EVALUATION OF CRUSHED SLATES AS A SUITABLE CAPPING MATERIAL FOR RAPID GRAVITY SAND FILTERS

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Evaluation of Crushed Slates as a Suitable Capping Material for Rapid Gravity Sand Filters

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DECLARATION

This thesis is my original work and has not been presented for the award of degree in any other University.

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DEDICATION

This research work is dedicated to God almighty for his grace and enablement. To my dad and mum who believed in the value of education and have stood with me in prayers and gave me moral support throughout the journey of this research work.

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ACRONYMS AND ABBREVIATIONS

BOD	Biochemical Oxygen Demand
BOPS	Burnt Oil Palm Shell
BS	British Standard
DeKUT	Dedan Kimathi University of Technology
JKUAT	Jomo Kenya University of Agriculture and Technology
KS	Kenyan Standards
LECA	Lightweight Expanded Clay Aggregates
MWI	Ministry of Water and Irrigation (Kenya)
NTU	Nephelometric Turbidity Units
pH	Potential of Hydrogen
PVC	Polyvinyl Chloride
RGSF	Rapid Gravity Sand Filter
RUJWASCO	Ruiru – Juja Water and Sewerage Company
WASREB	Water Services Regulatory Board
WHO	World Health Organization

ABSTRACT

In the potable water treatment process, Rapid Gravity Sand Filters (RGSF) are commonly adopted as the last solid-liquid separation stage. Cleaning of the RGSF is done through backwashing. RGSF is widely adopted all over the World due to its ease of operation and high filtration rates. However, these filters suffer from stratification of the sand media, which causes floc removal to occur only at the topmost layer of the filter bed, leaving the remaining depth unutilized. Capping is a technique whereby a thin layer of sand filter media is replaced with a suitable coarse material to overcome the problem of stratification and transform a single-media RGSF into a dual-media filter. The objective of this study is to determine the suitability of crushed slates as a capping material. The study evaluated the impact of introducing crushed expanded slate on length of filter run and turbidity removal efficiency, physical and chemical characterization and the cost benefit of introducing crushed expanded slate to RGSF. Laboratory tests were conducted to assess the physical and chemical characteristics of slates from Maji ya Chumvi (Coast, Kenya). This included specific gravity, acid solubility, water extractable substances, silica content, and friability. Length of the filter run and turbidity removal efficiency comparison was carried out by means of a fabricated model filtration unit set up within an existing community water treatment plant. The model filtration unit was fed with pretreated raw water of varying influent turbidities. Crushed expanded slate met the chemical and physical characterization for use as a capping material and increased the length of filter run by an average of 25% and 52% for medium (50 - 150NTU) and high (150 – 300NTU) influent turbidities respectively. Improvement in turbidity removal was insignificant. The total present value (CAPEX and OPEX) for capping with 25mm crushed expanded slates gave an overall cost reduction of 11%. Considering the highlighted benefits and the non-hazardous nature of the material, the study recommends the use of crushed expanded slates from Maji ya Chumvi for use as a capping material for Rapid Sand Filters.

CHAPTER ONE

INTRODUCTION

1.1 Background Information

The Kenyan potable water standards have been developed and published under schedules 1 to 5 of the Water Services Regulatory Board (WASREB) guidelines on water quality and effluent monitoring of March 2008. The degree and type of treatment required for raw water, to meet potable water standards, primarily depend on the raw water characteristics (Malcolm et al., 2017). Different water treatment technologies have been developed and are considered as either conventional or advanced treatment systems. The Kenyan Water Supply Design Manual (MWI, 2005) recommends the adoption of conventional water treatment systems with minimal mechanization. These systems have proved to be economical and sustainable for the local context. A similar observation for other developing countries such as India is reported by Sabale et al., 2014.

A conventional water treatment process entails: pretreatment (screening, flocculation and clarification), filtration and disinfection. Depending on the raw water quality, pretreatment can be excluded (MWI, 2005). In any domestic water treatment process, filtration and chlorination remains the basic and widely adopted stages (Lin, 2010).

Sabale et al., (2014) defines filtration as a physical, chemical, and in some instances, a biological process involving the separation of suspended and colloidal impurities from water by passage through porous media. Malcolm et al., (2017) discusses the different types of filtration systems and further notes that Rapid Gravity Sand Filters (RGSF) remain the widely and most commonly adopted all over the world due to ease of operation and high filtration rates.

RGSF consists of a layer of graded sand supported on a gravel bed through which the raw water percolates and gets filtered. Cleaning of the filter is through backwashing. The frequency of backwashing and the general performance of the filter is primarily dependent on the influent water quality and the filter media characteristics (Jusoh et al., 2007).

Al-Rawi (2017) indicates that sand as a filter media has widely been adopted because of its (local) availability, low cost, and the satisfactory results obtained in turbidity removal. A minimum depth of sand must be provided to ensure flocs are captured within the filter media before breaking through to the supporting gravel bed (Ansari et al., 2017).

The introduction of anthracite coal overlying sand forms a dual-media RGSF. Anthracite coal helps RGSF to overcome the problem of stratification and came into use between 1960 to 1970. The use of dual-media filters is expected to become more popular in countries where there is availability of suitable filter media (Shirule and Sonwane, 2019). In dual media filters, the coarse size anthracite coal layer increases the sludge storage capacity of the filter bed thereby increasing the length of the filter runs (Al-Rawi, 2017). The intermix between the anthracite coal and sand enhances the robustness of the dual filter media to deal with turbidity shock loads. Differences in specific gravities of the anthracite coal and sand, ensures that they retain their relative positions after upward fluidization during backwashing (Shirule and Sonwane, 2019).

Among all other coals, anthracite coal has the highest carbon content and is commonly used as a source of energy (Jusoh et al., 2007). Anthracite coal is not only costly but difficult to obtain uniform grade with adequate wear resistance and satisfactory length of useful life. Assessment of other locally available materials remains an area of interest to many researchers all over the world in the water supply industry. This includes bituminous coal, PVC granules, crushed coconut shells, fiber mat, synthetic nylon fibers amongst others (Sabale et al, 2014).

Malcolm et al., (2017) reports that low specific gravity in comparison to sand is a key attribute that has made anthracite coal perform exceedingly well in solving the problem of stratification of Rapid Sand Filters. Chen et al., (2012), Donna (2001), Cardenes and Garcia (2023) amongst others, have reported that slate of diverse origin have thermally unstable elements that allow exfoliation during heating resulting to expanded slate that have specific gravities of 1.2 – 1.7. This makes slate a potential candidate for consideration as a capping material for Rapid Sand Filters.

This research aims at assessing the suitability of crushed slate, locally known as *mazeras*, as a suitable capping material for RGSF. Slate is commonly used for outdoor tiling and decoration and is sourced from Maji ya Chumvi (Coast, Kenya). During shaping of *mazeras*, a lot of solid waste is generated. Decorative slate and the waste generated by the vendors are illustrated in Plate 1.1.

Plate 1.1: Decorative Shaped Mazeras and Solid Wastes - Kahawa Sukari, Kenya

1.2 Problem Statement

Numerous studies indicate that during backwashing of RGSF, stratification of sand media takes place (Sabale et al., 2014; Al-Rawi, 2017; Farjana et al., 2018; Ansari et al., 2017; Delbazi et al., 2011). Sand grains having small particle size raise to the top of the RGSF. During the next cycle of filtration, removal of flocs occurs at the topmost layer of the filter bed; this leaves the remaining depth of the RGSF bed unutilized. It is estimated that sand has a voidage ratio of 40 - 45% which is available for sludge storage during filtration. However, due to the stratification arising during backwashing only about a quarter of the available voidage is utilized (Malcolm et al., 2017). Stratification reduces the sludge storage capacity of the filter bed and further reduces the porosity of the top layer hence increasing the head loss which results to short filter runs. Short filter runs demand high frequency of backwashing which increases energy consumption and hence the operating cost of the water treatment system (Kalibbala, 2007).

1.2 Justification

Majority of the urban centers in Kenya are experiencing rapid population growth primarily due to the rural – urban migration in search of employment opportunities. The Kenyan Constitution 2010 stipulates that it is a basic human right for every citizen to have access to potable water in adequate quantities. Local water utilities continue to identify and develop new water sources and water treatment technologies to meet the rapidly increasing potable water demands particularly in the urban areas (MWI,2005).

Some of the existing and new water sources are run-off river intakes that experience high turbidity levels during wet seasons. These sources have high operational costs during wet seasons due to the high requirements for chemicals and energy for increased frequency of filter backwashing (Lin, 2010).

The introduction of a suitable locally available, cost effective and sustainable capping material can significantly extend the length of the filter run and turbidity removal efficiency for the RGSF. This would reduce the overall operational costs for water treatment making potable water more affordable, especially for low-income urban dwellers. This study aims to assess the suitability of crushed expanded slates as a capping material for RGSF and targets to extend the length of the filter run and improving the efficiency of turbidity removal.

1.3 Objectives

1.3.1 Main Objective

This research aims at evaluating the suitability of crushed slate as a capping material for improving the performance of RGSF.

1.3.2 Specific Objectives

1. To assess the physical and chemical characteristics of crushed expanded slate.
2. To evaluate the length of the filter run and turbidity removal of crushed expanded slate capped filter.
3. To assess the cost benefit of a crushed expanded slate capped filter.

1.4 Scope and Limitations

1.4.1 Scope of the Research

In this study, crushed slate from Maji ya Chumvi were assessed on their suitability as a capping material for RGSF. The physical and chemical characteristics that were assessed include specific gravity, acid solubility, water extractable substances, silica content and friability / attrition.

To evaluate the performance of the crushed expanded slate RGSF, a model filtration unit was designed and fabricated. The model was set up within an existing water treatment plant and fed with raw water that had undergone pretreatment. Data collected includes influent turbidity, effluent turbidity and filtration rate against time. The key performance index was turbidity removal and length of filter run which were used for comparison between the crushed slate capped and single media RGSF.

1.4.2 Limitations

Due to the limitation of resources and time required, this research was limited to the following:

i. The research work and findings were limited to slate sourced from Maji ya Chumvi, Coast Region in Kenya. Slate from other sources may have varying physical and chemical characteristics.

ii. Performance comparison between crushed slate capped and conventional RGSF was limited to turbidity removal and length of filter run. These are the primary benefits of the capping technique.

iii. The research work is limited to a model / laboratory scale and the results may not be directly inferred to a full scale RGSF. Literature indicates that in some cases model / laboratory scale studies tend to overestimate some parameters which in a full scale would be overshadowed.

iv. The research work is limited to water that has undergone pretreatment (coagulation and flocculation). Unlike slow sand filters, it is a recommended best practice that RGSF should always be preceded by pretreatment.

CHAPTER TWO

LITERATURE REVIEW

2.1 Water Filtration

Water demand continuous to increase rapidly all over the World due to improved lifestyle, industrial development and population growth. Increased demand faces a paradox to produce safe drinking water at lower cost. Cost reduction can be achieved by optimization of water treatment costs (Treacy, 2019).

Water treatment technologies have evolved for the past few centuries with an objective to protect the public health from chemicals and pathogens. Sustainability of water treatment systems includes an aspect of the use of locally available material (Ray, 2011).

Water filtration is one of the oldest water treatment stages employed worldwide and ranges from advanced filtration processes in developed countries to the use of multi-layer silk fabric filters in rural areas of developing countries (Steven et al., 2014). Filtration is commonly the last solid-liquid separation stage in the potable water treatment process (Malcolm et al., 2017).

Membrane filtration membrane is currently the most advanced filtration system and consists of; microfiltration, ultrafiltration, nanofiltration and reverse osmosis. It is envisaged that the membrane filtration technology will eventually replace granular filter media filtration due to its superiority of not requiring coagulation, flocculation and sedimentation (Steven et al., 2014).

Slow sand filters remove suspended particles through physical filtration of particles and biological removal of pathogens and organics by use of a biologically active layer of sand known as biofilm. They have the potential to improve the physical, chemical and microbiological quality of raw water in a single treatment without addition of chemicals (Guchi, 2015).

Rapid sand filters require addition of a coagulant to permit removal of smaller particles through the formation of flocs. The primary filtration mechanisms include sedimentation, interception, hydrodynamic diffusion, attraction and repulsion. The contribution of each mechanism in the water filtration process depends on the nature of the water and the chemical treatment (Malcolm et al., 2017).

2.2 Rapid Gravity Sand Filters (RGSF)

2.2.1 Introduction

RGSF are an upgrade of the slow sand filters which are limited by their large land requirements (MWI, 2005). The first RGSF was constructed in 1884 in the USA and since then, RGSF have been constructed in large number all over the world (Sabale et al., 2014).

2.2.2 Filter Media

There is a wide range of filter media in conventional water treatment process. These include sand, anthracite, granular activated carbon (GAC), garnet, pumice, expanded clay particles, glass amongst others. Some of the filter medias are used as a single media or in combination with others in a multimedia filtration system (Malcolm et al., 2017).

Sand has been used traditionally as the filter media because of its wide availability, low cost, and the satisfactory results that it gives in filtration. Sand remains the predominant filter media in developing countries (Al-Rawi, 2017). A filter media is defined by its Effective Size (ES) and Uniformity Coefficient (UC). ES, also known as d_{10}, is the aperture size in millimeters through which 10% by weight of the filter media passes. UC gives the size distribution characteristic and is the ratio of d_{60} to d_{10}.Both ES and UC are determined through the standard sieve analysis (MWI, 2005).

The concept of suitable ES and UC for sand has widely been studied. Davies and Wheatley (2012) reports that for a mono-media RGSF the recommended ES and UC is 0.45 – 0.65 and 1.4 -1.7 respectively. BS EN 12904:2005 recommends an upper limit of 1.5 for the UC. The above recommendation of size specification for sand is a guideline for design of RGSF and if necessary, the designer can adjust based on operational requirements.

During filtration, flocs should be captured within the filter bed otherwise they will appear in the filtered water defeating the purpose of filtration. Minimum depth of filter media should be determined to assist in determining the actual depth of sand to be provided. Malcolm et al., (2017) recommends the use of Hudson Formula (equation 2.1) to determine the minimum depth of a filter bed in RGSF.

$$Q * D^3 * \frac{H}{L} = Bi * 29323 \tag{2.1}$$

Where;

> Q = filtration rate in m3/m2/h, D = sand size in mm, L = depth of sand in meters, H = terminal headloss in meters, Bi = breakthrough index whose value ranges between 0.00004 to 0.006 depending on response to coagulation and degree of pretreatment in the filter influent.

2.2.3 Filtration Rate

RGSF to be used after coagulation and flocculation are designed for filtration rates of 6 - 12 $m^3/h.m^2$. The higher rate is adopted when a combined pretreatment is adopted of a coagulant and a polyelectrolyte (Malcolm et al., 2017). Data collected across utilities in the UK indicates that actual filtration rates are 4 – 12 $m^3/h.m^2$ with most RGSF filtration systems operating at the lower values and rarely at the maximum capacity (Davies and Wheatley, 2012). High filtration rates for single media RGSF could be attractive to water utilities, however, they result to rapid development of headloss which is undesirable (MWI,2005).

Anna and Jiang (2020) indicate that when a RGSF is backwashed and returned into use, at the initial period the quality of effluent is generally not acceptable as the filter media is reconditioned (filter ripening). It is recommended to run effluent to waste during the ripening period or adopt a slow start. This reduces floc breakthrough which could end up in domestic water supply systems. To limit the risk of particulate breakthrough especially for cryptosporidium oocysts and Giardia cysts in raw water, Malcolm et al., (2017) recommends that RGSF be designed for 6 – 7 $m^3/h.m^2$.

2.2.4 Filter Underdrain and Backwash System

Filtered water exits the filtration system through the underdrain system (also known as the collector system). During backwashing of RGSF, the underdrain systems is essential in uniform distribution of air and water aiding in effective and efficient filter bed expansion and cleaning (MWI,2005).

There are different available options for the filter underdrain systems which includes nozzles set in PVC laterals, nozzles set in reinforced concrete false floors, perforated laterals amongst others (Malcolm et al., 2017). Nozzles are required in systems with a combination of air and water cleaning which takes advantage of the collapse pulsing mechanism to dislodge and remove dirt attached to the filter media. Air-water backwashing systems have proved efficient for large systems otherwise for small filtration systems backwash by water only has proved adequate (MWI, 2005).

The local water supply design manual (MWI, 2005) recommends adoption of simple underdrain system comprising of perforated pipes (Figure 2-1). Imported nozzles are to be considered under very exceptional circumstances. This recommendation could be attributed to the lack of capacity of majority of the local water utilities in operation and maintenance of complex underdrain systems. A visit to some of the existing local community water treatment plants indicates that the nozzle underdrain systems is gradually being adopted in Kenya. Financing agencies in water industry have incorporated an aspect of capacity building and knowledge transfer, for the water utilities, which has facilitated the uptake of this technology.

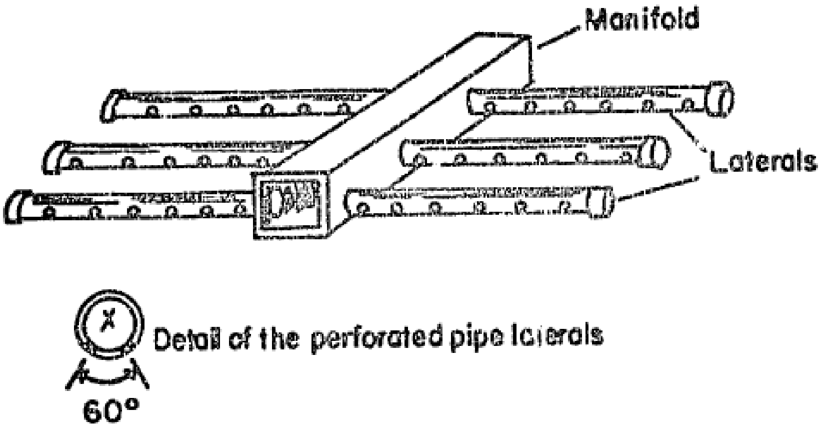

Figure 2.1: Perforated Pipes Underdrain System

Source: (MWI, 2005)

2.2.5 Constant and Declining Rate RGSF

RGSF has two commonly operated mode of operation, constant rate and declining rate (Degremont, 2016). According to Ababu et al., (2019), constant filtration rate is achieved through either of the following means (1) downstream valve control mode, the valve is gradually opened (2) constant filter water level mode, sensors trigger further downstream valve opening in response to headloss development (3) rising filter water level mode, proportional rise in water level in response to headloss increase.

Declining rate RGSF have a reducing filtration rate in response to headloss development and water levels remains constant throughout the filtration cycle (Degremont, 2016). A series of filters share a common inlet channel and no uniform flow split devices are required. According to Ababu et al., (2019), the filtration rates decrease from the maximum (after backwashing) to the minimum (filter has clogged and requires backwashing). When a filter has been cleaned, the initial filtration rate has to be controlled either though a designed orifice or by use of outlet regulating valve. This is required to limit the filtration rates to maximum designed flow rates. Otherwise, rapid development of headloss would be experienced (Malcolm et al., 2017).

Some of the key benefits of declining rate compared to constant rate include; terminal breakthrough is reduced giving better water quality, longer filter runs, not dependent on functioning of costly mechanical devices, headloss and flow rate measurement for each filter is not necessary, simpler to operate and maintain (Ababu et al., 2019).

2.2.6 Backwashing Requirement

Davies and Wheatley (2012) indicate that the primary objective of backwashing a filter is to remove suspended material that has been deposited in the filter bed. Backwashing entails upward flow at a sufficient rate to allow accumulated contaminants to be carried away by wash water to waste and the process takes three to fifteen minutes (Mota, 2014). RGSF are backwashed when any of the following occurs; headloss is too high such that the output is lower than the desired filtration rate, flocs start to breakthrough, the defined maximum number of hours of operation are reached or when troubleshooting operational challenges (Piyali, 2013).

Constant filtration rate filters require backwashing either when the terminal headloss or effluent turbidity values are breached, or after achieving the maximum operation time (24 – 60 hours). It is recommended that the limiting headloss of 1.5 – 2.0 m occur at the same time as the breakthrough to optimize the filtration capacity (Anna and Jiang, 2020).

Backwashing requirement for declining rate filter is majorly a factor of the decline in filtration rate. Based on the designed output range, the designer presets the minimum filtration rate to warrant a backwash ensuring that the net production of the treatment systems is within the acceptable range (Anna and Jiang 2020). Malcolm et al., (2017) recommends that declining rate RGSF be designed for 150% - 50% of the average filtration rate. This implies that when the filtration rate drops below 50%, the filter should be backwashed.

2.2.7 Capping of Rapid Sand Filters

In water filtration, replacement of a thin layer of sand in a RGSF with a coarse material is known as capping and transforms a single media sand filter into a dual media filter

(Tamakhu and Iswar, 2021). Dual-media RGSF possesses several distinct advantages over conventional single media RGSF. These advantages include: (1) higher filtration rates are allowed than those for conventional filters, resulting in a reduction in the total filter area required for a given design rate of flow; (2) more impurities removed from the water are retained in the filter bed, thereby improving filter effluent quality; (3) the length of filter run is increased before the terminal head loss is reached; and (4) by the conversion to dual-media beds, the capacity of existing sand filters can be easily increased at low cost (Sabale et al., 2014; Shirule and Sonwane, 2019; Jusoh et al., 2007). The unique characteristics of dual-media beds are such that they can be incorporated into an existing filtration system without change in plant structure or method of operation (Al-Rawi, 2017).

A typical Dual media filter consists of anthracite coal overlaying silica sand. Anthracite having lower Specific Gravity will ‘float’ on top of the higher specific gravity sand (Al-Rawi, 2017). Some mixing between the two materials inevitably occurs which is managed through proper selection of the uniformity coefficients (UC) and effective size (ES) of the respective media (Malcolm et al., 2017). Despite the many benefits of the dual filter, the integrity and hence performance of the dual filter can be destroyed through improper backwashing for example by initialization of backwashing at a very high rate (Engelhardt, 2010).

Al-Rawi (2017) study compares three capped sand filters against one single media filter through a pilot plant similar to the conventional water treatment process. The capping materials used were granular ninivite rock, granular activated carbon and anthracite coal. The results indicate that capping of a sand filter with granular activated carbon gave the best performance for turbidity removal and bacterial removal. This study demonstrated that there could be other capping materials with equal or better performance than the recommended anthracite coal.

Ansari et al., (2017) using a pilot scale filter a dual and single media filter evaluated the performance of crushed coconut shells as suitable capping material. The study focusses on the length of the filter run, quality of effluent and the backwash water requirement. Results of the study indicate the benefit of capping using coconut shells as follows: increased filter run by 80%, 33% reduction in backwash requirements and higher efficiency in turbidity removal. The study recommends testing of capping of crushed coconut shells in a full-scale plant.

Ahammed and Meera (2010) compared the performance between dual media filter consisting of manganese oxide coated sand (MOCS) and iron hydroxide-coated sand (IOCS) and uncoated sand filter in treating water contaminated by microorganisms, heavy metals and turbidity. Roof-harvested rainwater and canal water were adopted as raw water sources. Results illustrate that the dual media filter was more efficient in removing bacteria and heavy metals compared to IOCS filter, while the uncoated sand filter showed very poor performance.

Delbazi et al., (2011) research focused on the performance of dual media filters (anthracite/LECA) in removing organic materials and turbidity through pilot plants. The removal of organic matter by a single-layer filter (sand), dual media filter (anthracite and sand), dual media filter (LECA and sand) was 7%, 12%, 4/2% respectively. Turbidity removal by the single-layer filter (sand), dual media filter (anthracite and sand) and dual media filter (LECA and sand) was also 69%, 80%, 74% respectively. These results reaffirmed the superiority of anthracite coal.

Jusoh et al., (2007) study assessed the performance of single and dual media filters of sand and burnt oil palm shell (BOPS) at different Effective Sizes of the filter media. Results demonstrated that both filters are capable of producing water with acceptable turbidity unit (<1 NTU). This study reveals that BOPS and sand dual media filter is a better solution in turbidity reduction. With a dual filter, the filter run time is extended and the quality of effluent is within the acceptable limits. The study reaffirmed the benefits of dual filters against single media filters.

Madhukar et al., (2012) study focused on the performance of chitosan – sand dual media filter on a laboratory scale. Chitosan is a fiber obtained from the exoskeleton of insects and shells of crustaceans. Chitosan flakes of depth 20mm were used, above the sand layer of depth 250mm, through which sample water was passed at flow rates of 100mL/min. Dual filter media was effective in reducing turbidity by 93%, nitrate by 85 % and total Coliform by 100%. It was found that there was no significant reduction in total solids (45%), total dissolved solids (3%), total hardness (27%), permanent hardness (31%) and fluoride (25%). pH remained unchanged.

Sanyaolu (2010) compared the performances of a charcoal dual media filter and a conventional rapid sand filter. Media characteristics analyzed include appearance, size, relative gravity, acid solubility and physical stability. The dual media filter exhibited a turbidity removal capacity of 1.4 times that of the conventional rapid sand filter. Gradients obtained from plots of head loss against time for the RGSF and dual media filter were 0.2 and 0.5 respectively indicating a higher rate of head loss development in the RGSF compared to the dual media filter.

2.3 Slates

2.3.1 Introduction

Slate is a fine-grained, repetitive layered, homogeneous metamorphic rock derived from an original shale-type sedimentary rock composed of clay or volcanic ash. Slate is formed by low grade metamorphism that gives a slaty cleavage or schistosities. They form in giant veins which run dimensionally through the ground. The presence of discontinuities such as bedding planes and schistosities plays an important role on the deformation behavior of Slate (Lee et al., 2018).

Slate is one of the most durable stone and its use originated from Egypt and Greece in the ancient civilizations. Slate has been used for roofing, tiling and cladding representing a typical example of the use of local and traditional raw materials in vernacular architecture (Sitzia et al., 2023).

2.3.2 Characterisation of Slates

Slate is generally light weight and come in many colors including black, blue, purple, red, green or gray. Dark Slate owe its color to carbonaceous materials or to finely divided iron sulfide whereas reddish and purple varieties owe their color to the presence of iron oxide. Predominant chlorite in slates will be evidenced by green color (Lee et al., 2018).

Some slates are prone to deterioration particularly due to sand intercalation, microfractures and high presence of carbonates. The origin of slate determines its physical, mechanical and aesthetic properties (Sitzia et al., 2023). Lee et al., (2018) reports that the orientation of schistosities is the critical aspect in the deformation of slate. Water absorption in slate is below 0.8% and almost virtually nonexistent due to the fine grain and low development of pore system. This makes slate not to be affected by freeze-thaw cycles (Cardenes and Garcia, 2023).

Sitzia et al., (2023) reports that some slates could originate from natural geological materials enriched with potentially toxic elements. The distribution of heavy metals in the earth's crust is predominantly because of bedrock geochemistry and anthropogenic inputs. Black Slates from Okchon, Korea were reported to have high proportions of Cu, Pb and Zn as residue fractions and Cd as non-residual fraction (Sitzia et al., 2023).

Slate from Valongo region of Portugal, which have an age of 350 million years, are noted to have physical-mechanical characteristics similar to slates from European origin. Semi-quantitave analysis by X-ray diffraction (XRD) patterns highlighted the peaks corresponding to the mineralogy composition; muscovite - 22.3%, clinochlore - 9.6%, quartz - 62%, K-feldspar - 5.1% and kaolinite - 1% (Sitzia et al., 2023).

2.3.2 Local Availability of Slates

Slate is found in large quantities in the Maji ya Jumvi formation in the Coastal region in Kenya. Maji ya Chumvi beds overlie the Taru grits with a slight disconformity. They are characterized by thinly bedded shales in silty sandstones or fine sandstones so that they easily split into slates or slabs along the shale partings. In Kenya, slate quarries are found in Galana, Mazeras, Mariakani, Maji Ya Chumvi, Lunga Lunga and Shimba Hills. Maji-ya-Chumvi beds which yield slate continue to accumulate slowly in semi-arid climate (Caswell and Baker, 2007).

A visit to Maji ya Chumvi slates quarries indicated that the local community quarry slate for sale using very basic tools. This could be attributed to the availability of slate at relatively shallow depths. At the quarry sites, the vendors retail slate at USD 0.25 per meter square. Photographs taken at Maji ya Chumvi quarries are given in Plate 2.1.

Plate 2.1: Maji ya Chumvi Slate Quarries

2.3.3 Heat Expansion of Slates

In response to fire, slate is known to be unique compared to other types of rocks. They are dense (2-7 – 2.8g/cm^3) with very low porosity and water absorption and do not portray thermal gradient during heating. It is common knowledge that slate is nonflammable (Cardenes and Garcia, 2023).

At temperatures above 900^{o}C, the primary minerals forming slate start to undergo thermal evolution resulting in loss in weight. When temperatures exceed the point of incipient fusion, gas - liquid forms resulting in entrapped gasses during cooling, a phenomenon commonly known as bloating. The gases causing expansion comes from the thermally instable materials such as F and Cl from clay (Chen et al., 2012). Donna (2001) reports that Pyrite mineral which is common in slate of diverse origins also contributes significantly to heat expansion of Slate.

2.3.4 Slates in Water Filtration

According to the BS and AWWA standards, crushed slate is not an approved filter media material. The approved filter media listed by AWWA includes silica sand, granular activated carbon, anthracite coal and gravel. Assessment of suitability of other locally available materials remains an area of interest to many researchers all over the world in the water supply industry.

Davies and Wheatley (2012) assessed the suitability of broken slate as a replacement of sand in single filter media with more focus on the particle shape (sphericity). Broken slate was compared with filtralite, recycled glass, limestone and sand. Broken slate was expected to perform poorly which is attributed to low sphericity (0.49) against a minimum limit of 0.6. Slate indicated excellent performance and very close to sand in turbidity removal. This was beyond what the sphericity alone would suggest and could be due to the low surface area and surface roughness.

2.3.5 Potential of Capping Sand Filters Using Slates

Malcolm et al., (2017) reports that low specific gravity in comparison to sand is a key attribute that has made anthracite coal perform exceedingly well in solving the problem of stratification of Rapid Sand Filters. Low specific gravity allows selection of a coarse size of the capping material which intermixes with the small sand grains at the top of the filter media preventing the formation of semi porous sand layer. During upward fluidization of the filter media when backwashing, the low specific gravity allows the capping material to retain its relative position (Tamakhu and Iswar, 2021).

Chen et al., (2012), Donna (2001), Cardenes and Garcia (2023) amongst others, have reported that slate of diverse origin have thermally unstable elements that allow exfoliation during heating resulting to expanded slate that have specific gravities of 1.2 – 1.7. This makes slate a potential candidate for consideration as a capping material for Rapid Sand Filters.

2.4 Cost Benefit Analysis

In design of water supply systems where two or more solutions are available to meet the same objective, it is critical that a cost analysis is performed by discounting each option to the present to obtain the total present value cost. The present value includes both Capital and Operational Expenditure (Capex and Opex) which when summed up give the Total Expenditure (Malcolm et al., 2017).

The capital expenditure and works renewal costs, including the operational costs for each year are estimated and discounted to give their equivalent present value cost (equation 2.2) and then summed up for the economic lifetime of the infrastructure. Inflation should be considered when computing the amount payable for the future year before discounting. Alternatively, the discount rate can include inflation (Malcolm et al., 2017). Inflation measures how expensive items have become over a defined duration. It erodes the value of money over time. In April 2022, the Central Bank of Kenya reported an annual average inflation rate of 7.5%.

$$\text{Present Value Cost} = \frac{R_t}{(1+i)^t} \tag{2.2}$$

Where;

R_t: amount to be paid in 't' years
i: discount rate
t: time / duration

Discount rate is the cost of capital incurred when raising funds from various sources such as debt, equity or other financing options. It is affected by interest rates, inflation, market conditions and government policies (Ochoki et al., 2023). Ghanbariamin (2015) study reports that the local prevailing discount rate for infrastructural development projects range between 10% and 14.5%. The study recommends adoption of 12% discount rate when computing the net present value for projects in Kenya.

The duration when an infrastructure remains useful to a proponent is known as the economic lifetime. MWI, 2005 recommends that water treatment plants should be designed for an economic lifetime of 30 years. Beyond the 30 years, major overhaul will be required triggering a substantial amount of capital investment.

2.5 Conceptual Framework

The conceptual framework for this study is summarized in **Figure 2-2** below.

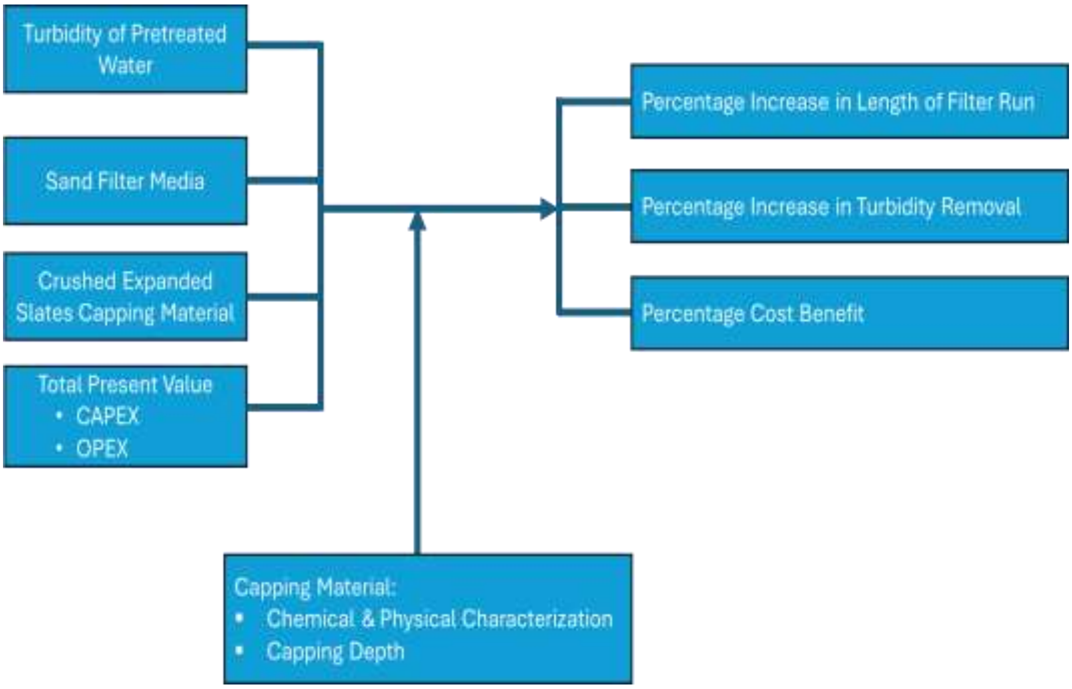

Figure 2.2: Conceptual Framework

2.6 Research Gap

Tamakhu and Iswar (2021) study focuses on the effect of capping of sand filters by anthracite coal in a pilot scale with varying influent turbidities which includes 0-25, 25-50, 50-100, 100-150, 150-200, 200-250 and 250-300 NTU. The influent turbidity 0-100NTU for both capped and uncapped produced effluent turbidity below 5 NTU. Above 100NTU, the effluent standard for both capped and uncapped exceeded the maximum threshold of 5NTU. The filter run time for anthracite capped filter was in average 52.03% more than that of sand filter. Most developing countries abstract water from river intakes that has high turbidity levels above 100NTU (Malcolm et al., 2017). Anthracite coal evaluated by Tamakhu and Iswar (2021) did not demonstrate any benefit in improving the efficiency of RGSF for high influent turbidity above 100NTU. Despite the results of the study demonstrating an increased length of the filter run, the cost benefit of introducing anthracite coal to a conventional RGSF has not been quantified. Anthracite coal is locally available in Mosul/Iraq but scarce and expensive in Kenya.

Farjana et al., (2018) assessed the performance of crushed coconut shell in improving the performance of the RGSF. The study focused on pH, Turbidity, BOD and TS. The raw water was sourced from a lake and stored in a container for detention period of 3-4 hours giving a constant influent turbidity of 22NTU to the filter unit. The study concludes that crushed coconut shells that are locally available in most developing countries gives good efficiency in reduction of turbidity, TS, pH and BOD. The study has omitted the aspect of seasonal variation in influent raw water characteristics by keeping a constant influent turbidity (22NTU). Further, the study has not quantified the cost benefit of introducing crushed coconut shells to the conventional RGSF.

Sabale et al., (2014) focuses on a capping by use of PVC granules that are cheaper and readily available in India. The study maintains a constant influent turbidity of 25 NTU and varies the filtration rate between 5.4m/hr and 7.2 m/hr. The key performance indicators are turbidity removal, head loss development, filter run length. The study concludes that capping with PVC granules demonstrated an improved efficiency in turbidity removal (up to 96%), increased filter run length (up to 2.5 times) and reduced backwash water requirement (up to 60%). Similar to the Farjana et al., (2018) study, Sabale et al., (2014) has omitted the aspect of seasonal variation in influent raw water characteristics by keeping a constant influent turbidity level at 25NTU. PVC granules are by products of crude oil and are manufactured in specialized plants and sold to other companies for use in making plastic products. Despite their good performance improving the performance of sand filters, PVC granules are not locally available.

The current study focusses on assessing the suitability of locally available slate in improving the turbidity removal and increasing the length of filter run of RGSF under varying seasonal influent turbidities. The cost benefit of using crushed expanded slate for improving the performance of rapid sand filters has been quantified.

CHAPTER THREE

METHODOLOGY

3.1 Introduction

This chapter describes the procedures adopted for the evaluation of the suitability of crushed slates as a capping material for improving the performance of RGSF. Key physical and chemical characteristics of the crushed slates that influence its performance were determined through a series of standardized laboratory tests. This was then followed by designing, fabricating and running a pilot scale model filtration unit to compare the performance of crushed expanded slates capped RGSF against a convention single media RGSF. Photographs taken in the course of the research works are given at **Appendix 1.0**.

3.2 Chemical and Physical Characterisation

3.2.1 Filter Media Sourcing and Preparation

In this study, crushed expanded slates were assessed as a capping material with sand as the primary filter media and coarse aggregates as the supporting bed. Slates were procured from Maji ya Chumvi, Coast Region - Kenya and transported in bags to the JKUAT Materials Laboratory for processing. This involved manually crushing with a hammer to smaller sizes and subsequent sieve analysis to achieve the required size of 0.3-5.0 mm. Thereafter, the crushed slates were washed to remove dust and subjected to continuous heating (expansion) in a kiln to temperatures between 1200 – 1350^{o}C at the Ministry of Mining and Geology laboratories.

A sand filter media was procured from a Kamp General Engineering Materials Ltd who are locally re-known filter media supplier for the local water companies. The origin of the sand was from rivers within Machakos County. Davies and Wheatley (2012) reports that for a mono-media RGSF the recommended Effective Size (ES) and Uniformity Coefficient (UC) is 0.45 – 0.65 and 1.4 -1.7 respectively. BS EN 12904:2005 recommends an upper limit of 1.5 for the UC. The procured sand had an

ES of 0.6 and UC of 1.5 which lies within the recommended range and was therefore considered acceptable for use as a primary filter media.

Graded coarse aggregates were sourced from Kilimambogo quarries in the following two particle sizes: 2-5mm and 5-12mm. The purpose of the coarse aggregates was to support the sand filter media and provide an interface between the filter media and the perforated pipes underdrain system.

3.2.2 Chemical and Physical Characterization

Acid solubility test, also known as acid loss test, was carried out for crushed expanded slates, sand and coarse aggregates. The test procedure entailed immersion of three 50g samples of each material in Hydrochloric (HCL) acid for 24 hours and determination of the mass loss. This is a standard procedure given in BS EN 12902-2004 (Products used for treatment of water intended for human consumption – Methods of test). The test was carried out at JKUAT Materials Laboratory.

Water extractable substances test was carried out for three samples of crushed expanded slates. The procedure entails immersing the samples in extraction water for 30 minutes and analyzing the leachate for the presence of Cadmium, Chromium, Lead, Mercury, Nickel and Cyanide. This is a standard procedure given in BS EN 12902-2004 (Products used for treatment of water intended for human consumption – Methods of test). Extraction water including the leachate was carried out in JKUAT chemistry laboratory with the tests on the presence of Cadmium, Chromium, Lead, Mercury, Nickel and Cyanide carried out at the Ministry of Public Works, Nairobi.

Silica content test was carried out for three samples of crushed expanded slates. An XRF (X-ray fluorescence) method was adopted which a standard procedure is provided under ASTM D5381-93 (2021) – Standard guide for X-ray Florescence Spectroscopy of Pigments and Extenders. XRF gives elemental composition of materials in a given substrate. Crushed expanded slates were ground into a powder and subjected to XRF spectroscopy at the Ministry of Mining and Geology Laboratories, Nairobi. A printout was obtained from the spectrometer giving the element composition of crushed slates.

Specific gravity for crushed slates (expanded and unexpanded) and sand was determined through standard procedures given in BS 812-2:1995 – Testing Aggregates. For aggregates larger than 10mm, a wire basket method was adopted whereas for aggregate sizes below 10mm a pycnometer method was used. The tests were carried out at JKUAT Materials laboratory.

Friability test, also known as attrition test, was carried for a sample of coarse aggregates and crushed expanded slates. The test method adopted was Los Angeles Abrasion Test (LAA) supplemented by Aggregate Crushing Value (ACV) both in accordance with the standard method given in ASTM C131 / C131M – 20. The tests were carried out at the Ministry of Public Works laboratories.

3.3 Evaluation of the Length of Filter Run and Turbidity Removal

3.3.1 Materials Preparation

The sand filter media was delivered in 25Kg bags and thoroughly washed and dried. This was to remove fines which would clog the air spaces, and free dirt, silt and all other foreign materials. The clean filter media was stored in clean polythene bags to ensure no contamination. Similarly, the coarse aggregate samples were washed and dried.

Based on the determined specific gravity of crushed expanded slates (1.68), the Effective Size was determined through Stoke’s Law to ensure that crushed expanded slates particles and small grains of sand had equivalent settling velocity. The calculated and adopted ES and EC for crushed expanded slates was 1.2 and 1.5 respectively. Through particle size distribution, a 15Kg sample of crushed expanded slate was prepared at JKUAT materials laboratory.

A sample of crushed expanded slate is illustrated in Plate 3.1.

Plate 3.1: Crushed Expanded Slates

3.3.3 Model Filter Design

The primary purpose of the model filtration unit was to evaluate the effectiveness of crushed expanded slates as a capping material for conventional RGSF. The assessment was to be done for two key performance aspects: turbidity removal and length of filter run.

A model declining rate Rapid Gravity Sand Filtration (RGSF) unit was designed for an average filtration rate of 6m^3/m^2/hr. The adopted filtration rate was in-line with the recommendations of Malcolm et al., (2017) which indicates that design of RGSF should be between 6 -7 m^3/h.m^2 with the lower limit being preferred to limit the risk of particulate breakthrough especially for cryptosporidium oocysts and Giardia cysts.

The model filtration unit consisted of the following components: inlet pipe with a sampling point (1” diameter hosepipe and PPR pipe), 4” uPVC inlet channel, 3mm thick acrylic rectangular filter unit (0.3m x 0.3m x 1m high) strengthened by mild steel angle sections, perforated pipe underdrain outlet and an 1 ½ ” overflow uPVC pipe. The backwash system comprised of a ½ ” hosepipe tapped from an existing pressurized 6” HDPE treated water main connected to the filter underdrain system with multiple regulating valves. Three similar model filtration units were fabricated to ensure the three scenarios under consideration were compared under the same influent turbidity conditions.

The primary filter media was sand supported by a gravel bed with a perforated pipe underdrain system. A perforated pipe underdrain system was adopted due its simplicity in design, operation and maintenance. The local water supply design manual recommends the use of perforated pipes under drain system with very exceptional cases where the nozzle system can be considered (MWI, 2005).

Through Hudson Formular (equation 2.1), the minimum depth of sand to limit floc breakthrough was determined as 250mm. Actual depth of sand provided in the model filtration unit was 300mm.

By calculation, the minimum required depth of the capping material for the model filtration unit was 33mm. However, the desired conventional metric systems recommend measurements in multiples of 25mm (equivalent to 1 inch in the imperial units). Therefore, this study included an assessment to evaluate if adoption of either the lower (25mm) or the upper (50mm) limit for the depth of the crushed expanded slates capping material would have significant impact to the filter performance. The hydraulic design of the model filtration unit including the determination of minimum depth of sand and slates is given in **Appendix II.**

The end of a filtration cycle is marked by the need for backwashing. Considering the model filtration unit was designed as a declining rate filter with an average filtration rate of $6m^3/m^2/hr$ (equivalent to 0.15 litres / sec), the filtration unit required backwashing when the filtration rate reduced below 50% (0.08 litres / sec). The backwash requirement for declining rate filters is discussed in Section 2.3.5. The designed model filtration unit is illustrated in **Figure 3.1**.

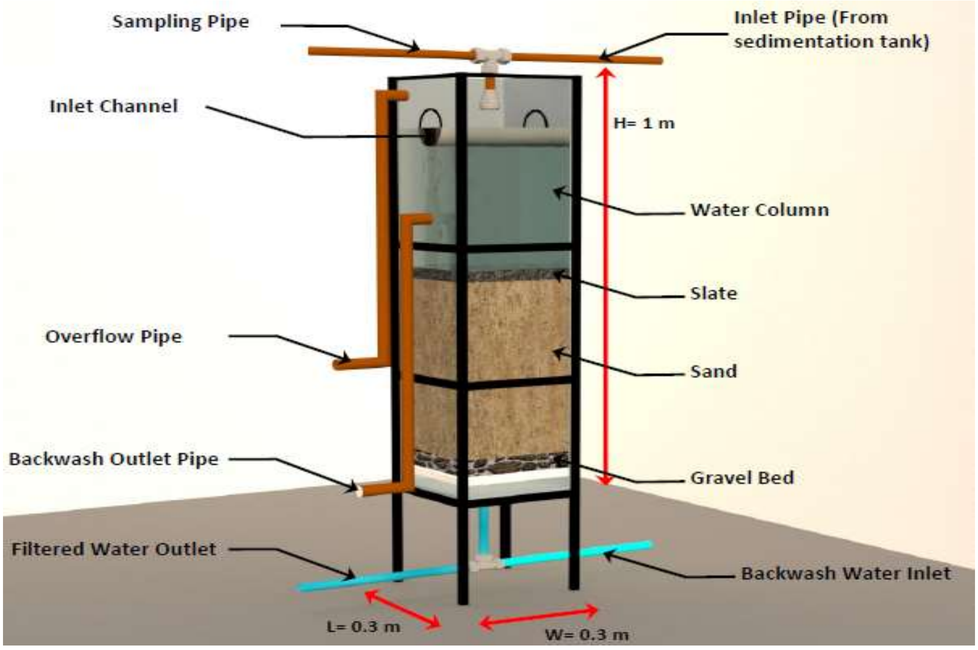

Figure 3.1: Model Filtration Unit (Designed)

3.3.4 Experimental Set-Up

The three model filtration units were set up within the premises of an existing conventional community water treatment plant operated by Ruiru - Juja Water and Sewerage Company (RUJWASCO). The water treatment plant abstracts raw water from Ruiru river which, similar to any other surface water sources, experiences shock turbidity loads during wet seasons.

In this existing conventional water treatment plant, raw water is dosed with Alum to aid in the coagulation and flocculation processes then followed by rapid sand filtration. To ensure the model filtration units mimics as close as possible the actual operating conditions for conventional RGSF, the raw water for the model filtration unit was abstracted through siphoning from the point of entry in to the existing conventional RGSF.

Influent to the filter should never cause disturbance to the filter media, to ensure this requirement is met, an outlet hose pipe was adopted which was positioned at a level which maintains at least 150mm water column above the filter media. Maintaining a water column above the filter media was also useful in preventing drying up and cracking of the filter media which can easily results to floc breakthrough.

The model filtration units went through trial testing for ten days where any design and operational shortcomings were identified and addressed. The model greatly benefited from the transition between the wet season to the dry season reflecting considerable variations in influent turbidities.

Influent turbidity is a key factor in evaluation of the performance of any filter. Ideally, there are two approaches to the influent turbidity; water of a known turbidity can be prepared by adding mud slurry to natural water and then continuously stir throughout the filtration cycle. Alternatively, a model filtration unit can be fed from an existing surface water source whose turbidity varies on hourly and daily basis depending on the precipitation within the catchment. In this option, the varying influent turbidity is then grouped in the turbidity bands during the data processing and analysis. The second option was adopted in this study.

In normal practice, the influent turbidities for conventional filtration systems are expected to vary since this is not within the control of the water service providers. To consider the effect of the varying influent turbidities, in the processing of this data, influent turbidity was analyzed in ranges of 0-50 NTU, 50-150 NTU and 150-300 NTU. The categorization of the turbidity bands was guided by existing literature that has illustrated a significant change from one upper limit to the next with marginal variations within a given turbidity band (Malcolm et al., 2017 and Tamakhu and Iswar, 2021).

As illustrated in Plate 4.1, the three model filtration units representing uncapped, 25mm and 50mm capping with slates, were operated simultaneously under the same varying influent turbidities. The actual model set up within the water treatment plant is illustrated in Plate 4.1. Additional photographs taken during the research work are given at **Appendix VI.**

Plate 3.2: Actual Model Filtration Unit Set Up, Ruiru

3.3.5 Data Sampling and Collection

The model filtration units were continuously run from 0900 hours to 1600 hours and the influent turbidity, effluent turbidity and filtration rate were measured. Influent turbidity measurement was done at the point of feeding into the model filtration unit after the raw water had undergone coagulation and flocculation within the existing Ruiru water treatment plant. Backwashing was done every morning before commencing a new filtration cycle. Adequacy of the backwashing was judged by observing the clarity of the backwash effluent.

The filtration units were designed and operated as a declining rate RGSF with the throughput at the start adjusted to ensure the model operated within the designed filtration rate, otherwise rapid development of headloss would be experienced. A stopwatch and a calibrated one litre glass jar were used to determine the flow rate at one-hour intervals. A calibrated turbidimeter (HACH 2100Q Model - USA), with an accuracy of ± 2 % of reading plus stray light, was used to measure the influent and effluent turbidities similarly at one-hour interval.

During the operation of the model filtration units, data for the decreasing filtration rate and effluent turbidities were collected on hourly intervals under varying influent turbidities for the three scenarios. The length of the filter run for the model filtration unit was determined as the duration of the filtration cycle from the start (0900 hours) to when the filtration rate declined to the set minimum limit (0.08 litres / sec) to trigger backwashing. Efficiency in turbidity removal was determined using equation 3.1. Preliminary analysis of the data collected for the filtration rate and effluent turbidities is given in **Appendices III** and **IV** respectively.

$$Turbidity\ Removal = \frac{influent}{effluent} turbidty * 100\% \tag{3.1}$$

3.3.6 Statistical Data Analysis

The significance of capping a RGSF with crushed expanded slates was evaluated using a one-tailed t-test with a significance level of 5% and the results verified using single factor ANOVA. Detailed statistical analysis is presented in **Appendix 6.0**. Statistical data processing and analysis was carried out using the add-in data analysis tool in Microsoft Excel.

3.4 Cost Benefit Analysis

A cost benefit analysis was carried out to assess the financial viability of the proposed capping of RGSF with crushed expanded slates. This analysis has been done on a model filtration unit scale through discounting and comparing the total present value cost for uncapped and capped RGSF (see details in Section 2.4).

Capital expenditures (CAPEX) considered cover the cost of fabricating the model filtration unit and cost for the filter medias (sand, crushed expanded slates and coarse aggregates). To enhance the accuracy of the cost analysis, the actual incurred CAPEX costs were compared with the prevailing market prices and where necessary adjustments were made.

Operational expenditure (OPEX) primarily entailed the energy costs incurred as a result of backwashing of the model filtration units. Energy demand for backwashing was calculated using the equation 3.2 given below:

$$E = (Q * H)/e \tag{3.2}$$

Where: E = energy demand in kWh per year, Q = pumped quantity of water per day (m^3/d), H = pumping head in meters, e = pumping efficiency

The overall backwashing energy costs have been estimated based on the frequency of backwashing, energy demand and the prevailing unit cost for power of Kshs. 26 / kWh as provided in the Kenya Power and Lighting Company (KPLC) power tariffs under the commercial power consumption category. An average rate of inflation of 7.5% has been adopted as published by Central Bank of Kenya for the month of April 2022. The discounted cost analysis was based on a useful economic life of 30 years for the filters after which a complete overhaul would be required. A discount factor (cost of capital) of 12% was adopted as recommended by Ghanbariamin, 2015. Detailed cost analysis for the model filtration units is presented in **Appendix V**.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

This Section contains results obtained from the laboratory tests and experiments conducted with the data collected presented in the form of tables and graphs wherever possible. The values of key parameters have been analyzed, inferential statistical analysis carried out and discussions offered where applicable.

4.2 Chemical and Physical Characterization

4.2.1 Acid Solubility / Loss

Acid solubility test was carried out for sand and crushed expanded slate. After the 24-hour contact time with Hydrochloric Acid (HCL), Sand remained intact with zero loss in weight whereas crushed expanded Slates experienced 0.003% weight loss. The acceptable acid loss for aluminosilicate and sand, which are approved filter media materials, are given in Table 4-1.

Table 4.1: Maximum Limits for Acid Loss

Published Standard	Aluminosilicate	Sand
ANSI/AWWA B100-01)	**5%**	**5%**
BS EN 12905-2012	**7%**	**2%**

Acid loss is an important aspect for filter media materials and determines the presence of acid-soluble minerals or other impurities that may be present in the filter material. The maximum published limits of acid loss (Table 4-1) ensures that there is no substantial loss of the filter media in acidic waters or during an acid cleaning (AWWA, 2001).

The limits for acid loss for filter medias are published in ANSI/AWWA B100-01 and BS EN Standards. BS EN 12905-2012 is the most stringent standard giving a maximum acid loss of 2%. Crushed expanded Slates from Maji ya Chumvi have an acid loss of 0.003% which is with the set maximum limit of 2%.

Ahammed and Meera (2010) reports that acid loss of any filter media material is primarily dependent on the particle size, silica composition and dust content. A material with higher silica composition and less dust content exhibit minimal or negligible acid loss. All the crushed slate and sand samples in the current study were thoroughly washed and oven dried prior to testing for acid loss, therefore the results were not affected by dust content.

Slate from New York were reported to have an acid loss of 2.58% (Davies and Wheatley, 2012) which is higher that the acid loss for crushed slates from Maji ya Chumvi in the current study. Sitzia et al., 2023 study notes that origin of slate determines its physical and mechanical properties.

Additionally, expanded slates are known to be chemically inert (Chen et al., 2012). During heating there is change in physical characteristics which gives low particle density due to the change in the internal cellular pore system. Incipient fusion occurs releasing gases within the pyroclastic mass, causing expansion that is retained upon cooling. The particles are fused together enabling slates to resist acid attack more effectively than other natural materials. The amorphous nature of the material, where all elements are tightly bound, is not easily accessed for any substantial acid loss (Chen et al., 2012).

4.2.2 Water Extractable Substances

Water extractable substances test evaluates the probability of a filter media to release any harmful compounds to the filtered water which can be harmful to public health. The results of the water extractable substances for crushed expanded slates against the limits set in BS EN 12903:2009 are provided in Table 4-2.

Table 4.2: Results of Water Extractable Substances

Element	Slates (%)	% Limits (Max.)
Cadmium	Nil	0.0005
Chromium	1.81×10^{-5}	0.005
Lead	Nil	0.001
Mercury	6.0×10^{-5}	0.0001
Nickel	Nil	0.002
Cyanide	Nil	0.005

In human beings, Cadmium and Nickel damages kidneys, liver, skeletal system and cardiovascular system. Chromium causes painless skin ulcers and dermatitis. Lead and Mercury affects the brain and central nervous system and may result to coma, convulsions or death. Cyanide damages the heart, nervous and respiratory systems in human beings (Jamal et al., 2013).

Based on the results presented in Table 4-2, most of the hazardous heavy metals are completely absent in slates sourced from Maji ya Chumvi. Traces of Chromium and Mercury were identified but at negligible quantities which are below the acceptable maximum limits in BS EN 12903:2009.

Sitzia et al., (2023) notes that some slates could originate from natural geological materials enriched with potentially toxic elements. Water extractable substances results in the current study confirms that the Maji ya Chumvi slates formation is not toxic.

4.2.3 Silica Content

The silica content of crushed slate from Maji ya Chumvi and sand was 80.4% and 91.3% respectively. BS EN 12904 has set the minimum silica content for sand to be used for filter media as 80%. Expanded Aluminosilicate has lower silica content requirement of 55-75% (BS EN 120905).

Silica (also known as Quartz) is one of the hardest naturally known existing natural material with a value of seven on Morhs scale of mineral hardness. This explains the wide usage of silica sand in blasting of metal surfaces. Silica is chemically sound and thus does not degrade when exposed to acidic solutions such as those used in water treatment. A high content of Silica implies lesser fractions of other impurities in the filter material (Platias et al., 2014).

Sitzia et al., (2023) study reports a silica content of 62% for crushed slate from Valongo (Portugal) which is substantial low compared to 80.4% of slate sourced from maji ya Chumvi. This confirms the wide variability of chemical and physical characteristics of slates based on their origins. Based on the Silica content limits published in BS EN 12904 and BS EN 120905, crushed expanded Slates from Maji ya Chumvi meet the minimum Silica Content for use as a filter media in a water filtration.

4.2.4 Specific Gravity

The specific gravity of sand, crushed slate and crushed expanded slate was 2.55, 2.20 and 1.68 respectively. In dual media filters, specific gravity of the various filter medias is a key aspect in ensuring that each material retain its relative position during upward fluidization during filter backwashing (Tamakhu and Iswar, 2021). Davies and Wheatley (2012) reported a specific gravity of 1.5 for crushed expanded slate sourced from New York.

In geology, the density of rocks is primarily dependent on its mineral composition. Majority of the minerals that form the rocks have densities ranging from 2600 Kg/ m^3 to 3000Kg/m^3. Some rocks have thermally instable minerals such as pyrite, which when heated beyond the point of incipient fusion which undergo bloating resulting to lower specific gravity and lightweight aggregates (Chen et al., 2012). Donna (2001) indicates that slate is in this category of rocks that undergoes bloating hence the decrease of specific gravity from 2.20 to 1.68. The recommended specific gravity for capping materials is between 1.4 to 1.95 (AWWA, 2001), therefore crushed expanded slate with specific gravity of 1.68 meet this requirement.

4.2.5 Friability

Crushed expanded slate gave a Los Angeles Abrasion (LAA) value of 27.2% and an Aggregate Crushing Value (ACV) of 21.6%. LAA and ACV gives an indication of the mechanical strength of the aggregates to resist substantial physical breakdown (attrition). During backwashing of the Rapid Sand Filter, a combination of air and water scouring is used through an aggressive phenomenon commonly known as collapse pulsing mechanism. It is probable that a filter media can undergo physical breakdown and is continuous lost as fines (Malcolm et al., 2017).

BS EN 12905 and ANSI/AWWA B100-01 acknowledges the absence of a standard method for determining the mechanical resistance of filter media. BS EN 12905 proposes the use of one similar test, any that exists for testing abrasive resistance, for the comparison of different filter media under investigation but does not give the criteria for acceptance or rejection.

The Geological Society, London (GSL) has provided indicative acceptance criteria for filter media which is based on LAA (<40%) and ACV (<30%). Bitumen roads which are subjected to high abrasion from traffic loads in their service life have a limiting LAA value of 40% -50%. A filter media experiences attrition only during backwashing and is not expected to be as severe abrasion conditions as that of a bitumen road.

A comparison of attrition levels of crushed expanded slate against pumice was conducted through extended backwashing for 50 hours which is equivalent to 2 years of normal operation (Davies and Wheatley, 2012). Results indicate that crushed expanded slate from New York had an average loss of 8% compared to pumice which had an average loss of 27%.

The results in the current study supported by Davies and Wheatley (2012) indicate that crushed expanded slate has good resistance to attrition. However, considering the shape of the crushed slate, irregular plate like, substantially attrition is expected at the initial period which rapidly reduces once all the sharp corners and edges are worn away. Davies and Wheatley (2012) indicate that the method of rotating drum with steel balls tends to exaggerate the level of attrition which can never be experienced in the life span of a filtration unit.

4.3 Evaluation of Filter Run Length and Turbidity Removal

4.3.1 Length of Filter Run

The length of a filter run is the maximum number of hours of operation of a filtration unit to warrant backwashing (Piyali, 2013). As discussed in Section 2.2.6, the fabricated model filtration unit used in the current study requires backwashing when the rate of filtration reduces below 0.08ltrs/s. The collected raw data for the declining filtration rate for the model filtration has been analyzed and the results for the 0-50NTU, 50-150NTU and 150-300NTU influent turbidity bands are presented graphically in Figures 4.1, 4.2 and 4.3.

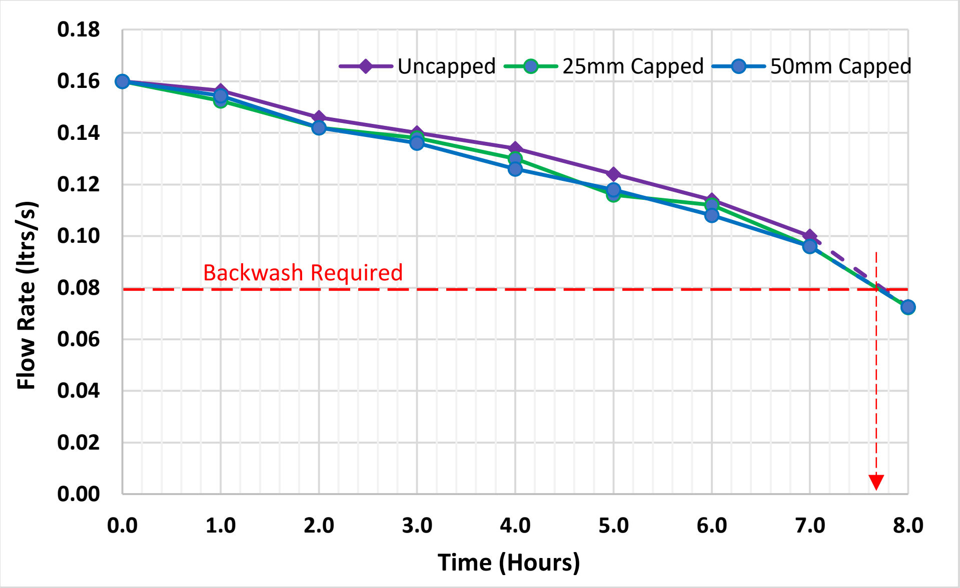

Figure 4.1: Results of Filter Run Length (0 – 50NTU)

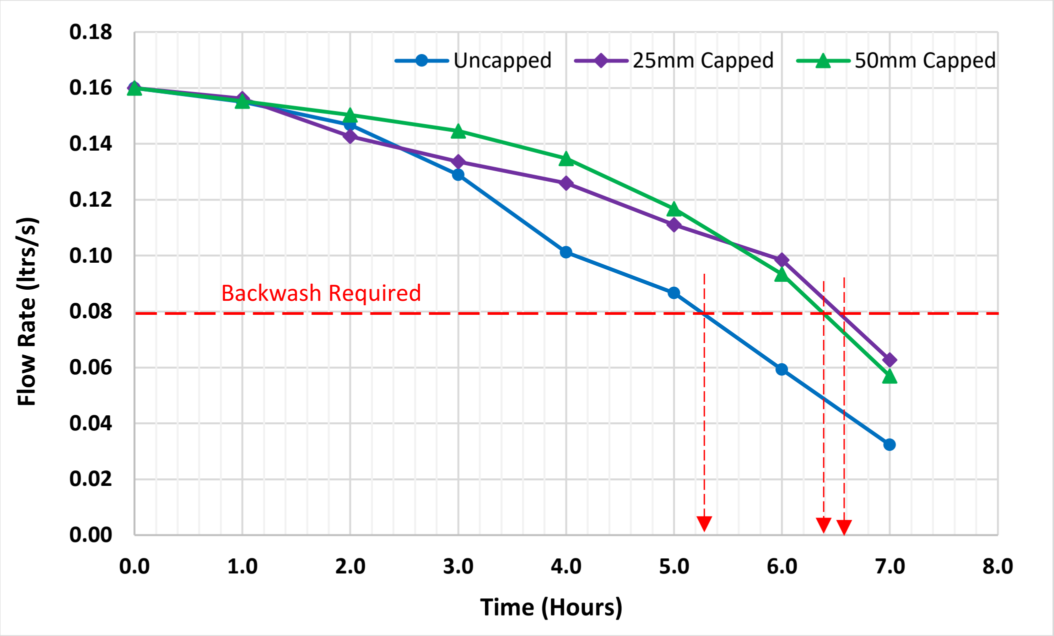

Figure 4.2: Results of Filter Run Length (50 – 150NTU)

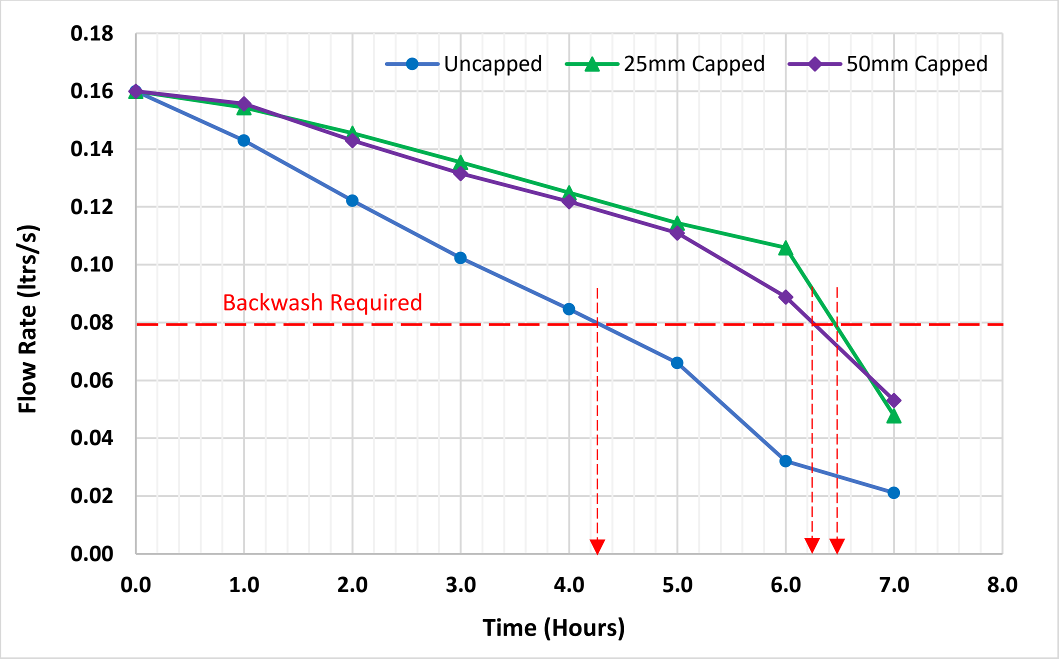

Figure 4.3: Results of Filter Run Length (150 – 300NTU)

In a conventional RGSF, raw water percolates and gets filtered leaving suspended flocs within the voidage of the filter media. As the voidage within the filter media reduces the headloss increases and the rate of filtration decreases. This is evident in Figures 4-

1 to 4-3 where under all scenarios the filtration rate starts at 0.16 ltrs/s and continuously declines to the backwash trigger point of 0.08 ltrs/s.

High influent turbidity accelerates headloss development due to rapid deposition of flocs and sludge depleting the voidage much earlier compared to low influent turbidities (Jusoh et al., 2007). This phenomenon is illustrated in Figure 4-1 (0-50NTU) where the uncapped filtration unit required backwashing after 7.7 hours compared to 4.2 hours in Figure 4-3 (150-300NTU).

At low influent turbidity of 0-50NTU (Figure 4-1), the introduction of crushed expanded slate did not demonstrate any increase in the length of the filter run. All the three scenarios (uncapped,25mm and 50mm capped) gave the same length of the filter run of approximately 7.7 hours. One tailed t-test statistical analysis confirmed that the variance in the length of the filter run for the three scenarios (uncapped, 25mm and 50mm capped) was statistically insignificant.

In the medium influent turbidity band of 50-150NTU (Figure 4-2), introduction of crushed expanded slate increased the length of the filter run with 24% and 27% for the 25mm and 50mm capping respectively. One tailed t-test statistical analysis confirmed that the increased length of filter run for both 25mm and 50mm capping was statistically significant. However, the variance between 25mm and 50mm capping was statistically insignificant.

In the high influent turbidity band of 150-300NTU (Figure 4-3), introduction of crushed expanded slate increased the length of the filter run with 55% and 48% for the 25mm and 50mm capping respectively. One tailed t-test statistical analysis confirmed that the increased length of filter run for both 25mm and 50mm capping was statistically significant. However, the variance between 25mm and 50mm capping was statistically insignificant.

Tamakhu and Iswar (2021) study reports that anthracite coal gave an average of 52.03% increase in the length of the filter run for a model filtration unit subjected to varying influent turbidity bands of 0-300NTU. Anthracite coal is an approved capping material for Rapid Sand Filters. Ansari et al., (2017) study reports an increased length of filter run of 80% for crushed coconut shells capped model filtration unit. Al-Rawi and Al-Najjar (2009) study reports a 35% and 24% increase in the length of the filter run for Granular Activated Carbon (GAC) and anthracite coal respectively for a 7.3m/hr filtration rate. At higher filtration rate of 9.8m/hr, the increased length of filter run for GAC and anthracite coal is 58% and 42% respectively. Sabale et al., (2014) study that focused on capping with PCV granules, reported an increased length of filter run of 43% and 75% for 3cm capping depth at filtration rates of 5.4m/hr and 7.2m.h respectively.

Compared to other capping materials, crushed expanded slate from Maji ya Chumvi has demonstrated satisfactory results in increasing the length of the filter run for conventional Rapid Sand Filters particularly under high influent turbidities. This can be hypothesis to be attributed to low specific gravity enabling crushed expanded slates to retain their relative position at the top and allowing intermixing with small grains of sand overcoming the problem of stratification.

The increase of the capping depth from 25mm to 50mm had an insignificant effect on the length of the filter run. This could be attributed to the marginal increase in filter media voidage between the two depths under consideration.

The estimated voidage of crushed expanded slates is 50% against 35-40% of sand (Malcolm et al., 2017). Based on Al-Rawi (2017), Farjana et al., (2018), Ansari et al., (2017) and Tamakhu and Iswar (2021), significant results would be achieved when the capping material depth to sand ratio is above 1:6. It should be noted that increase in capping depth results to proportional increase in length of filter run with a direct increase in cost. Therefore, the minimum depth of capping material is determined with no upper limit provided. Malcolm et al., (2017) suggests that the depth of capping material to sand can be up to 2.5:1.

4.3.2 Turbidity Removal

The collected raw data on turbidity removal for the model filtration unit has been analyzed and the results for the 0-50NTU, 50-150NTU and 150-300NTU influent turbidity bands are presented graphically in Figures 4-4, 4-5 and 4-6.

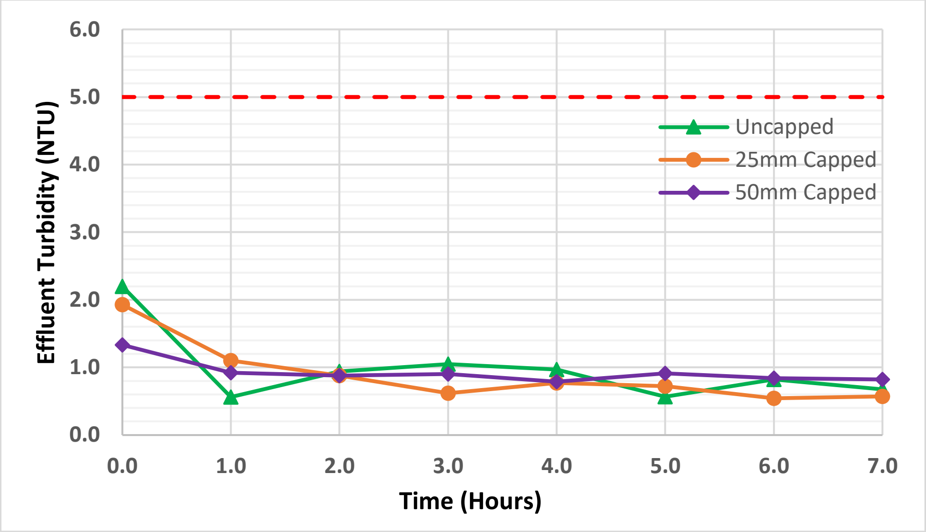

Figure 4.4: Results of Turbidity Removal (Influent Turbidity 0-50NTU)

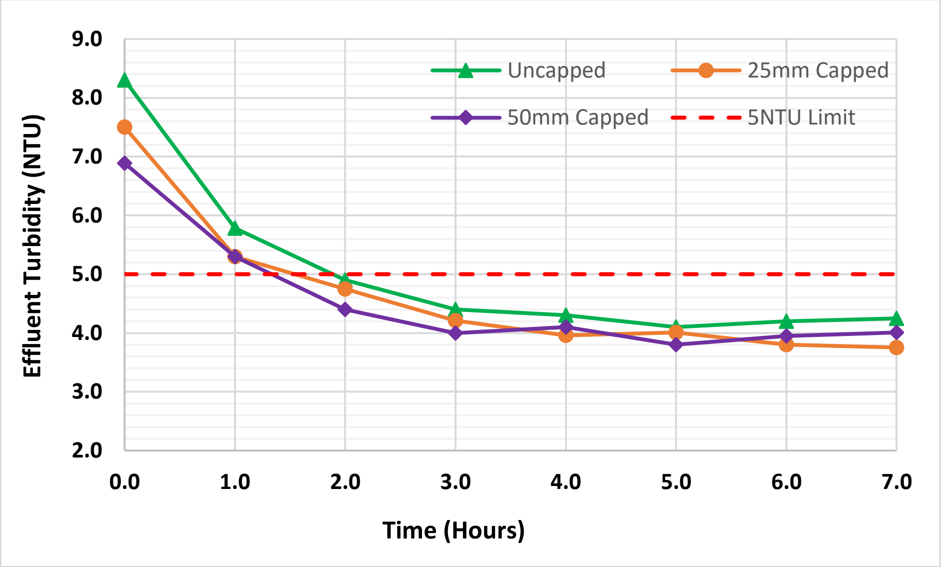

Figure 4.5: Results of Turbidity Removal (Influent Turbidity 50-150 NTU)

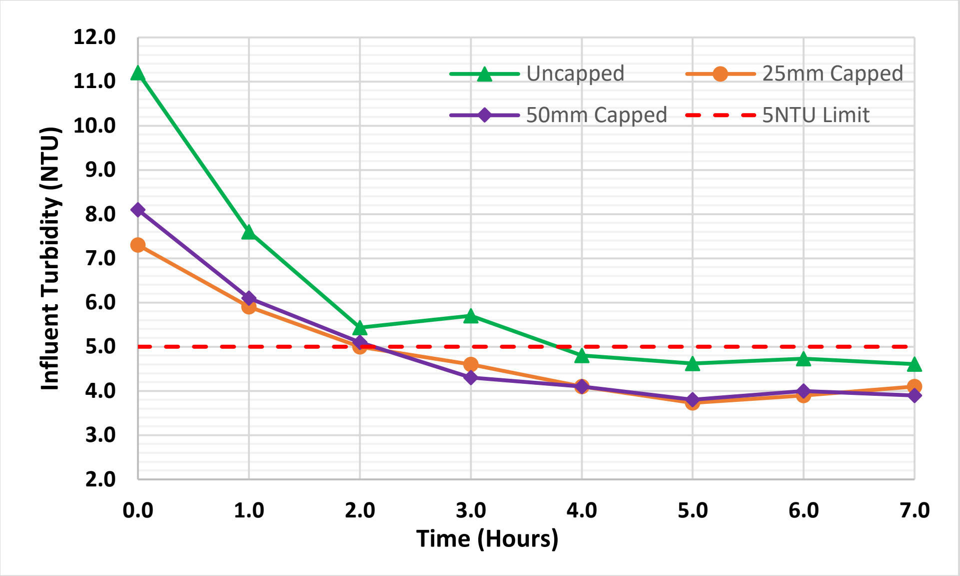

Figure 4.6: Results of Turbidity Removal (Influent Turbidity 150-300 NTU)

At influent turbidities 0 – 50NTU and 50 – 150NTU (Figures 4-4 and 4-5), the effluent water quality for all the three scenarios (uncapped, 25mm and 50mm capped) was below 5NTU and therefore meets the Kenyan drinking water standards. In the high influent turbidity band (150 – 300 NTU), the effluent quality for the uncapped RGSF deteriorated and exceeded the maximum limit of 5NTU illustrating the early breakthrough of the flocs (Figure 4-6). At the same high influent conditions, the 25mm and 50mm crushed expanded slates capped filter remained consistently below 5NTU indicating robustness in dealing with high influent turbidities. Results of one tailed t-test indicates that the observed improvement in turbidity removal in the 150-300 NTU influent turbidity band was statistically insignificant.

Figures 4-5 and 4-6 indicate that there was a floc breakthrough at the beginning of a new filtration cycle. This occurred after backwashing and can be attributed to filter ripening. The filter media is generally highly porous and is undergoing reconditioning.

Turbidity removal for 25mm and 50mm depth of capping was similar and any variance observed was statistically insignificant.

Tamakhu and Iswar (2021) study reports that anthracite coal, which is an approved capping material, gave a 3% increase in efficiency of turbidity removal at low influent turbidities of 0-25NTU and 25-50NTU. At high influent turbidity, anthracite coal did not yield any improvement in turbidity removal. Sabale et al., (2014) study indicates that capping with PVC granules resulted in 5% increment on turbidity removal efficiency. Al-Rawi and Al-Najjar (2009) study reports an average of 1% increment in turbidity removal by use of Granular Activated Carbon (GAC), NINIVITE and anthracite coal.

The current study and past studies highlighted in the preceding section concurs that capping materials have minimal contribution in improving the efficiency of turbidity removal for Rapid Sand Filters. This could be attributed to the excellent performance of sand in turbidity removal. Sand as the primary filter media has an efficiency of up to 90% (Al-Rawi, 2017).

4.4 Cost Benefit Analysis

The results of cost analysis through discounting and comparing the total present value for conventional and 25mm crushed expanded slate model filtration unit are presented graphically in Figure 4-7.

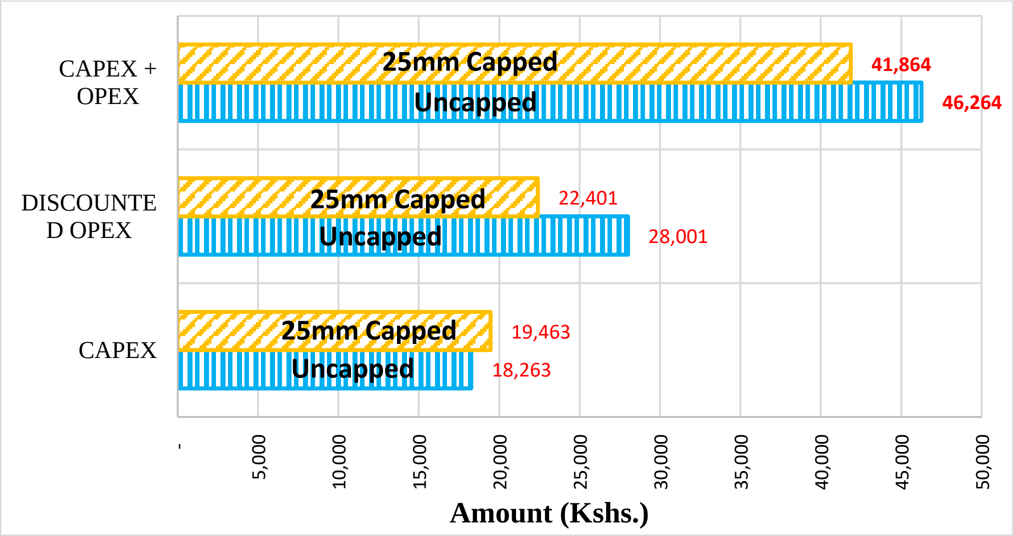

Figure 4.7: Results of Cost Comparison Analysis

The CAPEX for 25mm crushed expanded slates capped model filtration unit 6.5% higher compared to the conventional uncapped model filtration unit. This could be attributed to the additional cost of sourcing, crushing and expanding the slates through heating. The concept of expansion of a filter media by heating may be new in water industry but not new in the construction industry. Expansion of coarse aggregates has been adopted in construction industry to achieve structural light weight concrete for low-cost housing and for structures in earthquake prone areas (Teo et al.,2006). Teo et al., (2006) notes that despite the additional cost for processing lightweight aggregates the overall cost benefit outweighs the additional capital expenditure.

The OPEX for uncapped model filtration unit is 25% higher that the 25mm crushed expanded slate capped filtration unit. The main operational expenditure in filtration is the cost of energy for backwashing. The cost reduction in capping using expanded slates could be attributed to the increase in the length of the filter run which effectively reduces the frequency of backwashing.

The total present value (CAPEX and OPEX) indicates that the 25mm capping with crushed expanded slates results to an overall cost reduction of 11% at model filtration unit. The benefit of saving the backwashing energy costs outweighs the additional cost of introducing crushed expanded slates in Rapid Sand Filters. Considering the economies of scale, in a full-scale system, the cost of producing expanded slate is expected to be much cheaper.

Davies and Wheatley (2012) indicate that within a water treatment system, the highest operating costs are typically chemicals and power required mainly for pumping. Reduction in operational costs in water treatment, which capping technique contributes, is essential in provision of affordable potable water.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The conclusions of the study are summarized as follows:

1. Crushed expanded slate from Maji ya Chumvi meet the minimum chemical and physical characterization requirements for use as a capping material for convention Rapid Sand Filters.
2. Capping by crushed expanded slate increases the length of filter run of Rapid Sand Filters by an average of 25% and 52% for medium (50 - 150NTU) and high (150 – 300NTU) influent turbidities respectively. Improvement in turbidity removal by introduction of crushed expanded slate is insignificant.
3. The total present value (CAPEX and OPEX) for capping with 25mm crushed expanded slates results to an overall cost reduction of 11% at model filtration unit. The benefit of saving the backwashing energy costs outweighs the additional cost of introducing crushed expanded slates.

5.2 Recommendations

The recommendations of the study are summarized as follows:

1. The study recommends the use of crushed expanded slates as a capping material for Rapid Sand Filters.
2. The study recommends additional studies to assess the effect of introducing crushed expanded slate to the backwashing water requirements.

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APPENDICES

Appendix I: Photographs taken during Research Work

Collection of Slates

Crushing of Slates

Specific Gravity Test - Wire Basket Method

Specific Gravity Test - Pycnometer/ Gas Jar Method

Fabricated Model Filtration Unit

Pretreated Raw Water Source – Existing Clarifiers

Model Filtration Unit Setup within an Existing Water Treatment Plant

Model Filtration Unit Setup within an Existing Water Treatment Plant

Model Filtration Unit Setup within an Existing Water Treatment Plant

Ongoing Filtration Process

Turbidity Measurement and Recording

Appendix II: Hydraulic Design of Model Filtration Unit

Page 1 of 2

General:

1. Entry to filter unit will be controlled by a gate valve to regulate flow.
2. Flow into filters to be in such a way as to utilise the whole surface area for uniform filtration.
3. Level of Water in the Filter Unit to always be above the filter bed at any given time not unless during maintenance.
4. Backwashing of filter to be by water only.
5. Pipework arrangement to provide for complete drainage of water from a filter during maintenance/repair works

Design Parameters:

Design Flow, Q = 13 m^3/day
= **0.54** m^3/hr
= **0.0002** m^3/s
= **0.15 ltrs/s**

Surface Loading = **4.0** - **6.0** m^3/m^2/hr

Allowed Filter Bed expansion = 25%

Design Calculations and Checks:

1. No of Filters = 1 arranged in **1** row

Take width of each filter bed = 0.3 m

Q per filter = 0.54 m^3/hr

2. Filtration rate = 6 m^3/m^2/hr

3. Area required per filter = 0.09 m^2

4. Length of each filter bed = 0.30 m

Total Length of filtration unit, L = 0.3 m
Total Width of filtration unit, W = 0.3 m

5. The filter media for the Model Unit will consist of:

sand 300
Gravel 2 30
Gravel 1 30

Gravel	1	2
Depth (mm)	30	30
Passing square mesh (	12	5
Retained (mm)	5	2

Top sand layer 300mm, Effective size 0.7mm

6. A perforated plate will be provided under the filter media to collect filtered water and will also be used for backwashing by water.

Backwashing of Filters

Design is based on backwashing by water only

Backwash rate (q) = 50 m^3/m^2/hr
Period of Backwashing (t) = 5 min
Ministry of water Design Manual

Area of One filter unit (a) = 0.09 m^2

Volume of Water Required for backwashing one filter unit (V) = (q x a x t)

V = 0.38 m^3

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Backwash water flow rate	=	**0.001**	**m^3/s**
	=	**1.3**	**l/s**

Height of Trough Above Filter Media

Minimum free height between top of the filter media and wash water outlet pipe

filter media height	=	0.3	m	
min free height	=	0.075	m	
provide	=	0.3	m	for ease of operation

Min. Depth of Sand (Hudson Formulae)

Filtration Rate	6	$m^3/m^2/hr$
Terminal Headloss	0.66	m
Mean Diameter - Sand	0.85	mm
Breakthro' Index	0.0004	
Min. Depth (Hudson Formular)	**0.24**	**m**
	237	**mm**
Adopted Sand Depth	**300**	**mm**

DETERMINING THE APPROPORIATE SIZE OF CRUSHED SLATES (STOKE'S LAW)

A. SAND

Diameter of small particles/grains	0.00001	*m*
Specific Gravity of particle	2.42	
Kinematic viscocity of water	0.00089	*$N.s/m^2$ or Pa.s*
Vel. Of settlement (V_s)	***0.0000***	***m/s***

B. CRUSHED SLATES

Vel. Of settlement (V_s)	0.0000001	*m/s*
Specific Gravity of particle	1.65	
Diameter of particle	**0.00001**	**m**
	0.015	**mm**

C. DEPTH OF CAPPING

Size of Sand Grains to Stratify	0.0000	*m*
Depth of sand	0.3	*m*
Area of Filter Unit	0.09	*m^2*
Volume of Sand	0.027	*m^3*
% of small grains(grading envelope for filter media)	11.2%	
Volume of Sand	0.003024	*m^3*
Theoritical Capping Depth	**0.03**	**m**
	33.60	**mm**

Appendix III: Preliminary Analysis of Data Collected for the Filtration Rate

				Day 1	Day 2	Day 3	Day 4	Day 5	
		Time (Hours)		Flow Rate (ltrs/s)	Flow Rate (ltrs/s)	Flow Rate (ltrs/s)	Flow Rate (ltrs/s)	Flow Rate (ltrs/s)	Average
Uncapped	**0 - 50NTU**	**0.00**	**09:00:00**	0.16	0.16	0.16	0.16	0.16	**0.16**
		1.00	**10:00:00**	0.16	0.16	0.15	0.15	0.16	**0.16**
		2.00	**11:00:00**	0.15	0.14	0.14	0.14	0.16	**0.15**
		3.00	**12:00:00**	0.15	0.14	0.14	0.13	0.14	**0.14**
		4.00	**13:00:00**	0.14	0.13	0.14	0.12	0.14	**0.13**
		5.00	**14:00:00**	0.13	0.12	0.13	0.12	0.12	**0.12**
		6.00	**15:00:00**	0.12	0.11	0.12	0.11	0.11	**0.11**
		7.00	**16:00:00**	0.11	0.10	0.10	0.10	0.09	**0.10**
		8.00	**17:00:00**	0.07	0.07	0.07	0.08	0.07	**0.07**
		Filter Run		**7.75**	**7.71**	**7.69**	**7.90**	**7.56**	**7.73**
	50 - 150NTU	**0.00**	**09:00:00**	0.16	0.16	0.16	0.16	0.16	**0.16**
		1.00	**10:00:00**	0.15	0.16	0.16	0.16	0.15	**0.16**
		2.00	**11:00:00**	0.14	0.15	0.16	0.15	0.14	**0.15**
		3.00	**12:00:00**	0.12	0.12	0.15	0.13	0.13	**0.13**
		4.00	**13:00:00**	0.11	0.10	0.11	0.09	0.10	**0.10**
		5.00	**14:00:00**	0.09	0.08	0.09	0.08	0.09	**0.09**
		6.00	**15:00:00**	0.03	0.07	0.06	0.07	0.07	**0.06**
		7.00	**16:00:00**	0.02	0.03	0.04	0.04	0.03	**0.03**
		Filter Run		**5.20**	**5.00**	**5.33**	**5.00**	**5.50**	**5.24**
	150 - 300NTU	**0.00**	**09:00:00**	0.16	0.16	0.16	0.16	0.16	**0.16**
		1.00	**10:00:00**	0.14	0.14	0.14	0.14	0.15	**0.14**
		2.00	**11:00:00**	0.13	0.12	0.10	0.12	0.14	**0.12**
		3.00	**12:00:00**	0.10	0.09	0.09	0.10	0.13	**0.10**
		4.00	**13:00:00**	0.08	0.08	0.09	0.08	0.09	**0.08**
		5.00	**14:00:00**	0.07	0.07	0.07	0.05	0.07	**0.07**
		6.00	**15:00:00**	0.03	0.05	0.03	0.03	0.03	**0.03**
		7.00	**16:00:00**	0.02	0.02	0.02	0.02	0.02	**0.02**

		Filter Run		4.29	4.19	4.36	4.04	4.50	4.25

				Day 1	Day 2	Day 3	Day 4	Day 5	
		Time (Hours)		Flow Rate (ltrs/s)	Flow Rate (ltrs/s)	Flow Rate (ltrs/s)	Flow Rate (ltrs/s)	Flow Rate (ltrs/s)	Average
25mm Capped	0 - 50NTU	0.00	09:00:00	0.16	0.16	0.16	0.16	0.16	0.16
		1.00	10:00:00	0.15	0.16	0.15	0.15	0.15	0.15
		2.00	11:00:00	0.14	0.14	0.15	0.14	0.14	0.14
		3.00	12:00:00	0.14	0.14	0.14	0.13	0.14	0.14
		4.00	13:00:00	0.12	0.14	0.13	0.13	0.13	0.13
		5.00	14:00:00	0.11	0.12	0.12	0.11	0.12	0.12
		6.00	15:00:00	0.10	0.12	0.11	0.11	0.12	0.11
		7.00	16:00:00	0.10	0.10	0.10	0.09	0.09	0.10
		8.00	17:00:00	0.07	0.07	0.07	0.08	0.07	0.07
		Filter Run		7.67	7.71	7.69	7.77	7.56	7.68
	50-150NTU	0.00	09:00:00	0.16	0.16	0.16	0.16	0.16	0.16
		1.00	10:00:00	0.16	0.16	0.15	0.16	0.16	0.16
		2.00	11:00:00	0.14	0.15	0.15	0.14	0.14	0.14
		3.00	12:00:00	0.13	0.13	0.14	0.13	0.13	0.13
		4.00	13:00:00	0.13	0.13	0.13	0.12	0.12	0.13
		5.00	14:00:00	0.12	0.11	0.12	0.10	0.12	0.11
		6.00	15:00:00	0.11	0.09	0.10	0.09	0.10	0.10
		7.00	16:00:00	0.05	0.07	0.05	0.08	0.05	0.06
		Filter Run		6.50	6.77	6.45	6.88	6.37	6.70
	150-300NTU	0.00	09:00:00	0.16	0.16	0.16	0.16	0.16	0.16
		1.00	10:00:00	0.15	0.15	0.16	0.16	0.15	0.15
		2.00	11:00:00	0.14	0.14	0.14	0.14	0.15	0.15
		3.00	12:00:00	0.13	0.14	0.14	0.13	0.13	0.14
		4.00	13:00:00	0.12	0.12	0.12	0.12	0.13	0.12
		5.00	14:00:00	0.11	0.12	0.11	0.11	0.12	0.11
		6.00	15:00:00	0.11	0.11	0.10	0.10	0.11	0.11
		7.00	16:00:00	0.05	0.04	0.05	0.05	0.05	0.05
		Filter Run		6.26	5.98	6.22	6.20	6.34	6.22

	Day 1	Day 2	Day 3	Day 4	Day 5	

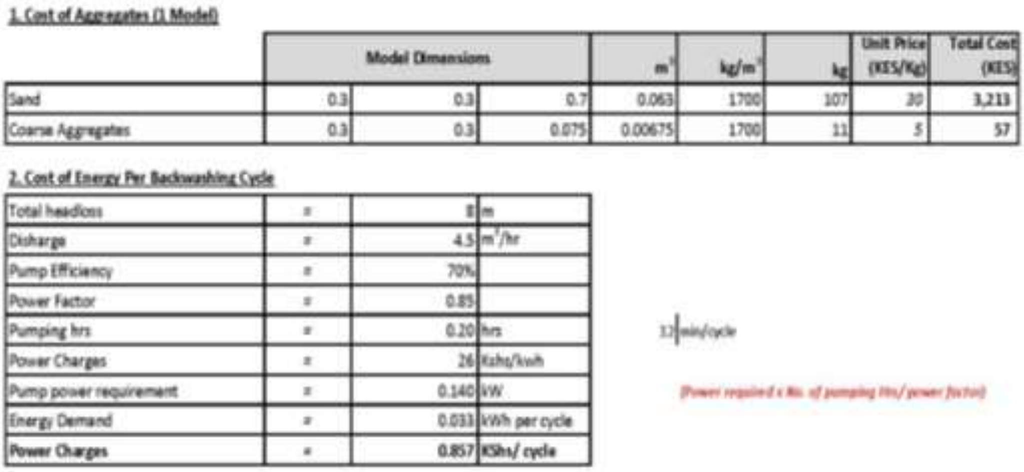
		Time (Hours)		Flow Rate (ltrs/s)	Flow Rate (ltrs/s)	Flow Rate (ltrs/s)	Flow Rate (ltrs/s)	Flow Rate (ltrs/s)	Average
50mm Capped	**0 - 50NTU**	**0.00**	**09:00:00**	0.16	0.16	0.16	0.16	0.16	**0.16**
		1.00	**10:00:00**	0.15	0.16	0.15	0.15	0.16	**0.15**
		2.00	**11:00:00**	0.14	0.14	0.15	0.14	0.14	**0.14**
		3.00	**12:00:00**	0.13	0.14	0.14	0.13	0.14	**0.14**
		4.00	**13:00:00**	0.12	0.13	0.13	0.12	0.13	**0.13**
		5.00	**14:00:00**	0.11	0.12	0.13	0.11	0.12	**0.12**
		6.00	**15:00:00**	0.11	0.11	0.10	0.11	0.11	**0.11**
		7.00	**16:00:00**	0.10	0.09	0.10	0.10	0.09	**0.10**
		8.00	**17:00:00**	0.07	0.07	0.07	0.08	0.07	**0.07**
		Filter Run		**7.67**	**7.56**	**7.69**	**7.87**	**7.56**	**7.68**
	50-150NTU	**0.00**	**09:00:00**	0.16	0.16	0.16	0.16	0.16	**0.16**
		1.00	**10:00:00**	0.15	0.15	0.15	0.15	0.16	**0.16**
		2.00	**11:00:00**	0.15	0.14	0.15	0.15	0.15	**0.15**
		3.00	**12:00:00**	0.15	0.14	0.14	0.15	0.15	**0.14**
		4.00	**13:00:00**	0.14	0.13	0.13	0.14	0.14	**0.13**
		5.00	**14:00:00**	0.12	0.12	0.11	0.12	0.12	**0.12**
		6.00	**15:00:00**	0.09	0.09	0.09	0.10	0.10	**0.09**
		7.00	**16:00:00**	0.06	0.06	0.06	0.05	0.06	**0.06**
		Filter Run		**6.43**	**6.42**	**6.43**	**6.31**	**6.63**	**6.47**
	150-300NTU	**0.00**	**09:00:00**	0.16	0.16	0.16	0.16	0.16	**0.16**
		1.00	**10:00:00**	0.15	0.15	0.16	0.15	0.15	**0.16**
		2.00	**11:00:00**	0.14	0.14	0.14	0.15	0.14	**0.14**
		3.00	**12:00:00**	0.13	0.12	0.13	0.13	0.14	**0.13**
		4.00	**13:00:00**	0.12	0.12	0.12	0.13	0.12	**0.12**
		5.00	**14:00:00**	0.11	0.11	0.12	0.11	0.11	**0.11**
		6.00	**15:00:00**	0.09	0.09	0.09	0.09	0.09	**0.09**
		7.00	**16:00:00**	0.05	0.05	0.06	0.05	0.05	**0.05**
		Filter Run		**6.11**	**6.06**	**6.24**	**6.16**	**6.13**	**6.16**

Appendix IV: Preliminary Analysis of Data Collected for the Turbidity Removal

Inlet Turbidity	Time (Hours	Uncapped		25mm Capped		50mm Capped	
		Inlet Turbidity (NTU)	Outlet Turbidity (NTU)	Inlet Turbidity (NTU)	Outlet Turbidity (NTU)	Inlet Turbidity (NTU)	Outlet Turbidity (NTU)
0-50NTU	09:00:00	10.30	2.20	14.90	1.93	13.94	1.33
	10:00:00	10.70	0.56	15.40	1.10	15.70	0.92
	11:00:00	17.30	0.94	15.10	0.88	17.23	0.88
	12:00:00	12.10	1.05	11.31	0.62	9.87	0.90
	13:00:00	10.20	0.97	9.85	0.77	8.89	0.79
	14:00:00	9.20	0.57	12.30	0.72	13.86	0.91
	15:00:00	8.83	0.82	13.51	0.54	15.21	0.84
	16:00:00	5.20	0.67	17.20	0.57	11.93	0.82
50-150 NTU	09:00:00	146.80	8.30	58.60	7.50	72.90	6.89
	10:00:00	113.50	5.78	73.90	5.30	86.20	5.30
	11:00:00	92.30	4.90	76.40	4.75	97.60	4.40
	12:00:00	108.70	4.40	97.50	4.21	113.50	4.00
	13:00:00	62.50	4.30	114.20	3.96	129.80	4.10
	14:00:00	51.80	4.10	148.60	4.01	141.10	3.80
	15:00:00	56.40	4.20	150.10	3.80	146.90	3.95
	16:00:00	61.50	4.25	143.90	3.75	135.70	4.01
150-300 NTU	09:00:00	170.37	11.20	152.30	7.30	297.60	8.10
	10:00:00	206.07	7.60	168.50	5.90	284.40	6.10
	11:00:00	288.83	5.43	188.60	5.00	257.90	5.10
	12:00:00	221.93	5.70	193.80	4.60	230.50	4.30
	13:00:00	202.30	4.80	234.90	4.10	207.80	4.10
	14:00:00	185.17	4.62	233.80	3.73	194.40	3.80

Inlet Turbidity	Time (Hours	Uncapped		25mm Capped		50mm Capped	
		Inlet Turbidity (NTU)	Outlet Turbidity (NTU)	Inlet Turbidity (NTU)	Outlet Turbidity (NTU)	Inlet Turbidity (NTU)	Outlet Turbidity (NTU)
	15:00:00	160.23	4.73	241.80	3.90	162.90	4.00
	16:00:00	150.57	4.61	278.60	4.10	155.70	3.90

Appendix V: Detailed cost analysis for the model filtration units



1. Cost of Aggregates (1 Model)

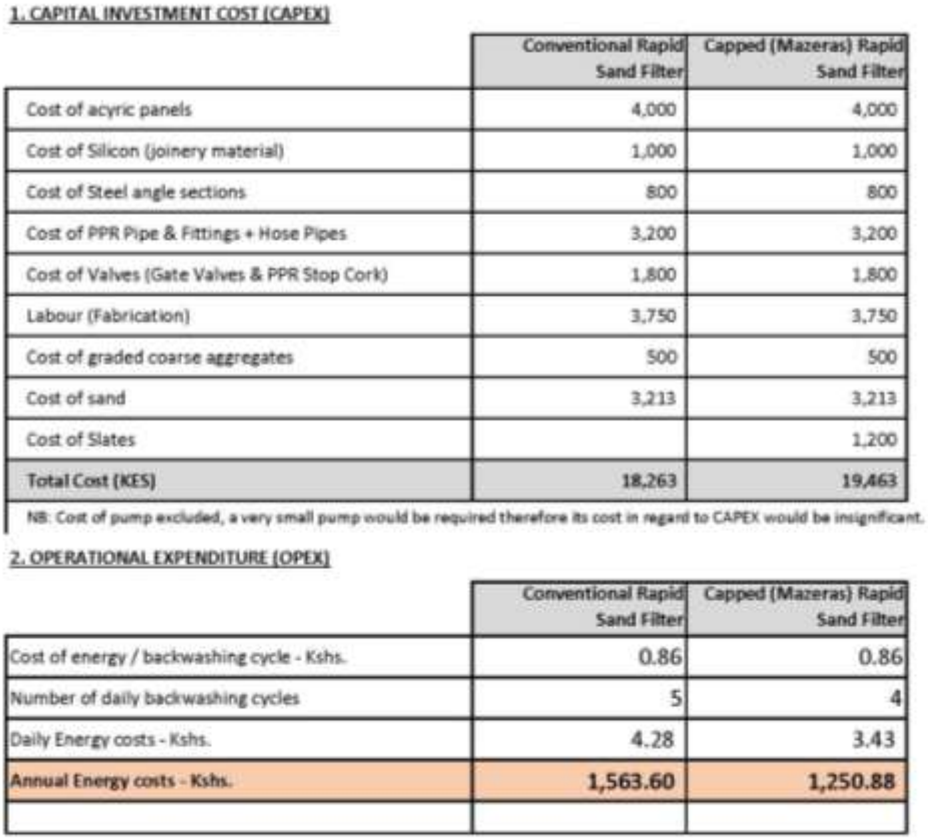
	Model Dimensions			m^3	kg/m^3	kg	Unit Price (KES/Kg)	Total Cost (KES)
Sand	0.3	0.3	0.7	0.063	1700	107	30	3,213
Coarse Aggregates	0.3	0.3	0.075	0.00675	1700	11	5	57

2. Cost of Energy Per Backwashing Cycle

Total headloss	=	8	m
Disharge	=	4.5	m^3/hr
Pump Efficiency	=	70%	
Power Factor	=	0.85	
Pumping hrs	=	0.20	hrs
Power Charges	=	26	Kshs/kwh
Pump power requirement	=	0.140	kW
Energy Demand	=	0.033	kWh per cycle
Power Charges	=	**0.857**	**KShs/ cycle**

12 min/cycle

(Power required x No. of pumping Hrs/ power factor)



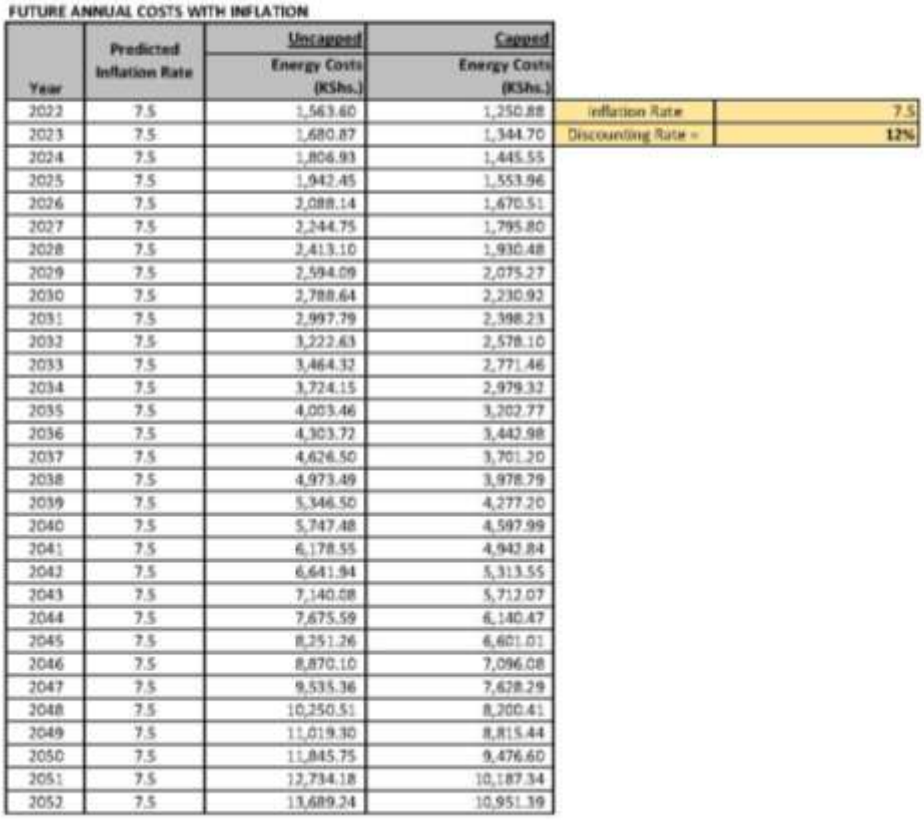
1. CAPITAL INVESTMENT COST (CAPEX)

	Conventional Rapid Sand Filter	Capped (Mazeras) Rapid Sand Filter
Cost of acyric panels	4,000	4,000
Cost of Silicon (joinery material)	1,000	1,000
Cost of Steel angle sections	800	800
Cost of PPR Pipe & Fittings + Hose Pipes	3,200	3,200
Cost of Valves (Gate Valves & PPR Stop Cork)	1,800	1,800
Labour (Fabrication)	3,750	3,750
Cost of graded coarse aggregates	500	500
Cost of sand	3,213	3,213
Cost of Slates		1,200
Total Cost (KES)	**18,263**	**19,463**

NB: Cost of pump excluded, a very small pump would be required therefore its cost in regard to CAPEX would be insignificant.

2. OPERATIONAL EXPENDITURE (OPEX)

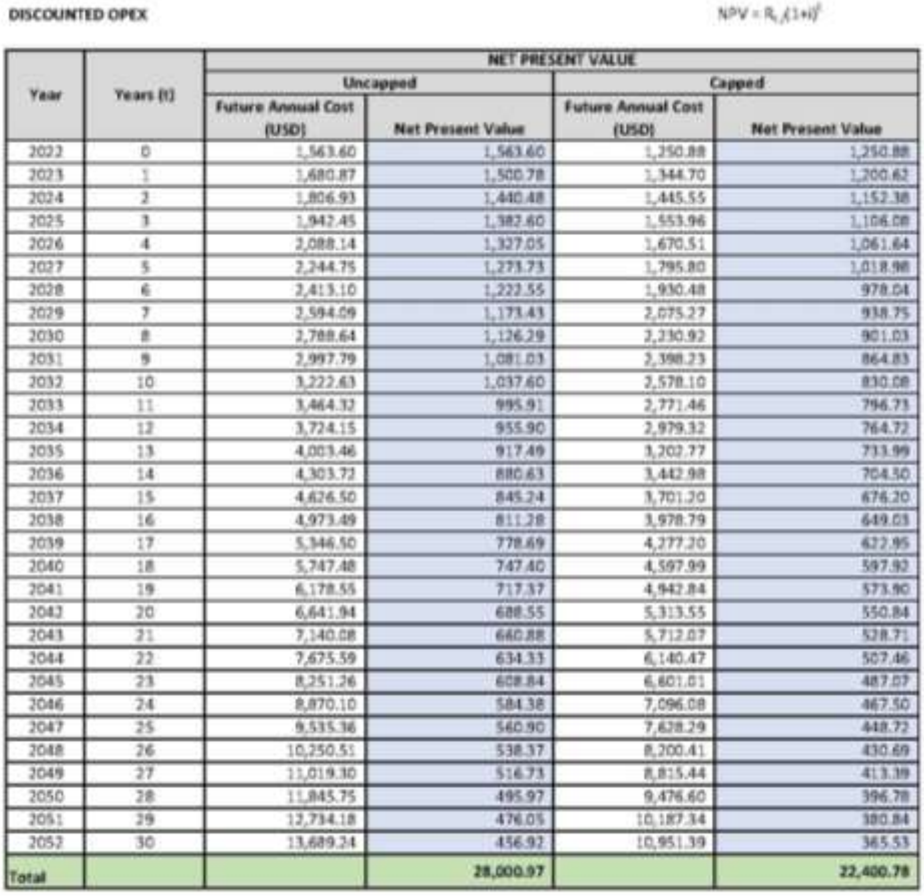
	Conventional Rapid Sand Filter	Capped (Mazeras) Rapid Sand Filter
Cost of energy / backwashing cycle - Kshs.	0.86	0.86
Number of daily backwashing cycles	5	4
Daily Energy costs - Kshs.	4.28	3.43
Annual Energy costs - Kshs.	**1,563.60**	**1,250.88**



FUTURE ANNUAL COSTS WITH INFLATION

Year	Predicted Inflation Rate	Uncapped Energy Costs (KShs.)	Capped Energy Costs (KShs.)
2022	7.5	1,563.60	1,250.88
2023	7.5	1,680.87	1,344.70
2024	7.5	1,806.93	1,445.55
2025	7.5	1,942.45	1,553.96
2026	7.5	2,088.14	1,670.51
2027	7.5	2,244.75	1,795.80
2028	7.5	2,413.10	1,930.48
2029	7.5	2,594.09	2,075.27
2030	7.5	2,788.64	2,230.92
2031	7.5	2,997.79	2,398.23
2032	7.5	3,222.63	2,578.10
2033	7.5	3,464.32	2,771.46
2034	7.5	3,724.15	2,979.32
2035	7.5	4,003.46	3,202.77
2036	7.5	4,303.72	3,442.98
2037	7.5	4,626.50	3,701.20
2038	7.5	4,973.49	3,978.79
2039	7.5	5,346.50	4,277.20
2040	7.5	5,747.48	4,597.99
2041	7.5	6,178.55	4,942.84
2042	7.5	6,641.94	5,313.55
2043	7.5	7,140.08	5,712.07
2044	7.5	7,675.59	6,140.47
2045	7.5	8,251.26	6,601.01
2046	7.5	8,870.10	7,096.08
2047	7.5	9,535.36	7,628.29
2048	7.5	10,250.51	8,200.41
2049	7.5	11,019.30	8,815.44
2050	7.5	11,845.75	9,476.60
2051	7.5	12,734.18	10,187.34
2052	7.5	13,689.24	10,951.39

Inflation Rate	7.5
Discounting Rate =	12%



DISCOUNTED OPEX

$NPV = R_t/(1+i)^t$

Year	Years (t)	NET PRESENT VALUE			
		Uncapped		Capped	
		Future Annual Cost (USD)	Net Present Value	Future Annual Cost (USD)	Net Present Value
2022	0	1,563.60	1,563.60	1,250.88	1,250.88
2023	1	1,680.87	1,500.78	1,344.70	1,200.62
2024	2	1,806.93	1,440.48	1,445.55	1,152.38
2025	3	1,942.45	1,382.60	1,553.96	1,106.08
2026	4	2,088.14	1,327.05	1,670.51	1,061.64
2027	5	2,244.75	1,273.73	1,795.80	1,018.98
2028	6	2,413.10	1,222.55	1,930.48	978.04
2029	7	2,594.09	1,173.43	2,075.27	938.75
2030	8	2,788.64	1,126.29	2,230.92	901.03
2031	9	2,997.79	1,081.03	2,398.23	864.83
2032	10	3,222.63	1,037.60	2,578.10	830.08
2033	11	3,464.32	995.91	2,771.46	796.73
2034	12	3,724.15	955.90	2,979.32	764.72
2035	13	4,003.46	917.49	3,202.77	733.99
2036	14	4,303.72	880.63	3,442.98	704.50
2037	15	4,626.50	845.24	3,701.20	676.20
2038	16	4,973.49	811.28	3,978.79	649.03
2039	17	5,346.50	778.69	4,277.20	622.95
2040	18	5,747.48	747.40	4,597.99	597.92
2041	19	6,178.55	717.37	4,942.84	573.90
2042	20	6,641.94	688.55	5,313.55	550.84
2043	21	7,140.08	660.88	5,712.07	528.71
2044	22	7,675.59	634.33	6,140.47	507.46
2045	23	8,251.26	608.84	6,601.01	487.07
2046	24	8,870.10	584.38	7,096.08	467.50
2047	25	9,535.36	560.90	7,628.29	448.72
2048	26	10,250.51	538.37	8,200.41	430.69
2049	27	11,019.30	516.73	8,815.44	413.39
2050	28	11,845.75	495.97	9,476.60	396.78
2051	29	12,734.18	476.05	10,187.34	380.84
2052	30	13,689.24	456.92	10,951.39	365.53
Total			28,000.97		22,400.78

Appendix VI: Detailed Statistical Analysis (T-test)

t-Test: Two-Sample Assuming Equal Variances

	Uncapped	***25mm Capped***
Mean	7.722	7.679
Variance	0.015	0.006
Observations	5	5
Pooled Variance	0.011	
Hypothesized Mean Difference	0	
df	8	
t Stat	0.654	
P(T<=t) one-tail	0.266	
t Critical one-tail	1.860	
P(T<=t) two-tail	0.532	
t Critical two-tail	2.306	

t-Test: Two-Sample Assuming Equal Variances

	25mm Capped	***50mm Capped***
Mean	7.68	7.67
Variance	0.006	0.017
Observations	5	5
Pooled Variance	0.01	
Hypothesized Mean Difference	0	
df	8	
t Stat	0.173	
P(T<=t) one-tail	0.434	
t Critical one-tail	1.860	
P(T<=t) two-tail	0.867	
t Critical two-tail	2.306	

t-Test: Two-Sample Assuming Equal Variances

	Uncapped	*25mm Capped*
Mean	5.206	6.594
Variance	0.047	0.048
Observations	5	5
Pooled Variance	0.047	
Hypothesized Mean Difference	0	
df	8	
t Stat	- 10.077	
P(T<=t) one-tail	0.000	
t Critical one-tail	1.860	

P(T<=t) two-tail	0.000
t Critical two-tail	2.306

t-Test: Two-Sample Assuming Equal Variances

	25mm Capped	*50mm Capped*
Mean	6.594	6.443
Variance	0.048	0.013
Observations	5	5
Pooled Variance	0.031	
Hypothesized Mean Difference	0	
df	8	
t Stat	1.359	
P(T<=t) one-tail	0.106	
t Critical one-tail	1.860	
P(T<=t) two-tail	0.211	
t Critical two-tail	2.306	

t-Test: Two-Sample Assuming Equal Variances

	Uncapped	***25mm Capped***
Mean	4.273	6.200
Variance	0.031	0.018
Observations	5	5
Pooled Variance	0.024	
Hypothesized Mean Difference	0	
df	8	
t Stat	- 19.470	
P(T<=t) one-tail	0.000	
t Critical one-tail	1.860	
P(T<=t) two-tail	0.000	
t Critical two-tail	2.306	

t-Test: Two-Sample Assuming Equal Variances

	25mm Capped	***50mm Capped***
Mean	6.200	6.137
Variance	0.018	0.005
Observations	5	5
Pooled Variance	0.011	
Hypothesized Mean Difference	0	
df	8	
t Stat	0.927	

P(T<=t) one-tail	0.190
t Critical one-tail	1.860
P(T<=t) two-tail	0.381
t Critical two-tail	2.306

t-Test: Two-Sample Assuming Equal Variances

	Uncapped	*25mm Capped*
Mean	0.973	0.891
Variance	0.280	0.210
Observations	8	8
Pooled Variance	0.245	
Hypothesized Mean Difference	0	
df	14	
t Stat	0.330	
P(T<=t) one-tail	0.373	
t Critical one-tail	1.761	
P(T<=t) two-tail	0.746	
t Critical two-tail	2.145	

t-Test: Two-Sample Assuming Equal Variances

	25mm Capped	*50mm Capped*
Mean	0.891	0.924
Variance	0.210	0.029
Observations	8	8
Pooled Variance	0.119	
Hypothesized Mean Difference	0	
df	14	
t Stat	- 0.188	
P(T<=t) one-tail	0.427	
t Critical one-tail	1.761	
P(T<=t) two-tail	0.853	
t Critical two-tail	2.145	

t-Test: Two-Sample Assuming Equal Variances

	Uncapped	*25mm Capped*
Mean	5.029	4.660
Variance	2.052	1.595
Observations	8	8
Pooled Variance	1.824	
Hypothesized Mean Difference	0	
df	14	
t Stat	0.546	
P(T<=t) one-tail	0.297	
t Critical one-tail	1.761	
P(T<=t) two-tail	0.594	
t Critical two-tail	2.145	

t-Test: Two-Sample Assuming Equal Variances

	25mm Capped	*50mm Capped*
Mean	4.660	4.556
Variance	1.595	1.111
Observations	8	8
Pooled Variance	1.353	
Hypothesized Mean Difference	0	
df	14	
t Stat	0.178	
P(T<=t) one-tail	0.430	
t Critical one-tail	1.761	
P(T<=t) two-tail	0.861	
t Critical two-tail	2.145	

t-Test: Two-Sample Assuming Equal Variances

	Uncapped	*25mm Capped*
Mean	6.086	4.829
Variance	5.264	1.495
Observations	8	8
Pooled Variance	3.380	
Hypothesized Mean Difference	0	
df	14	
t Stat	1.368	
P(T<=t) one-tail	0.036	
t Critical one-tail	1.761	
P(T<=t) two-tail	0.019	
t Critical two-tail	2.145	

t-Test: Two-Sample Assuming Equal Variances

	25mm Capped	*50mm Capped*
Mean	4.829	4.925
Variance	1.495	2.248
Observations	8	8
Pooled Variance	1.872	
Hypothesized Mean Difference	0	
df	14	
t Stat	- 0.141	
P(T<=t) one-tail	0.445	
t Critical one-tail	1.761	
P(T<=t) two-tail	0.890	
t Critical two-tail	2.145	