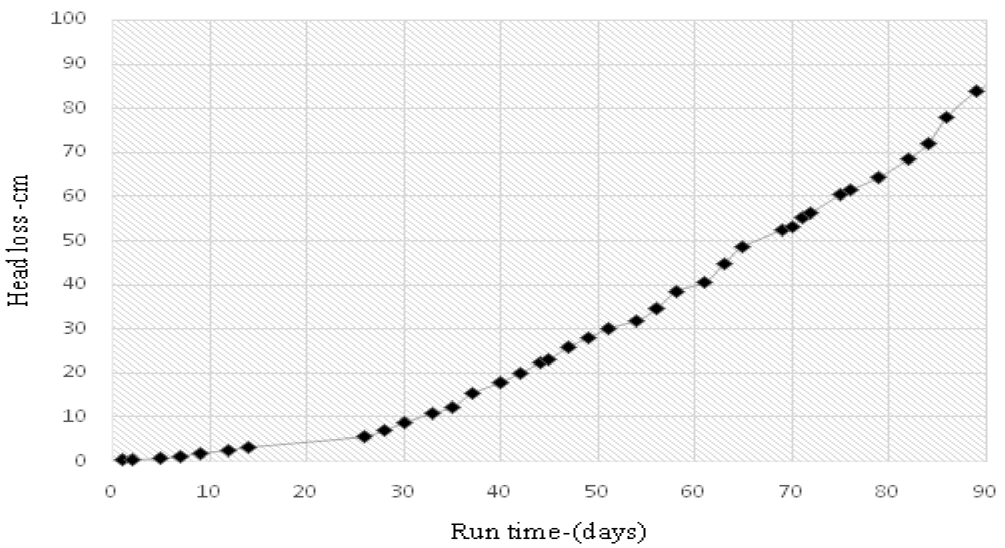


Figure 4.16 Head-loss development in the SSF unit.

4.7 Operation and Maintenance (O&M) of MSF units.

Operation and maintenance of the MSF units was necessary to ensure good performance of the unit to avoid any disruption which would have otherwise affected the results. The procedures were executed either on a daily, weekly or Monthly basis depending on the type as summarised in Table 4.16. These procedures are easy in their execution and do not require special equipment or highly qualified staff.

Table 4.16 Operation and Maintenance tasks of MSF units

MSF unit	Maintenance task		
	Daily tasks	**Weekly tasks**	**Monthly tasks**
1. DyGF	▪ Checking changes in flow velocity and head loss ▪ Removing floating material from the supernatant water	▪ Hydraulic cleaning of the filter	▪ Sludge removal
2. HRF	▪ Checking changes in flow velocity and head loss ▪ Removing floating material from the supernatant water	▪ Hydraulic cleaning of the filter media	▪ Cleaning of inlet and outlet box of and sludge removal
3. SSF	▪ Checking changes in flow velocity and head loss ▪ Removing floating material from the supernatant water	▪ Pipe cleaning	▪ Filter cleaning

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Based on the field tests, observation and Laboratory analysis on the Multi-Stage Filtration (MSF) pilot unit, the following conclusions were made:

- **Performance of Dynamic Gravel Filter (DyGF)**

  It was observed that DyGF unit was capable of "handling" raw water with high level of Turbidity (up to 400NTU). On average, 59% Turbidity removal was achieved by the DyGF unit during the experimental run. With respect to Suspended Solids (SS), the DyGF unit achieved an average removal efficiency of 63%. The DyGF units were not very efficient in colour removal recording an average removal value of 33%.

- **Performance of HRF unit.**

  HRF unit registered 86% Turbidity and 85% Suspended Solids removal. The unit apart from being used as a pre-treatment of Turbidity and Suspended Solids also played a significant role in both Faecal and Total coliform reduction. On average, HRF unit reduced Faecal coliform load by 36% and Total coliform load by 38% respectively. On average HRF, unit reduced dissolved Iron load by 42% and Manganese by 57%.

- **Performance of SSF**

  It was noted that the Slow Sand Filter (SSF) unit was very efficient in microbiological water improvement. The SSF unit registered on average 98% removal for faecal coliforms and 96% removal of Total coliforms after maturation. With respect to other parameters it was observed that the SSF unit registered on average 70% removal of Iron, and 64% removal of Manganese.

- **Performance of Multi-Stage Filtration compared to conventional System (CS)**.

  Although the MSF unit didn't incorporate the use of Chemicals as it is the case in Conventional Systems (CS), the performance of the MSF unit was similar to the performance of the CS with respect to most of the selected water parameters. However the MSF unit proved very efficient relative to CS with respect to Bacteriological water quality improvement with the unit recording an average efficiency of 98 % for faecal coliform removal and 96 % for Total coliform removal. The CS on the other hand gave average removal value of 76 % for Faecal Coliform and 78 % for Total coliform before chlorination.

- **Meeting the WHO and KEBS drinking water Standards**

  It was observed that with respect to Turbidity, MSF met the general minimum set WHO and KEBS standard for drinking water of 5NTU by registering an average Turbidity value of 0.97 NTU. For the case of SS, it was observed that the MSF unit had an average value of 0.69mg/l against the set nil value. With respect to E.Coli, the MSF unit registered average value of 3.7 CFU/100ml (with raw water range of 20 to 372 CFU/100ml) as compared to the set nil value. The MSF unit registered an average value of 5 CFU/100ml (with raw water range 20 to 684 CFU/100 ml) with respect to T.Coli removal against the set nil value. For Iron and Manganese the MSF unit met the KEBS by registering very low traces in the final effluent. For colour the MSF unit met the set standard of <15mg/l pt. Generally it can be concluded that that although the MSF unit proved efficient in removal of the selected parameters, chlorination should act as a final buffer to guide against pathogen breakthrough. However, in this case dosing will be minimal relative to Conventional System.

5.2 RECOMMENDATIONS

Based on the field tests, observation and Laboratory analysis on the Multi-Stage Filtration (MSF) pilot unit, the following recommendations are made:

i. 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.

ii. Research to examine the impact of a two SSF filters connected in series on raw water quality improvement should be carried out.

iii. Research should be carried to establish the impact of long detention time on HRF unit performance (i.e. operating the HRF unit at filtration rates lower than 0.5m/h).

iv. Research should be carried out to establish the impact of different SSF filter bed depth on raw water quality improvement.

v. Further research targeted on development of a design manual for a number of populations as a function of raw water quality.

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APPENDIX 1 - FIELD DATA

Table A1.1 Dissolved Iron and Manganese removal In HRF and SSF units

Run time (days)	Raw water		HRF out		SSF in		SSF out		% Removal			
									Manganese		Iron	
	Iron	Mang-anese	Iron	Mang-anese	Iron	Mang-anese	Iron	Mang-anese	HRF	SSF	HRF	SSF
1	0.195	0.026	0.191	0.021	0.189	0.02	0.15	0.018	19.23	10	2.051	20.63
5	0.15	0.027	0.13	0.019	0.15	0.018	0.069	0.015	29.63	16.67	13.33	54
7	0.19	0.05	0.16	0.003	0.165	0.002	0.098	0.001	94	50	15.79	40.61
9	0.81	0.009	0.39	0.005	0.43	0.005	0.18	0.002	44.44	60	51.85	58.14
12	0.98	0.008	0.41	0.001	0.4	0.0001	0.03	0	87.5	100	58.16	92.5
14	0.99	0.009	0.38	0.005	0.36	0.003	0.096	0.002	44.44	33.3	61.62	73.33
26	0.185	0.023	0.145	0.014	0.123	0.009	0.037	0.003	39.13	66.67	21.62	69.92
48	0.82	0.021	0.4	0.006	0.38	0.006	0.053	0.001	71.43	83.33	51.22	86.05
54	0.78	0.045	0.33	0.021	0.35	0.013	0.085	0.003	53.33	76.92	57.69	75.71
58	0.198	0.029	0.123	0.013	0.123	0.002	0.056	0	55.1	100	37.88	54.47
61	0.199	0.002	0.163	0.001	0.158	0.001	0.008	0	50	100	18.09	94.94
65	0.185	0.019	0.023	0.009	0.025	0.003	0.001	0.002	52.6	33.33	87.6	96
69	0.173	0.02	0.059	0	0.053	0.001	0.001	0	100	100	65.9	98.1
72	0.25	0.041	0.102	0.005	0.113	0.006	0.039	0.002	87.8	66.66	59.2	65.49
79	0.88	0.037	0.43	0.01	0.099	0.013	0.043	0.005	72.9	61.53	51.1	56.5
82	0.82	0.04	0.55	0.02	0.12	0.002	0.04	0.001	50	50	32.9	66.6
86	0.99	0.036	0.47	0.01	0.045	0.003	0.02	0	72.2	100	52.53	55.56
91	0.83	0.016	0.41	0.008	0.04	0.009	0.01	0	50	100	50.6	75

TABLE A 1.2: Percentage Removal of Turbidity in HRF, SSF, MSF and CS

Run time (days)	Turbidity (NTU)								
	HRF in	HRF out	HRF % Rvl	SSF in	SSF out	SSF % Rvl	MSF % Rvl	CS out	CS % Rvl
1	12.5	4.63	62.96	4.75	2.73	42.5	78	1.9	84
2	13.2	4.62	65	4.83	2.69	44.3	79	0.98	92
5	18.7	6.3	66.31	6.4	1.8	71.9	90	2.2	88
7	17.67	6.11	65.42	6.23	1.42	77.2	92	4.31	75
9	16.02	5.49	65.73	5.82	2.37	59.3	85	0.95	94
12	15.35	4.61	69.97	4.52	0.48	89.4	97	3.07	80
14	17.06	4.26	75.03	4.01	0.82	79.6	95	1.88	88
26	38.53	4.05	89.49	4	1.32	67	97	5.26	86
28	50.78	5.35	89.46	6.23	2.62	57.9	95	9.69	80
30	75.23	8.23	89.06	4.52	0.94	79.2	98	10.92	85
33	120.57	16.27	86.51	3.7	0.73	80.3	99	9.42	92
35	183.11	19.52	89.34	3.2	0	100	99	4.3	97
37	202.52	21.5	89.38	4.8	0.08	98.3	99	2.89	98
40	235.63	23.78	89.91	4.2	0.12	97.1	99	4.9	97
42	350.52	24.53	93	5.85	0.97	83.4	99	5.45	98
44	203.64	8.05	96.05	4.2	1.04	75.2	99	3.75	98
45	80.52	6	92.55	7.99	1.5	81.2	98	3.76	95
47	189.2	5.49	97.1	5.2	1.2	76.9	99	3.74	98
49	105	4.61	95.61	4.4	0.8	81.8	99	4.65	95
51	106.74	4.26	96.01	4.2	0.5	88.1	99	2.76	97
54	120.63	4.05	96.64	4.11	0.97	76.4	99	4.02	96
56	127.67	5.35	95.81	5.43	1.34	75.3	98	3.98	96
58	83.23	8.23	90.11	8.71	0.42	95.2	99	3	96
61	202	5.49	97.28	5.35	0	100	99	4.83	97
63	150.45	4.61	96.94	4.02	0.43	89.3	99	3.86	97
65	125	4.26	96.59	4.13	0.1	97.6	99	4.3	96
69	186.3	4.05	97.83	4.11	0.42	89.8	99	4.98	97
71	105	7.3	93.05	6.87	0.83	87.9	99	2.94	97
72	88	5.8	93.41	4.6	1.2	73.9	98	3.91	95
76	96	3.98	95.85	4.2	0	100	99	4	95
79	75	4.81	93.59	4.83	0.94	80.5	98	4.35	94
82	125	4	96.8	4.02	0.83	79.4	99	7.31	94
86	82	3.76	95.41	3.5	1.2	65.7	98	1.2	98
89	74	4.27	94.23	4.2	0.98	76.7	98	6.95	90
91	155	3.06	94.44	3.05	0.3	90.2	99	10.7	93

TABLE A 1.3: Percentage Removal of Suspended Solids in HRF, SSF, MSF and CS

Run time (days)	Suspended Solid(mg/l)								
	HRF in	HRF out	HRF % Rvl	SSF in	SSF out	SSF % Rvl	MSF % Rvl	CS out	CS % Rvl
1	9.6	3.5	63.54	2.98	1.73	41.95	81	1.98	79
2	10.2	4.3	57.84	3.32	1.69	49.1	83	2.6	74
5	12.4	4.32	65.16	4	1.8	55	85	2.3	81
7	14.2	3.9	72.54	4.8	1.42	70.42	90	2.2	84
9	13.7	4.67	65.91	4.25	1.37	67.76	90	1.7	87
12	13.2	4.53	65.68	4.36	0.48	88.99	96	1.8	86
14	15.3	4.3	71.9	4.3	0.82	80.93	95	0.93	93
26	42.5	4.76	88.8	3.8	1.32	65.26	97	1.32	96
28	45.8	4.13	90.98	4.65	0.62	86.67	99	0.71	98
30	55.34	4.86	91.22	3.98	0.94	76.38	98	0.44	99
33	113.3	8.67	92.35	8.43	0.73	91.34	99	0.31	99
35	125.4	9.9	92.11	5.38	0	100	100	0.33	99
37	133.2	10.63	92.02	9.35	0.08	99.14	99	0.78	99
40	143.6	11.54	91.96	8.32	0.12	98.56	99	0.21	99
42	162.5	12.98	92.01	7.98	0.97	87.84	99	1.79	98
44	123.4	9.87	92	8.02	1.04	87.03	99	1.44	98
45	65.4	5.65	91.36	4.3	1.5	65.12	98	2.5	96
47	119.6	8.58	92.83	5.5	0	100	100	2.3	98
49	86.7	6.33	92.7	5.33	0.8	84.99	99	1.82	97
51	83.6	6.89	91.76	5.98	0.5	91.64	99	0.93	98
54	115.7	8.8	92.39	7.83	0.97	87.61	99	0.97	99
56	118.9	9.84	91.72	7.28	1.34	81.59	99	1.34	98
58	84.5	7.68	90.91	7.68	0.42	94.53	99	0.42	99
61	116.8	9.02	92.28	7.25	0	100	100	1.82	98
63	105.6	8.34	92.1	5.32	0.43	91.92	99	0.43	99
65	120.2	8.92	92.58	7.62	0.1	98.69	99	2.17	98
69	127.4	9.5	92.54	9.65	0.42	95.65	99	0.02	99
71	116	5.2	95.52	5.28	0.78	85.23	99	0.87	99
72	95.3	6	93.7	6.95	0.63	90.94	99	1.6	99
76	73	1.98	97.29	2.54	0.04	98.43	100	0.04	99
79	99.2	2.5	97.48	2.73	0.5	81.68	99	1.35	98
82	67.3	3.72	94.47	3.8	0.01	99.74	99	1.3	98
86	42.8	2.2	94.86	2.28	0.67	70.61	98	0.73	98
89	39	2.6	93.33	3	0.01	99.67	99	1.51	96
91	31.7	2	93.69	3.12	0.03	99.04	99	1.33	95

TABLE A 1.4: Percentage Removal of Colour in HRF, SSF, MSF and CS

COLOUR (mg/l pt.)									
Run time (days)	**HRF in**	**HRF out**	**HRF % Rvl**	**SSF in**	**SSF out**	**SSF % Rvl**	**MSF % Rvl**	**CS out**	**CS % Rvl**
1	70	40	42	35	20	42	71	25	64
2	110	60	45	55	35	36	68	40	63
5	90	45	50	40	15	62	83.	15	83
7	120	55	54	55	5	90	95	15	87
9	110	55	50	50	0	100	100	5	95
12	135	70	48	65	0	100	100	10	92
14	95	45	52	35	5	85	94	5	94
26	115	75	34	85	5	94	95	10	91
28	110	45	59	45	0	100	100	5	95
30	125	65	48	65	10	84	92	10	92
33	135	70	48	35	5	85	96	5	96
35	70	35	50	40	0	100	100	0	100
37	85	40	52	45	0	100	100	5	94
40	95	55	42	50	0	100	100	0	100
42	105	60	42	55	5	90	95	5	95
44	90	75	16	70	0	100	100	5	94
45	115	50	56	45	0	100	100	0	100
47	125	50	60	45	5	88	96	5	96
49	85	35	58	35	0	100	100	5	94
51	85	35	58	35	5	85	94	5	94
54	95	40	57	45	10	77	89	10	89
56	115	55	52	50	5	90	95	5	95
58	110	60	45	55	0	100	100	10	90
61	115	35	69	35	15	57	86	15	86
63	125	40	68	40	10	75	92	5	96
65	105	55	47	55	0	100	100	0	100
69	115	60	47	55	5	90	95	5	95

TABLE A 1.5: pH, Temperature and DO levels in HRF and SSF units

Run time (days)	Raw water. (RW)			HRF out			SSF in			SSF out		
	pH	Temp	DO	pH	Temp	DO	pH	Temp	DO	pH	Temp	DO
1	8.32	21.3	9.3	8.1	21	6.9	8.1	21.3	6.5	7.3	19.5	3.53
2	8.11	21	9.7	7.93	21.2	6.82	7.91	21	6.53	7.1	20.1	4.5
5	7.97	22.6	8.85	7.9	22.6	6.93	7.84	22.6	6.8	7.4	19.2	5.3
7	8.01	22.3	8.5	7.94	22.3	6.5	7.9	22.2	6.4	6.9	19.6	6.02
9	8.3	21.5	8.26	7.8	21.5	6.63	7.79	21.4	6.57	7.5	20.3	4.56
12	7.8	22.5	8.23	7.79	22.5	6.02	7.63	22.4	6	7.21	20.5	3.56
14	7.81	25.2	9.11	7.67	25.2	6.57	7.61	25.2	6.43	7.01	19	3.87
26	7.54	22.3	13.1	8.24	22.3	6.05	8.2	22.3	5.99	7	19.4	6.83
28	7.53	22.3	8.53	7.53	22.1	5.92	7.49	22	5.8	6.87	19.7	5.99
30	7.81	22	7.93	7.52	22	5.85	7.5	21.9	6.04	7.23	20.7	4.56
33	7.63	21.5	7.23	7.83	21.5	5.55	7.67	21.5	5.96	7.45	20.03	3.95
35	8.11	25.2	7.51	7.65	26.7	6.58	7.46	26.6	6.52	7.32	20.1	3.47
37	8.44	25.1	8.85	8.01	25.1	6.5	7.98	25.1	5.81	7.62	19.9	3.92
40	8.24	26.3	8.52	8.47	25.6	6.47	8	25.6	6.34	7.08	21	5.4
42	7.77	22.5	6.53	8.11	26.3	7.3	7.5	26.2	6.96	7	20.9	5.02
44	8	21	6.42	7.92	22.5	8.02	7.89	22.5	6.06	6.98	19.8	6.58
45	7.75	22.3	9.21	7.6	21.2	6.83	7.58	21.2	5.76	7.45	20.1	5.98
47	7.57	25.2	7.23	7.79	22.3	6.05	8.2	22.2	6.8	7.32	19.9	4.56
49	7.8	22.3	7.51	7.37	22.1	5.92	7.49	21.4	5.4	7.62	20.9	3.56
51	7.62	22	8.85	8.24	22.2	5.85	7.5	22.4	6.57	6.97	20.8	4.8
54	8.14	23	8.52	7.79	21.3	6.05	8.2	25.2	5.6	6.87	20.7	4.83
56	8.44	21.5	8.23	7.17	22.3	5.92	7.49	22.3	6.43	7.23	20.3	5.99
58	8.23	22.3	9.11	8.43	22.1	6.43	7.35	22.2	3.99	7.21	19	4.53
61	7.77	22	13.1	7.53	22.4	5.99	7.67	21.4	5.8	7.01	19.4	3.95
63	7.55	22.3	8.53	7.5	21.5	5.8	7.43	22.4	6.14	6.87	19.7	3.43
65	7.83	21.5	7.93	7.83	26.7	6.34	7.98	25.2	5.26	6.87	20.2	3.91
69	7.63	22.5	8.52	7.65	25.1	4.3	8.1	22.3	6.52	7.23	20	5.4
70	7.29	23.2	7.26	7.25	23	5.75	7.2	23.2	6.23	7.2	19.8	4.5
72	8.26	23.6	9.2	8	23.6	5.32	7.52	23.6	5.85	7.45	19.5	4.95
76	7.98	23.9	7.68	7.72	23.8	5.64	7.53	23.9	6.08	7.5	20.5	3.98
79	7.56	22.8	7.85	7.37	22.7	6.91	7.35	22.6	5.91	7.24	19.9	5.94
82	8.53	22.7	7.29	8.13	22.6	5.86	7.2	22.5	4.8	7.01	19.5	6.02
84	7.55	23.8	9.89	7.48	23.8	5.93	7.48	23.9	6.99	7.38	20.3	3.73
86	7.98	22.9	8.5	7.63	22.8	6.06	7.62	23	7.25	7.52	21.2	6.55
89	7.45	24.1	6.98	7.36	24	7.55	7.35	23.9	6.84	7.4	20.4	5.52
91	7.81	23.6	11.45	7.8	23.6	7.98	7.81	23.6	7.59	7.68	21.2	4.37

TABLE A 1.6: Removal of Turbidity at SSF sampling points

Run time (days)	Turbidity (NTU)						
	SSF in	SP1	SP2	SP3	SP4	SP5	SSF out
1	4.75	4.01	3.93	3.57	3.23	2.99	2.73
2	4.83	4.2	3.98	3.65	3.3	2.86	2.69
5	6.4	5.03	4.54	3.55	2.92	2.06	1.8
7	6.23	5.31	4.58	3.35	2.98	1.97	1.42
9	5.82	5.61	4.47	3.3	2.88	2.52	2.37
12	4.52	4.36	3.5	2.4	1.67	0.81	0.48
14	4.01	3.65	2.83	2	1.53	0.93	0.82
26	4	3.59	2.71	1.8	1.52	1.45	1.32
28	6.23	5.56	4.03	3.82	3.59	2.88	2.62
30	4.52	3.62	3.51	3.29	2.53	1.97	0.94
33	3.7	3.28	3	2.75	2.04	1.73	0.73
35	3.2	2.63	2.48	2.36	1.98	1	0
37	4.8	3.78	3.36	2.66	1.2	0.16	0.08
40	4.2	3.41	3.28	3.2	2	0.18	0.12
42	5.85	4.66	4.55	3.33	2.53	1.54	0.97
44	4.2	3.35	3.29	3.04	2.7	1.64	1.04
45	7.99	6.4	6.28	5	4.05	2.32	1.5
47	5.2	4.06	4	2.8	3.3	1.29	1.2
49	4.4	3.63	3.34	2	1.63	0.79	0.8
51	4.2	3.53	3.47	2.93	1.77	0.68	0.5
54	4.11	3.32	3.3	2.65	2.5	1.99	0.97
56	5.43	4.4	4.38	3.2	2.98	1.63	1.34
58	8.71	6.68	6.04	3.67	1.96	0.65	0.42
61	5.35	4	3.95	2.73	0.71	0.07	0
63	4.02	3.21	2.94	2.34	1.89	1.9	0.43
65	4.13	3.03	2.56	1.27	0.63	0.21	0.1
69	4.11	3.74	3.45	3.06	2.16	1.73	0.42
71	6.87	5.6	5.48	4.45	3	1.88	0.83
72	4.6	3.73	3.35	3.3	2.03	1.96	1.2
76	4.2	3.07	3	2.53	0.55	0.42	0
79	4.83	3.48	3.27	2.6	1.9	1.11	0.94
82	4.02	2.98	2.52	1.88	1.5	0.87	0.83
86	3.5	2.69	2.33	2.07	1.84	1.2	1.2
89	4.2	3.35	2.5	1.83	1.69	0.99	0.98
91	3.05	2.4	1.73	1.26	0.6	0.41	0.3

TABLE A 1.7: Removal of Suspended Solids (SS) at SSF sampling points.

Run time (days)	Suspended Solids (SS) (mg/l)						
	SSF in	SP1	SP2	SP3	SP4	SP5	SSF out
1	2.98	2.62	2.47	2.33	2.01	1.9	1.73
2	3.32	2.6	2.05	1.8	1.73	1.7	1.69
5	4	3.2	2.6	2.1	2	2	1.8
7	4.8	4.47	3.96	2.9	2.7	1.8	1.42
9	4.25	3.99	3.1	2.8	2.3	2	1.37
12	4.36	3.8	3	2.6	2.5	1.7	0.48
14	4.3	4.18	2.61	2.49	1.8	1.2	0.82
26	3.8	2.6	2.28	1.72	1.49	1.37	1.32
28	4.65	3.23	2.9	2.1	5.3	2.8	0.62
30	3.98	2.57	1.68	1.08	0.99	0.95	0.94
33	8.43	5.4	4.05	3.63	2.11	1.9	0.73
35	5.38	5.16	4.8	4.5	2.92	1.2	0
37	9.35	6.8	4.7	4.7	3.96	1.71	0.08
40	8.32	6.95	5.8	4.28	2.63	1.6	0.12
42	7.98	7.1	6.38	5.81	3.51	1.5	0.97
44	8.02	6.85	5.32	4.7	3.6	2.2	1.04
45	4.3	3.85	3.71	3.67	3.62	2.3	1.5
47	5.5	4.3	3.8	3.11	2.46	1.7	0
49	5.33	3.91	2.73	1.76	1.32	1.08	0.8
51	5.98	3.58	2.36	1.27	1.09	1	0.5
54	7.83	6.5	5.14	3.5	2.7	1.8	0.97
56	7.28	6.28	5.23	4.39	3	1.8	1.34
58	7.68	5.94	4.18	3.81	2.3	1.1	0.42
61	7.25	6.07	5.9	4	2.92	1.5	0
63	5.32	3.56	2.47	1.69	1.2	0.8	0.43
65	7.62	6.41	5.29	4.66	2.8	1.56	0.1
69	9.65	7.39	6.86	6.3	1.8	1.1	0.42
71	5.28	3.8	2.61	2.07	1.87	1.63	1.43
72	6.95	6.57	5.26	3.9	2.59	1.08	0.78
76	2.54	2	1.75	1.01	0.99	0.8	0.63
79	2.73	2.58	2.17	1.8	1.5	1.3	0.05
82	3.8	2.96	1.69	1.43	1.31	1.2	0.04
86	2.28	1.95	1.86	1.6	0.98	0.83	0.5
89	3	2.3	1.85	1.04	0.63	0.5	0.01
91	3.12	2.78	1.74	1.4	1.3	1	0.02

TABLE A 1.8: Removal of Colour at SSF sampling points.

Run time (days)	Colour (mg/l pt.)						
	SSF in	SP1	SP2	SP3	SP4	SP5	SSF out
1	35	35	30	30	25	20	20
2	55	50	45	45	40	40	35
5	40	35	30	30	25	20	15
7	55	55	50	35	20	10	5
9	50	45	30	25	15	5	0
12	65	60	45	40	25	10	0
14	35	30	20	15	10	10	5
26	85	75	60	35	20	5	5
28	45	40	35	30	25	5	0
30	65	65	50	40	25	15	10
33	35	35	30	25	10	5	5
35	40	35	20	15	15	5	0
37	45	45	40	35	25	15	0
40	50	40	40	35	30	5	0
42	55	45	40	25	15	10	5
44	70	65	55	40	25	15	0
45	45	40	25	20	15	10	0
47	45	45	30	25	15	10	5
49	35	30	20	15	10	5	0
51	35	25	15	10	10	5	5
54	45	40	35	25	20	15	10
56	50	40	35	20	15	10	5
58	55	45	45	30	25	15	0
61	35	30	25	25	20	15	15
63	40	35	20	20	15	10	10
65	55	50	40	35	20	10	0
69	55	40	35	20	15	10	5

TABLE A 1.9: Removal of Turbidity at HRF sampling points

Run time (days)	Turbidity (NTU)				
	HRF in	SP1	SP2	SP3	HRF out
1	12.5	10.03	7.52	5.91	4.63
2	13.2	9.76	6.95	5.27	4.62
5	18.7	11.73	9	6.98	6.3
7	17.67	13.63	9.53	6.84	6.11
9	16.02	12.94	8.97	6.55	5.49
12	15.35	11.9	7.81	5.82	4.61
14	17.06	13.02	9.05	6	4.26
26	38.53	20.23	12.6	7.92	4.05
28	50.78	23.5	14	8.07	5.35
30	75.23	45	28.8	12.58	8.23
33	120.57	86.71	48.34	23	16.27
35	183.11	105.79	75.38	39.06	19.52
37	202.52	118	83.42	48	21.5
40	235.63	138.43	95	53.56	23.78
42	350.52	217	103.72	65	24.53
44	203.64	120	85.3	40.98	8.05
45	80.52	58.08	21	11.75	6
47	189.2	110.96	81.64	36.87	5.49
49	105	72	27.5	11.91	4.61
51	106.74	75.58	36.53	13.06	4.26
54	120.63	78.02	42.37	19.52	4.05
56	127.67	80.01	44.95	21.97	5.35
58	83.23	56.01	23.96	15	8.23
61	202	100.8	52.06	18.95	5.49
63	150.45	96.04	63	20.06	4.61
65	125	85.65	38	17.5	4.26
69	186.3	98	59.95	19.67	4.05
70	123	81	39.63	18	8.5
71	105	70.23	34.54	20.07	7.3
72	88	43.03	28.91	16.05	5.8
75	203	78.43	43.22	19.57	4.2
76	96	45.06	24.98	15.06	3.98
79	55	27.98	18.65	12.95	4.81
82	125	82	39.54	18.55	4
84	58	28.76	20	12.33	3.03
86	82	48.93	21.6	11.93	3.76
89	74	41.07	25.08	11.94	4.27
91	155	56.28	23.57	13	7.06

TABLE A 1.10: Removal of Colour at HRF sampling points

Run time (days)	Colour (mg/l pt.)				
	HRF in	SP1	SP2	SP3	HRF out
1	70	65	55	50	40
2	110	105	90	75	60
5	90	80	75	55	45
7	120	100	85	60	55
9	110	95	80	65	55
12	135	110	95	80	70
14	95	80	75	55	45
26	115	100	95	80	75
28	110	95	80	65	45
30	125	105	75	70	65
33	135	120	105	80	70
35	70	65	55	40	35
37	85	80	65	55	40
40	95	90	75	60	55
42	105	100	80	75	60
44	90	85	80	75	75
45	115	105	75	60	50
47	125	100	85	55	50
49	85	80	55	40	35
51	85	75	50	45	35
54	95	90	75	55	40
56	115	105	90	65	55
58	110	95	80	65	60
61	115	100	75	50	35
63	125	105	70	55	40
65	105	85	65	60	55
69	115	105	75	70	60

TABLE A 1.11: Removal of Suspended Solids (SS) at HRF sampling points

Run time (days)	Suspended Solids (mg/l)				
	HRF in	SP1	SP2	SP3	HRF out
1	9.6	6.53	4.57	3.98	3.5
2	10.2	7.65	5.91	5.03	4.3
5	12.4	8	6.2	5.5	4.32
7	14.2	9.5	7.3	4.5	3.9
9	13.7	7.6	6.1	5	4.67
12	13.2	6.9	5.3	4.9	4.53
14	15.3	8.2	5.8	4.4	4.3
26	42.5	24	16.7	8.2	4.76
28	45.8	26.8	18.5	9.1	4.13
30	55.34	29.5	20	11.4	4.86
33	113.3	65	29.1	15.3	8.67
35	125.4	73.4	34	19.8	9.9
37	133.2	82	48.2	25	10.63
40	143.6	86.4	52.2	30.13	11.54
42	162.5	90.7	63.8	34.4	12.98
44	123.4	69.2	31.6	19.2	9.87
45	65.4	33.6	28	17.8	5.65
47	119.6	65.9	32.1	15.7	8.58
49	86.7	46.8	26.9	16	6.33
51	83.6	50.6	32	18.8	6.89
54	115.7	77	42.3	26.4	8.8
56	118.9	76.8	38.5	22	9.84
58	84.5	54.7	30.1	18.9	7.68
61	116.8	76.4	43.7	25.8	9.02
63	105.6	71.8	39.5	20.7	8.34
65	120.2	78.2	40	22.8	8.92
69	127.4	87.3	45.7	28.5	9.5
70	99.3	67.3	39.2	23.06	7.6
71	116	78.5	35.6	19.3	5.2
72	95.3	54.2	28.7	17.4	6
75	58.7	29.3	18.9	10.1	2.7
76	73	37.1	18.3	12.3	1.98
79	99.2	45.6	28.5	16.9	2.5
82	67.3	36.8	21.3	12.5	3.72
84	48.7	27.84	18	9.66	3
86	42.8	25	16.65	10.02	2.2
89	39	23.99	14.87	9.04	2.6
91	31.7	20.26	15	8.47	2

TABLE A 1.12: Removal of Turbidity, Suspended Solids and Colour at DyGF unit

Run time (days)	TURBIDITY			SUSPENDED SOLIDS			COLOUR		
	DyGF in	DyGF out	DyGF % Rvl	DyGF in	DyGF out	DyGF % Rvl	DyGF in	DyGF out	DyGF % Rvl
1	187.8	50.78	73	238.6	45.8	81	140	110	21
3	198.87	75.23	62	260.4	55.34	79	145	125	14
6	255.3	120.57	52	262.5	113.3	57	165	135	18
8	375.8	183.11	51	255.6	125.4	51	140	70	50
10	392.52	202.52	48	259.3	133.2	49	145	85	41
13	395.63	235.63	40	260.8	143.6	45	165	95	42
15	398.6	350.52	12	262.5	162.5	38	155	105	32
17	376.4	203.64	46	253.2	123.4	51	150	90	40
19	280.7	80.52	71	259.5	65.4	75	145	115	21
21	362.2	189.2	48	260.6	119.6	54	140	125	11
23	298.5	105	65	248.9	86.7	65	150	85	43
25	250.3	106.74	57	258.3	83.6	68	145	85	41
28	353.63	120.63	66	262.5	115.7	56	150	95	37
30	377.7	127.67	66	263	118.9	55	165	115	30
32	283.38	83.23	71	261.8	84.5	68	150	110	27
35	391.7	202	48	256.3	116.8	54	155	115	26
37	369.5	150.45	59	259.1	105.6	59	165	125	24
39	221	125	43	262.5	120.2	54	150	105	30
43	396.53	186.3	53	257.5	127.4	51	135	115	15
45	278.4	105	62	260.9	116	56	140	55	61
46	259.8	88	66	259.3	95.3	63	145	60	59
50	338.36	96	72	258.3	73	72	130	75	42
53	298	75	75	261.5	99.2	62	155	55	65
56	368	125	66	260.7	67.3	74	140	95	32
60	288	82	72	254.8	42.8	83	125	105	16
63	291.56	74	75	241	39	84	120	95	21
65	385	155	60	233	31.7	86	135	75	44

TABLE A 1.12: Head loss development in the SSF unit.

Run time (days)	Head loss (cm)
1	0.55
2	0.6
5	0.85
7	1.2
9	1.85
12	2.55
14	3.2
26	5.8
28	7.2
30	8.85
33	11
35	12.3
37	15.35
40	18
42	20
44	22.3
45	23
47	25.75
49	28
51	30.25
54	32
56	34.5
58	38.65
61	40.45
63	44.8
65	48.5
69	52.35
70	53
71	55.4
72	56.2
75	60.6
76	61.5
79	64.3
82	68.4
84	72
86	78
89	84
91	86

APPENDIX 2 - DATA ANALYSIS

Table A 2.1 Slow Sand Filter effluent (SSF out) Turbidity statistics

SSFout

N	35
Mean	0.9740
Std. Deviation	0.75506
Skewness	0.922
Kurtosis	0.494

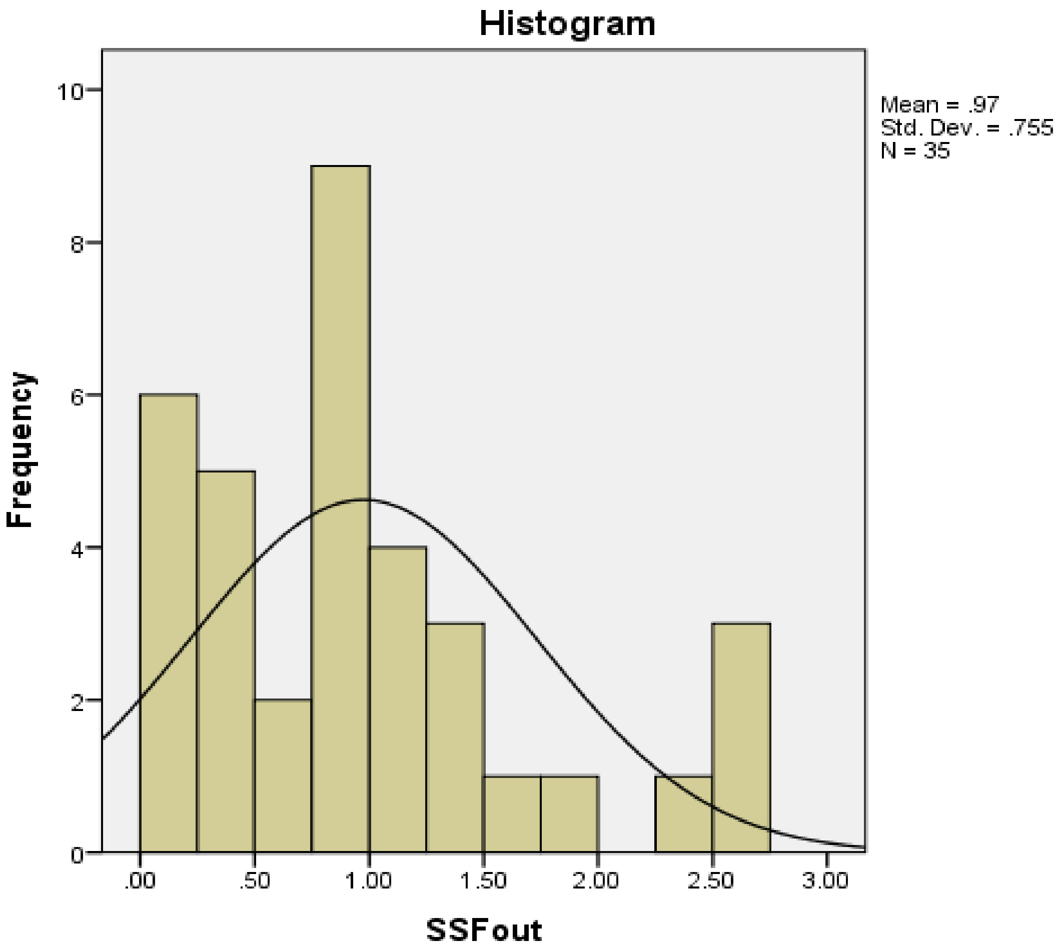


Table A 2.2 Slow Sand Filter effluent (SSF out) Colour statistics

Colour SSF out

N	27
Mean	5.93
Std. Deviation	7.971
Skewness	2.195
Kurtosis	6.005

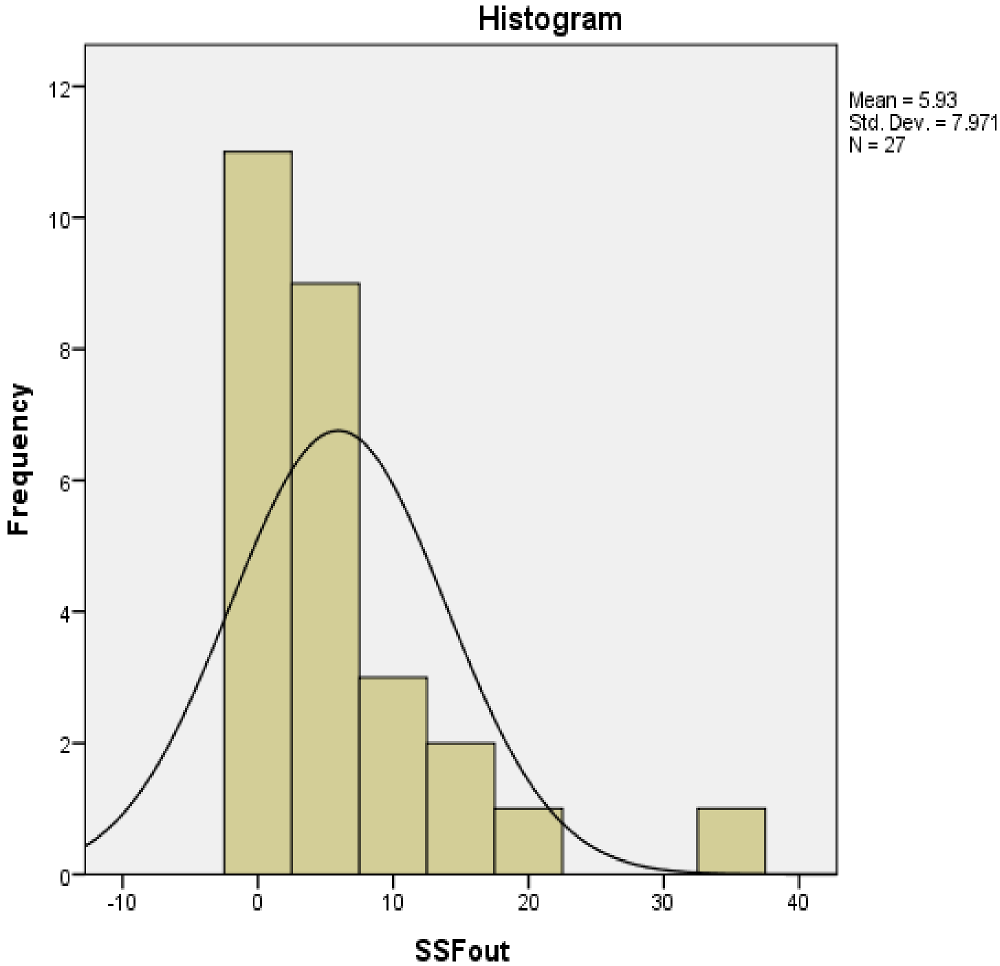


Table A 2.3 Slow Sand Filter effluent Suspended Solids (SS) statistics

SSFout

N	35
Mean	0.716
Std. Deviation	0.575
Skewness	0.335
Kurtosis	-1.086

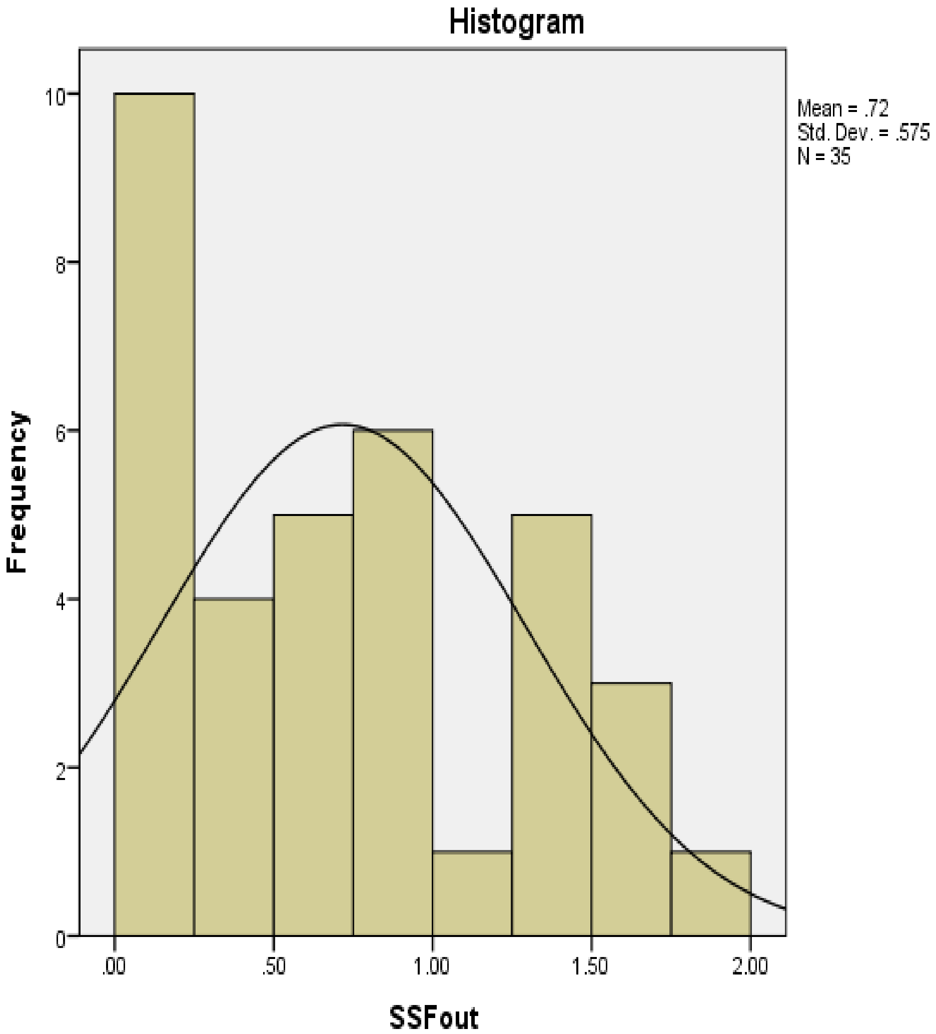


Table A 2.4 Slow Sand Filter effluent Total coliform statistics

SSFout

N	14
Mean	5.571
Std. Deviation	6.4416
Skewness	1.323
Kurtosis	0.100

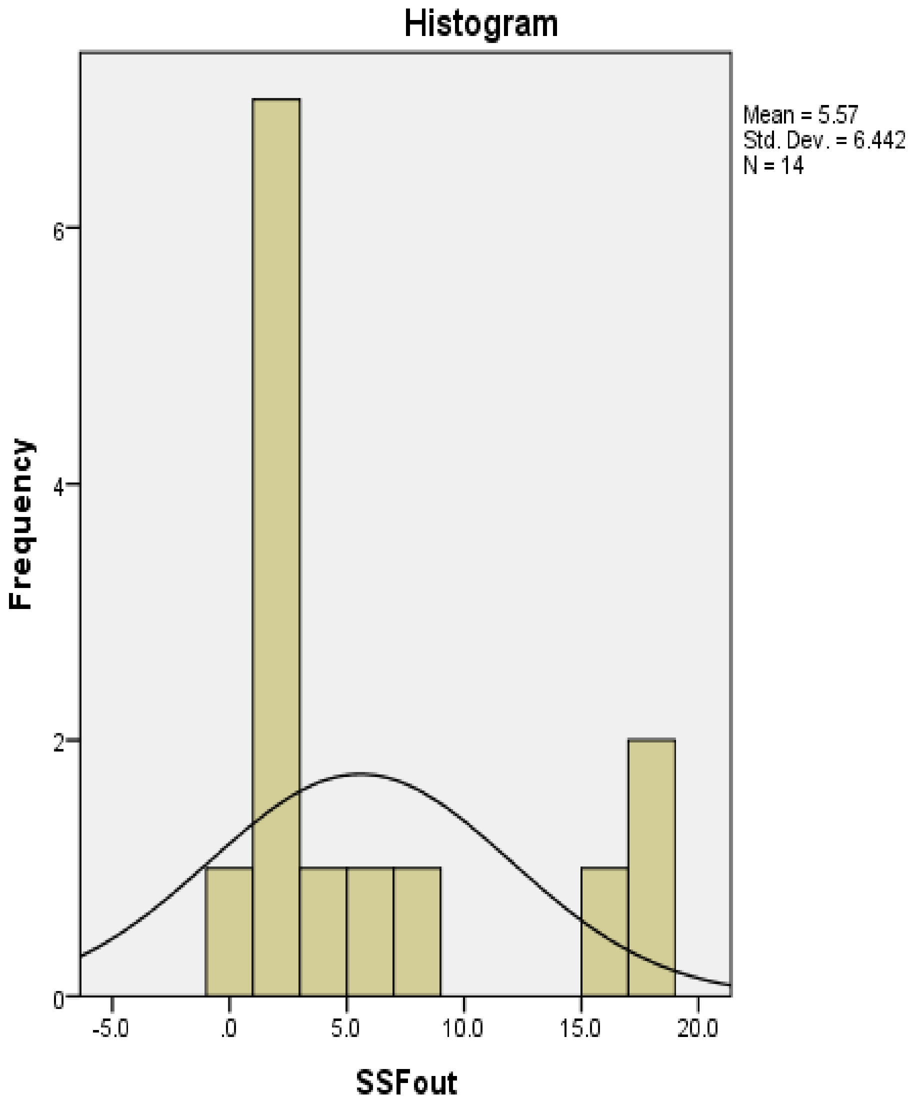
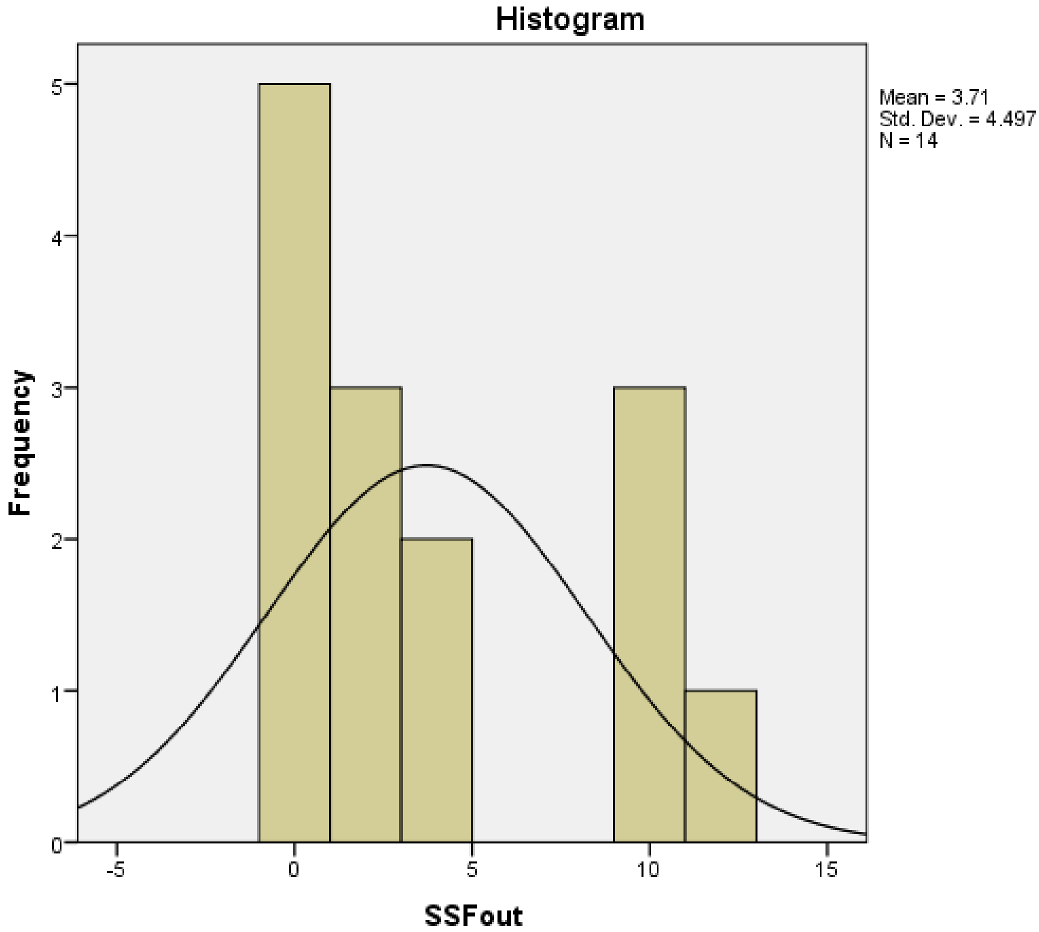


Table A 2.5 Slow Sand Filter effluent Faecal coliform statistics

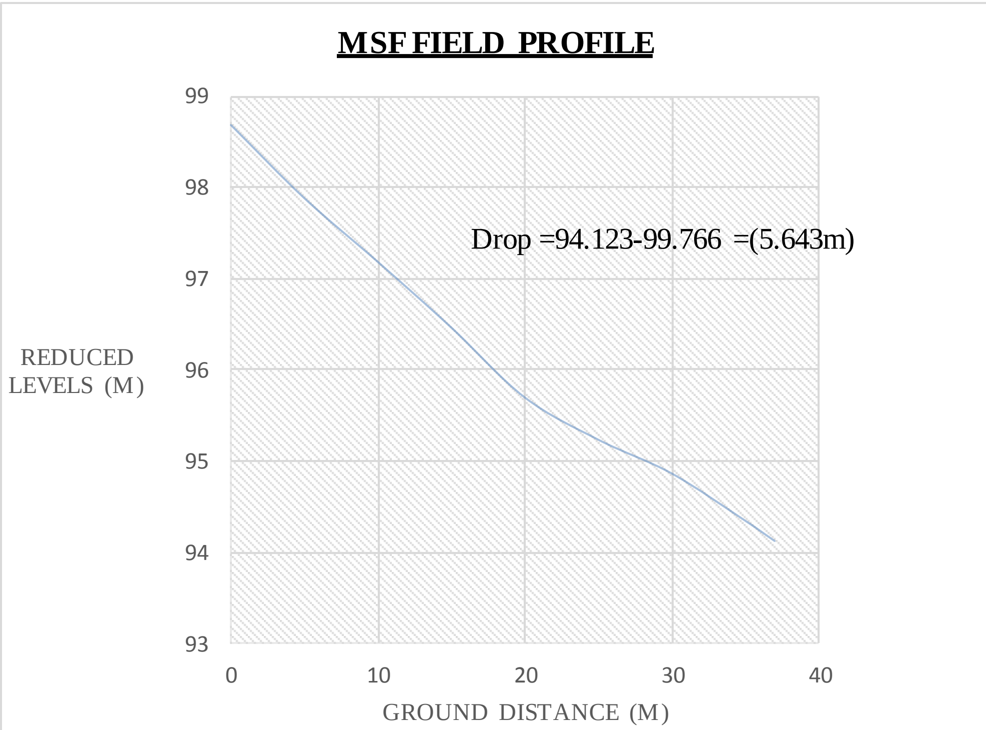
SSFout

N	14
Mean	3.71
Std. Deviation	4.497
Skewness	0.900
Kurtosis	-0.942



APPENDIX 3 - MSF FIELD SURVEY DATA

B.S	**IS**	**FS**	**HC**	**Distance.**	**R.L**	**Remarks**
					100	T.BM (Assumed)
0.39			100.39		100	
	0.624		100.39		99.766	Water level(intake)
	1.714		100.39	0+000	98.676	
	2.215		100.39	0+005	97.875	
	3.212		100.39	0+010	97.178	
	3.931		100.39	0+015	96.459	
0.484		2.7	98.174		97.69	
	2.48		98.174	0+020	95.694	
	2.942		98.174	0+025	95.232	
	3.312		98.174	0+030	94.862	
	3.829		98.174	0+035	94.345	
	4.051		98.174	0+037	94.123	lowest point



APPENDIX 4 - PLATES

Plate A4.1 Field demonstration.

(a) Slow Sand Filter (SSF) in operation.

Plate A 4.2 Sampling process and Laboratory analysis

(a) Field Sampling process (Final SSF effluent).

(b) Laboratory analysis (photo taken at ELDOWAS).