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# A STUDY OF PERFORMANCE OF GROUND CHARCOAL AS THE COARSE MEDIUM IN DUAL MEDIA FILTRATION OF POTABLE WATER

BY

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## DEPARTMENT OF CIVIL ENGINEERING

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# A STUDY OF PERFORMANCE OF GROUND CHARCOAL AS THE COARSE MEDIUM IN DUAL MEDIA FILTRATION OF POTABLE WATER

BY

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This thesis is my original work and has not been submitted for a degree in any other university.

**Bernard Ochieng'**

This thesis has been submitted for examination with my approval as University Supervisor.

**Mr. S.K. Ngari**

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## Dedication

To

Philister and my parents

Whose unfaltering patience and encouragement formed the impetus to the successful completion of this research work.

## Abstract

The study investigated the performance of ground charcoal as the coarse medium in dual media filtration of potable water. Filtration tests were carried out on bench scale models to assess the performance of the dual media filter as compared to a conventional rapid sand filter for the same influent water quality. The analyses commenced by assessing the media characteristics, namely, appearance, size, relative density, acid solubility, and physical stability. The performance of the filters was evaluated on the basis of turbidity removal, headloss development, and backwashing requirements.

The results from the filtration tests showed better performance of the ground charcoal dual media filter as compared to the conventional rapid sand filter. The dual media filter exhibited a removal capacity between 1.5 to 2 times that of the conventional rapid sand filter. The rapid sand filter registered a higher rate of headloss development than the dual media filter, and needed about 1.1 times more water for backwashing than the dual media filter. The dual media filter also exhibited a unique quality of removal of organic particulates from the raw water.

The results obtained showed that the ground charcoal can be applied as a coarse, light medium in dual media filtration of potable water. However, further research was recommended on the applicability of this media. The application of charcoal is also economically sound due to its widespread availability throughout the country.

## Table of Contents

## Acronyms

| | |
|---|---|
| **WHO** | World Health Organization |
| **NTU** | Nephelometric Turbidity Unit |
| **AWWA** | American Water Works Association |
| **SSF** | Slow Sand Filter |
| **RSF** | Rapid Sand Filter |
| **DMF** | Dual Media Filter |
| **MMF** | Multi Media Filter |
| **GAC** | Granular Activated Carbon |
| **MoWD** | Ministry of Water Development |
| **PVC** | Polyvinyl Chloride |

# Chapter One

## 1.0 Introduction

### 1.1 General

Filtration can be broadly defined as the deliberate passage of raw water or polluted water through a porous medium, thus utilising the principle of natural cleansing of the porous media. The process commonly involves passing the water through a stationary bed of granular medium into which solids in the water are retained. Several modes of operations are possible in granular media filtration. These include upflow, biflow, pressure and vacuum filtration. While any of these may find application under specialised conditions, the most common practice is gravity filtration in a downward mode, with the weight of the water column above the filter providing the driving force.

The filter units play a very important role in water treatment. Filtration normally follows the sedimentation basin. Its main role is to remove suspended matter as well as some particulate contaminants. Although about 90% of turbidity and colour are removed in coagulation and sedimentation, a certain amount of floc is carried over from the settling tanks and requires removal in filtration (Tebbutt, 1991).

Many variables influence the performance of granular media filters. An understanding of filter hydraulics, media characteristics, and operating procedures is necessary for the design of effective granular medium filters. Disinfection, which normally follows filtration is generally affected by the performance of the filter units in several ways.

On one hand, if the filtration is not efficient, resulting in the passage of suspended organic matter, then the addition of some disinfectants such as chlorine can give rise to the formation of harmful halogenated organic compounds such as trihalomethanes.

On the other hand, if the filtration is so efficient such that it removes the particulate contaminants, then the amount of disinfectant needed in the disinfection process is greatly reduced.

There has been an evolution over the years of potable water standards as knowledge of the nature and effects of various contaminants has grown. Currently, it is considered desirable that drinking water be free of suspended solids and turbidity, that it be tasteless and odourless, that dissolved inorganic solids be in moderate quantities, and that organics, toxic substances, and pathogens be absent. As more is learnt about the constituents of water, additional requirements will probably be added to this list, making potable water requirements even more stringent.

The World Health Organisation (WHO) has established minimum criteria for drinking water that all nations are urged to meet. Nevertheless, countries with more advanced technology generally have standards that exceed the quality stipulated by the World Health Organisation.

The duties which the filter is required to perform form the basis on which the method of filtration can be categorised. If the necessity is only the partial removal of suspended matter, then the requirement is for a roughing filter. In the case of filtration for potable water supply, roughing filters are used only for pre-treatment. In this situation, there is need for terminal filters which receive water from other pre-treatment units such as a roughing filter or a clarification process to produce final quality water. Filters which produce final quality water without prior sedimentation or roughing filtration are referred to as direct filters.

Filtration is also employed in providing tertiary treatment to sewage effluents. However, there are some significant differences between filtration of pre-treated wastewater and potable water. Flow rates in water plants are generally constant over extended periods of time because of the use of both upstream and downstream storage. When the flow does change, it is changed deliberately, and adjustments can be made in the number of units in service.

In wastewater plants, on the other hand, the flow is seldom controlled by the operator and fluctuations in flow rate will affect the upstream treatment process. In particular, the suspended solids concentration in the effluent of secondary clarifiers generally increase with increased flow. Thus, at peak flow rates, the filters will experience not only the worst flow but also the worst influent quality. For this reason, design must be based on peak flow rather than the average flow conditions which would be used in drinking water plant design.

There has been a remarkable historical development in filtration. A chronology of this development is as follows:

| | |
|---|---|
| • 1830's | Introduction of slow sand filters in potable water treatment. |
| • 1880's | Introduction of rapid sand filters in potable water treatment. |
| • 1940's | Introduction of rapid sand filters in waste water treatment. |
| • 1960's | Improvement of rapid sand filters by introducing inverse grading |
| • Currently | Application of dual and multi media filters in potable water treatment |

## 1.2 Objectives of the study

The current development in filtration has been the application of dual and multi media filters. There has been a wide variety of materials tested and applied as media in such filters. Amongst these materials, granular activated carbon has generally been recommended for its good performance. It is however unfortunate that activated carbon is not commonly found in Kenya. For this reason, ground charcoal is investigated in this study with a view to establish its performance as a substitute for granular activated carbon. The objective of this study is to compare the performance of the ground charcoal / sand dual media filter with that of a conventional rapid sand filter. The main investigations are:

### Media characteristics:

1. To determine the media characteristics, including appearance, size, density, porosity, acid solubility and physical stability.

**Performance expectations:**

2. To determine the degree of turbidity removal and length of filter runs of the dual media filter as compared to the conventional rapid sand filter.
3. To monitor the headloss development for the dual media filter as compared to the conventional rapid sand filter.
4. To determine the backwash characteristics for the dual media filter as compared to the conventional rapid sand filter.
5. To establish the performance of ground charcoal as the coarse medium in dual media filtration based on the results obtained from objectives 1 to 4

# Chapter Two

## 2.0 Literature review

## 2.1 Theory of filtration

### 2.1.1 General

Most of the theories of filtration dwell primarily on the physical aspects of filtration which include the formulation of changes in headloss as well as concentration of suspended matter throughout the course of a filter run. These parameters are derived from an equation of continuity and an equation stating that the rate of removal of suspended matter per unit depth of filter is proportional to the concentration of suspended matter in the influent to that layer. The constant of proportionality also referred to as the "impediment modulus" is a variable both in time and along the depth of the filter.

The impediment modulus or filter coefficient of a clean filter is a function of the following variables:

- Media size
- Filtration rate
- Viscosity of the water
- Properties of the suspension being filtered

Ives (1972) reviewed the findings of various investigators of the dependence of the impediment modulus on media size $d_m$, filtration rate $v$, and viscosity $\mu$. The modulus is reported to vary from:

$d_m^{-1}$ to $d_m^{-3}$

$v^{0}$ to $v^{-1.56}$

$\mu^{-2.0}$ to $\mu^{+0.5}$

Most of the theoretical treatment of filtration process have assumed that the size of the suspended matter to be filtered is small enough to penetrate into the pores of the filter. If this is not the case, a mat can develop, leading to very rapid increase in headloss as smaller particulate matter is filtered out on the mat. This commonly occurs when large numbers of diatoms are in the water, particularly if the upper filter layer has a small effective size (Ives, 1972).

The most common parameter used in filtration assessment is *turbidity*. The term *turbid* is applied to water containing suspended matter that interferes with the passage of light through the water or in which visual depth is restricted. Turbidity may be caused by a wide variety of suspended materials, which range in size from colloidal to coarse dispersions, depending upon the degree of turbulence. The materials causing turbidity may range from purely inorganic substances to those that are largely organic in nature.

Turbidity is an important consideration in public water supplies for the following reasons:

- **Aesthetics** - Consumers of public water supplies expect and have a right to demand turbidity-free water.
- **Filterability** - Filtration of water is rendered more difficult and costly when turbidity increases.
- **Disinfection** - In turbid waters, pathogenic organisms may be encased in the particles and thus get protected from the disinfectant (Sawyer, 1994).

Turbidity is commonly expressed in *Nephelometric Turbidity Units*, (NTU). Raw water turbidity can vary from less than 1NTU to greater than 1000NTU. Removal of turbidity is achieved by simple filtration, or more effectively, by a combination of coagulation, sedimentation, and filtration.

The World Health Organisation (WHO) states that turbidity value in excess of 5NTU is generally objectionable to consumers. It has set guidelines that turbidity should be kept low, preferably below 1NTU (WHO, 1984).

### 2.1.2 The filtration process

Herbert (1969) reported that the floc particles that reach the filters are those remaining after settling and are not usually representative of those in the flocculation outlet. Large particles break up as they enter and move through the filter bed. At the beginning of the filter run, the floc lodges in the medium near the top of the bed. As the deposited matter collects between the medium grains, the void area diminishes, and the bed offers increasing resistance to the flow of water. Conditions then begin to change. The flow through the larger openings increases, and flow through the smaller and partly clogged openings diminishes. As filtration continues, the small openings become so clogged that they get almost closed. Larger openings, always present, permit the shearing of floc as the hydraulic gradient increases, and floc penetration progresses downward.

It was further reported that in order to produce good quality water with a conventional sand filter, a penetration of no more than 5 to 10cm is desirable, and a penetration of this magnitude is necessary to obtain reasonably long filter runs. When there is little penetration, the hydraulic gradient rapidly becomes large, and the filter runs are too short for practical operation. There is little dislodgement of previously removed particles. Instead, the material most recently applied to the filter generally was found at the greatest depth. This was observed by the use of radioactive tracers (Herbert, 1969).

The flocculated matter removed in the filter compacts during the filtration process, and the process of compacting causes the removed materials to adhere more firmly to the filter media or to other compacted material. The compaction takes time, and if too great a volume of suspended matter is applied to a filter, it may breakthrough before it becomes compacted. The compaction of the material has been observed by comparing the nature of flocculated material in filter waste wash water with that of the floc of the water applied to the filters. Filter waste wash water contains very compact flocs (Herbert, 1969).

### 2.1.3 Removal efficiency of a clean filter

The efficiency of a filter in removing suspended solids depends on:

- the characteristics of the suspended solids;

- the characteristics of the water;
- the characteristics of the filter media;
- the method of filter operation.

Many possible mechanisms for particle removal by granular filters have been proposed by researchers. It has been generally accepted that two processes contribute to the separation of suspended matter from a liquid stream. These two phenomena are:

- *Transport* of particulate to a contact point on a grain of the filter media.
- *Attachment* of the particles to the grain surface or to particulates that had previously adhered to grain surfaces (Kuan, 1971).
-

### 2.1.4 Transport mechanism

The particle may be conveyed to the filter medium by one or more physical processes, including mainly interception, sedimentation, diffusion and straining. The chemical nature of the particle is of no major significance in these processes. An illustration is given in Figure 2.1 expounding on the transport to the surface of a single filter grain (collector).

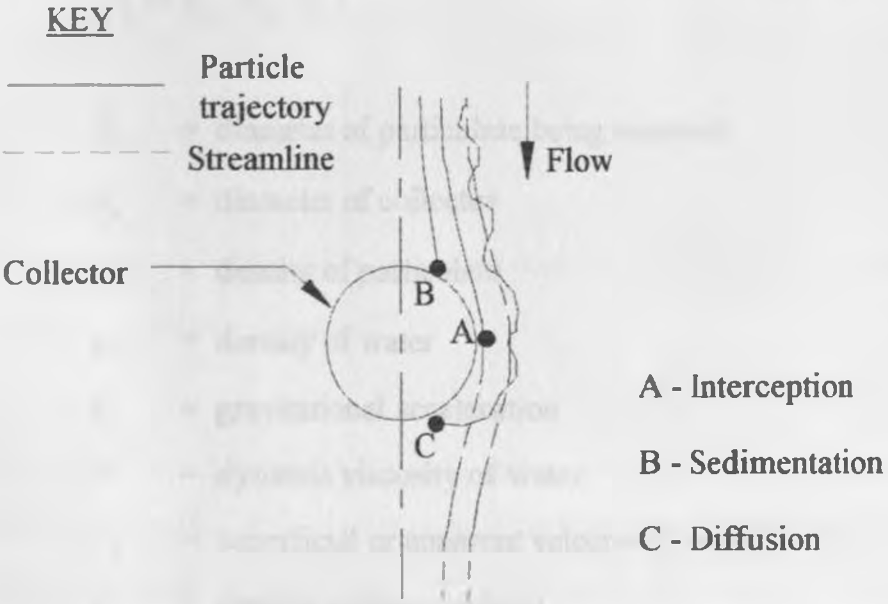

Figure 2.1: Basic transport mechanisms in water filtration (Kuan, 1971).

The contact efficiency in the transport mechanism is a summation of the efficiencies of the three main processes of interception, sedimentation and diffusion as is given in Equation 2.1 (Kuan, 1971)

$$\eta_{contact} = \eta_I + \eta_S + \eta_D \qquad \text{.................................(Eqn. 2.1)}$$

where $\eta_I$ = contact efficiency by interception

$\eta_S$ = contact efficiency by sedimentation

$\eta_D$ = contact efficiency by diffusion

$$\eta_I = \frac{3}{2}\left({}^{d_p}\!/_{d_g}\right)^2 \qquad \text{.................................(Eqn. 2.2)}$$

$$\eta_S = \frac{(\rho_p - \rho_w)\cdot g \cdot d_p^{\,2}}{18\cdot \mu \cdot v_0} = {}^{v_s}\!/_{v_0} \qquad \text{.................................(Eqn. 2.3)}$$

$$\eta_D = 4.04(Pe)^{-2/3} = 0.9\left[\frac{K\cdot T}{\mu \cdot d_p \cdot d_g \cdot v_0}\right]^{2/3} \qquad \text{.................................(Eqn. 2.4)}$$

where $d_p$ = diameter of particulate being removed

$d_g$ = diameter of collector

$\rho_p$ = density of particulate

$\rho_w$ = density of water

$g$ = gravitational acceleration

$\mu$ = dynamic viscosity of water

$v_0$ = superficial or apparent velocity of water

$v_s$ = particle settling velocity

$Pe$ = Peclet number

$K$ = Boltzmann's constant

$T$ = absolute temperature

### 2.1.5 Attachment step

The attachment step is very much affected by the chemical and physico-chemical variables. It consists of the actual joining of the particulate to the filter grain by either the Van der Waals forces, double layer interaction, or hydrogen bonding. The filter grain in this case can therefore be viewed as including material that has been removed from the suspension and is attached to the bed grains. Attachment can be enhanced by the use of coagulants: Fe(III) or Al(III) if added prior to the filter.

The attachment efficiency can be analysed by the use of Equation 2.5

$$\alpha = \frac{\text{number of contacts resulting in adhesion}}{\text{total number of contacts}} \qquad \text{.................................(Eqn. 2.5)}$$

where $\alpha$ = attachment efficiency

$\alpha = 1$ for ideally destabilised particles.

$\alpha \ll 10^{-2}$ for stable colloids.

$\alpha \approx 10^{-1}$ to $10^{-2}$ typically obtained by chemical destabilisation under conditions of water treatment (Kuan, 1971).

### 2.1.6 Overall efficiency

The overall collection efficiency of a single grain is given as the product of the collection efficiencies for transport and attachment as is given in Equation 2.6. The typical values of the overall collection efficiencies are of the order $10^{-5}$ to $10^{-3}$ (Kuan, 1971).

$$\eta_{collection} = \eta_{contact} \times \alpha \qquad \text{.................................(Eqn. 2.6)}$$

## 2.2 Advances in filtration methods

Advances in the conventional filtration methods have been concerned mainly with the optimum choice of filter media to improve filter bed capacity and to improve filtration rates.

The down-flow hydraulically graded single-medium filter was dismissed to be a poor design since the water to be filtered first encountered the finest medium, and most of the removal took place at or near the surface. This situation was initially improved by specifying media of nearly uniform sizes and using coarser media than the 0.4 - 0.5mm sand that had been commonly used in rapid filters. In the US, sand of 0.6 - 0.8mm came into use, and European designers used sand from 1.0 - 2.0mm in diameter (Ives, 1972).

Improvement was further made by the introduction of the coal-sand dual-media filter, which permitted the use of a relatively coarse coal over a finer sand to obtain a closer approach to the ideal coarse-to-fine grading of media in the direction of flow. There has recently been some applications of three-media beds using coal, silica sand, and garnet. It has been observed that the two or three media filters, where installed, have shown superiority in performance over single-medium down-flow filters (Ives, 1972).

Similarly, advancements gave rise to what is termed as *capped filters*. Capping filters involve the removal of 5 - 15cm of the top sand from a conventional rapid sand filter and replacing it with 0.9mm of anthracite coal (Nelson, 1969). The coal serves as a roughing pre-filter and relieves the sand of much of the load. The filter runs are therefore greatly lengthened. This is enhanced by a combination of low clogging rate of the coarse material together with the high filtering ability of the finer material beneath it.

A test carried out in Illinois (Nelson, 1969) involved the removal of 13cm of 0.5mm sand which was replaced by 0.9mm of anthracite coal. The results were astounding. At equal rates of filtration, the sand filters were averaging 35-hour runs at 2.7m loss of head. The anthracite coal capped filter had the following results.

- 1st run 121 hours at 1.9m loss of head

- 2nd run 216 hours at 2.5m loss of head
- 3rd run 187 hours at 2.7m loss of head

All these tests were done in a 23 day period.

The use of filter aids has further advanced the filtration process. The development of activated silica as a coagulant aid has led to an increase in the shear strength of floc and reduction in the penetration of floc into filters. Activated silica has been used in small concentrations immediately ahead of filters to control floc penetration. This has helped in controlling turbidity breakthrough. The use of activated silica in addition to organic polyelectrolytes (which are also filter aids) have given remarkable results in prolonging of filter runs until the limiting headloss is reached (Ives, 1972).

## 2.3 Types of filters

There has been a remarkable metamorphosis in the physical structure of the filter units, with the slow sand filters being the original filters used in the early 19th century. This has gradually been replaced by the rapid sand filters which have shown better performance especially in terms of rate of filtration. The rapid sand filters have of late been modified into what is termed as multi media filters whose physical structure comprises of strata of different media. The multi media filters have shown an even better performance as compared to rapid sand filters. Several materials have been proposed for use in multi media filters, such as shale, pumice, anthracite, activated carbon, plastics, limestone, crushed coconut shell, several forms of coal, amongst others.

### 2.3.1 Slow sand filters (SSF)

These are an imitation of natural percolation of water into the ground. They are mainly used for the removal of micro-organisms by straining at or near the bed surface. There is normally a formation of a gelatinous biologically active layer called the “schumtzdecke” or filter skin and biodegradation occurs here of micro-organisms and biodegradable dissolved and colloidal organic matter. This schmutzdecke requires time in the range of 6 hours to as much as 30 days to form (Terence, 1991). This is referred to as filter ripening. The slow sand filter is therefore also referred to as *surface filter* or *biological filter*.

The principle purification processes taking place during slow sand filtration are sedimentation, mechanical straining, adsorption and biochemical processes in the biological layer. The biochemical processes of significance are:

- partial oxidation and breakdown of organic substances forming water, $CO_2$ and inorganic salts;
- conversion of soluble iron and manganese compounds into insoluble hydroxides which attach themselves to the grain surfaces;
- killing of E. Coli and of pathogens.

In the United States, slow sand filters are typically applied to waters with very low turbidity and thus require no pre-treatment (Terence, 1991).

### 2.3.2 Rapid sand filters (RSF)

Rapid filtration is mainly based on the principle of mechanical straining of suspended matter due to the screening effect of the filter bed (sand, gravel, etc). The particles in the water pass into the filter bed and lodge in the voids between grains of the medium. It is because of this phenomenon that rapid filters are sometimes referred to as *space filters*. Also operative to some degree in rapid filters are boundary layer and biological mechanisms whose extent largely depend on the filtration rate, filter medium, depth of the filter bed, and quality of the raw water (Gabriele, 1985).

The filter media in RSF is coarser than in SSF and the hydraulic loading rate is also much higher. The suspended solids in the RSF penetrate deeply into the bed and are accumulated throughout the filter bed. The headloss rises rapidly and the filter must be cleaned regularly (backwashing). Twort (1985) reported that the particles which may be removed by simple filtration, for example, mineral particles or diatoms, may be at least twenty times smaller than the size of the grain of the filter media.

The following are some of the problems encountered in the operation and maintenance of rapid sand filters.

(i) Mud balls

These are caused by the suspended matter (dirt) cementing the sand particles. The mud balls do not allow air or water to pass through them. They occur when there is insufficient backwashing caused by insufficient backwashing time. A schematic representation of a mud ball is shown in Figure 2.2

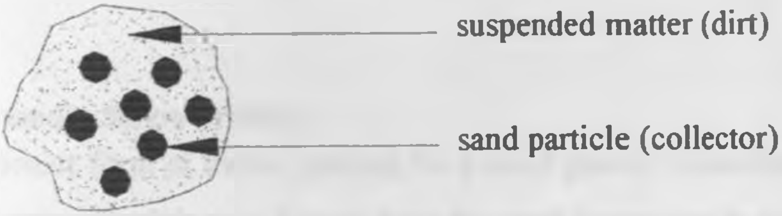

Figure 2.2: Schematic representation of a mud ball

(ii) Loss of fine sand

Fine particles at the surface are washed away during backwashing thereby changing the grading. This occurs gradually even over a decade. After some time, the sand should be replaced to conform to the required grading.

(iii) Sand boils

During backwashing, the gravel may be pushed up or right through the filter bed due to a larger flow rate than the design, hence the surface appears as if it is boiling. The whole mass of the filter bed then rises up.

(iv) Filter cracks

These are caused by uneven flows resulting in cracks along the bed. They are more distinct in dirt cemented sand. Filter cracks result in uneven flow in the filter bed. Figure 2.3 shows an illustration of filter cracks.

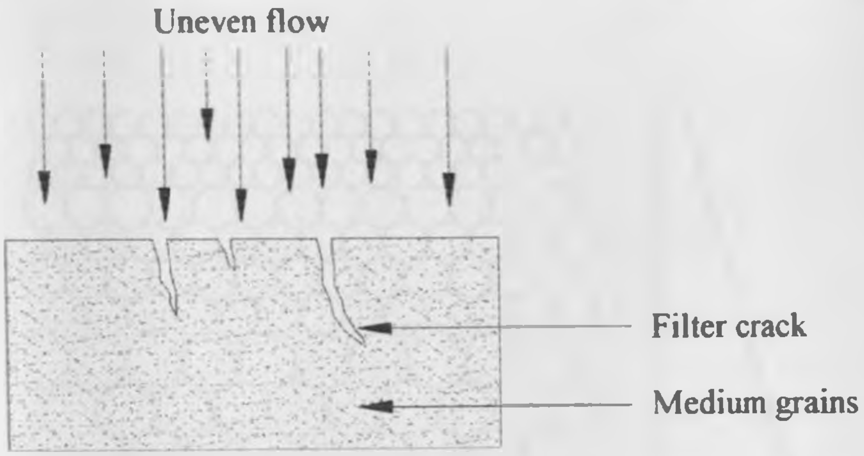

Figure 2.3: Schematic representation of filter cracks.

### 2.3.3 Multi media filters (MMF)

The most efficient form of media grading for a rapid gravity down-flow filter in order to obtain maximum capture of solids would be to have the sand decreasing in size in the direction of flow. However, this is not possible because hydraulic regrading takes place during backwash, so that the finer sand collects at the surface of the bed. This can be countered by using separate layers of different filter materials having different density and grain size.

Multi media filters are composed of media of several different materials. Normally, the lightest coarsest material is segregated towards the top of the filter, and the heaviest, finest material is segregated towards the bottom. This arrangement of coarser to finer filtration has several advantages over the single medium filtration. Some of the advantages are listed below.

- large solids storage capacity in the coarser layer
- good protection against solid breakthrough in the fine grained layer
- good overall utilisation of the entire filter volume
- lower headloss and longer run time before maximum headloss is reached
- higher permissible solids loading
- ability to filter large particulates without danger of straining and surface filtration

Graphical representations of various media designs are given in Figures 2.4 to 2.7

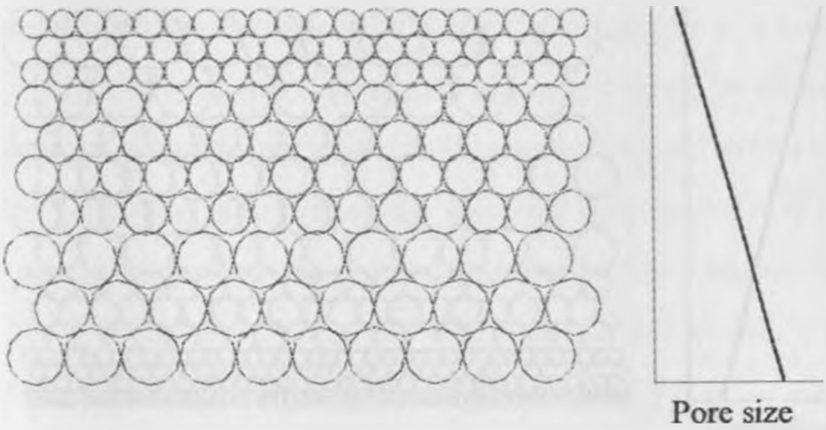

Figure 2.4: Cross-section through single medium bed, such as conventional rapid sand filter.

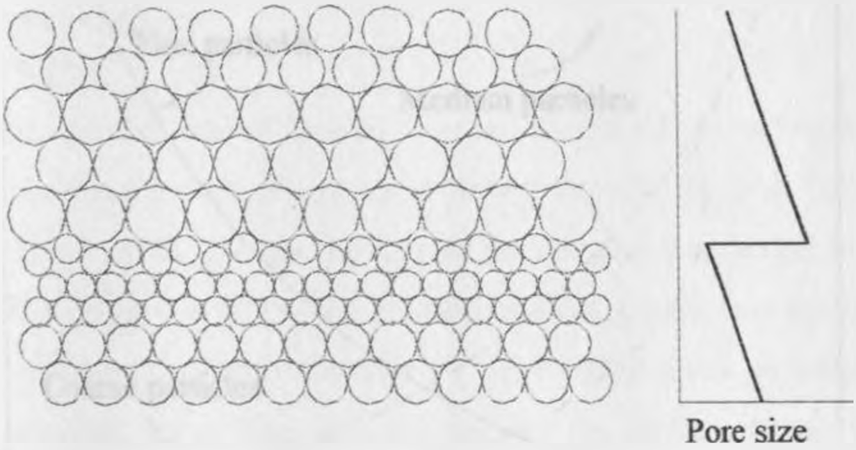

Figure 2.5: Cross-section through dual media bed; Coarse medium above fine sand.

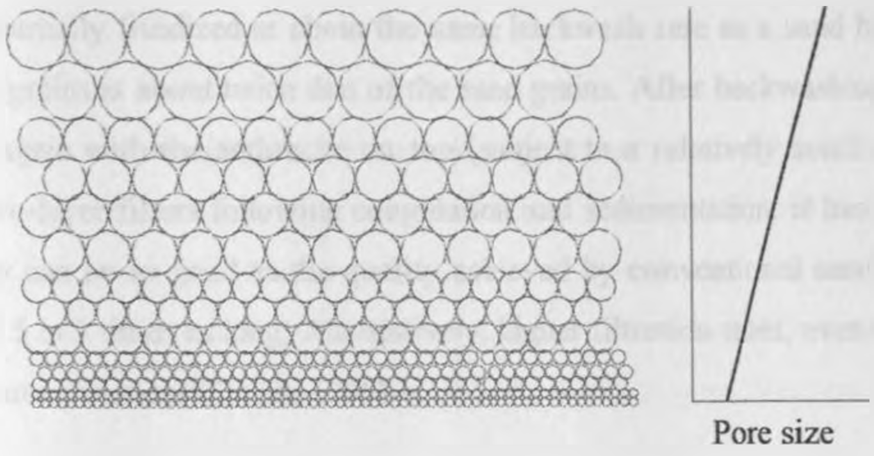

Figure 2.6: Cross-section through ideal filter:
Uniformly graded from coarse to fine from up to bottom.

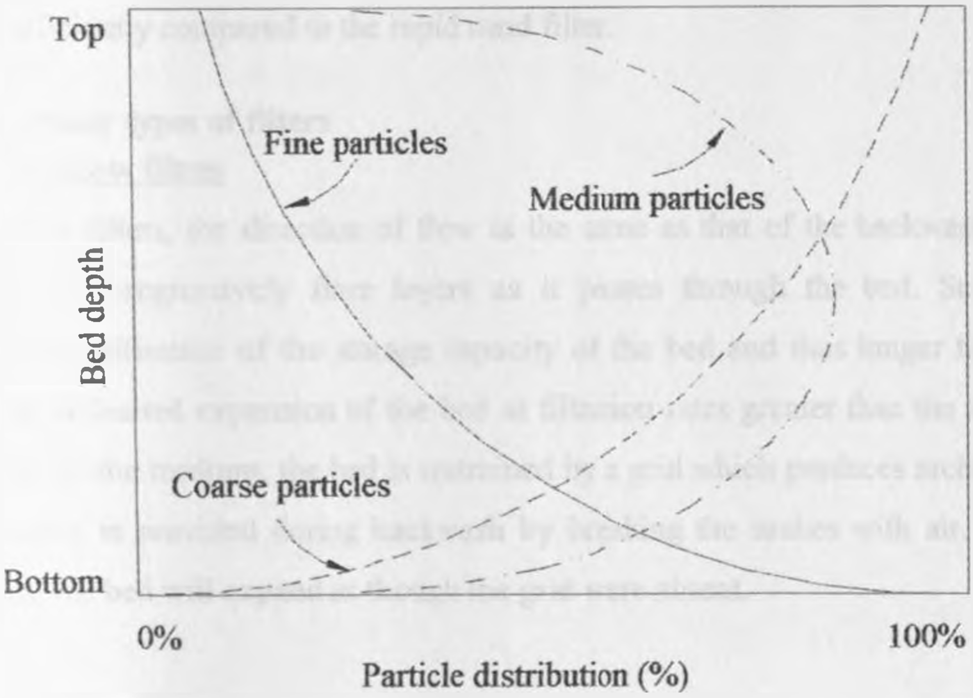

Figure 2.7: Distribution of media in a properly designed
mixed-media filter.

One type of multi media filter bed in wide use at present is the two-layer filter using anthracite over sand. The relative density of anthracite is lower than that of sand. Beds of anthracite can be expanded or partially fluidized at about the same backwash rate as a sand bed when the size of the anthracite grains is about twice that of the sand grains. After backwashing, the two layer bed settles down again with the anthracite on top (subject to a relatively small amount of mixing). With these two-layer filters following coagulation and sedimentation, it has been found that the filtrate quality can be as good as the quality achieved by conventional sand filtration, but filter runs can be 1.5 to 3 times as long. Alternatively, higher filtration rates, even up to 17m/h, can be achieved in some instances (Twort, 1985).

Ndiba (1992) reported that the RSF took only 4 to 5 hours to achieve a headloss of 164cm while a dual media filter with crushed coconut shell took 14 hours to achieve a headloss of 153cm. He further reported that approximately 30% of the headloss in the dual media filter was found to be in the crushed coconut shell layer, and that the dual media filter could handle unsettled water more efficiently compared to the rapid sand filter.

### 2.3.4 Other types of filters

(i) Upflow filters

In upflow filters, the direction of flow is the same as that of the backwash, hence the water is filtered by progressively finer layers as it passes through the bed. Such a design permits maximum utilisation of the storage capacity of the bed and thus longer filter runs. In order to prevent undesired expansion of the bed at filtration rates greater than the minimum fluidization velocity of the medium, the bed is restrained by a grid which produces arching in the fine grains. Expansion is provided during backwash by breaking the arches with air. Once the arches are broken, the bed will expand as though the grid were absent.

(ii) Biflow filters

These employ a modification of the upflow principle in which the expansion of the bed is restrained by directing a portion of the flow downwards. Effluent is collected through a screened pipe a few centimetres below the upper surface of the sand. Approximately 80 percent of the flow is directed upward and 20 percent downward in this system (Terence, 1991).

(iii) Pressure filters

Pressure filters are rapid filters contained in a pressure vessel. The filter cross section and medium are similar to those in standard rapid filters. Pressure filters are primarily applied in removal of precipitated iron and manganese, in treating industrial process waters, and in filtration of re-circulated swimming-pool water. The advantage of pressure filters over gravity units is that more pressure is available to drive the water through the filter and filter runs are proportionately longer.

A summary of some of the operation and design features for slow sand filters, rapid sand filters, and general properties of multi media filters are given in Table 2.1

Table 2.1: General operation and design features for SSF, RSF, and MMF

| Feature | Slow sand filters | Rapid sand filters | Multi media filters |
|---|---|---|---|
| Filtration rate | 0.04 - 0.4 m/h | 3.0 - 10 m/h | 2 - 3 times as RSF |
| Length of run | 20 - 60 days | 12 - 72 hours | longer than RSF |
| Size of bed | Large: around $200m^2$ | Small: 40 - $400m^2$ | Same as RSF |
| Size of sand | E = 0.25 - 0.35mm<br>U = 2 - 3 | E = 0.45mm or higher<br>U = 1.3 - 1.8 | Sand - same as RSF + coarse media |
| Depth of bed | 300mm gravel supporting 1.0m sand (reduced to 600mm by scraping when cleaning) | 300 - 450mm gravel + 600 - 900mm sand (no gravel in some) | 300 - 400 sand + layers of other coarse media |
| Method of cleaning | i) Scraping off 15cm surface layer<br>ii) In-place washing by travelling washer | Scouring by air and / or water or mechanical rakes. Removal of dislodged particles by stream of backflowing water stratified due to backwash. | Backwashing with filtered water |
| Grain pattern | Unstratified | Stratified | Stratified |
| Loss of head | 60mm initial to 1.2m final | 300mm initial to 2.6m final | Lower headloss |
| Penetration by particles | Superficial | Deep | Deep |
| Pre-treatment of raw water | Generally none. If very turbid, then roughing filtration | Coagulation / flocculation followed by sedimentation | Need for pre-treatment depends on type of MMF |
| Secondary treatment | Chlorination (precautionary) | Chlorination | Chlorination |
| Bacteria removal | 99 - 99.9% removal of pathogenic bacteria and E. Coli. Complete removal of cysts, helminth-eggs and schistosoma-larvae | Removal of some 50% at low filtration rate and fine material. Subsequent disinfection is required. | Not reported |

## 2.4 Filter media

### 2.4.1 Common filter media

#### 2.4.1.1 Sand

The cheapest and most commonly available filter medium is sand. Sand used in slow and rapid sand filters should be free of dirt, be hard and resistant to abrasion, and preferably be quartz or quartzite. It should not loose more than 5% by weight after 24 hours immersion in 40% hydrochloric acid. In present practice, sand with an effective size of 0.45 to 0.55mm and a uniformity coefficient from 1.2 to 1.7 is used in rapid filters. Slow sand filters commonly employ effective sizes of 0.1 to 0.3mm and uniformity coefficients of 2 to 3 (Terence, 1991).

Filter sands are classified as *coarse*, *medium*, or *fine*. Steel (1953) gave the sand sizes as shown in Table 2.2

Table 2.2: Filter sand grain size distribution by percent size* (Steel, 1953)

| Percent size | Grain size, mm | | | | | |
|---|---|---|---|---|---|---|
| | Fine | | Medium | | Coarse | |
| | Min. | Max. | Min. | Max. | Min. | Max. |
| 1 | 0.26 | 0.32 | 0.34 | 0.39 | 0.41 | 0.45 |
| 10 | 0.35 | 0.45 | 0.45 | 0.55 | 0.55 | 0.65 |
| 60 | 0.53 | 0.75 | 0.68 | 0.91 | 0.83 | 1.08 |
| 99 | 0.93 | 1.50 | 1.19 | 1.80 | 1.46 | 2.00 |

**Note: A percent size of 10 means that 10 percent of the sand is smaller than the size given*

*Coarse sands* are suitable when:

- pre-treatment can be expected to be good;
- the water to be treated is not highly polluted;
- benefits resulting from the longer filter runs that will be obtained and the smaller amount of wash water used will offset any disadvantages from water of lower quality;
- the filter design will permit the necessarily high backwash rates.

*Fine sands* are suitable when:

- pre-treatment may be poor at times;
- high efficiency in removal of bacteria and turbidity is needed;
- saving of wash waters and other benefits of longer filter runs are not important;
- filter design permits low backwash rates that will clean the fine sands only;
- if softening of the water will be practiced and rapid increase in sand grain size with calcium carbonate is expected (Steel, 1953).

*Medium sands* are a compromise between coarse and fine and are suitable for average conditions.

#### 2.4.1.2 Gravel

Gravel is used to support the sand, permit the filtered water to move freely to the underdrains, and also to allow wash water to move more or less uniformly upwards to the sand. It is placed to a depth of about 300mm. It should be hard, rounded, durable, free from flat, thin or long pieces, and contain no loam, sand, clay or other foreign material (Steel, 1953)

Commonly, unequal distribution of wash water causes a jet action and moulding of gravel at the sand-gravel interface. Steel (1953) reported that this might be reduced by use of a layer of coarse sand in addition to graded gravel. A 10cm layer of material between 1 and 2mm in size would improve the conditions.

#### 2.4.1.3 Anthracite coal

Crushed anthracite has been used as a substitute for sand in a number of plants. The crushed anthracite has an effective size of 0.70 to 0.75mm and a uniformity coefficient not exceeding 1.75 (Steel, 1953).

The following advantages have been noted in the use of anthracite:

- less wash water required

longer filter runs

higher filtration rates

### .4.1.4 Granular activated carbon (GAC)

\ctivated carbon can be prepared from virtually any organic solid (coal, lignite, wood, etc) by a listinctive distillation process which drives off the volatile components of the material, leaving behind a porous carbon skeleton which has very large surface area per unit volume. This skeleton s then "activated" by steam in an oxygen depleted atmosphere at temperatures ranging from 750 o 950° C. often with addition of dehydrating agents such as zinc chloride or phosphoric acid Terence. 1991).

The molecules in the solution are attracted to. and held by a surface in contact with the solution. The forces holding adsorbed molecules to the surface may result from either chemical bonding or van der Waals attraction. Adsorption then removes the molecules from solution.

The use of activated carbon is generally the most effective of all methods of removing "earthy" or "mouldy" tastes or odours. Activated carbon is also effective in removing a wide range of complex organic substances, for example pesticides and aromatic hydrocarbons (Twort, 1985).

Experiments were conducted in Zurich, Switzerland with single medium and dual media rapid filters. The dual media filter, consisting of 60cm quartz sand and 20cm GAC were compared with a single medium filter filled only with 80cm quartz sand. The filter run was five times longer for the dual media GAC filters, compared to the single medium filters, with the removal efficiency being equal.

The length of the filter run for the dual media filter was also found to be dependent upon the grain size of the GAC. The headloss took place in the GAC layer. After intensive air rinsing, it was possible to rigorously separate the quartz sand and the GAC with a backwash water velocity f only 15m$^3$/m$^2$/hr. It was finally noted that the GAC must be either replaced or reactivated very two years (Schalekamp. 1979).

### .4.2 Other media

everal materials have been proposed for use as filter media. Some of these materials have been ested and applied in pilot plants, for example, a two-layer coconut fibre/burnt rice husk filter vas developed and tested in Southeast Asia where it is widely used (Gabriele, 1985). Other naterials include charcoal, garnet sand, ilmenite and plastics.

## .5 Specifications for filter media

### .5.1 Testing of filter media

Engineering specifications usually require associated methods of testing, and as the filtration of water for potable purposes has a common basis internationally, it should be possible to specify tests for filter media which are generally applicable. There are several tests which can be carried out on the filter media to determine the media's physical and chemical characteristics. The most common tests have been described below.

(i) Appearance

The homogeneity and cleanliness of a sample of granular material can be determined by assessing it by the eye. Dirty samples should be thoroughly washed and dried before further tests are conducted. Detailed information regarding shape, surface texture and uniformity can be yielded by the examination of some of the cleaned, dried grains under low-power microscopy. Magnifications of 20 times to 80 times are sufficient for most grain sizes, and the use of stereomicroscopy enhances the images, particularly surface texture and shape (Ives, 1990).

(ii) Sieve sizing

Sieve sizing is the most common specification of granular filter material. The sieving results, reported by the mass (or weight) of grains retained on each successively finer sieve, are usually presented as a cumulative weight curve. When presented as cumulative percentage finer than the given sieve opening, it is then possible to read directly the Hazen effective size ($d_{10}$), and to determine the Hazen uniformity coefficient ($d_{60}/d_{10}$). The uniformity coefficient is a measure of the spread of sizes, accounting for a range of 50% by weight. The larger its value, the greater the range of sizes.

According to Ives (1990), there is no size specification that is best for all cases of water filtration. The size specification must be appropriate to the water to be filtered; its pre-treatment, the flow rate, the desired filtrate quality, length of filter run, backwash conditions, etc.

### (iii) Density

The density of granular material is vital when considering the backwashing / fluidization behaviour of the filter grains particularly in the case of stratified filters with multiple layers. The density can be easily determined by the use of a density bottle. This should be done after all the air has been expelled from the sample. With some porous materials, like anthracite, this may require soaking in water for 24 hours and slow stirring (Ives, 1990).

### (iv) Settling velocity

The settling velocity is a useful characteristic for two reasons. First, it determines the stratification behaviour if water alone is used for the final phase of a backwashing sequence. Secondly, interpretation of the settling velocity, using fluid mechanical theory (often in the transitional, or non-Stokesian, settling regime) can give the equivalent hydraulic diameter of a sphere of the same settling velocity. This leads to the calculation of hydraulic shape (Ives, 1990).

The settling velocity can be observed by timing the fall of 20 individual grains through a 1m column of water of known temperature (20°C is usual). The grains should be pre-wetted, and the insertion with tweezers allows their release approximately on the column axis (Ives, 1990).

### (v) Shape

As has already been mentioned, the fall velocity can be useful to derive the hydraulic shape, or sphericity, of the grains. For a sphere, sphericity ($\varphi$) = 1.0, and for a non sphere, $\varphi < 1.0$

Flaky shapes are normally not desirable as filter material. This is because flaky shapes may settle after backwashing in a flat layer with extremely different vertical and horizontal permeabilities, which can lead to clogging of particles. Angular grains have more surface area than a spherical grain of the same sieve size. This accounts for improved filtration when angular grains are used instead of spherical grains (Ives, 1990).

(vi) Porosity

Porosity, which is the pore volume per unit filter volume, is a useful measure for it enables the mass (weight) of media to be calculated to fill a given volume of the filter. Porosity depends on the sphericity of the grains. Particles of sphericity close to 1.0 pack more closely and hence have a lower porosity (Ives, 1990).

Porosity ($\varepsilon$) is calculated from Equation 2.7 given below.

$$\varepsilon = 1 - \left(\frac{M}{\rho_g \cdot V}\right) \qquad \text{.................................(Eqn. 2.7)}$$

where $M$ = mass of media in the filter column

$\rho_g$ = density of the media

$V$ = apparent volume occupied by media in the column

(vii) Acid solubility

A test with hydrochloric acid is commonly required in filter media specifications. This ensures the integrity of the grains; that they are solid and not aggregated particles which may be cemented. Also, the presence of calcium carbonate shell fragments will be detected by the loss of weight, and effervescence in acid.

A severe acid test using 50% HCl. with a loss of weight limit of 5% is the requirement stated by AWWA. The practice at University College of London applies 20% HCl with immersion of the grains for 24 hours at 20°C. The grains are then washed with distilled water and dried at 110°C and then re-weighed. A weight loss of more than 2% is regarded as unsatisfactory (Ives, 1990).

### 2.5.2 Characteristics of a filter medium

The choice of size, size distribution, and density of the filter medium is an important aspect of the filter design. Through these variables, the engineer attempts to match the filter to the characteristics of the water to be filtered and also to the desired quality and quantity of the output.

The two parameters which are used in describing the characteristics of the medium are *effective size* and *uniformity coefficient*. The effective size is the sieve size which permits 10% of the medium by weight to pass. The uniformity coefficient is the ratio of the sieve size which permits 60% by weight to pass to the effective size.

It has been observed that finer materials produce higher headloss but provide better protection against passage of small particles. On the other hand, coarse materials require higher backwash velocities for fluidization, but are less likely to form mud balls during backwashing. Uniform materials permit deeper penetration of flocs and better utilisation of the storage capacity of the bed.

## 2.6 Performance of a clean filter

### 2.6.1 Filtration requirements

Filtration is an interaction between a suspension and a filtration material. In some cases coarse grains are required, in others fine grains, or multiple layers of different materials. The designer has to decide on the medium, depth, rate of flow, filtrate quality, length of run and backwash conditions. Most of these filtration requirements can be determined by use of pilot or bench scale plants, but some initial testing can be carried out using a Filterability Number Test. In this test, the pre-treatment conditions can be tested on a very small scale, to achieve the optimum conditions for a given filter material.

Alternatively, different filter materials (size, shape) can be tested against a given suspension, and the effect of flow rate can be evaluated to give an optimum. This is not a design procedure, but can reduce the number of pilot trials by initial testing of some of the alternatives, such as pre-flocculation, sedimentation, flow rate and filter medium.

### 2.6.2 Determination of performance of filter media

The basis of the measurement of the performance of a clean filter is the *headloss*. The headloss (expressed in metres of water) in a clean bed of porous media can be estimated by means of the Kozeny Carman equation given in Equation 2.8

$$\frac{h}{L}=\frac{k\cdot\gamma}{g}\cdot\frac{(1-\varepsilon)^2}{\varepsilon^3}\cdot\left(\frac{6}{\varphi}\right)^2\cdot\frac{v_0}{d_g{}^2} \quad \text{for laminar flow} \quad \text{......................(Eqn. 2.8)}$$

where $h$ = headloss, m

$L$ = depth of filter bed, m

$k$ = fitting parameter, $5<k<7$

$\gamma$ = kinematic viscosity, $m^2s^{-1}$

$g$ = gravitational acceleration, $ms^{-2}$

$\varepsilon$ = bed porosity, typically $0.35<\varepsilon<0.5$

$\varphi$ = sphericity $\approx$ 1.0 for spheres

$\approx$ 0.8 for angular grains

$v_0$ = apparent velocity of flowing water based on empty cross-sectional area of bed, $ms^{-1}$

$d_g$ = grain diameter of filter media, m

A filter run is usually terminated and the filter cleaned either because the headloss through the filter has reached the operationally determined maximum or because the suspended matter has penetrated the filter and the effluent turbidity exceeds the amount considered acceptable. It is desirable to have the limiting headloss reached at about the same time as onset of turbidity breakthrough.

### 2.6.3 Headloss and negative pressure

When water passes through filter and underdrains, it experiences frictional resistance and therefore a loss of head occurs. When this loss of head exceeds 1.5 - 2.5m, the filter needs cleaning. The top layer offers maximum resistance and the loss of head due to friction in this layer exceeds the static head or depth of water above this layer; a vacuum is created below this layer which is called a "negative head" which causes a suction effect (Husain, 1994).

## 2.7 Backwashing of granular filters

After reaching the limiting conditions of solids breakthrough or maximum headloss, the filter is backwashed. The filter gets fluidized during backwashing and the grains are cleaned of the deposited solids by hydraulic shear and abrasion.

There are various categories of backwashing. These are:

1. High-rate backwashing - This provides full bed fluidization and substantial bed expansion (20 - 50%). It is normally preceded and followed by a lower rate backwash. This backwash system can be used with single and multi media filters.
2. Low-rate backwash with little or no bed fluidization or bed expansion - In this category, auxiliary scour is essential. This system can be used with single medium filters only.
3. Water backwash with surface-wash auxiliary.
4. Water backwash with air auxiliary
    a) Air scour followed by low-rate water backwash - for use with single medium filters only.

b) Air scour followed by high-rate water backwash - for use with single and multi media filters.

c) Simultaneous air scour and low-rate water backwash followed by high-rate water backwash alone - for use with single and multi media filters.

The complexity of the backwash problem is compounded by the types of media being used and special needs related to the various media. For example, the use of air scour auxiliary during backwash causes mixing of the media. On the other hand, the use of high-rate water backwash causes some stratification of the media, in which the fine sized grains of the medium collect at the upper layers.

The effectiveness of the various backwashing systems are influenced by the following factors:

1. Media size - coarse media will react differently to high or low upflow velocity or to surface wash or air scour from fine media.
2. Media shape - rounded grains are generally thought to be easier to clean than angular grains or flat grains.
3. Media density - denser material needs higher velocities to suspend it in the upflow, increasing the hydrodynamic forces at the water - filter-grain interfaces.
4. Water quality - coloured, turbid, or softened water behave differently regarding ability to form mud balls or to attach the dirt firmly to the grains.
5. Coagulant used - the amount and type of coagulants used (metallic coagulant or polyelectrolyte) change the “adhesiveness” of the film formed around the grains. Weak or strong flocs will also behave differently with regard to ease of backwashing.

These factors are interrelated and make drawing definite conclusions about the best backwashing systems for general use difficult. Comparison must be made for each case according to the media and the water characteristics involved. The fact that so many variables have to be taken into account probably explains why the same backwashing procedure may be a success in one treatment plant and a failure in another (Cleasby, 1977).

## 2.8 Research done on characteristics of dual and multi media filters

*I.* ***Testing different filter materials (for shape, size, etc) against a given suspension and evaluating the effect of flow rate to give an optimum*** *(Mohanka, 1969).*

The selection of media for the multi media filter was a result of various individual investigations of densities, settling velocities, and sieve sizes for various plastic grains, anthracite, crushed flint sand, garnet, magnetite and alumina. The final multi media filter was composed of extruded granules of polystyrene, anthracite, crushed flint sand, garnet, and magnetite. The apparatus was designed in such a way that it allowed for comparison between a conventional sand filter and a multi media filter. The conventional sand filter contained equivalent gradings of flint sand and ordinary sand only.

The suspension selected for use in the test comprised of particulate matter which was the flocculant hydrolysis product of Iron Chloride ($FeCl_3$) in London tap water. It was representative of the flocculant matter in the influent to a rapid sand filter, and its concentration was determinable with relative ease.

Experimental results

*(i) Initial headloss* - several filter runs were made at different filtration rates. The headloss at various points throughout the depth of filter was recorded. Plots were then made of headloss versus depth from the inlet surface. The hydraulic gradient calculated from the experimental results showed good agreement with the theoretical value obtained from Kozeny's equation.

*(ii) Backwashing tests* - The headloss and percentage expansion of various media were plotted against backwash rate. It was observed that the expansion of polystyrene was very high, as expected, because its density is very close to that of water.

*(iii) Filtration tests* - The results obtained from experiments were plotted and a set of curves prepared as follows

- Total headloss versus time
- Headloss versus depth, for varying time intervals
- Percentage of iron concentration versus depth, for varying time intervals

- Hydraulic gradient versus time, for various depths
- Filtrate versus time, for varying flow rates

Conclusions

The researcher gave the following conclusions:

i) The multi media filter permitted deeper penetration of flocs. It could therefore be utilised more efficiently than the sand filter.

ii) The main problem with the multi media filter concerned backwashing. It required more backwash water and sufficient room for the expansion of the top layer.

iii) Programmed backwashing cycle was necessary for progressively expanding and fluidizing the bed. This was necessary for ensuring proper cleaning of the multi media filter.

iv) Garnet and magnetite exhibited similar performance to crushed flint sand of equivalent gradation under identical flow conditions, that is, they had the same removal characteristics.

v) For the same filtrate concentration during a given run time, the ratio of headloss in sand filter to that of multi media filter was found to range between 2.5 and 1.6 for the various filtration rates.

vi) The use of polystyrene as a top layer did not prove so efficient as expected; there was therefore need for careful selection of the top layer of a multi media filter bed.

vii) The performance of the multi media filter was governed both by the filtering velocity and by the applied inlet concentration.

Further research

The researcher reported that since multi media filtration allowed the floc to penetrate deeper into the bed, it can serve well where the influent is comprised of suspensions of high concentrations. He therefore recommended it for the tertiary treatment of sewage where large amounts of suspended solids could be handled by this type of filter.

The researcher also recommended that this type of filter might be useful for the reclamation of large storm water flows, where coarse media could be used to remove effectively large amounts of suspended solids.

*II.* ***Pilot scale testing of pre-treatment conditions (such as pre-flocculation, sedimentation, flow rate and filter medium etc) to achieve optimum conditions for a given filter material*** *(Ndiba, 1992).*

The research was done using crushed coconut shells as the coarse medium in a dual media filter. The crushed coconut shells was tried as a substitute to anthracite coal which has for a long time been recommended as the coarse medium but is, unfortunately, not available in many countries. Lack of widespread availability of anthracite coal has retarded the development and use of dual and multimedia filters in these countries.

Experimental investigations

Pilot plant filtration studies were carried out in Thika Water Treatment Plant. The pilot plant consisted of two identical filtration columns which allowed comparison of various designs of the crushed coconut shell dual media filter with that of a typical rapid sand filter. The factors investigated were:

- Filtration rate
- Size of the crushed coconut shell medium
- Relative depth of media
- Backwash requirements

Experimental results

Headloss development and effluent quality were used to evaluate the first three factors. The filtration rate was found to have a significant effect on performance of the filter. At a filtration rate of 12m/hr, a dual media filter of total depth 700mm with equal depths of 1.2mm effective size crushed coconut shell medium and 0.42mm effective size sand was found to give the same length of filter runs and the same effluent quality as the rapid sand filter. Crushed coconut shell sizes between 0.7mm and 1.2mm did not affect the performance of the filter significantly as determined by both headloss and effluent quality. The length of filter runs were seen to increase significantly with the relative depth of the coconut shell layer. However, at depths greater than 350mm, the effluent quality of the dual media filter was less than that of the rapid sand filter.

Conclusions

The researcher reported the following conclusions:

i) The dual media filter with crushed coconut shell can operate at 2.4 times the filtration rate of a rapid sand filter while having the same length of filter run and same effluent quality.
ii) A dual media filter with a total bed depth of 700mm with equal depths of crushed coconut shells and sand of effective sizes 1.20mm and 0.42mm respectively was the best design.
iii) Substantial saving on the cost of filtration could be made if the dual media filters were constructed in place of rapid sand filters.

Recommendations and further research

The researcher's recommendations were:

i) A full scale experimental filter should be set up to carry out further tests.
ii) The optimum coagulation conditions for the coconut shell dual media filter should be established.
iii) A machine for large scale crushing of coconut shell should be developed.

# Chapter Three

## 3.0 Trial studies: Filter media characterization

### 3.1 Introduction

Most researchers on multimedia filtration generally agree that multimedia filters are superior to the conventional sand filters. Most of the research work has, therefore, been based on the selection of effective materials which can be used as the media in these filters. The various materials tested have shown different unique qualities which may not be found on other materials. For this reason, their general recommendations have been that further research be carried out with the objective of trying to exhaust the list of potential materials for use in multimedia filtration.

Sand has been universally accepted to form an integral proportion of dual and multi media filters. In this research study, ground charcoal is being tested as the coarse, less dense medium overlying the sand bed in a dual media filter. The ground charcoal has a relatively lower specific gravity than sand, and can yield higher filtration rates and lower headloss than a conventional sand bed. Also, due to its relatively lower specific gravity, a bed of ground charcoal is more easily fluidized and expanded during backwashing. The marked difference between the specific gravities of sand and ground charcoal makes a dual-media filter composed of these two materials remain graded even after backwashing. Thus the suspended particle penetration gets uniform even after several filter runs.

The composition of charcoal is to some degree similar to that of activated carbon mainly due to the carbonization process which the two materials have to undergo during their production. Past experiences (using briquetted rice husks) have confirmed that such carbonised materials have similar properties to activated carbon (Vigneswaran, 1983). It can therefore be speculated that the adsorptive characteristics of the ground charcoal, however small, may coincidentally improve the filter efficiency. The closest to activated carbon that the charcoal can get depends on the effectiveness of the carbonization process.

## 3.2 The carbonization process

Charcoal is produced as a result of the chemical reduction of organic materials under controlled conditions, that is, the heating of wood with restricted air flow. Ideally, charcoal should be produced in kilns capable of reaching high temperatures since higher temperatures drive off greater proportions of the acids, tars and volatile gases making the resulting charcoal purer with a higher carbon content. Good quality charcoal requires temperatures up to 500°C to achieve a fixed carbon content of 75%. However, high purity charcoal is more friable than charcoals produced in lower temperature kilns and so a maximum kiln temperature of 450-500°C is often considered as the optimum. The variation of carbon contents with kiln temperatures is given in Table 3.1

A soft burned charcoal (carbonized at lower temperatures) has a high volatile matter content and a low fixed carbon content, is corrosive to metals, paper, fibre and packaging material (but not to plastic) and it also tends to smoke during burning. Hard burned charcoal, on the other hand, is high in fixed carbon content, low in volatiles and is much more friable (Kristoferson, 1987).

Table 3.1: Carbon contents of charcoal at different kiln temperatures (Kristoferson, 1987)

| **Carbonization temperature (°C)** | **Proportion of carbon as % of dry weight of charcoal** |
|---|---|
| 200 | 52.3 |
| 250 | 70.6 |
| 300 | 73.2 |
| 500 | 89.2 |
| 700 | 92.8 |
| 800 | 95.7 |
| 900 | 96.1 |
| 1000 | 96.6 |

## 3.3 Process of adsorption

*Adsorption* can be defined as the accumulation of substances at the interface between two phases. In water and waste water treatment, the interface is between the liquid and the solid surfaces. The material being removed from the liquid phase is called the *adsorbate*, and the material providing the solid surface is called the *adsorbent*.

Activated carbon is the adsorbent most commonly used in water and waste water treatment. It is manufactured from carbonaceous material such as wood, coal, petroleum residues, e.t.c. A char is made by burning the material in the absence of air. The char is then oxidised at higher temperatures to create a very porous structure. This "activation" step provides irregular channels and pores in the solid mass, resulting in a very large surface-area-per-mass ratio. Dissolved organic material adsorbs to both exterior and interior surfaces of the carbon (Peavy *et al*, 1985).

Adsorption is a three-step process:

Macro-transport (bulk transport) - This first step is the movement of the organic particulates with the liquid.

Micro-transport - The second step involves the diffusion of the particulates in the quiescent liquid layer to the solid phase.

Sorption - This third step describes the attachment of the particulates to the surface of the solid media. Sorption is a non-specific term referring to either adsorption or absorption, where *adsorption* refers to accumulation *on the surface*, while *absorption* refers to accumulation *in the phase*.

## 3.4 Media characteristics

The following media characteristics were obtained after testing in accordance with the specifications laid out in the literature review. Initially, the study was intended to use ground coffee husk billets as the coarse medium in the dual media filter. However, the coffee billets failed to meet the requirements of media characteristics, and charcoal was then used in place of the coffee billets.

### 3.4.1 Appearance

The media: gravel, sand, ground coffee husk billets, and ground charcoal were cleaned and dried before being applied to the models. The ground coffee husk billets did not appear to be getting clean regardless of the amount of time spent on cleaning it. It persistently yielded stained water while being cleaned. The charcoal and sand at first produced dirty water, which gradually cleared up as the washing proceeded on.

### 3.4.2 Size

The size of the media was determined by use of British Standard sieves. The choice of the various media sizes was in accordance to the size specification laid out in literature, which gives a guideline of 0.45mm or higher for the effective size of sand to be used in rapid sand filters. For granular activated carbon, the media should be coarser than the sand, with an effective size above 0.7mm.

The media tested for the study were in the size ranges shown in Table 3.2.

Table 3.2: Size range for the filter media

| Media | Size range (mm) |
|---|---|
| Sand | 0.5 - 0.8 |
| Charcoal | 0.8 - 1.2 |
| Coffee billets | 0.8 - 1.2 |

The sieve analysis was carried out for the media, which yielded the grading curves as shown in Figures 3.1 to 3.3.

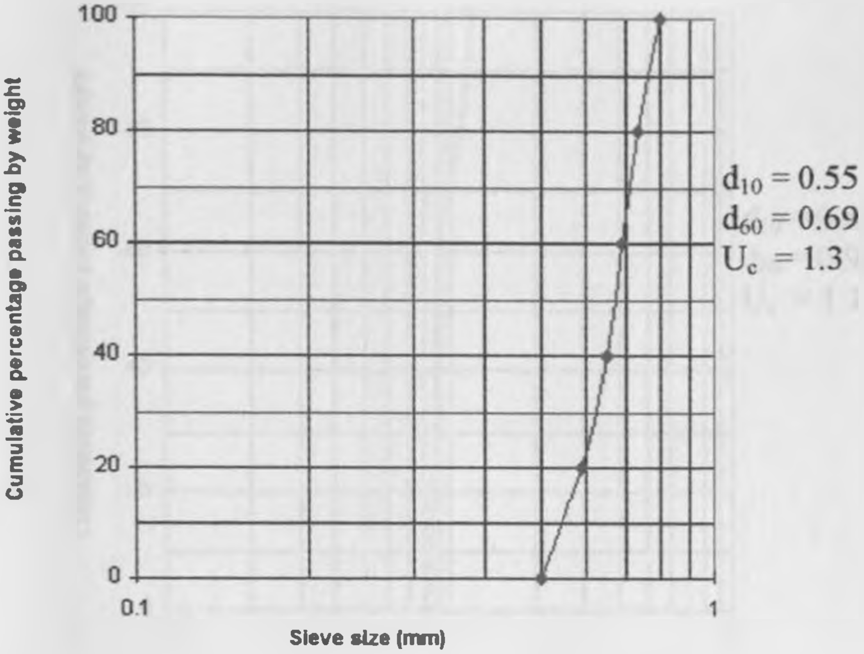

Figure 3.1: Grading curve for sand

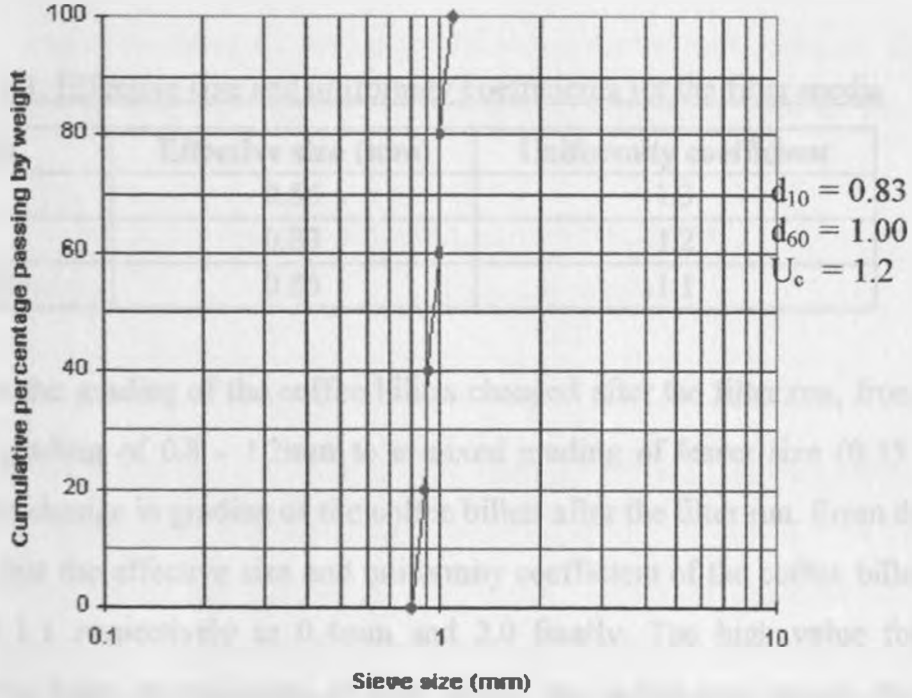

Figure 3.2: Grading curve for charcoal

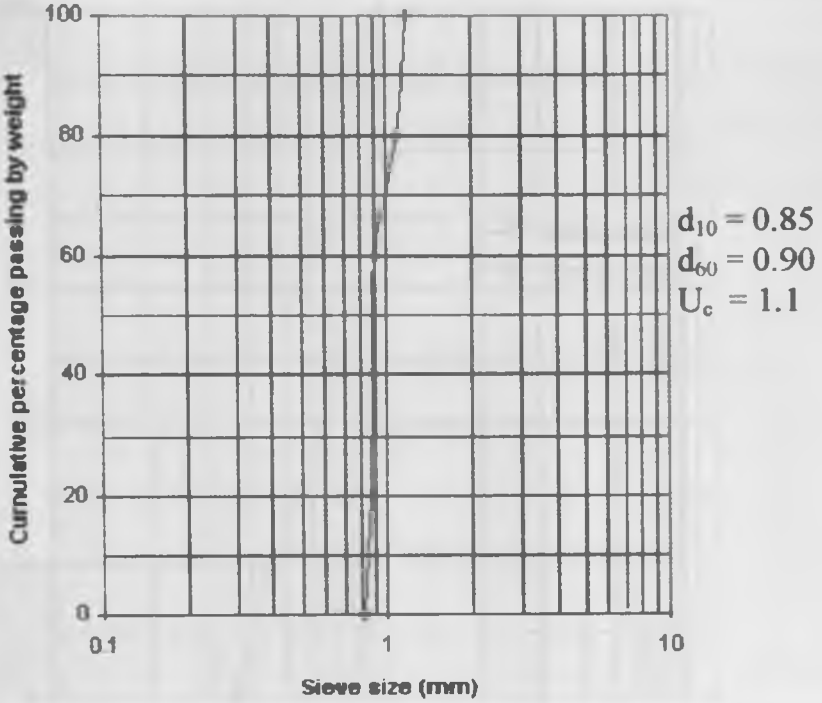

Figure 3.3: Grading curve for ground coffee husk billets

From these grading curves, the effective size and uniformity coefficients were calculated for the media, as is shown in Table 3.3

Table 3.3: Effective size and uniformity coefficients for the filter media

| Media | Effective size (mm) | Uniformity coefficient |
|---|---|---|
| Sand | 0.55 | 1.3 |
| Charcoal | 0.83 | 1.2 |
| Coffee billets | 0.85 | 1.1 |

It was observed that the grading of the coffee billets changed after the filter run, from the initial relatively uniform grading of 0.8 - 1.2mm to a mixed grading of lesser size (0.35 - 1.0mm). Figure 3.4 shows the change in grading of the coffee billets after the filter run. From these curves it can be observed that the effective size and uniformity coefficient of the coffee billets changed from 0.85mm and 1.1 respectively to 0.4mm and 2.0 finally. The high value for the final uniformity coefficient gives an indication of how widely the coffee size spread after the filter run, possibly because the media underwent disintegration during backwashing operation.

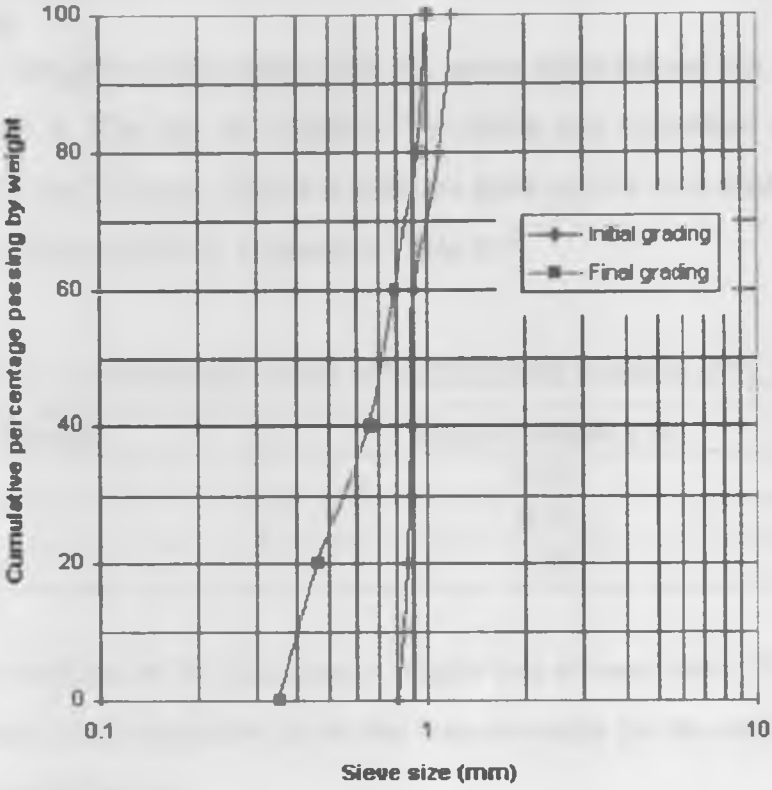

Figure 3.4: Grading curves for coffee before and after a filter run

### 3.4.3 Relative density

The relative density was determined by preparing three samples of each medium, and working out the average of the three samples. The relative densities calculated are given in Table 3.4

Table 3.4: Relative densities for the filter media

| Media | Relative density |
|---|---|
| Sand | 2.92 |
| Charcoal | 1.33 |
| Coffee billets | 1.57 |

Some of the charcoal chippings had a relative density less than 1.0 and therefore floated in water. The charcoal applied to the filter was the portion which settled in water. For this reason, this value of relative density is an average figure. The actual density of charcoal varies widely, depending on the species of tree used to make the charcoal. Similarly, the relative density of the coffee billets also has some slight variation, although not as much as for charcoal.

### 3.4.4 Acid solubility

This test ensures the integrity of the grains; that the grains are solid and not aggregated particles which may be cemented. The loss of weight of the media was calculated after the media was immersed in 20% HCl for 24 hours. This was done for three sets of each medium and the average percentage loss of weight calculated, as given in Table 3.5.

Table 3.5: Percentage weight loss of the filter media in 20% HCl

| Media | Loss of weight (%) |
|---|---|
| Sand | 0.89 |
| Charcoal | 0.94 |
| Coffee billets | 1.57 |

In the specifications laid out in the literature, a weight loss of more than 2% after immersion in 20% HCl for 24 hours is not acceptable. Note that loss of weight for the coffee billets was almost twice as much as for the charcoal.

There was effervescence when the acid was added to the charcoal, and even more when added to the coffee billets. The coffee also substantially stained the acid. The effervescence was an indicator of the reaction which took place between the acid and the calcium carbonate shell fragments present in the charcoal and coffee billets. This is clearly seen by looking at the percentage loss of weight shown in Table 3.5.

### 3.4.5 Physical stability

Sand and charcoal were noted to be physically stable in water, while the coffee husk billets proved not to be. When applied to water, the billets simply disintegrated into very fine particles thereby staining the water. This was the main indicator of the failure of the coffee husk billets. The disintegration of the ground coffee billets was the primary contributor to the change of size grading after the application of the medium to water, as shown in Figure 3.4.

# Chapter Four

## The filtration bench scale model

### General

e bench scale model was set up at the Environmental Health Engineering Laboratory, partment of Civil Engineering of the University of Nairobi. The model was designed such that omparison could be made between the performance of a dual media filter against that of a nventional rapid sand filter. Initially, the coarse medium for the dual media filter had been und coffee husk billets, which failed the preliminary media characteristics tests. Ground arcoal was therefore used as a replacement of the ground coffee billets.

e model consisted of two identical columns of 150mm diameter, one for the dual media filter d the other for the conventional rapid sand filter. The assembly of the models is shown in Plate 1, with a schematic representation of the same in Figure 4.1

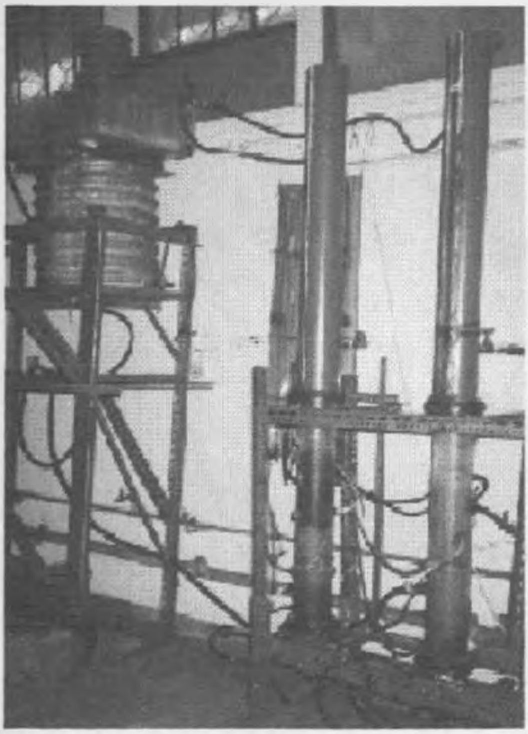

Plate 4.1: Assembly of the filtration bench scale model

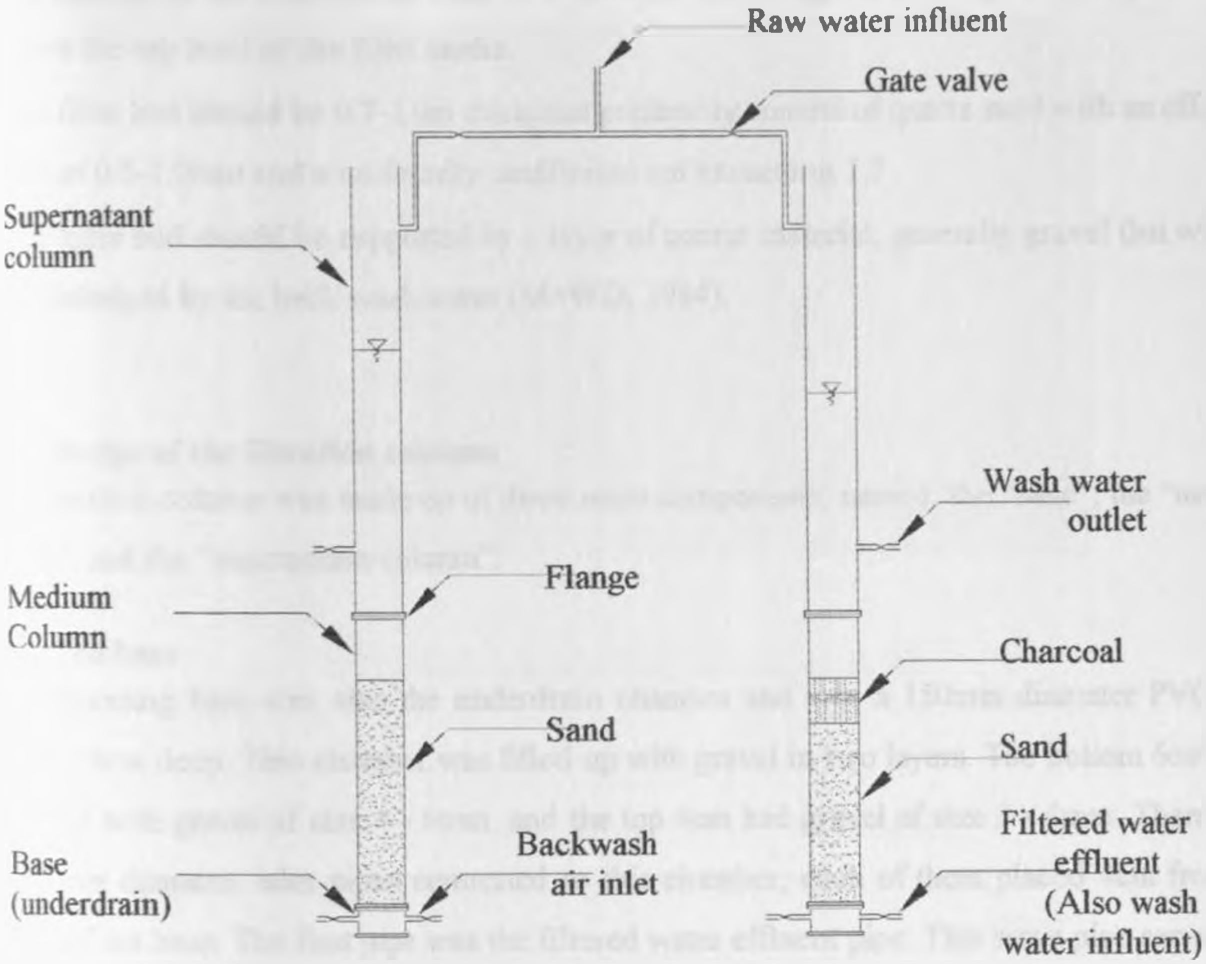

Figure 4.1: Schematic representation of the filtration bench scale model

## 4.2 Specifications from the Design Manual for Water Supply in Kenya

Some of the design details specified in the design manual for final rapid sand filters succeeding flocculation and sedimentation are:

- Each filter unit should have individual inlet that can be closed for servicing and backwashing.
- The surface loading shall be $5m^3/m^2/hr$
- The filter structure shall be designed with a minimum free height between the top of the filter media and the bottom of the wash water troughs of 40% of the height of the filter media.
- There should be a first filtrate connection on the outlet pipe through which filtered water can be let to waste the first 10 minutes after backwashing.

Air binding of the filter media must be prevented by raising the outlet pipe to at least 50mm above the top level of the filter media.

The filter bed should be 0.7-1.0m thick and preferably consist of quartz sand with an effective size of 0.5-1.0mm and a uniformity coefficient not exceeding 1.5

The filter bed should be supported by a layer of coarse material, generally gravel that will not be dislodged by the back wash water (MoWD, 1984).

## .3 Design of the filtration columns

Each filtration column was made up of three main components, named: the "base", the "medium column", and the "supernatant column".

### 4.3.1 The base

This supporting base was also the underdrain chamber and was a 150mm diameter PVC pipe section, 10cm deep. This chamber was filled up with gravel in two layers. The bottom 6cm layer was filled with gravel of size 4 - 6mm, and the top 4cm had gravel of size 2 - 4mm. There were two 13mm diameter inlet pipes connected to this chamber, each of them placed 4cm from the bottom of the base. The first pipe was the filtered water effluent pipe. This same pipe served as a backwash water inlet. The second pipe was the backwash air inlet pipe. The air inlet pipe was connected to an air pump which was used to pump in air during the backwashing operations. The top of the underdrain chamber was covered by a screen. This screen served three main roles:

(i) It prevented the movement of the sand into the underdrain chamber.

(ii) It prevented the movement of the gravel into the sand during backwashing.

(iii) It helped to distribute the backwash water uniformly across the cross-sectional area of the sand.

The assembly of the base (underdrain) is shown in Plate 4.2, with a schematic representation in Figure 4.2

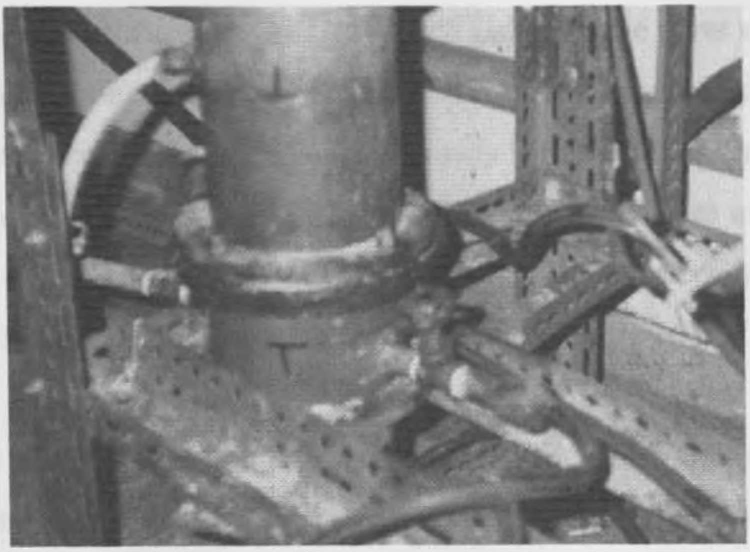

Plate 4.2: Assembly of the base (underdrain)

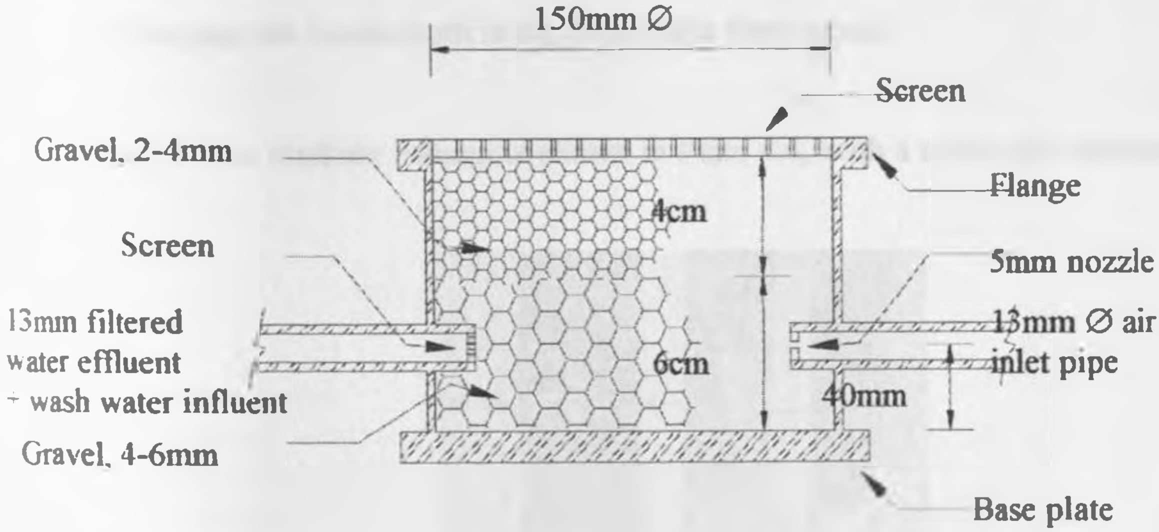

Figure 4.2: Schematic representation of the base (underdrain)

### 4.3.2 The medium column

This middle component of the filtration column was 90cm high. It held the filter media above the underdrain. In the conventional RSF model, the sand was added to a depth of 70cm. The dual media filter model was tested with depths of charcoal varying from 10cm to 30 cm, with the underlying sand depth varying accordingly to maintain a total media depth of 70cm.

There were 8 ports spiralling around the entire height of each column. The ports were spaced at 0cm centre to centre, with the bottom most port being 5cm from the bottom of each of the medium columns. These ports were used for collecting samples for turbidity measurement. The ame ports were connected using rubber tubings to glass manometers which were used to monitor the headloss development, by measuring the water head in the manometers using the tape measure attached alongside the manometers, as is shown in Plate 4.3

The medium columns were made up of 140mm diameter clear perspex which enabled direct observation of the media depth, especially for the purpose of monitoring the expansion of the fluidised bed during backwashing. The perspex columns were connected both to the underdrain bases and the supernatant columns by means of flanges. The connection to the supernatant column gave the convenience of separating the top component from the middle one for the purpose of changing the media depth in the dual media filter model.

The assembly of the medium column is shown in Plate 4.4, with a schematic representation in Figure 4.3

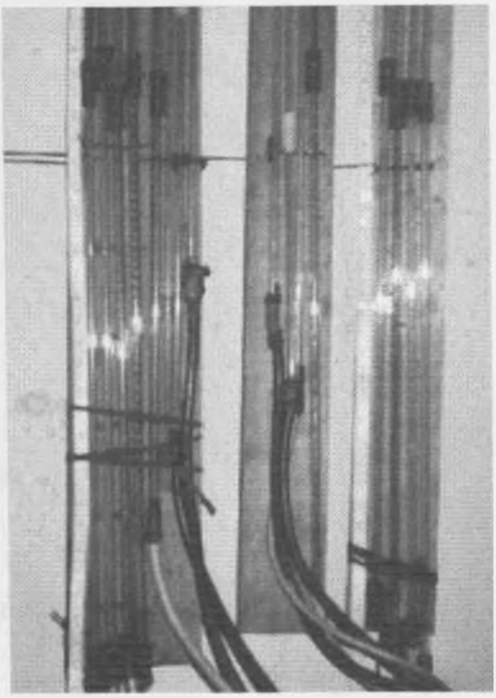

Plate 4.3: Assembly of the glass manometers

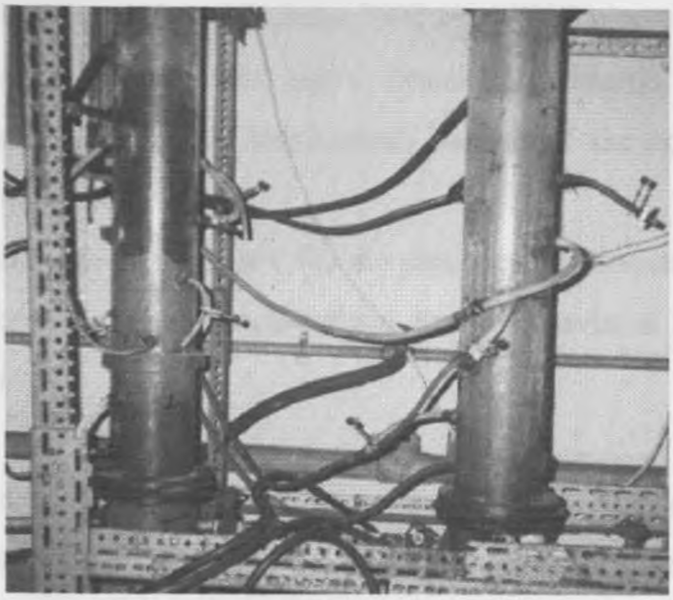

Plate 4.4: Assembly of the medium column

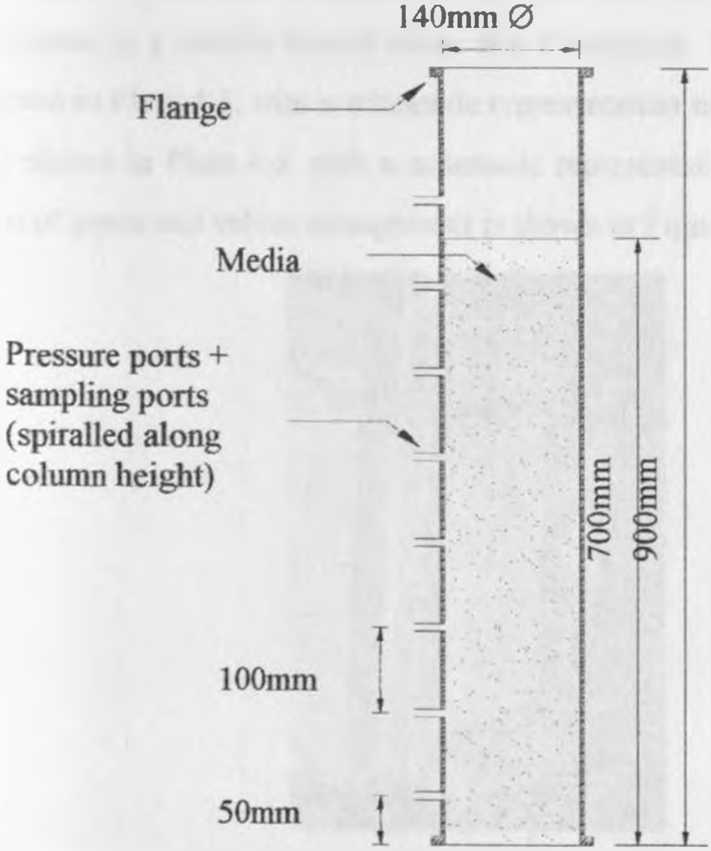

Figure 4.3: Schematic representation of the medium column

### 3.3 The supernatant column

his piece was a 1.2m long, 150mm diameter PVC pipe. PVC pipe was used here because of the navailability of surplus clear perspex pipes. However, to enable visual observations, a long lender window was cut along the longitudinal surface of the columns, and a flat strip of ansparent perspex was pasted to it.

he supernatant columns were necessary for the provision of adequate depth for the supernatant. hey were also necessary during backwashing for the provision of adequate height for the xpansion of the bed.

ach of the supernatant columns had two ports: one port, placed at a distance of 20cm from the ottom of the column was the outlet of the backwash water. The second port which was 25cm rom the top of this column was the raw water influent port. The raw water was fed into the filtration columns from the outlet of a combined horizontal and up-and-down baffled flocculator. The influent into the flocculator consisted of tap water flowing in and mixing with drips of very turbid water stored in a bucket located above the flocculator. The assembly of the supernatant column is shown in Plate 4.5, with a schematic representation in Figure 4.4. The assembly of the flocculator is shown in Plate 4.6, with a schematic representation in Figure 4.5. The schematic representation of pipes and valves arrangement is shown in Figure 4.6.

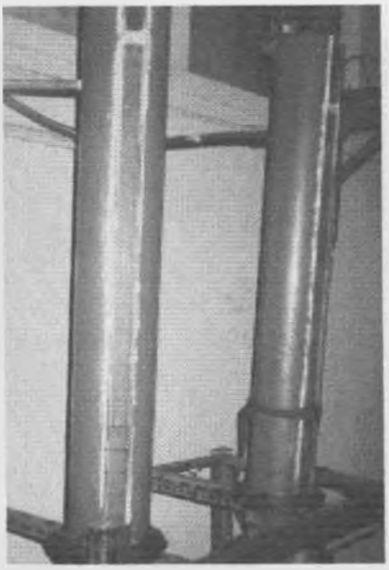

Plate 4.5: Assembly of the supernatant column

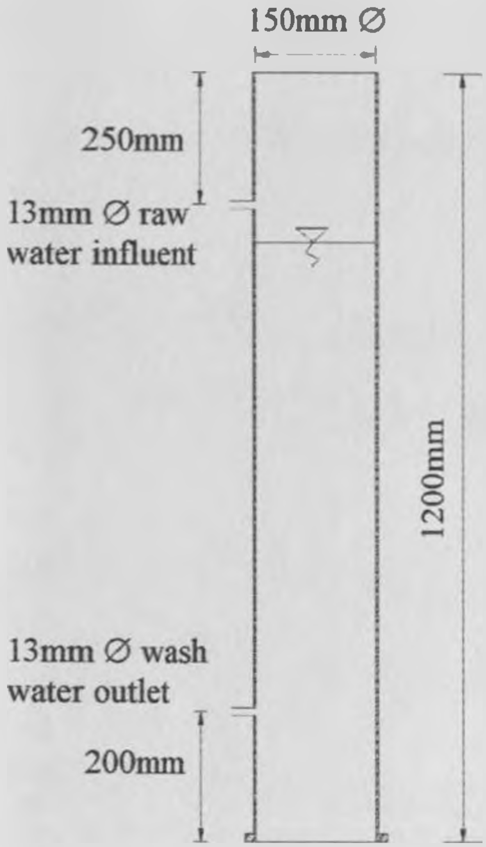

Figure 4.4: Schematic representation of the supernatant column

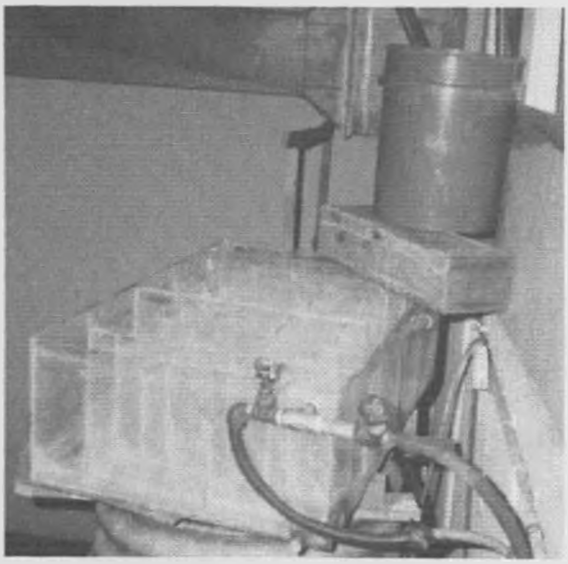

Plate 4.6: Assembly of the flocculator

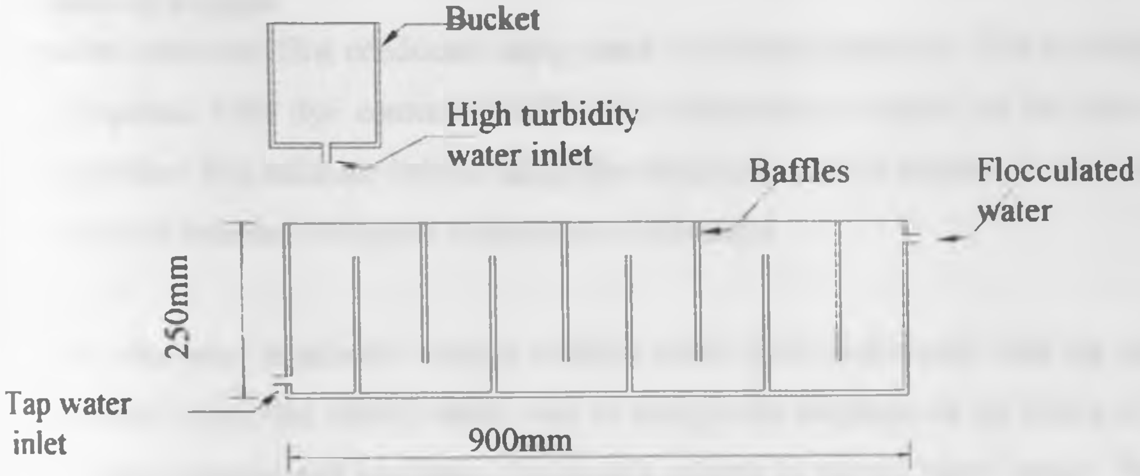

Figure 4.5: Schematic representation of the flocculator

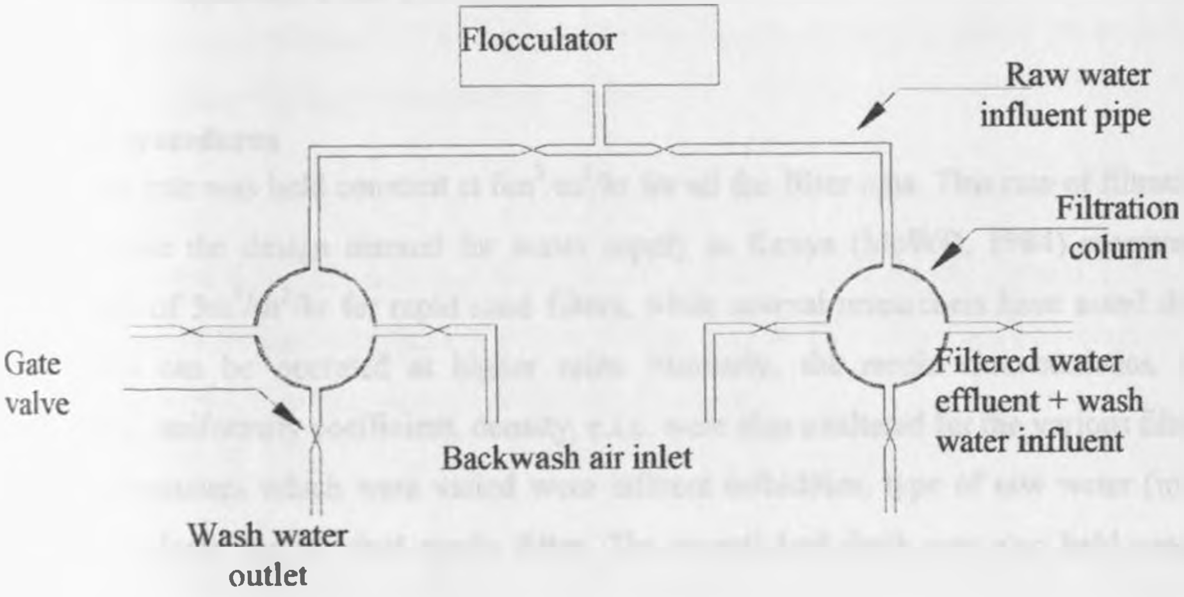

Figure 4.6: Schematic representation of the pipes and valves arrangement

## .4 Data collection methodology

### .4.1 Choice of sample

The filtration tests were first conducted using water containing tartrazine. This is a hygroscopic rganic compound with dye content of 80%. It is commonly available in the form of food olouring powder. The rationale behind using this compound was to analyse the response of the ilters in terms of removal of organic compounds in the water.

Subsequent tests were conducted using a solution made up of soil mixed with tap water. The rationale behind using this muddy water was to analyse the response of the filters in terms of removal of both organic and inorganic compounds present in natural turbid water. The muddy water was initially applied at high turbidities in the range of 30 - 60NTU. However, the final filter runs were conducted with practical (assuming coagulation and sedimentation prior to filtration) influent turbidities of less than 10NTU.

The last two filter runs, (no. 7 and 8), unlike all the other preceding runs, were conducted using coagulated, flocculated water. This was to give a general overview of the expected response of the filters when applied to a full water treatment plant.

### 4.4.2 Test procedures

The filtration rate was held constant at $6m^3/m^2/hr$ for all the filter runs. This rate of filtration was chosen because the design manual for water supply in Kenya (MoWD, 1984) recommends a filtration rate of $5m^3/m^2/hr$ for rapid sand filters, while several researchers have noted that dual media filters can be operated at higher rates. Similarly, the media characteristics, namely effective size, uniformity coefficient, density, e.t.c. were also unaltered for the various filter runs. The only parameters which were varied were influent turbidities, type of raw water (influent), and charcoal depth for the dual media filter. The overall bed depth was also held constant at 70cm.

e initial filter runs ranged for periods of 12 - 14 hours. These filter runs were specifically for e analysis of turbidity removal as well as headloss development in relation to depth of media d time. Backwashing characteristics were also analysed using the data from these filter runs. he last four filter runs were conducted until terminal headlosses of 1.5m (as stipulated in the sign manual) were achieved. This was done using both muddy water influent as well as trazine as influent. The data from the first two of these four filter runs were used for the omputation of relationships between turbidity removal and headloss development both with time nd depth of media, for full filter runs; while the data from the last two filter runs gave the erformance of the filters when applied to coagulated, flocculated water as compared to the erformance when coagulation is not carried out.

ach filter run had a unique combination of the variable parameters, as has been laid out in the nsuing section.

ilter run no. 1

This filter run was conducted using tartrazine as the influent substance. Its main role was to give a quick assessment of the assumption made earlier that "the charcoal would be effective in the removal of organic particulates". The dual media filter had a charcoal depth of 20cm and a sand depth of 50cm. Filtration was conducted for 13 hours.

Filter run no. 2

The influent in this filter run was muddy water. The removal of combined organic and inorganic particulate was to be analysed from the data collected from this filter run. The charcoal depth was set at 10cm, and filtration was conducted for 14 hours.

Filter run no. 3

This filter run which was conducted for 12 hours had muddy water as the influent. The data from this filter run was to be used in the analysis of the removal of combined organic and inorganic particulate from the sample. The charcoal depth in the dual media filter for this filter run was set at 20cm.

Filter run no. 4

This 13 hour filter run had muddy water influent. The dual media filter had a charcoal depth of 30cm for this filter run. The data from this filter run was also to be used in the analysis of the removal of combined organic and inorganic particulate from the sample.

Filter run no. 5

This was a full filter run, running to 22 hours. The influent was tartrazine, which was to be used to assess the effectiveness of organic particulate removal when the filters had been subjected to full filter runs. The charcoal depth for the dual media filter was set at 30cm.

Filter run no. 6

This was a replica of filter run no. 5, but using muddy water influent. The data from this filter run was to be used for the assessment of the effectiveness of combined organic and inorganic particulate removal for a full filter run. The charcoal depth for the dual media filter was maintained at 30cm, and filtration was conducted for 23 hours.

Filter run no. 7

The filtration was conducted for a full run of 32 hours. The influent was muddy water, but was coagulated at an alum dosage of 10mg/l, and then flocculated. The charcoal depth for the DMF was maintained at 30cm. The data from this filter run was to be used for the assessment of the effect of pre-treatment of the raw water prior to filtration. In this filter run, the manometric heads were measured only at ports 1 and 8; and only influent and effluent turbidities were noted, all at two hour intervals.

Filter run no. 8

This filter run lasted for 38 hours. The influent was again muddy water which was coagulated at an alum dosage of 30mg/l, and then flocculated. The charcoal depth was 30cm for the DMF. The data from this filter run, together with that from filter run no. 7, were to be used to give an indication of the performance of the filters when the raw water was coagulated at different alum dosages. The manometric heads, just like in filter run no. 7, were measured only at ports 1 and 8, and turbidities taken only at the influent and effluent.

All the filtration data collected from the tests have been presented in the tables (Table A.1 to Table A.16) in the Appendix.

### 4.4.3 Operational limitations and constraints

The main difficulties encountered during the filtration exercises were:

(i) Leakages from several points along the column height. These leakages gave rise to irregular head readings from the manometers. The magnitude of this problem was however minimised by continuous application of vacuum wax to seal the leaking points.

(ii) Difficulty in maintaining a constant influent turbidity during the filter run. The influent turbidities fluctuated during the filtration exercise leading to fluctuations in the filtered water turbidities. These fluctuations were reduced by striving to maintain uniform drip of the muddy water and tartrazine solution from the bucket into the flocculator.

(iii) There was loss of some media during sampling for turbidity measurement. Some loss of media was also observed during backwashing. This was however reduced by covering the ports with sieves.

(iv) Obsolescence of the equipment (turbidimeter) resulted in lack of precision of the readings taken.

# Chapter Five

## 5.0 Data analysis and discussion

### 5.1 Introduction

The performance of the models was evaluated on the basis of turbidity removal, headloss development and backwashing requirements. The headloss development was monitored by reading the water heads in the manometers at various media depths and at various time spans. Likewise, turbidity removal was monitored by measuring the turbidity at various media depths and at various durations. The turbidity was measured using Model 2100A Turbidimeter.

Due to the speculated adsorptive properties of charcoal (which, like granular activated carbon, is expected to be effective in colour and odour removal), it would have been beneficial to monitor the removal of colour by the filters. This was however not possible because the colour measuring device which was available (Lovibond 1000 Comparator) had a disk which could only measure colour of 5, 10, 15, 20, 30, 40, 50, 60, and 70 Hazen units. This equipment could not be used because the sample applied was highly turbid and coloured. Consequently, the colour readings obtained from the trial filter run were constantly above 70 Hazen units.

The data collected from the filtration tests were used to formulate the following relationships.

- Turbidity removal versus depth of media at the beginning and at the end of the filter run;
- Turbidity removal versus time;
- Turbidity removal versus time, for various charcoal depths;
- Turbidity removal versus time, for full filter runs;
- Turbidity removal versus time, for coagulated, flocculated influent;
- Turbidity removal versus time, for various alum dosages;
- Ultimate headloss versus depth of media;
- Total headloss versus time;

- Total headloss versus time, for various charcoal depths;
- Total headloss versus time, for full filter runs;
- Total headloss versus time, for coagulated, flocculated influent;
- Total headloss versus time, for various alum dosages;
- Wash water turbidity versus time;
- Bed expansion versus backwash rate;
- Percentage of filtered water needed for backwashing.

## 5.2 Results and analysis

As had been mentioned earlier, the performance of the filters was to be evaluated on the basis of turbidity removal, headloss development, and backwashing requirements. For this reason, the discussions of the results and data analysis have been categorised into these three performance indicators.

### 5.2.1 Turbidity removal

The degree of turbidity removal was expressed in relation to both depth of media as well as time.

a) Turbidity removal versus depth of media

Table 5.1 gives the results of the variation of organic turbidity removal (expressed as a percentage of the influent turbidity) with depth of media, both at the beginning as well as at the end of the filter run. The results were derived from the data presented in Tables A.1 and A.2.

Table 5.1: Variation of turbidity removal with depth (organic influent)

| | Turbidity removal (%) | | | |
|---|---|---|---|---|
| **Depth (cm)** | **RSF (beginning)** | **RSF (end)** | **DMF (beginning)** | **DMF (end)** |
| 0 | 0 | 0 | 0 | 0 |
| 10 | 0 | 6 | 0 | 6 |
| 20 | 4 | 6 | 28 | 21 |
| 30 | 9 | 12 | 34 | 21 |
| 40 | 15 | 12 | 40 | 24 |
| 50 | 20 | 12 | 43 | 24 |
| 60 | 24 | 15 | 49 | 26 |
| 70 | 27 | 15 | 51 | 26 |

From Table 5.1 (which is for organic influent - tartrazine), graphs were drawn to show the variations of turbidity removal with depth, as is shown in Figure 5.1.

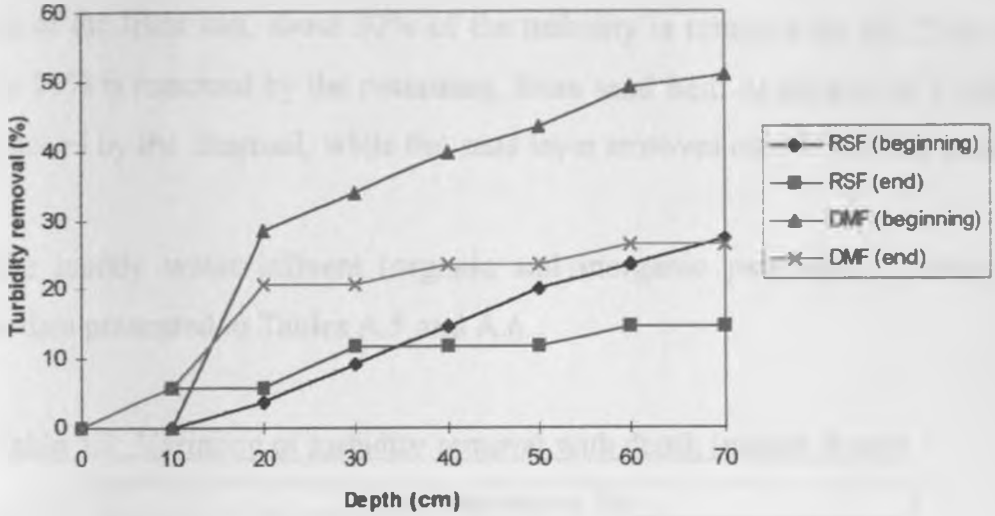

Figure 5.1: Variation of turbidity removal with depth, at beginning and end of filter run (organic)

From Figure 5.1, it can be observed that the dual media filter generally has a higher removal capacity for the organic particulate as compared to the conventional rapid sand filter. At the beginning of the filter run, the total removal by the dual media filter is about 50%, while the removal by the conventional rapid sand filter is about 25%. The dual media filter, therefore, exhibits a removal capacity of 2 times that of the conventional rapid sand filter.

At the end of the filter run, the removals are about 30% and 15% for the dual media filter and conventional rapid sand filter respectively. This exhibits 2 times removal capacity by the dual media filter.

Another observation which can be made from the graph is that the RSF curves have a relatively straight trend, which indicates that there is uniform turbidity removal throughout the media depth. This is in contrast with the DMF curves, which have kinks between 10 and 20cm depths with 0cm depth being the top of the bed. and 70cm being the bottom of the bed). This 10cm - 30cm depth range corresponds to the position of the charcoal layer. These kinks show that most of the removal of the organic particulate is by the charcoal layer.

At the beginning of the filter run, about 30% of the turbidity is removed by the 20cm charcoal layer, while only 20% is removed by the remaining 50cm sand bed. At the end of the filter run, about 20% is removed by the charcoal, while the sand layer removes only 5% of the turbidity.

Similarly, for the muddy water influent (organic and inorganic particulate), Table 5.2 was derived from the data presented in Tables A.5 and A.6.

Table 5.2: Variation of turbidity removal with depth (muddy water)

| | Turbidity removal (%) | | | |
|---|---|---|---|---|
| **Depth (cm)** | **RSF (beginning)** | **RSF (end)** | **DMF (beginning)** | **DMF (end)** |
| 0 | 0 | 0 | 0 | 0 |
| 10 | 0 | 0 | 1 | 0 |
| 20 | 2 | 4 | 31 | 9 |
| 30 | 9 | 3 | 34 | 18 |
| 40 | 13 | 7 | 40 | 16 |
| 50 | 17 | 11 | 43 | 18 |
| 60 | 23 | 9 | 50 | 25 |
| 70 | 28 | 17 | 51 | 32 |

From Table 5.2, the graphs for the organic and inorganic particulate removal were plotted as presented in Figure 5.2.

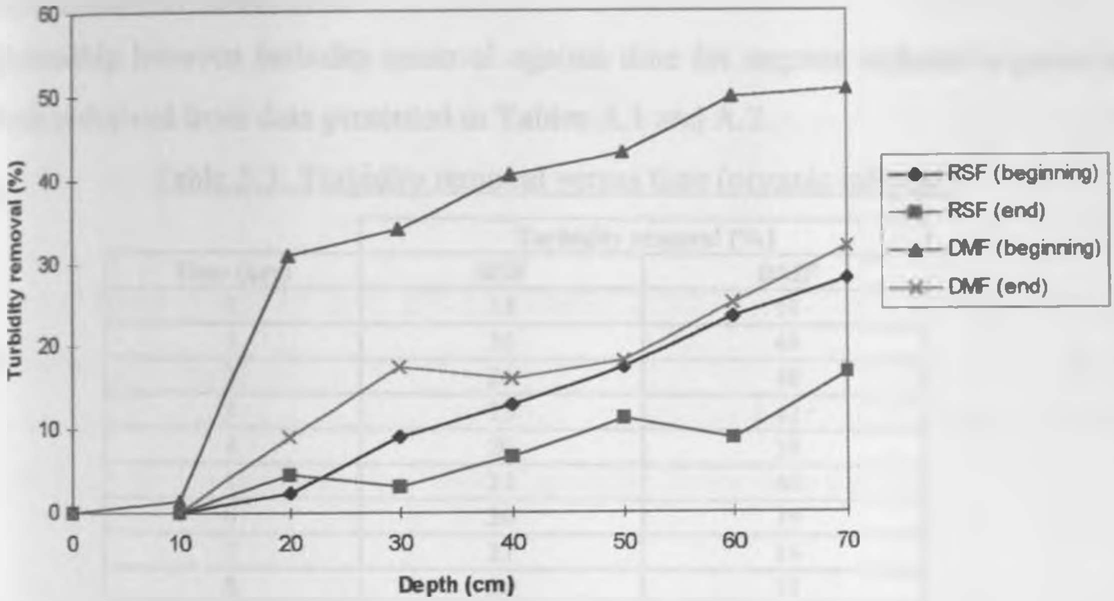

Figure 5.2: Variation of turbidity removal with depth, at beginning and end of filter run (muddy water)

The observations made from Figure 5.2 are very similar to those from Figure 5.1. Just like for the organic influent, the DMF has a higher organic and inorganic removal capacity than the RSF. At the beginning of the filter run, the total removal by the DMF is about 50%, while removal by the RSF is about 30%. The DMF. therefore, has an organic and inorganic removal capacity of about 1.7 times that of the RSF. At the end of the filter run, the removals are 30% and 20% for DMF and RSF respectively. This exhibits a 1.5 times removal capacity in favour of the DMF. The organic removal by the DMF is due to adsorptive properties of the charcoal, while the inorganic removal is attributed to the transport mechanism which has been discussed in section 2.1.4.

The other observation, which is also similar to Figure 5.1 is that there is relatively uniform removal by the RSF. For the DMF, there is 30% removal by the charcoal and 20% by the sand at the beginning of the filter run; while at the end of the filter run 20% of the organic and inorganic particulate is removed by the 20cm layer of charcoal, and only 10% is removed by the remaining 50cm sand bed.

b) Turbidity removal versus time

The relationship between turbidity removal against time for organic influent is given in Table 5.3, which is derived from data presented in Tables A.1 and A.2.

Table 5.3: Turbidity removal versus time (organic influent)

| | Turbidity removal (%) | |
|---|---|---|
| **Time (hrs)** | **RSF** | **DMF** |
| 0 | 33 | 51 |
| 1 | 26 | 48 |
| 2 | 24 | 48 |
| 3 | 25 | 42 |
| 4 | 20 | 39 |
| 5 | 24 | 40 |
| 6 | 20 | 39 |
| 7 | 21 | 31 |
| 8 | 20 | 32 |
| 9 | 13 | 23 |
| 10 | 16 | 20 |
| 11 | 15 | 23 |
| 12 | 13 | 22 |
| 13 | 15 | 24 |

From Table 5.3, graphs were plotted for the variations of turbidity removal with time for organic influent, as is shown in Figure 5.3.

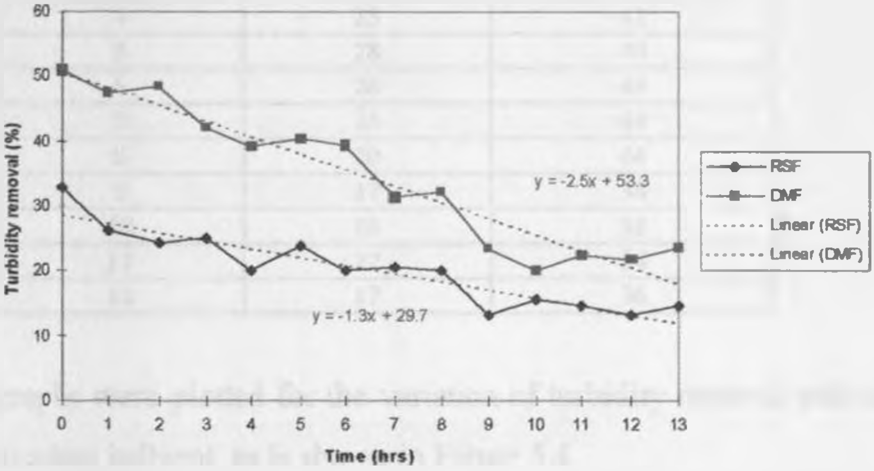

Figure 5.3: Variation of turbidity removal with time (organic)

From Figure 5.3, it can be observed that there is higher turbidity removal in the dual media filter than the conventional rapid sand filter. At the beginning of filtration, the dual media filter removed 50% of the organic particulate while the rapid sand filter removed 33%. The removal capacity of the DMF is therefore about 1.5 times that of the RSF. At the end of the filter run, the turbidity removals are 25% and 15% for the DMF and RSF respectively. Thus, the removal capacity of the DMF is 1.6 times more than that of the RSF.

Another observation is that for both filters, turbidity removal capacity falls with time, with the DMF registering a higher fall (gradient=2.5) than the RSF (gradient=1.3). This observation supports the initial observation that the DMF has a higher removal capacity since its media gets "saturated" faster thereby reducing its removal capability faster than the RSF.

Similarly, for organic and inorganic particulate influent, Table 5.4 was derived with data from Tables A.5 and A.6.

Table 5.4: Turbidity removal versus time (muddy water)

| | Turbidity removal (%) | |
|---|---|---|
| **Time (hrs)** | **RSF** | **DMF** |
| 0 | 32 | 51 |
| 1 | 31 | 50 |
| 2 | 35 | 51 |
| 3 | 30 | 47 |
| 4 | 25 | 42 |
| 5 | 28 | 40 |
| 6 | 24 | 48 |
| 7 | 24 | 44 |
| 8 | 20 | 44 |
| 9 | 17 | 38 |
| 10 | 18 | 38 |
| 11 | 22 | 34 |
| 12 | 17 | 36 |

From this table, graphs were plotted for the variation of turbidity removal with time for organic and inorganic particulate influent, as is shown in Figure 5.4.

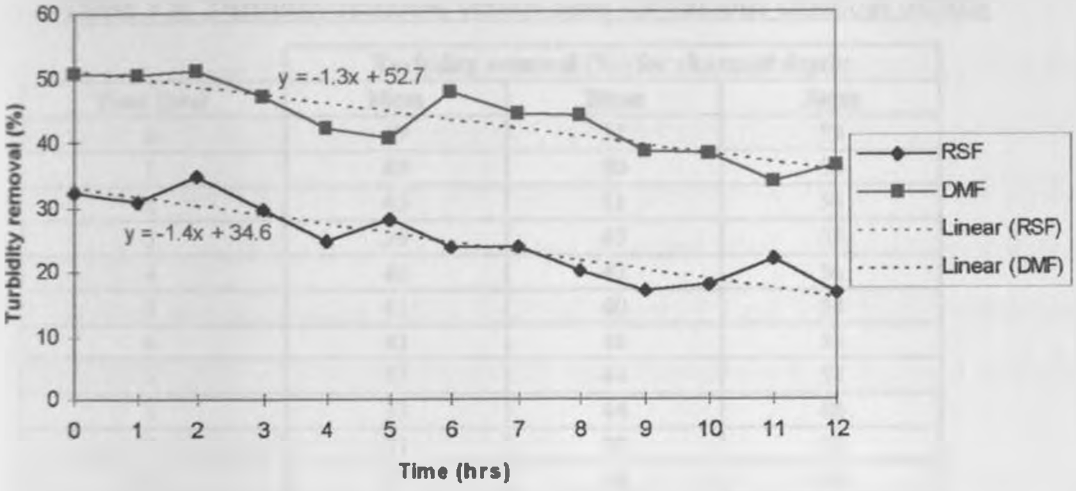

Figure 5.4: Variation of turbidity removal with time (muddy water)

From Figure 5.4, observations are made similar to those from Figure 5.3. The DMF exhibits a higher organic and inorganic removal capacity than the RSF. At the beginning of the filtration, 50% turbidity removal is registered by the DMF, while the RSF registers about 32%. Therefore, the DMF has a capacity which is 1.6 times that of the RSF. At the end of the filter run, the removal is 35% for the DMF and only 15% for the RSF. Thus the DMF is 2.3 times more effective than the RSF.

The other observation which is also similar to the observation made from Figure 5.3 is that turbidity removal for the organic and inorganic particulate falls with time. However, in this case, the gradients for the two filters are almost equal. The dual media filter has a gradient of 1.3 while the rapid sand filter has 1.4. This implies that despite the DMF having a higher removal capacity for the organic and inorganic particulate, its rate of removal is closely similar to that of the rapid sand filter, which has a lower removal capacity.

c) Turbidity removal versus time for various charcoal depths

An analysis was made on the variation of turbidity removal with time for various charcoal depths in the DMF. This was done for muddy water influent (combined organic and inorganic particulate). Table 5.5 gives the results for this analysis, and is derived from the data presented in Tables A.4, A.6, and A.8.

Table 5.5: Turbidity removal versus time for various charcoal depths

| | Turbidity removal (%) for charcoal depth: | | |
|---|---|---|---|
| Time (hrs) | 10cm | 20cm | 30cm |
| 0 | 49 | 51 | 59 |
| 1 | 49 | 50 | 56 |
| 2 | 45 | 51 | 54 |
| 3 | 39 | 47 | 54 |
| 4 | 40 | 42 | 56 |
| 5 | 41 | 40 | 54 |
| 6 | 41 | 48 | 54 |
| 7 | 33 | 44 | 52 |
| 8 | 33 | 44 | 48 |
| 9 | 31 | 38 | 50 |
| 10 | 37 | 38 | 50 |
| 11 | 33 | 34 | 50 |
| 12 | 32 | 36 | 45 |
| 13 | 24 | | 45 |
| 14 | 22 | | |

From Table 5.5, the relationship between turbidity removal and time for various charcoal depths were plotted and are shown in Figure 5.5.

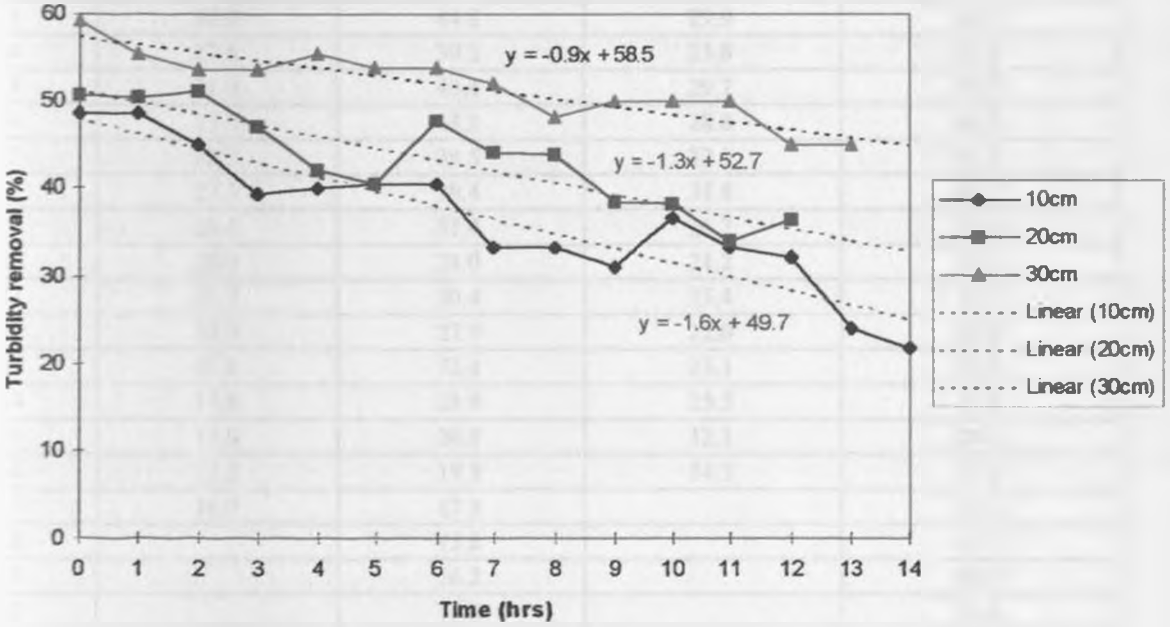

Figure 5.5: Variation of turbidity removal with time for various charcoal depths

From Figure 5.5, it is observed that at the beginning of the filter run, the 30cm charcoal depth filter removes more turbidity than the 10cm and 20cm filters. The removal is 60% for the 30cm filter, and about 50% initial removal for the 10cm and 20cm filters.

The other observation is that there is a general trend of removal efficiency falling with time, as is shown by the linear plots of the curves. Note that the gradients of the linear plots decrease with increase in depth of charcoal. For 10cm charcoal, the gradient is 1.6; for 20cm charcoal, the gradient is 1.3, and the gradient is 0.9 for the 30cm charcoal filter. This indicates that at lower charcoal depths there is greater reduction in removal capacity than with higher charcoal depths, and solids breakthrough probably occurs before the maximum allowable headloss is achieved.

### d) Turbidity removal versus time for full filter runs

This relationship was analysed for full filter runs for both RSF and DMF with both organic as well as muddy water influent. Table 5.6 gives the results, which were derived from the data presented in Tables A.9, A.10, A.11, and A.12.

Table 5.6: Turbidity removal versus time for full filter runs

| | Turbidity removal (%) | | | |
|---|---|---|---|---|
| **Time (hrs)** | **RSF (Tartrazine)** | **DMF (Tartrazine)** | **RSF (Muddy water)** | **DMF (Muddy water)** |
| 0 | 36.7 | 51.7 | 32.9 | 53.2 |
| 1 | 34.8 | 47.8 | 29.0 | 50.0 |
| 2 | 34.2 | 52.6 | 27.5 | 47.1 |
| 3 | 31.0 | 44.8 | 29.9 | 45.5 |
| 4 | 27.5 | 39.2 | 25.8 | 43.9 |
| 5 | 31.9 | 40.4 | 29.7 | 43.8 |
| 6 | 25.0 | 43.2 | 28.8 | 45.8 |
| 7 | 28.9 | 39.5 | 32.1 | 41.5 |
| 8 | 27.3 | 39.4 | 31.8 | 43.2 |
| 9 | 21.6 | 31.4 | 26.2 | 33.8 |
| 10 | 20.0 | 28.0 | 21.2 | 33.3 |
| 11 | 21.7 | 30.4 | 25.4 | 31.7 |
| 12 | 20.9 | 27.9 | 22.0 | 28.8 |
| 13 | 21.6 | 32.4 | 23.1 | 28.8 |
| 14 | 17.8 | 28.9 | 15.5 | 27.6 |
| 15 | 14.0 | 20.9 | 12.1 | 24.1 |
| 16 | 12.2 | 19.5 | 14.3 | 23.2 |
| 17 | 10.0 | 17.5 | | 20.4 |
| 18 | | 15.8 | | 15.7 |
| 19 | | 16.2 | | 16.7 |
| 20 | | 15.8 | | 16.0 |
| 21 | | 13.2 | | 18.0 |
| 22 | | 13.5 | | 18.4 |
| 23 | | | | 16.3 |

From Table 5.6, Figure 5.6 was prepared, which gives the plots for the variations of turbidity removal with time for the full filter runs.

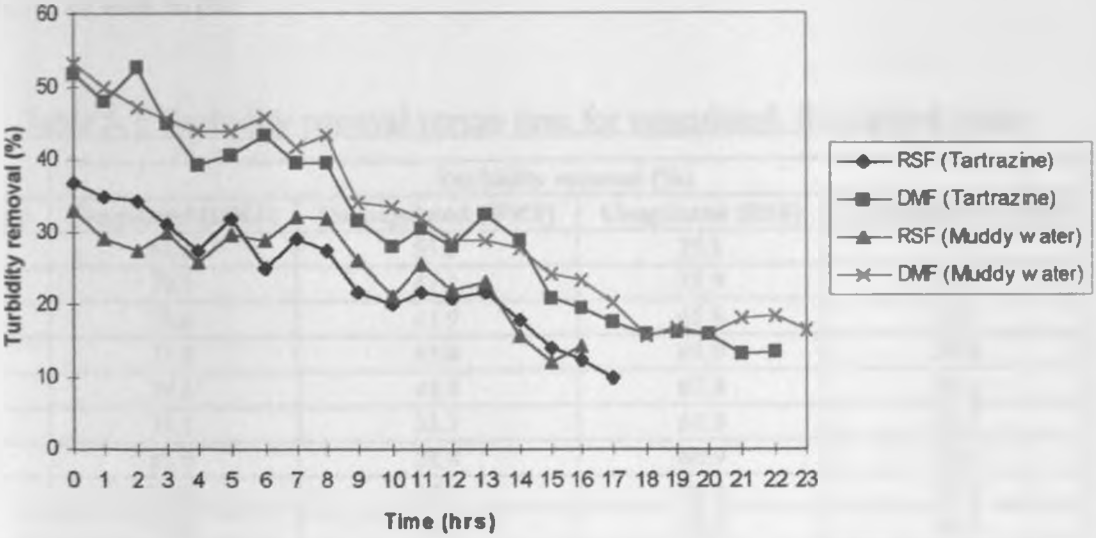

Figure 5.6: Variation of turbidity removal with time for full filter runs

From Figure 5.6, the general observation is that the dual media filter shows a higher turbidity removal capacity (for both organic as well as organic and inorganic particulate) than for RSF. The average turbidity removal at the beginning of the filter run is about 50% for the DMF and only 35% for the RSF. This gives a value of 1.4 times in favour of the DMF. However, for both RSF and DMF, the removal capacity for organic particulate does not vary much from that of the organic and inorganic particulate.

The length of filter run was noted to be about 23 hours for the DMF, while for RSF it is about 17 hours. The dual media filter therefore has 1.4 times longer filter run than the conventional rapid sand filter for the same influent water quality.

### e) Turbidity removal versus time, for coagulated, flocculated influent

This relationship was analysed for full filter runs for both RSF and DMF. A comparison is made between the performance of the filters in turbidity removal of coagulated water with that of uncoagulated water. Table 5.7 gives the results as derived from the data presented in Tables A.11, A.12, A.15 and A.16.

Table 5.7: Turbidity removal versus time for coagulated, flocculated water

| | Turbidity removal (%) | | | |
|---|---|---|---|---|
| **Time (hrs)** | **Coagulated (DMF)** | **Uncoagulated (DMF)** | **Coagulated (RSF)** | **Uncoagulated (RSF)** |
| 0 | 84.8 | 53.2 | 75.8 | 32.9 |
| 2 | 79.3 | 47.1 | 75.9 | 27.5 |
| 4 | 75.0 | 43.9 | 65.9 | 25.8 |
| 6 | 73.8 | 45.8 | 69.0 | 28.8 |
| 8 | 78.6 | 43.2 | 67.9 | 31.8 |
| 10 | 73.1 | 33.3 | 61.5 | 21.2 |
| 12 | 81.5 | 28.8 | 60.9 | 22.0 |
| 14 | 79.8 | 27.6 | 56.3 | 15.5 |
| 16 | 72.1 | 23.2 | 55.7 | 14.3 |
| 18 | 71.9 | 15.7 | 50.9 | |
| 20 | 74.3 | 16.0 | 53.4 | |
| 22 | 70.5 | 18.4 | 50.6 | |
| 24 | 68.6 | | | |
| 26 | 70.3 | | | |
| 28 | 64.8 | | | |
| 30 | 68.6 | | | |
| 32 | 67.4 | | | |
| 34 | 61.8 | | | |
| 36 | 57.7 | | | |
| 38 | 55.2 | | | |

The results tabulated in Table 5.7 were used to prepare Figure 5.7 which compares the turbidity removal for the coagulated water as opposed to uncoagulated water, for both RSF as well as DMF.

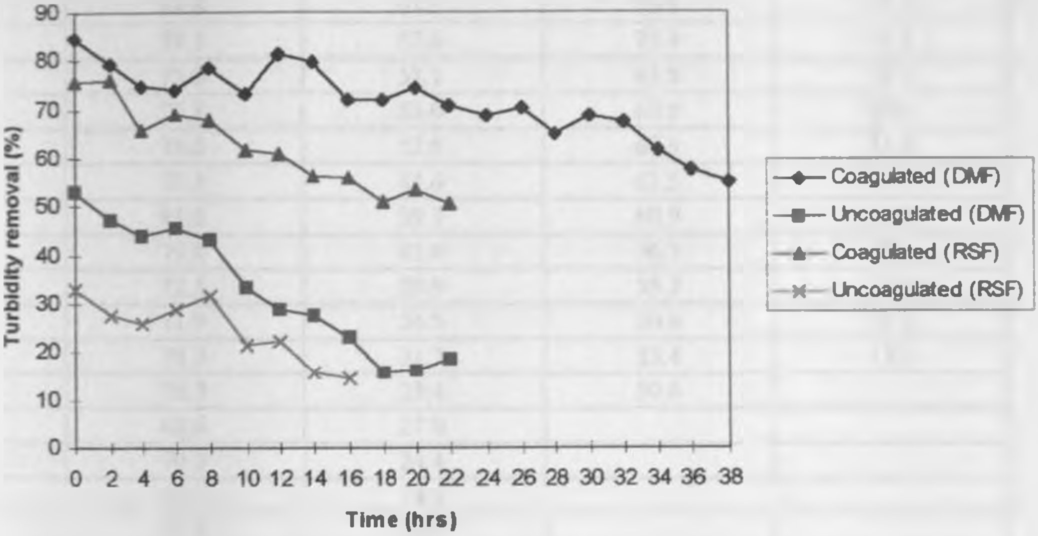

Figure 5.7: Variation of turbidity removal with time, for coagulated influent

From Figure 5.7, three main observations can be made. The first observation is that there is higher removal capacity for coagulated water than for uncoagulated water. The DMF shows about 1.5 times higher initial removal capacity for coagulated water than for uncoagulated water. The RSF on the other hand shows about 2 times higher initial removal capacity for coagulated water than for uncoagulated water.

The second observation is that also with coagulated water, the DMF shows a better performance than the RSF in turbidity removal.

Thirdly, there are longer filter runs for coagulated water as compared to uncoagulated water. The DMF has a filter run 1.7 times longer for coagulated water than for uncoagulated water. In RSF, the coagulated water has a filter run of 1.4 times longer than the uncoagulated water.

e) Turbidity removal versus time, for various alum dosages

For the purpose of establishing a general trend of the performance of the filter when applied to coagulated water of varying alum dosages, Table 5.8 was formulated using the data presented in Tables A.13, A.14, A.15, and A.16.

Table 5.8: Turbidity removal versus time for various alum dosages

| | Turbidity removal (%) | | | |
|---|---|---|---|---|
| Time (hrs) | DMF (30mg/l) | DMF (10mg/l) | RSF (30mg/l) | RSF (10mg/l) |
| 0 | 84.8 | 61.2 | 75.8 | 43.7 |
| 2 | 79.3 | 57.6 | 75.9 | 35.2 |
| 4 | 75.0 | 51.1 | 65.9 | 36.1 |
| 6 | 73.8 | 53.0 | 69.0 | 28.9 |
| 8 | 78.6 | 52.8 | 67.9 | 31.0 |
| 10 | 73.1 | 44.6 | 61.5 | 25.7 |
| 12 | 81.5 | 39.3 | 60.9 | 24.2 |
| 14 | 79.8 | 41.0 | 56.3 | 20.4 |
| 16 | 72.1 | 29.9 | 55.7 | 16.9 |
| 18 | 71.9 | 24.5 | 50.9 | 19.5 |
| 20 | 74.3 | 31.7 | 53.4 | 15.3 |
| 22 | 70.5 | 25.4 | 50.6 | |
| 24 | 68.6 | 27.0 | | |
| 26 | 70.3 | 24.4 | | |
| 28 | 64.8 | 18.4 | | |
| 30 | 68.6 | 20.6 | | |
| 32 | 67.4 | 18.7 | | |
| 34 | 61.8 | | | |
| 36 | 57.7 | | | |
| 38 | 55.2 | | | |

From Table 5.8, Figure 5.8 was prepared to show the difference in performance of the filters when applied to water coagulated at alum dosages of 10mg/l and 30mg/l.

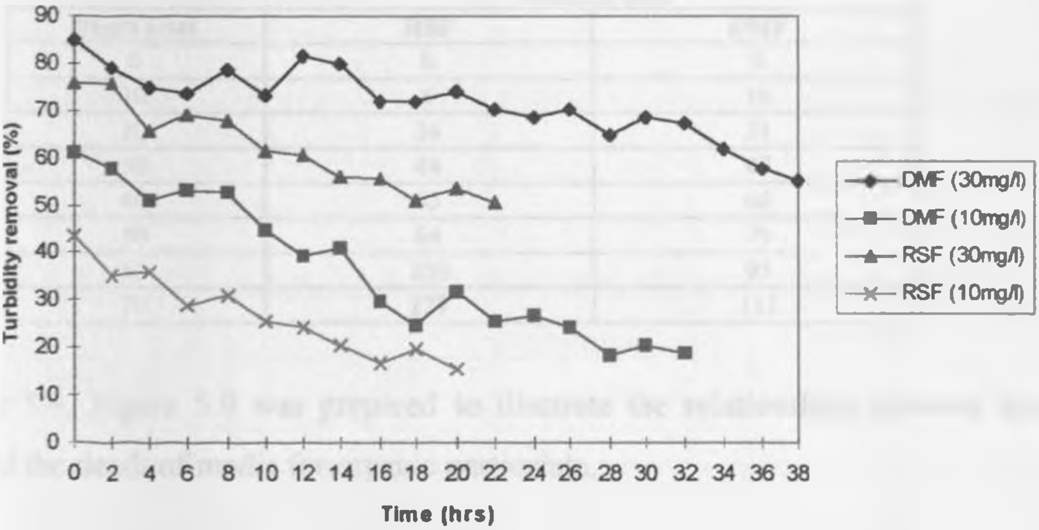

Figure 5.8: Variation of turbidity removal with time, for various alum dosages

From Figure 5.8, it is observed that different alum dosages result in different removal efficiencies and different lengths of filter runs. For this particular case, a dosage of 30mg/l resulted in higher removal efficiency than a dosage of 10mg/l. Likewise, the length of filter run was slightly longer for the 30mg/l dosage than for the 10mg/l dosage.

However, it should not be claimed that the higher the alum dosage, the better the performance. A jar test should be carried out to establish the optimum alum dosage for a given influent turbidity.

### 5.2.2 Headloss development

Just like for turbidity removal, the behaviour of headloss development was expressed in relation to both depth of filter media as well as time.

a) Ultimate headloss versus depth of media

The results for the variation of ultimate headloss with depth of media for tartrazine is given in Table 5.9. The values are obtained from data presented in Tables A.1 and A.2.

Table 5.9: Ultimate headloss versus depth of media (organic influent)

| | **Headloss (cm)** | |
|---|---|---|
| **Depth (cm)** | **RSF** | **DMF** |
| 0 | 0 | 0 |
| 10 | 6 | 16 |
| 20 | 24 | 31 |
| 30 | 44 | 47 |
| 40 | 63 | 66 |
| 50 | 84 | 79 |
| 60 | 106 | 95 |
| 70 | 127 | 111 |

From Table 5.9, Figure 5.9 was prepared to illustrate the relationships between the ultimate headloss and the depth of media for organic particulate.

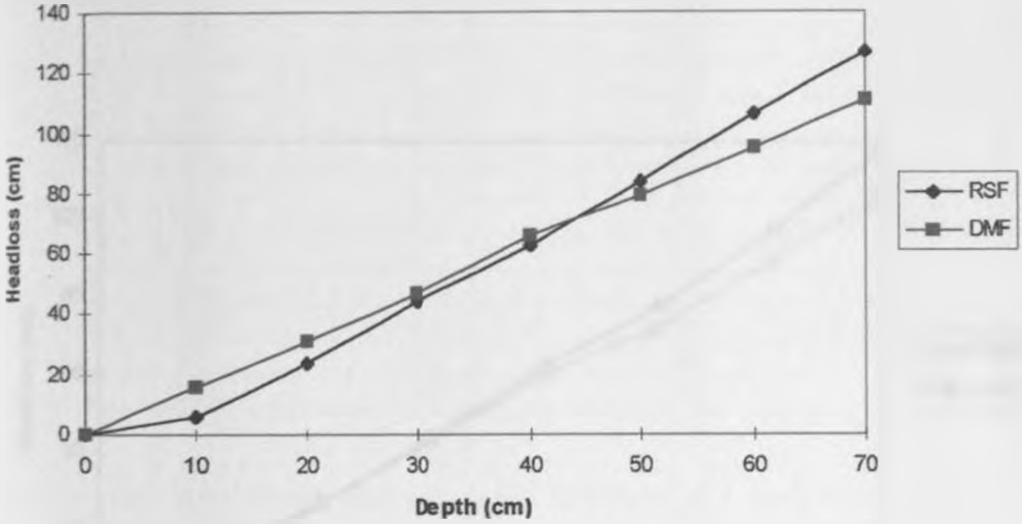

Figure 5.9: Variation of ultimate headloss with depth of media (organic)

From Figure 5.9, it can be seen that the headloss development for RSF and DMF do not greatly differ. Nevertheless, the ultimate headloss for the RSF is higher than that of the DMF. The RSF registered a maximum headloss of about 130cm while the DMF registered about 110cm for that filter run.

Similarly, for organic and inorganic particulate, Table 5.10 was prepared from the data presented in tables A.5 and A.6.

Table 5.10: Ultimate headloss versus depth of media (muddy water)

| | Headloss (cm) | |
|---|---|---|
| **Depth (cm)** | **RSF** | **DMF** |
| 0 | 0 | 0 |
| 10 | 11 | 13 |
| 20 | 27 | 28 |
| 30 | 45 | 43 |
| 40 | 63 | 61 |
| 50 | 78 | 72 |
| 60 | 97 | 90 |
| 70 | 119 | 107 |

Figure 5.10 was prepared from the results outlined in Table 5.10. The figure gives the variation of ultimate headloss with depth of media for organic and inorganic influent (muddy water).

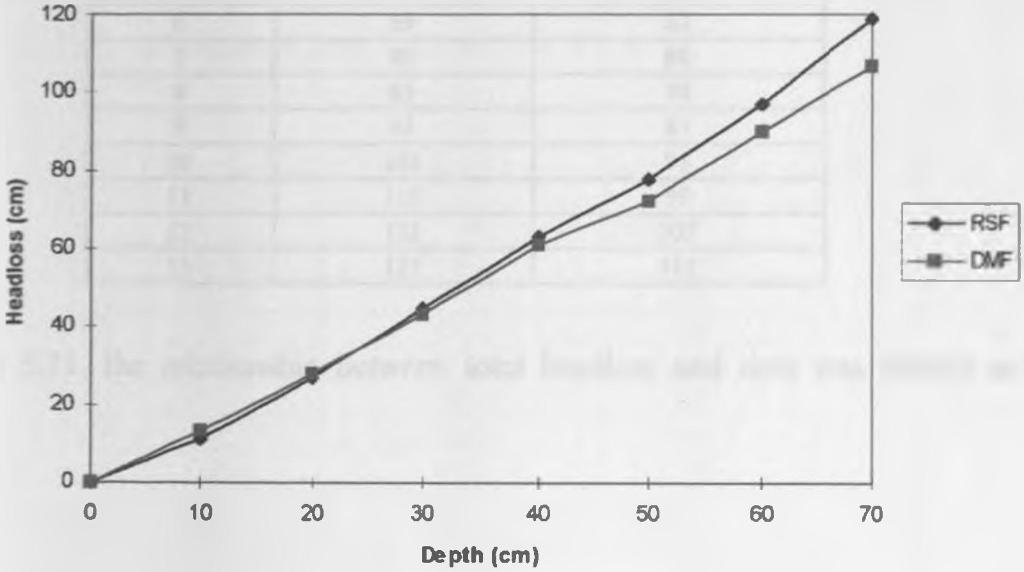

Figure 5.10: Variation of ultimate headloss with depth of media (muddy water)

The observations made from Figure 5.10 are very similar to the observations made for the organic influent as presented in Figure 5.9. The headloss development is very close for both filters, but the RSF ultimately registers more headloss of about 120cm as compared to the DMF which registers about 110cm. This can be attributed to the marked difference in the effective size of the media used in the filters. The RSF registers more headloss than the DMF because of the square of the effective size ($d_g^2$) in the Kozeny Carman equation (Equation 2.8).

b) Total headloss versus time

For the organic influent (tartrazine), the relationship between the total headloss and time is given in Table 5.11, which was derived from the data presented in Tables A.1 and A.2.

**Table 5.11: Total headloss versus time (organic influent)**

| | Total headloss (cm) | |
|---|---|---|
| Time (hrs) | RSF | DMF |
| 0 | 21 | 13 |
| 1 | 29 | 21 |
| 2 | 34 | 30 |
| 3 | 42 | 39 |
| 4 | 55 | 46 |
| 5 | 63 | 53 |
| 6 | 69 | 62 |
| 7 | 80 | 68 |
| 8 | 85 | 74 |
| 9 | 92 | 83 |
| 10 | 102 | 91 |
| 11 | 112 | 99 |
| 12 | 122 | 105 |
| 13 | 127 | 111 |

From Table 5.11, the relationship between total headloss and time was plotted as shown in Figure 5.11.

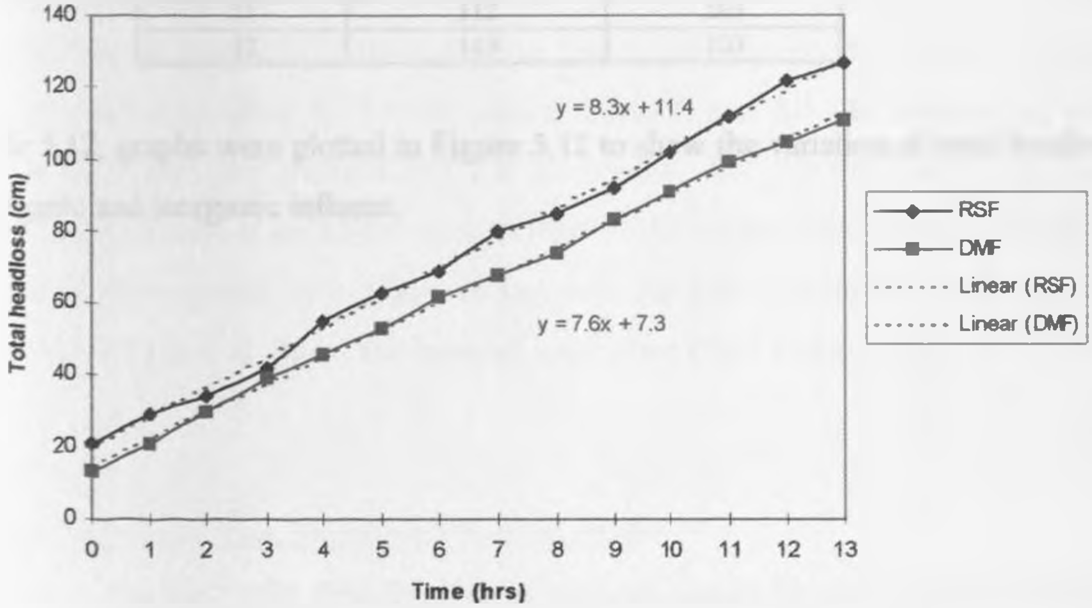

**Figure 5.11: Variation of total headloss with time (organic)**

From Figure 5.11, the RSF shows a slightly higher headloss profile than the DMF throughout the duration of the filter run. There is a slight difference in the rate of headloss development as is shown by the linear representations of the two curves. The RSF gives a gradient of 8.3 while the DMF has a gradient of 7.6. This means that the RSF is developing headloss faster than the DMF. That explains why the difference in total headloss between the DMF and RSF is about 15cm and yet it is barely 10cm at the beginning of the filter run. Similarly, for organic and inorganic influent, Table 5.12 was prepared from Tables A.5 and A.6.

Table 5.12: Total headloss versus time (muddy water)

| | **Total headloss (cm)** | |
|---|---|---|
| **Time (hrs)** | **RSF** | **DMF** |
| 0 | 20 | 12 |
| 1 | 28 | 19 |
| 2 | 35 | 30 |
| 3 | 42 | 39 |
| 4 | 53 | 46 |
| 5 | 64 | 50 |
| 6 | 68 | 63 |
| 7 | 79 | 68 |
| 8 | 85 | 74 |
| 9 | 93 | 80 |
| 10 | 105 | 91 |
| 11 | 112 | 101 |
| 12 | 119 | 107 |

From Table 5.12, graphs were plotted in Figure 5.12 to show the variation of total headloss with time for organic and inorganic influent.

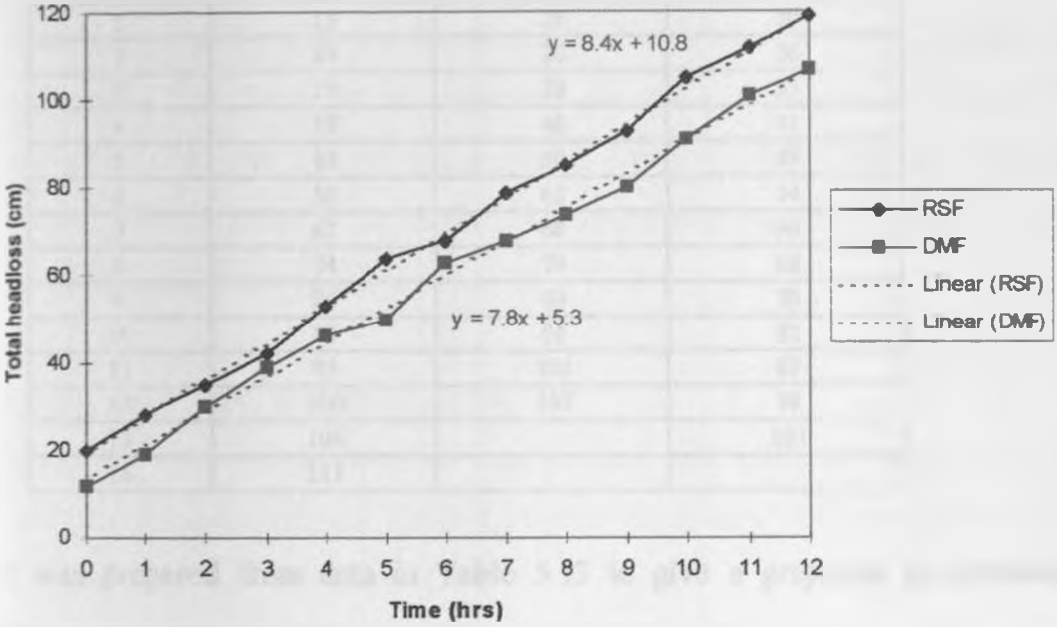

Figure 5.12: Variation of total headloss with time (muddy water)

These curves exhibit characteristics very similar to those found in Figure 5.11 for organic influent. Note that the gradients of the respective linear plots are also very similar. For the RSF, the linear plot had a gradient of 8.3 for organic influent, and 8.4 for organic and inorganic influent. For the DMF, the gradient was 7.6 for organic, and 7.8 for organic and inorganic particulate. The gradients of the linear plots in Figure 5.12 support the observation made earlier that the rate of development of headloss is higher in the RSF than in the DMF. This can be attributed to the in effective size of the charcoal used in the DMF and that of the sand used in the RSF.

c) Total headloss versus time, for various charcoal depths

The variation of headloss with time for various charcoal depths for the DMF was analysed for muddy water influent. The results of this analysis have been presented in Table 5.13 as derived from Tables A.4, A.6, and A.8.

Table 5.13: Total headloss versus time, for various charcoal depths

| | Total headloss (cm) | | |
|---|---|---|---|
| Time (hrs) | 10cm | 20cm | 30cm |
| 0 | 10 | 12 | 13 |
| 1 | 15 | 19 | 20 |
| 2 | 20 | 30 | 26 |
| 3 | 25 | 39 | 33 |
| 4 | 35 | 46 | 41 |
| 5 | 43 | 50 | 49 |
| 6 | 56 | 63 | 54 |
| 7 | 62 | 68 | 60 |
| 8 | 74 | 74 | 68 |
| 9 | 80 | 80 | 76 |
| 10 | 87 | 91 | 82 |
| 11 | 95 | 101 | 89 |
| 12 | 100 | 107 | 98 |
| 13 | 106 | | 103 |
| 14 | 111 | | |

Figure 5.13 was prepared from data in Table 5.13 to give a graphical presentation of the relationships.

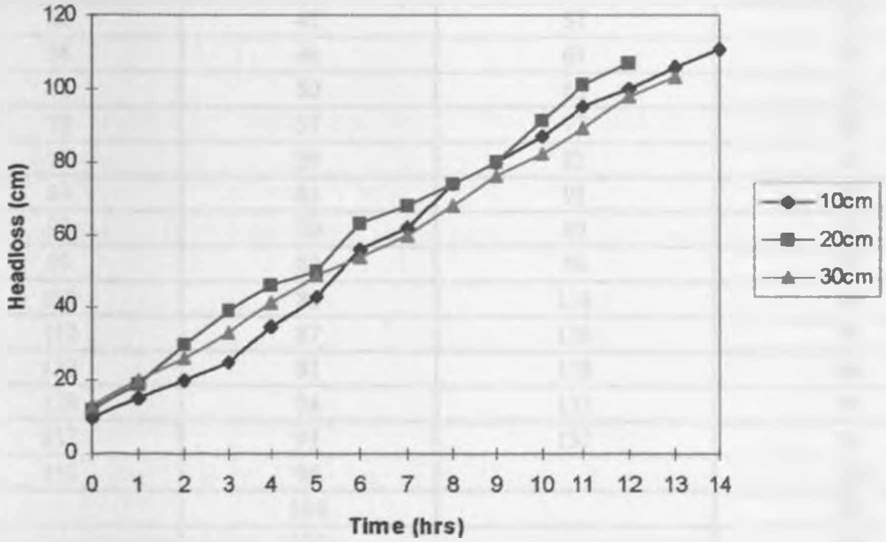

Figure 5.13: Variation of total headloss with time for various charcoal depths

The observations made from Figure 5.13 are that the headloss profiles for the three charcoal depths do not vary much. However, the 20cm charcoal depth filter run maintained a slightly higher headloss throughout the filtration duration. The 30cm filter was initially slightly higher in headloss development than the 10cm but ultimately showed a slightly lower headloss than the 10cm charcoal depth filter run. The various depths of charcoal exhibit similar headloss profiles due to the similar effective sizes of the media (charcoal) which was used, as is governed by the $d^2$ parameter in Kozeny Carman equation.

d) Total headloss versus time, for full filter runs

This relationship was analysed for full filter runs for both RSF and DMF using both organic as well as organic and inorganic influent. Table 5.14 gives the results, which was derived from data presented in Tables A.9, A.10, A.11, and A.12.

Table 5.14: Total headloss versus time, for full filter runs

| | Total headloss (cm) | | | |
|---|---|---|---|---|
| Time (hrs) | RSF (Tartrazine) | DMF (Tartrazine) | RSF (Muddy water) | DMF (Muddy water) |
| 0 | 20 | 13 | 19 | 10 |
| 1 | 28 | 22 | 27 | 19 |
| 2 | 34 | 29 | 37 | 23 |
| 3 | 42 | 38 | 41 | 32 |
| 4 | 50 | 42 | 57 | 37 |
| 5 | 56 | 46 | 63 | 41 |
| 6 | 62 | 50 | 65 | 46 |
| 7 | 72 | 57 | 77 | 54 |
| 8 | 76 | 59 | 82 | 56 |
| 9 | 84 | 63 | 91 | 67 |
| 10 | 97 | 70 | 89 | 65 |
| 11 | 99 | 80 | 96 | 79 |
| 12 | 109 | 86 | 114 | 84 |
| 13 | 112 | 87 | 116 | 91 |
| 14 | 122 | 91 | 128 | 86 |
| 15 | 128 | 94 | 133 | 96 |
| 16 | 137 | 91 | 152 | 99 |
| 17 | 152 | 96 | | 102 |
| 18 | | 104 | | 102 |
| 19 | | 104 | | 107 |
| 20 | | 123 | | 117 |
| 21 | | 138 | | 125 |
| 22 | | 153 | | 138 |
| 23 | | | | 152 |

From Table 5.14, Figure 5.14 was prepared giving the plots for the relationships for the variation of total headloss with time, for the full filter runs.

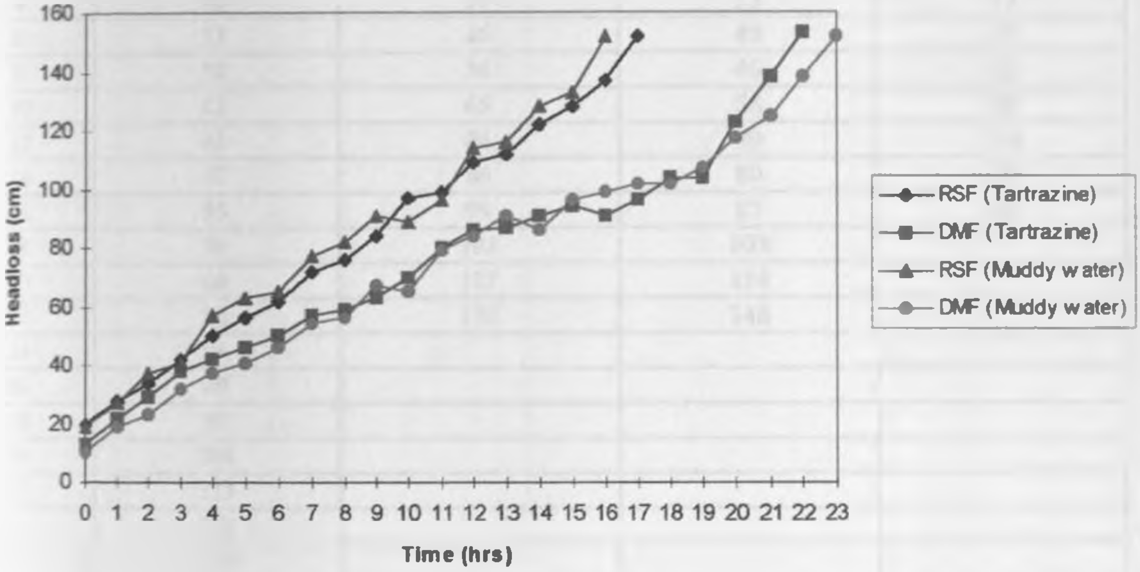

Figure 5.14: Variation of total headloss with time for full filter runs

From Figure 5.14, it can be observed that the RSF exhibits a higher headloss than the DMF. The RSF was the first to achieve the terminal headloss of 150cm. The DMF reached the terminal headloss about 6 hours after the RSF.

The other observation which is worth noting is that the rate of development of headloss is relatively uniform throughout the initial stages of the filter run, after which it rises exponentially with time for the last few hours of the filter runs, probably due to solids breakthrough in the filter media.

Total headloss versus time, for coagulated, flocculated influent

This relationship is for full filter runs for both filters. A comparison is made between the headloss development in coagulated water with that of uncoagulated water. The results from this analysis are given in Table 5.15, and is derived from the data presented in Tables A.11, A.12, A.15, and A.16.

Table 5.15: Total headloss versus time. for coagulated. flocculated water

| | **Total headloss (cm)** | | | |
|---|---|---|---|---|
| **Time (hrs)** | **Coagulated (DMF)** | **Uncoagulated (DMF)** | **Coagulated (RSF)** | **Uncoagulated (RSF)** |
| 0 | 26 | 10 | 26 | 19 |
| 2 | 28 | 23 | 30 | 37 |
| 4 | 30 | 37 | 33 | 57 |
| 6 | 33 | 46 | 40 | 65 |
| 8 | 38 | 56 | 46 | 82 |
| 10 | 42 | 65 | 58 | 89 |
| 12 | 45 | 84 | 70 | 114 |
| 14 | 47 | 86 | 80 | 128 |
| 16 | 53 | 99 | 87 | 152 |
| 18 | 59 | 102 | 103 | |
| 20 | 64 | 117 | 124 | |
| 22 | 76 | 138 | 148 | |
| 24 | 84 | | | |
| 26 | 89 | | | |
| 28 | 97 | | | |
| 30 | 104 | | | |
| 32 | 113 | | | |
| 34 | 126 | | | |
| 36 | 139 | | | |
| 38 | 152 | | | |

These results were used to prepare Figure 5.15 which shows the development of headloss in the coagulated water as compared to headloss development in uncoagulated water for both filters.

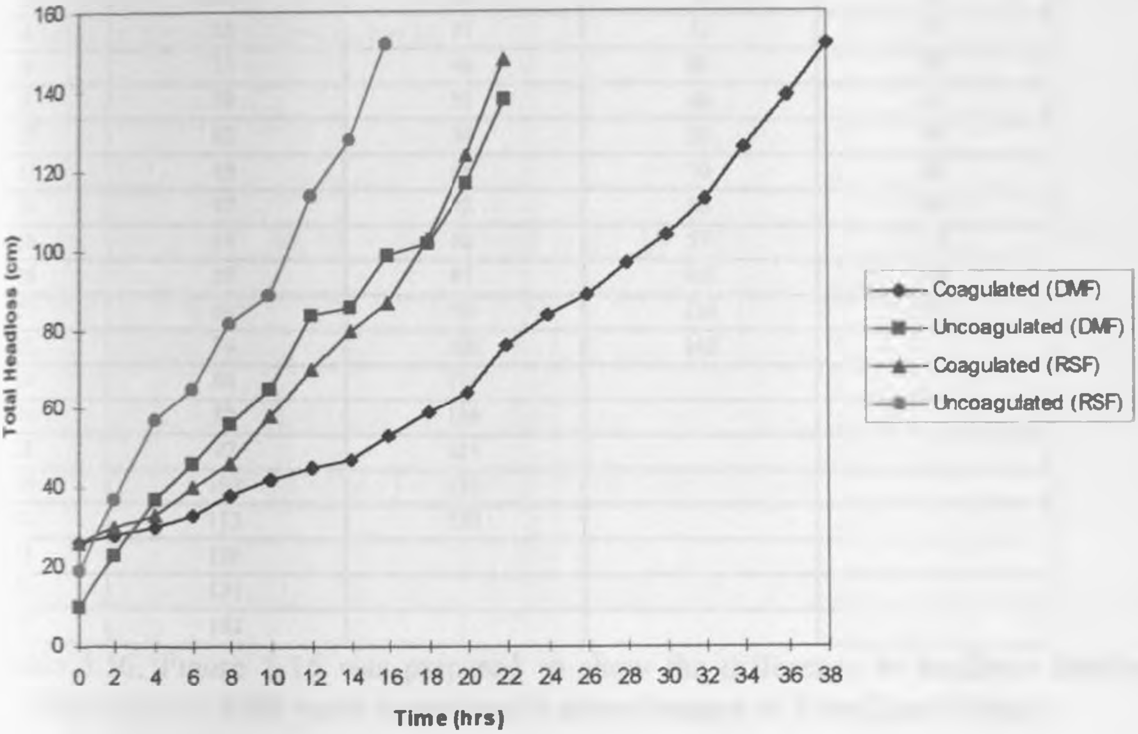

Figure 5.15: Variation of total headloss with time, for coagulated influent

From the graphs, it can be observed that the uncoagulated water gives rise to higher rate of headloss development as compared to that of the coagulated water. It is for this reason that the uncoagulated water attains the terminal headloss of 150cm much earlier than the coagulated water. A key observation can be made that the performance of uncoagulated DMF is relatively similar to coagulated RSF as far as headloss development is concerned. This points towards the elimination of coagulation when such dual media filtration is applied.

f) Total headloss versus time, for various alum dosages

The headloss development of the filter when subjected to varying alum dosages was analysed and is presented in Table 5.16. This table was formulated from the data presented in Tables A.13, A.14, A.15, and A.16.

Table 5.16: Total headloss versus time, for various alum dosages

| | Total headloss (cm) | | | |
|---|---|---|---|---|
| **Time (hrs)** | **DMF (30mg/l)** | **DMF (10mg/l)** | **RSF (30mg/l)** | **RSF (10mg/l)** |
| 0 | 26 | 28 | 26 | 35 |
| 2 | 28 | 30 | 30 | 45 |
| 4 | 30 | 37 | 33 | 57 |
| 6 | 33 | 46 | 40 | 58 |
| 8 | 38 | 51 | 46 | 67 |
| 10 | 42 | 56 | 58 | 76 |
| 12 | 45 | 64 | 70 | 88 |
| 14 | 47 | 72 | 80 | 102 |
| 16 | 53 | 80 | 87 | 114 |
| 18 | 59 | 87 | 103 | 130 |
| 20 | 64 | 93 | 124 | 151 |
| 22 | 76 | 100 | 148 | |
| 24 | 84 | 114 | | |
| 26 | 89 | 116 | | |
| 28 | 97 | 125 | | |
| 30 | 104 | 131 | | |
| 32 | 113 | 150 | | |
| 34 | 126 | | | |
| 36 | 139 | | | |
| 38 | 152 | | | |

From Table 5.16, Figure 5.16 was prepared to show the difference in headloss development when the filters are run with water coagulated at alum dosages of 10mg/l and 30mg/l.

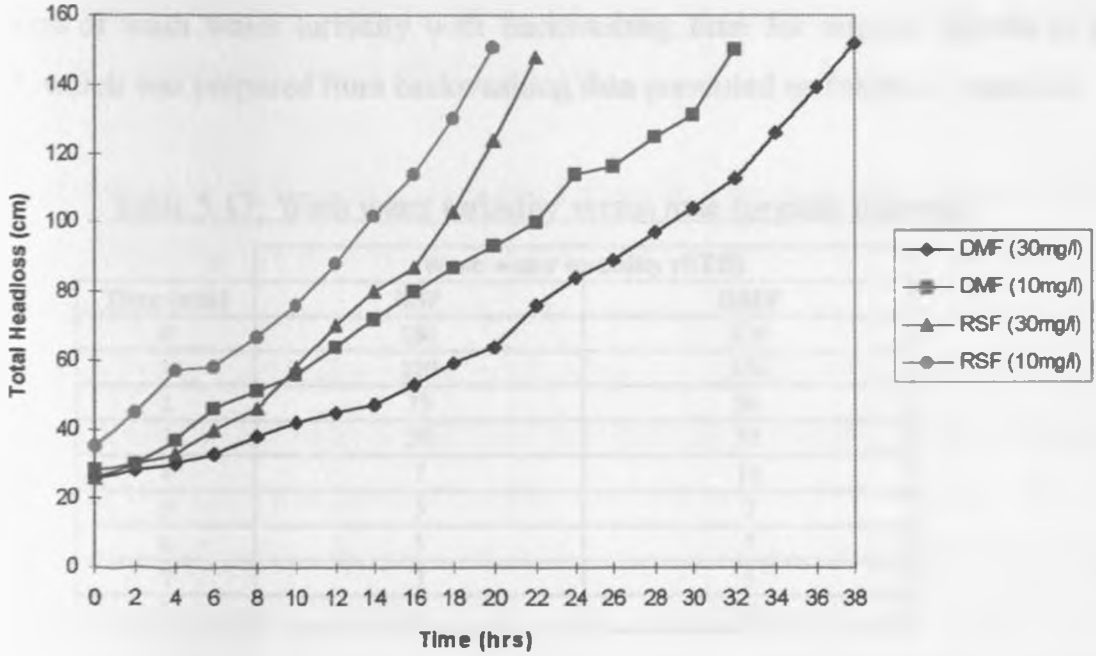

Figure 5.16: Variation of total headloss with time, for various alum dosages

From Figure 5.16, it is observed that just like in the case of turbidity removal for this particular set-up, different alum dosages result in different rates of headloss development and therefore different lengths of filter runs. A jar test should be able to establish the optimum alum dosage for the lowest rate of headloss development.

### 5.2.3 Backwashing characteristics

Backwashing was carried out by initially subjecting the filters to combined air and water scour for three minutes, thus enhancing the expansion of the bed. This was subsequently followed by five minutes of continuous wash water alone. The backwash air pressure was fixed at 20.7KN/mm$^2$, while the backwash water flow rate was varied slightly for the purpose of analyzing the relationship between bed expansion and backwash rate.

The analysis for backwashing was done by determining the variation of wash water turbidity with time, as well as relating the bed expansion to the backwash rate. Finally, computations were made of the average percentage of filtered water needed for backwashing of the filters.

a) <u>Wash water turbidity versus time</u>

The variation of wash water turbidity with backwashing time for organic influent is given in Table 5.17. which was prepared from backwashing data presented in Tables A.1 and A.2.

Table 5.17: Wash water turbidity versus time (organic influent)

| | **Wash water turbidity (NTU)** | |
|---|---|---|
| **Time (min)** | **RSF** | **DMF** |
| 0 | 180 | 230 |
| 1 | 120 | 150 |
| 2 | 75 | 90 |
| 3 | 20 | 35 |
| 4 | 7 | 11 |
| 5 | 5 | 7 |
| 6 | 5 | 5 |
| 7 | 3 | 5 |
| 8 | 3 | 4 |

With information from this table, the graphs shown in Figure 5.17 were plotted.

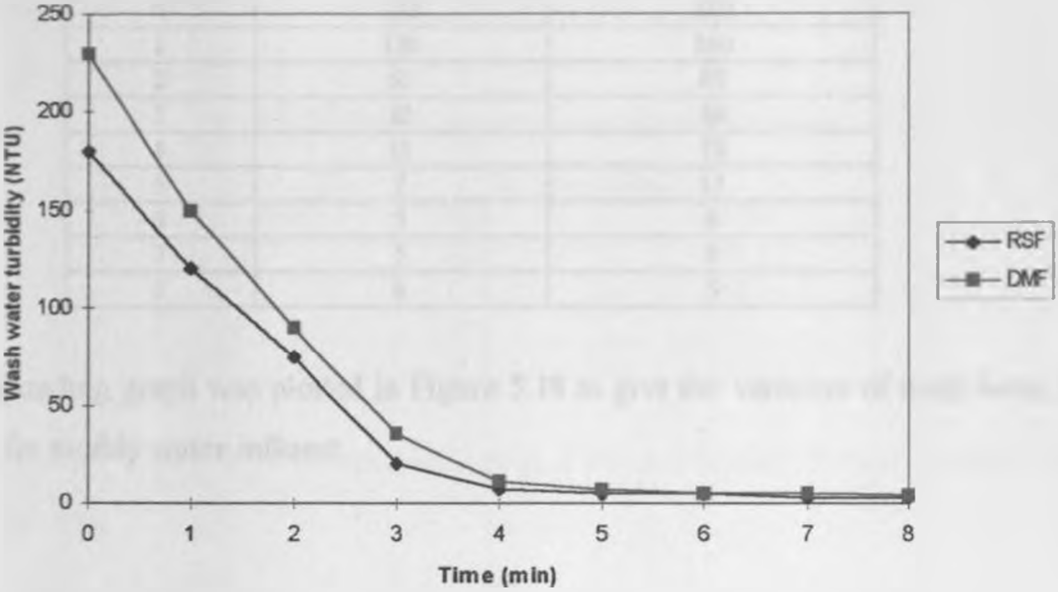

Figure 5.17: Variation of wash water turbidity with time (organic)

The wash water turbidities reported here appear to be generally low. This is associated with relatively short lengths of filter runs (about 12 hours) used in this analysis. The wash water from the DMF has higher turbidity than the RSF. This can be attributed to the higher degree of accumulation of particulate by the media in the DMF.

It is observed that about 80% of the accumulated material is washed away during the first three minutes of backwashing for both DMF and RSF. This 3-minute period coincides with the duration for combined air and water scouring. The remaining backwashing time serves to "polish up" the cleaning of the media, with just a small difference in wash water turbidity being noted. This observation suggest that most of this material is physically attached to the media, probably as a consequence of straining or transport mechanism both on the DMF and RSF. Note that the pores in the charcoal effectively increases the surface area to volume ratio, thereby creating more surface for straining or gravity settling of inorganic matter. alongside the organic particulate removal by the process of adsorption. Similarly, for organic and inorganic influent, Table 5.18 has the results as computed from Tables A.5 and A.6.

Table 5.18: Wash water turbidity versus time (muddy water)

| | Wash water turbidity (NTU) | |
|---|---|---|
| Time (min) | RSF | DMF |
| 0 | 200 | 220 |
| 1 | 120 | 160 |
| 2 | 63 | 85 |
| 3 | 22 | 40 |
| 4 | 11 | 18 |
| 5 | 7 | 11 |
| 6 | 5 | 6 |
| 7 | 5 | 8 |
| 8 | 6 | 5 |

The corresponding graph was plotted in Figure 5.18 to give the variation of wash water turbidity with time, for muddy water influent.

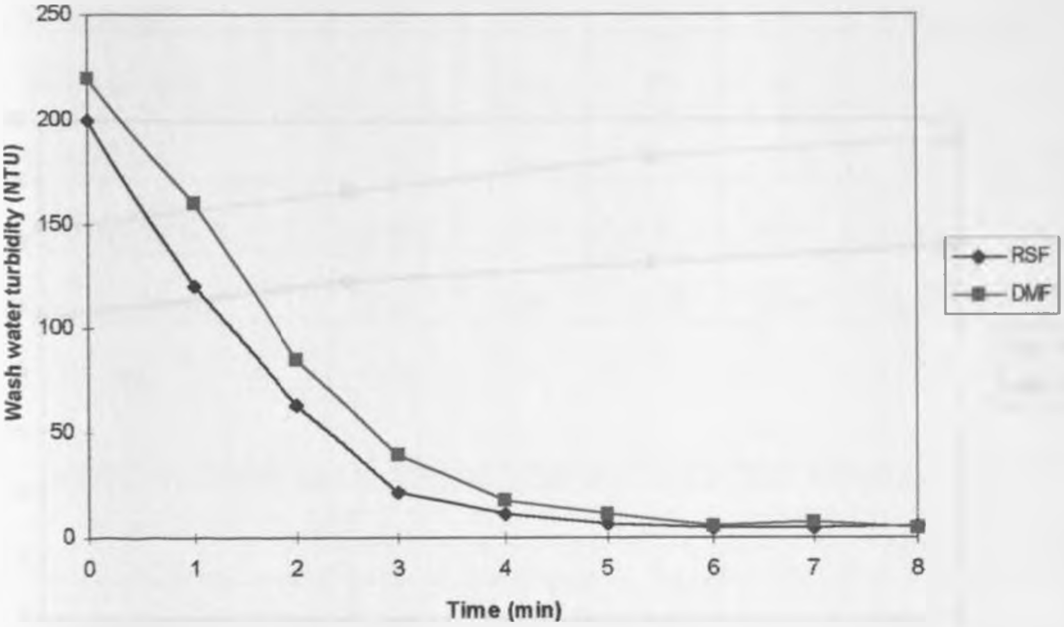

Figure 5.18: Variation of wash water turbidity with time (muddy water)

Figure 5.18 exhibits identical properties to those observed in Figure 5.17, with the DMF having wash water of higher turbidity than the RSF. Again, about 80% of the accumulated material is washed away within the first 3 minutes of backwashing.

### b) Bed expansion versus backwash rate

The results for the variation of bed expansion with backwash rate is given in Table 5.19. These results were derived from the backwashing data presented in Tables A.1 to A.8.

Table 5.19: Bed expansion versus backwash rate

| | Bed expansion (%) | |
|---|---|---|
| Rate ($m^3/m^2/hr$) | RSF | DMF |
| 30.6 | 24.3 | 31.4 |
| 31.2 | 27.1 | 34.3 |
| 31.8 | 28.6 | 37.1 |
| 32.4 | 30.0 | 38.6 |

With these results, Figure 5.19 was prepared to give the relationship between the bed expansion and backwash rate.

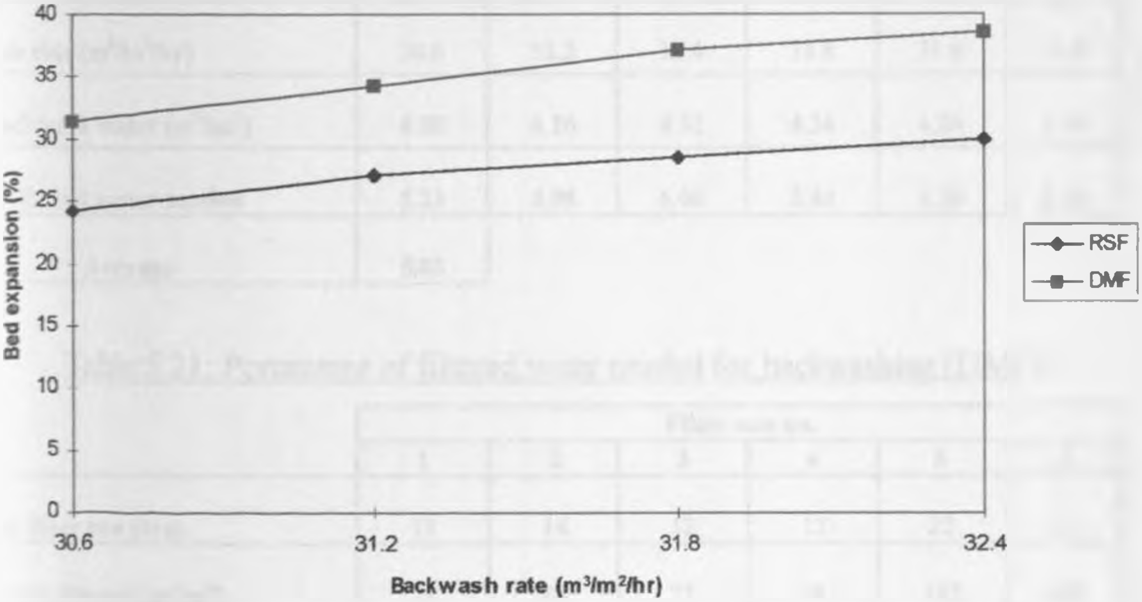

Figure 5.19: Variation of bed expansion with backwash rate

The direct observation from Figure 5.19 is that the DMF has a higher bed expansion than the RSF. This is due to the lower density of the charcoal as compared to that of sand. The charcoal is herefore more easily fluidized than the sand, thus increasing the expansion of the DMF bed. The DMF exhibits a bed expansion of about 1.2 times that of the RSF.

Another observation is that there is a general increase in the degree of bed expansion with increase in backwashing rate.

### c) Percentage of filtered water needed for backwashing

The amount of filtered water needed for backwashing was calculated for each filter run, and an average value was computed for the purpose of comparing the performance of the two filters in this regard. The results of these analysis are given in Tables 5.20 and 5.21.

Table 5.20: Percentage of filtered water needed for backwashing (RSF)

| | **Filter run no.** | | | | | |
|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** | **6** |
| **Length of filter run (hrs)** | 13 | 14 | 12 | 13 | 17 | 16 |
| **Vol of water filtered ($m^3/m^2$)** | 78 | 84 | 72 | 78 | 102 | 96 |
| **Backwash rate ($m^3/m^2/hr$)** | 30.6 | 31.2 | 32.4 | 31.8 | 31.8 | 31.8 |
| **Vol of backwash water ($m^3/m^2$)** | 4.08 | 4.16 | 4.32 | 4.24 | 4.24 | 4.24 |
| **%age of filtered water needed** | **5.23** | **4.95** | **6.00** | **5.44** | **4.16** | **4.42** |
| **Average** | **5.03** | | | | | |

Table 5.21: Percentage of filtered water needed for backwashing (DMF)

| | **Filter run no.** | | | | | |
|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** | **6** |
| **Length of filter run (hrs)** | 13 | 14 | 12 | 13 | 22 | 23 |
| **Vol of water filtered ($m^3/m^2$)** | 78 | 84 | 72 | 78 | 132 | 138 |
| **Backwash rate ($m^3/m^2/hr$)** | 30.6 | 31.2 | 32.4 | 31.8 | 31.8 | 31.8 |
| **Vol of backwash water ($m^3/m^2$)** | 4.08 | 4.16 | 4.32 | 4.24 | 4.24 | 4.24 |
| **%age of filtered water needed** | **5.23** | **4.95** | **6.00** | **5.44** | **3.21** | **3.07** |
| **Average** | **4.65** | | | | | |

From these tables, it is observed that for RSF, an average of 5.03% of the filtered water is needed for backwashing. On the other hand, only 4.65% of the filtered water is needed for the backwashing of the DMF. Therefore, the RSF needs 1.08 times more filtered water for backwashing than the DMF.

# Chapter Six

## 6.0 Conclusions and recommendations

### 6.1 Conclusions

The filtration curves generally show better performance of ground charcoal dual media filter as compared to the conventional rapid sand filter. This is seen from the higher turbidity removal in the dual media filter, as well as lower headlosses than in the conventional rapid sand filter. The volume of filtered water required for backwashing the dual media filter is lower than for the conventional rapid sand filter.

Coagulation and flocculation of the water prior to filtration has also proved to give better performance, both in terms of turbidity removal as well as headloss development. However, jar tests should be able to give the optimum chemical dosage to be applied for a given influent turbidity in order to attain the best performance.

The results obtained have shown that the ground charcoal can be applied as a coarse, light medium in dual media filtration of potable water. The application of charcoal is also economically sound due to its widespread availability throughout the country.

### 6.2 Recommendations

The following recommendations have been suggested for further research on the applicability of ground charcoal as a coarse filter medium in dual media filtration of potable water:

1. Research should be done to establish the species of tree which produces charcoal with "optimum" characteristics in terms of density, acid solubility, physical stability and degree of adsorption.

2. An assessment should be done to establish the optimum charcoal depth for best performance, while at the same time maintaining an acceptable bed expansion during backwashing.

3. For the dual media filter, research should be done to establish how long the filter can operate before having to regenerate the charcoal.

4. Research should establish the maximum filtration rates which can be applied to the dual media filter.

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# Appendix

**Table A.1 : Data for filter run no. 1 for the RSF model**

## Filtration data

6 / 3 / 99

Filter run no. 1

Column: RSF

ar time 07:00

Filtration rate: 6 $m^3/m^2/hr$

| ime | Head (cm) | | | | | | | | Turbidity (NTU) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Port 1 | Port 2 | Port 3 | Port 4 | Port 5 | Port 6 | Port 7 | Port 8 | Port 1 | Port 2 | Port 3 | Port 4 | Port 5 | Port 6 | Port 7 | Port 8 | Efflue |
| | | | | | | | | | | | | | | | | | |
| 07:00 | 134 | 134 | 133 | 130 | 127 | 123 | 119 | 113 | 55 | 55 | 53 | 50 | 47 | 44 | 42 | 40 | 37 |
| 08:00 | 136 | 133 | 130 | 126 | 120 | 115 | 115 | 107 | 42 | 40 | 38 | 37 | 36 | 36 | 33 | 32 | 31 |
| 09:00 | 133 | 130 | 127 | 122 | 117 | 111 | 105 | 99 | 33 | 32 | 30 | 27 | 26 | 26 | 26 | 25 | 25 |
| 10:00 | 133 | 130 | 125 | 120 | 112 | 107 | 98 | 91 | 52 | 50 | 47 | 43 | 42 | 41 | 40 | 40 | 39 |
| 11:00 | 135 | 131 | 126 | 119 | 108 | 97 | 89 | 80 | 45 | 45 | 43 | 43 | 41 | 42 | 40 | 38 | 36 |
| 12:00 | 134 | 130 | 125 | 119 | 101 | 90 | 79 | 71 | 42 | 40 | 37 | 34 | 33 | 32 | 32 | 31 | 32 |
| 13:00 | 134 | 128 | 118 | 103 | 95 | 82 | 76 | 65 | 40 | 41 | 38 | 37 | 38 | 36 | 35 | 33 | 32 |
| 14:00 | 134 | 128 | 116 | 102 | 90 | 79 | 66 | 54 | 34 | 32 | 30 | 31 | 31 | 30 | 28 | 26 | 27 |
| 15:00 | 135 | 127 | 117 | 103 | 90 | 77 | 64 | 50 | 30 | 28 | 25 | 26 | 26 | 25 | 25 | 24 | 24 |
| 16:00 | 134 | 126 | 116 | 103 | 89 | 73 | 58 | 42 | 45 | 44 | 42 | 41 | 41 | 41 | 42 | 40 | 39 |
| 17:00 | 133 | 127 | 115 | 98 | 81 | 62 | 48 | 31 | 45 | 43 | 41 | 40 | 40 | 39 | 38 | 37 | 38 |
| 18:00 | 135 | 127 | 113 | 95 | 77 | 59 | 41 | 23 | 41 | 41 | 38 | 38 | 36 | 35 | 35 | 34 | 35 |
| 19:00 | 136 | 126 | 108 | 91 | 74 | 57 | 41 | 14 | 38 | 36 | 36 | 36 | 34 | 33 | 33 | 32 | 33 |
| 20:00 | 134 | 128 | 110 | 90 | 71 | 50 | 28 | 7 | 34 | 32 | 32 | 30 | 30 | 30 | 29 | 29 | 29 |
| | | | | | | | | | | | | | | | | | |
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## Backwash

r + water: 3 minutes

Unexpanded bed depth: 70 cm

Backwash rate: 30.6 $m^3/m^2/hr$

ater: 5 minutes

Expanded bed depth: 87 cm

| me (min) | Turbidity (NTU) |
|---|---|
| 0 | 180 |
| 1 | 120 |
| 2 | 75 |
| 3 | 20 |
| 4 | 7 |
| 5 | 5 |

| Time (min) | Turbidity (NTU) |
|---|---|
| 6 | 5 |
| 7 | 3 |
| 8 | 3 |
| | |
| | |
| | |

## Observations

Leakages gave rise to irregular head readings

Backwash air pressure = 20.7 $KN/m^2$

Sand depth = 70 cm

Influent = food dye solution (Tartrazine)

**Table A.2 : Data for filter run no. 1 for the DMF model**

## Filtration data

Date: 6 / 3 / 99

Filter run no. 1

Column: DMF

Start time: 07:00

Filtration rate: 6 m$^3$/m$^2$/hr

| Time | Head (cm) | | | | | | | | Turbidity (NTU) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Port 1 | Port 2 | Port 3 | Port 4 | Port 5 | Port 6 | Port 7 | Port 8 | Port 1 | Port 2 | Port 3 | Port 4 | Port 5 | Port 6 | Port 7 | Port 8 | Efflue |
| | | | | | | | | | | | | | | | | | |
| 07:00 | 152 | 152 | 148 | 147 | 144 | 141 | 139 | 139 | 53 | 53 | 38 | 35 | 32 | 30 | 27 | 26 | 26 |
| 08:00 | 150 | 147 | 145 | 142 | 139 | 137 | 132 | 129 | 40 | 38 | 25 | 25 | 26 | 23 | 23 | 22 | 21 |
| 09:00 | 149 | 146 | 141 | 135 | 131 | 128 | 124 | 119 | 33 | 32 | 20 | 19 | 19 | 18 | 17 | 17 | 17 |
| 10:00 | 149 | 144 | 137 | 132 | 127 | 120 | 116 | 110 | 50 | 50 | 37 | 37 | 35 | 34 | 35 | 32 | 29 |
| 11:00 | 151 | 144 | 139 | 130 | 125 | 118 | 112 | 105 | 46 | 45 | 32 | 31 | 31 | 29 | 29 | 29 | 28 |
| 12:00 | 150 | 143 | 133 | 127 | 119 | 113 | 106 | 97 | 42 | 40 | 29 | 29 | 27 | 26 | 27 | 26 | 25 |
| 13:00 | 150 | 141 | 132 | 123 | 115 | 105 | 96 | 88 | 38 | 38 | 28 | 26 | 25 | 25 | 25 | 23 | 23 |
| 14:00 | 150 | 140 | 131 | 120 | 111 | 101 | 92 | 82 | 35 | 36 | 28 | 27 | 27 | 26 | 25 | 25 | 24 |
| 15:00 | 149 | 138 | 126 | 117 | 105 | 97 | 86 | 75 | 28 | 27 | 20 | 19 | 19 | 18 | 18 | 19 | 19 |
| 16:00 | 151 | 139 | 127 | 116 | 103 | 91 | 80 | 68 | 47 | 47 | 40 | 38 | 37 | 37 | 36 | 37 | 36 |
| 17:00 | 150 | 137 | 124 | 111 | 97 | 85 | 73 | 59 | 45 | 45 | 40 | 40 | 38 | 37 | 37 | 37 | 36 |
| 18:00 | 149 | 134 | 121 | 106 | 91 | 78 | 66 | 50 | 40 | 39 | 33 | 32 | 32 | 30 | 31 | 31 | 31 |
| 19:00 | 150 | 135 | 121 | 105 | 90 | 77 | 60 | 45 | 37 | 37 | 32 | 30 | 30 | 31 | 30 | 29 | 29 |
| 20:00 | 149 | 133 | 118 | 102 | 83 | 70 | 54 | 38 | 34 | 32 | 27 | 27 | 26 | 26 | 25 | 25 | 26 |
| | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | |
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## Backwash

Air + water: 3 minutes

Unexpanded bed depth: 70 cm

Backwash rate: 30.6 m$^3$/m$^2$/hr

Water: 5 minutes

Expanded bed depth: 92 cm

| Time (min) | Turbidity (NTU) |
|---|---|
| 0 | 230 |
| 1 | 150 |
| 2 | 90 |
| 3 | 35 |
| 4 | 11 |
| 5 | 7 |

| Time (min) | Turbidity (NTU) |
|---|---|
| 6 | 5 |
| 7 | 5 |
| 8 | 4 |
| | |
| | |
| | |

## Observations

Leakages gave rise to irregular head readings

Backwash air pressure = 20.7 KN/m$^2$

Sand depth = 50 cm Charcoal depth = 20 cm

Influent = food dye solution (Tartrazine)

**Table A.3 : Data for filter run no. 2 for the RSF model**

## Filtration data

Date 8 / 3 / 99 Filter run no 2 Column: RSF

Start time 06:30 Filtration rate: 6 $m^3/m^2/hr$

| Time | Head (cm) | | | | | | | | Turbidity (NTU) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Port 1 | Port 2 | Port 3 | Port 4 | Port 5 | Port 6 | Port 7 | Port 8 | Port 1 | Port 2 | Port 3 | Port 4 | Port 5 | Port 6 | Port 7 | Port 8 | Efflue |
| | | | | | | | | | | | | | | | | | |
| 06:30 | 137 | 136 | 135 | 130 | 126 | 121 | 114 | 110 | 35 | 32 | 31 | 29 | 28 | 26 | 24 | 23 | 22 |
| 07:30 | 137 | 134 | 128 | 122 | 117 | 111 | 107 | 105 | 35 | 33 | 31 | 28 | 28 | 25 | 22 | 21 | 20 |
| 08:30 | 138 | 134 | 127 | 119 | 112 | 103 | 99 | 100 | 31 | 30 | 30 | 29 | 28 | 26 | 23 | 22 | 21 |
| 09:30 | 137 | 133 | 123 | 117 | 107 | 96 | 90 | 90 | 28 | 26 | 24 | 25 | 25 | 24 | 23 | 21 | 20 |
| 10:30 | 136 | 133 | 122 | 114 | 101 | 87 | 82 | 78 | 30 | 29 | 28 | 28 | 27 | 24 | 22 | 21 | 19 |
| 11:30 | 136 | 133 | 118 | 112 | 97 | 80 | 75 | 70 | 32 | 30 | 27 | 25 | 26 | 25 | 24 | 22 | 19 |
| 12:30 | 137 | 134 | 120 | 107 | 91 | 71 | 69 | 63 | 32 | 31 | 28 | 26 | 23 | 22 | 20 | 19 | 18 |
| 13:30 | 135 | 132 | 120 | 105 | 85 | 64 | 62 | 51 | 30 | 27 | 25 | 23 | 23 | 22 | 21 | 20 | 19 |
| 14:30 | 137 | 132 | 119 | 101 | 80 | 60 | 57 | 48 | 30 | 28 | 27 | 25 | 23 | 21 | 20 | 18 | 18 |
| 15:30 | 137 | 132 | 118 | 98 | 76 | 57 | 48 | 41 | 29 | 27 | 25 | 24 | 22 | 20 | 19 | 19 | 18 |
| 16:30 | 136 | 131 | 118 | 97 | 73 | 54 | 41 | 33 | 30 | 27 | 27 | 24 | 23 | 21 | 19 | 17 | 17 |
| 17:30 | 138 | 130 | 117 | 95 | 71 | 52 | 33 | 20 | 30 | 28 | 26 | 23 | 21 | 19 | 16 | 17 | 16 |
| 18:30 | 137 | 131 | 117 | 95 | 69 | 50 | 26 | 13 | 28 | 26 | 24 | 22 | 19 | 19 | 18 | 17 | 17 |
| 19:30 | 136 | 130 | 116 | 94 | 69 | 49 | 21 | 6 | 25 | 24 | 23 | 22 | 20 | 17 | 17 | 16 | 15 |
| 20:30 | 137 | 130 | 116 | 94 | 69 | 48 | 17 | 3 | 23 | 23 | 23 | 21 | 20 | 18 | 17 | 17 | 15 |
| | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | |

## Backwash

Air + water: 3 minutes Unexpanded bed depth: 70 cm Backwash rate: 31.2 $m^3/m^2/hr$

Water: 5 minutes Expanded bed depth: 89 cm

| Time (min) | Turbidity (NTU) |
|---|---|
| 0 | 110 |
| 1 | 56 |
| 2 | 23 |
| 3 | 11 |
| 4 | 6.8 |
| 5 | 4.3 |

| Time (min) | Turbidity (NTU) |
|---|---|
| 6 | 3.7 |
| 7 | 1.9 |
| 8 | 1.5 |
| | |
| | |
| | |

## Observations

Leakages gave rise to irregular head readings

Backwash air pressure = 20.7 $KN/m^2$

Sand depth = 70 cm

Influent = muddy water

## Table A.4 : Data for filter run no. 2 for the DMF model

## Filtration data

Date: 8 / 3 / 99 Filter run no. 2 Column: DMF

Start time: 06:30 Filtration rate: 6 m$^3$/m$^2$/hr

| Time | Head (cm) | | | | | | | | Turbidity (NTU) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Port 1 | Port 2 | Port 3 | Port 4 | Port 5 | Port 6 | Port 7 | Port 8 | Port 1 | Port 2 | Port 3 | Port 4 | Port 5 | Port 6 | Port 7 | Port 8 | Efflue |
| | | | | | | | | | | | | | | | | | |
| 06:30 | 147 | 143 | 142 | 140 | 141 | 139 | 138 | 137 | 35 | 26 | 24 | 25 | 24 | 22 | 21 | 19 | 18 |
| 07:30 | 147 | 143 | 141 | 140 | 139 | 137 | 133 | 132 | 35 | 26 | 25 | 25 | 23 | 21 | 20 | 19 | 18 |
| 08:30 | 146 | 143 | 140 | 137 | 133 | 131 | 129 | 126 | 31 | 25 | 24 | 23 | 21 | 21 | 20 | 18 | 17 |
| 09:30 | 145 | 142 | 138 | 135 | 130 | 127 | 123 | 120 | 28 | 23 | 23 | 21 | 20 | 21 | 19 | 18 | 17 |
| 10:30 | 147 | 140 | 137 | 133 | 130 | 126 | 118 | 112 | 30 | 24 | 22 | 22 | 21 | 20 | 19 | 18 | 18 |
| 11:30 | 148 | 138 | 135 | 130 | 124 | 119 | 111 | 105 | 32 | 25 | 22 | 21 | 20 | 20 | 19 | 18 | 19 |
| 12:30 | 147 | 135 | 130 | 124 | 119 | 113 | 101 | 91 | 32 | 25 | 22 | 20 | 19 | 19 | 18 | 19 | 19 |
| 13:30 | 146 | 134 | 128 | 120 | 111 | 103 | 95 | 84 | 30 | 25 | 21 | 19 | 20 | 20 | 19 | 20 | 20 |
| 14:30 | 147 | 131 | 123 | 116 | 105 | 97 | 84 | 73 | 30 | 23 | 21 | 21 | 20 | 20 | 21 | 20 | 20 |
| 15:30 | 145 | 128 | 115 | 101 | 93 | 80 | 72 | 65 | 29 | 23 | 20 | 21 | 20 | 20 | 19 | 20 | 20 |
| 16:30 | 145 | 126 | 110 | 96 | 82 | 73 | 65 | 58 | 30 | 24 | 21 | 21 | 20 | 21 | 20 | 19 | 19 |
| 17:30 | 147 | 124 | 107 | 93 | 80 | 70 | 61 | 52 | 30 | 23 | 20 | 20 | 19 | 19 | 20 | 20 | 20 |
| 18:30 | 146 | 123 | 107 | 90 | 81 | 69 | 56 | 46 | 28 | 23 | 20 | 19 | 20 | 20 | 19 | 19 | 19 |
| 19:30 | 146 | 120 | 103 | 88 | 76 | 64 | 51 | 40 | 25 | 21 | 21 | 21 | 20 | 20 | 19 | 19 | 19 |
| 20:30 | 146 | 118 | 100 | 82 | 73 | 61 | 46 | 35 | 23 | 21 | 19 | 19 | 20 | 19 | 18 | 19 | 18 |
| | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | |

## Backwash

Air + water: 3 minutes Unexpanded bed depth: 70 cm Backwash rate: 31.2 m$^3$/m$^2$/hr

Water: 5 minutes Expanded bed depth: 94 cm

| Time (min) | Turbidity (NTU) |
|---|---|
| 0 | 120 |
| 1 | 63 |
| 2 | 28 |
| 3 | 16 |
| 4 | 9.3 |
| 5 | 5.6 |

| Time (min) | Turbidity (NTU) |
|---|---|
| 6 | 2.7 |
| 7 | 2.4 |
| 8 | 1.3 |
| | |
| | |
| | |

## Observations

Leakages gave rise to irregular head readings

Backwash air pressure = 20.7 KN/m$^2$

Sand depth = 60 cm Charcoal depth = 10 cm

Influent = muddy water

## Table A.5 : Data for filter run no. 3 for the RSF model

### Filtration data

Date: 10 / 3 / 99    Filter run no. 3    Column: RSF

Start time: 07 30    Filtration rate: 6 $m^3/m^2/hr$

| Time | Head (cm) | | | | | | | | Turbidity (NTU) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Port 1 | Port 2 | Port 3 | Port 4 | Port 5 | Port 6 | Port 7 | Port 8 | Port 1 | Port 2 | Port 3 | Port 4 | Port 5 | Port 6 | Port 7 | Port 8 | Efflue |
| | | | | | | | | | | | | | | | | | |
| 07 30 | 139 | 140 | 138 | 135 | 135 | 129 | 124 | 119 | 67 | 67 | 65 | 61 | 58 | 55 | 51 | 48 | 45 |
| 08 30 | 140 | 139 | 134 | 131 | 125 | 120 | 121 | 112 | 52 | 48 | 46 | 46 | 44 | 43 | 40 | 38 | 36 |
| 09 30 | 139 | 136 | 132 | 128 | 124 | 117 | 110 | 104 | 43 | 40 | 36 | 33 | 31 | 31 | 31 | 28 | 28 |
| 10 30 | 138 | 135 | 131 | 123 | 117 | 112 | 103 | 96 | 61 | 61 | 56 | 53 | 51 | 49 | 47 | 44 | 43 |
| 11 30 | 140 | 136 | 130 | 123 | 115 | 101 | 95 | 87 | 54 | 54 | 52 | 52 | 51 | 49 | 46 | 43 | 41 |
| 12 30 | 140 | 135 | 128 | 124 | 106 | 95 | 84 | 76 | 50 | 47 | 45 | 41 | 40 | 39 | 38 | 37 | 36 |
| 13 30 | 138 | 132 | 123 | 110 | 100 | 87 | 83 | 70 | 48 | 50 | 45 | 45 | 46 | 44 | 42 | 40 | 37 |
| 14 30 | 139 | 133 | 120 | 107 | 97 | 85 | 71 | 60 | 42 | 38 | 36 | 39 | 37 | 35 | 34 | 33 | 32 |
| 15 30 | 140 | 132 | 122 | 108 | 95 | 82 | 67 | 55 | 36 | 34 | 30 | 31 | 31 | 30 | 29 | 28 | 29 |
| 16 30 | 140 | 131 | 122 | 107 | 95 | 77 | 60 | 47 | 53 | 53 | 50 | 50 | 49 | 48 | 46 | 45 | 44 |
| 17 30 | 139 | 133 | 120 | 103 | 86 | 67 | 53 | 34 | 54 | 51 | 50 | 47 | 48 | 46 | 44 | 45 | 45 |
| 18 30 | 140 | 132 | 119 | 102 | 82 | 64 | 46 | 28 | 51 | 50 | 46 | 46 | 44 | 42 | 42 | 41 | 40 |
| 19 30 | 141 | 130 | 114 | 96 | 78 | 63 | 44 | 22 | 45 | 45 | 43 | 44 | 42 | 40 | 41 | 38 | 38 |
| | | | | | | | | | | | | | | | | | |
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### Backwash

Air + water: 3 minutes    Unexpanded bed depth: 70 cm    Backwash rate: 32.4 $m^3/m^2/hr$

Water: 5 minutes    Expanded bed depth: 91 cm

| Time (min) | Turbidity (NTU) |
|---|---|
| 0 | 200 |
| 1 | 120 |
| 2 | 63 |
| 3 | 22 |
| 4 | 11 |
| 5 | 7 |

| Time (min) | Turbidity (NTU) |
|---|---|
| 6 | 5 |
| 7 | 5 |
| 8 | 6 |
| | |
| | |
| | |

### Observations

Loss of media during sampling and backwashing

Backwash air pressure = 20.7 $KN/m^2$

Sand depth = 70 cm

Influent = muddy water

**Table A.6 : Data for filter run no. 3 for the DMF model**

## Filtration data

Date: 10 / 3 / 99

Filter run no. 3

Column: DMF

Start time: 07:30

Filtration rate: 6 $m^3/m^2/hr$

| Time | Head (cm) | | | | | | | | Turbidity (NTU) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Port 1 | Port 2 | Port 3 | Port 4 | Port 5 | Port 6 | Port 7 | Port 8 | Port 1 | Port 2 | Port 3 | Port 4 | Port 5 | Port 6 | Port 7 | Port 8 | Efflue |
| 07:30 | 144 | 145 | 140 | 140 | 138 | 135 | 133 | 132 | 65 | 64 | 45 | 43 | 39 | 37 | 33 | 32 | 32 |
| 08:30 | 143 | 142 | 138 | 135 | 132 | 130 | 125 | 124 | 48 | 45 | 30 | 30 | 31 | 29 | 28 | 26 | 24 |
| 09:30 | 142 | 139 | 134 | 127 | 124 | 121 | 117 | 112 | 41 | 39 | 22 | 21 | 21 | 21 | 20 | 20 | 20 |
| 10:30 | 144 | 137 | 132 | 125 | 120 | 115 | 108 | 105 | 61 | 60 | 46 | 45 | 43 | 42 | 38 | 35 | 32 |
| 11:30 | 144 | 135 | 132 | 122 | 120 | 111 | 105 | 98 | 57 | 54 | 39 | 37 | 38 | 35 | 35 | 35 | 33 |
| 12:30 | 142 | 136 | 128 | 120 | 112 | 106 | 99 | 92 | 51 | 48 | 35 | 35 | 33 | 32 | 33 | 32 | 30 |
| 13:30 | 143 | 134 | 125 | 116 | 108 | 99 | 89 | 80 | 46 | 45 | 35 | 31 | 30 | 30 | 29 | 26 | 24 |
| 14:30 | 143 | 132 | 122 | 115 | 102 | 94 | 87 | 75 | 43 | 44 | 34 | 32 | 32 | 31 | 28 | 25 | 24 |
| 15:30 | 142 | 131 | 119 | 110 | 98 | 90 | 79 | 68 | 34 | 33 | 23 | 23 | 21 | 21 | 20 | 19 | 19 |
| 16:30 | 143 | 132 | 120 | 109 | 96 | 83 | 73 | 63 | 57 | 57 | 49 | 46 | 45 | 43 | 40 | 37 | 35 |
| 17:30 | 143 | 129 | 119 | 103 | 93 | 78 | 66 | 52 | 55 | 55 | 48 | 47 | 46 | 43 | 39 | 37 | 34 |
| 18:30 | 144 | 127 | 114 | 99 | 84 | 71 | 57 | 43 | 48 | 47 | 40 | 39 | 40 | 37 | 37 | 34 | 32 |
| 19:30 | 143 | 130 | 115 | 100 | 82 | 71 | 53 | 36 | 44 | 44 | 40 | 36 | 37 | 36 | 33 | 30 | 28 |

## Backwash

Air + water: 3 minutes

Unexpanded bed depth: 70 cm

Backwash rate: 32.4 $m^3/m^2/hr$

Water: 5 minutes

Expanded bed depth: 97 cm

| Time (min) | Turbidity (NTU) |
|---|---|
| 0 | 220 |
| 1 | 160 |
| 2 | 85 |
| 3 | 40 |
| 4 | 18 |
| 5 | 11 |

| Time (min) | Turbidity (NTU) |
|---|---|
| 6 | 6 |
| 7 | 8 |
| 8 | 5 |

## Observations

Loss of media during sampling and backwashing

Backwash air pressure = 20.7 $KN/m^2$

Sand depth = 50 cm Charcoal depth = 20 cm

Influent = muddy water

## Table A.7 : Data for filter run no. 4 for the RSF model

## Filtration data

12 / 3 / 99 | Filter run no. 4 | Column: RSF

me 07:00 | Filtration rate: 6 m³/m²/hr

| | Head (cm) | | | | | | | | Turbidity (NTU) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Port 1 | Port 2 | Port 3 | Port 4 | Port 5 | Port 6 | Port 7 | Port 8 | Port 1 | Port 2 | Port 3 | Port 4 | Port 5 | Port 6 | Port 7 | Port 8 | Efflue |
| | | | | | | | | | | | | | | | | | |
| 00 | 136 | 133 | 127 | 121 | 115 | 111 | 108 | 107 | 27 | 27 | 26 | 26 | 24 | 23 | 22 | 20 | 18 |
| 00 | 135 | 129 | 123 | 118 | 112 | 107 | 104 | 103 | 27 | 26 | 25 | 25 | 24 | 23 | 21 | 19 | 18 |
| 00 | 135 | 128 | 121 | 116 | 108 | 103 | 100 | 99 | 28 | 26 | 24 | 24 | 25 | 23 | 20 | 18 | 18 |
| 00 | 136 | 125 | 117 | 108 | 100 | 97 | 90 | 87 | 28 | 25 | 24 | 23 | 23 | 20 | 20 | 19 | 19 |
| 1:00 | 135 | 124 | 116 | 107 | 101 | 91 | 84 | 76 | 27 | 24 | 24 | 23 | 22 | 20 | 20 | 19 | 18 |
| 2:00 | 134 | 123 | 113 | 104 | 94 | 85 | 78 | 68 | 26 | 23 | 22 | 20 | 21 | 19 | 18 | 17 | 17 |
| 3:00 | 135 | 122 | 111 | 102 | 93 | 82 | 71 | 62 | 26 | 24 | 21 | 20 | 19 | 19 | 19 | 18 | 17 |
| 4:00 | 135 | 122 | 110 | 98 | 85 | 74 | 62 | 50 | 25 | 22 | 20 | 18 | 18 | 19 | 18 | 17 | 16 |
| 5:00 | 136 | 122 | 109 | 97 | 85 | 72 | 59 | 46 | 27 | 23 | 21 | 20 | 18 | 17 | 17 | 16 | 15 |
| 6:00 | 136 | 121 | 108 | 93 | 81 | 66 | 53 | 39 | 26 | 23 | 20 | 19 | 18 | 18 | 17 | 15 | 15 |
| 7:00 | 135 | 121 | 106 | 91 | 73 | 59 | 45 | 30 | 24 | 22 | 19 | 19 | 17 | 16 | 16 | 15 | 14 |
| 18:00 | 134 | 118 | 102 | 84 | 70 | 53 | 37 | 21 | 22 | 22 | 20 | 18 | 17 | 16 | 14 | 13 | 13 |
| 19:00 | 135 | 117 | 100 | 82 | 66 | 48 | 30 | 14 | 20 | 20 | 20 | 18 | 17 | 15 | 13 | 14 | 14 |
| 20:00 | 135 | 117 | 98 | 80 | 64 | 44 | 27 | 9 | 20 | 20 | 20 | 17 | 16 | 15 | 15 | 14 | 14 |
| | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | |

## Backwash

r + water: 3 minutes | Unexpanded bed depth: 70 cm | Backwash rate: 31.8 m³/m²/hr

ater: 5 minutes | Expanded bed depth: 90 cm

| me (min) | Turbidity (NTU) |
|---|---|
| 0 | 87 |
| 1 | 26 |
| 2 | 14 |
| 3 | 8.3 |
| 4 | 7.1 |
| 5 | 4.6 |

| Time (min) | Turbidity (NTU) |
|---|---|
| 6 | 2.8 |
| 7 | 1.7 |
| 8 | 1.3 |
| | |
| | |
| | |

## Observations

Leakages gave rise to irregular head readings

Backwash air pressure = 20.7 KN/m$^2$

Sand depth = 70 cm

Influent = muddy water

## Table A.8 : Data for filter run no. 4 for the DMF model

## Filtration data

Date 12 / 3 / 99 Filter run no. 4 Column: DMF

Start time 07:00 Filtration rate: 6 $m^3/m^2/hr$

| Time | Head (cm) | | | | | | | | Turbidity (NTU) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Port 1 | Port 2 | Port 3 | Port 4 | Port 5 | Port 6 | Port 7 | Port 8 | Port 1 | Port 2 | Port 3 | Port 4 | Port 5 | Port 6 | Port 7 | Port 8 | Efflue |
| | | | | | | | | | | | | | | | | | |
| 07:00 | 141 | 141 | 140 | 135 | 133 | 132 | 130 | 128 | 27 | 26 | 25 | 19 | 18 | 16 | 15 | 13 | 11 |
| 08:00 | 142 | 141 | 140 | 136 | 133 | 129 | 126 | 122 | 27 | 27 | 26 | 20 | 19 | 17 | 15 | 14 | 12 |
| 09:00 | 141 | 140 | 140 | 135 | 131 | 126 | 121 | 115 | 28 | 27 | 27 | 20 | 19 | 18 | 15 | 14 | 13 |
| 10:00 | 141 | 139 | 137 | 130 | 125 | 119 | 113 | 108 | 28 | 26 | 26 | 19 | 18 | 17 | 16 | 14 | 13 |
| 11:00 | 140 | 138 | 137 | 126 | 119 | 113 | 105 | 99 | 27 | 26 | 25 | 18 | 18 | 17 | 15 | 13 | 12 |
| 12:00 | 141 | 137 | 136 | 124 | 115 | 108 | 101 | 92 | 26 | 25 | 25 | 18 | 17 | 16 | 14 | 13 | 12 |
| 13:00 | 141 | 137 | 135 | 119 | 112 | 102 | 95 | 87 | 26 | 26 | 24 | 17 | 17 | 16 | 15 | 13 | 12 |
| 14:00 | 140 | 136 | 134 | 116 | 106 | 98 | 88 | 80 | 25 | 25 | 24 | 17 | 17 | 16 | 14 | 12 | 12 |
| 15:00 | 142 | 137 | 134 | 113 | 103 | 93 | 84 | 74 | 27 | 26 | 24 | 18 | 17 | 16 | 15 | 14 | 14 |
| 16:00 | 141 | 136 | 133 | 109 | 98 | 88 | 76 | 65 | 26 | 24 | 25 | 18 | 17 | 16 | 14 | 13 | 13 |
| 17:00 | 141 | 135 | 131 | 106 | 95 | 82 | 71 | 59 | 24 | 24 | 23 | 17 | 16 | 15 | 13 | 12 | 12 |
| 18:00 | 142 | 135 | 130 | 102 | 90 | 77 | 65 | 53 | 22 | 21 | 21 | 16 | 14 | 14 | 13 | 12 | 11 |
| 19:00 | 142 | 134 | 130 | 99 | 85 | 72 | 58 | 44 | 20 | 20 | 19 | 15 | 14 | 13 | 12 | 12 | 11 |
| 20:00 | 142 | 133 | 128 | 97 | 83 | 68 | 53 | 39 | 20 | 20 | 19 | 15 | 15 | 13 | 13 | 12 | 11 |
| | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | |

## Backwash

Air + water: 3 minutes Unexpanded bed depth: 70 cm Backwash rate: 31.8 $m^3/m^2/hr$

Water: 5 minutes Expanded bed depth: 96 cm

| Time (min) | Turbidity (NTU) |
|---|---|
| 0 | 95 |
| 1 | 36 |
| 2 | 11 |
| 3 | 7.8 |
| 4 | 6.5 |
| 5 | 3.6 |

| Time (min) | Turbidity (NTU) |
|---|---|
| 6 | 1.4 |
| 7 | 1.2 |
| 8 | 1.1 |
| | |
| | |
| | |

## Observations

Leakages gave rise to irregular head readings

Backwash air pressure = 20.7 $KN/m^2$

Sand depth = 40 cm Charcoal depth = 30 cm

Influent = muddy water

## Table A.9 : Data for filter run no. 5 for the RSF model

## Filtration data

Date: 15 / 3 / 99

Filter run no. 5

Column: RSF

Start time: 07:00

Filtration rate: 6 m$^3$/m$^2$/hr

| Time | Head (cm) | | | | | | | | Turbidity (NTU) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Port 1 | Port 2 | Port 3 | Port 4 | Port 5 | Port 6 | Port 7 | Port 8 | Port 1 | Port 2 | Port 3 | Port 4 | Port 5 | Port 6 | Port 7 | Port 8 | Efflue |
| | | | | | | | | | | | | | | | | | |
| 07:00 | 153 | 151 | 149 | 149 | 146 | 142 | 138 | 133 | 6.0 | 6.0 | 5.7 | 5.4 | 5.0 | 4.7 | 4.5 | 4.2 | 3.8 |
| 08:00 | 153 | 150 | 148 | 144 | 139 | 133 | 132 | 125 | 4.6 | 4.4 | 4.2 | 4.1 | 4.0 | 3.9 | 3.6 | 3.3 | 3.0 |
| 09:00 | 151 | 149 | 145 | 140 | 134 | 128 | 122 | 117 | 3.8 | 3.6 | 3.3 | 3.0 | 2.9 | 2.8 | 2.6 | 2.5 | 2.5 |
| 10:00 | 152 | 148 | 143 | 137 | 131 | 125 | 116 | 110 | 5.8 | 5.5 | 5.3 | 4.6 | 4.5 | 4.4 | 4.3 | 4.0 | 4.0 |
| 11:00 | 152 | 149 | 143 | 139 | 127 | 115 | 106 | 102 | 5.1 | 5.0 | 4.8 | 4.7 | 4.5 | 4.3 | 4.0 | 3.8 | 3.7 |
| 12:00 | 152 | 148 | 142 | 136 | 119 | 107 | 98 | 96 | 4.7 | 4.4 | 4.1 | 3.7 | 3.5 | 3.3 | 3.2 | 3.1 | 3.2 |
| 13:00 | 151 | 147 | 135 | 121 | 114 | 100 | 94 | 89 | 4.4 | 4.4 | 4.2 | 4.1 | 4.0 | 3.8 | 3.6 | 3.4 | 3.3 |
| 14:00 | 151 | 149 | 133 | 121 | 106 | 95 | 86 | 79 | 3.8 | 3.5 | 3.3 | 3.3 | 3.4 | 3.3 | 3.0 | 2.9 | 2.7 |
| 15:00 | 152 | 145 | 133 | 120 | 109 | 96 | 82 | 76 | 3.3 | 3.1 | 2.8 | 2.8 | 2.9 | 2.7 | 2.5 | 2.4 | 2.4 |
| 16:00 | 152 | 144 | 135 | 120 | 108 | 92 | 75 | 68 | 5.1 | 4.8 | 4.7 | 4.6 | 4.5 | 4.3 | 4.1 | 4.0 | 4.0 |
| 17:00 | 151 | 144 | 134 | 116 | 98 | 80 | 67 | 54 | 5.0 | 4.7 | 4.6 | 4.4 | 4.4 | 4.1 | 4.0 | 4.0 | 4.0 |
| 18:00 | 152 | 144 | 132 | 112 | 96 | 77 | 60 | 53 | 4.6 | 4.5 | 4.3 | 4.2 | 4.0 | 3.9 | 3.9 | 3.7 | 3.6 |
| 19:00 | 152 | 143 | 126 | 109 | 93 | 76 | 59 | 43 | 4.3 | 4.1 | 4.0 | 4.1 | 3.7 | 3.6 | 3.6 | 3.5 | 3.4 |
| 20:00 | 151 | 144 | 127 | 108 | 88 | 67 | 47 | 39 | 3.7 | 3.6 | 3.5 | 3.4 | 3.3 | 3.3 | 3.1 | 3.0 | 2.9 |
| 21:00 | 152 | 134 | 115 | 95 | 77 | 58 | 37 | 30 | 4.5 | 4.3 | 4.3 | 4.4 | 4.3 | 4.2 | 4.0 | 3.9 | 3.7 |
| 22:00 | 152 | 132 | 113 | 92 | 73 | 53 | 34 | 24 | 4.3 | 4.2 | 4.2 | 4.0 | 4.0 | 4.0 | 3.9 | 3.9 | 3.7 |
| 23:00 | 153 | 131 | 111 | 91 | 68 | 49 | 28 | 16 | 4.1 | 4.1 | 3.9 | 4.0 | 3.9 | 3.9 | 3.8 | 3.7 | 3.6 |
| 00:00 | 153 | 131 | 109 | 87 | 66 | 45 | 23 | 1 | 4.0 | 4.0 | 4.0 | 3.9 | 4.0 | 3.9 | 3.8 | 3.7 | 3.6 |
| | | | | | | | | | | | | | | | | | |

## Backwash

Air + water: 3 minutes

Unexpanded bed depth: 70 cm

Backwash rate: 31.8 m$^3$/m$^2$/hr

Water: 5 minutes

Expanded bed depth: 88 cm

| Time (min) | Turbidity (NTU) |
|---|---|
| 0 | 46 |
| 1 | 21 |
| 2 | 11 |
| 3 | 9.1 |
| 4 | 7.3 |
| 5 | 5.2 |

| Time (min) | Turbidity (NTU) |
|---|---|
| 6 | 3.1 |
| 7 | 1.6 |
| 8 | 1.2 |
| | |
| | |
| | |

## Observations

Filtration done until terminal headloss of 1.5m achieved

Backwash air pressure = 20.7 KN/m$^2$

Sand depth = 70 cm

Influent = food dye solution (Tartrazine)

## Table A.10 : Data for filter run no. 5 for the DMF model

### Filtration data

Date: 15/3/99 Filter run no. 5 Column: DMF

Start time: 07:00 Filtration rate: 6 $m^3/m^2/hr$

| Time | Head (cm) | | | | | | | | Turbidity (NTU) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Port 1 | Port 2 | Port 3 | Port 4 | Port 5 | Port 6 | Port 7 | Port 8 | Port 1 | Port 2 | Port 3 | Port 4 | Port 5 | Port 6 | Port 7 | Port 8 | Efflue |
| | | | | | | | | | | | | | | | | | |
| 07:00 | 156 | 155 | 152 | 152 | 148 | 145 | 144 | 143 | 6.0 | 5.9 | 5.8 | 3.9 | 3.6 | 3.3 | 3.1 | 3.0 | 2.9 |
| 08:00 | 155 | 152 | 149 | 147 | 143 | 141 | 137 | 133 | 4.6 | 4.2 | 4.1 | 2.8 | 2.7 | 2.5 | 2.5 | 2.4 | 2.4 |
| 09:00 | 153 | 149 | 147 | 140 | 135 | 131 | 128 | 124 | 3.8 | 3.6 | 3.5 | 2.0 | 2.0 | 1.9 | 1.9 | 1.8 | 1.8 |
| 10:00 | 152 | 147 | 141 | 136 | 131 | 123 | 121 | 114 | 5.8 | 5.6 | 5.5 | 4.1 | 3.9 | 3.7 | 3.4 | 3.2 | 3.2 |
| 11:00 | 156 | 148 | 143 | 135 | 129 | 122 | 116 | 114 | 5.1 | 5.0 | 5.0 | 3.4 | 3.3 | 3.3 | 3.2 | 3.1 | 3.1 |
| 12:00 | 153 | 147 | 138 | 130 | 123 | 117 | 110 | 107 | 4.7 | 4.5 | 4.4 | 3.2 | 3.0 | 3.1 | 2.9 | 2.8 | 2.8 |
| 13:00 | 154 | 145 | 137 | 126 | 117 | 109 | 100 | 104 | 4.4 | 4.3 | 4.1 | 2.9 | 2.7 | 2.6 | 2.6 | 2.5 | 2.5 |
| 14:00 | 153 | 144 | 135 | 125 | 114 | 105 | 97 | 96 | 3.8 | 3.7 | 3.6 | 3.1 | 2.9 | 2.8 | 2.6 | 2.4 | 2.3 |
| 15:00 | 152 | 142 | 130 | 121 | 108 | 102 | 97 | 93 | 3.3 | 3.1 | 3.0 | 2.1 | 2.0 | 2.0 | 1.9 | 2.0 | 2.0 |
| 16:00 | 156 | 144 | 130 | 121 | 107 | 100 | 98 | 93 | 5.1 | 5.0 | 4.8 | 4.2 | 4.2 | 4.0 | 3.7 | 3.6 | 3.5 |
| 17:00 | 154 | 141 | 129 | 114 | 101 | 95 | 88 | 84 | 5.0 | 4.8 | 4.7 | 4.3 | 4.1 | 3.9 | 3.8 | 3.7 | 3.6 |
| 18:00 | 153 | 137 | 123 | 109 | 96 | 82 | 77 | 73 | 4.6 | 4.4 | 4.4 | 3.5 | 3.4 | 3.3 | 3.3 | 3.2 | 3.2 |
| 19:00 | 154 | 139 | 126 | 108 | 93 | 81 | 75 | 68 | 4.3 | 4.3 | 4.2 | 3.3 | 3.2 | 3.3 | 3.2 | 3.2 | 3.1 |
| 20:00 | 153 | 137 | 122 | 105 | 87 | 75 | 70 | 66 | 3.7 | 3.5 | 3.5 | 2.8 | 2.6 | 2.6 | 2.7 | 2.6 | 2.5 |
| 21:00 | 153 | 136 | 120 | 104 | 86 | 71 | 66 | 62 | 4.5 | 4.4 | 4.3 | 3.8 | 3.7 | 3.5 | 3.3 | 3.2 | 3.2 |
| 22:00 | 152 | 134 | 117 | 100 | 84 | 75 | 67 | 58 | 4.3 | 4.1 | 4.0 | 3.7 | 3.6 | 3.5 | 3.5 | 3.4 | 3.4 |
| 23:00 | 155 | 135 | 118 | 99 | 81 | 71 | 67 | 64 | 4.1 | 3.9 | 3.8 | 3.6 | 3.6 | 3.5 | 3.6 | 3.5 | 3.3 |
| 00:00 | 154 | 134 | 116 | 96 | 85 | 77 | 65 | 58 | 4.0 | 3.8 | 3.8 | 3.5 | 3.5 | 3.5 | 3.4 | 3.3 | 3.3 |
| 01:00 | 154 | 133 | 114 | 92 | 78 | 64 | 58 | 50 | 3.8 | 3.8 | 3.8 | 3.3 | 3.3 | 3.3 | 3.2 | 3.2 | 3.2 |
| 02:00 | 153 | 132 | 112 | 90 | 73 | 64 | 56 | 49 | 3.7 | 3.7 | 3.7 | 3.4 | 3.3 | 3.2 | 3.1 | 3.1 | 3.1 |
| 03:00 | 152 | 131 | 111 | 91 | 68 | 49 | 35 | 29 | 3.8 | 3.7 | 3.7 | 3.4 | 3.4 | 3.3 | 3.3 | 3.2 | 3.2 |
| 04:00 | 153 | 130 | 110 | 89 | 68 | 47 | 26 | 15 | 3.8 | 3.7 | 3.6 | 3.4 | 3.4 | 3.3 | 3.4 | 3.4 | 3.3 |
| 05:00 | 154 | 131 | 110 | 89 | 66 | 45 | 24 | 1 | 3.7 | 3.7 | 3.6 | 3.3 | 3.3 | 3.3 | 3.2 | 3.2 | 3.2 |
| | | | | | | | | | | | | | | | | | |

### Backwash

Air + water: 3 minutes Unexpanded bed depth: 70 cm Backwash rate: 31.8 $m^3/m^2/hr$

Water: 5 minutes Expanded bed depth: 102 cm

| Time (min) | Turbidity (NTU) |
|---|---|
| 0 | 55 |
| 1 | 36 |
| 2 | 21 |
| 3 | 17 |
| 4 | 9.6 |
| 5 | 5.4 |

| Time (min) | Turbidity (NTU) |
|---|---|
| 6 | 2.7 |
| 7 | 2.1 |
| 8 | 1.5 |
| | |
| | |
| | |

### Observations

Filtration done until terminal headloss of 1.5m achieved

Backwash air pressure = 20.7 $KN/m^2$

Sand depth = 40 cm Charcoal depth = 30 cm

Influent = food dye solution (Tartrazine)

## Table A.11 : Data for filter run no. 6 for the RSF model

## Filtration data

Date: 22/3/99

Filter run no. 6

Column: RSF

Start time: 07:00

Filtration rate: 6 $m^3/m^2/hr$

| Time | Head (cm) | | | | | | | | Turbidity (NTU) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Port 1 | Port 2 | Port 3 | Port 4 | Port 5 | Port 6 | Port 7 | Port 8 | Port 1 | Port 2 | Port 3 | Port 4 | Port 5 | Port 6 | Port 7 | Port 8 | Efflue |
| | | | | | | | | | | | | | | | | | |
| 07:00 | 156 | 155 | 153 | 152 | 149 | 146 | 142 | 137 | 7.9 | 7.7 | 7.4 | 7.0 | 6.6 | 6.3 | 6.0 | 5.6 | 5.3 |
| 08:00 | 155 | 153 | 150 | 147 | 142 | 136 | 134 | 128 | 6.2 | 5.8 | 5.6 | 5.4 | 5.4 | 5.3 | 4.9 | 4.7 | 4.4 |
| 09:00 | 154 | 153 | 148 | 143 | 136 | 131 | 125 | 117 | 5.1 | 4.9 | 4.4 | 4.0 | 3.8 | 3.7 | 3.7 | 3.6 | 3.7 |
| 10:00 | 155 | 150 | 147 | 139 | 134 | 128 | 119 | 114 | 7.7 | 7.3 | 6.0 | 5.9 | 5.9 | 5.8 | 5.7 | 5.5 | 5.4 |
| 11:00 | 156 | 153 | 147 | 141 | 130 | 118 | 110 | 99 | 6.6 | 6.6 | 6.4 | 6.2 | 6.2 | 6.0 | 5.7 | 5.3 | 4.9 |
| 12:00 | 155 | 151 | 144 | 139 | 122 | 110 | 102 | 92 | 6.4 | 5.9 | 5.3 | 4.9 | 4.6 | 4.6 | 4.5 | 4.4 | 4.5 |
| 13:00 | 153 | 150 | 138 | 124 | 117 | 104 | 96 | 88 | 5.9 | 5.8 | 5.6 | 5.4 | 5.2 | 5.0 | 4.7 | 4.5 | 4.2 |
| 14:00 | 154 | 152 | 136 | 125 | 109 | 97 | 89 | 77 | 5.3 | 4.9 | 4.6 | 4.4 | 4.5 | 4.4 | 4.1 | 3.8 | 3.6 |
| 15:00 | 154 | 147 | 136 | 124 | 112 | 99 | 85 | 72 | 4.4 | 4.1 | 3.8 | 3.7 | 3.7 | 3.6 | 3.3 | 3.2 | 3.0 |
| 16:00 | 155 | 147 | 138 | 122 | 110 | 95 | 78 | 64 | 6.5 | 6.3 | 6.1 | 6.0 | 5.7 | 5.4 | 5.2 | 5.0 | 4.8 |
| 17:00 | 154 | 146 | 138 | 119 | 101 | 84 | 70 | 65 | 6.6 | 6.3 | 6.1 | 5.8 | 5.7 | 5.5 | 5.4 | 5.3 | 5.2 |
| 18:00 | 155 | 147 | 135 | 115 | 98 | 79 | 64 | 59 | 6.3 | 6.1 | 5.8 | 5.5 | 5.3 | 5.2 | 5.1 | 4.8 | 4.7 |
| 19:00 | 154 | 147 | 129 | 113 | 97 | 79 | 62 | 40 | 5.9 | 5.6 | 5.4 | 5.4 | 4.9 | 4.8 | 4.8 | 4.7 | 4.6 |
| 20:00 | 154 | 146 | 129 | 111 | 91 | 71 | 50 | 38 | 5.2 | 5.0 | 4.7 | 4.5 | 4.4 | 4.3 | 4.1 | 4.0 | 4.0 |
| 21:00 | 155 | 137 | 118 | 99 | 79 | 60 | 40 | 27 | 5.8 | 5.7 | 5.7 | 5.7 | 5.5 | 5.4 | 5.3 | 5.1 | 4.9 |
| 22:00 | 155 | 136 | 117 | 95 | 77 | 56 | 37 | 22 | 5.8 | 5.6 | 5.5 | 5.3 | 5.4 | 5.4 | 5.2 | 5.1 | 5.1 |
| 23:00 | 156 | 136 | 114 | 95 | 69 | 52 | 29 | 4 | 5.6 | 5.5 | 5.2 | 5.2 | 5.1 | 5.0 | 5.0 | 4.9 | 4.8 |
| | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | |

## Backwash

Air + water: 3 minutes

Unexpanded bed depth: 70 cm

Backwash rate: 31.8 $m^3/m^2/hr$

Water: 5 minutes

Expanded bed depth: 89 cm

| Time (min) | Turbidity (NTU) |
|---|---|
| 0 | 57 |
| 1 | 26 |
| 2 | 14 |
| 3 | 11 |
| 4 | 9.2 |
| 5 | 6.4 |

| Time (min) | Turbidity (NTU) |
|---|---|
| 6 | 4.2 |
| 7 | 2.1 |
| 8 | 1.5 |
| | |
| | |
| | |

## Observations

Filtration done until terminal headloss of 1.5m achieved

Backwash air pressure = 20.7 $KN/m^2$

Sand depth = 70 cm

Influent = muddy water

## Table A.12 : Data for filter run no. 6 for the DMF model

## Filtration data

Date: 22/3/99 Filter run no. 6 Column: DMF

Start time: 07:00 Filtration rate: 6 m$^3$/m$^2$/hr

| Time | Head (cm) | | | | | | | | Turbidity (NTU) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Port 1 | Port 2 | Port 3 | Port 4 | Port 5 | Port 6 | Port 7 | Port 8 | Port 1 | Port 2 | Port 3 | Port 4 | Port 5 | Port 6 | Port 7 | Port 8 | Efflue |
| | | | | | | | | | | | | | | | | | |
| 07:00 | 154 | 154 | 153 | 152 | 149 | 147 | 145 | 144 | 7.9 | 7.8 | 7.7 | 5.2 | 4.9 | 4.4 | 4.1 | 3.9 | 3.7 |
| 08:00 | 155 | 154 | 150 | 148 | 144 | 143 | 139 | 136 | 6.2 | 5.6 | 5.4 | 3.7 | 3.6 | 3.4 | 3.3 | 3.2 | 3.1 |
| 09:00 | 155 | 151 | 148 | 140 | 134 | 134 | 133 | 132 | 5.1 | 4.8 | 4.5 | 2.9 | 2.9 | 2.8 | 2.9 | 2.8 | 2.7 |
| 10:00 | 153 | 148 | 144 | 137 | 130 | 123 | 122 | 121 | 7.7 | 7.4 | 7.3 | 5.4 | 5.2 | 5.0 | 4.5 | 4.3 | 4.2 |
| 11:00 | 154 | 146 | 144 | 135 | 128 | 123 | 117 | 117 | 6.6 | 6.6 | 6.5 | 4.6 | 4.4 | 4.3 | 4.1 | 3.9 | 3.7 |
| 12:00 | 153 | 146 | 139 | 131 | 122 | 117 | 113 | 112 | 6.4 | 6.1 | 5.8 | 4.3 | 4.1 | 4.1 | 3.9 | 3.7 | 3.6 |
| 13:00 | 155 | 145 | 138 | 129 | 119 | 112 | 111 | 109 | 5.9 | 5.7 | 5.4 | 3.8 | 3.7 | 3.5 | 3.4 | 3.3 | 3.2 |
| 14:00 | 155 | 144 | 135 | 123 | 116 | 108 | 104 | 101 | 5.3 | 4.9 | 4.7 | 4.1 | 3.8 | 3.5 | 3.4 | 3.2 | 3.1 |
| 15:00 | 154 | 140 | 131 | 121 | 109 | 100 | 99 | 98 | 4.4 | 4.2 | 4.0 | 2.9 | 2.7 | 2.6 | 2.4 | 2.5 | 2.5 |
| 16:00 | 154 | 140 | 128 | 120 | 106 | 94 | 90 | 87 | 6.5 | 6.4 | 6.3 | 5.1 | 4.9 | 4.7 | 4.6 | 4.4 | 4.3 |
| 17:00 | 153 | 140 | 126 | 112 | 101 | 92 | 90 | 88 | 6.6 | 6.4 | 6.2 | 5.2 | 4.9 | 4.7 | 4.6 | 4.5 | 4.4 |
| 18:00 | 153 | 136 | 124 | 103 | 98 | 85 | 80 | 74 | 6.3 | 5.9 | 5.6 | 4.6 | 4.5 | 4.4 | 4.4 | 4.3 | 4.3 |
| 19:00 | 154 | 136 | 123 | 106 | 93 | 80 | 75 | 70 | 5.9 | 5.7 | 5.5 | 4.4 | 4.2 | 4.3 | 4.3 | 4.2 | 4.2 |
| 20:00 | 154 | 135 | 121 | 103 | 85 | 77 | 70 | 63 | 5.2 | 4.9 | 4.6 | 3.9 | 3.9 | 3.8 | 3.7 | 3.8 | 3.7 |
| 21:00 | 153 | 134 | 120 | 102 | 84 | 73 | 69 | 67 | 5.8 | 5.8 | 5.7 | 5.0 | 4.9 | 4.7 | 4.4 | 4.2 | 4.2 |
| 22:00 | 153 | 134 | 118 | 101 | 83 | 65 | 60 | 57 | 5.8 | 5.6 | 5.3 | 4.9 | 4.9 | 4.7 | 4.6 | 4.4 | 4.4 |
| 23:00 | 154 | 133 | 117 | 97 | 79 | 62 | 59 | 55 | 5.6 | 5.4 | 5.2 | 4.7 | 4.8 | 4.6 | 4.6 | 4.5 | 4.3 |
| 00:00 | 154 | 133 | 115 | 94 | 76 | 60 | 56 | 52 | 5.4 | 5.1 | 5.0 | 4.6 | 4.6 | 4.7 | 4.5 | 4.4 | 4.3 |
| 01:00 | 153 | 131 | 114 | 91 | 72 | 56 | 53 | 51 | 5.1 | 5.0 | 4.9 | 4.4 | 4.4 | 4.3 | 4.3 | 4.2 | 4.3 |
| 02:00 | 154 | 130 | 111 | 89 | 71 | 49 | 48 | 47 | 4.8 | 4.9 | 4.8 | 4.5 | 4.4 | 4.2 | 4.1 | 4.1 | 4.0 |
| 03:00 | 153 | 130 | 109 | 89 | 70 | 48 | 41 | 36 | 5.0 | 4.9 | 4.9 | 4.5 | 4.5 | 4.4 | 4.3 | 4.3 | 4.2 |
| 04:00 | 153 | 129 | 108 | 89 | 69 | 48 | 33 | 28 | 5.0 | 4.9 | 4.8 | 4.5 | 4.4 | 4.3 | 4.3 | 4.2 | 4.1 |
| 05:00 | 154 | 130 | 108 | 88 | 67 | 46 | 24 | 16 | 4.9 | 4.9 | 4.8 | 4.4 | 4.4 | 4.3 | 4.2 | 4.1 | 4.0 |
| 06:00 | 153 | 128 | 107 | 86 | 66 | 45 | 22 | 1 | 4.9 | 4.9 | 4.8 | 4.5 | 4.4 | 4.4 | 4.3 | 4.2 | 4.1 |

## Backwash

Air + water: 3 minutes Unexpanded bed depth: 70 cm Backwash rate: 31.8 m$^3$/m$^2$/hr

Water: 5 minutes Expanded bed depth: 104 cm

| Time (min) | Turbidity (NTU) |
|---|---|
| 0 | 74 |
| 1 | 43 |
| 2 | 28 |
| 3 | 19 |
| 4 | 10 |
| 5 | 6.3 |

| Time (min) | Turbidity (NTU) |
|---|---|
| 6 | 2.8 |
| 7 | 2.2 |
| 8 | 1.6 |
| | |
| | |
| | |

## Observations

Filtration done until terminal headloss of 1.5m achieved

Backwash air pressure = 20.7 KN/m$^2$

Sand depth = 40 cm Charcoal depth = 30 cm

Influent = muddy water

## Table A.13 : Data for filter run no. 7 for the RSF model

### Filtration data

Date: 20 / 4 / 99    Filter run no. 7    Column: RSF

Start time: 07:00    Filtration rate: 6 $m^3/m^2/hr$

| Time | Head (cm) | | | | | | | | Turbidity (NTU) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Port 1 | Port 2 | Port 3 | Port 4 | Port 5 | Port 6 | Port 7 | Port 8 | Port 1 | Port 2 | Port 3 | Port 4 | Port 5 | Port 6 | Port 7 | Port 8 | Efflue |
| | | | | | | | | | | | | | | | | | |
| 07:00 | 156 | | | | | | | 121 | 4.6 | | | | | | | | 2.6 |
| 09:00 | 155 | | | | | | | 110 | 4.3 | | | | | | | | 2.8 |
| 11:00 | 156 | | | | | | | 99 | 3.1 | | | | | | | | 2.0 |
| 13:00 | 156 | | | | | | | 98 | 4.7 | | | | | | | | 3.3 |
| 15:00 | 155 | | | | | | | 88 | 5.2 | | | | | | | | 3.6 |
| 17:00 | 154 | | | | | | | 78 | 5.0 | | | | | | | | 3.7 |
| 19:00 | 155 | | | | | | | 67 | 4.5 | | | | | | | | 3.4 |
| 21:00 | 155 | | | | | | | 53 | 4.1 | | | | | | | | 3.3 |
| 23:00 | 154 | | | | | | | 40 | 3.8 | | | | | | | | 3.2 |
| 01:00 | 155 | | | | | | | 25 | 3.3 | | | | | | | | 2.7 |
| 03:00 | 156 | | | | | | | 5 | 3.1 | | | | | | | | 2.6 |
| | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | |
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| | | | | | | | | | | | | | | | | | |

### Observations

Filtration done until terminal headloss of 1.5m achieved
Alum dosage = 10 mg/l
Sand depth = 70 cm
Influent = muddy water

## Table A.14 : Data for filter run no. 7 for the DMF model

## Filtration data

Date 20 / 4 / 99 Filter run no. 7 Column: DMF

Start time: 07:00 Filtration rate: 6 $m^3/m^2/hr$

| Time | Head (cm) | | | | | | | | Turbidity (NTU) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Port 1 | Port 2 | Port 3 | Port 4 | Port 5 | Port 6 | Port 7 | Port 8 | Port 1 | Port 2 | Port 3 | Port 4 | Port 5 | Port 6 | Port 7 | Port 8 | Efflue |
| | | | | | | | | | | | | | | | | | |
| 07:00 | 154 | | | | | | | 126 | 4.6 | | | | | | | | 1.8 |
| 09:00 | 154 | | | | | | | 124 | 4.3 | | | | | | | | 1.8 |
| 11:00 | 154 | | | | | | | 117 | 3.1 | | | | | | | | 1.5 |
| 13:00 | 155 | | | | | | | 109 | 4.7 | | | | | | | | 2.2 |
| 15:00 | 155 | | | | | | | 104 | 5.2 | | | | | | | | 2.5 |
| 17:00 | 154 | | | | | | | 98 | 5.0 | | | | | | | | 2.8 |
| 19:00 | 153 | | | | | | | 89 | 4.5 | | | | | | | | 2.7 |
| 21:00 | 153 | | | | | | | 81 | 4.1 | | | | | | | | 2.4 |
| 23:00 | 153 | | | | | | | 73 | 3.8 | | | | | | | | 2.7 |
| 01:00 | 154 | | | | | | | 67 | 3.3 | | | | | | | | 2.5 |
| 03:00 | 154 | | | | | | | 61 | 3.1 | | | | | | | | 2.1 |
| 05:00 | 154 | | | | | | | 54 | 4.8 | | | | | | | | 3.6 |
| 07:00 | 155 | | | | | | | 41 | 4.4 | | | | | | | | 3.2 |
| 09:00 | 154 | | | | | | | 38 | 4.2 | | | | | | | | 3.2 |
| 11:00 | 155 | | | | | | | 30 | 3.6 | | | | | | | | 2.9 |
| 13:00 | 155 | | | | | | | 24 | 3.4 | | | | | | | | 2.7 |
| 15:00 | 155 | | | | | | | 5 | 3.2 | | | | | | | | 2.6 |
| | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | |

## Observations

Filtration done until terminal headloss of 1.5m achieved

Alum dosage = 10 mg/l

Sand depth = 40 cm Charcoal depth = 30 cm

Influent = muddy water

## Table A.15 : Data for filter run no. 8 for the RSF model

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## Filtration data

Date: 23 / 4 / 99

Filter run no 8

Column: RSF

Start time: 07 00

Filtration rate: 6 m$^3$/m$^2$/hr

| Time | Head (cm) | | | | | | | | Turbidity (NTU) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Port 1 | Port 2 | Port 3 | Port 4 | Port 5 | Port 6 | Port 7 | Port 8 | Port 1 | Port 2 | Port 3 | Port 4 | Port 5 | Port 6 | Port 7 | Port 8 | Efflue |
| | | | | | | | | | | | | | | | | | |
| 07:00 | 156 | | | | | | | 130 | 3.3 | | | | | | | | 0.8 |
| 09:00 | 156 | | | | | | | 126 | 2.9 | | | | | | | | 0.7 |
| 11:00 | 156 | | | | | | | 123 | 4.4 | | | | | | | | 1.5 |
| 13:00 | 155 | | | | | | | 115 | 4.2 | | | | | | | | 1.3 |
| 15:00 | 155 | | | | | | | 109 | 2.8 | | | | | | | | 0.9 |
| 17:00 | 156 | | | | | | | 98 | 2.6 | | | | | | | | 1.0 |
| 19:00 | 154 | | | | | | | 84 | 2.7 | | | | | | | | 0.6 |
| 21:00 | 155 | | | | | | | 75 | 5.3 | | | | | | | | 0.5 |
| 23:00 | 155 | | | | | | | 68 | 4.9 | | | | | | | | 1.9 |
| 01:00 | 156 | | | | | | | 53 | 5.7 | | | | | | | | 1.7 |
| 03:00 | 156 | | | | | | | 32 | 3.5 | | | | | | | | 1.1 |
| 05:00 | 156 | | | | | | | 8 | 4.0 | | | | | | | | 0.8 |
| | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | |
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| | | | | | | | | | | | | | | | | | |

## Observations

Filtration done until terminal headloss of 1.5m achieved

Alum dosage = 30 mg/l

Sand depth = 70 cm

Influent = muddy water

## Table A.16 : Data for filter run no. 8 for the DMF model

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## Filtration data

Date 23 / 4 / 99 Filter run no. 8 Column: DMF

Start time 07:00 Filtration rate: 6 $m^3/m^2/hr$

| Time | Head (cm) | | | | | | | | Turbidity (NTU) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Port 1 | Port 2 | Port 3 | Port 4 | Port 5 | Port 6 | Port 7 | Port 8 | Port 1 | Port 2 | Port 3 | Port 4 | Port 5 | Port 6 | Port 7 | Port 8 | Efflue |
| | | | | | | | | | | | | | | | | | |
| 07:00 | 154 | | | | | | | 128 | 3.3 | | | | | | | | 0.5 |
| 09:00 | 154 | | | | | | | 126 | 2.9 | | | | | | | | 0.6 |
| 11:00 | 155 | | | | | | | 125 | 4.4 | | | | | | | | 1.1 |
| 13:00 | 154 | | | | | | | 121 | 4.2 | | | | | | | | 1.1 |
| 15:00 | 153 | | | | | | | 115 | 2.8 | | | | | | | | 0.6 |
| 17:00 | 153 | | | | | | | 111 | 2.6 | | | | | | | | 0.7 |
| 19:00 | 152 | | | | | | | 107 | 2.7 | | | | | | | | 0.5 |
| 21:00 | 152 | | | | | | | 105 | 5.3 | | | | | | | | 0.5 |
| 23:00 | 153 | | | | | | | 100 | 4.9 | | | | | | | | 1.6 |
| 01:00 | 153 | | | | | | | 94 | 5.7 | | | | | | | | 1.6 |
| 03:00 | 152 | | | | | | | 88 | 3.5 | | | | | | | | 0.9 |
| 05:00 | 154 | | | | | | | 78 | 4.0 | | | | | | | | 0.5 |
| 07:00 | 154 | | | | | | | 70 | 3.5 | | | | | | | | 0.5 |
| 09:00 | 153 | | | | | | | 64 | 3.3 | | | | | | | | 0.4 |
| 11:00 | 153 | | | | | | | 56 | 2.9 | | | | | | | | 0.4 |
| 13:00 | 154 | | | | | | | 50 | 4.3 | | | | | | | | 0.6 |
| 15:00 | 154 | | | | | | | 41 | 8.6 | | | | | | | | 2.8 |
| 17:00 | 155 | | | | | | | 29 | 8.1 | | | | | | | | 2.3 |
| 19:00 | 154 | | | | | | | 15 | 7.2 | | | | | | | | 1.9 |
| 21:00 | 155 | | | | | | | 3 | 7.6 | | | | | | | | 2.4 |
| | | | | | | | | | | | | | | | | | |

## Observations

Filtration done until terminal headloss of 1.5m achieved

Alum dosage = 30 mg/l

Sand depth = 40 cm Charcoal depth = 30 cm

Influent = muddy water

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EAST AFRICANA COLLECTION