Experimental Validation of Roughing Filtration Theory for High Turbidity Water

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In the name of Allah, the Most Beneficent, the Most Merciful

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Abbreviations

GDWQ	Guidelines for Drinking Water Quality
HFRF	Horizontal Flow Roughing Filters
HF	Horizontal Filter
HLR	Hydraulic Loading Rate
MSF	Multi-Stage Filtration
SSF	Slow Sand Filter
RF	Roughing Filtration
NTU	Nephelometric Turbidity Unit
PSD	Particle Size Distribution
SCE	Single Collector Efficiency
WHO	World Health Organization
SS	Suspended Particles
TDS	Total Dissolved Solids
NDWQS	National Drinking Water Quality Standards
VFRF	Vertical Flow Roughing Filters
RW	Raw Water
CHT	Constant Head Tank
RWT	Raw Water Tank

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ABSTRACT

As an agricultural country Pakistan depends primarily on glacial melts and monsoon rains. Water from these sources flows down to rivers finding its way to Arabian Sea. The surface water thus collected is the chief source of drinking water in majority rural areas of Pakistan. However this water quality is objectionable. Typical problems regarding the use of surface water are presence of suspended solids, colloidal particles, turbidity, and agriculture runoff. Roughing filters are one of the economical solutions to remove the suspended particles from the surface water. Lab scale setup of three roughing filters was designed and operated using synthetic raw water of high turbidity, having turbidity up to 200 NTU. Turbidity of the influent water was maintained by intermittent manual mixing and flow rate of the influent water was maintained by using the pipe and valve assembly. Three filters were have different size of media and were operated at three different loading rates i-e., 1.1 m/hr, 1.5 m/hr and 1.9 m/hr. Best flow rate and media size was selected to operate the roughing filters at high turbid water. It is concluded from this study that 1.5 m/hr hydraulic loading rate and 8-12 mm media size is most appropriate to operate the roughing filter. Hypothesis of the study is that “rapid filtration theory can be applied to roughing filters”. It is concluded from this study that rapid filtration theory can be applied to roughing filtration. Comparison between two theories was carried out

i-e., rapid sand filtration theory and roughing filtration theory. Filtration theory was used to determine the transport coefficient, filtration coefficient and attachment coefficient for the validation of the roughing filtration theory. It is also concluded from this study that Tufenjiki theory is more precise that Yao's theory to determine the transport as well as attachment coefficients.

Chapter 1

INTRODUCTION

As an agricultural country Pakistan depends primarily on glacier melts and monsoon rains. Water from these sources flows down to rivers finding its way to Arabian ocean. The surface water thus collected is the chief source of drinking water in majority of rural areas of Pakistan. However, water quality of surface sources is often objectionable. Typical problems regarding the use of surface water are presence of suspended solids, colloidal particles, turbidity, agriculture runoff (Nkwonta, 2009). Water pollution, discharge of unwanted effluents and unsafe drinking water are some of the threats that our ecosystems have to face. These factors pose threats not only to human health but to the environment as well. Unsafe drinking water is responsible for various diseases like diarrhea, dysentery, typhoid and gastroenteritis etc. According to UNICEF (2009) report around 54,000 children die annually in Pakistan because of diarrheal diseases alone.

In many cities of our country water is being supplied through dams e.g. Rawalpindi, Islamabad and Chakwal. Run off generated from the mountains are being collected in dams. Water collected through this way contains suspended solids and colloidal particles which increase the water turbidity. Sometimes untreated water from dams is supplied through supply lines or a preliminary treatment is given by adding some chemicals before pumping it into the distribution system. Water quality thus reaching at the consumer's end, does not meet the World Health Organization's (WHO) guidelines for drinking purpose or Pakistan's drinking water quality.

In today's world water treatment plants are the primary and vital remedy of this problem. However operational and maintenance cost of a conventional treatment plant is usually high and hard to bear especially for developing countries. Mechanical processes like coagulation, flocculation and sedimentation add up to this cost. On the other hand skillful labor and expensive chemicals are also required to bring it up to drinking water standards. Cost factor is of more consideration in low populated societies where full-fledged drinking water treatment plants are not viable (Dastanaieet al, 2007).

Roughing filters have often been used as pre-filters for the removal of suspended solids present in water. These filters are also used to increase the operational life of slow sand filters (Declan Page, 2007). Roughing filters are named so because the media used to remove the suspended particles from water have a rough surface. Due to this, colloidal particles are attached to the media owing to friction or uneven surface. Hence the terminology "roughing filtration" is used to refer this kind of filtration. Media commonly used is graded gravel (Wegelin, 1996).

Roughing filtration is the most economical method for the removal of suspended solids from water to reduce it turbidity. These filters are generally of rectangular shape having granular media. Due to low cost media, low maintenance cost and relatively unskilled labor, roughing filtration is the most cost-effective method of pretreatment which if designed & operated well may treat water to WHO's required level.

These filters are initially used to separate fine solids from the water that are not retained at all by sedimentation tanks. These are often used as physical filters but due to sedimentation phenomena and comparatively small loading rates, help adsorption as well as chemical and biological processes (Nkwonta, 2009). Roughing filters do not simply improve the physical quality of water but also helps in the reduction of the bacteria and viruses ranging from 10 to 20 µm and 0.4 to 0.02 µm respectively (Dome Sittivate, 2000).

1.1 Types of Roughing Filters

There are two main types of roughing filters.

- Vertical Roughing filter
- Horizontal roughing filter

These two filters are further divided into three sub-categories on the basis of flow direction of water (Fig 1-1)

- Down flow roughing filters
- Vertical or up flow roughing filter
- Horizontal flow roughing filter

Raw water characteristics and operation requirements define which type of roughing filter (i-e., horizontal or vertical) and which type of flow direction is suitable for the removal of turbidity (Galvis et al, 1998). It is proved that roughing filtration is the most suitable pretreatment of slow sand filtration (El-Taweel et al., 2000).

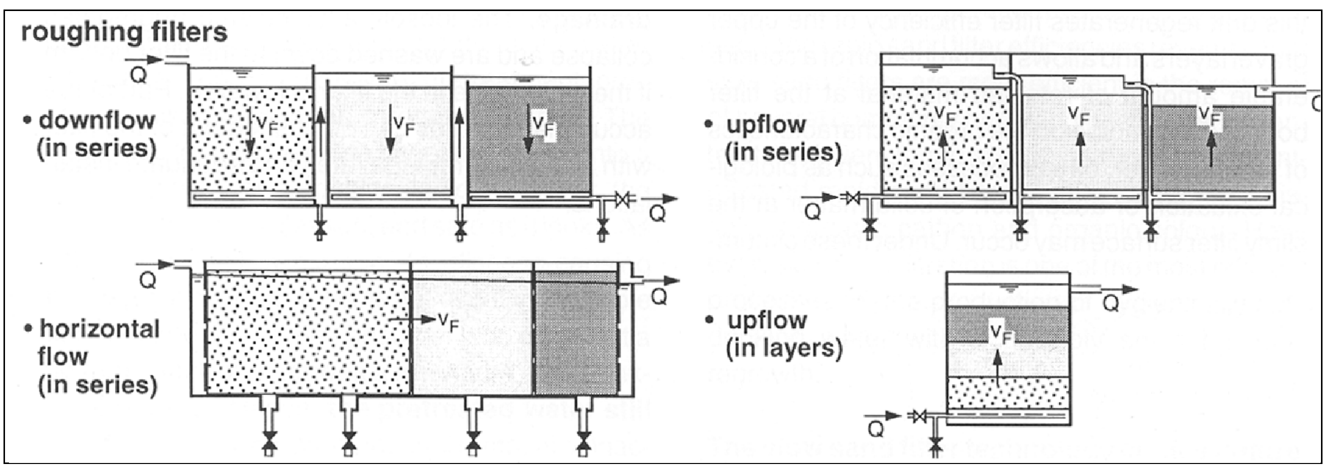


Figure 1-1: Types of roughing filters (Wegelin, 19996).

1.2 The Problem

The major issue in roughing filtration is the removal of the solid particles from the surface water which is used for the drinking purpose in most of the rural and some urban areas of Pakistan. Drinking water treatment plants might be an affordable solution for densely populated big cities but for small cities or rural areas where surface water is the main source for potable and non-potable uses, full scale water treatment plants are not feasible option for the removal of the suspended solids.

Theory of rapid sand filtration is well developed, hardly any literature can be found on theory of particulate removal in roughing filtration. In this study, the roughing filtration data has been applied to the existing rapid sand filtration theories to examine whether these can be used for predicting the outcome of roughing filters.

Roughing filtration is one of the most rational methods which give turbidity removal up to 90% and microbial pollution up to 25%. Roughing filtration reduces the cost of water treatment by reducing the use of chemicals as well as reducing the requirements of skilled labor. It is one of the best pre-treatment processes to remove fine solid particles from the water without chemical addition (Nkwonta et al., 2010).

1.3 Objective

Following were the objectives of this study.

- To design, construct and test a lab scale horizontal flow roughing filter (HFRF) for the removal colloidal & suspended particulate matter.

- To compare the rapid filtration and roughing filtration theory in terms of transport and attachment coefficients.
- Study the application of existing colloidal filtration theory to roughing filtration.

1.4 Methodology

Brief Methodology adopted to achieve the above mentioned objectives.

- Designing of three horizontal roughing filters having same dimensions but different media sizes.
- Segregation of the media into three different sizes by using different size screens.
- Construction of three horizontal roughing filters by acrylic material.
- Determining the best hydraulic loading rate to get maximum turbidity removal with longer run time
- Selection of the best media for each hydraulic rate to get maximum turbidity removal.
- Measurement of the HFRF effluent turbidity and particle size distribution to estimate the filter performance.

1.5 Scope of the Study

Lab prepared synthetic raw water was used in this study. Different media size was used in each filter. Length of the filter was limited to 1.5 m only. Microbial and natural organic matter removal was not studied. Mechanism of particulate matter was the main focus of this work.

Chapter 2

LITERATURE REVIEW

2.1 Importance of Clean Water

Water is the most important thing in this planet for life (Miller 1999). No living organism can survive without water (Krishna & Mohini, 2011). Water is one of the fundamental resources require to live life (Nkwonta & Ochieng, 2009). It is important to stay hydrated with contamination-free water. However our dilemma is that despite of the known importance of clean drinking water a huge part of the world's total population is compelled to survive on polluted water. According to United Nations report 1.1 billion people are living in this world without access to the safe drinking water. Its mean 6 % of the total global population do not have access to safe drinking water. Clean and safe drinking water is the water free from microorganisms, turbidity, taste, colour and toxic substances. Drinking water also has minerals up to acceptable limit (Tanh and Hettiaratchi, 1982). Huge population in developing countries is facing health problems related to the drinking water or issues of water scarcity (Haider et al, 2009).

It is estimated that 44 % of the total population in Pakistan are living without access to the safe quality drinking water. In rural area about 90 % peoples are facing this problem (Nilsrosemann, 2005). 200,000 children died in Pakistan due to the limited approach to safe drinking water (Nilsroseman, 2005).

2.2 Water Sources

Surface water and ground water are two major sources of drinking water in the world. Surface water sources are lakes, rivers and canals and ground water sources are wells or pumps, used to pump out ground water (Krishna & Mohini, 2011).

2.2.1 Problems with Surface Water Source

Sometimes surface water is the only available water source for rural areas even though most of the times this water is not suitable for drinking. Problems associated with its usage are the presence of unavoidable concentration of suspended solids, turbidity, coliform bacteria and agriculture runoff (Nkwonta & Ochieng, 2009). 70 % of the world's population lives in rural areas. Rural communities usually rely on surface water sources (rivers, lacks, ponds) in developing and as well as developed countries (Ghalib & Zahirudin, 2011). Ground water scarcity in Pakistan occurs due to reduction in the rain water infiltration. Another reason is the over use of ground water resources due to increase in urbanization. Small communities do not have the resources or power to pump out ground water; hence they rely on poor surface water sources (Le crew et al., 2004).

Surface water is used as a main drinking water source in most of the small communities in Pakistan. However it is being polluted by natural and anthropogenic contaminants. Natural contaminants are due to seasonal precipitation and runoff events that bring mud, dirt etc. with it resulting in intensification of issues like turbidity, nutrients and suspended solids. Anthropogenic impurities include industrial pollution, municipal waste water discharge and agricultural fertilizer. Both natural and anthropogenic sources are having large impact on surface water quality (Ghalib & Zahiruddin, 2011).

2.3 Water Quality Parameters

Three main parameters are used to check the water quality.

- Physical (suspended solids & turbidity)
- Chemical (dissolved solids, pH& hardness)
- Biological (fecal Coliform bacteria)

2.3.1 WHO Guidelines

World Health Organization (WHO) was established in 1958. It developed guidelines for drinking water for developed and developing countries. These guidelines are accepted globally. The recent 3rd addition of WHO guidelines for drinking water was published in 2008.

Table 2-1: WHO Guidelines for drinking water 2008

	Parameters	**WHO standards**
Physical parameters	Colour	≤ 15
	Taste	Non objectionable/acceptable
	Odor	Non objectionable/acceptable
	Turbidity	< 5 NTU
Chemical parameters	Total hardness as $CaCO_3$	< 500 mg/l
	TDS	< 1000
	pH	6.5-8.5
Biological parameters	Coliform bacteria	Must not be detectable in any 100 ml of water

2.3.2 National Drinking Water Quality Standards (NDWQS)

National quality standards for drinking water were revised in 2010 by Ministry of Environment Pakistan. These standards are almost similar as that of the WHO guidelines given in the table 3-1.

2.4 Design Parameters for Surface Water Treatment

Water treatment plant design is based on the raw water quality. Turbidity is one of the most important parameter to design the treatment plant because it is further related to chlorination process effectiveness (Wegelin, 1991). Bacterial load of water is second important parameter. Bacterial load is important due to its potential to cause diseases.

2.4.1 Turbidity

The particles that can cause turbidity in water are of colloidal range i-e. 10 nm to 0.1mm (Guidelines and standards for Pakistan 2010). Turbidity is mineral or organic matter in water that causes light absorption and scattering (Eaton et al, 2005). Turbidity is measured in Nephelometeric turbidity unit. Type of pre-treatment process required is determined by the turbidity of raw water (Okun and Schulz, 1984). Raw water having turbidity greater than 50 NTU requires pre-treatment.

According to WHO guidelines for drinking water quality, turbidity should not be more than 0.1 NTU for effective disinfection. Turbidity itself does not cause adverse health effects but turbidity when correlates with microbial contamination known as “sporadic high turbidity” can devastate treatment process allowing enteric pathogen into treated water and the disinfection system.

2.4.1.1 Particulate Properties of High Turbidity Water

Particulate matter enhances the microbial growth in water so in highly turbid water there is more chance of microbial activity and disinfection of this water is more expensive (Health Canda, 2001). Rain water usually carries few particles; rain water runoff carries suspended particles into the reservoirs affecting the water's physical quality. Other sources of suspended particles in surface water are injection of wastewater in to fresh water sources without any treatment, algal growth, fishing and boating and human and animal's access to the reservoirs. Soil erosion and deposition from the air is another source of suspended particles to surface water.

2.4.1.2 Particle Sizes

Particles vary in their size and settling properties. (Table 2-2 & Figure 2-1). Levin (1991) describes a table and figure to show particle sizes and their settling properties.

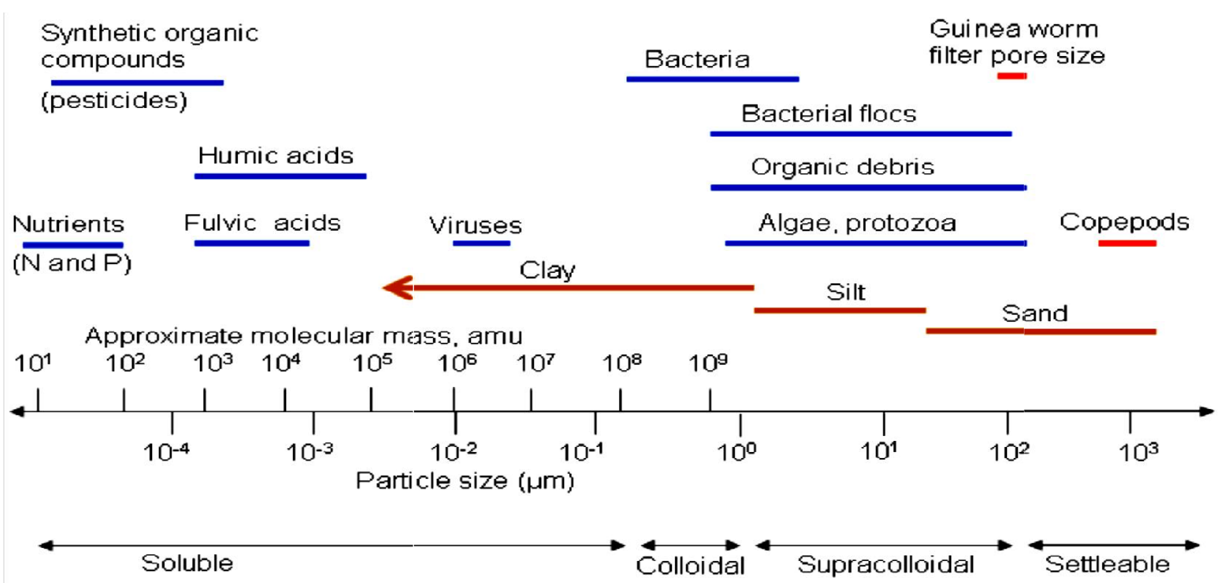


Figure 2-1: Particle sizes and their settling properties (Levine et al., 1991)

Table 2-2: Particle Sizes Categories (Levine et al., 1991)

Size categories	Size (µm)
Dissolved	<0.001
Colloidal	0.001-1
Super colloidal	1-100
Settle able	>100

2.4.2 Bacterial Load

As turbidity of the surface water increases there is more chance for microbial activity to increase and pollute the water. Several diseases can be transmitted to human body by water born bacteria. Total coliform and Escherichia coli are used as main indicators of water contamination (Pronk et al, 2007). Turbidity enhances the chance of presence of these indicator microorganisms hence makes water more vulnerable to cause diseases. Therefore turbidity is usually interpreted as indicator of microbial contamination (Kistemann*et al.,* 2002). Bacterial load further determines whether water requires chlorination or not.

2.5 Surface Water Treatment Techniques

Techniques used for surface water treatment are

- Protecting the source
- Plain sedimentation
- Slow sand filtration
- Rapid sand filtration

- Multi-stage filtration
- Conventional filtration

2.5.1 Protecting the Source

It is best to protect the surface water by shielding it against all pollutant encounters. Proper management of surface water this way reduces further treatment cost and makes it suitable for drinking in areas where surface water is the only source of potable water. Surface water can be contaminated by the introduction of waste water into it without any treatment. So by protecting the surface water from particulate matter and untreated waste water streams we can protect the surface water. According to WHO (2004) minimal further treatment will be required by protecting the surface water sources

2.5.2 Plain Sedimentation

Plain sedimentation is a simple process used to separate large and heavy particles by gravity. Horizontal flow sedimentation basin is an efficient design because it does not need mechanical sludge removal equipment. Unskilled labor can be used for cleaning. Plain sedimentation is one of the best techniques to remove turbidity from the surface water in developing countries. In addition the removal of organic particles, enteric viruses and protozoa, which survive longer in the environment, is also achieved through settling and the predation of indigenous microbes.

Settling tanks are effective treatment for a limited amount of water but removal efficiencies are related to the physical characteristics of water like particle size, density, water viscosity and temperature.

Table 2-3: Particle sizes and there settling time (Schulz and Okun, 1984)

Diameter of particle (µm)	Particle size	Settling time
10,000	Gravel	0.3 sec
1,000	Coarse sand	3 sec
100	Fine sand	38 sec
10	Silt	33 min
1	Bacteria	55 hr
0.1	Colloidal particles	230 days
0.01	Colloidal particles	6.3 yr
0.001	Colloidal particles	63 yr

2.5.3 Slow Sand Filtration (SSF)

Slow sand filtration has been an effective surface water treatment technique successfully implemented in northern Europe and North America (Slezak & Sims, 1984). Slow sand filters are used for the reduction of microbial contaminants from the surface water. These filters do not require skilled labor to operate and monitor hence it is an appropriate technology to remove microbial contamination in developing countries (Logsdon et al., 2002). SS filtration has limitations. It requires low influent turbidity and larger filter area. Influent turbidity limit of water is about 5 to 50 NTU (Clesby, 1991) but Hendricks (2000) considered this range about 10 to 50 NTU. Slow sand filtration is reliable pre-treatment for highly turbid water which is caused by the clay particles in raw water (Ellis, 1985).

2.5.4 Rapid Sand Filtration (RSF)

Pre mature clogging in slow sand filtration is a failure to this technique that contributes to an increased interest in rapid sand filtration. RSF has evolved quickly during past decades. Latin American engineers have a huge contribution in upgrading and simplifying the operation and maintenance techniques. This technology is better suited to large treatment plants. Management and technical limits restrained its wider application for small and medium size rural communities (Visscher, 2006).

2.5.5 Multi Stage Filtration

SS and RS filtration techniques have some limitations. High turbidity clogs filters earlier and biological treatment requires continuous flow of raw water for continuous supply of oxygen and nutrients. SS and RF techniques are affected by low dissolved oxygen, nutrients concentration and low temperature.

Because of these limitations a pretreatment system is used before SS filtration which improves the influent water quality of SS filtration. Multi stage filtration was started in Latin America in 1980's with promising results (Galvis et al., 1998).

Multi stage filtration (MSF) is a combination of coarse gravel filtration and slow sand filtration. This combination is used to reduce more suspended particles from the surface water as compared to the SS filters alone. This combination does not require any skilled labor and can easily be maintained and run by the labor with minimal education. It is most suitable for the treatment of surface water in the small comminutes and towns in developing countries (Galvis et al, 1998).

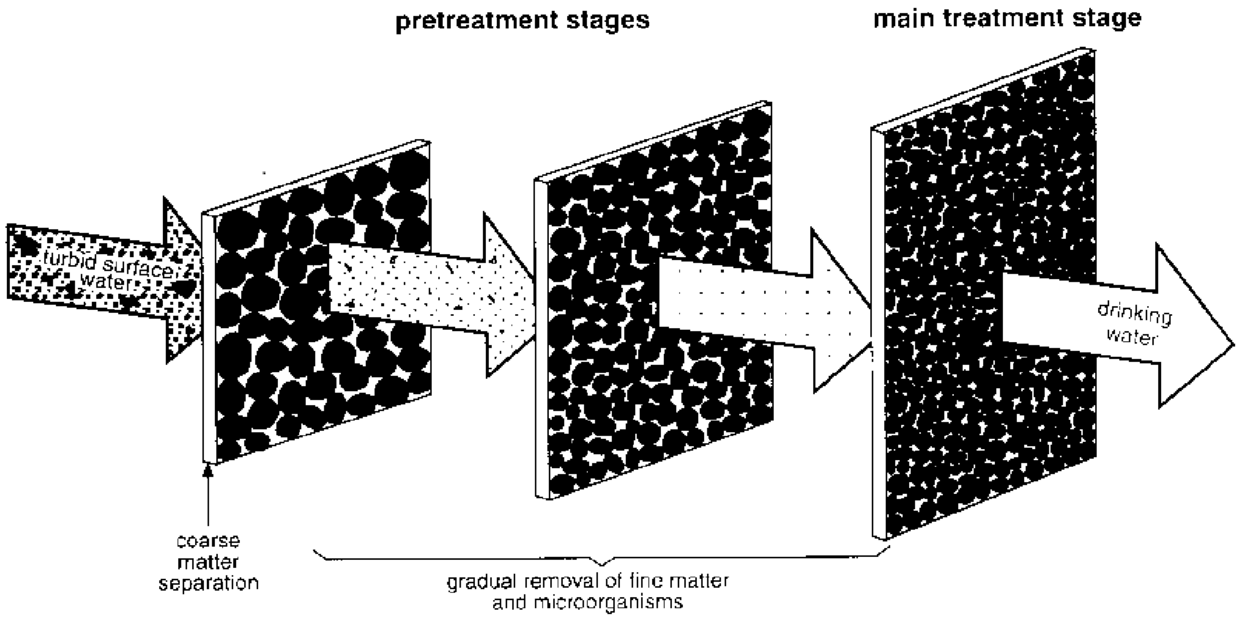


Figure 2-2: Multi stage filtration (Wegelin, 1996)

2.5.6 Conventional Water Treatment System

Coagulation, flocculation, sedimentation and conventional filtration are the processes for conventional water treatment of high turbid water (Mwh, 2005). Coagulation and flocculation are the pre-treatment techniques which are used in conventional treatment system of highly turbid water but there uses in developing countries like in Pakistan may cause serious operational and cost problems, especially when it is required to control flocculation in turbid water (Skouras et al., 2007)

Direct filtration is another technique which excludes sedimentation and direct filtration is done after flocculation (Mahvi, 2004). Alum and iron are the most common coagulants which are used as a chemical in conventional and direct treatment of turbid water. Chemicals used to form flocks in water treatment are used widely and without calculation. As a result large amount of alum is used in treatments plants. In this way large amount of residue is available for dumping. It is important to conduct jar test for the determination of alum dose for raw water (Losleben, 2008).

2.6 Filtration

Filtration is the oldest and simplest method used to remove the suspended particles from the surface water (Onyeka, 2010). Filtration is a unit operation which is widely used in the water and wastewater treatment for the removal of the suspended and colloidal particles present in water. In this operation particulate matter either accumulates on the surface of water or settles down due to sedimentation phenomena. Filtration operation are used to remove particulate matter of all ranges, including algae, and viruses (unit operation of water treatment by Montgomery).

2.6.1 Roughing Filtration (RF)

Roughing filtration is used to remove fine solids and particulate matter from surface water and wastewater. RF acts as physical filters and reduces the mass of solids. Besides solid matter separation, RF also removes microorganisms, so it also improves water quality by reducing the bacterial load up to some extent. It can also improve the water colour and reduces the dissolve organic matter (Oyneka & George, 2009).

SS filtration is possible when influent water turbidity and suspended solids range is low so, when surface water is of high turbidity and has a large amount of suspended solids then roughing filtration is used before SS filtration operation (Oyneka, 2010). RF can also reduce the organic matter from mine water and wastewater so RF is used to polish the water before it is discharged to the environment (Younger, 2001). RF is used as a pretreatment for slow sand filtration. It can be used without SS filtration if raw water originates from protected catchment area and if it is free from bacteriological impurities (Oyneka, 2010).

RF operates without the addition of chemicals. It is constructed by local material and manpower. It can work long enough without any maintenance (Oyneka, 2010). By roughing filtration turbidity removal can be achieved up to 60 to 95 percent (Rabindra, 2008 & Dastanie 2007). In 1990's many global organizations promoted the RF for surface water treatment and standardize design parameters, operation and maintenance practices (Wegelin, 1996). Horizontal flow roughing filtration technique is used in many countries of different continents like Colombia, Poru, Bolivia, Argenttina (Latin America), Ghana, Sudden, Ethiopia, Kenya, Tanzania, Zimbabwe, South Africa (Africa), Pakistan, India, Srilanka, Burma, China, Thailand, Malaysia (Asia) and Australia (Wegelin, 1996).

RF is carried out at high loading rates and it is a pretreatment for SS filtration so, by using RF as a pretreatment SS filtration has advantages that it can be operated at relatively high loading rates, required less area for operation and in this way it reduces the construction cost (Galvis et al, 1998).

2.6.2 Historical Background of RF

RF is one of the oldest techniques used to remove the suspended particles from the surface water and is still in practice. A great number of castles and forts were constructed in Europe in middle ages. These were usually situated at places which were strategically important, difficult to conquer and near the water supply. A good example is the former castle of Hohenzollern located on the top of a steep rocky reef in the Swiss Alpine valley of the river Rhine. During the times of war people used to store the rain water in cistern for their daily uses.

This area was extensively used so, chances of contamination of the stored water were great. To treat this stored water, gravel pack was installed around the inlet of the cistern. This might be one of the first examples of RF (Oyneka, 2009).

John Gibb was the man who constructed the first water filtration plant to supply the water to public in Scotland. In order to provide the muddy river water to the public John constructed a roughing filter about 75 meters long. This roughing filter consisted of chips and free stones. These stones were 8 ft wide and 4 feet deep and were covered by the Russian mats. Pretreated water was then lifted by the steam engine driven pump to a place 16 feet higher than the river from where it followed the water treatment plant through gravity (Oyneka, 2009).

In recent years roughing filtration technology has been revived in Europe through its use in artificial ground water recharging plants. In the early 1960's the water works of Dortmund(Germany), constructed horizontal flow roughing filters of 50-70 meter long, which are operated at filtration rate of 10 m/hr.

2.6.3 Types of Roughing Filtration

Roughing filters are divided into two categories on the basis of flow direction

- Horizontal flow roughing filters (HFRF)
- Vertical flow roughing filters (VFRF)

HFRF are simple in design and have unlimited filter length. This is the main advantages of HFRF (Wegline, 1996). HFRF have large capacity to store the gravel in it. Suspended particles are settled down on the surface of the filter medium and grow small heaps of loose aggregates with progressive filtration time. Part of this is settled down as soon as they become unstable.

HFRF are less sensitive to the filtration rates changes as number of suspended particles are drift towards the filter bottom (Oneyka, 2010). Head loss in HFRF is less as compared to VFRF (Clarke et al, 1996).

VFRF are operated either as down flow or as vertical flow. It mean these filter are provided with the influent water either from the top of the filter or from the bottom. VFRF are constructed in vertical direction but flow of influent water is provided either from the bottom of the filter or from the top of the filter (Oneyka, 2010). VFRF are simple self-cleaning filters and consume less space as compared to the HFRF (Dastanaie, 2003). In VFRF media is completely submerged in influent water.

Galvis et al. (1996) compared the performance of HFRF and VFRF either in vertical flow direction or down flow direction, with natural water in Cali, Columbia and found that removal efficiencies have no significant differences but maintainnes cost is of HFRF and also have less pressure drop.

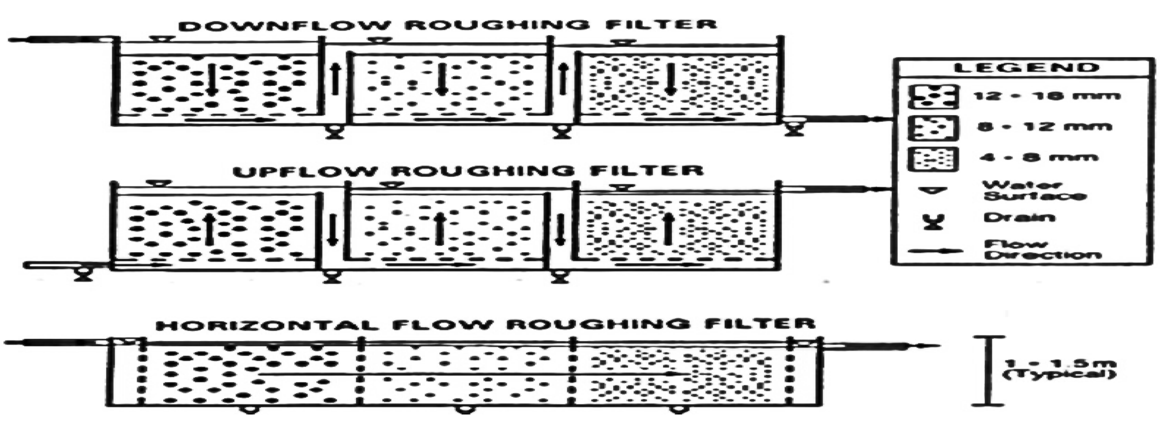


Figure 2-3: Types of Roughing Filters (Wegellin, 1996).

2.6.4 Roughing Filter Operation

RF treatment process is divided into two categories. Steady state i.e. when removal efficiency of filter remains constant and Choking i.e. when removal efficiency is decreased due to particle deposition in the filter (Collines, 1994).

Particle removal efficiency and particle penetration play a key role in determining filter run lengths. During a filter run, particles in a filter drift deeper in the direction of flow and also downward by gravity (Wegelin, 1996). Unlike in HFRF, particles drift in VFRF occurs only in the direction of water flow allowing deeper penetration of particles in the filter and generally shorter filter run lengths (Collins, 1994).

The end of a filter run is typically determined when the quality of filter effluent deteriorates due to increased solids deposition until minimum water treatment targets are exceeded.

2.6.5 Design Parameter of RF

There are three main design parameters for roughing filters

- Media sizes
- Hydraulic loading rate
- Filter length

2.6.5.1 Media Sizes

Commonly quartz sands, charcoal and gravel are used in roughing filtration but it can be replaced by any clean and resistive material (Nkwonta & Ochieng, 2009). Wegilin (1986) showed that there is minor effect of porosity and roughness of filter media. Smaller the media size greater will be the removal efficiency (Collins, 1994). Filter media have a large specific surface to increase the sedimentation phenomenon taking place in RF. Mostly gravel is used in RF but broken stones, Clay bricks, plastic material, coconut fiber and burnt charcoal can also be used as alternative media.

Table 2-4: Different Sizes of Roughing Filters Media (Wegelin, 1996)

Roughing filters sizes	Size (mm)	Size (mm)	Size (mm)
Coarse	24-16	18-12	12-8
Normal	18-12	12-8	8-4
Fine	12-6	8-4	4-2

2.6.5.2 Hydraulic Loading Rate

Main factor due to which suspended particles are removed from influent water is sedimentation (Wegelin, 1987). Roughing filters work under laminar flow conditions to enhance the sedimentation phenomenon. Good removal efficiency is achieved at low loading rates (Boller, 1993) this is because low filtration rates are critical to retain particles that reside at the surface due to gravity (Nkwonta & Oching, 2009). Hendricks (1991) suggested the hydraulic loading rates for roughing filtration i-e., 0.3 to 1.5 m/hr but Dastanaie (2007) run roughing filter at 1.8 m/hr.

Key factor to determine the loading rates for RF is that flow must be laminar that can be determined by this equation

$$Re = (vd_c)/\upsilon$$

Where,

V = hydraulic loading rate (m/s)

d_c = media diameter (m)

υ = kinematic viscosity = $1.004*10^{-6}m^2/s$ at 20 C^o

By this equation we can estimate the Reynolds number value and the hydraulic loading rate for the RF can be used provided its value is less than 10 (Wegelin, 1996).

2.6.5.3 Filter Length

Removal efficiency is typically increases by increasing the filter length. Media sizes of filter also influence the filter length. Smaller the size of media shorter will be the length of filter (Nkwonta & Ochineg, 2009).

2.6.6 The "1/3-2/3" Filter Theory

The "1/3-2/3" is conceptual filter theory by Wegelin (1996). It is observed that particle in water bypass the gravel grain either on left side or on right side or settle on the surface of the filter media. So, chance of the particles to fall on the grain is 1/3 to 2/3. The process continuous as there is a 2^{nd}, 3^{rd}, and many other grains to settle on. Thus, if a given quantity of settle able particles enters the filter, the quantity would be reduced in successive layers as per this probability along the flow path. This theory is used to form models that gives a simple indication of the removal mechanism of the roughing filters and hence are further used to describe the filter efficiency in HRF design.

This theory based on the Fick's law equation.

$$dc/dx = -\lambda c$$

Where;

c = solids concentration

x = filter depth

λ = filter coefficient

2.6.7 Removal Mechanism in RF

Suspended particles in raw water can be removed by RF by one of the three mechanisms i-e.

- Surface (diffusion)
- Straining (interception)
- Physical- Chemical (sedimentation)

Surface phenomenon occurs when suspended particles settle on the surface of the collector or media; this process is also called diffusion. Staring filtration occurs when particles penetrate into the porous media but later it lodges in the filter due to their large size. This phenomenon occurs due to interception of the particles. Straining filtration occurs for the range of 10< dc/dp,20 (Mcdowell-boyer et al, 1986). Main mechanism for the removal of suspended particles is sedimentation. Large particles which are greater than 20µm are removed due to sedimentation (Wegelin, 1996).

Filter cake development in horizontal roughing filters and vertical up-flow roughing filters are limited by particle drift and secondary particle detachment, respectively. For all configurations, periodic filter maintenance limits the filter cake development.

Surface filtration may become more significant in the latter stages of a filter run as particles retained in the filter act as strainers for smaller particles. A filter cake of up to 7 mm of kaolin clay was observed at the completion of filter runs in direct horizontal filtration experiments with 2.68mm diameter media (Collins, 1994)

2.6.8 Colloidal Filtration Theory

Colloidal filtration theory was described by three scientists.

- Iwaski (1937)
- Yao (1971)
- Tufenjiki&Elimelech (2004)

2.6.8.1 Iwaski Theory

Colloidal filtration theory was describe by Iwaski in 1937 and established an equation. He initially proposed the use of an impediment modulus, a coefficient which controls the amount of suspended solids being removed from a flowing suspension and retained on the surface of sand particles. The impediment modulus was mathematically defined as the change of concentration of material per unit depth. If the instantaneous concentration of suspended solids in the flowing suspension is C and depth of the filter is L then the equation established by the Iwaski is

$$dc/dx = -\lambda c$$

2.6.8.2 Yao's Theory (1971)

The particle removal efficiency is dominated by successful transport and attachment of particle to media (or collector) surface. This is described by trajectory approach to modeling deep-bed filters and is evaluated using colloidal filtration theory (CFT). In trajectory model approach, the three dominant processes governing transport of particles to a collector are diffusion, interception and sedimentation.

Diffusion = $\eta_d = 0.9(kT/\mu d_p d_c v)$

Interception = $\eta_I = (3/2)(d_p/d_c)^2$

Sedimentation = $\eta_G = (\rho_p - \rho_f)\times g d_p^2/18\mu v$

The Yao et al.(1971) equation is written as

$\eta_{total} = \eta_{d} + \eta_{I} + \eta_G$

$\eta_{total} = 0.9(kT/\mu d_p d_c v) + (3/2)\times(d_p/d_c)^2 + (\rho_p - \rho_f)\times g\times d_p^2/18\mu v$

2.6.8.3 Tufenjiki & Elimelech Theory (2004)

Yao's work was further refined by tufenjiki and Elimelech (2004) to consider close range forces, including hydrodynamic interactions and universal van der Waals attractive forces. This refined equation SCE correlation is defined by Tufenjiki and Elimelech

Tufenjiki Equation can be expressed as

Diffusion = $\eta_D = 2.4A_s^{1/3}N_R^{-0.081} N_{pe}^{-0.715} N_{udw}^{-0.052}$

Interception = $\eta_I = 0.55\ A_s N_R^{1.675} N_A^{-0.125}$

Sedimentation = $\eta_G = 0.22 N_R^{-0.124} N_G^{1.11} N_{udw}^{-0.053}$

$\eta_{total} = \eta_d + \eta_I + \eta_G$

$\eta_{total} = 2.4 A_s^{1/3} N_R^{-0.081} N_{pe}^{-0.715} N_{udw}^{-0.052} + 0.55 A_s N_R^{1.675} N_A^{-0.125} + 0.22 N_R^{-0.124} N_G^{1.11} N_{udw}^{-0.053}$

Where

$A_S = 2(1-\gamma^5)/(2-3\gamma + 3\gamma^5 - 2\gamma^6)$

$\gamma = (1-\varepsilon)^{1/3}$

Where "ε" is the porosity of the collector media.

$N_R = d_p/d_c$ (Aspect ratio)

$N_{pe} = vd_c/(kT/3\pi d_p\mu)$ (Peclet number)

$N_{vdw} = A/kt$ (ratio of van der waals attraction energy to the particle thermal energy)

And "A" is the Hamaker constant whose value for gravel is $6.15\text{-}6.6 * 10^{-20}$ J (Edwin et al.2004)

$N_A = A/12\pi\mu(d_p/2)^2 v$ (Attraction number)

$N_G = (\rho_p - \rho_f)gd_p^2/18\mu v$ (Gravity number)

By using these equations we can calculate single collector efficiency that is transport coefficient (η), filter coefficient (λ) and attachment coefficient (α).

2.6.9 Factors Affecting the RF Performance

The main disadvantage of the roughing filter is low hydraulic rate but this disadvantage can be overcome by constructing large roughing filters (Boller, 1993). In this way we can say roughing filters having large surface area can be operated at high hydraulic rate. Hydraulic filtration rate depend upon the type of filter, flow direction, influent characteristics and desired turbidity reduction.

High sludge storage spaces can be advantageous in lengthening filter runs but becomes problematic when the filter finally needs to be cleaned. If small size media is being used for filtration then it would choke earlier. Smaller the media size smaller will be the filter run time (Nkwonta, 2010). Periodic drainage through perforated or corrugated pipe may be able to improve the filter run time between cleanings and needs to be further developed (Boller,1993).

As the loading rate increased to 2 m/hr particles penetrate deeper in the filter bed and clog the smaller filter gravel media. Smaller media size at high rate reduces the performance of roughing filter (Cleary, 2005).

Removal of particulate matter in roughing filters also depends upon the particles' characteristics. So, it is necessary to study the characteristics of particulate matter of surface water and its sources. Removal of mineral particles are mainly affected by bed depth, media size and filtration rate.

2.6.10 Advantages of Roughing Filter

In conventional water treatment system chemicals are used. However it is quite expensive due to energy input, chemicals, mechanical work and skilled labor. Roughing filtration is free of all these expenses. In roughing filtration land and gravel as a media is required only. Roughing filtration is widely used in developing countries like Tanzania, Kenya and Srilanka (Nkwonta & Ochieng, 2009).

2.6.11 Disadvantages of Roughing Filter

RF does not improve the colour quality of water. In some cases it requires large land so in countries where land is expensive roughing filter construction is not applicable. RF can handle limited amount of organic load as compared to conventional treatment plant (Nkwonta & Ochieng, 2009).

2.7 Performance of RF in Different Areas

In this section RF performance in different area are reported. Different parameters like turbidity, color, TSS and coliforms are checked in influent and effluent water.

2.7.1 Experience in Iran

A vertical flow RF was designed and run by Dastanaie (2007) at the bank of Zayandehroud River near the village Chamkhalifeh in 2003. In this plant 64 % turbidity removal, 20 % color removal and 90 % TSS removal was achieved (Nkwonta & Ochieng, 2009).

2.7.2 Experience in Malaysia

In Malaysia a pilot plant was constructed by NordinAdlan and he examined the removal of turbidity, suspended solids and coliform organism from wastewater. Different sizes of limestone were used as media. Results indicated that removal efficiency depend upon the size of filter medium and applied loading rates. Turbidity, suspended solids and coliform removal were 92%, 88 %, and 67 % respectively (Nkwonta & Ochieng, 2009).

2.7.3 Experience in Africa

Ochieng and Otieno constructed a pilot plant at MoiUnversity in Kenya using a broken burnt bricks and charcoal as a filter media. In this study maize cobs was also used as filter media and examined that these were also used as a filter media effectively. 0.75 m/hr hydraulic loading rate was used. In this study pilot plant was run for 52 days and turbidity reduced from 305 NTU to less than 50. Overall removal efficiency was 84 %. Pilot plant was run at 0.4, 0.5 and 0.75 m/hr and turbidity removal was in between 32 % to 93% (Nkwonta & Ochieng, 2009).

2.7.4 Experience in India

A pilot plant was constructed at Jadavpur University to investigate the objectives of the research study. This plant was constructed by fiber glass sheet which consisted of three compartments. Different sizes of gravel were used in different compartments. Hydraulic loading rate of 0.75m/hr was used to operate the RF plant. Experiment was carried out for 70 days. Local pond of water was used as influent for the treatment plant (Nkwonta & Ochieng, 2009).

2.7.5 Experience in Srilanka

A pilot plant was constructed in Srilanka by Jayalath (2004). In this plant higher percentage of turbidity removal was obtained at hydraulic loading rate less than 1.5 m/hr. Hydraulic loading rate was maintained at 1.0 – 2.5 m/hr Turbidity removal, color removal and coliform removal was maximum at this rate but as the loading rate increased up to 4.5 m/hr removal efficiencies decreased. Turbidity removal achieved was up to 90 %.

Table 2-5 Results from other researcher on HRF and VRF (Nkwonta, 2010)

References	Filtration rate (m/hr)	% age turbidity removal
Pacini (2005)	1.20	85 to 95
Dome (2000)	0.3	90
Mahvi (2004)	1.5	90
Ochieng and Otieno (2004)	0.75	90
Dastanaie (2007)	1.8	94
Jayalath (1994)	1.5	60
Rabindra (2008)	1.0	95
Nkwonta and Ochieng (2009)	1.0	72
Reed and Kapranis (1998)	0.75	42

Chapter 3

MATERIALS AND METHODS

3.1 Materials

This section comprises of materials used in order to carry out the research work

3.1.1 Raw Water

Preparation of raw water was carried out in lab to eliminate the cost of labor and transportation of turbid water that had to be collected from dams otherwise. Kaolin clay was used to make the synthetic raw water having turbidity of 200 NTU. Raw water turbidity values fluctuated between 200 to 220 NTU but for experimental purpose it was considered at 200 NTU.

3.1.2 Kaolin Clay

It is soft white clay which is mined from the Kao-Ling hills in china thus named as kaolin clay. It is also commonly referred as china clay. It has flat odor having particle density 2.60 g/cm^3 (Declan Page, 2007). Kaolin clay supplied by BDH Limited Pool England was used to prepare the raw water.

3.1.3 Synthetic Raw Water

Raw water with turbidity of 200 NTU was prepared in a 22 liter bucket using predetermined dose of Kaolin clay. To find out the real mass of clay required to prepare raw water of nearly 200 NTU. 5, 6, 8, 10, gram clay was added to 22 L buckets separately, mixed for 24 hours and allowed to settle for 8 hours. Turbidity was measured for settled water every hour. After the significantly change in turbidity that occur in 3-4 hours, manual mixing was carried out to maintained the turbidity of raw water. 5 gram of clay was determined to make the raw water of 200-220 NTU.

Water tank of 550 liters was used to make raw water of turbidity 200 NTU. 110 grams of clay was introduced into 1 liter of water and was mixed for 30 min on jar test apparatus. This mixture was then added in raw water tank full of water and manual mixing was carried out using iron rod. In this way raw water of turbidity 200-230 NTU was prepared.

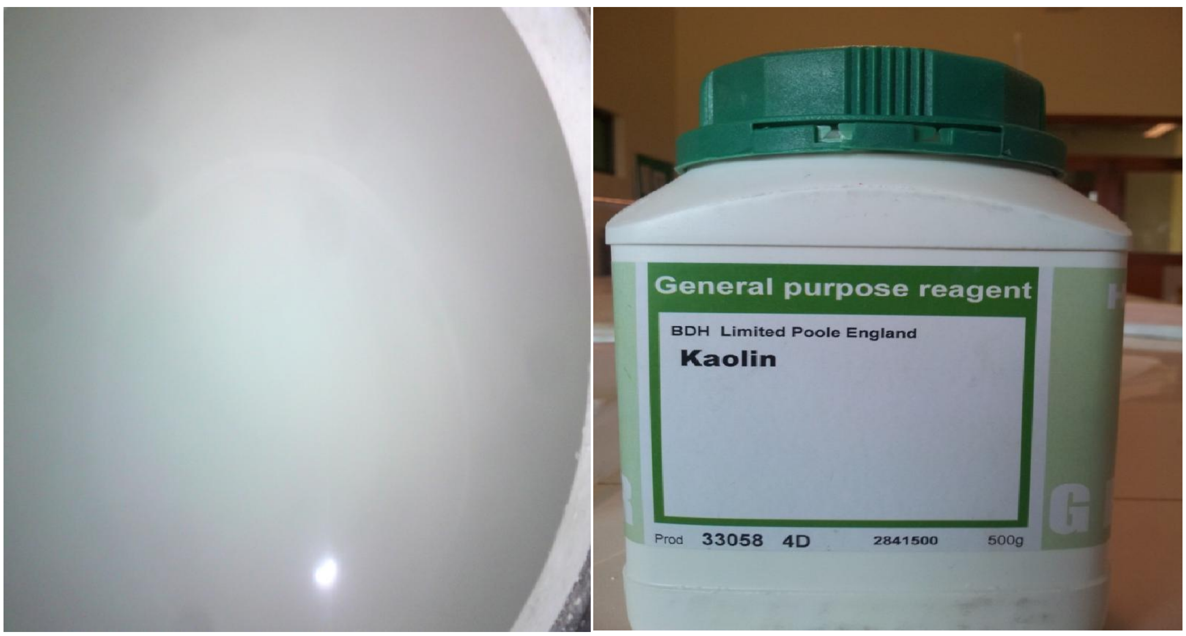


Figure 3-1: Inside view of raw water tank (Left) kaolin clay pack (Right)

3.1.4 The Lab Scale Setup.

Lab scale setup of HFRF consisted of two tanks i-e. Raw water tank and constant head tank which was used to maintain a constant flow rate. Three horizontal roughing were of the same dimensions having media of different size each were used.

Figure 3-2: Constant head tank (Left) Raw water tank (Right)

Centrifugal pump was used to pump raw water into constant head tank having capacity of 100 liters. This tank is called constant head tank because it is used to maintain the constant flow rate. Water was introduced through centrifugal pump with flow rate of 15 liters per minute into constant head tank which was suited 4.6 m above the ground. An over flow pipe was connected to 0.30m above the bottom of the constant head tank.

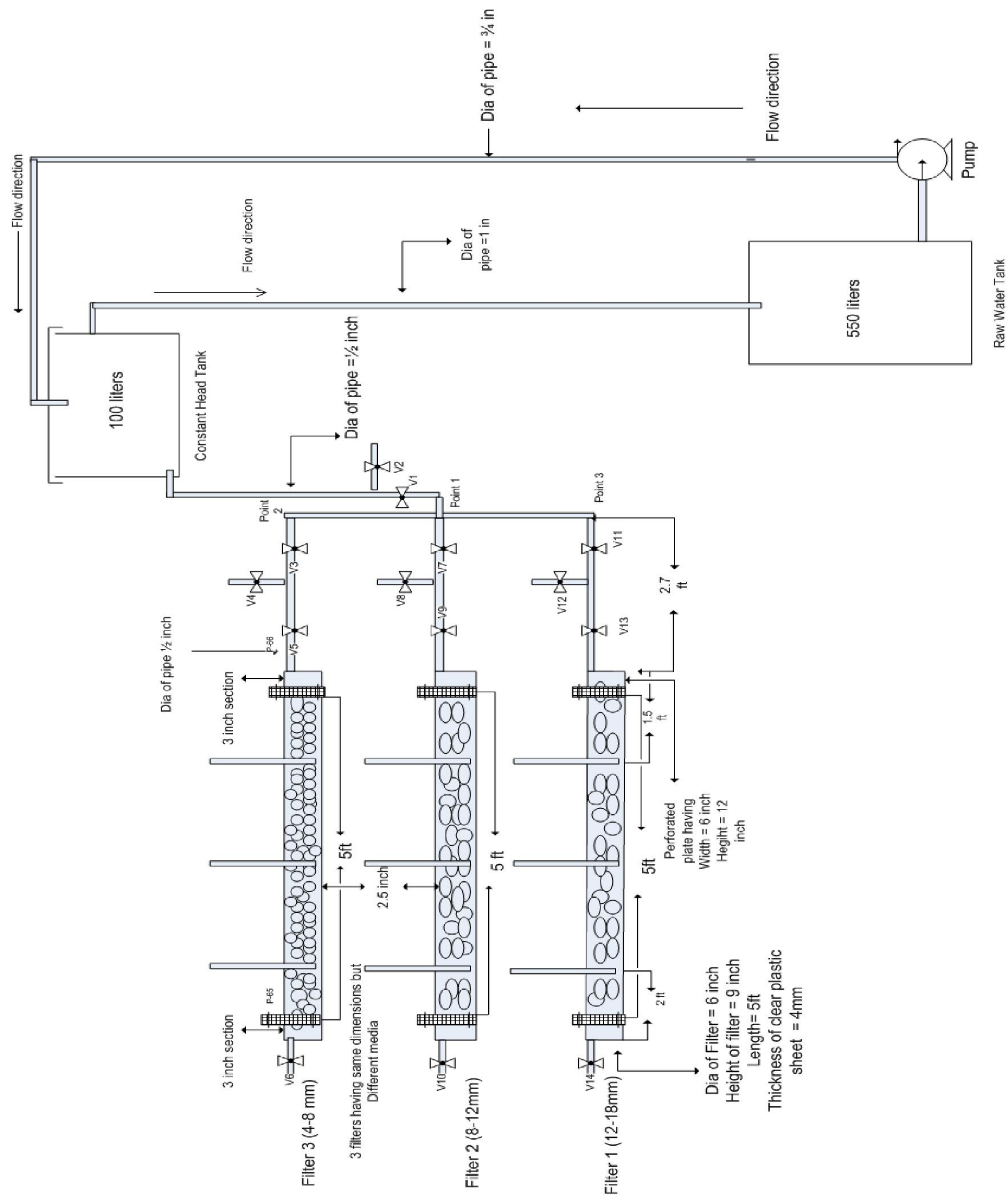


Figure 3-3: Lab scale setup of horizontal flow roughing filtration (HFRF)

Table 3-1: Design details of lab scale HFRF setup

HFRF Setup Sections	Material	Dimensions (m)/capacity (liters)		Media	
			Size(mm)	Depth & width (m)	Filter length (m)
Raw Water Tank	PVC	550 liters	None	None	None
Constant Head Tank	PVC	100 liters	None	None	None
HFRF 1	Acrylic	L.W.H (1.52*0.15*0.23) m	12-18	0.20 & 0.15	1.52
HFRF 2	Acrylic	L.W.H (1.52*0.15*0.23) m	8-12	0.20 & 0.15	1.52
HFRF 3	Acrylic	L.W.H (1.52*0.15*0.23) m	4-8	0.20 & 0.15	1.52

.

Over flow pipe line have two elbows of 45 degrees. These two elbows increased flow rate of over flow pipe line. Raw water was pumped into constant head tank from the top. Constant head tank have one over flow line and one pipe line at the bottom which was further attached to three roughing filters. Inlet pipe line and over flow pipe line was attached by the plastic pipe. Length of inlet pipe line was 5.18 m and its diameter is ¾ inch. Over flow pipe line length was of 2.2 m and its diameter is 1 inch. Diameter of over flow pipe line was greater as compared to inlet line to maintain the constant head in the tank and prevent water to be over flowed from the top of the tank.

PVC piping having diameter of ½ inch was used to connect the constant head tank with three HFRFs. PVC pipe of 0.7 m was connected from the bottom of the constant head tank and then elbow of 90 degree was connected to this pipe. A pipe of 1.9 m was connected to another end of elbow. In this way pipe was reached at the level of HFRF.

"T" was attached at the end of pipe. PVC ball valve V1 attached at another end of T and 3 inch pipe attached at center of the T. ball valve V2 attached at end of 3 inch pipe. This assembly helped to measure the flow rate of raw water came from the constant head tank. This assembly also helped to control the over flow rate of raw water from constant head tank to raw water tank. Flow rate of pump was 15 liter per minute so pump introduced raw water in the constant head tank at flow rate of 15 liters per minute. We opened the ball valve V1 in such a manner that a constant head of water maintained in the tank and it would give constant over flow of raw water into the raw water tank without over flowing from the top of constant head tank.

Valve V1 was attached to elbow, which further attached to the pipe have length 0.41 m. This pipe further attached to 4 way converter fitting at point 1. Left and right end of the 4 way fitting was connected to the pipes of length 0.41m. Elbows of 90 degree were attached at both ends of pipes i-e was point 1 and point 2 as shown in figure 3-2. Front end of the 4 way converter was attached to the pipe. This pipe was further attached to valve V7 and then attached to T. Center end of the T was connected to PVC pipe which further attached to the ball valve V8. Straight end of the T was connected to ball valve V9 which further attached to the PVC pipe. The end of this pipe was inlet of HFRF 2 have media of size 8-12mm.

Point 2 was further attached to the ball valve V3. This ball valve was further attached to T. Center end of the T was further attached to ball valve V4. Straight end of the T was attached to the ball valve V5. PVC pipe was attached at the end of ball valve V5. End of the PVC pipe was inlet of the filter # 3 have media of size 4-8mm.

Point 3 was further attached to the ball valve V11. This ball valve was attached to fitting T. Center end of the T was further attached to ball valve V12. Straight end of the T was attached to the ball valve V13. PVC pipe was attached to at the end of ball valve V13. End of the PVC pipe was inlet of the filter # 1 have media of size 12-18mm.

Every inlet line to the HFRF has a bypass line which has ball valve at start and at the end of it. There was also a ball valve in the bypass line .This type of assembly build to control inlet flow rate of each filter. For example by closing the ball valve V5 and open the ball valve V3 and also open the ball valve of bypass line V4, I could observe the flow rate which would give to the filter # 3.

Figure 3-4: Valve and pipe assembly used to control the flow rate

HFRF were made of acrylic material. Length of each HFRF was 1.5m, width of filter was 0.15m and the height of each filter was 2.23m. Each filter has perforated plate in it. Perforated plate was used to homogenize the flow of raw water. HFRF have 3 inch section before and after the media. Water was introduced from the top of the 3 inch section. A socket was fixed at the top of 3 inch section, an elbow of 90 degree was attached to it and the 1 inch size PVC pipe was attached to another end of the elbow. Valve and pipe assembly attached to the HFRF by plastic pipe. In this way HFRF can easily be attached and dispatched from the valve and pipe assembly.

Raw water entered from the top of the filter into 3 inch section passed through perforated plate and then passed through media. After passing through media, water entered into last 3 inch section of the filter. At the end of the filter outlet pipe was fixed 8 inch above from the bottom. Outlet pipe was attached to the ball valves V6, V10 and V14.

Figure 3-5: Showing the HFRF Shape

3.1.4 Media Specifications

Media used for experiments was multi graded gravel. These gravels were purchased from the local market. Gravels had different sizes and further segregated into different sizes by using the different size of screens. Block diagram shows the screens arrangement. Gravel of different sizes were passed through the top of the screens and collected at the bottom. In this way gravel was divided into three different sizes i-e., 12-18 mm, 8-12 mm, and 4-8 mm. Filter # 1 was filled with gravel of size 12-18 mm, Filter # 2 with 8-12 mm and Filter # 3 was filled with gravel of size 4-8 mm.

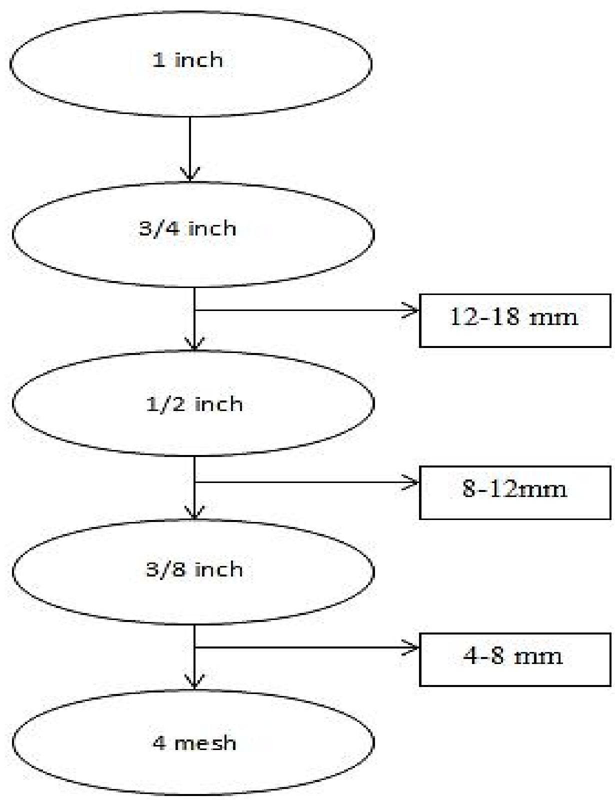
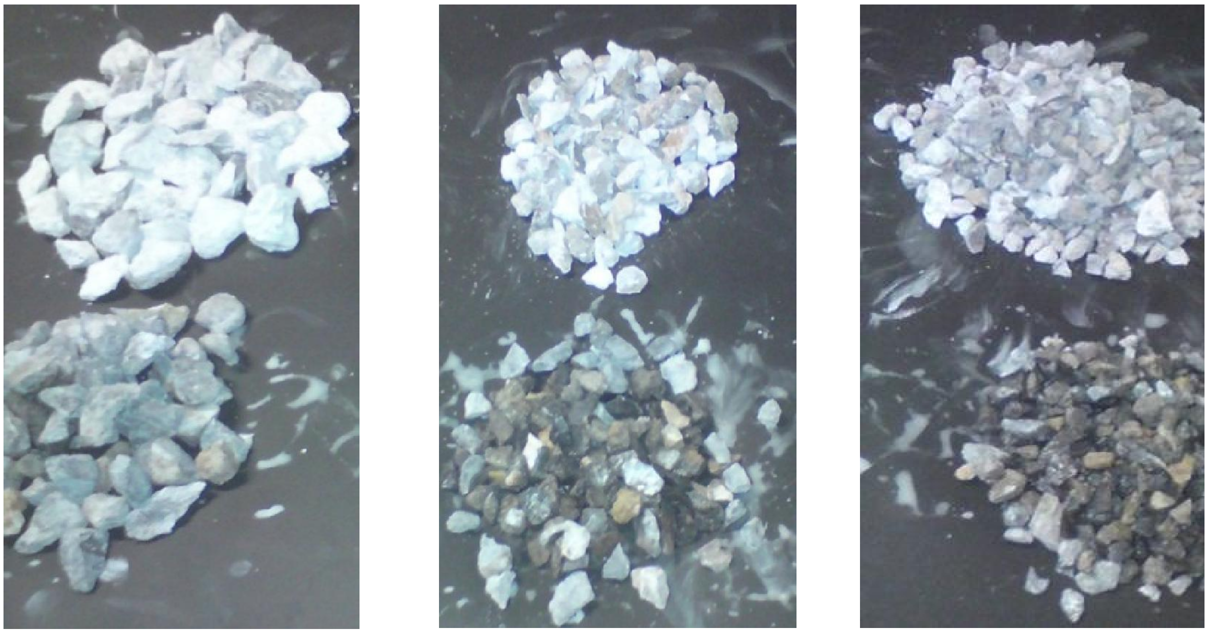


Figure 3-6: Block diagram showing sieves arrangement



12-18 mm 8-12 mm 4-8mm

Figure 3-7: Showing three different sizes of media segregated by screens (Chocked & washed)

Mechanical sieves were used to segregated gravels into different sizes which were available in Geological lab of NICE, NUST.

3.2 Methodology

3.2.1 Operation of Lab Scale HFRF

Raw water having turbidity of 200 NTU using Kaolin clay was prepared at first. A centrifugal pump having flow rate 15 L/min was used to pump the raw water or turbid water into constant head tank. Raw water (RW) was pumped into the tank from the top. Constant head tank (CHT) had an over flow pipe line at 0.304 m from the base of the tank and an outlet line from the left bottom of the tank. When CHT was filled with water RW over flowed from the over flow pipe line. Over flow pipe line maintained the water level in CHT and also increased the mixing in RWT. Turbid water from the CHT continuously entered into the raw water tank (RWT). In this way it created a fluctuation in water and helped to maintain the suspended particles in suspension. Manual mixing by an iron rod was carried after every hour. Valve V1 was opened in such a manner that continuous over flow was maintained in over flow line. A pipe and valve assembly helped to maintain a specific flow rate. Three hydraulic loading rates were chosen from the literature to run the three HFRF.

Table 3-2 Flow and Loading rates were used in the study.

Flow rate ml/min	**Loading rate = flow rate/area (m/hr)**
600	1.1
800	1.5
1000	1.9

There are three HFRF filters having different media in it. To maintain the flow rate outlet valve from the valve assembly was closed e.g. in Filter # 1 (media size of 12-18 mm) valve V13 was closed and Valve V12 and V11were opened. Valve V11 was the controlling valve. Raw water flow rate was maintained according to the requirements and then flow rate was measured through valve V12. Hence by using hit and trial method the flow rate was maintained and the valve opening of valve V11 remained untouched until the experiment for specific filter ended. After maintaining the flow rate valve V13 was fully opened and RW was allowed to enter into the roughing filter. Outlet of each filter was 0.20 m above from the base at another end of the horizontal filter (HF).

3.2.2 Roughing Filter (RF) Variables

Design variables of RF are filter media size, filter length and hydraulic loading rate (Nkwonta , 2009). Optimizations of two design variables were focused in this study.

3.2.2.1 Optimization of Hydraulic Loading Rate

Three hydraulic loading rates were selected to work on i-e., 1.1 m/hr, 1.5m/hr, and 1.9 m/hr. High loading rates were selected to check what would be the effect on effluent turbidity of high turbid water at these loading rates. Influent turbidity considered, remained constant for each filter and effluent turbidity was measured after every hour. Filter was run until it had given consistent result or HF was chocked.

Roughing filter must be operated under the laminar flow conditions (Wegelin, 1996). This would increase the maximum removal efficiency. Flow is described by Reynolds's number. This can be calculated by following equation (Wegelin, 1996)

$$Re = (vdc)/\upsilon$$

Where,

V = hydraulic loading rate (m/sec)

dc = media average diameter (m)

υ = kinematic viscosity = $1.004*10^{-6}$ m^2/sec at 20 C^o

Table 3-3: Reynolds number of various media size at each hydraulic loading rate

Media size	Reynolds number		
	Q = 1.1 m/hr	Q = 1.5 m/hr	Q = 1.9 m/hr
Filter # 1 (12-18mm),Avg = 0.015m	4.5	6.22	7.88
Filter # 2 (8-12mm), Avg = 0.01m	3.04	4.15	5.26
Filter # 3 (4-8mm), Avg = 0.006	1.83	2.49	3.15

Roughing filtration is carried out when Reynolds's number value is less than 10 (Wegelin, 1996 and Ochieng, 2006). As Reynolds's number values at all loading rates and media sizes were less than 10 hence it is concluded that roughing filtration was carried out under these conditions.

3.2.2.2 Media Sizes

Three different sizes of media were selected for the roughing filtration in the sense of large, medium and fine gravel. Large size media which was 12 to 18 mm used in Filter # 1, medium size media that was 8 to 12 mm used in Filter # 2 and fine media size of 4 to 8 mm was used in Filter # 3. Each filter was run at all three loading rates and effluent turbidity was measured after every hour. Different sizes of media have different porosity which is an important factor in colloidal filtration theory.

Table 3-4: Sizes of media using in HRF filters and there porosity

Filter #	Size ranges(mm)	Porosity
Filter 1	12 -18	0.48
Filter 2	8 – 12	0.45
Filter 3	4 – 8	0.42

3.3 Sample Analysis Procedures

Samples of influent and effluent water we recollected from the lab scale setup of HFRF. These samples were analyzed in IESE labs. All tests and analysis were carried out according to the standard methods.

3.3.1 Turbidity Measurements

Turbidity of the raw water as well as effluent water was measured by the turbidity meter (Hach 2100N). Turbidity of effluent and influent was measured after every hour.

3.3.1.2 Working Principal of Turbidity Meter

Turbidity meter is used to indicate the level of clarity of water. It works on the principle of light scattering phenomenon. Turbidity is basically an optical property of water based on the amount of light scattered by the suspended particles. When a sample of water is exposed to light it usually happens that light passes through it directly. However a part of it is reflected at various angles due to the presence of suspended particles that block the light from passing.

In turbidity meter laser is used as source of light. Two photodiodes are used as detectors to detect the intensity of transmitted and reflected rays. Difference of these two intensities gives the concentration of suspended particles present in water. Using this relation turbidity is calculated.

3.3.2 Particle Size Distribution (PSD) Analysis

PSD analysis of influent and effluent water was carried out using Particle size distribution analyzer LA-300 to determine the sizes of particles present in influent and effluent water. PSD analysis was carried out to select 5 sizes of influent particles. These sizes were used in colloidal filtration theory. By comparing the influent and effluent PSD result we concluded that which size of particles can be removed by HFRF.

3.3.2.1 Working Principal of PSD

PSD analyzer is based on the laser scattering working principal. It calculates particle size distribution from the scattered light intensity distribution which is created after laser irradiation of the particles. Upon irradiation if the particle size exceeds the wavelength of the laser, most of the particles will scatter the light in the same direction as the laser light. On the other hand, when the particle size is almost the same or smaller than the wavelength of the light, the scattered light increases in perpendicular direction, and in the direction towards the light source.

The particle size can be calculated from the scattering pattern by using Mie scattering theory. When a sample contains particles of various sizes, the scattering pattern will represent the sum of all particle sizes. This measured composite scattering pattern can be used to determine particle size distribution by comparing it with pre calculated scattering patterns of particles in the same size range.

In order to measure particles in the size range from 0.1 to 600m simultaneously, the LA-300 analyzer uses a ring shaped silicon photo-diode array, to detect the forward scattered light resolution, and 6 discrete types silicon photo-diodes, to measure scattered light at right angles and backward.

3.4 Maintenance of HFRF

Lab scale setup of HFRF was completely a self-designed one. This setup was constructed in 4 Months and operated for 3 months. Filters were operated for 24 hours and 7 days a week until the filter chocked.

Main problem in the maintenance was of leakage. To overcome this problem a fine powder of acrylic material mixed in chloroform was used. This solution was used to prevent the water leakage from the filters.

In case of any leakage filter was dispatched from the valve and pipe assembly. Media was removed from the filter and then the above mentioned solution of acrylic powder was applied to prevent leakage.

3.5 Washing of Media

As choked filter cannot be used to run the filter at next loading rate hence washing of media was carried out. RF was dispatched from the pipe and valve assembly. RF filters were attached with pipe and valve assembly through plastic pipe so it was very easy to dispatch them. Media from the filter was introduced into the plastic bucket which had a hole at the bottom. Tap water from the top was introduced and turbid water from the bottom of the bucket flowed out.In this way filter media was cleaned. Filters were also washed thoroughly after taking out the media.

Figure 3-8: Choked filters

3.6 Filtration Theory

Colloidal filtration theory was used for the calculation of attachment coefficient, transport coefficient and filtration coefficient. Two different equations were used to calculate these parameters.

Yao's equation (1971)

Tufenjiki equation (2004)

3.6.1 Yao's Equation

According to yao's equation transport coefficient was calculated as

$\eta_{total} = 0.9(kT/\mu d_p d_c v) + (3/2)*(d_p/d_c)^2 + (\rho_p - \rho_f)\times g\times d_p^2/18\mu v$

3.6.2 Tufenjiki's Equation

Tufenjiki's refined the work of Yao in 2004. According to him transport coefficient calculated as

$$\eta_{total} = 2.4A_s^{1/3}N_R^{-0.081} N_{pe}^{-0.715} N_{udw}^{-0.052} + 0.55 A_sN_R^{1.675}N_A^{-0.125} + 0.22N_R^{-0.124}N_G^{1.11}N_{udw}^{-0.053}$$

Where

$$A_S = 2(1-\gamma^5)/(2-3\gamma + 3\gamma^5 - 2\gamma^6)$$

$$\gamma = (1-\varepsilon)^{1/3}$$

Where "ε" is the porosity of the collector media. Porosity of media showed in Table 3-4.

These two equations are used to calculate the transport coefficient, Attachment coefficient and filter coefficient was determined by the equations described below.

$\lambda = (-3/2)\ \eta*\alpha*(1-e)/d_c$(Tufenjiki.2004)

and λ which is filter coefficient is calculated by this equation

$E = e^{-\lambda L}$ (Weglin. 1996).

Chapter 4

Results and Discussions

The results obtained by using synthetic raw water having turbidity of 200 NTU are discussed in detail in this chapter. Synthetic raw water was prepared by using kaolin clay. Three runs of three different filters having same media but different sizes were carried out.

4.1 Particle Size Distribution

Particle size distribution (PSD) analysis was performed on influent i-e., turbid water having turbidity of 200 NTU and the effluent of all three filters at loading rates of 1.1m/hr, 1.5 m/hr and 1.9 m/hr.

4.1.1 PSD Analyses of Influent Water

PSD analyses for influent i-e., 200 NTU water showed that average particle size is 11.34 µm. Average sizes of the suspended particles was used to calculate the single collector efficiency (SCE), attachment factor and all other calculation.

Initial 5 values of average diameter are used for the calculation because maximum number of suspended particles is present in this range.

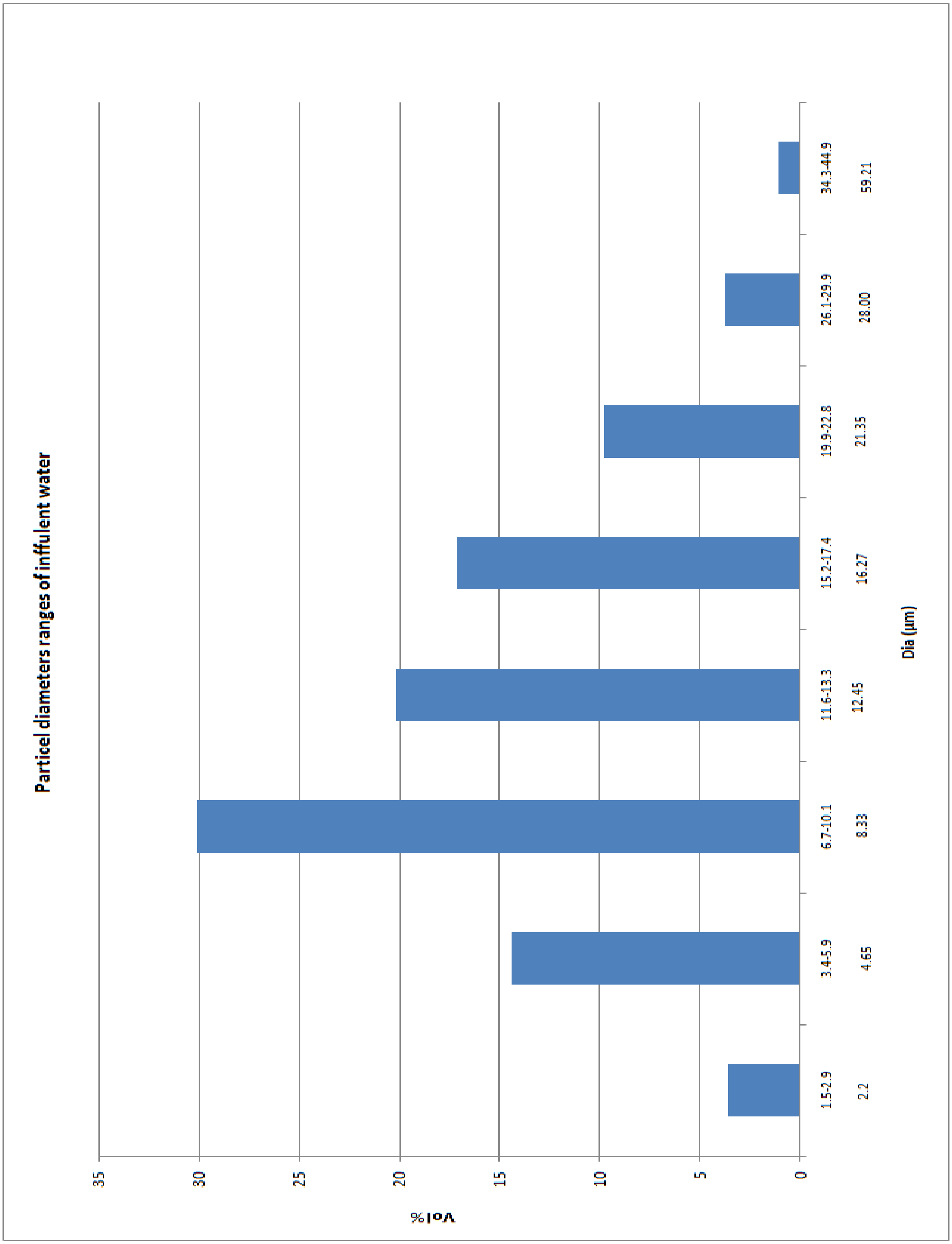

Particel diameters ranges of influlent water
Vol%
0
5
10
15
20
25
30
35
1.5-2.9
2.2
3.4-5.9
4.65
6.7-10.1
8.33
11.6-13.3
12.45
15.2-17.4
16.27
19.9-22.8
21.35
26.1-29.9
28.00
34.3-44.9
59.21
Dia (μm)

Fig 4-1

4.1.2 PSD vs Loading Rate for Filter # 1 (12-18mm)

Comparison of influent PSD and effluent PSD shows the size of suspended particles present in the effluent of the filters.

- Inlet PSD shows that maximum number of particles had size of 10-15 µm and average particle size given by PSD is 11.34 µm.
- To start with, Filter # 1 (12-18mm) was subjected to the three loading rates. Results are shown in fig 4-2 and discuss below.
- At loading rate of 1.1 m/hr. maximum number of suspended particles was present at outlet of Filter # 1 (12-18mm). This was because at low loading rate, hydrodynamic forces were weak so large particles did not turn into small particles even by striking against the collector and due to the presence of large pores in the Filter # 1 (12-18mm) large particles were easily passed throw the filter.
- At loading rate of 1.5 m/hr, particles present at outlet were about 1µm to 5µm in size. This shows that at this loading rate major fraction of suspended particles was removed.
- At loading rate of 1.9 m/hr. particles present at outlet were about 1-10µm.This is because at high rates large particles easily passed through the media and did not get the opportunity to settle due to relatively high hydrodynamic forces.
- PSD analysis shows that 1.5 m/hr was most appropriate loading rate to use in horizontal roughing filter of media size 12-18mm.

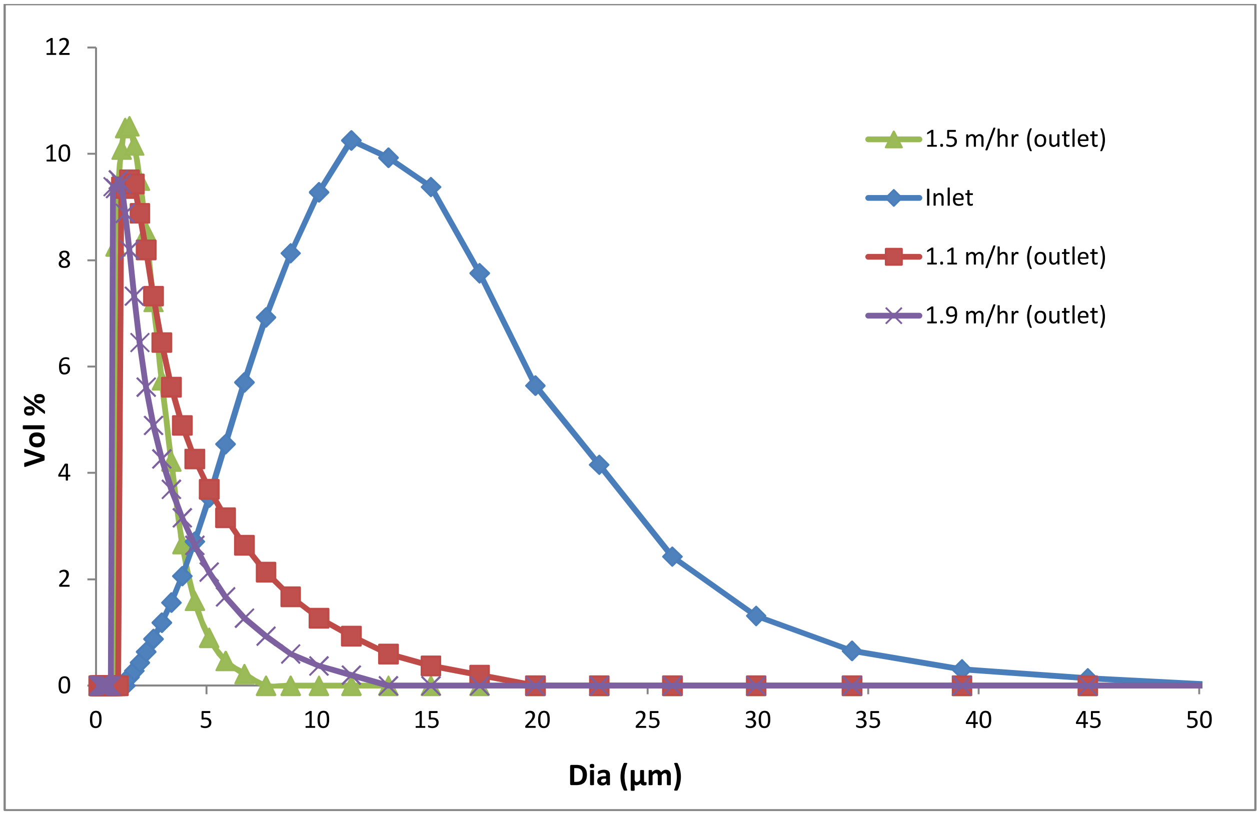


Figure 4-2(a): PSD removal at various loading rates (Filter # 1, media size 12-18mm)

4.1.3 PSD vs Loading Rate for Filter # 2 (8-12mm)

Next, Filter # 2 was subjected to the pre- selected filtration rates. Result are shown in Fig 4-3 and discussed below.

- Inlet has maximum number of particles of size 10µm-25µm but at outlet small size particles are present which is due to hydrodynamic forces.
- At loading rate 1.1 m/hr 1µm to 5µm particles are present in effluent but volume %age is more than that at 1.5 m/hr. loading rate.
- At loading rate 1.5 m/hr, 1µm to 5µm are present in effluent but volume %aegis less than as compared to 1.1 m/hr. and 1.9 m/hr. This shows that 1.5 m/hr loading rate is finest because it gives less effluent turbidity.

- At loading rate 1.9 m/hr particles of 1µm to 12µm were present. This is because at high loading rate large particles can easily pass through media**.**

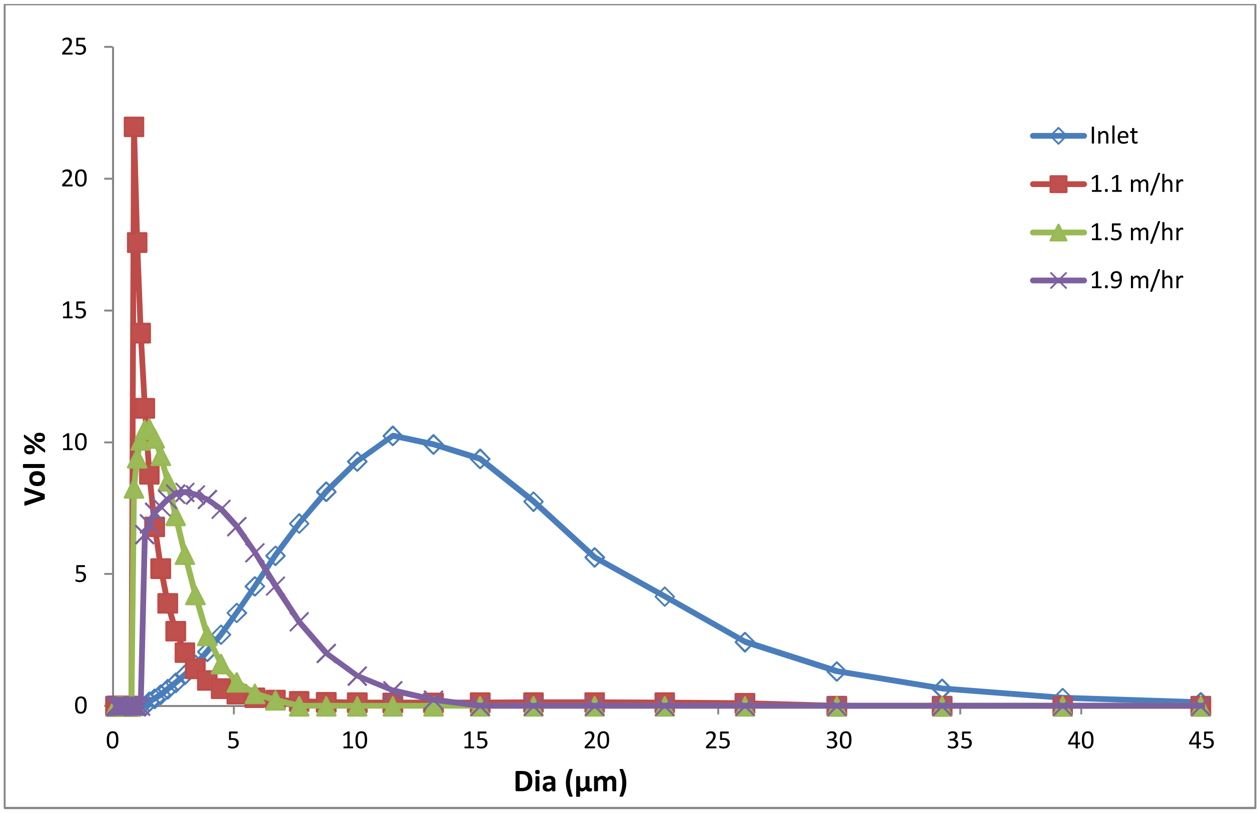


Figure 4-2(b): PSD removal at various loading rates (Filter # 2, Media size 8-12mm)

4.1.4 PSD vs Loading Rate for Filter # 3 (4-8mm)

Next, Filter # 3 was subjected to the pre-selected filtration rates. Result are shown in Fig 4-4 and discussed below

- At all loading rates the number of small particles in effluent is maximum due to small gravel size, hydrodynamic force increase infect strike of the suspended particles against the gravel increase so in this way large size particles are converted into smaller one.
- Large size particle concentration is less for all three flow rates. Hence by using small size gravel large size suspended particles of large size can easily remove.

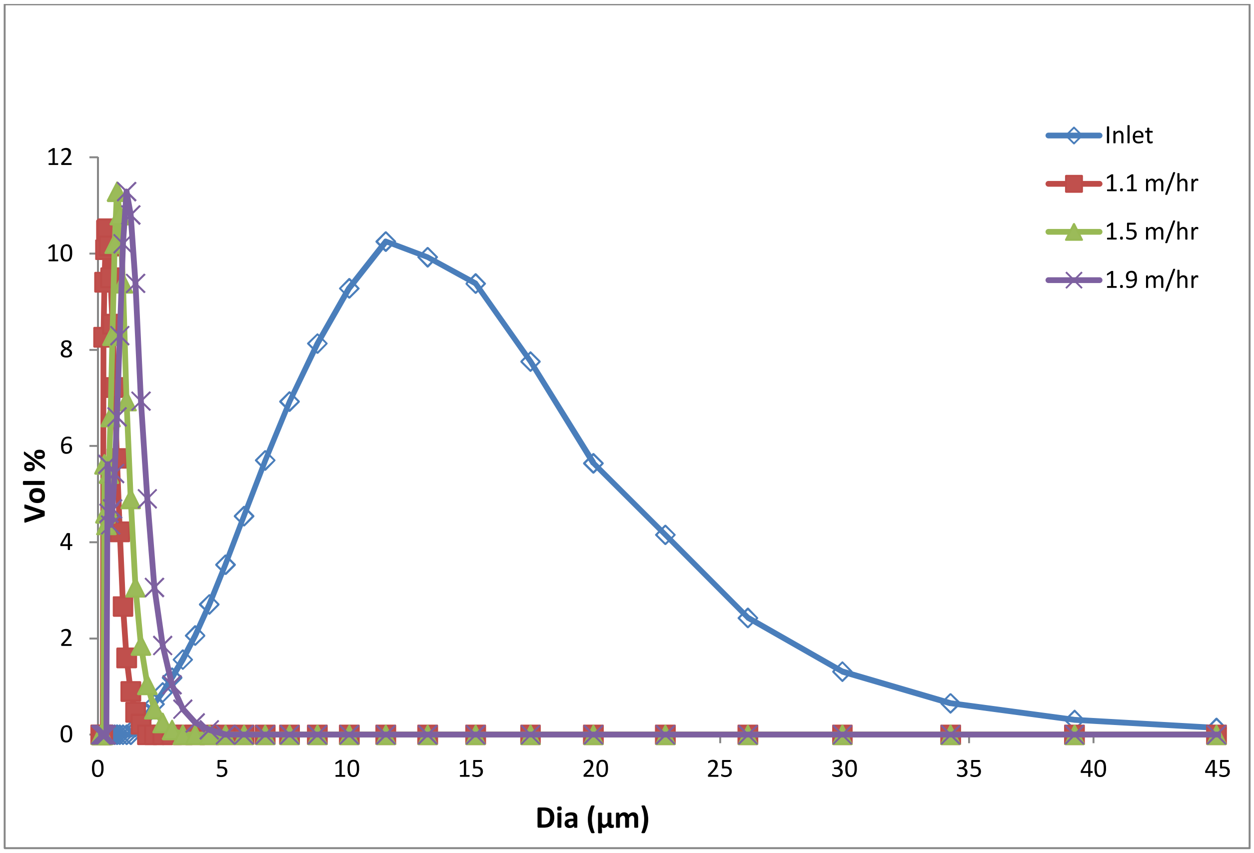


Figure 4-2©: PSD removal at various loading rates (Filter # 3, Media size 4-8mm)

4.2 Turbidity Removal Studies

The comparison of turbidity removal by three HRF runs made at three different loading rates (1.1 m/hr, 1.5 m/hr and 1.9 m/hr.) is discussed in this section.

4.2.1 Performance Evaluation of Filter # 1 (12-18mm)

Filter 1 which has a gravel size 12mm to 18mm was run at three different loading rates until the filter exhausted or gave a constant effluent turbidity for an extended period.

- At loading rate 1.1 m/hr filter exhausted at about 140 hours and the effluent turbidity fluctuated between 30 to 15 NTU.

- At loading rate 1.5 m/hr filter run up to 140 hours and the effluent turbidity fluctuated between 14 to 4 NTU.
- At loading rate 1.9 m/hr filter run up to 100 hours and the effluent turbidity fluctuated between 30 to 17 NTU
- Loading rate 1.5, 1.9 m/hr almost gave the same effluent value but at loading rate 1.5 m/hr effluent turbidity reduced up to 5 NTU.
- At loading rate 1.1, 1.5 m/hr choking time for filter remained same but loading rate 1.5 m/hr gave least effluent turbidity.
- 1.5 m/hr is best hydraulic loading rate to operate the HRF with media size 12-18mm.

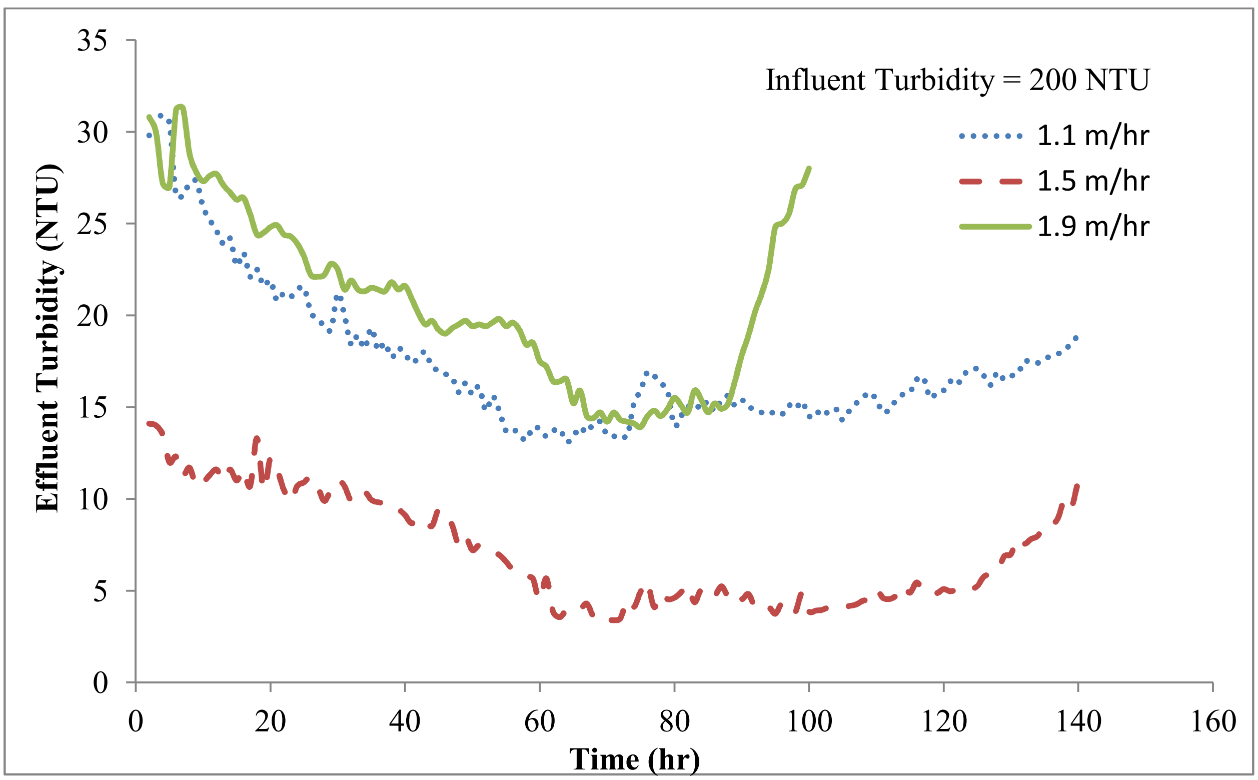


Figure 4-3(a): Comparison of turbidity removal of Filter # 1 (12 -18mm) at different flow rate

4.2.2 Performance Evaluation of Filter # 2 (8-12mm)

Filter 2 which have a gravel size 8mm to 12mm was run at three different loading rates until the filter choked or given a constant effluent turbidity for a long time.

- At loading rate 1.1 m/hr the effluent turbidity fluctuated between 22 to 10 NTU. At this rate filter run up to 120 hrs.
- At loading rate 1.5 m/hr the effluent turbidity fluctuated between 10 to 3 NTU. Filter run at this rate was about 110 hrs.
- At high loading rate i-e 1.9 m/hr the effluent turbidity fluctuated between 33 to 10 NTU. At this rate filter run for about 80 hours and choked in for about 70 hr.
- 1.5 m/hr is best loading rate to run the HRF. At this rate filter gives minimum effluent turbidity and almost maximum run time.

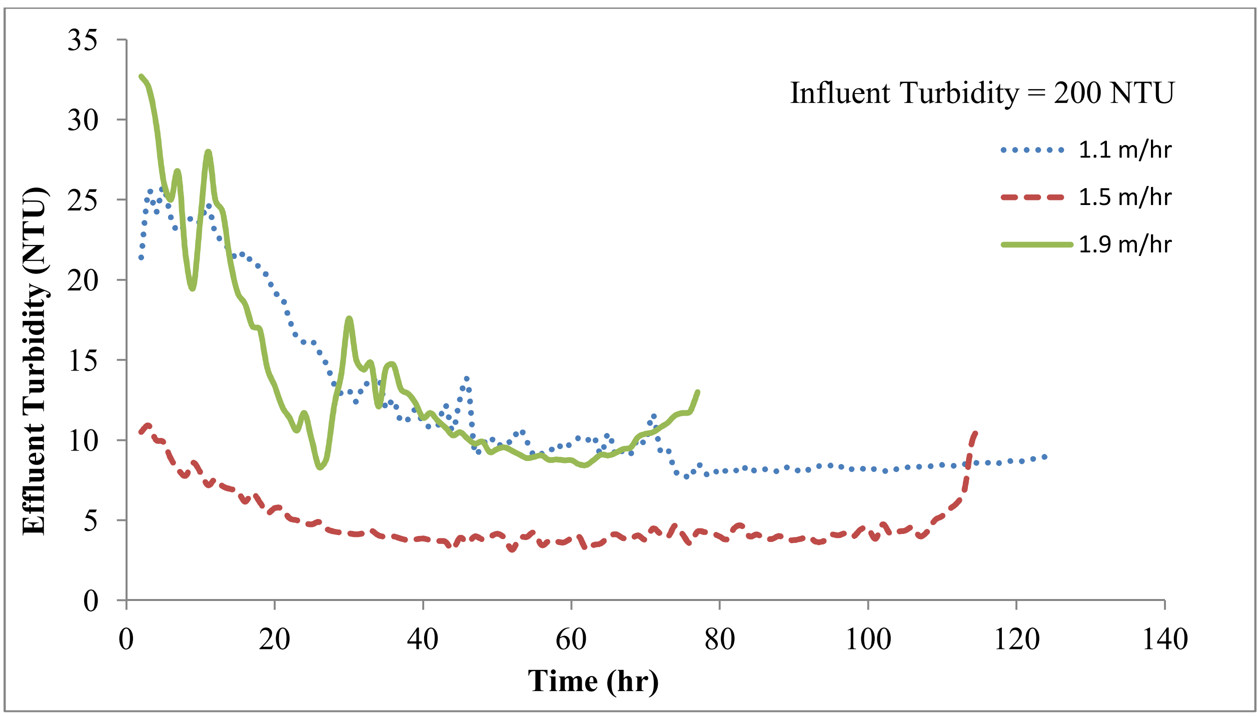


Figure 4-3(b): Comparison of turbidity removal by Filter # 2 (8-12mm) at different flow rate

4.2.3 Performance Evaluation of Filter # 3 (4-8mm)

Filter 3 which have a gravel size 4mm to 8mm was run at three different loading rates until the filter choked or given a constant effluent turbidity for a long time.

- At loading rate 1.1 m/hr effluent turbidity fluctuated between 15 to 4 NTU and running time of the filter was 110 hr. At this rate filter did not give the consistent result
- At loading rate1.5 m/hr, filter run was about 100 hr. At this rate effluent turbidity fluctuated between 8 to 2 NTU.
- Loading rate 1.9 m/hr gave effluent turbidity fluctuated between 10 to 2 NTU. Running time of the filter at this rate was about 60 hr.
- 1.5 m/hr was best flow rate to run this HRF having media of size 4mm-8mm because at this rate effluent turbidity is consistent between 2 to 4 NTU.
- 1oading rate 1.9 m/hr also gave the effluent turbidity in between 2 to 4 NTU but for a very short period of time and filter choked after 50 hr run.

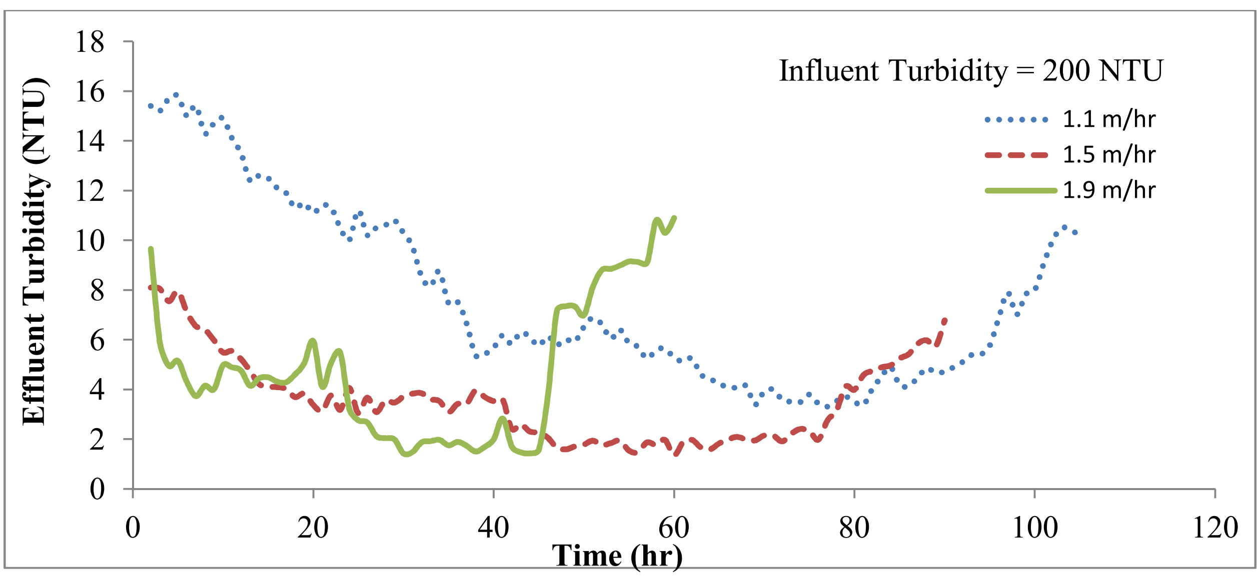


Figure 4-3©: Comparison of turbidity removal of Filter # 3 (4-8mm) at different HLR

4.3 Effect of Media Sizes at Turbidity Removal

Comparing the effluent turbidity results of different filters at the same loading rate has been discussed in this section. Raw water turbidity was considered at 200 NTU.

4.3.1 At loading rate 1.1 m/hr

- At this rate effluent turbidity of Filter # 1 (12-18 mm) fluctuated between 30 to 15 NTU.
- Effluent turbidity of Filter # 2 fluctuated between 25 to 10 NTU
- For Filter # 3 effluent turbidity fluctuated between 15 to 5 NTU.
- These results show that media sizes is inversely proportional to turbidity removal efficiency and is directly proportional to filter run time
- On the basis of filter run time and effluent turbidity results, filter 2 having a media size of 12mm to 18mm is the most suitable to use for HRF.

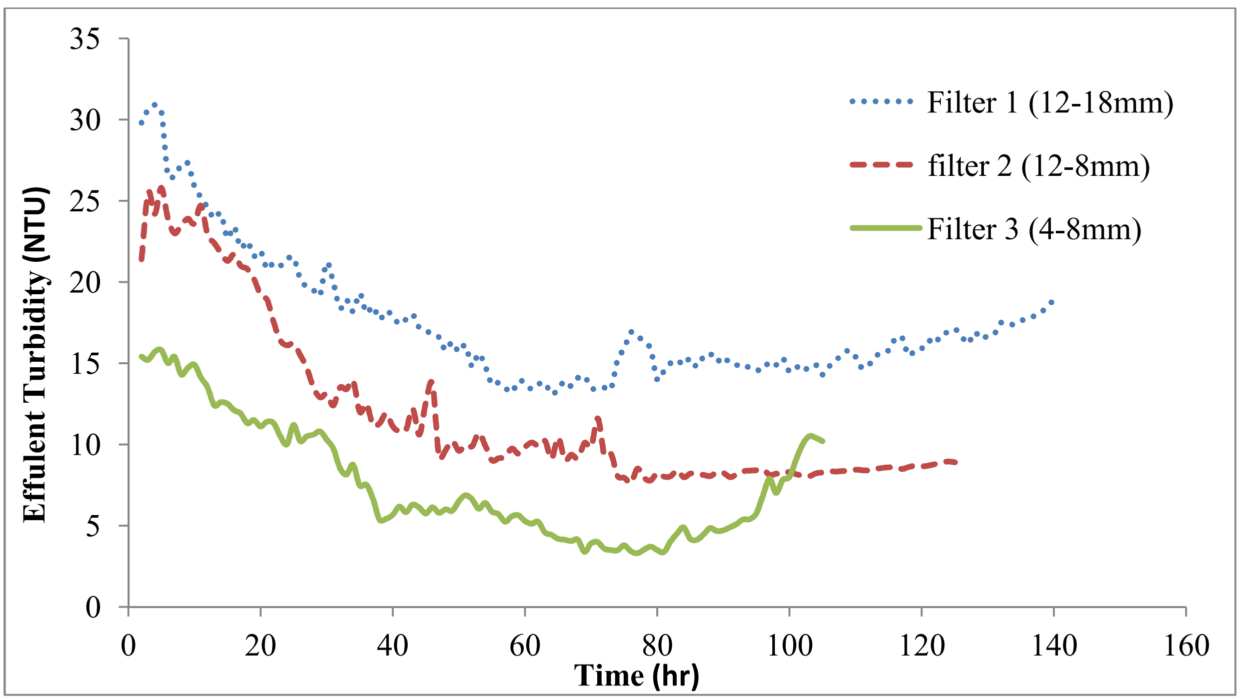


Figure 4-4(a): Turbidity removal comparison of different filters at 1.1 m/hr

4.3.2 At loading rate 1.5 m/hr

- Filter 1 effluent turbidity fluctuated between 14 to 4 NTU.
- Filter 2 effluent turbidity fluctuated between 11 to 3 NTU.
- Filter 3 effluent turbidity fluctuated between 14 to 2 NTU.
- Filter 2 showed most consistent result so at loading rate 1.5 m/hr filter 2 having media 8mm-12mm is most appropiate on the basis of the filter run and effluent turbidity.

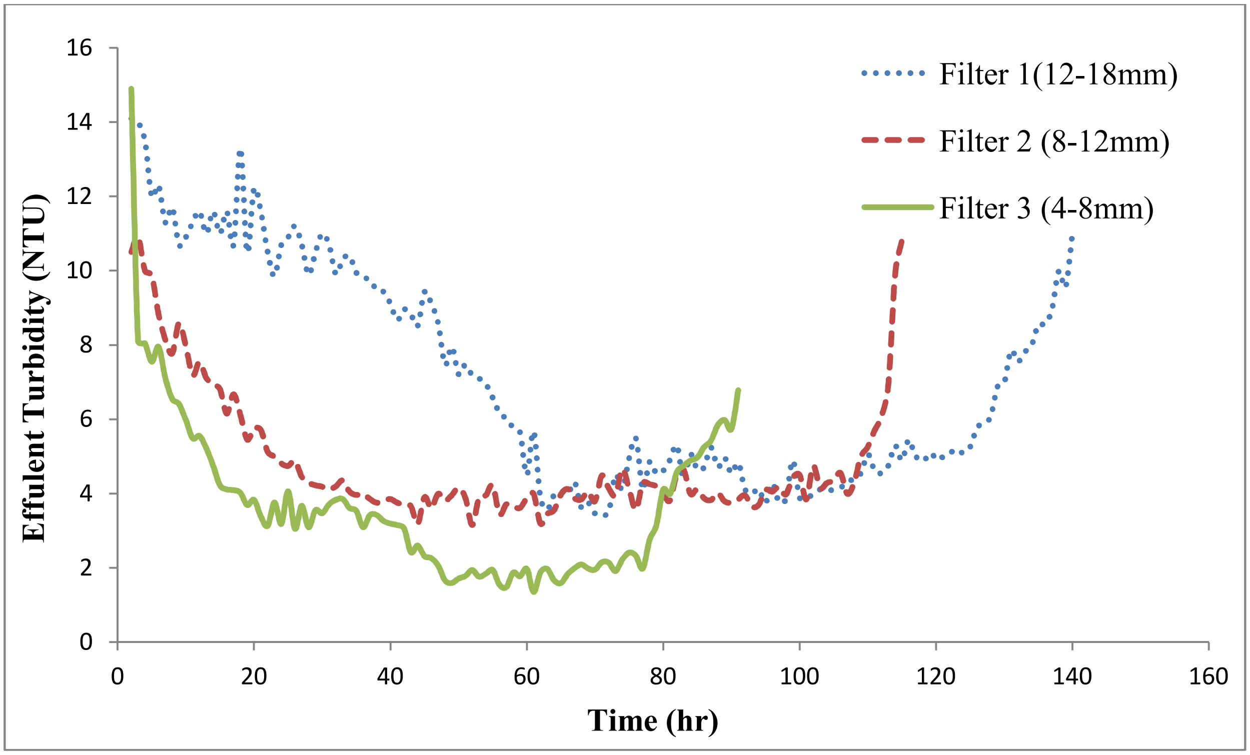


Figure 4-4(b): Turbidity removal comparison of different filters at flow rate 1.5 m/hr

4.3.3 At loading rate 1.9 m/hr

- At this rate filter1 effluent turbidity fluctuated between 32 to 15 NTU. Filter 1 choked after 90 hours.

- Filter 2 gives effluent turbidity fluctuated between 35 to 4 NTU. At this loading rate filter choked after 75 hours.
- Filter 3 at this loading rate effluent turbidity fluctuated between 12 to 1.5 NTU. Filter 3 choked after 55 hours.
- Filter 2 having media 8mm-12mm gave most appropriate result on the basis of filter run and effluent turbidity**.**

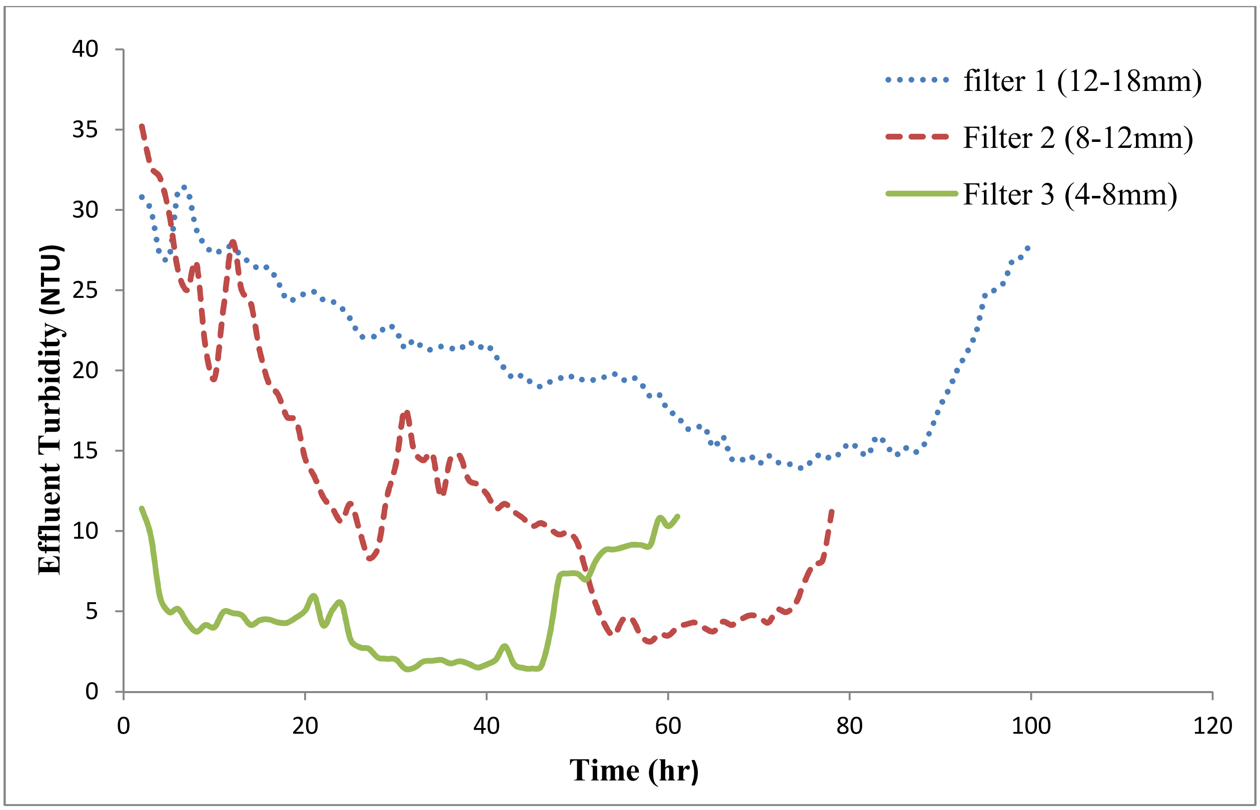
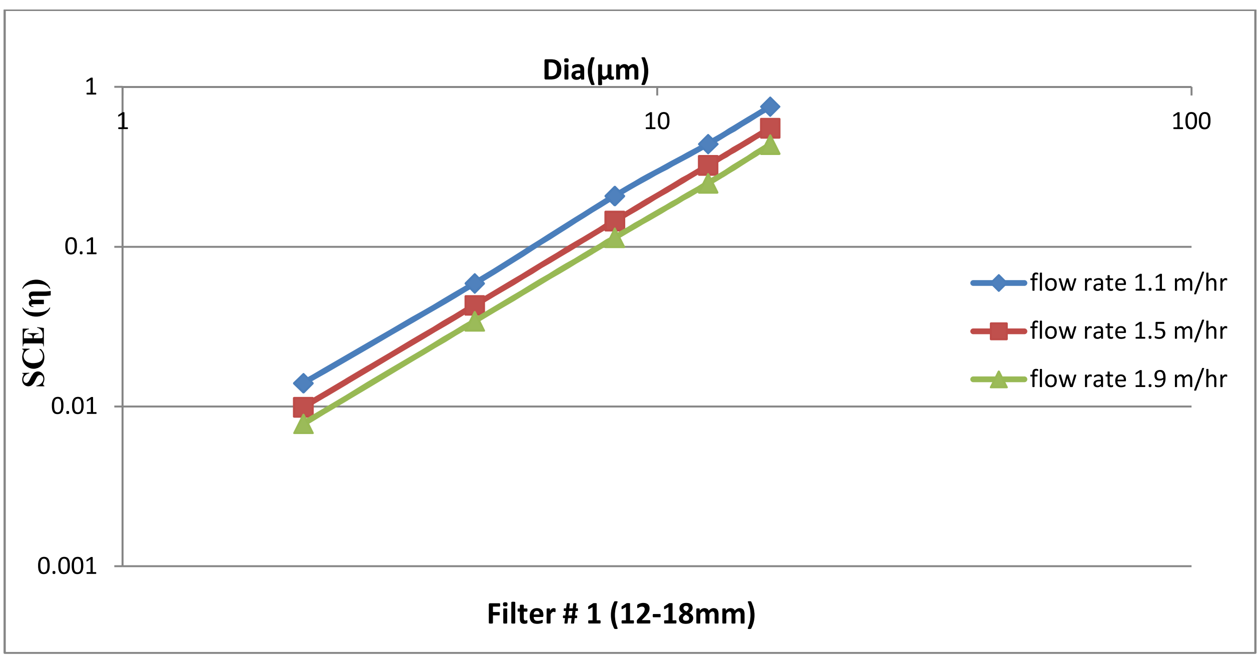


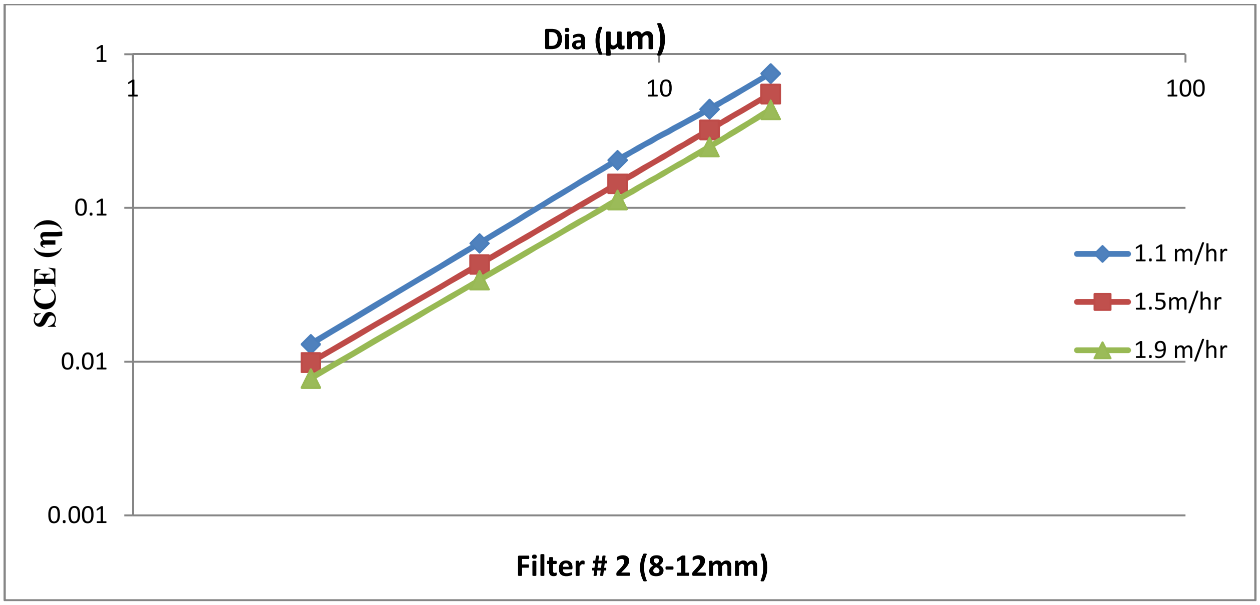
Figure 4-4©: Turbidity removal comparison of different filters at flow rate 1.9 m/hr

4.4 Single Collector Efficiency (SCE) by Yao's Equation

In Yao's equation gravity factor is important therefore by changing the diameter of collector or media (gravel) there is no effect on transport coefficient or single collector efficiency but there is definitely an effect of flow rate on S.C.E or transport coefficient.

- We can see from the graph that with increasing diameter of the particles in the influent, S.C.E increases but as the flow rate of the influent increases, S.C.E decreases with respect to diameter of influent particles.(as shown in the fig4-1(a,b,c)).
- Sedimentation is the core phenomena for the removal of suspended particles.
- As size of the suspended particles increases due to sedimentation phenomenon SCE increases.
- SCE at low loading rate (1.1m/hr) is higher as compared to high loading rate (1.9 m/hr). This because at low loading rate suspended particles has more time to settle down as compared to high loading rate.
- There is no remarkable effect of media size on SCE. At the same flow rate all three filters of different sizes showed same result. So the comparison cannot be done at same flow rate.
- Removal efficiencies were evaluated with respect to previously reported studies on SCE of horizontal roughing filters (Edwin et al.2004)





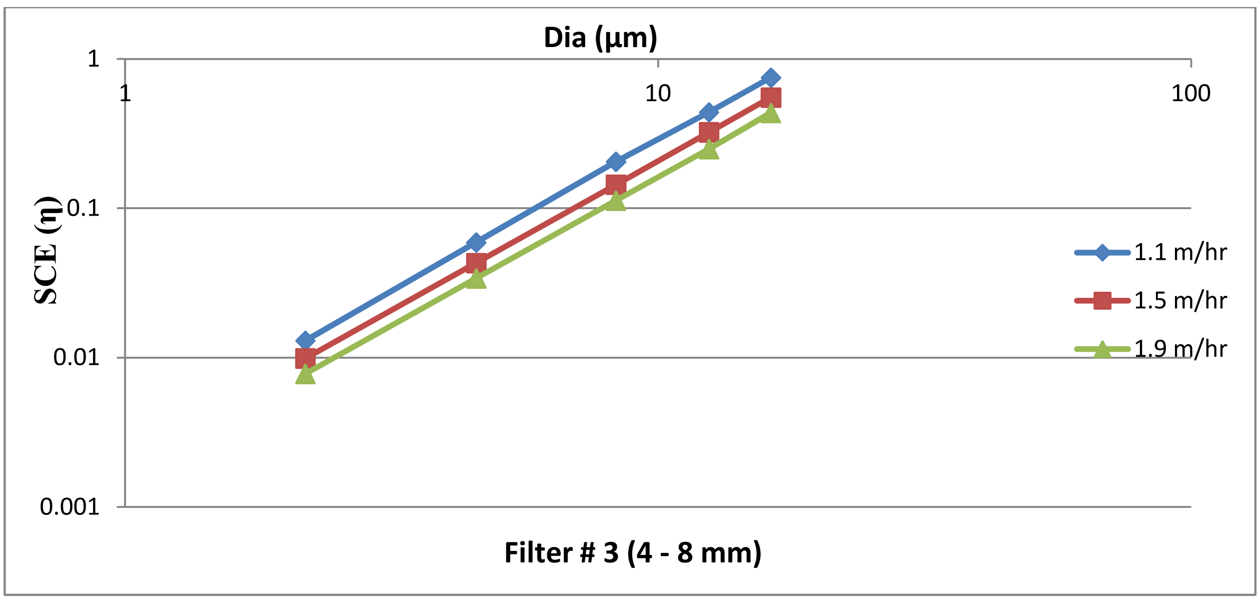


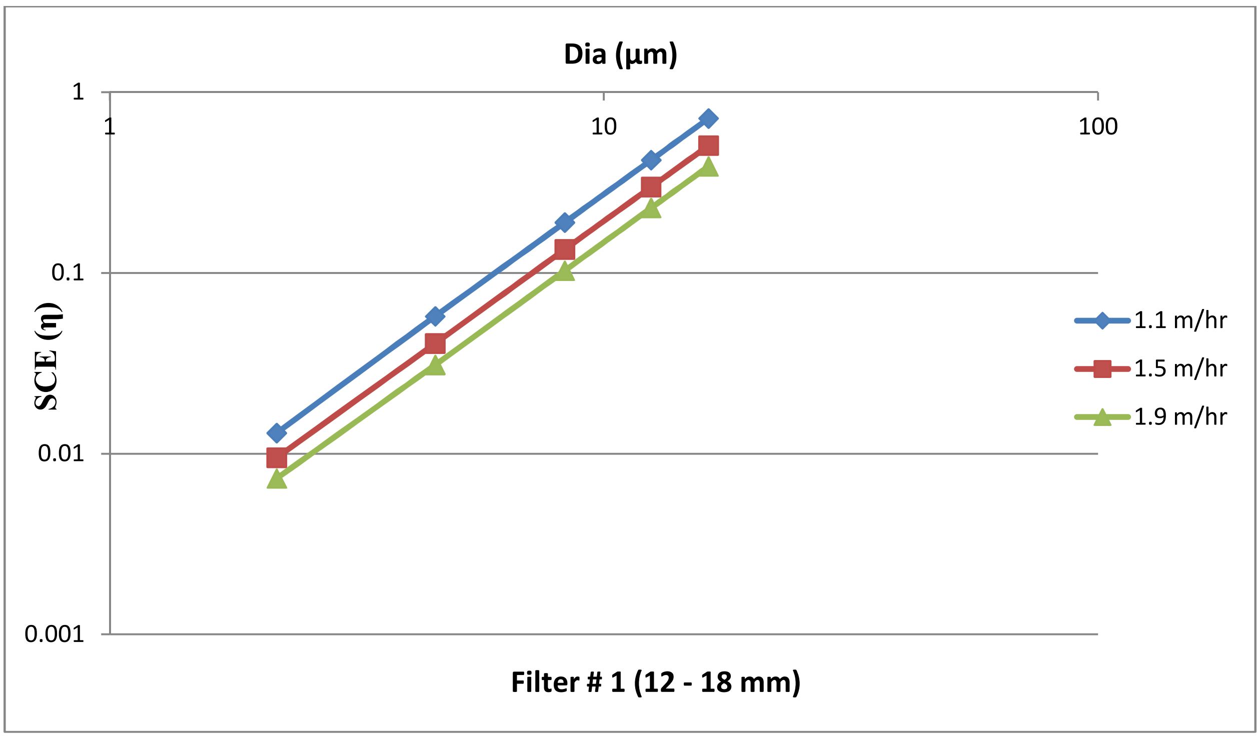
Figure 4-5(a,b,c): Suspended particles dia. vs SCE at varying HLR & media size by using Yao's equation

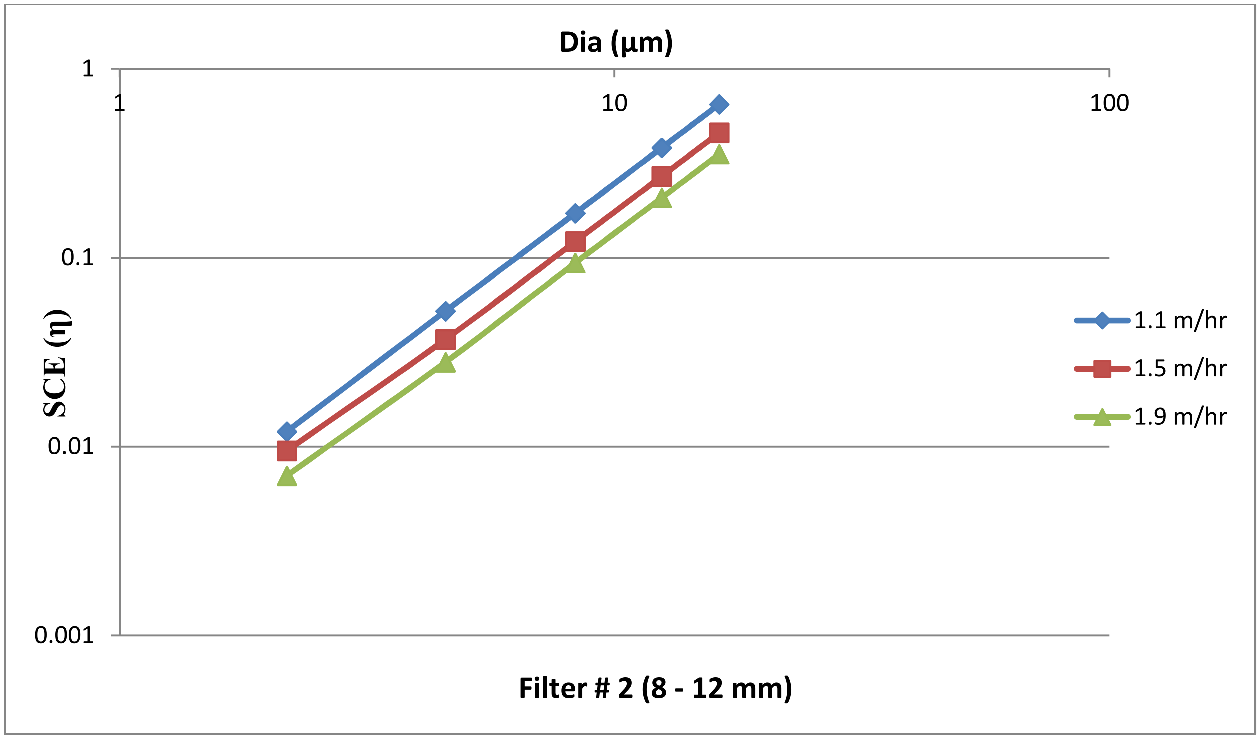
4.5 SCE by using Tufenjiki Equation

Yao's equation was refined by Tufenjiki and Elimelech (2004) to consider close range forces, including hydrodynamic interactions and universal van der waals attraction forces. Fig 4-

2 (a,b,c) represent the graphs between S.C.E and influent particles diameters by using Tufenjiki equation.

- These graph show similar results as shown in fig 4-1 (a,b,c) i.e. With the increase in influent particle diameter, S.C.E or transport coefficient increases.
- S.C.E decreases with the increase in hydraulic loading rate due to the increasing effect of van der Waals attractive forces (which increase particle deposition rate) and decreasing effect of hydrodynamic forces.





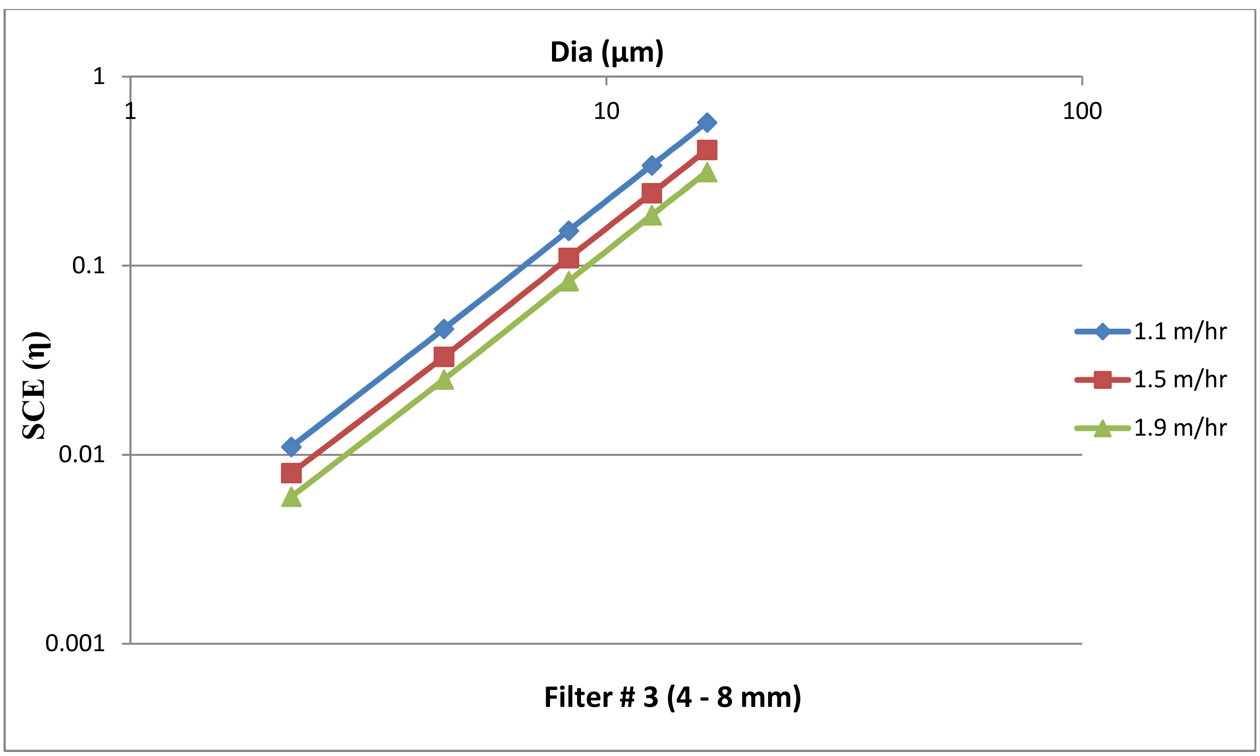
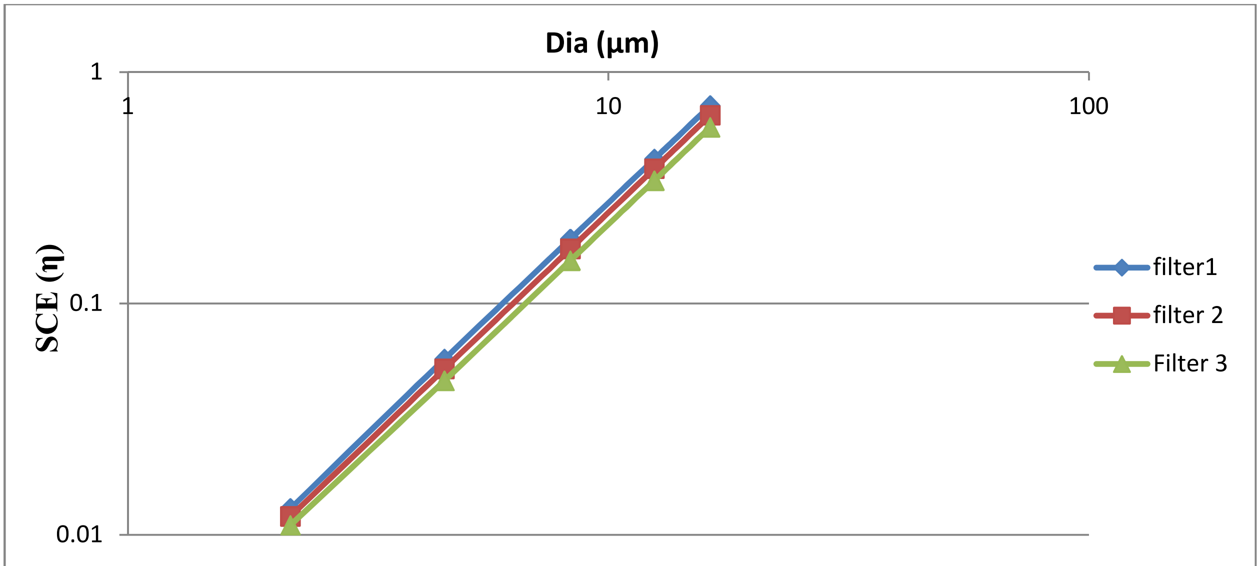


Figure 4-6 (a,b,c): Suspended particles dia. Vs SCE at varying HLR & media size by using Tufenjiki equation.

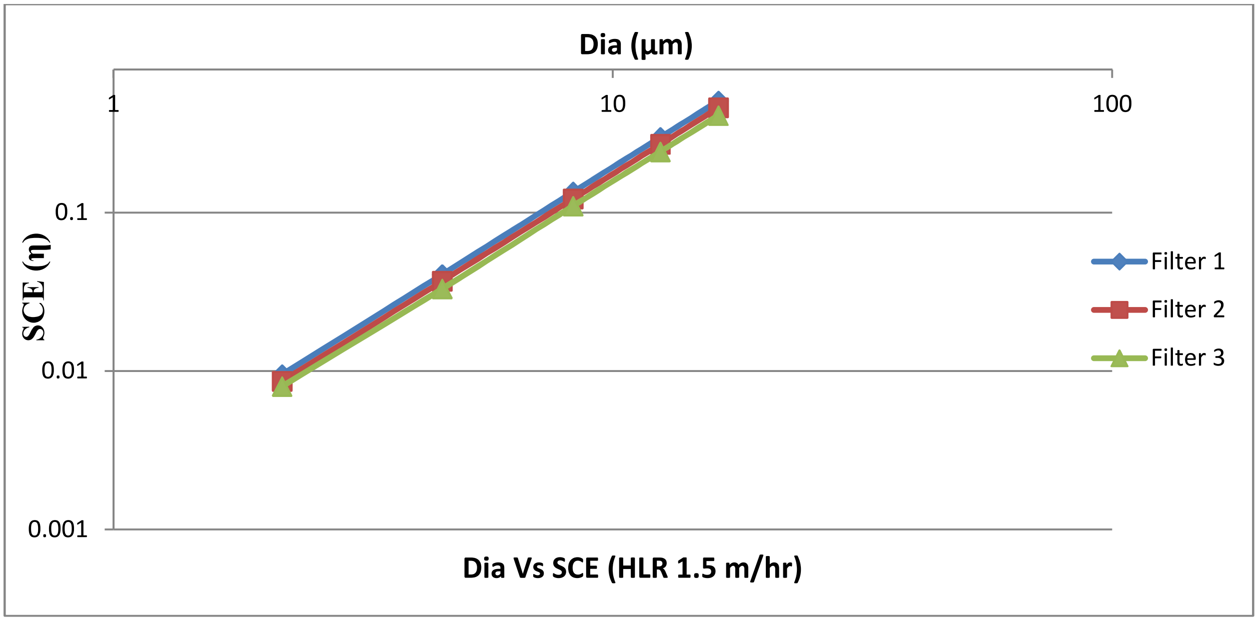
4.5.1 SCE at Same Hydraulic Loading Rate by using Tufenjiki Eq.

Tufenjiki equation has an advantage that we can compare three filters at different flow rates because in Tufenjiki equation S.C.E is not only dependent on gravity factor (sedimentation) but also on hydrodynamic and van der waals forces (Edwin et al. 2004).

- With the reduction of filter media size, S.C.E slightly decreases. This happens because hydrodynamic forces increase, hence large particles are converted into smaller ones and these small size suspended particles are difficult to get settled.
- Filter # 3 (4-8mm) shows minimum value at all flow rates because of the enhanced effect of hydrodynamic forces with the reduction of media size.
- With the increase in the diameter of influent particle, SCE also increases. This is because large particles get easily settled down due to sedimentation.



Dia Vs SCE (HLR 1.1 m/hr)



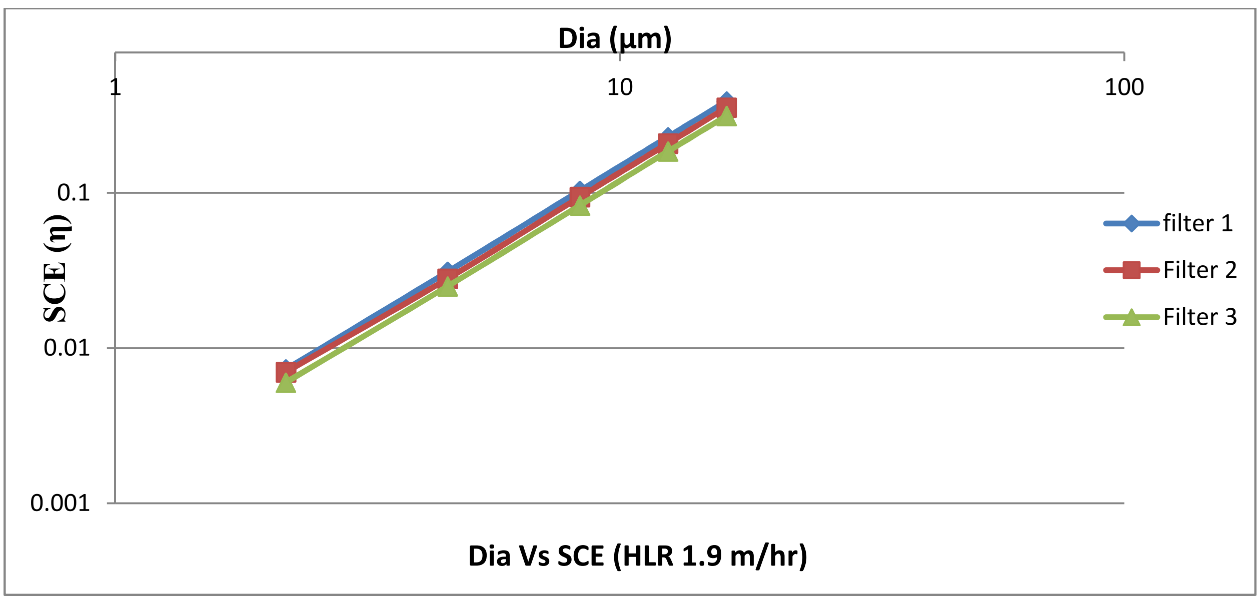


Figure 4-7 (a,b,c): Suspended particles dia. vs SCE at varying media sizes & same HLR

4.6 SCE as calculated using Yao's Eq. and Tufenjiki Eq.

Yao's equation was developed in 1971 and according to this equation gravity factor plays the main role for the removal of suspended particles. Tufenjiki refined the work of Yao in 2004 and developed another equation which includes the hydrodynamic and van der Waals attraction forces. The comparison of these two equations show which equation is more useful for getting better results.

- There is minute difference between S.C.E, calculated by Yao and Tufenjiki equation at different flow rates. The value of S.C.E given in Yao's equation is slightly higher as compared to Tufenjiki's equation.
- As the media size decreases the difference between both the equations' results increases because of hydrodynamic and van der Waals force.
- At filter 3 (4-8mm) difference between these two equations increases. So it is clear that Tufenjiki equation is more useful when it comes to small size media because by reducing the media size attraction forces between them increases. The effect of these forces is not covered in Yao's equation.
- By reducing the media size S.C.E calculates by Yao equation is same but as the media size decrease S.C.E calculated by Tufenjiki equation is reduced in this way difference between these two equation increases by reducing the media size. S.C.E decrease with decreasing media size due to the increase effect of hydrodynamic forces, which retard particle deposition.
- Inclusion of hydrodynamic and attractive van der waals forces resulted in lower uncertainty and hence improved estimation of SCE.

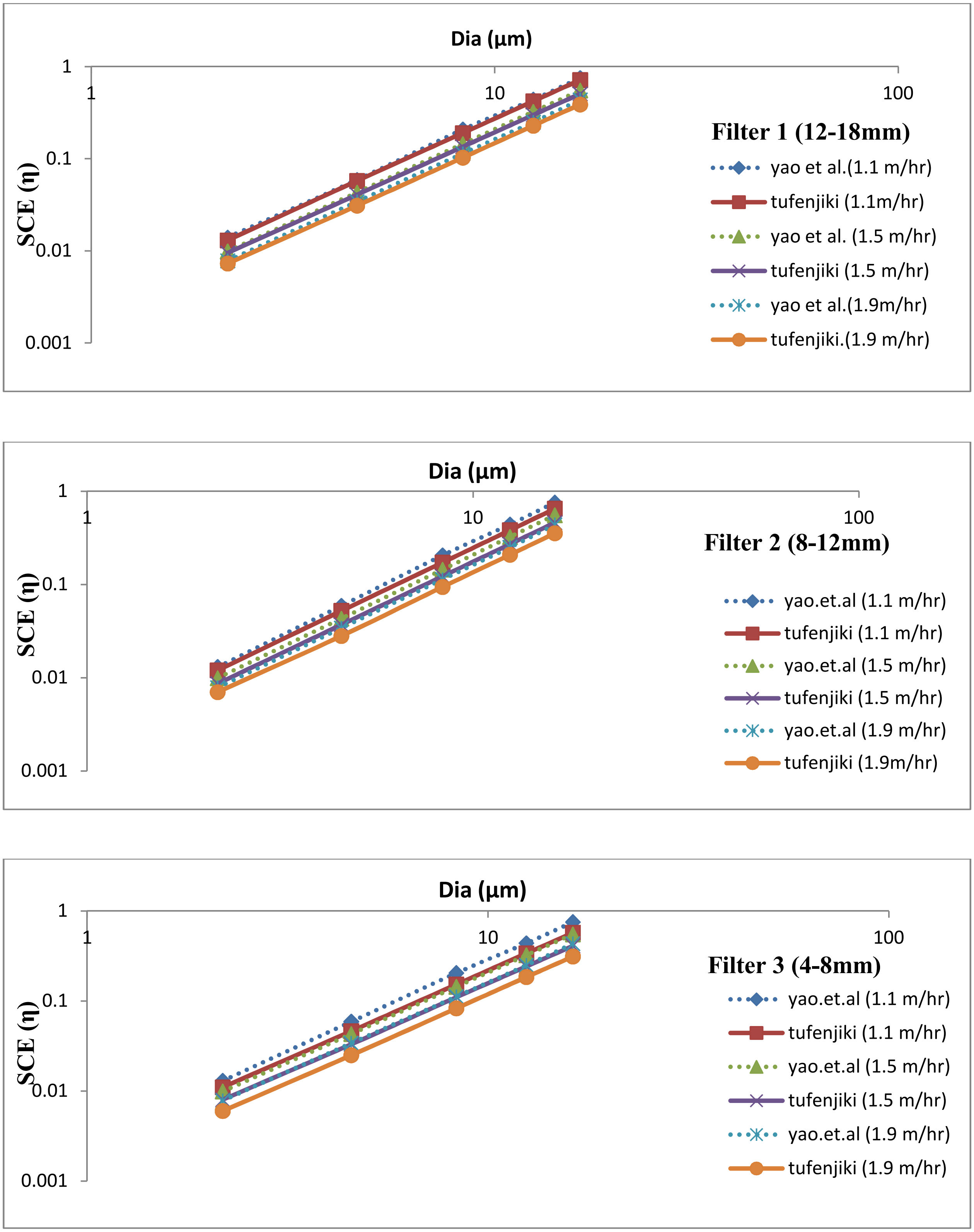


Figure 4-8(a,b,c): Comparison of Yao's eq. and Tufenjiki eq. at varying HLR & media sizes

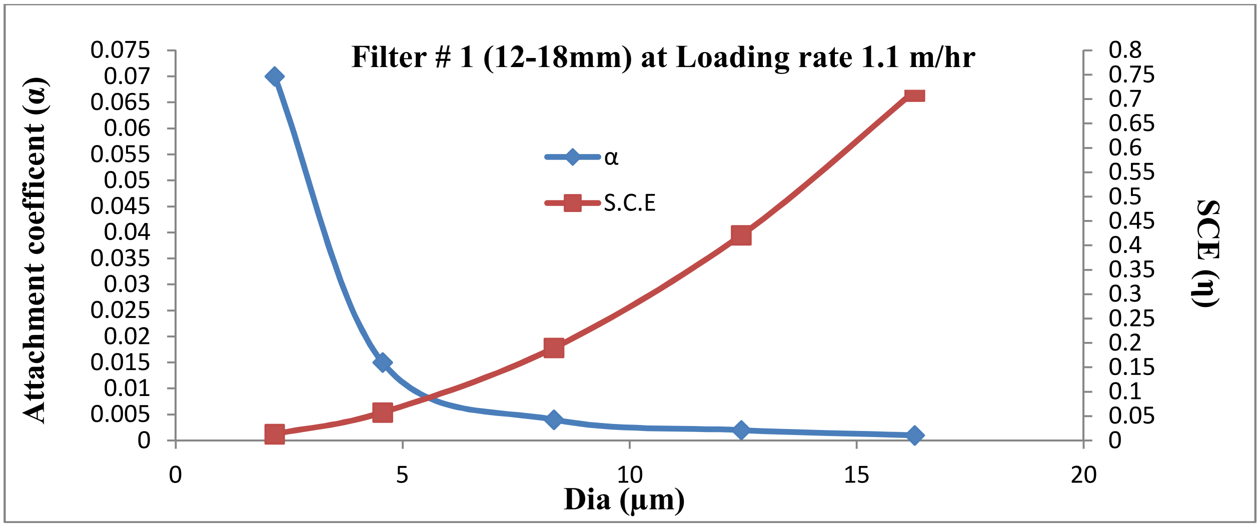
4.7 Attachment Coefficient Relation with SCE and Dia. by Using Tufenjiki Eq.

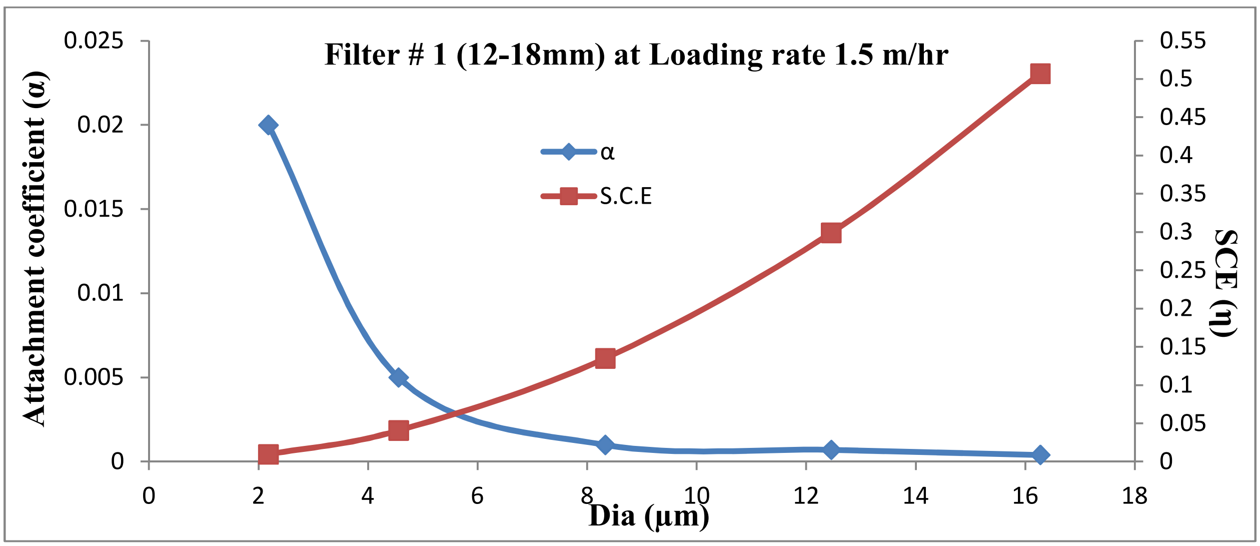
As particles approach the surface of the media, short range surface forces like van der waals attraction forces and electrostatic forces will begin to influence particles' dynamics. If particles have been destabilized, the collision between the particulates and the media or collector surface is likely to be successful. Attachment can only occur when the surface of the particulate and media are oppositely charged. (Yao 1968) .Attachment factor is calculated by using equation as shown and λ which is filter coefficient is calculated by this equation

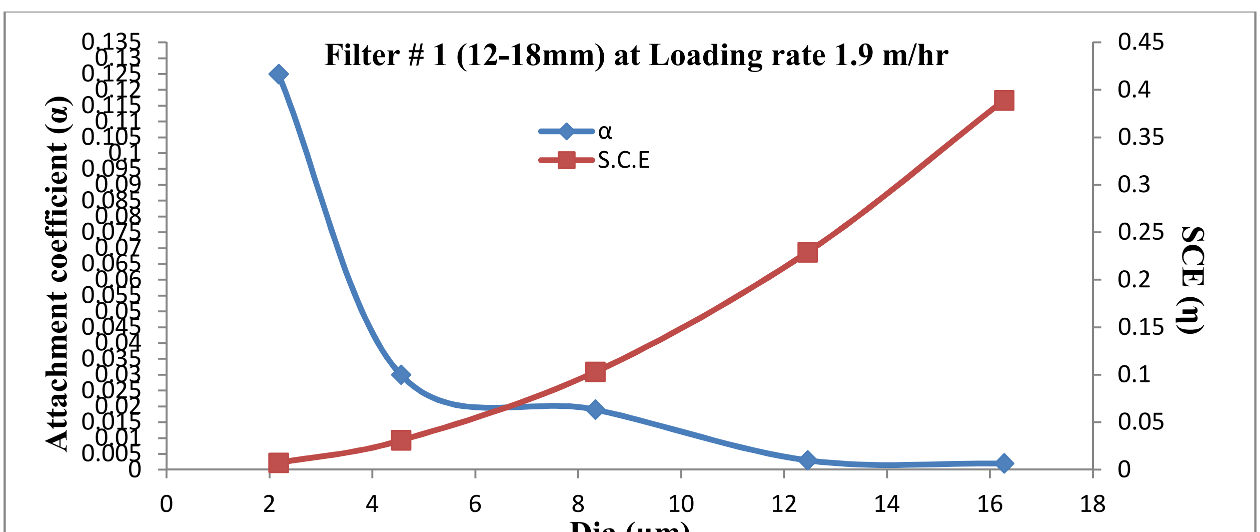
$$\lambda = (-3/2)\ \eta^*\alpha^*(1-e)/d_c \text{(Tufenjiki.2004)}$$

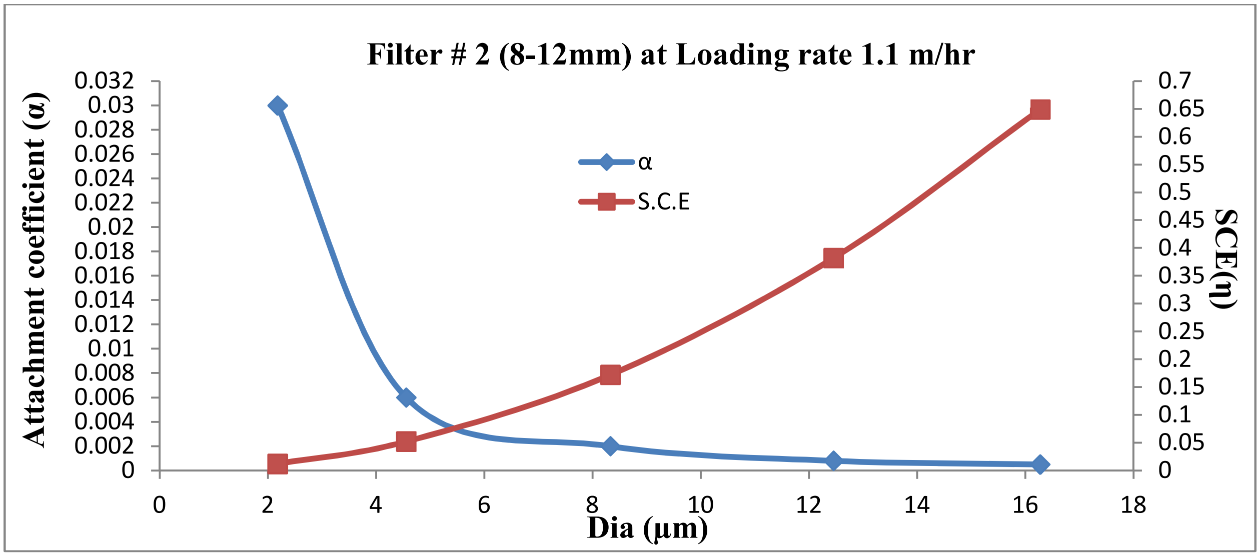
$$E = e^{-\lambda L} \text{ (Weglin. 1996)}$$

- SCE increases with respect to dia. As dia. of suspended particles increases SCE increases because of sedimentation phenomena i.e. greater the size of the suspended particles greater will be the SCE.
- The observed decline in calculated SCE with decreasing media size is due to the combination of various factors, including a large uniformity coefficient, resulting in improved removal efficiency due to higher grain density and heterogeneity in the particle population.
- With the increase in the influent particle diameter, S.C.E increased and attachment coefficient decreased at all flow rates for all three filters.
- Attachment coefficient and single collector efficiency reduced with increased Loading rate.
- The results remained similar when Yao's equation was applied.


Filter # 1 (12-18mm) at Loading rate 1.1 m/hr
Attachment coefficent (α)
SCE (η)
Dia (µm)
α
S.C.E


Filter # 1 (12-18mm) at Loading rate 1.5 m/hr
Attachment coefficient (α)
SCE (η)
Dia (µm)
α
S.C.E


Filter # 1 (12-18mm) at Loading rate 1.9 m/hr
Attachment coefficient (α)
SCE (η)
Dia (µm)
α
S.C.E


Filter # 2 (8-12mm) at Loading rate 1.1 m/hr
Attachment coefficient (α)
SCE(η)
α
S.C.E
Dia (µm)
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
0.016
0.018
0.02
0.022
0.024
0.026
0.028
0.03
0.032
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
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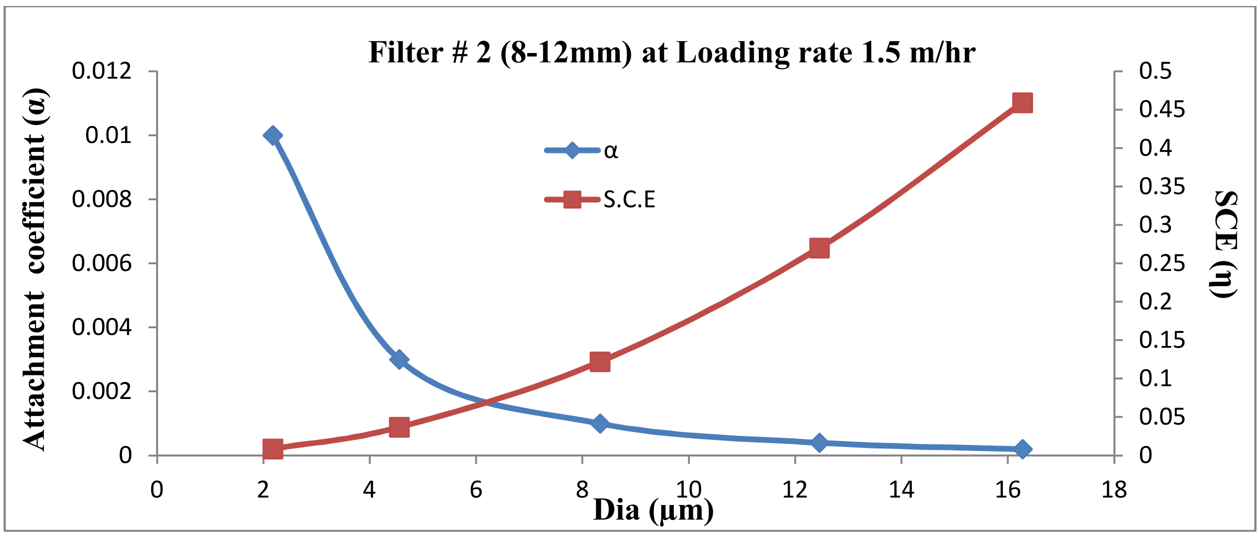
Filter # 2 (8-12mm) at Loading rate 1.5 m/hr
Attachment coefficient (α)
SCE (η)
α
S.C.E
Dia (µm)
0
0.002
0.004
0.006
0.008
0.01
0.012
0.05
0.1
0.15
0.2
0.25
0.3
0.35
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0.45
0.5
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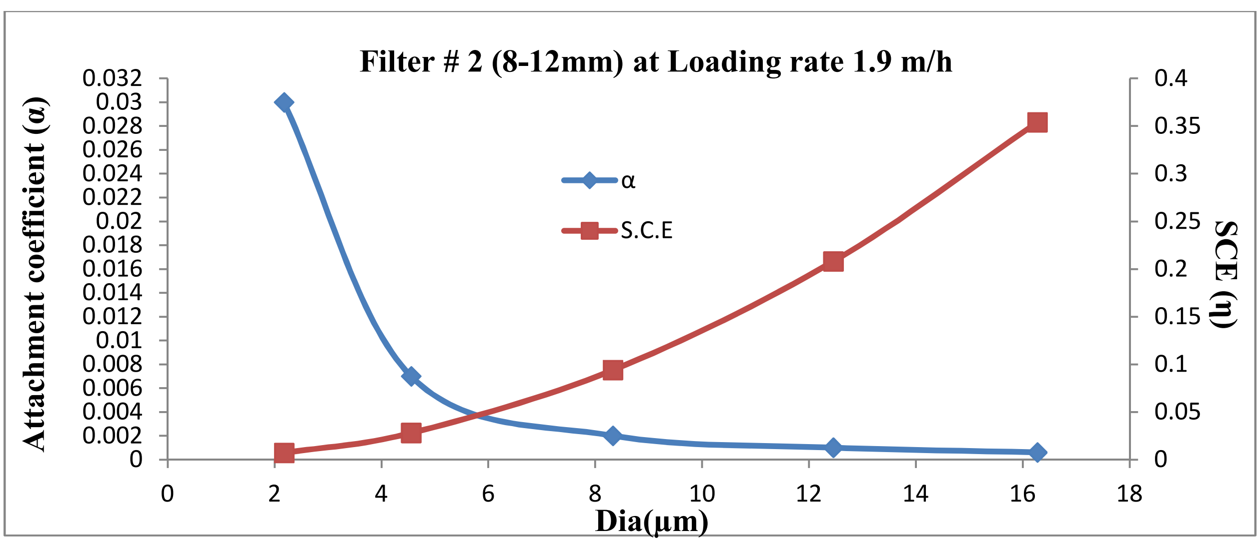
18


Filter # 2 (8-12mm) at Loading rate 1.9 m/h
Attachment coefficient (α)
SCE (η)
α
S.C.E
Dia(µm)
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
0.016
0.018
0.02
0.022
0.024
0.026
0.028
0.03
0.032
0.05
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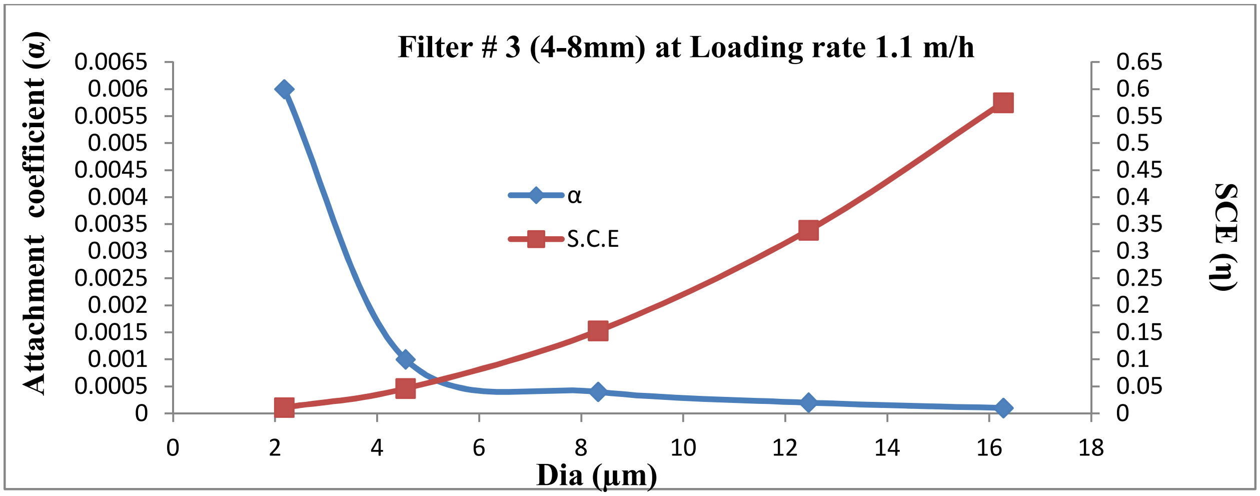
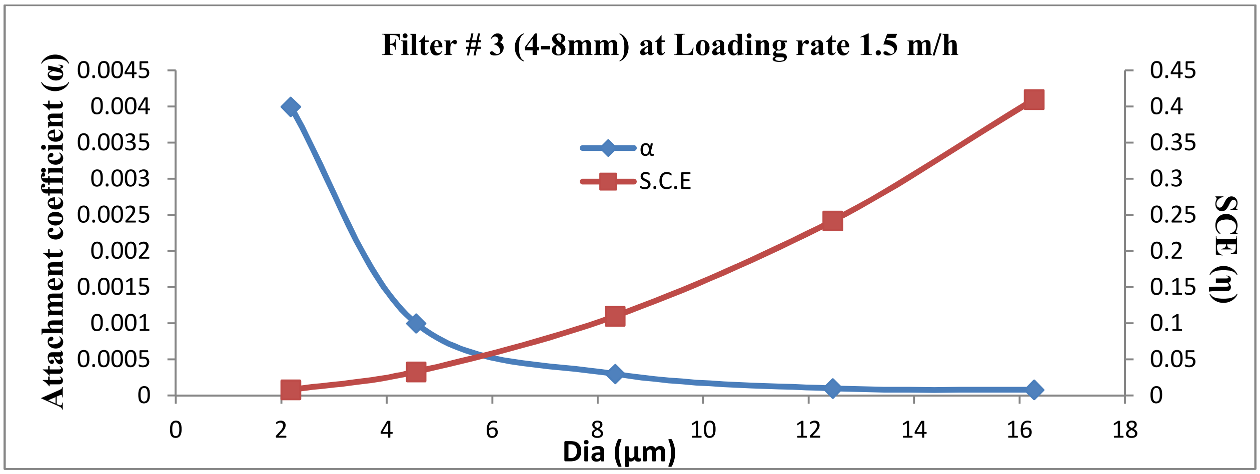




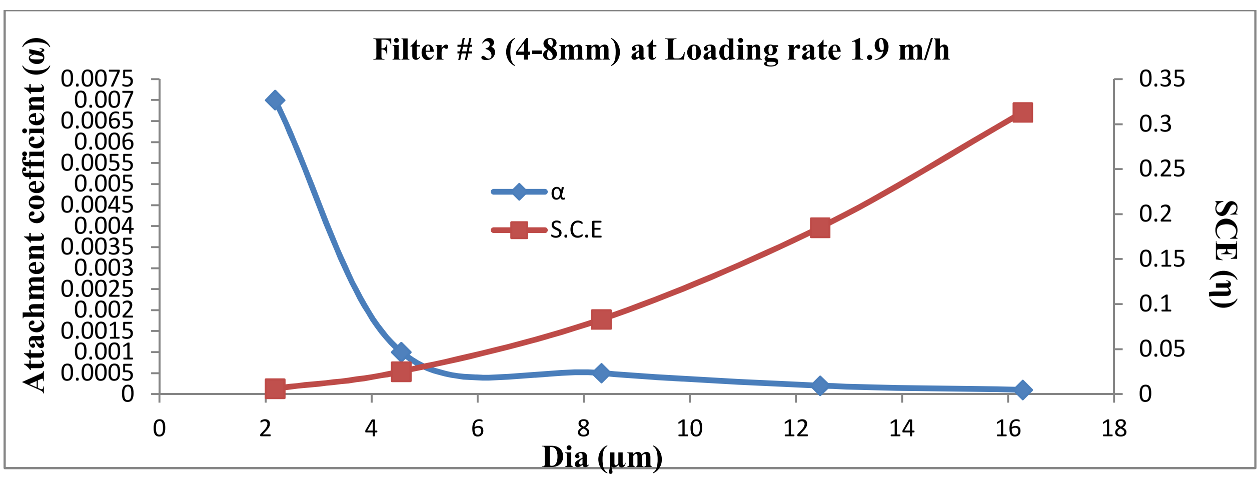
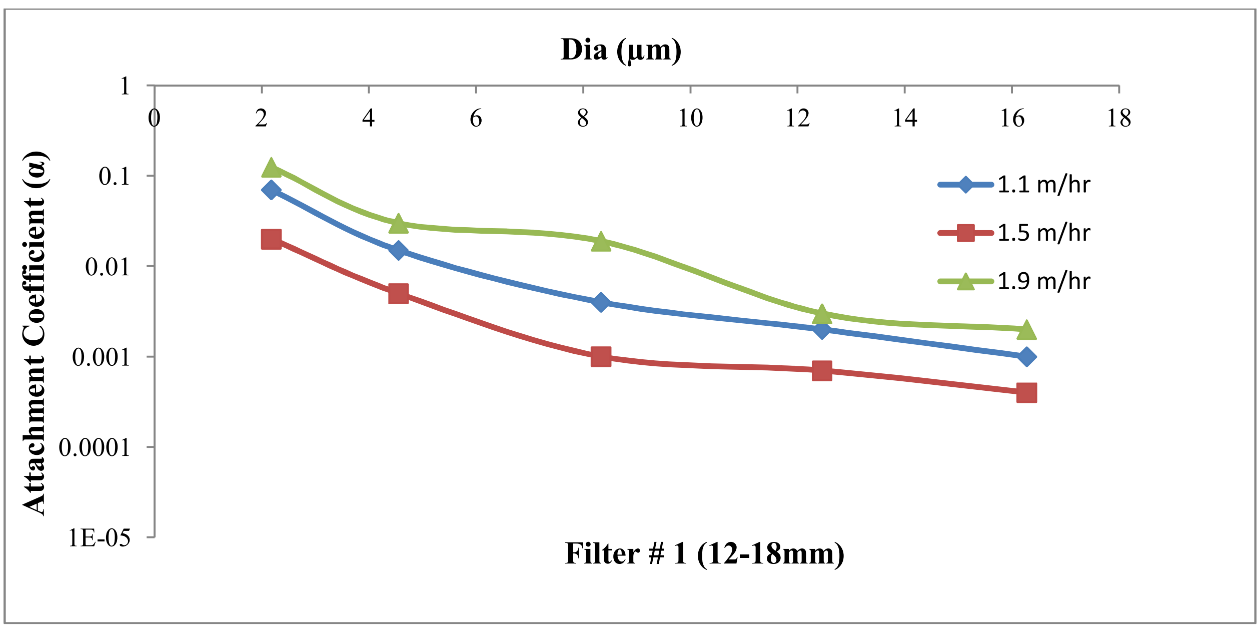


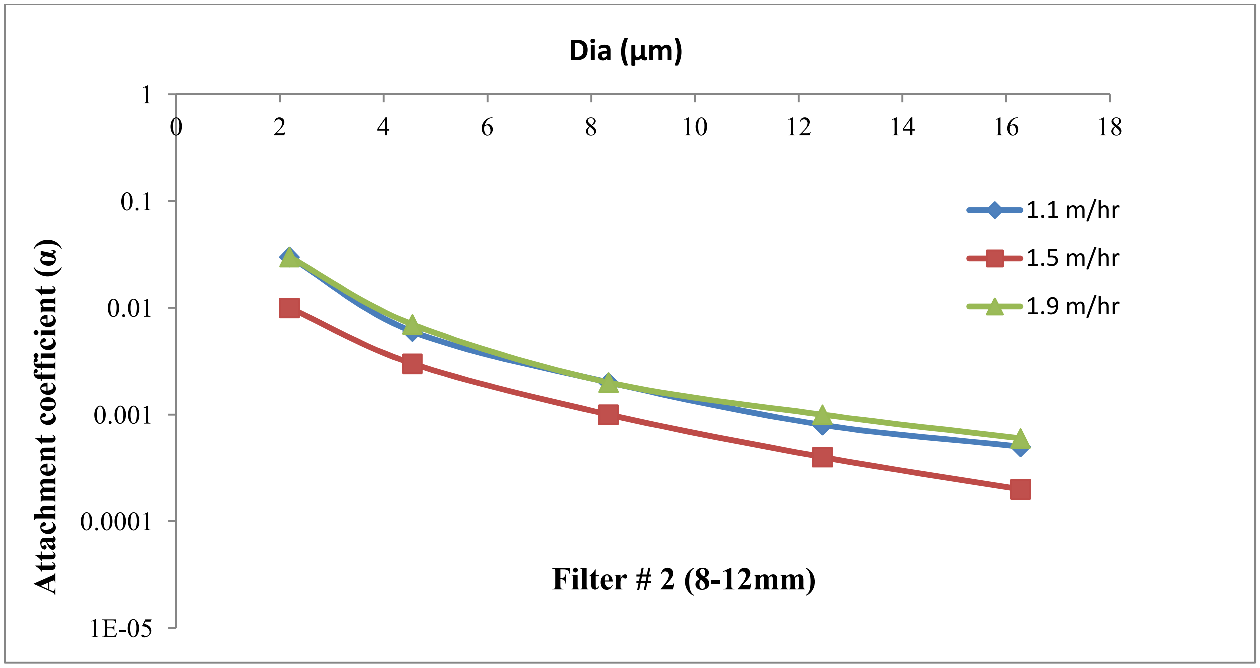
Figure 4-9(a,b,c,d,e,f,g,h,i): Comparison of SCE and attachment coefficient with dia. of suspended particles at HLR & media size (Tufenjiki eq.)

4.8 Attachment Coefficient vs Influent Particle Diameter Using Tufenjiki Equation

To show the relationship between Attachment factor and the diameter of the suspended particles these figures are drawn.

- Attachment factor is decreased by increasing the size of the suspended particles. This is due to the increase in size of the particles which causes sedimentation phenomenon to dominate. As a result particles settled down by striking against the media so in this way less chance is available for the attachment of the particles.
- At loading rate of 1.5 m/hr. less attachment occurred because of high SCE. This is due to the sedimentation.
- At loading rate of 1.9 m/hr. maximum attachment occurred due to lower SCE but as the media size decreased attachment factor at 1.1 m/hr and 1.9 m/hr remained almost same but lessened at 1.5 m/hr.as compared to other both loading rate. This is because of the higher SCE at 1.5 m/hr.





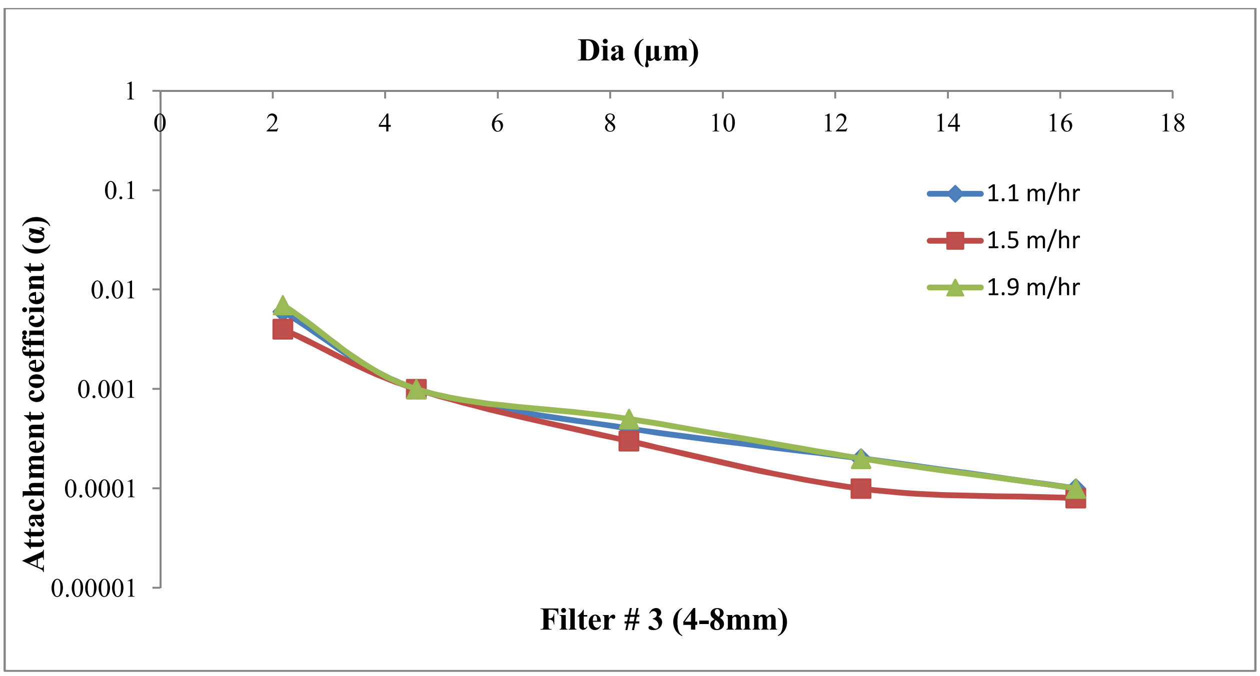
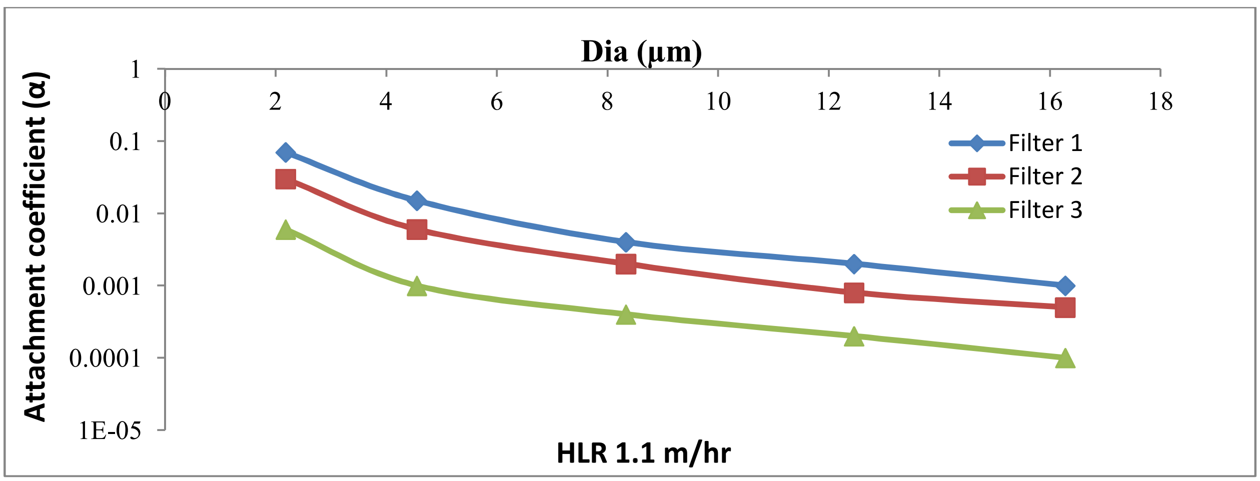


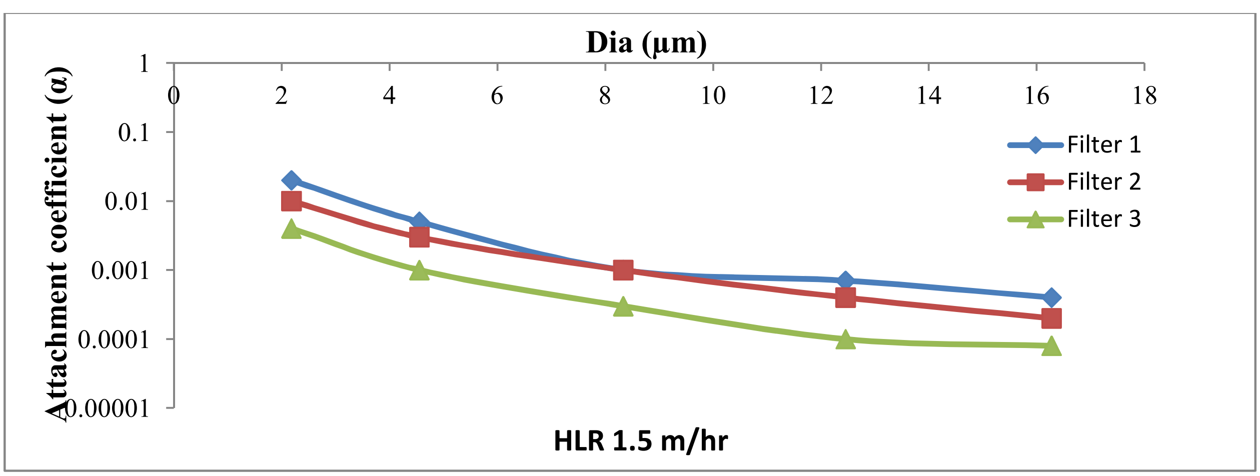
Figure 4-10(a,b,c): Suspended particles dia. vs Attachment coefficient at varying HLR & same media size (Tufenjiki eq.)

4.8.1 Attachment Coefficient vs Influent Particle Diameter at Same HLR Using Tufenjiki Equation:

By using Tufenjiki equation, the relation of attachment coefficient of different filters at same HLR with respect to diameter can be established.

- At the same flow rate, by reducing the media size, the attachment factor reduced.
- Attachment of the suspended particles is maximum at large size media rather than small size media.
- At all loading rates attachment factor is maximum at Filter # 1 (12-18mm)





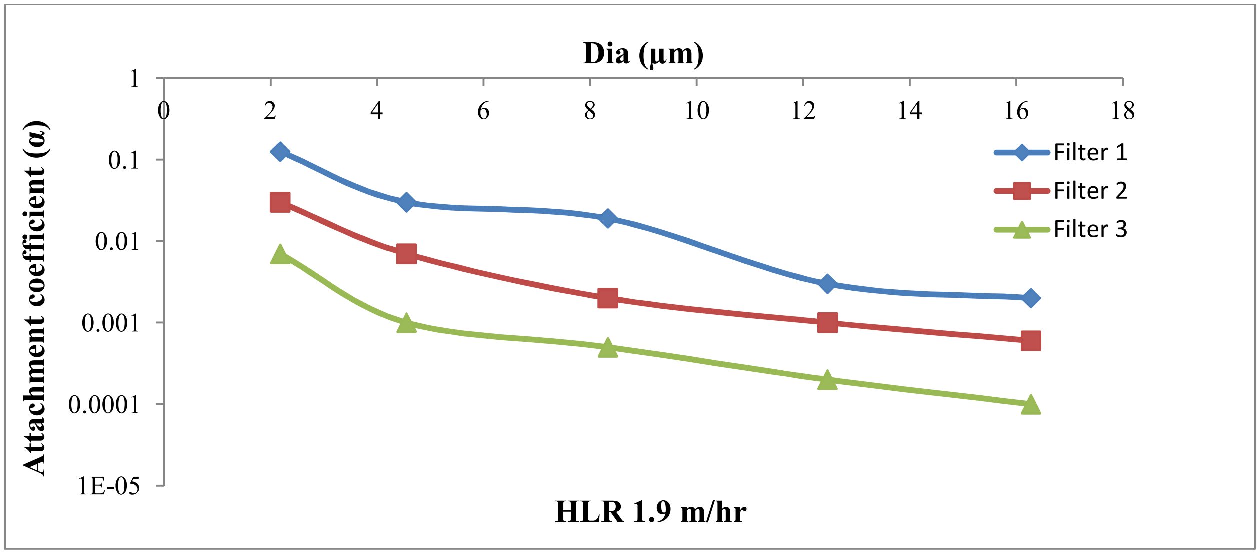


Figure 4-11(d,e,f): Suspended particles dia. vs attachment coefficient at varying media & same HLR (Tufenjiki eq.)

4.9 Attachment Coefficient Vs Influent Particle Diameter Using Yao Equation:

- At loading rates 1.1 m/hr and 1.9 m/hr attachment factor is almost same because efficiency is less at this loading rate.
- Attachment coefficient at 1.5 m/hr is minimum because at this loading rate efficiency is maximum
- Smaller the media size smaller will be the attachment of suspended particles on the media. Gravity factor will be dominated.
- Attachment coefficient is almost similar at media size 4-8mm.

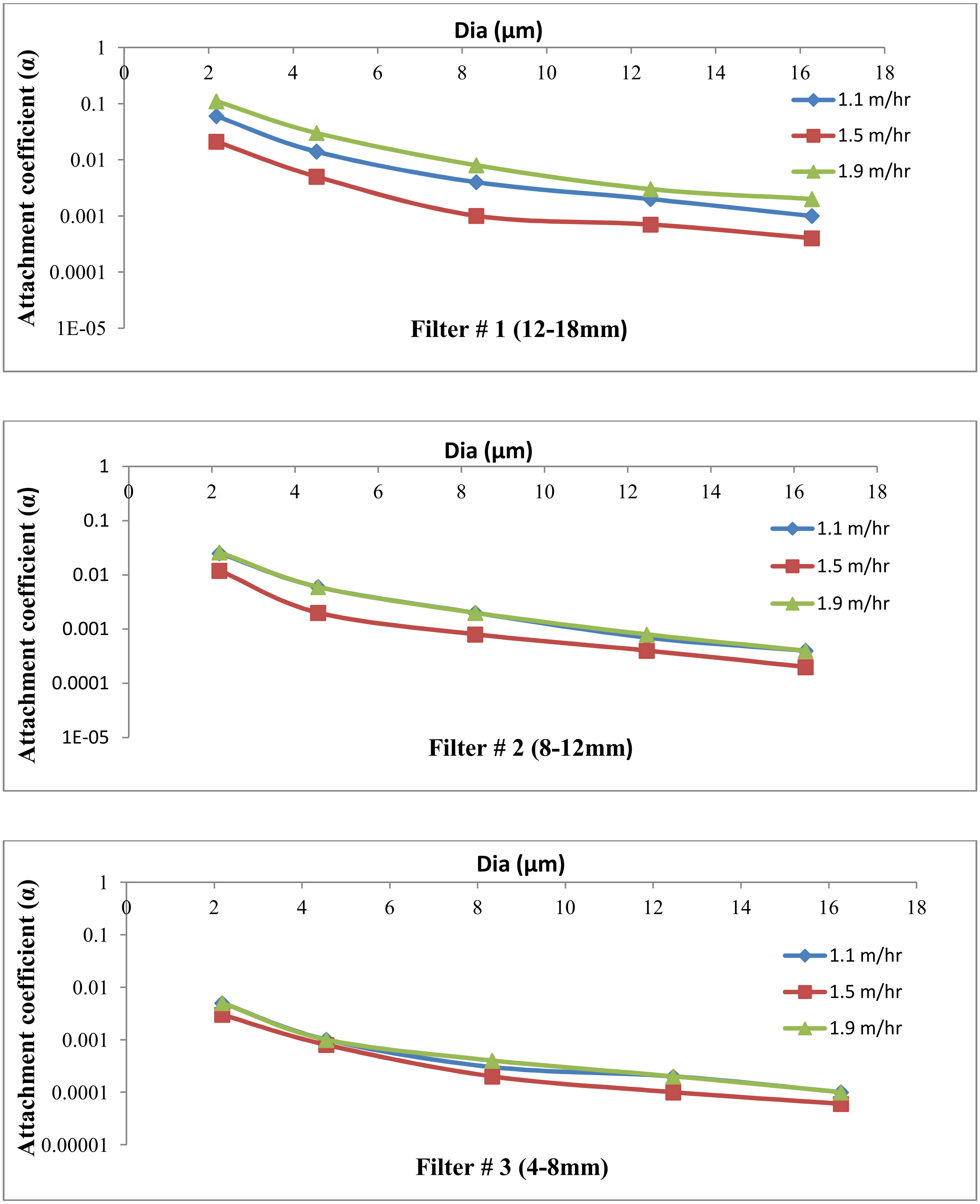


Figure 4-12(a,bc): Suspended particles dia vs attachment coefficient at varying HLR and same media (Yao's eq.)

Chapter 5

CONCLUSIONS & RECMONDATIONS

5.1 Conclusions

- At all three media sizes (12-18mm, 8-12, & 4-8mm) maximum turbidity removal was obtained at the smallest size media that was 4-8mm.
- At all three loading rates (1.1 m/hr, 1.5m/hr & 1.9 m/hr) maximum removal efficiency was obtained at loading rate of 1.5 m/hr.
- Among all three filters (Filter#1, Filter#2 & Filter#3) Filter # 2 gave maximum removal efficiency. Effluent turbidity value of this filter at loading rat 1.5 m/hr was more consistent for a long time.
- Filter had longer run time at loading rate 1.5 m/hr and media size 8-12mm
- Tufenjiki theory is most appropriate to determine the Transport coefficient in rapid rate and roughing filtration
- By reducing media size gravity force dominates the interception transport mechanism
- Rapid filtration theory can be applied to roughing filtration with due consideration to hydrodynamic forces
- Attachment coefficient decreased with decreasing media size as well as by decreasing influent particle size
- Filter coefficient was independent of influent particle size
- HFRF operated without coagulation is more effective for the removal of particles having large size particles

- As media size decreases, large size particles which are present in the raw water are converted into smaller one's after striking against the collector or media.

5.2 Recommendations

- A slow sand filter will be installed after roughing filter to obtain the water up to drinking level
- Continuous stirring should be carried out for the mixing of the raw water instead of manual mixing
- Addition of different types of minerals like iron and magnesium can be used in raw water to observe their %age removal.
- Run all three filters at loading rates less than 1 m/hr and greater than 2 m/hr to observe the trend of %age removal of turbidity at very low as well as high hydraulic load.
- Two design parameters were optimized in this study i-e., loading rate and media size. Design a filter to optimize the length of the HFRF.
- Increase bacterial load artificially to observe their % age removal at different size of media and at different loading rates.

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APPENDICES

APPENDIX-A: Effluent Turbidity of Filter # 1 (12-18 mm)

Raw Water Turbidity = 200 NTU

Time Elapse (hr)	Effluent Turbidity (NTU)		
	1.1 m/hr	1.5 m/hr	1.9 m/hr
2	29.8	14.1	30.8
3	30.6	14	30
4	30.9	13.5	27.2
5	30.5	12	27
6	26.5	12.3	31.2
7	26.5	11.3	31.3
8	27.2	11.7	28.8
9	27.3	10.7	27.8
10	25.9	10.9	27.3
11	25.2	11.3	27.6
12	24.6	11.6	27.7
13	23.9	11.0	27.1
14	24.2	11.6	26.7
15	22.7	11.0	26.3
16	23.4	11.6	26.4
17	22.1	10.7	25.5
18	22.5	13.3	24.4
19	21.6	10.5	24.5
20	21.9	12.2	24.8
21	20.8	11.6	24.9
22	21.2	10.5	24.4
23	21	9.86	24.3
24	21.4	10.7	23.9
25	21.5	10.9	23.2
26	20.2	11.2	22.2
27	19.7	10.7	22.1
28	19.5	9.89	22.2
29	19.2	10.5	22.8
30	21.2	11.0	22.5
31	20	10.7	21.4

32	18.4	9.91	21.9
33	18.9	10.3	21.4
34	18.2	10.4	21.3
35	19.3	9.95	21.5
36	18.1	9.82	21.4
37	18.5	9.75	21.3
38	17.7	9.48	21.8
39	18.2	9.43	21.4
40	17.9	9.11	21.6
41	17.4	8.67	20.9
42	17.7	8.96	20.1
43	18.0	8.82	19.5
44	17.2	8.52	19.7
45	17.0	9.43	19.2
46	16.8	9.11	19.0
47	16.6	8.58	19.3
48	15.8	7.47	19.5
49	16.3	7.95	19.7
50	15.7	7.21	19.4
51	16.1	7.47	19.5
52	14.8	7.18	19.4
53	15.6	7.1	19.6
54	14.8	6.95	19.8
55	13.7	6.58	19.4
56	13.8	6.16	19.6
57	13.5	6.02	19.2
58	13.2	5.77	18.4
59	13.9	5.65	18.5
60	13.8	4.5	17.5
61	13.4	5.67	17.2
62	13.7	3.85	16.4
63	13.8	3.56	16.4
64	13.1	3.96	16.5
65	13.4	4.06	15.2
66	13.9	3.98	15.9
67	13.6	4.3	14.5
68	14.1	3.62	14.4
69	14.2	3.75	14.7
70	13.5	3.46	14.2

71	13.4	3.4	14.7
72	13.5	3.5	14.3
73	13.4	4.5	14.2
74	15.2	4.11	14.1
75	15.9	4.95	13.9
76	16.9	5.48	14.5
77	16.7	4.11	14.8
78	16.3	4.85	14.5
79	15.9	4.54	14.9
80	14.0	4.61	15.5
81	14.5	4.91	15.1
82	15.0	5.29	14.7
83	15.2	4.37	15.9
84	14.9	5.05	15.4
85	15.3	4.64	14.7
86	14.8	4.71	15.2
87	15.4	5.24	14.9
88	15.6	4.71	15.2
89	15.1	4.96	16.4
90	15.4	4.54	17.8
91	15.0	4.82	18.9
92	14.9	4.11	20.2
93	14.7	3.99	21.2
94	14.8	4.12	22.5
95	14.6	3.75	24.8
96	14.6	4.28	25
97	15.1	3.75	25.5
98	14.9	3.85	26.9
99	15.3	4.89	27.1
100	14.5	3.88	28
101	14.8	3.91	-
102	14.5	3.96	-
103	14.8	4.11	-
104	14.9	4.1	-
105	14.3	4.09	-
106	14.8	4.17	-
107	15.2	4.25	-
108	15.5	4.45	-
109	15.8	4.55	-

110	15.4	5.06	-
111	14.7	4.61	-
112	14.9	4.55	-
113	15.4	4.75	-
114	15.7	5.29	-
115	15.8	4.89	-
116	16.5	5.45	-
117	16.6	4.99	-
118	15.5	5.04	-
119	15.8	4.87	-
120	15.9	5.09	-
121	16.4	4.97	-
122	16.2	5.08	-
123	16.8	5.19	-
124	16.9	5.09	-
125	17.1	5.25	-
126	16.7	5.77	-
127	16.2	5.89	-
128	16.9	6.06	-
129	16.5	6.87	-
130	16.7	6.99	-
131	16.8	7.85	-
132	17.5	7.55	-
133	17.4	7.81	-
134	17.4	7.99	-
135	17.6	8.55	-
136	17.8	8.56	-
137	17.9	8.96	-
138	18.1	9.99	-
139	18.5	9.57	-
140	18.9	11.0	-

APPENDIX-B

Effluent Turbidity of Filter # 2 (8-12 mm)

Raw Water Turbidity = 200 NTU

Time Elapse (hr)	Effluent Turbidity (NTU)		
	1.1 m/hr	1.5 m/hr	1.9 m/hr
2	21.4	10.5	32.7
3	25.5	10.9	32
4	24.2	10	29.8
5	25.8	9.87	26.2
6	23.9	8.83	25
7	23	8.14	26.7
8	23.5	7.77	21.5
9	23.9	8.58	19.5
10	23.6	7.97	19
11	24.7	7.18	18.8
12	22.9	7.54	19.2
13	22.4	7.11	19.7
14	21.8	6.94	19.4
15	21.3	6.81	19.2
16	21.7	6.15	18.5
17	21	6.67	17.1
18	20.8	6.12	16.9
19	20.2	5.45	14.5
20	19.2	5.75	13.4
21	18.9	5.71	12.1
22	17.5	5.12	11.4
23	16.4	4.99	10.6
24	16.1	4.81	11.7
25	16.2	4.74	10
26	15.5	4.88	8.31
27	14.7	4.45	8.92
28	13.5	4.29	12.1
29	12.9	4.22	14.2
30	13.1	4.18	14.9
31	12.4	4.11	15.0

32	13.5	4.19	14.4
33	13.4	4.35	14.8
34	13.9	4.05	12.1
35	12.0	3.96	14.5
36	12.5	3.99	14.7
37	11.2	3.85	13.2
38	11.3	3.75	12.9
39	11.9	3.8	12.3
40	11.1	3.85	11.4
41	10.8	3.75	11.7
42	10.9	3.7	11.2
43	12.2	3.66	10.8
44	10.6	3.18	10.3
45	12.6	3.9	10.5
46	13.7	3.6	10.1
47	9.18	3.99	9.78
48	9.67	3.81	9.91
49	10.2	3.95	9.26
50	9.61	4.15	9.45
51	9.97	3.88	9.55
52	9.89	3.15	9.35
53	10.7	3.89	9.11
54	9.91	3.95	8.88
55	9.02	4.22	8.96
56	9.15	3.44	9.05
57	9.23	3.71	8.77
58	9.75	3.66	8.8
59	9.43	3.61	8.75
60	9.85	3.87	8.75
61	10.12	3.99	8.5
62	9.93	3.19	8.45
63	10.23	3.45	8.77
64	9.12	3.55	9.1
65	10.42	3.97	9.05
66	9.05	4.12	9.22
67	9.37	3.87	9.45
68	9.15	3.84	9.55
69	10.1	4.05	10.2
70	9.86	3.79	10.4

71	11.6	4.48	10.5
72	9.32	4.15	10.8
73	9.41	3.95	11.1
74	8.04	4.66	11.55
75	7.95	4.12	11.7
76	7.63	3.56	11.8
77	8.51	4.28	14
78	7.94	4.25	-
79	7.79	4.19	-
80	8.25	3.98	-
81	8.02	3.81	-
82	8.035	4.52	-
83	8.4	4.64	-
84	7.98	3.99	-
85	8.21	4.11	-
86	8.19	3.87	-
87	8.12	3.82	-
88	8.05	4.01	-
89	8.29	3.79	-
90	8.24	3.75	-
91	7.99	3.84	-
92	8.16	3.95	-
93	8.35	3.65	-
94	8.39	3.69	-
95	8.41	4.09	-
96	8.45	4.05	-
97	8.12	4.18	-
98	8.2	3.97	-
99	8.17	4.42	-
100	8.31	4.5	-
101	8.16	3.84	-
102	8.09	4.74	-
103	8.05	4.15	-
104	8.22	4.28	-
105	8.28	4.35	-
106	8.35	4.55	-
107	8.33	3.99	-
108	8.36	4.29	-
109	8.39	4.99	-

110	8.45	5.25	-
111	8.41	5.69	-
112	8.4	6.07	-
113	8.5	6.88	-
114	8.55	9.87	-
115	8.59	10.8	-
116	8.6	-	-
117	8.49	-	-
118	8.61	-	-
119	8.69	-	-
120	8.65	-	-
121	8.7	-	-
122	8.79	-	-
123	8.91	-	-
124	8.95	-	-
125	8.9	-	-

APPENDIX-C

Effluent Turbidity of Filter # 3 (4-8 mm)

Raw Water Turbidity = 200 NTU

Time Elapse (hr)	Effluent Turbidity (NTU)		
	1.1 m/hr	1.5 m/hr	1.9 m/hr
2	15.4	8.1	9.66
3	15.2	8.05	5.9
4	15.7	7.55	4.95
5	15.8	7.95	5.15
6	15	7.11	4.3
7	15.4	6.55	3.73
8	14.3	6.41	4.15
9	14.7	5.98	4.01
10	14.9	5.49	4.97
11	14.1	5.55	4.89
12	13.5	5.22	4.76
13	12.4	4.75	4.15
14	12.6	4.22	4.45
15	12.5	4.11	4.49
16	12.1	4.09	4.31
17	11.9	4.02	4.29
18	11.3	3.69	4.61
19	11.5	3.83	5.05
20	11.1	3.38	5.95
21	11.4	3.13	4.11
22	11.3	3.76	5.09
23	10.5	3.18	5.48
24	10	4.06	3.22
25	11.2	3.05	2.76
26	10.2	3.67	2.67
27	10.5	3.09	2.12
28	10.6	3.55	2.04
29	10.8	3.47	1.99
30	10.3	3.71	1.42
31	9.75	3.83	1.48

32	8.56	3.85	1.87
33	8.14	3.61	1.92
34	8.75	3.53	1.97
35	7.47	3.09	1.75
36	7.52	3.42	1.89
37	6.67	3.42	1.73
38	5.37	3.96	1.5
39	5.42	3.7	1.69
40	5.66	3.53	1.99
41	6.17	3.59	2.83
42	5.83	2.42	1.71
43	6.29	2.6	1.47
44	6.11	2.31	1.43
45	5.75	2.26	1.58
46	6.13	2.06	3.73
47	5.79	1.66	7.17
48	6.01	1.59	7.35
49	5.91	1.71	7.34
50	6.5	1.78	6.99
51	6.87	1.94	8.14
52	6.62	1.76	8.81
53	6.04	1.84	8.85
54	6.4	1.94	8.99
55	5.86	1.54	9.15
56	5.71	1.48	9.13
57	5.24	1.87	9.11
58	5.57	1.77	10.8
59	5.64	1.97	10.3
60	5.28	1.35	10.9
61	5.12	1.88	-
62	5.24	1.97	-
63	4.59	1.66	-
64	4.44	1.59	-
65	4.19	1.83	-
66	4.13	1.99	-
67	4.05	2.09	-
68	4.14	1.98	-
69	3.39	1.95	-
70	3.91	2.15	-

71	3.99	2.14	-
72	3.58	1.91	-
73	3.5	2.22	-
74	3.48	2.41	-
75	3.79	2.32	-
76	3.43	1.98	-
77	3.3	2.75	-
78	3.52	3.15	-
79	3.71	4.11	-
80	3.5	3.99	-
81	3.37	4.58	-
82	4.01	4.75	-
83	4.5	4.89	-
84	4.9	4.97	-
85	4.19	5.25	-
86	4.13	5.42	-
87	4.45	5.84	-
88	4.85	5.98	-
89	4.67	5.74	-
90	4.71	6.78	-
91	4.89	-	-
92	5.1	-	-
93	5.38	-	-
94	5.4	-	-
95	5.75	-	-
96	6.85	-	-
97	7.89	-	-
98	7.01	-	-
99	7.82	-	-
100	7.99	-	-
101	9.05	-	-
102	9.99	-	-
103	10.5	-	-
104	10.4	-	-
105	10.2	-	-

APPENDIX-D

Effluent PSD of Filter # 1 (12-18 mm)

Diameter (µm)	Influent Particles (Vol.%age)	Effluent Particles (Vol. %age)		
		1.1 m/hr	1.5 m/hr	1.9 m/hr
0.115	0	0	0	0
0.131	0	0	0	0
0.15	0	0	0	0
0.172	0	0	0	0
0.197	0	0	0	0
0.226	0	0	0	0
0.259	0	0	0	0
0.296	0	0	0	0
0.339	0	0	0	0
0.389	0	0	0	0
0.445	0	0	0	0
0.51	0	0	0	0
0.584	0	0	0	0
0.669	0	0	0	0
0.766	0	0	0	9.385
0.877	0	0	8.263	9.351
1.005	0	0	9.408	9.514
1.151	0	9.385	10.083	9.436
1.318	0	9.351	10.49	8.884
1.51	0.164	9.514	10.522	8.197
1.729	0.279	9.436	10.161	7.326
1.981	0.434	8.884	9.499	6.454
2.269	0.638	8.197	8.535	5.615
2.599	0.879	7.326	7.219	4.896
2.976	1.187	6.454	5.746	4.265
3.409	1.563	5.615	4.22	3.694
3.905	2.062	4.896	2.667	3.158
4.472	2.71	4.265	1.597	2.641
5.122	3.535	3.694	0.902	2.137
5.867	4.544	3.158	0.468	1.672
6.72	5.705	2.641	0.22	1.271

7.697	6.927	2.137	0	0.933
8.816	8.133	1.672	0	0.597
10.097	9.279	1.271	0	0.373
11.565	10.253	0.933	0	0.2
13.246	9.928	0.597	0	0
15.172	9.379	0.373	0	0
17.377	7.758	0.2	0	0
19.904	5.643	0	0	0
22.797	4.156	0	0	0
26.111	2.428	0	0	0
29.907	1.314	0	0	0
34.255	0.655	0	0	0
39.234	0.306	0	0	0
44.938	0.14	0	0	0
51.471	0	0	0	0
58.953	0	0	0	0
67.523	0	0	0	0
77.339	0	0	0	0
88.583	0	0	0	0
101.46	0	0	0	0
116.21	0	0	0	0
133.103	0	0	0	0
152.453	0	0	0	0
174.616	0	0	0	0
200	0	0	0	0
229.075	0	0	0	0
262.376	0	0	0	0
300.518	0	0	0	0
344.206	0	0	0	0
394.244	0	0	0	0
451.556	0	0	0	0
517.2	0	0	0	0
592.387	0	0	0	0

APPENDIX-E

Effluent PSD of Filter # 2 (8-12 mm)

Diameter (µm)	Influent Particles (Vol.%age)	Effluent Particles (Vol. %age)		
		1.1 m/hr	1.5 m/hr	1.9 m/hr
0.115	0	0	0	0
0.131	0	0	0	0
0.15	0	0	0	0
0.172	0	0	0	0
0.197	0	0	0	0
0.226	0	0	0	0
0.259	0	0	0	0
0.296	0	0	0	0
0.339	0	0	0	0
0.389	0	0	0	0
0.445	0	0	0	0
0.51	0	0	0	0
0.584	0	0	0	0
0.669	0	0	0	0
0.766	0	0	0	0
0.877	0	21.978	8.263	0
1.005	0	17.592	9.408	0
1.151	0	14.151	10.083	0
1.318	0	11.303	10.49	6.509
1.51	0.164	8.796	10.522	6.917
1.729	0.279	6.8	10.161	7.35
1.981	0.434	5.219	9.499	7.568
2.269	0.638	3.899	8.535	7.836
2.599	0.879	2.845	7.219	8.043
2.976	1.187	2.029	5.746	8.109
3.409	1.563	1.416	4.22	8.014
3.905	2.062	0.972	2.667	7.84
4.472	2.71	0.662	1.597	7.47
5.122	3.535	0.454	0.902	6.81
5.867	4.544	0.318	0.468	5.819
6.72	5.705	0.231	0.22	4.557

7.697	6.927	0.177	0	3.2
8.816	8.133	0.146	0	2
10.097	9.279	0.129	0	1.14
11.565	10.253	0.122	0	0.584
13.246	9.928	0.124	0	0.232
15.172	9.379	0.13	0	0
17.377	7.758	0.136	0	0
19.904	5.643	0.138	0	0
22.797	4.156	0.128	0	0
26.111	2.428	0.106	0	0
29.907	1.314	0	0	0
34.255	0.655	0	0	0
39.234	0.306	0	0	0
44.938	0.14	0	0	0
51.471	0	0	0	0
58.953	0	0	0	0
67.523	0	0	0	0
77.339	0	0	0	0
88.583	0	0	0	0
101.46	0	0	0	0
116.21	0	0	0	0
133.103	0	0	0	0
152.453	0	0	0	0
174.616	0	0	0	0
200	0	0	0	0
229.075	0	0	0	0
262.376	0	0	0	0
300.518	0	0	0	0
344.206	0	0	0	0
394.244	0	0	0	0
451.556	0	0	0	0
517.2	0	0	0	0
592.387	0	0	0	0

APPENDIX-F

Effluent PSD of Filter # 3 (4-8 mm)

Diameter (µm)	Influent Particles (Vol.%age)	Effluent Particles (Vol. %age)		
		1.1 m/hr	1.5 m/hr	1.9 m/hr
0.115	0	0	0	0
0.131	0	0	0	0
0.15	0	0	0	0
0.172	0	0	0	0
0.197	0	0	0	0
0.226	0	8.263	0	0
0.259	0	9.408	5.623	0
0.296	0	10.083	4.605	0
0.339	0	10.49	4.362	0
0.389	0	10.522	4.696	5.623
0.445	0	10.161	5.431	4.605
0.51	0	9.499	6.609	4.362
0.584	0	8.535	8.297	4.696
0.669	0	7.219	10.208	5.431
0.766	0	5.746	11.292	6.609
0.877	0	4.22	10.806	8.297
1.005	0	2.667	9.384	10.208
1.151	0	1.597	6.937	11.292
1.318	0	0.902	4.906	10.806
1.51	0.164	0.468	3.064	9.384
1.729	0.279	0.22	1.857	6.937
1.981	0.434	0	1.04	4.906
2.269	0.638	0	0.533	3.064
2.599	0.879	0	0.247	1.857
2.976	1.187	0	0.103	1.04
3.409	1.563	0	0	0.533
3.905	2.062	0	0	0.247
4.472	2.71	0	0	0.103
5.122	3.535	0	0	0
5.867	4.544	0	0	0
6.72	5.705	0	0	0

7.697	6.927	0	0	0
8.816	8.133	0	0	0
10.097	9.279	0	0	0
11.565	10.253	0	0	0
13.246	9.928	0	0	0
15.172	9.379	0	0	0
17.377	7.758	0	0	0
19.904	5.643	0	0	0
22.797	4.156	0	0	0
26.111	2.428	0	0	0
29.907	1.314	0	0	0
34.255	0.655	0	0	0
39.234	0.306	0	0	0
44.938	0.14	0	0	0
51.471	0	0	0	0
58.953	0	0	0	0
67.523	0	0	0	0
77.339	0	0	0	0
88.583	0	0	0	0
101.46	0	0	0	0
116.21	0	0	0	0
133.103	0	0	0	0
152.453	0	0	0	0
174.616	0	0	0	0
200	0	0	0	0
229.075	0	0	0	0
262.376	0	0	0	0
300.518	0	0	0	0
344.206	0	0	0	0
394.244	0	0	0	0
451.556	0	0	0	0
517.2	0	0	0	0
592.387	0	0	0	0

APPENDIX-G

Attachment Coefficients by Tufenjiki Eq.

Diameter (µm)	HLR = 1.1 m/hr		
	Filter # 1	Filter # 2	Filter # 3
2.177	0.07	0.03	0.006
4.555	0.015	0.006	0.001
8.33	0.004	0.002	0.0004
12.455	0.002	0.0008	0.0002
16.274	0.001	0.0005	0.0001
	HLR = 1.5 m/hr		
2.177	0.02	0.01	0.004
4.555	0.005	0.003	0.001
8.33	0.001	0.001	0.0003
12.455	0.0007	0.0004	0.0001
16.274	0.0004	0.0002	0.00008
	HLR = 1.9 m/hr		
2.177	0.125	0.03	0.007
4.555	0.03	0.007	0.001
8.33	0.019	0.002	0.0005
12.455	0.003	0.001	0.0002
16.274	0.002	0.0006	0.0001

APPENDIX-H

Attachment Coefficients by Yao's Eq.

Diameter (μm)	HLR = 1.1 m/hr		
	Filter # 1	**Filter # 2**	**Filter # 3**
2.177	0.06	0.025	0.005
4.555	0.014	0.006	0.001
8.33	0.004	0.002	0.0003
12.455	0.002	0.0007	0.0002
16.274	0.001	0.0004	0.0001
	HLR = 1.5 m/hr		
2.177	0.021	0.012	0.003
4.555	0.005	0.002	0.0008
8.33	0.001	0.0008	0.0002
12.455	0.0007	0.0004	0.0001
16.274	0.0004	0.0002	0.00006
	HLR = 1.9 m/hr		
2.177	0.11	0.026	0.005
4.555	0.03	0.006	0.001
8.33	0.008	0.002	0.0004
12.455	0.003	0.0008	0.0002
16.274	0.002	0.0004	0.0001

APPENDIX-I

Transport Coefficients by Tufenjiki Eq.

Diameter (μm)	HLR = 1.1 m/hr		
	Filter # 1	**Filter # 2**	**Filter # 3**
2.177	0.013	0.012	0.011
4.555	0.0575	0.0521	0.0463
8.33	0.19	0.172	0.153
12.455	0.421	0.382	0.339
16.274	0.716	0.649	0.572
	HLR = 1.5 m/hr		
2.177	0.0095	0.0095	0.008
4.555	0.0407	0.0369	0.033
8.33	0.135	0.122	0.11
12.455	0.299	0.27	0.242
16.274	0.507	0.459	0.41
	HLR = 1.9 m/hr		
2.177	0.0073	0.007	0.006
4.555	0.031	0.028	0.025
8.33	0.103	0.094	0.083
12.455	0.229	0.208	0.185
16.274	0.389	0.354	0.313

APPENDIX-J

Transport Coefficients by Yao's Eq.

Diameter (μm)	HLR = 1.1 m/hr		
	Filter # 1	**Filter # 2**	**Filter # 3**
2.177	0.014	0.013	0.013
4.555	0.059	0.059	0.059
8.33	0.208	0.205	0.205
12.455	0.44	0.44	0.44
16.274	0.755	0.75	0.75
	HLR = 1.5 m/hr		
2.177	0.0099	0.0099	0.0099
4.555	0.043	0.043	0.043
8.33	0.145	0.144	0.144
12.455	0.324	0.323	0.323
16.274	0.553	0.552	0.552
	HLR = 1.9 m/hr		
2.177	0.0078	0.0078	0.0078
4.555	0.0342	0.034	0.034
8.33	0.114	0.113	0.113
12.455	0.25	0.25	0.25
16.274	0.437	0.436	0.436