UNIVERSITY OF NAIROBI

APPLICATION OF GROUND CHARCOAL IN THE REMOVAL OF ORGANIC MATTER IN WATER TREATMENT

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SIMON MBURU NJOROGE

A thesis submitted in part fulfilment for the degree of
Master of science in Civil Engineering (Environmental Health Engineering)
University of Nairobi.

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DECLARATION

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

S. M. Njoroge ______________ Date 23·10·2001
CANDIDATE

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

Mr. S.K. Ngari ______________ Date 23/10/2001
SUPERVISOR

DEDICATION

This thesis is dedicated to my dear wife Martha Mburu and our beloved daughter, Noam Mburu

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ABSTRACT

The organic matter in water has potential to cause serious effects on human health due to the formation of carcinogenic trihalomethanes with chemical disinfectants such as chlorine. The organic matter in water may be removed by filtration (straining) and adsorption. Granular activated carbon is best known in the removal of organic material by adsorption. However, its availability is limited by its nature of production and cost. On the other hand, wood charcoal is common and easy to produce. Investigation on use of ground wood charcoal in the removal of organic matter in water when used as a filter media in water treatment process is presented. Black wattle tree charcoal, produced by the carbonisation process and containing 76.5% carbon content was used in this investigation as filter media in comparison to the sand used in rapid sand filters in terms of organic matter removal by chemical oxygen demand (COD), turbidity removal and head loss development from water that had been sampled from the upper reaches of the Nairobi River.

The filtration tests were carried out at $2m^3/m^2/hr$ and showed better performance by ground charcoal than sand both in terms of COD and turbidity removal. The charcoal exhibited higher turbidity removal of between 40-52% in high turbidity waters and 40-65% in low turbidity waters whereas the sand exhibited 38-49% and 25-56% turbidity removals in the respective waters. The removal rates were better than sand by 1.2-2.0 times. Head loss development was more pronounced in sand than in charcoal and the rate was more by between 1.2 and 2 times. COD removal was between 56-100% for ground charcoal and the rate of removal was better than sand by 2-3 times.

The results showed that charcoal can replace sand in rapid sand filtration stage of a water treatment process for waters having turbidity amounts of up to 10 NTU. Ground charcoal's ability to remove organic material makes it more suitable for treatment of individual, small community and rural community water supplies where water contains organic matter, and chlorine is used as a disinfectant.

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CHAPTER ONE

INTRODUCTION

1.1 General

Freshwater is a finite resource. essential for agriculture. industry and even human existence Without freshwater of adequate quantity and quality sustainable development will not be possible Water pollution and wasteful use of freshwater threatens development projects and make water treatment essential in order to produce safe drinking water Most people in the rural areas of Kenya use untreated water from rivers and streams for drinking purposes Where water treatment is provided in piped water supplies. treatment failures are known to occur frequently due to operation and maintenance problems

With the advent of industrialisation and increasing populations. the range of requirements for water has widened together with greater demands for high quality water Over time. water requirements have emerged for drinking and personal hygiene. fisheries. agriculture (irrigation and livestock supply). navigation for transport of goods. industrial production. hydropower generation and recreational activities such as bathing or fishing Fortunately, the largest demands for water quantity. such as for agricultural irrigation and industrial cooling. require the least in terms of water quality. Drinking water supplies and specialised industrial manufacturers exert the most sophisticated demands on water quality but their quantitative needs are relatively low.

The nature of pollutants in drinking water include microbiological organisms such as viruses. bacteria. protozoa and worms Other pollutants are radioactive materials, decaying organic matter. inorganic substances such as chloride. fluorides. manganese. sulphate, iron, lead. sodium and zinc.

There has been great interest in the study of organic compounds in drinking water This interest largely followed the results of a 1974 study by the U S Environmental Protection Agency (EPA) which showed that trihalomethanes (THMs) were formed during the chlorination step of the water treatment process (Jolley. 1978) High potential for organic chemical transport in drinking water continues to exist even with source protection because of the multitude of chemical types and quantities Contamination of drinking water sources by organic micro-pollutants may occur from numerous sources including natural products, by-products of the chemical reaction between natural products and the oxidising agents used in the treatment of drinking water, commercial and industrial production and use activities. and waste disposal (Contruvo, 1985)

The principal concern raised about the contamination of drinking water by trace amounts of synthetic organic chemicals has been the possible increased risk of cancer in the population. Organic materials. such as decaying leaves. present in raw water supply. react with chlorine (residual) used for disinfecting water or chlorine from other sources such as industrial processes, to form a group of chlorinated compounds called trihalomethanes (THMs). Some forms of THMs for example. chloroform, bromodichloromethane. and dibromochloromethane have been determined to be mutagen (Jolley, 1978). Dissolved organic matter from decaying vegetation cause taste and colour in water Gross organic pollution leads to disturbance of the oxygen balance and is often accompanied by severe pathogenic contamination Accelerated eutrophication results from enrichment with nutrients from various origins. particularly domestic sewage, agricultural run-off and agro-industrial effluents Lakes and impounded rivers are especially affected

Organic particulates occur in water in colloidal forms Some are capable of migrating to surface waters in solution and others adsorbed on clay from natural stream waters Chemicals in drinking water have motivated interest in adsorption as a treatment process for removal of toxic and potentially carcinogenic compounds present in minute but significant quantities. Adsorption is a mass transfer process wherein a substance is transferred from the liquid phase to the surface of solid where it is bound by chemical or physical forces

Granular activated carbon (GAC) has commonly been used for organic chemical removal either as a filter media replacement or as a separate contactor, due to its high adsorptive property (Mackenzie and Cornwell, 1998). Few other processes can remove synthetic organic chemicals to the required low level. In-depth granular media are not capable of removing fine particulate and colloidal forms of suspended matter from applied water without prior coagulation (Kawamura. 1975) Waters containing organic colloids derived from pollution by sewage and industrial wastes are invariably more difficult to coagulate. and coagulant doses can rise because of the extensive chemical reactions that can occur between the coagulant and the colloidal organic matter (AWWA. 1971) Particulate removal involving coagulation and filtration is also limited to the removal of organic chemicals that are readily bound to sediments. Availability of GAC is not widespread due to the sophisticated nature of its production Ordinary black wattle tree charcoal on the other hand is common and easy to produce

Conventional treatment process for surface waters requiring particulate removal normally involves coagulation and filtration This however, is difficult for small communities and individual homesteads located in isolated or remote areas and for developing countries where both chemical coagulants and skilled plant operators, necessary for the successful process control are in short supply if available at all

Small point-of-use units containing GAC have been shown to be effective in some applications for removal of organic chemicals at the consumers' tap or for a household water supply (Contruvo. 1985) The use of ground charcoal as a replacement to filtration in the conventional treatment process could provide a possible alternative method to such communities and developing countries

The application of ground charcoal as a filter media has been investigated in this study This study has also determined how ground charcoal would perform if it replaced a sand filter in the removal of turbidity and organic matter from polluted water

1.2 Objectives of the study

The objectives of this study was to compare the performance of ground charcoal with that of rapid sand in terms of organic matter removal by COD reduction, turbidity removal and head loss development

CHAPTER TWO

LITERATURE REVIEW

2.1 General water quality characteristics

The uses we make of water in lakes, rivers, ponds, and streams are greatly influenced by the quality of water found in them Activities such as fishing, swimming, boating, shipping and waste disposal have very different requirements for water quality Water of a particularly high quality is needed for potable water supplies In many parts of the world, the introduction of pollutants from human activity has seriously degraded water quality even to the extent of turning streams into foul open sewers with few life forms and fewer beneficial uses

Water quality is a term used to express the suitability of water to sustain various uses or processes. Pure water is tasteless, odourless, and colourless liquid at room temperature The physical, chemical and biological characteristics of water vary widely in nature They are products of the changes that occur from the moment of condensation in the atmosphere, through the accumulation of materials from the air, and from contacts in the smaller streams and the rivers, each of which reflects the land activities in the local watershed

Quality identifies the degree of excellence, which a thing possesses A fundamental point is that the assignment of a level of quality to water is relative, depending on the use To evaluate the characteristics of water, it is essential to know whether these characteristics have any detrimental effect on the assigned use of the water. Thus pollution has come to mean the introduction to or presence of any material in the resource which interferes with, alters, or destroys some beneficial use Any particular use will have certain requirements for the physical, chemical or biological characteristics of water, for example, water that is to be used for drinking should not contain any chemicals or micro-organisms that could be hazardous to health. Similarly, water for agricultural irrigation should have low sodium content, while that used for steam generation and related industrial use should be low in certain other organic chemicals

Consequently, water quality can be defined by a range of variables, which limit their use Although many uses have some common requirements for certain variables, each use will have its own demands and influences on water quality Quantity and quality requirement of different users will not always be compatible, and the activities of one user may restrict the activities of another, either by demanding water of a quality outside the range required by the other user or by lowering quality during use of the water Efforts to improve or maintain a certain water quality often compromise between the quality and quantity demands of different users

The composition of surface and underground water is dependent on natural factors (geological, topographical, meteorological, hydrological and biological) in the drainage basin and varies with seasonal differences in run off volumes, weather conditions and water levels Large natural variations in water quality may, therefore, be observed even where only a single watercourse is involved Human intervention also has significant effects on water quality. Some of these effects are the result of hydrological changes, such as the building of dams, draining of wetlands and diversion of flow More obvious are the polluting activities, such as the discharge of domestic, industrial, urban and other wastewater into the watercourse and the spreading of chemicals on agricultural land in the drainage basin. Satisfaction of water quality standards for various uses exerts a demand for analysis of water treatment technologies, some of which may be simple and easy to do or sophisticated

2.1.1 Water quality for drinking and domestic use

Microbiological Characteristics

Microbiological agents are very important in their relation to public health and may also be significant in modifying the physical and chemical characteristics of water Water for drinking must be made free from disease causing organisms (pathogens) These organisms include viruses. bacteria. protozoa and helminths (worms)

Radiological Characteristics

Radiological factors must be considered in areas where there is a possibility that the water may have come in contact with radioactive substances The radioactivity of the water is of public health concern in these areas The development and use of atomic energy as a power source and the mining of radioactive materials, as well as naturally occurring radioactive materials, have made it necessary to establish limiting concentrations for the intake into the body of radioactive substances. including drinking water

Physical Characteristics

These relate to the quality of water for domestic use and are usually associated with the appearance of water. its colour. turbidity. temperature, and in particular. taste and odour

The type and concentration of suspended matter controls the turbidity and the transparency of the water Suspended matter consists of clay. silt. fine particles of organic and inorganic matter. plankton and other microorganisms. Such particles vary in size from approximately 10 nm to 100 μm diameter, although it is usually accepted that suspended matter is the fraction that will not pass through a 0 45 μm pore diameter filter (Mackenzie and Cornwell, 1998). Turbidity results from the scattering and absorption of incident light by the particles, and the transparency is the limit of visibility in the water The most reliable method of determining turbidity uses nephelometry (light scattering by suspended particles) by means of turbidity meter which gives values in Nephelometric Turbidity Units (NTU) Normal values range from 1 to 1000 NTU and levels can be increased by the presence of organic matter pollution, other effluents, or run-off with a high suspended matter content

The visible colour of water is the result of the different wavelengths not absorbed by the water itself or the result of the dissolved and particulate substances present It is possible to measure both true and apparent colour in water Natural minerals such as ferric hydroxide and organic substances such as humic acids give true colour to water True colour is measured in a sample after filtration or centrifugation Apparent colour is caused by coloured particulates and the refraction and reflection of light on suspended particulates. Polluted water may therefore have quite a strong apparent colour Dissolved organic material from decaying vegetation and certain inorganic matter cause colour in water Occasionally, excessive blooms of algae or the growth of aquatic micro-organisms may also impart colour. While colour itself is not usually objectionable from the standpoint of health its presence is aesthetically objectionable and suggests that the water needs appropriate treatment

Odour in water is usually the result of volatile organic compounds and may be produced by phytoplankton and aquatic plants or decaying organic matter Industrial and human wastes also create odours, directly or as a result of stimulating biological activity Organic compounds, inorganic chemicals, oil and gas can all impart odour to water The presence of odour is a simple test for the suitability of drinking water

The most frequent causes of taste and odour in water supply are algae and decaying vegetation. Taste and odour problems are occasionally the result of hydrogen sulphide, agricultural run off, industrial chemical spills, illegally discharged industrial chemicals and pollution by sewage Drinking water should be free from any objectionable taste or odour at point of use

The most desirable drinking waters are consistently cool and do not have temperature fluctuations of more than a few degrees Ground water and surface water from mountainous areas generally meet these criteria Most individuals find that water having a temperature between 10 °C - 15 °C is most palatable

Table 2 1 compares the maximum contaminant levels given by the Kenya Bureau of Standards (KEBS, 1985) and the maximum contaminant level goals issued by the American Water Works Association (AWWA), (Mackenzie and Cornwell, 1998)

Table 2.1 Maximum contaminant levels and goals

Contaminant	AWWA goals	KEBS requirements
Turbidity	<0.1 NTU	5 NTU*
Colour	<3 Hazen Units	15 Hazen Units
Odour	None	Unobjectionable
Taste	Unobjectionable	Unobjectionable

* Preferably 1.0 NTU for disinfection efficiency

Chemical Characteristics

(a) Inorganic compounds

These are sometimes evidenced by their observed reactions, such as the comparative performance of hard and soft waters in laundering. Most often, differences are not visible Waters may contain chloride, fluorides, iron, lead, manganese, sodium, sulphate and zinc Some of these minerals impart colour while others produce taste in drinking water Drinking water should not contain excessive concentrations of these minerals

The amount of chloride present in surface waters can be caused by pollution from sea water, brine, or industrial or domestic wastes. Chloride concentrations in excess of about 250 mg/l usually produce a noticeable taste in drinking water (WHO, UNESCO, UNEP, 1992)

In some areas water sources contain natural fluorides. Where the concentrations approach optimum levels, beneficial health effects have been observed. In such areas, the incidence dental carries has been found to be below the levels observed in areas without natural fluorides. Excessive fluorides in drinking water supplies may produce fluorosis (mottling) of teeth, which increases as the optimum fluoride level is exceeded

Small amounts of iron frequently are present in water because of the large amount of iron in the geologic materials. The presence of iron in water is considered objectionable because it imparts a brownish colour to laundered goods and affects the taste of beverages such as tea and coffee

Manganese imparts a brownish colour to water and to cloth that is washed in it. Waters containing high concentrations of sulphate, caused by leaching of natural deposits of magnesium sulphate or sodium sulphate, may be undesirable because of their laxative effects. Zinc is found in some natural waters, particularly in areas where zinc ore deposits have been mined. Zinc is not considered detrimental to health, but it will impart an undesirable taste to drinking water

The nitrate ion (NO_3^-) is the common form of combined Nitrogen found in natural waters. Natural sources of nitrate to surface waters include igneous rocks, land drainage and plant and animal debris. Natural levels which seldom exceed 0.1 mg/l NO_3-N, may be enhanced by municipal and industrial waste waters, including leachates from waste disposal sites and sanitary land fills. In rural and suburban areas the use of inorganic nitrate fertilizers can be a significant source. Seasonal fluctuations in nitrate occur with aquatic plant growth and decay, as they are essential nutrients for aquatic plant. When influenced by man's activities. surface waters normally contain, nitrate concentrations up to 5 mg/l NO_3-N, but often less than 1 mg/l NO_3-N. Levels in excess of 5 mg/l NO_3-N usually indicate pollution by human or animal waste, or fertilizer runoff. In cases of extreme pollution, concentrations may reach 200 mg/l NO_3-N (WHO; UNESCO; UNEP, 1992)

Phosphorus is an essential nutrient for living organisms and exists in water bodies as both dissolved and particulate. It is generally the limiting nutrient for algal growth and, therefore, controls the primary productivity of a water body. In natural waters, phosphorus occurs mostly dissolved as orthophosphates and polyphosphates, and organically bound phosphates. Changes between these forms occur continuously due to decomposition and synthesis of organically bound forms and oxidized inorganic forms. Natural sources of phosphorus are mainly the weathering of phosphorus bearing rocks and the decomposition of organic matter. Domestic waste waters, particularly those containing detergents, industrial effluents and fertilizer runoff contribute to elevated levels in surface waters. Phosphorus is rarely found in high concentrations in fresh waters as is actively taken up by plants. In most natural surface waters, phosphorus ranges from 0.005 to 0.02 mg/l PO_4-P. High concentrations of phosphates can indicate the presence of pollution and are largely responsible for eutrophic conditions in surface waters. Concentrations as low as 0.001 mg/l PO_4-P may be found in some pristine waters and as high as 200 mg/l PO_4-P in some enclosed saline waters (WHO; UNESCO; UNEP, 1992).

The maximum contaminant levels of the various minerals set by the Kenya Bureau of Standards (KEBS, 1985) and by the National Safe Drinking Water Act (SDWA) of the United States of America are compared in Table 2.2.

Table 2.2 Maximum contaminant levels of some minerals (Mackenzie and Cornwell, 1998) (KEBS, 1985)

Contaminant	Maximum contaminant levels (mg/l)	
	KEBS	SDWA
pH	6.5-8.5	6.5-8.5
chloride	250	250
Iron	0.3	0.3
Manganese	0.1	0.05
Sulphate	400	250
Zinc	5	5
Total hardness as $CaCO_3$	500	500
Fluorides	1.5	4
Phosphates	-	-
Nitrates + Nitrite	10	10
Chromium	0.05	0.1
Copper	1.0	1.0
BOD	6	-
COD	10	-

(b) Organic Compounds

High potential for organic chemical transport in drinking water continues to exist even with source protection because of the multitude of chemical types and quantities. Many thousands of individual organic compounds enter water bodies as a result of human activities. These compounds have significantly different physical, chemical and toxicological properties. Various organic compounds are present in water. They include:

- Organic materials from decaying vegetation
- Synthetic organic chemicals (SOCs)
- Volatile Organic Chemicals (VOCs)
- Naturally occurring organic matter, such as trihalomethane (THM) precursors
- disinfectant by-products (DBPs) such as THMs

2.1.2 Sources of organic micro-pollutants in drinking water

Contamination of drinking water sources by organic micro-pollutants may occur from numerous sources, including natural products, by-products of the chemical reaction between natural products and the oxidizing agents used in the treatment of drinking water and waste water, commercial and industrial production and use activities, and waste disposal (Contruvo, 1985)

Natural products in water

These diverse and mostly unidentified components of all natural waters include broad classes such as humic and fulvic acids which act as precursor substances (i.e. react with chlorine) in the formation of trihalomethanes (THMs). Humic and fulvic acids are the by-products of decomposition. Humus is formed as the result of the chemical and biochemical decomposition of vegetative residues and from the synthetic activity of micro-organisms. Humus enters water bodies from the soil or it can be formed directly within water bodies as a result of biochemical decompositions. It is operationally separated into fulvic and humic acid fractions, each being an aggregate of many organic compounds of different masses. Fulvic acid has molecular masses mostly in the range 300 - 5000 whereas the dominant masses in the humic acid exceed 5000. The relative content of fulvic acid in the dissolved humic substances present in freshwaters is between 60 and 90 per cent (WHO; UNESCO; UNEP, 1992)

Fulvic and humic acid concentrations in river and lake waters are usually in the range of tens and hundreds of micrograms of carbon per litre (WHO; UNESCO, UNEP, 1992). However, levels can reach milligrams of carbon per liter in waters of marshy and woodland areas. Other classes of organic micro-pollutants from natural products are tannins, terpines; amino acids and proteins and a variety of other nitrogen and sulphur containing substances. Total fulvic and humic acid content can be determined photometrically and their separate determination can be made with spectrophotometric methods

Organic micro-pollutants from organic products may also be identified in surrogate general parameters such as total organic carbon (TOC), total organic nitrogen (TON), colour, or absorbance spectra Total concentrations range from about 0.1 mg/l in deep ground waters to 1 - 5 mg/l in many surface waters to 20 - 25 mg/l in some highly coloured surface and ground waters (Contruvo, 1985)

Treatment by-products

The most studied treatment generated products are those derived from chlorination; however, all active treatment chemicals including ozone, chlorine dioxide, iodine and chloroamines are known to produce reaction products in water Chlorine is a greenish-yellow, gaseous chemical element used in the disinfection of water Chlorine available in tap water as residual chlorine react with fulvic and humic acids creating a group of chlorinated chemical compounds called trihalomethanes (THMs). There are various classes of trihalomethanes that include

- Chloroform ($CHCL_3$),
- Bromodichloromethane ($CHBrCL_2$).
- Dibromochloromethane ($CHBr_2CL$).
- Bromoform ($CHBr_3$)

Of this four, chloroform appears more frequently and is found in highest concentrations (Jolley, 1978)

Industrial products

Chlorine is found in various industrial products. A large number of halogenated hydrocarbon solvents, aerosol propellants and refrigerants including trichloroethylene, tetrachloroethylene, carbon tetrachloride, methylene chloride and freons are produced world wide in large quantities. They tend to be the most frequently found synthetic contaminants in drinking water because of their huge production, highly decolorized use patterns, chemical and biological stability, volatility and negligible adsorption to soils and sediments. Drinking water concentration ranging from 0.1 μg/l to several milligrams per litre have been reported (Proposed Regulation, 1984).

Literally hundreds of other synthetic organic chemicals have been reported in drinking water (AWWA, 1990). Individual frequencies and concentrations are usually at parts per billion or less in finished drinking water. Principal contamination potential seems to be associated with surface waters receiving industrial discharges

Petroleum products

Water contamination from gasoline and other refined fuels and solvents is becoming a more frequent occurrence. The most significant problem appear to be during transportation (spills and leaks from pipelines) and storage. Underground gasoline storage tanks used are subject to damage from mechanical stress and corrosion with ultimate great potential for leaks and environmental contamination

Pesticides

Hundreds of pesticides are in use worldwide. Some are applied above the ground and they may migrate to surface waters by runoff or by evaporation and deposition in rainfall. Irrigation waters can contaminate surface and ground waters. Some herbicides are highly mobile in water and are frequently found in surface waters. Most of these water contaminants are a result of uses and from manufacturing or disposal of pesticides

Waste disposal

The disposal of chemical wastes is a mounting problem in industrialized countries Contamination of surface and ground waters from improper disposal practices has been identified as the most significant source of present and future contamination of these waters

2.1.3 Biomedical effects of chloro-organics

The principal concerns raised about the contamination of drinking water by trace amounts of synthetic organic chemicals has been the possible increased risk of cancer in the population There has also been some discussion on the possibility of reproductive or teratogenic risks.

Three THMs are considered human carcinogens chloroform. bromodichloromethane. and dibromochloromethane They have been determined to be mutagen. which means they alter the genetic makeup Not only are mutagens considered potential human carcinogens. they threaten the genetic make up of future generations In addition four more potential carcinogenic THMs are Carbon Tetrachloride. 1.2-Dichloroethane, Trichloroethane and Vinyl Chloride THMs have been linked with diseases ranging from nervous system depression to liver and kidney damage

Drinking is not the only way we get dangerous chemicals from water into our bodies THMs belong to a group of man-made chemical solvents called Volatile Organic Chemicals (VOCs) Under ordinary conditions these chemicals can turn into gases and evaporate When VOCs evaporate. some of them are taken into the body when breathing and the rest rise into the earth's atmosphere In addition. the VOCs easily permeate the skin when bathing in VOCs contaminated waters

2.1.4 Control of organic contaminants in water supplies

Source protection

The most desirable means of assuring the quality and safety of drinking water would be to prevent contamination of source waters by potentially harmful organic chemicals However, source protection at a high level may not always be possible for these substances The problem is attributable to the potentially large number, variety and quantity of the contaminants and ubiquitous sources and uses Some are capable of migrating to surface waters in solution and others adsorbed to particulates

Treatment

Drinking water supplies will always need to rely on treatment processes tailored to the potential contaminants in the source to assure the safety of the finished water The control of THMs in water supplies can be accomplished by control of the natural organic content in water prior to chlorination Their control can be accomplished through treatment processes that take advantage of the physical and chemical properties of these contaminants.

Conventional treatment processes normally applied to surface waters, consisting of a particulate removal stage involving coagulation and filtration are reasonably effective for removal of a number of organic chemicals that are readily bound to sediments Coagulation can also remove the more soluble humic and fulvic substances Waters containing organic colloids derived from pollution by sewage and industrial wastes are invariably more difficult to coagulate, and coagulant doses can rise because of the extensive chemical reactions that can occur between the coagulant and the colloidal organic matter (AWWA, 1971)

Aeration (air stripping) technology is a highly effective method for removal of volatile synthetic chemicals, i.e. those with high Henry's law constant. These include such common contaminants as THMs, benzene, trichloroethylene and vinyl chloride. Packed tower aeration systems can be designed and operated to remove those types of substances.

Activated carbon (AC) can be used in both large and small public water systems to remove organic material. AC can effectively remove high and low molecular weight organic chemicals that are hydrophobic, including many volatile chemicals. The performance of a AC system for organic chemicals is a function of numerous factors including contact time and type of carbon.

Small point-of-use units containing AC have been shown to be effective in some applications for removal of organic chemicals at the consumer's tap or for a household water supply. Cases exist where with effective external management the point-of-use approach is an effective and efficient control measure.

Legislation controls

Legislation and regulations to protect drinking water supplies and their sources and to control waste disposal have been installed in many countries. These require control of effluent discharges to surface waters through both technology requirements and permits. Ambient water quality is regulated through criteria related to ultimate use e.g. agricultural or drinking water source.

The National Safe Water Drinking Act (SDWA) of the United States of America has set *maximum contaminant levels* (MCLs), and *maximum contaminant level goals* (MCLGs) for 83 contaminants which are monitored by the Environmental Protection Agency (EPA). Maximum contaminant levels have not been set for individual THMs. Instead, there is only a maximum contaminant level for total THMs. Total THMs is the sum of the concentrations of chloroform, bromodichloromethane, dibromochloromethane and bromoform. Table 2.3 lists some of the contaminants discussed in this section and summarizes their adverse health effects

Table 2.3: Standards and potential health effects of the contaminants regulated under the SDWA (Mackenzie and Cornwell, 1998) and set by the Kenya Bureau of Standards (KEBS), (1985)

Contaminant	SDWA-(MCLGs), (mg/l)	SDWA-(MCLs), (mg/l)	(KEBS)-(MCLs), (mg/l)	Potential health effects
Bromodichloromethane	0	NA	-	cancer
Bromoform	0	NA	-	cancer
Carbon Tetrachloride	0	0.005	0.003	cancer
Chloroform	0	NA	0.03	cancer
Dibromochloromethane	0.06	NA	-	cancer
cis-1,2-Dichloroethylene	0.07	0.07	-	liver, kidney, nervous system, circulation effects
trans-1,2-Dichloroethylene	0.1	0.1	-	liver, kidney, nervous system, circulation effects
Trichloroethylene	0	0.005	0.03(T*)	cancer
Vinyl Chloride	0	0.002	-	cancer
Total THMs	-	0.08	-	cancer, mutagen
Tetrachloroethylene	0	0.005	0.01(T*)	cancer

T* = Tentative guideline

When selecting a list of variables for a survey of organic contaminants, parameters such as TOC, BOD and COD are used. The COD usually includes all, or most of the BOD as well as some other chemical demands.

2.1.5 Chemical oxygen demand (COD)

The chemical oxygen demand is a measure of the oxygen equivalent of the organic matter in a water sample that is susceptible to oxidation by a strong chemical oxidant such as dichromate. The COD is widely used as a measure of the susceptibility of oxidation of organic and inorganic materials present in water bodies and in the effluents from sewage and industrial plants. The COD is non-specific, i.e. it does not identify the oxidisable material or differentiate between the organic and inorganic material present. Similarly it does not indicate the total organic carbon present, since some organic compounds are not oxidised by the dichromate method whereas some inorganic compounds are oxidised. Nevertheless, COD is a useful, rapidly measured, variable for many industrial wastes and has been in use for many decades. The concentrations of COD observed in surface waters range from 20 mg/l O_2 or less in unpolluted waters to greater than 200 mg/l O_2 in waters receiving effluents.

Samples for COD analysis should be collected in bottles which do not release organic substances into the water, such as glass-stoppered glass bottles. Ideally samples should be analysed immediately, or if unpolluted within 24 hours provided they are stored cold. If analysis can not be undertaken immediately, the samples should be preserved with sulphuric acid. For prolonged storage, samples should be deep frozen.

The standard method for measurement of COD is oxidation of the sample with potassium dichromate in a sulphuric acid solution followed by titration. Since it is impractical to exclude extraneous organic matter in the COD test, blank samples are required in COD determination. Calculation of COD is made using the following formula (Standard methods handbook, 1985):

$$COD\ (mg/l) = \frac{(a-b) \times N \times 800}{ml\ of\ sample} \quad \text{--------------------------------} 2.1$$

where a = ml of titrant used for blank

b = ml of titrant used for the sample

N = normality of ferrous ammonium sulphate, $[Fe(NH_4)_2(SO_4)_2]$

2.2 Surface water treatment systems

2.2.1 Introduction

From an environmental engineering point of view, substances can exist in water in one of the three classifications suspended, colloidal or dissolved (Mackenzie and Cornwell, 1998).

A dissolved substance is one, which is truly in solution. The substance is homogeneously dispersed in the liquid Dissolved substances can be simple atoms or complex molecular compounds Dissolved substances are in the liquid (i.e. there is only one phase present) and they cannot be removed from the liquid without accomplishing a phase change such as distillation, precipitation, adsorption, or extraction *In distillation* either the liquid or the substance itself is changed from a liquid phase to a gas phase in order to achieve separation. *In precipitation* the substance in the liquid phase combines with another chemical to form a solid phase thus achieving separation from the water. *Adsorption* also involves a phase change, wherein the dissolved substance reacts with a solid particle to form a solid particle complex. *Liquid extraction* can separate a substance from water by extracting it into another liquid, hence a phase change from water to a different liquid. Physical methods such as sedimentation filtration or centrifugation cannot, however, remove dissolved substances Suspended solids are large enough and can be removed from water by physical methods such as sedimentation, filtration and centrifugation. In environmental engineering, suspended solids are defined as those solids that can be filtered by a glass fibre disc and are properly called filterable solids

Colloidal particles are in the size range between dissolved substances and suspended particles. They are in the solid state and can be removed from the liquid by physical means such as a very high force centrifugation or filtration through membranes with very small pore spaces However, the particles are too small to be removed by sedimentation or by normal filtration processes. The degree to which a colloidal suspension reflects light at a 90° angle to the entrance beam is measured by turbidity. Turbidity in water is caused by the presence of suspended matter such as clay, silt, non living organic substances, plankton and other microscopic organisms (Sanks, 1980).

Treatment plants can be classified as simple disinfection filter plants, or softening plants. Plants employing simple chlorination have a high water quality source and chlorinate to ensure that the water reaching consumers contain safe bacteria levels. Generally a filtration plant is used to treat surface water and a softening plant to treat ground water. In a filtration plant, rapid mixing, flocculation, sedimentation, filtration and disinfection are employed to remove colour, turbidity, taste and odours, and bacteria. There are however, a few exceptions in direct filtration where the sedimentation step is omitted. Pre-treatment of water ahead of filtration is essential in order to reduce the solids load going to the filter. The main aim of pre-treatment is to produce a stabilization of colour, turbidity, at the lowest possible values before filters. Where granular activated carbon is used as a filter replacement, the physical and chemical properties of the organic compounds strongly affect the type and the level of pre-treatment prior to the granular activated bed.

2.2.2 Filtration

The water leaving the sedimentation tank still contains floc particles. The settled water turbidity is generally in the range from 1 to 10 NTU with a typical value being 3 NTU. In order to reduce this turbidity to 0.3 NTU, a filtration process is normally used. Water filtration is a process for separating suspended or colloidal impurities from water by passage through a porous medium, usually a bed of sand or other medium. Filtration is accomplished by passing the influent through a filter bed composed of granular material with or without the addition of chemical. Within the granular filter bed, a complex process involving one or more removal mechanisms. such as straining. interception, impaction sedimentation and adsorption accomplishes the removal of the suspended matter The overall collection or removal of suspended matter is conveniently divided into two sequential steps *transport* and *attachment*

The rate of particle transport from the bulk fluid to the surface of the filter grain or collector. is determined primarily by three physical processes (O'melia, 1985) The first is the Brownian or molecular diffusion. in which random motion of small particles is brought about by thermal effects Kinetic energy of water molecules is transferred into small particles during the continuous collision of water molecules with these particles The second process affecting suspended particle transport is fluid motion. In water filtration, suspended particles following the flowing fluid in the pores of the filter bed can collide with filter grains. which are stationary in a process called interception The third force is gravity. which produces vertical transportation of particles and depends upon the buoyant weight of these particles.

The attachment of a suspended particle at the solid liquid interface presented by a filter bed can be controlled by the surface properties of these solids (O' Melia et al, 1967) Both the suspended particles and the filter grain react with the inorganic and organic dissolved species in solution Both solids have an electrical charge that is balanced by accumulation of solute ions of opposite charge arranged in compact and diffuse layers near the solid surfaces so that each interfacial region is electrically neutral When both diffuse layers have charges of similar sign, a repulsive potential energy is generated that increases as the separating distance decreases Attachment is possible due to the van der Waals forces In many cases. the sum of repulsive and attractive energies is repulsive and has a magnitude of 5 kT or more (O' Melia et al, 1967). where k is the Boltzmann's constant and T the absolute temperature Experimental results indicate that attachment under these conditions is unfavourable, i.e deposition is small even if mass transport to the media grain is rapid Under conditions of unfavourable filtration (net repulsive interaction). deposition is poor For favourable filtration (no net repulsive interaction). deposition is good The effects of repulsive surface forces are observed to be more important for the deposition of submicron particles where transport is by diffusion than for larger particles where transport is by interception and gravity

During filtration. both head loss and removal efficiency change with time. Filters are said to become "dirty" or to "ripen " The actual process of particle removal is important in improving filter efficiency Changes in head loss and filtration efficiency are brought about by particles that are removed from suspension and retained in the bed Head loss increases with time as filtration at a constant flow rate proceeds Effluent quality usually improves at the beginning of a run and then may deteriorate in time

In water treatment practice. the filter run usually terminates either due to turbidity breakthrough or terminal head loss. and sometimes due to extraordinary run length (Al-Ani and Al-Baldawi. 1990). Turbidity breakthrough occurs when filter effluent turbidity exceeds the acceptable turbidity limit This occurs when the clogging front (filtration zone) described by Adin and Rebhan (1974). reaches the bottom of the filter medium and appears in the filter effluent

Type of filters

There are several methods of classifying filters One way is to classify them according to the type of medium used such as sand. coal (called anthracite). dual media (coal plus sand). or mixed media (e g coal sand and garnet). Another common way to classify the filters is by allowable loading rate Loading rate is the flow rate of water applied per unit area of the filter It is the velocity of the water approaching the filter Based on loading rate. the filters are described as being slow sand filters rapid sand filters. or high-rate sand filters. Slow sand filtration consist in percolating water through a filtering medium composed of a 0 6 m – 1 0 m thick sand bed Sand can have an effective grain size structure varying from 0 15 mm to 1 0 mm The rates of filtration can vary from 2-12 m^3/m^2/day After a few days, a complex biocenosis composed of algae, bacteria and zooplankton develops in the top layer of the filtering media and extremely complex phenomena take place. This bio-filtration process clarifies the water and remove organic and mineral micro pollutants as well as micro-organisms contained in the water to be treated

In rapid sand filters the principle modes of action are physical and physico-chemical. Biological processes are unimportant or absent (Ives. 1970), unlike slow sand filters in which a great part of filtration is dependent upon the biological processes Characteristically the filter comprises fine granular media (traditionally sand, but in recent years some alternative grain materials have been considered). The sand grain size distribution is selected to optimize the passage of water while minimizing the passage of particulate matter. Most waterworks filters rely principally on sand from 0.4–1 0 mm size, and a uniformity coefficient of 1.4–1 7 Traditionally, rapid sand filters have been designed to operate at a loading rate of $5m^3/m^2$ h This is also the loading rate specified by the Kenya Ministry of water Development design manual (MoWD, 1984). The bed remains saturated with suspensions which moves through the pore spaces because of an applied hydraulic pressure gradient

Dual media filters, in which coarse anthracite overlies finer sand, are becoming increasingly used as they can sustain higher rates of flow, for comparable performance than single media filters Pilot-plant studies carried out on dual media filters have shown that by using two media the filter capacity could be doubled by increasing the filtration rate from 5m/h to 10m/h with lower head-loss and a longer filter run of acceptable filter effluent turbidity (Al-Ani and Al-Baldawi. 1986. Craft. 1971 Ndiba, 1992). Usually, a layer of 1 0-2.5 mm anthracite is placed above 0 4-1 0 mm sand (Ives, 1970)

Multi-media (mixed media) filter beds are composed of media of several different materials The materials are chosen so that the media will be stratified in the filter during backwashing This is done in such a way that the lightest, coarsest material is segregated towards the top of the filter. and the heaviest, finest material is segregated toward the bottom

Performance of filters

Filter performance is based on head-loss and effluent quality. During filtration, both head-loss and removal efficiency changes with time When suspended particles are removed or collected within the filter bed the filter ripens and is termed "dirty".

Changes in head-loss and filtration efficiency are brought about by particles that are removed from suspension and retained in the bed Head-loss increases with time as filtration at a constant flow rate proceeds Effluent quality usually improves at the beginning of a run and then may deteriorate in time. In water treatment practice. the run usually terminates either due to turbidity breakthrough or terminal head loss. and sometimes due to extraordinary run length (Al-Ani and Al-Baldawi. 1990) It is sometimes suggested that the optimal filtration design is one in which the available head-loss is exhausted at the same time that the filtrate concentration increases (deteriorates) to some predetermined critical value (O'Melia, 1985). In practice. however it is more desirable to design a filter with some factor of safety Effluent quality is generally more important than head-loss dissipation Hence it is more important that filters maintain excellent performance throughout their service; filter run length is best determined by head-loss utilization and not by planned filtrate deterioration Emphasis is therefore placed on head-loss increases and effluent improvements due to filter ripening, rather than effluent deterioration due to exhaustion of the removal capacity of a dirty filter

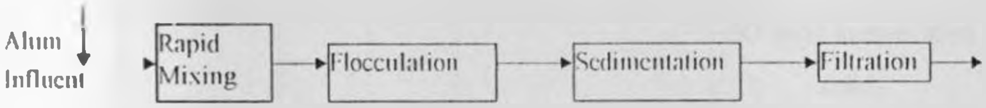
Observations made by Habibian et al (1975) indicate that retained particles act as collectors (serve as filter media for other suspended particles).

Therefore, in most of the filters used in water filtration, the actual filter media operative during most of the filter run are not sand or other media specified by the designer. Rather, they are the particles present in the water applied to the bed and retained in the filter. Stated another way, the actual filter media active during most of the filter run are formed from particles present in the water and altered during pre-treatment processes. Habibian et al. (1975) observed that head loss development within a filter bed varied inversely with the size of the particles removed from suspension. For a given mass of material removed therefore, small suspended particles produce much larger head losses than larger ones as filtration proceeds. They also observed that filtrate quality continues to improve over considerable time periods when filtration is favourable so that suspended particles can adhere to previously retained particles

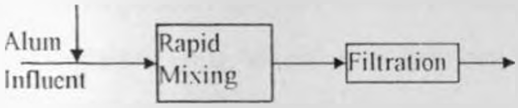
The filter is backwashed after reaching the limiting conditions of solids breakthrough or maximum head-loss. During backwashing, the filter is fluidized and cleaning is achieved by two mechanisms: abrasion between particles and by hydrodynamic shear. Evidence from fluidization literature (Amirtharaj, 1978) has shown that particle collisions in sand filters are negligible. Consequently, cleaning by abrasion between particles is extremely limited and the principal mechanism of cleaning is by hydrodynamic shear. A study carried out by Cleasby and Lorence (1978) showed that simultaneous air scour and subfluidization backwash of coarse sand filters to be the most effective method of backwash. They however warned that the choice of simultaneous air and water subfluidization backwash should be made with full awareness of its potential hazard, i.e., the potential loss of filter media during backwash overflow due to violence of the air-water action. Adequate free board to overflow must be provided, and the rates of air and water flow must be selected to ensure that loss of media will be minimized. Backwashing operation with air alone is normally done for 3 to 5 minutes at a rate of 1 to 2 $m^3/m^2/hr$ and air (at 1 to 2 $m^3/m^2/hr$) and water (at 25 to 1000 $m^3/m^2/hr$) combined, for a duration of 5 to 10 minutes (Msc. class lecture notes, Njoroge, 1999)

Direct filtration

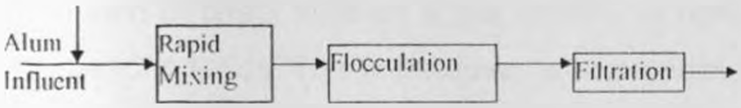
Direct filtration has been defined as the water treatment system in which filtration is not preceded by sedimentation (Letterman and Logsdon, 1976). Fig. 2.1 below compares direct filtration and the conventional treatment process.



(a) Flow sheet for typical design trends for conventional filter plant



(b) Flow sheet for typical direct filtration using alum coagulation



(c) Flow sheet for typical direct filtration using alum coagulation and a flocculation basin

Fig. 2.1: Comparison between direct filtration and conventional filter plant

<u>*Raw water quality for direct filtration*</u>

The raw water quality is the principal factor in considering the potential for direct filtration. Waters with high colour, clay, silt or algae contents are difficult to treat and therefore unsuitable for direct filtration. Numerous guidelines in considering the potential for direct filtration have been suggested in literature. A sampling of reported limiting raw water conditions is shown in Table 2.4.

Table 2.4 Reported limiting conditions of raw water for direct filtration (Odira, 1985)

Turbidity		Colour	Other
Average	Maximum		
14 TU	-	30-40 CU	10-20 hr minimum filter length
25 TU	40 TU	25 CU	100 asu/ml diatoms
-	-	-	50 mg/l suspended solids
-	50-60 TU	-	-

The objection to high colour contents in raw water is the usually high - metal coagulant (e g alum) requirement for the removal by coagulation. Therefore all the above guidelines relate to the presence of excessive suspended solids: algae and chemical precipitates. According to Culp (1977), the limitation of direct filtration is the inability to handle high concentrations of suspended solids. This is because, at some point, the suspended solids will be too high for reasonable filter runs. Culp, therefore recommended that settling before filtration will be necessary for such waters.

Pre-treatment for direct filtration

Pre- treatment for direct filtration is highly variable. A direct filter may be preceded by flocculation or non-mechanical contact basins or both. Culp (1977) suggested that separate flocculation basins may be eliminated allowing for contact flocculation in the granular filter bed

Polyeletrolytes are widely employed in direct filtration practices both to prevent early turbidity breakthrough and to reduce suspended solids quantities. According to Stump and Novak (1979), cationic polymers consistently achieve superior turbidity removal, when compared to non-ionic or anionic polymers. They concluded that anionic polymers are not appropriate in direct filtration due to unacceptably rapid head-loss development Kawamura (1977) also discouraged the use of anionic polymers as filter aids Conventional metal salt coagulants usually alum, in addition to cationic or non-ionic polymer are still used at most full - scale direct filtration plants described in literature

2.2.3 Adsorption

Adsorption is a mass transfer process wherein a substance is transferred from the liquid phase to the surface of a solid where it is bound by chemical or physical forces Generally, in water treatment, the adsorbent (solid) is activated carbon, either granular activated carbon or powdered activated carbon The powdered activated carbon has a diameter less than 0 075 mm, and granular activated carbon has a diameter greater than 0.1 mm (Metcalf, 1990) Powdered activated carbon is fed to the raw water in slurry and is generally used to remove taste - and odour - causing substances or to provide some removal of synthetic organic chemicals Granular activated carbon is added to the existing filter system by replacing the anthracite with granular activated carbon, or an additional contactor is built and is placed in the flow scheme after primary filtration for the removal of disinfection by-products.

Adsorption on granular activated carbon is a diffusion process consisting of the following steps (Cheremisinoff and Ellerbusch, 1978)

1) bulk diffusion of the adsorbate from the liquid to the film around the carbon particle
2) Diffusion through the film, and
3) Internal pore diffusion to the adsorption sites

The applications of adsorption in water treatment are for taste and odour removal However, adsorption is increasingly being considered for removal of synthetic organic chemicals (SOCs) volatile organic chemicals (VOCs) and naturally occurring organic matter such as THM precursors and disinfection by- products (DBPs) (Mackenzie and Cornwell. 1998) Concern about synthetic organic chemicals in drinking water has motivated interest in adsorption as a treatment process for removal of toxic and potentially carcinogenic compounds present in minute. but significant quantities Few other processes can remove synthetic organic chemicals to the required low level. Generally. granular activated carbon is used for synthetic organic chemical removal either as a filter media replacement or as separate contactor. The effectiveness of contaminants removal by granular activated carbon varies greatly depending on types and quantity of contaminants and the age of the filter Granular activated carbon has been proposed to be used to remove naturally occurring organic matter that would. in turn. reduce the formation of DBPs. particularly THMs Testing has shown that GAC will remove these organics (Mackenzie and Cornwell. 1998). Adsorption process can be effected by a number of factors such as the adsorbent surface area, pore size distribution. surface chemistry and pH of the water The amount of adsorption is proportional to the surface area that is available for adsorption

Adsorption using granular activated carbon (GAC)

Granular activated carbon (GAC) has been recently used as a substitute for granular filter medium or as an additional process in the conventional treatment process. for the removal of organic compounds. including disinfection by-products. those producing taste and odour. pesticides. and other synthetic organic compounds (Kawamura. 1991) Contact time is the single most important design parameter for GAC and is most commonly described by the empty bed contact time (EBCT) (AWWA. 1990),

$$EBCT = \frac{V}{Q} = \frac{\text{Volume of empty bed}}{\text{Volumetric flow rate}}$$

$$EBCT = \frac{V_{BED}}{\left(\frac{Q}{A}\right)} = \frac{V_{BED}}{\text{Approach velocity}} \qquad \text{------------------------------------2.2}$$

The actual contact time is the product of the EBCT and interparticle porosity The critical depth of a column. $L_{critical}$, is the depth that leads to the immediate appearance of an effluent concentration equal to C C is defined as the limiting detectable concentration, the critical depth of an activated carbon column is equal to the length of the *mass transfer zone* (MTZ) The MTZ is that length of the adsorbent bed wherein the adsorbate concentration in the liquid varies from the effluent concentration to zero or the specification value, C. (Cheremisinoff and Ellerbusch.1978)

The critical depth, area A and the flow rate. can be used to calculate the minimum EBCT For a given situation a critical depth of GAC and corresponding minimum EBCT exists that must be exceeded if the adsorber is to produce water of acceptable quality A practical EBCT is one that ranges from 7.5 to 30 minutes (Kawamura 1991) The shorter EBCT may be used when removing synthetic organic chemicals (SOCs) since these are easily adsorbed. but the longer contact time must be used in removing the more soluble and less adsorbable organic compounds Existing data show range of EBCT between 3 to 34 minutes for 47 plants analysed in the United States, with EBCT of 10 minutes as the median (AWWA. 1990). With EBCT below 10 minutes the adsorber life needs regeneration less than 30 days of operation

Table 2.5 shows some properties of some commercial granular activated carbon while Table 2 6 shows some typical design characteristics of granular activated carbon adsorption bed in water treatment

Table 2.5 Properties of some commercial granular activated carbon (Cheremisinoff and Ellerbusch. 1978)

Property	Typical Range
Particle density (g/cm^3)	0.92 - 1.5
Uniformity coefficient	1.44 - 1.9
Pore volume. cm^3/g	0.60 - 0.95

Table 2.6: Typical design characteristics of granular activated carbon bed {(Cheremisinoff and Ellerbusch. 1978). (Kawamura. 1991)}

Characteristic	Typical range
Superficial contact time (min)	7.5 - 30
linear flow rate (m/hr)	5 -12.5
Carbon bed depth (m)	0.5 - 10
Range of removal of impurity (%)	30 - 99

Adsorption using Charcoal

Laboratory studies have shown that ground charcoal could be used as the coarse medium in dual media filters (Ochieng'. 1999) Various materials are available for conversion into charcoal (carbon) These include wood. lignite. bituminous coal. coconut shells. and pulp mill residue

The black wattle tree (acacia mearnsii)

The black wattle is a small tree native to Australia where it grows from southern New South Wales to Tasmania It has now been introduced worldwide and is grown in huge plantations in South Africa. Kenya. Tanzania and Zimbabwe (Lewington. 1990) A rounded or rather shapeless tree and up to 15m in height. the black wattle is commonly planted in the highlands up to 2,500m and is widely naturalized It is grown in commercial plantations and farm woodlots in western Kenya The trunk is often bent when trees are grown outside plantations The bark is smooth and black in mature trees and is split to give resinous gum The leaves are feathery dull green with extremely small leaflets and the upper surface of leaf stalk is scattered with glands The black wattle has many pale yellow fragment flowers, in small round heads and numerous pods, which are dull brown when dry with small and black seeds

The black wattle is propagated as seedlings or direct sowing As a pre-sowing treatment the seeds are immersed in hot water and soaked for 12 hours The tree is fast growing but thin if established by direct sowing The black wattle produces hard, valuable timber and generally useful for fencing and implement handles and excellent for firewood and charcoal (Noad and Birnie, 1989). Other uses of the black wattle are tannin, short fibre pulp, windbreaks, ornamental, soil conservation and gum

The process of carbonization

Activated carbon is charcoal, which has been burned in the absence of oxygen. This process creates crevices in the carbon which traps contaminants when water is passed through the activated carbon filter cartridge. Charcoal is produced as a result of the chemical reduction of organic materials under controlled conditions and the heating of wood with restricted airflow The carbonization process takes place in four main stages determined by the temperature reached in each stage

Stage 1

The first stage is endothermic (a reaction requiring heat input) and result in the initial drying of the wood to be carbonized The stage is divided into three sub-stages

(i) Water in wood pores is driven off through heating up to 110 ^{0}C

(ii) Water in cell walls is driven off with the wood heated up to 150 ^{0}C.

(iii) Chemically bound water in the wood is driven off by applying heat up to 200 ^{0}C

Stage 2

The second stage in the process is the pre-carbonization stage. which is also endothermic During this stage. which occurs in the 170- 300 ^{0}C temperature range, some pyroligneous liquids (in the form of methanol and acetic acid) and a small amount of non-condensable gases (mainly CO and CO_2) are obtained.

Stage 3

The third stage is in the 250-300 ^{0}C temperature range. which is exothermic (a reaction producing heat). During this stage. the bulk of the light tars and pyrolysis process are released from the wood and the stage continues until only the carbonized residue of the wood - charcoal - remains

Stage 4

The fourth stage is in temperature exceeding 300 ^{0}C during which the carbon content of the charcoal increases as the remaining volatile content is driven off Maximum operating temperature for this stage is about 500 ^{0}C

Once these stages have been allowed to occur. the final charcoal produced is allowed to cool - a process which can take from a few hours to many days depending on which of many different charcoal production kilns is being used. Once cool. the charcoal is exposed to air for at least 24 hours during which time it stabilizes and the risk of spontaneous combustion is reduced making it safe for packing. storing and transportation.

Ideally, charcoal should be produced in kilns capable of reaching high temperatures since higher temperatures drive off greater proportions of the acids, tars and volatile gases making the resulting charcoal purer with a higher carbon content. Good quality charcoal requires temperatures up to 500 °C, which produce charcoal with a fixed carbon content of 75 percent. However, high purity charcoal is more friable than charcoals produced in lower temperature kilns and so a maximum kiln temperature of 450 - 500 °C is often considered the optimum (Kristoferson and Bokalders 1987)

A soft burned charcoal (carbonized at lower temperatures) has a high volatile matter content and a low fixed carbon content, is corrosive to metals, paper fibre and packaging material (but not to plastic) and it also tends to smoke during burning. Hard burned charcoal, on the other hand, is high in fixed carbon content, low in volatiles and is much more friable. Hard burned charcoal burns cleanly but may be difficult to ignite. The ideal compromise product, when dry, has a fixed carbon content of about 75 percent; a volatile content of about 20 percent, and ash content of about 5 percent (Kristoferson, and Bokalders, 1987). In terms of volume, charcoal produced represents about half the original volume of wood used in the carbonization process. Table 2.7 shows the variation of carbon content with kiln temperatures.

Table 2.7: **Carbon** contents of charcoal made at different kiln temperatures (Kristoferson, and Bokalders, 1987)

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

Carbon Activation

The activation of carbon involves a process of burning off tars and pore enlargement of the carbon material (charcoal) produced at temperatures of 400-600 °C. Activation of this product follows with the use of steam or carbon dioxide as an activating agent (Cheremisinoff and Ellerbusch, 1978). The superheated steam, 750-950 °C, passes through the carbon burning out by-product blockages, and expanding and extending the pore network.

Carbon regeneration

Granular activated carbon will typically last 90 to 120 days until it loses its adsorptive capacity (Mackenzie and Cornwell, 1998). The economics of carbon are such that costs could be prohibitive if it could not be reused. Therefore GAC must be periodically reactivated to remove accumulated chemicals and prevent breakthrough into finished water. Thus spent carbon passes through a regeneration or reactivation process in a furnace so that the organics are desorbed. Furnace temperatures usually range between 870 - 1000 ^{0}C during which time carbon is dried of residual waters and the organic adsorbent is volatized and oxidized. Combustion conditions within the furnace are controlled to limit oxygen content to effect oxidation of the adsorbed material rather than the carbon.

After thermal regeneration, the carbon is quenched in a water bath, washed of carbon fines and recycled back to the adsorber column, or sent to storage. During each treatment cycle carbon losses can vary from 2 and 10 per cent and must be replaced with new or virgin carbon. The entire thermal regeneration process usually lasts about 30 minutes (Cheremisinoff and Ellerbusch, 1978). The capacity of regenerated carbon is slightly less than that of the virgin carbon. A major problem with the use of powdered activated carbon is that the methodology for its regeneration is not well defined.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Materials

3.1.1 Water

There are several rivers draining through the City of Nairobi; the bigger ones include Nairobi, Ngong', Mathare, Ruaraka and Kasarani. All these rivers eventually drain into Nairobi River which in turn empties into the Athi River, which is the main source of water supply for people living along its course through Machakos, Kitui and Kilifi districts. It is also a source of water supply for Mombasa.

The water used in this study was drawn from the upper reaches of Nairobi River, on the upper parts of Nairobi City, where pollution with industrial wastes is less compared to the lower parts. One sample was drawn at Kirichwa Dogo tributary, Hurlinghum and the second sample at the Chiromo bridge. The fact that water above Chiromo is not very polluted (i.e. there are no industrial wastes) was the criteria used to select the sampling site for use in this study. This is because the study aimed at treating water for drinking purpose and therefore a waste that was strongly concentrated with industrial wastes was not preferred

Raw water characteristics

The quality of raw water drawn at the Chiromo bridge is shown in Table 3.1. It is seen from Table 3.1 that the raw water has a neutral pH. The amount of turbidity and alkalinity classifies the water as low turbidity, low alkalinity (Sanks, 1980). It is also seen that the water meets the requirement for being

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Raw water characteristics

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Some of the characteristics that were observed in water drawn from Kirichwa Dogo tributary are

- the water had a foul smell.
- the water foamed when disturbed e g when emptying in a container,

the water had a faint yellow green colour indicating organic contamination by algae among others. Chlorophyll-a-test confirmed that the water had an algae concentration of 3 mg/L

- the COD of raw water was 168 mg/l.
- the turbidity was between 29 5 and 46 NTU

Table 3.1 Raw water characteristics (Chiromo Bridge sample)

PARAMETER	RESULT
PH	6.87
Apparent colour, ° H	20
True colour, ° H	10
Conductivity, μS/cm	325
Turbidity, N.T.U.	9.4
Calcium hardness as $CaCO_3$, mg/l	18
total hardness as $CaCO_3$, mg/l	42
total alkalinity as $CaCO_3$, mg/l	63
Carbonate alkalinity, mg/l	0
Iron, mg/l	0.4
Fluorides, mg/l	0.51
Sulphates, mg/l	38
Phosphates, mg/l	0.01
Silica, mg/l	32
dissolved oxygen, p.p.m	5.8
Nitrates, mg/l	0.02
Manganese, mg/l	0
Chlorides, mg/l	68
Chromium, mg/l	0.01
Copper, mg/l	0.01
Dissolved solids, mg/l	110
Suspended solids, mg/l	30
Total solids, mg/l	140
Biochemical oxygen demand, mg/l	10
Chemical oxygen demand, mg/l	16

3.1.2 Filter media

Ground charcoal

Availability of activated carbon is not widespread due to the sophisticated nature of its production and cost Ordinary black wattle tree charcoal on the other hand is common and easy to produce Charcoal is produced in a similar process as granular carbon The only difference is that. charcoal which is sold as a domestic source of energy is produced in conditions whose carbonization temperatures can not be controlled and therefore the desired amount of carbon in charcoal cannot be achieved It was for this reason that a small amount of charcoal was prepared using a furnace at 450 ^{0}C in the laboratory for the purpose of comparing it with commercial charcoal which was used in this study. Both commercial and laboratory prepared charcoal were made from the black wattle tree Details of the characteristics of the wattle tree used to prepare the charcoal in the laboratory namely; moisture content and specific gravity are given in Appendix 1A The difference between charcoal used in this study and activated carbon is that this charcoal was not activated (i e., the charcoal used in this study is the porous carbon material that has not been activated).

The ground charcoal was prepared by crushing the charcoal using a falling weight and then sieved using BS sieves Particles that were greater than 1.00 mm were further crushed using a roller on a screen made of steel. whose sieve diameters were greater than 2 mm The charcoal was again sieved and the process repeated until enough charcoal was prepared. Crushing on a screen gave ground charcoal grains that were more round than those initially crushed using a falling weight The ground charcoal was then washed before any tests were carried out.

Testing of filter media

Every new filter media must first satisfy various requirements before it can be considered for use (Eves. 1990. Morgoli et al . 1977) These concern its form, size. density, pore volume. solubility, durability, settling rate and purity. For adsorption studies using ground charcoal the amount of carbon in ground charcoal is also important The following tests were carried out to satisfy the above requirements

- Purity,
- Size,
- Density,
- Porosity,
- acid solubility. and,
- carbon content

Purity

The media were assessed to determine their homogeneity and cleanliness. The sand appeared dusty possibly because it had been stored outside during the rainy season and so had received some dirt from surface run off. The ground charcoal also contained dust from powdered charcoal resulting from crushing Both the sand and the charcoal were therefore washed before any tests were carried out and before they were put in the columns.

Size

The sieve results are reported by the mass (or weight) of grains retained in each successively finer sieve Sieve sizes of the range 0 42 -1.00 mm were used for both sand and charcoal The choice of the size range for sand was chosen based on the literature which specifies a size range of 0.4 mm to 1.00 mm The choice of the size range for ground charcoal was based on the fact that activated carbon is classified as granular activated carbon when the size is greater than 0 1 mm. However, a size range of 0 42 mm to 1 00 mm was chosen so that a comparison of the performance could be made between sand and ground charcoal of the same size range The coefficients of uniformity were also selected to conform to the ranges given in the literature review (1 4 -1 7 for sand and 1 44 -1 9 for granular activated carbon) Table 3 2 below gives the results of sieve analysis for both sand and ground charcoal

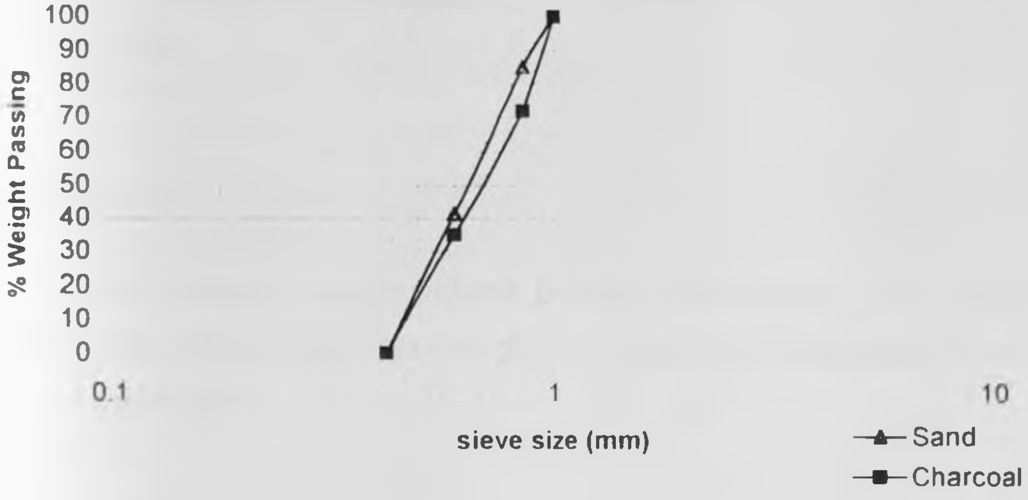

Fig. 3.1 Sieve analysis

Table 3.2: Results of sieve analysis for ground charcoal and sand

Media	Size range (mm)	d_{10}	d_{60}	UC
Ground charcoal	0 42 - 1.00	0 47	0 76	1.6
Sand	0 42 - 1 00	0 45	0 70	1 6

Density

The density was determined by a standard method of physics using a density bottle with careful weighing The densities were determined after all air had been expelled from the sample by shaking the bottle Since charcoal is a porous material it was soaked in water for 24 hours with slow stirring as recommended by Ives (1990). Several samples had their densities determined and their averages taken Table 3 3 gives the densities of the ground charcoal and sand. The density of the ground charcoal prepared in the laboratory at 450 ^{0}C is also given.

Table 3.3 Density of ground charcoal and sand

Media	Density kg/m^3
Ground charcoal (commercial)	1138
ground charcoal (laboratory made)	1129
Sand	2656

Porosity

Porosity is defined as the pore volume per unit filter volume. It is a useful measure for it enables the mass (weight) of media to be calculated to fill a given volume of filter.

Porosity ε is calculated from:

$$\varepsilon = 1 - \frac{m}{\rho_s V} \text{ ---------------------------- } 3.1$$

where m is the mass of media, p_s is the density of media, and V is the apparent volume occupied by media in the column. The porosity of ground charcoal and sand were determined according to equation 4.1 above and the results tabulated in Table 3.4

Table 3.4 Porosity of ground charcoal and sand

Media	Porosity
Ground charcoal (commercial)	0.824
Ground charcoal (laboratory made)	0.825
Sand	0.447

It is observed that the porosity of ground charcoal made in the laboratory and commercial charcoal is the same, indicating that the porosity was not affected by the method of carbonization. The same property may also mean that the carbonisation temperature in local methods of producing charcoal are within the recommended range of 400 - 600 ^{0}C (Cheremisinoff and Ellerbusch, 1978).

Acid solubility

A test with hydrochloric acid is commonly required in filter media specifications. The test ensures the integrity of the grains; that they are solid and not aggregated particles which may be cemented. Acid solubility is a surrogate test for the chemical inertness that is desirable for filter materials.
The media were subjected to the acid test according to the University College London procedure (Ives, 1990), where they were immersed in 20 percent HCl for 24 hours at 20 ^{0}C. They were then washed in distilled water, and dried at 110 ^{0}C and reweighed. In the University College London procedure, a weight loss of more than 2 percent is unsatisfactory. The results of the acid test are given in Table 3.5.

Table 3.5: Results of acid test

Media	**percent Weight Loss**
Ground charcoal (commercial)	1.47
Ground charcoal (laboratory made)	-
Sand	0.80

Carbon content

The amount of carbon in ground charcoal was determined using the Exeter Analytical Model 440 Elemental Analyzer, which provides a direct automated elemental analysis. In the 440 Analyzer, the carbon, hydrogen, and nitrogen content in organic and inorganic compounds can be determined. Combustion of the weighed sample (typically 1-3 mg; in certain cases up to 500 mg) occurs in pure oxygen under static conditions.

The combustion train and analytical system are shown in Figure 3.2. Helium is used to carry the combustion products through the analytical system to the atmosphere, as well as for purging the instrument. Helium was selected for this purpose because it is chemically inert relative to tube packing chemicals, and it has a very high coefficient of thermal conductivity. Argon can be used with some Model 440 modifications, but is not recommended since instrument performance deteriorates. Solenoid valves **A** through **G** control the gas flow through the system; valves **H** and **I** are used for automatic leak testing and other maintenance purposes.

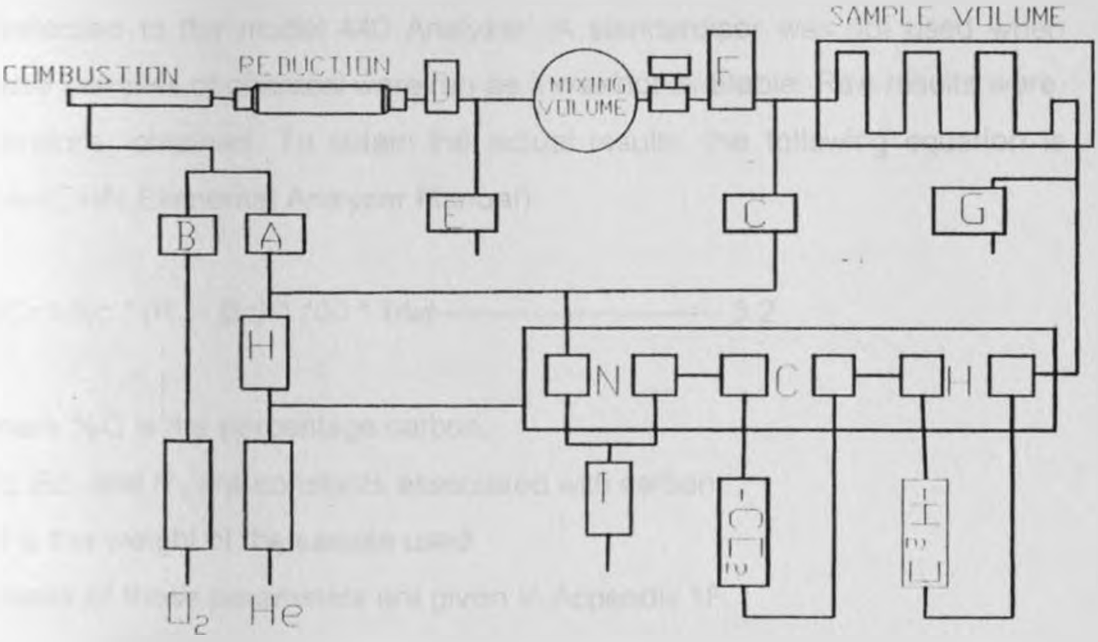

Figure 3.2: Model 440 Elemental Analyzer flow diagram

The products of combustion are passed over suitable reagents in the combustion tube to assure complete oxidation and removal of undesirable by-products such as sulphur, phosphorous, and halogen gases. In the reduction tube, oxides of nitrogen are converted to molecular nitrogen and residual oxygen is removed. In the mixing volume the sample gases are thoroughly homogenized at precise volume, temperature, and pressure. This mixture is released through the sample volume into the thermal conductive detector.

Between the first three pairs of the thermal conductivity cells an absorption trap removes water from the sample gas. The differential signal before and after the trap reflects the water concentration and, therefore, the amount of hydrogen in the original sample. A similar measurement is made of the output of a second pair of thermal conductivity cells, between which a trap removes carbon dioxide, thus determining the carbon content. The remaining gas now consists only of helium and nitrogen. This gas passes through a thermal conductivity cell and the output signal is compared to a reference cell through which pure helium flows. This gives the nitrogen concentration. When a standardiser is used direct results can be calculated using a computer connected to the model 440 Analyzer. A standardiser was not used when these samples of charcoal were run as it was not available. Raw results were, therefore, obtained. To obtain the actual results, the following equation is used(CHN Elemental Analyzer Manual).

$\%C=1/Kc * (R_{.z} - Bc) * 100 * 1/wt$-------------------------- 3.2

where %C is the percentage carbon.
Kc, Bc, and $R_{.z}$ are constants associated with carbon.
wt is the weight of the sample used
Details of these parameters are given in Appendix 1F

The amounts of carbon in both commercial charcoal which was used in this study and the laboratory made charcoal were determined. Two samples of the charcoal were run for carbon determination and an average taken. The results are given in Table 3.6 below

Table 3.6. results of carbon content in ground charcoal

Sample	% Carbon content
Commercial charcoal	76 53
Laboratory made charcoal	80.3

The content of carbon in the laboratory made charcoal is in agreement with the results given in literature Cheremisinoff and Ellerbusch (1978) reported that nearly 80 percent elemental carbon can be effected by prolonged exposure of the product of carbonisation to 400-600 ^{0}C Kristoferson and Bokalders (1987), have also reported that good quality charcoal requires temperatures up to 500 ^{0}C, with kiln temperature of 450-500 ^{0}C producing charcoal with a fixed carbon content of about 75 percent The carbon content of 76.5% in commercial charcoal also shows that the ordinary charcoal sold as a domestic source of energy is made at temperatures that are within the same range given by these authors and may therefore be applied as filter media.

3.2 Methods

3.2.1 Laboratory filtration model

In order to investigate the ability of charcoal to remove organic matter and to compare the filtration performance of ground charcoal and sand, laboratory experiments were conducted using equipment set up in the Environmental Health Engineering Laboratory at the University of Nairobi The experimental set up consisted of two laboratory model filtration columns connected to source of water whose turbidity and organic matter was to be reduced by ground charcoal and sand contained in either of the columns The experimental set up is illustrated in Figure 3 3 To maintain the flow constant, two alternating pumps delivered water from storage sump to an overhead constant head tank Water then flowed through a basin, which was used for reducing the turbulence of water into the filtration columns

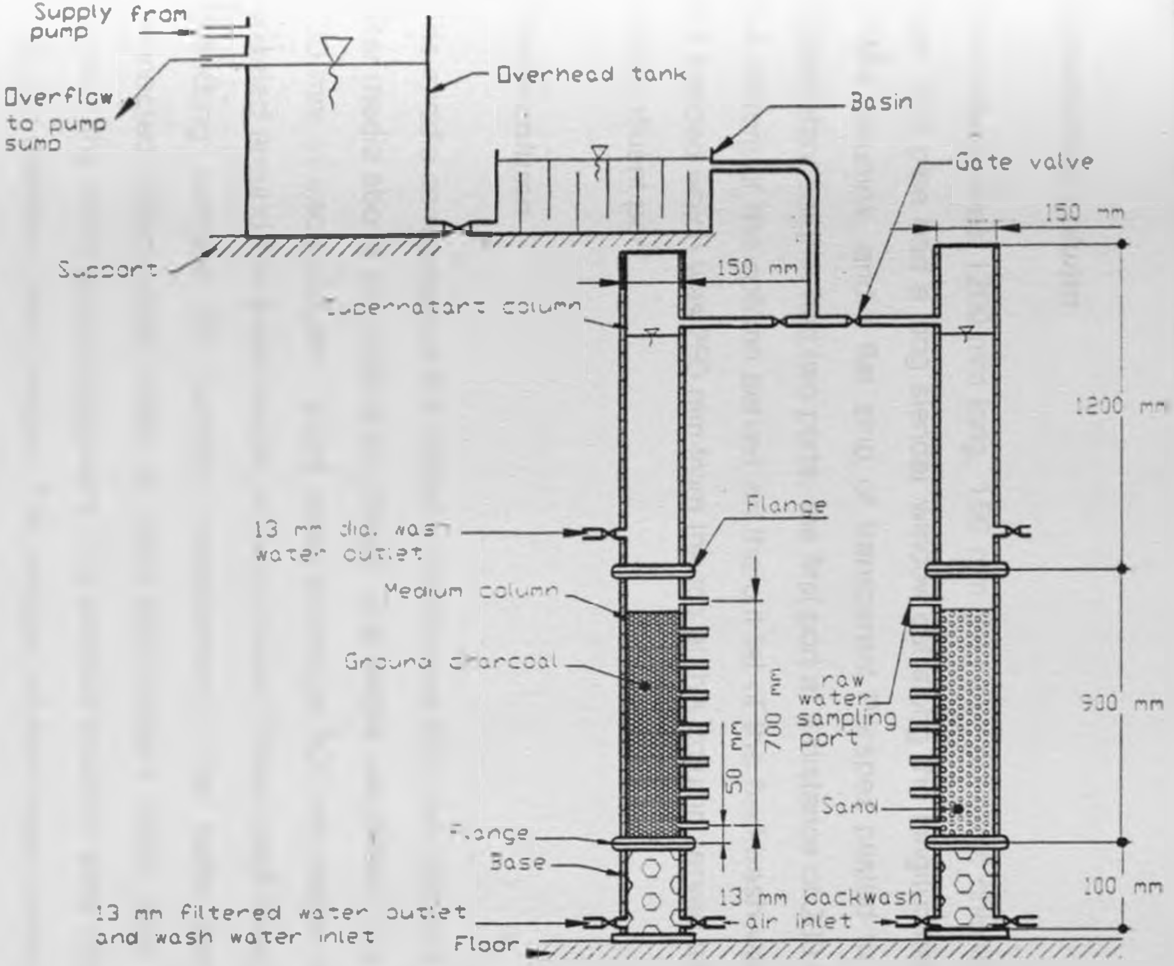

Figure 3.3: Schematic representation of the laboratory filtration model and experimental set up

Filtration columns

Two columns, one containing ground charcoal and the other sand for rapid sand filtration were used The columns consisted of the supernatant column, media column and the base

Supernatant column

This column was 1200 mm long, 150 mm diameter polyvinyl chloride (PVC) pipe. The pipe had a long slender window cut along the longitudinal surface of the columns, and a flat strip of transparent Perspex pasted to it. Each supernatant column had two ports: the first port at a distance of 200 mm from the bottom of the column served as the out let of the backwash water while the second which was 250 mm from the top of this column served as the raw water influent port

Media column

The middle component of the filtration column was 900 mm high and held the filter media above the underdrain (base). The media was added to a depth of 730 mm in each column Eight ports spaced at 100 mm center to center spiraled around the entire height of each column These ports were used for collecting samples for turbidity measurement The same ports were connected using rubber tubes to glass manometers which were used to monitor the head loss development The medium columns were made up of 140 mm diameter clear perspex. The perspex columns were connected both to the bases and the supernatant columns by means of flanges.

The base

The base which served as the under-drain system of the filter was 150 mm diameter PVC pipe section 100 mm deep This chamber was filled up with gravel in two layers The bottom 60 mm layer was filled with gravel of size 4 - 6 mm, and the top 40 mm had gravel of size 2 - 4 mm There were two 13 mm diameter inlet pipes connected to this chamber each of them placed 40 mm from the bottom of the base One pipe served both as filtered water effluent pipe and backwash water inlet The second served as the backwash air inlet pipe This pipe was connected to an air pump which was used to pump in air during the backwashing operations The top of the underdrain chamber was covered by a screen The assembly of the base is shown in Figure 3 4

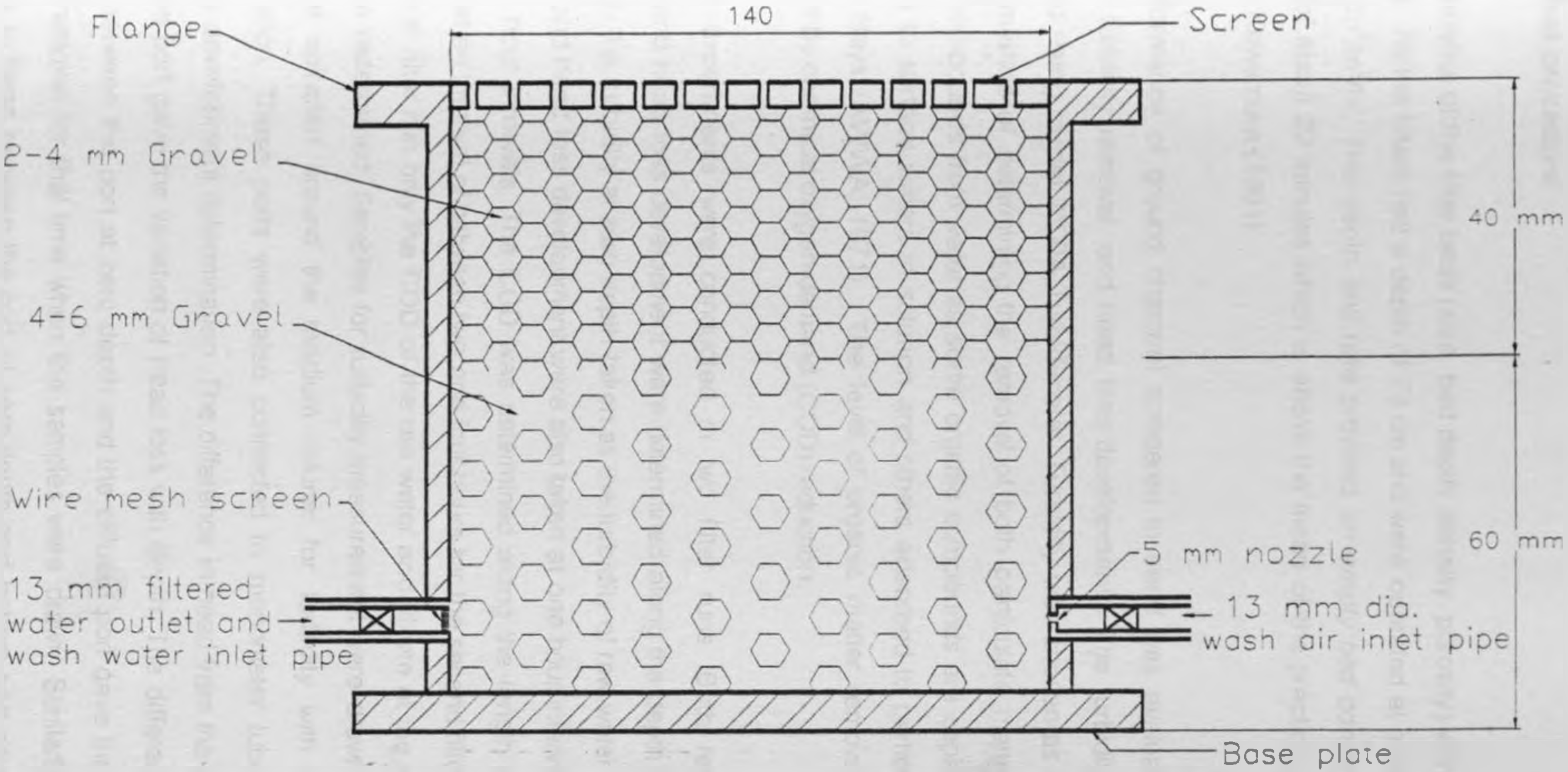

Figure 3.4: Schematic representation of the underdrain

3.3 Test procedure

Characteristics of the filter beds (size bed depth. density. porosity) were kept constant All the filters had a depth of 73 cm and were operated at a filtration rate of $2m^3/m^2/hr$ This depth and rate provided an *empty bed contact time (EBCT)* of about 22 minutes which is above the mean of the practical range given by Kawamura (1991)

The performance of ground charcoal compared to sand was evaluated in terms of turbidity removal. and head loss development The turbidity was measured using model 2100A Turbidimeter Turbidity was chosen as a non specific method of determining the removal of both particulate matter and organic compounds from water as some organic compounds are capable of migrating to surface waters in solution and others adsorbed to particulates such as clays (AWWA. 1971) The level of organic matter removal was evaluated by chemical oxygen demand (COD) reduction

Filtration experiments were conducted in two filter runs Both residual turbidity and head loss development were determined along the depth of the filters with the turbidity at zero depth taken as the turbidity of raw water. Both turbidity and head loss development were also taken at one hour interval and later two hour intervals The COD was determined along the length of the filter run at an interval of between two and four hours for the second filter run. For the first filter run only the COD of the raw water and filtrate at the eighth hour were determined Samples for turbidity measurement were drawn from ports that spiralled around the medium column for turbidity with depth determination. These ports were also connected to manometer tubes for head loss development determination The difference in head from the top to the bottom port gave the variation of head loss with depth. The difference in turbidity between the port at zero depth and the effluent port gave the total turbidity removal for that time when the samples were drawn. Similarly, the difference in head between the port at zero depth and bottom port gave the total head loss for that point of time After each filter run, the sand filter was backwashed for 3 minutes with air at a rate of 4 psi (27.6 Kpa), and then with water (at a rate of $25m^3/m^2/hr$) and air combined until the backwash water turbidity was less than 5 NTU A virgin ground charcoal was used for each filter run Below is a brief description of the nature of each of the two filter runs whose waters were sampled at different seasons.

Filter run no.1

The filter run was conducted at a filtration rate of $2m^3/ m^2/$ hr. The raw water was sampled at Kirichwa Dogo tributary and the filter run was terminated after 12 hours on the basis of turbidity breakthrough The filter run was conducted in order to investigate the performance of ground charcoal when the raw water turbidity and COD are high Water for this filter run was sampled in March 2000.

Filter run no.2

The filter run was operated at a filtration rate of $2m^3/ m^2/$ hr. This filter run received water sampled at the Chiromo bridge The filter run was terminated after 32 hours on the basis of terminal head loss The aim of this filter run was to determine the performance of ground charcoal with waters of low turbidity and COD. Water for this filter run was sampled in July 2000.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

The data collected was used to determine the removal of organic matter by ground charcoal. This was accomplished by comparing the performance of ground charcoal and sand. The following relationships were formulated from the data collected:

- residual turbidity with depth.
- residual turbidity with time,
- turbidity removal with depth.
- turbidity removal with time,
- initial and terminal head loss with depth.
- total head loss with time,
- COD remaining with time.
- COD removal with time

4.2 Analysis of results

4.2.1 Low turbidity water

Residual turbidity with depth

Figure 4.1 shows the turbidity remaining with depth of the filter bed

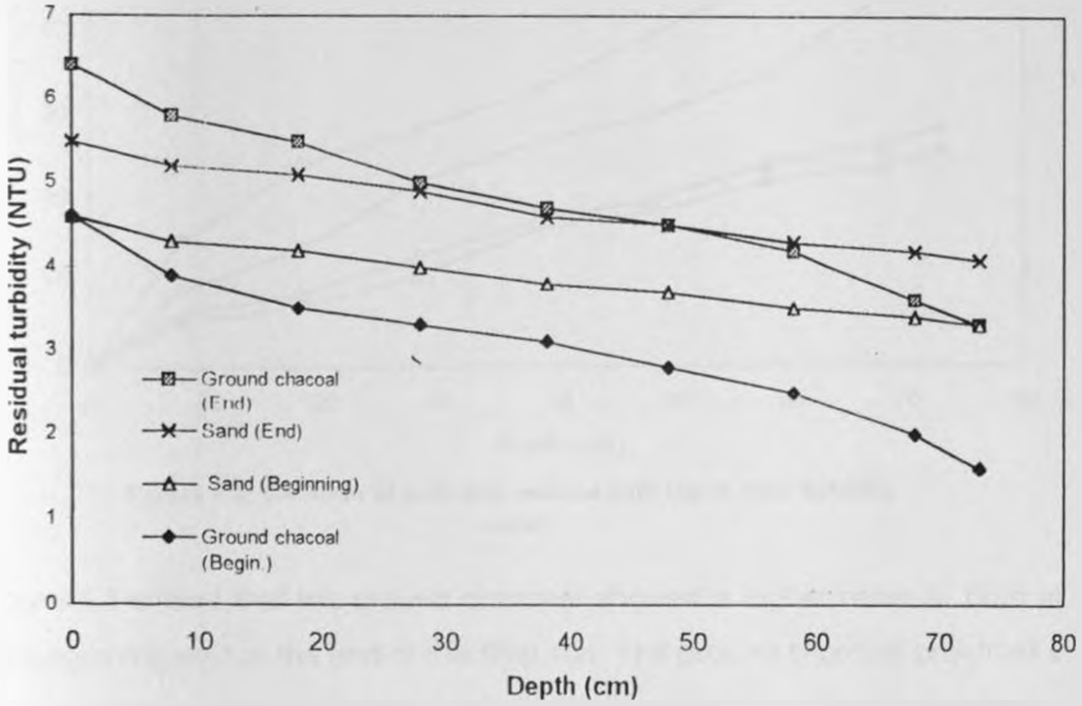

Fig. 4.1: Residual turbidity with depth (low turbidity water)

It is seen that the residual turbidity was less than 5 NTU in both ground charcoal and sand. The influent turbidity of 4 6 NTU at the beginning of the filter run is close to the practical average of 3 NTU that has been observed in most filtration plants before reaching the filter bed. It is observed that the removal in sand was very small compared to ground charcoal as shown by the slopes of residual turbidity curves Higher residual turbidities of less than 1 NTU can be achieved by increasing the depth of the filter bed or by enlarging the surface area of the bed at the same filtration rate.

Turbidity removal with depth

The results of turbidity removal with depth are shown in Figure 4.2

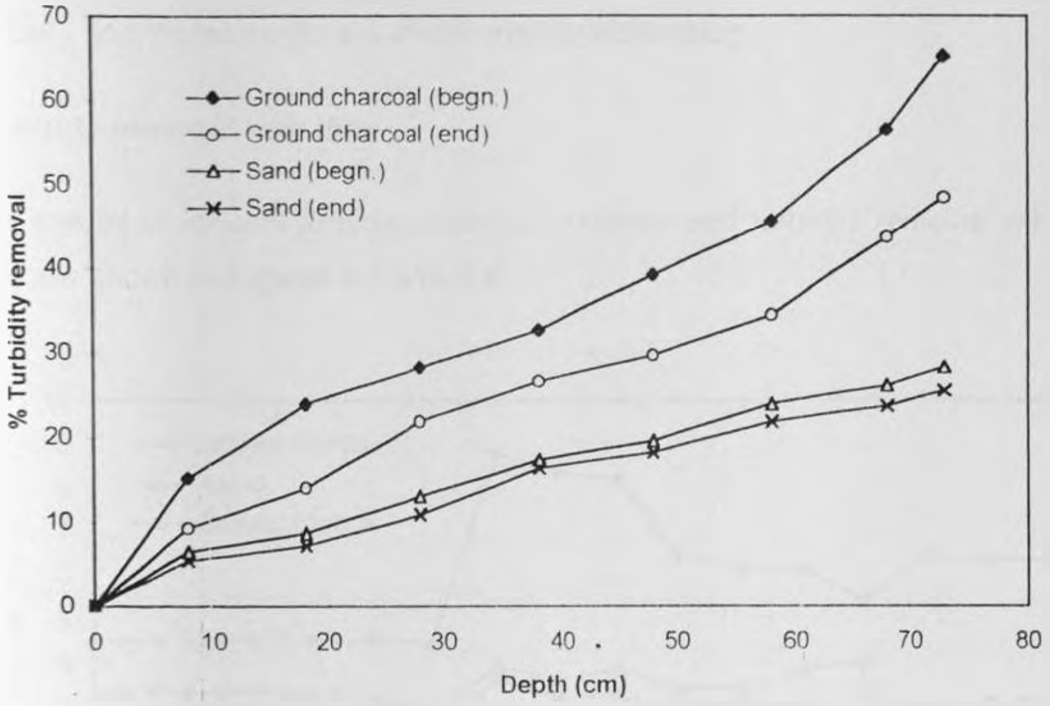

Figure 4.2: Variation of turbidity removal with Depth (low turbidity water)

Figure 4.2 shows that the ground charcoal showed a higher removal both at the beginning and at the end of the filter run. The ground charcoal provided a total turbidity removal of 65% at the beginning while the sand provided a removal of only 30%. This is about 2.2 times more removal provided by ground charcoal compared to that by sand At the end of the filter run the removals were about 50% and 25% in ground charcoal and sand, respectively, giving about 2 times more removal in ground charcoal than sand.

The mechanisms of removal in sand is a combination of straining, interception, impaction and sedimentation with straining as the dominant mechanism (Tchobanoglous. 1979) Ground charcoal also posses all these mechanisms with adsorption as an added removal mechanism This explains why ground charcoal provided more removal than sand It also explains why the graphs follow the same trend or pattern given that the media sizes of both ground charcoal and sand were the same (i.e 0.42-1.0 mm) The ability of charcoal to remove the turbidity by adsorption is because the humic acid in water is attached to the carbon in charcoal The charcoal also has a high porosity and therefore more surface area for adsorption

Turbidity removal with time

The results of influent turbidity residual turbidity and turbidity removal with time are shown in Figures 4.3 and 4.4

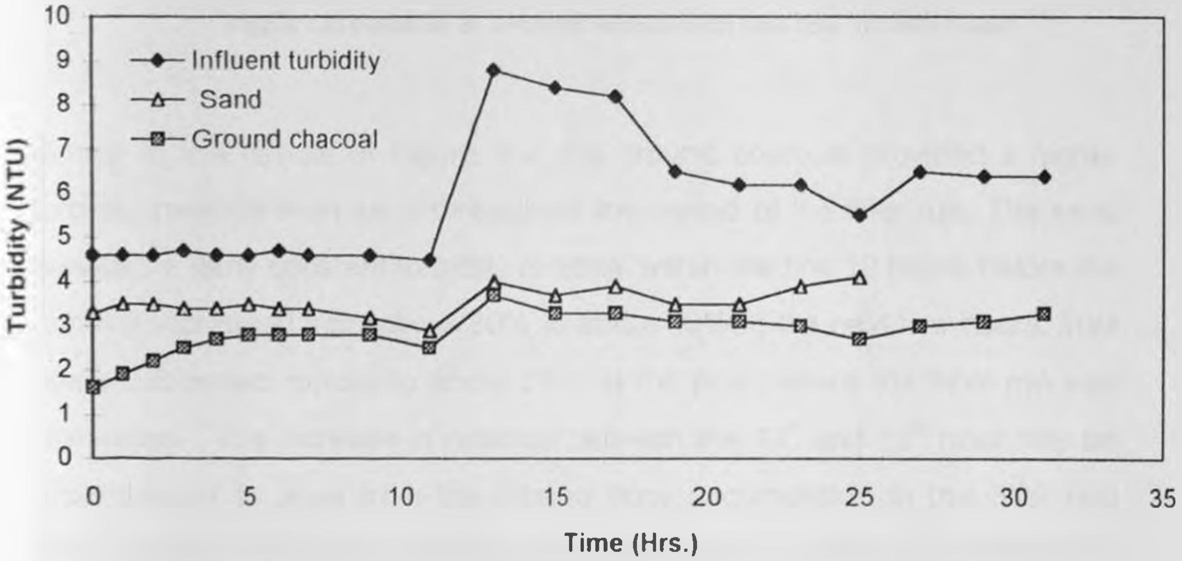

Figure 4.3: Influent turbidity and residual turbidity (low turbidity water)

The influent turbidity was constant for about 11 hours then immediately rose from 4.6 to 8.8 NTU. This rise resulted due to change of raw water turbidity. The waters shown during the first hours of the filter run and that shown towards the end had been drawn in two different days The sharp rise is also due to the disturbance of particles in the settled water in the storage tank by water which was being emptied to it from the plastic cans used in transporting water to the laboratory. The water drawn in the second day was more turbid than that which had been drawn in the previous day (7.4 NTU). Although there was some variation in influent turbidity the removal by sand and ground charcoal was somehow constant with ground charcoal providing the higher turbidity removal of 41 - 65% compared to 25 - 56% shown by sand.

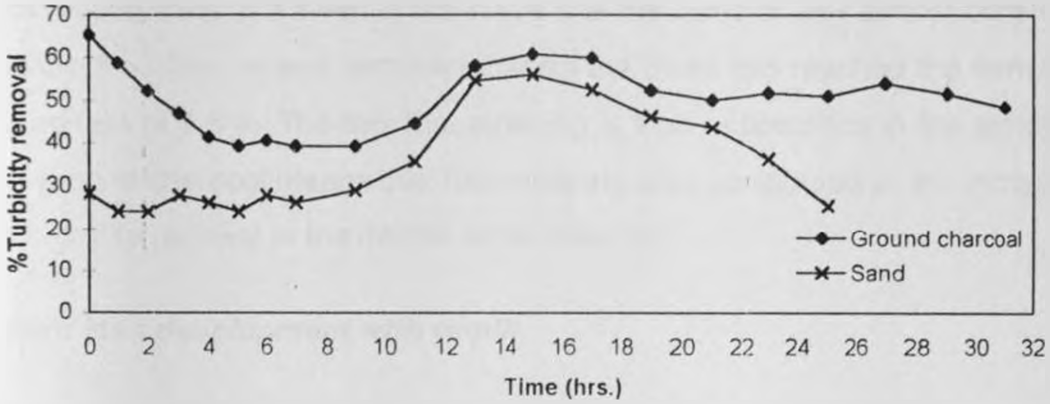

Figure 4.4: Variation of turbidity removal with time (low turbidity water)

Similar to the results of Figure 4.2, the ground charcoal provided a higher turbidity removal than sand throughout the period of the filter run. The sand provided a fairly constant turbidity removal within the first 12 hours before the removal increased from about 30% to about 50% in the next five hours. This again decreased rapidly to about 25% at the point where the filter run was terminated. The increase in removal between the 12th and 15th hour may be hypothesized to arise from the filtered flocs accumulating in the filter bed acted as filter media themselves due to filter ripening thereby increasing the removal efficiency. This increased the quality of the effluent. After many hours of filter operation, that is above 15 hours, many flocs were deposited within the bed thus reducing the available removal capacity. This resulted in some impurities passing unfiltered with the result that the effluent continued to deteriorate as shown in Figure 4.3

The ground charcoal had turbidity removal decrease with time at the beginning. The removal was then constant up to about the 11th hour. The removal increased slightly to about 60% before decreasing slightly. Adsorption on carbon is a diffusion process which is thought to consist of the following steps (Cheremisinoff and Ellerbusch, 1978): bulk diffusion of the adsorbate from the liquid to the film around the carbon particle; diffusion through the film; and internal pore diffusion to the adsorption sites This explains why there was some time lapse before the increase in turbidity removal at the fourteenth hour; the time when the impurities reached the adsorption sites. It is seen in the curve that the removal was almost constant before the filter run was terminated when the head loss reached the terminal head loss of 1.5 m The fact that straining is also in operation in the removal by ground charcoal means that filter ripening also contributed to the increase in turbidity removal in the middle of the filter run.

Head loss development with depth

Figure 5.5 shows the distribution of initial and terminal head losses with depth.

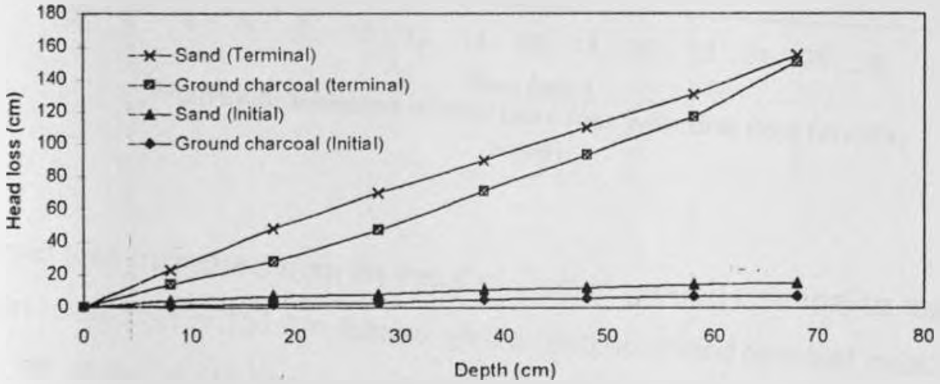

Figure 4 5: Distribution of initial and terminal head loss with depth (low turbidity water)

It is seen that the head loss increase was high in sand both at the beginning and at the end of the filter run. Both ground charcoal and sand had head loss increase linearly at the beginning and at the end of the filter run. The head losses at respective depths were seen to be about 2 times more in sand than in ground charcoal at the beginning of the filter run and between 1.2 to 2 times towards the end of the filter run. The total initial head losses were 7 cm and 15 cm in ground charcoal and sand . respectively. This is about 2.1 times more initial head loss in sand compared to ground charcoal The curves are linear indicating depth filtration which is the desired norm where there is deep penetration of accumulated solids This filter run was terminated based on the terminal head loss of 1.5 m

Head loss development with time

The development of total head loss with time is shown in Figure 4.6.

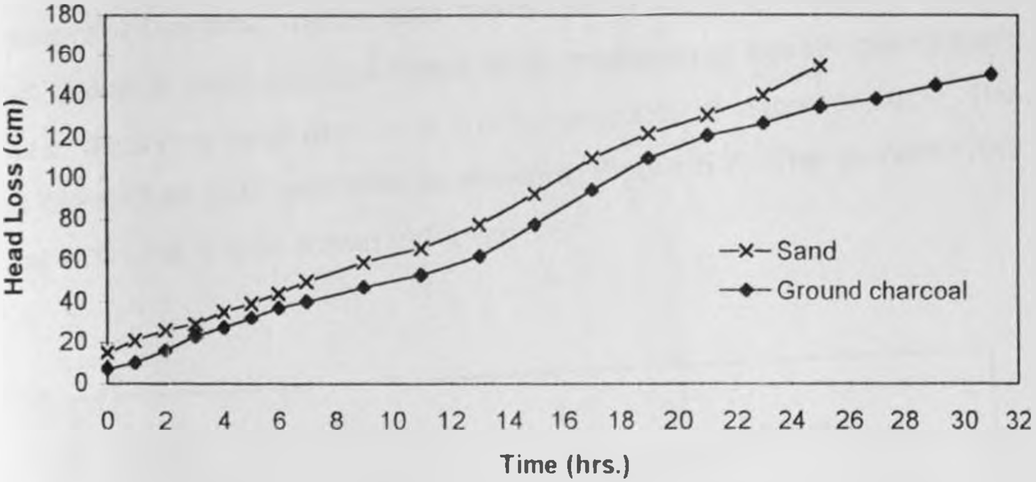

Figure 4.6: Variation of total head loss with time (low turbidity water)

The head loss increased from an initial of 7 cm in ground charcoal to reach a terminal head loss of 151 cm, based on the recommended terminal head loss of 150 cm given in the design manual of the Ministry of Water Development (MoWD, 1984). The terminal head loss was reached in 32 hours. The sand, on the other hand had an initial head loss of 15 cm which increased to reach a terminal head loss of 155 cm in 26 hours It is seen that the sand developed about 1.1 times or 10% more head loss compared to the ground charcoal throughout the length of the filter run. The ground charcoal developed a lower head loss due to the added removal mechanism by adsorption and high porosity. This means that many impurities were removed by adsorption into the charcoal given that the porosity of ground charcoal was higher than that of sand For both ground charcoal and sand the relationship between head loss and time was approximately linear. This indicates that the filters were typical deep-bed filters

The lengths of filter runs indicates about 30% extra time of operation provided by ground charcoal than sand and therefore 30% increase in filtered water by ground charcoal

COD Removal

The removal of organic matter was measured in terms of COD reduction. Organic matter in water are as a result of the presence of aquatic plants such as algae, decaying vegetation and the by-products of decomposition. The results of residual COD with time is shown in Figure 5.7. The percent COD removal with time is also shown in Figure 5.8.

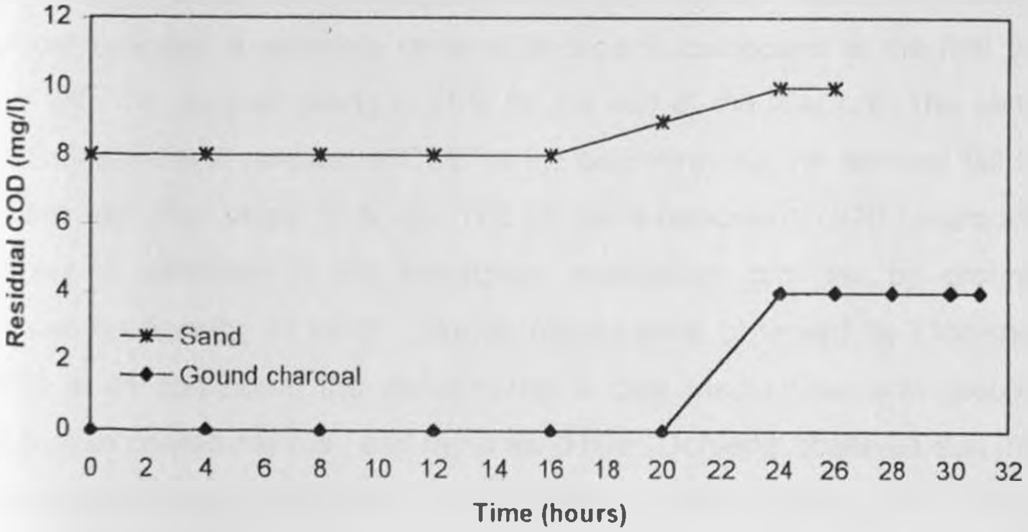

Figure 4.7: Residual COD with time

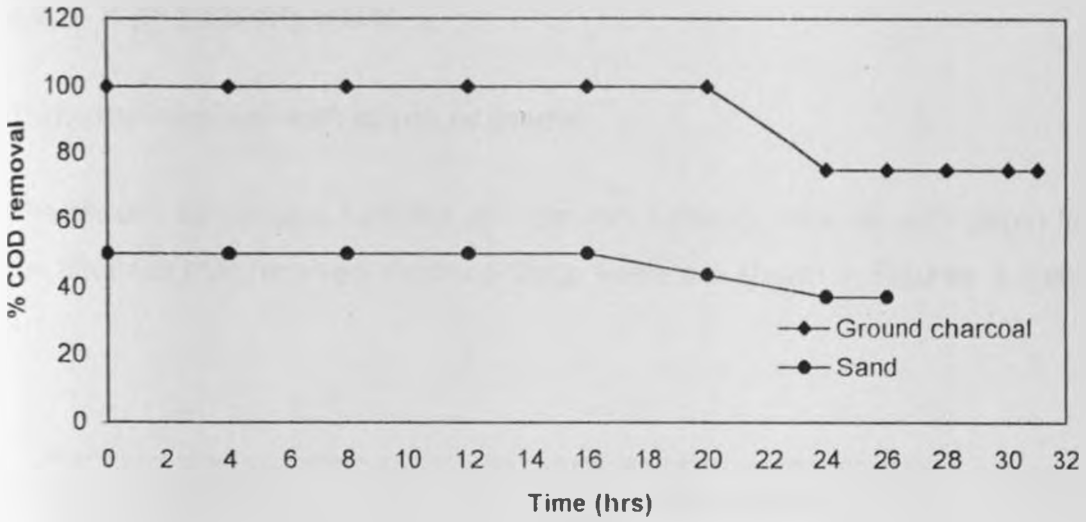

figure 4.8: COD removal with time

It is seen that the ground charcoal provided a higher removal of organic matter compared to sand throughout the length of the filter run. Ground charcoal provided a complete removal of organic compound at the first 20 hours with the removal falling to 75% for the rest of the filter run. The sand provided about half removal of COD at the beginning but the removal fell to less that half after about 16 hours The complete removal of COD by ground charcoal is attributed to the adsorption mechanism provided by ground charcoal but lacking in sand. Similar results were observed by Ochieng' (1999) when comparing the performance a dual media filter with ground charcoal as coarse medium, and rapid sand filter. Ochieng' observed that the dual media filter provided about 2 times more removal of organic particulates than the rapid sand

From the analysis of the raw water it was seen that the raw water had more dissolved and suspended solid than organic matter The filters therefore had more of inorganic impurities to remove and therefore reached terminal head loss due to the deposited flocs, and little due to the removal of organic matter. The filter beds would therefore need to be cleaned before carrying out another filter run It can therefore be said that the ground charcoal could still operate for a longer period of time before the regeneration process of removing the adsorbed organic matter is carried out.

4.2.2 High turbidity water

Turbidity removal with depth of media

The results of residual turbidity and percent turbidity removal with depth for the filter run that received Kirichwa Dogo water are shown in Figures 4.9 and 4.10.

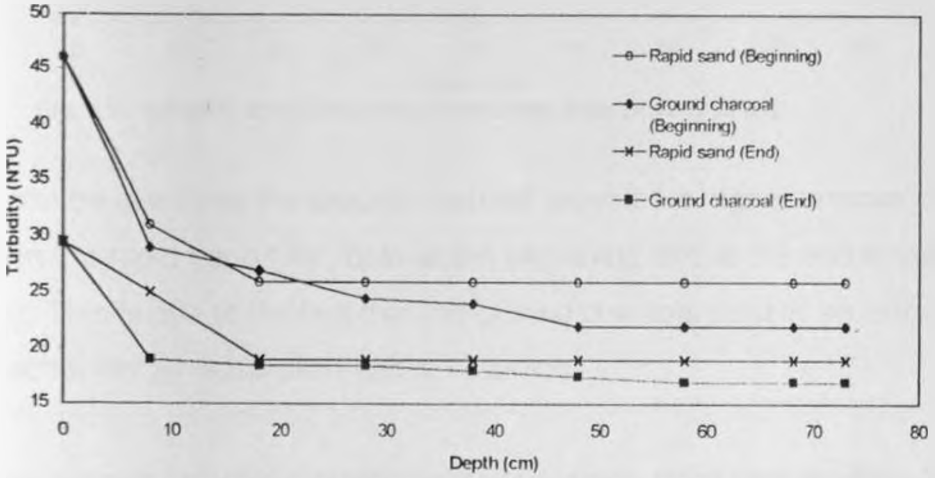

Fig. 4.9: Turbidity remaining with depth (high turbidity water)

From Figure 4.9, it is seen that the turbidity remaining after filtration with sand and ground charcoal is greater than 20 NTU and 15 NTU, respectively. These values are far much higher than the limiting value of 5 NTU given by the Kenya Bureau of Standards (KEBS, 1985) and the run was therefore terminated after 12 hours on the basis of turbidity breakthrough. For this reason some form of pre-treatment is required to reduce the load of impurities reaching the sand and the ground charcoal beds. Plain sedimentation may be a good pre-treatment method as no chemicals are required and may therefore be applied in isolated or remote areas where conventional water treatment methods are inaccessible. A study by Yao (1975) showed that Plain sedimentation is technically feasible for reducing a substantial amount of turbidity of natural waters. Yao observed that a residual turbidity lower than 10 TU can be obtained if reasonable settling time is provided

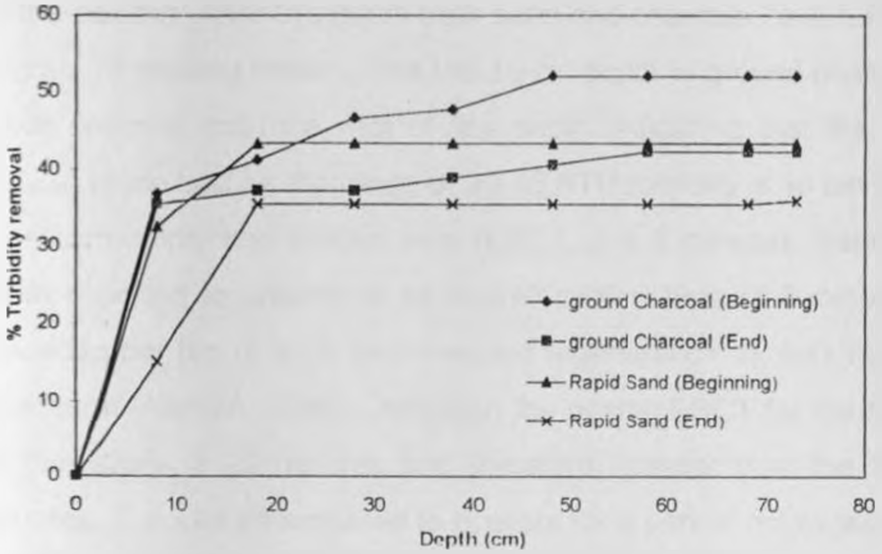

Fig. 4.10: Variation of turbidity removal with depth (high turbidity water)

It can be seen that the ground charcoal provided a higher removal of turbidity than the rapid sand filter, both at the beginning and at the end of the filter run. This is due to the fact that the ground charcoal posses an extra removal mechanism by adsorption above straining.

The percent turbidity removal increased rapidly from zero to about 37 percent in ground charcoal and 32 percent in sand within the first 10 cm depth at the beginning. At the end of the run, the removal was still high (36 percent) in ground charcoal at the same depth However, the percent removal fell rapidly in sand, with only about 15 percent removal within the same depth. This indicates about 3 percent loss of adsorption capacity of ground charcoal and 46 percent loss of removal efficiency by sand within the top 10 cm depth

The total removal in ground charcoal was about 52 percent while that of sand was 43 percent at the beginning of the filter run then 42 and 38 percent in ground charcoal and sand, respectively. at the end of the filter run. The total removal at the beginning indicates 20 percent and 10 percent at the end of filter run more removal in ground charcoal than sand

The curves representing the removal by sand and ground charcoal are seen to follow the same trend with the removal being more at the top 10 cm depth of the column. After this depth both sand and charcoal have turbidity removal slightly increasing linearly. The top 10 cm depth in ground charcoal provided more removal than the rest of the depth indicating that the critical depth ($L_{critical}$) of the bed for the range of 30-46 NTU turbidity is 10 cm. Therefore the minimum empty bed contact time ($EBCT_{min}$) is 3 minutes. Some plants have been reported to operate at an overall contact time of 3 minutes. However, the adsorber life of such beds needed regeneration in less than 30 days of operation (AWWA, 1990). Although the overall EBCT for the filter bed used in this study is 22 minutes and therefore, greater than the minimum of 3 minutes, it would be expected to operate for a period not exceeding 30 days. This is because the turbidity of the water is much greater than 10 NTU which as was seen in the previous section. The behaviour observed in Figure 4.10 is that of surface filtration. Surface filtration occurs if the solids content of the influent is very high or if the solids collection is too effective. The solids therefore collect at the top surface of the filter bed. This observation means that ground charcoal will not perform well in high turbidity waters and may require pre-treatment to reduce the amount of solids going into the filter bed. To achieve depth filtration with sand, a dual media filter may be used in place of rapid sand.

Although the rest of the bed provided little removal, it is important in both ground charcoal and sand. In sand the extra depth is important in preventing early turbidity breakthrough. Sources in literature comments that if the adsorber is to produce water of acceptable quality, then the critical depth of GAC and the corresponding minimum EBCT must be exceeded. Thus the depth of ground charcoal in excess of 10 cm (i.e. 53 cm) was important for the same reason of maintaining a quality of effluent provided by the minimum depth. However, the effluent had a turbidity greater than 5 NTU and was therefore terminated on the basis of turbidity breakthrough.

Turbidity removal with time

Figures 4.11 and 4.12 show the results of turbidity remaining and turbidity removal with time.

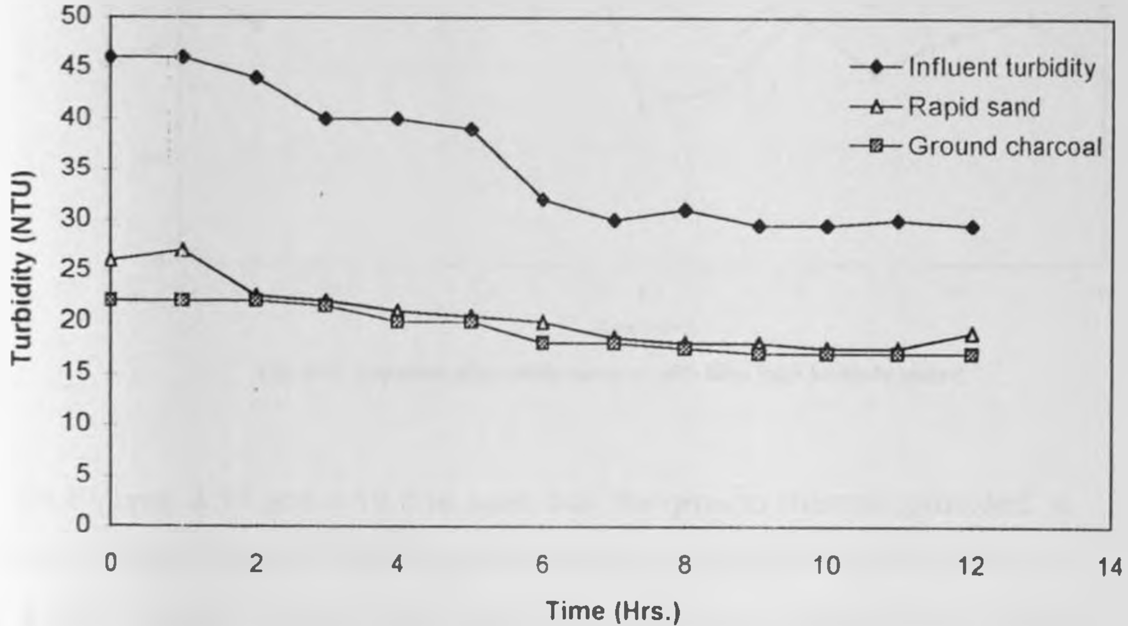

Fig. 4.11: Influent turbidity and turbidity remaining with time (high turbidity water)

The turbidity remaining throughout the period of the filter run was greater than the limit of 5 NTU indicating that a form of pre-treatment prior to filtration with both ground charcoal and sand is required to reduce the amount of impurities reaching the filter beds

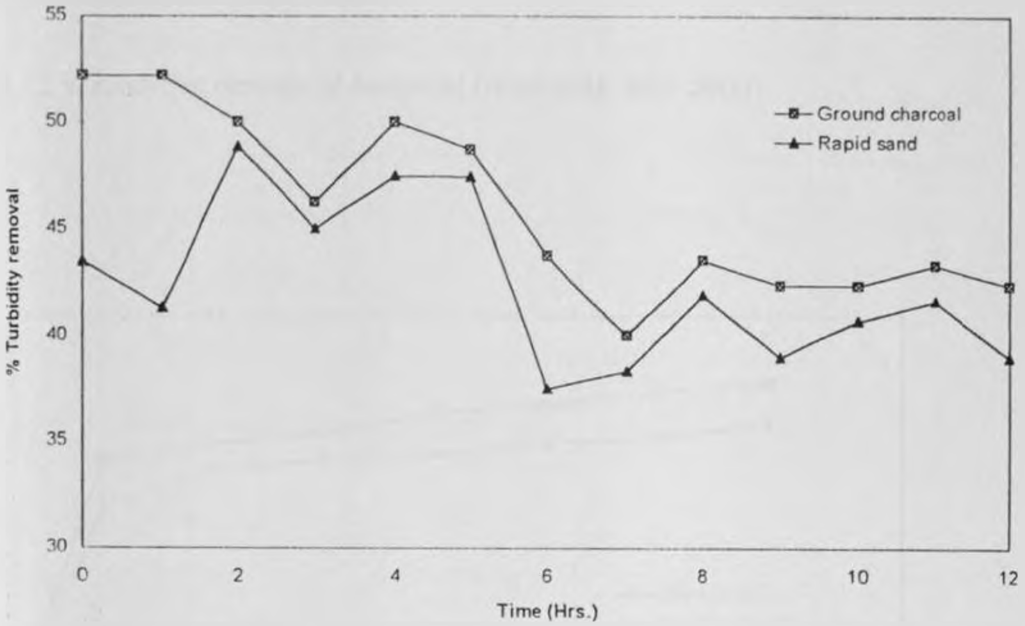

Fig. 4.12: Variation of turbidity removal with time (high turbidity water)

From Figures 4.11 and 4.12 it is seen that the ground charcoal provided a higher turbidity removal than the sand throughout the period of the filter run. The initial turbidity removal was about 52% in ground charcoal and 43% in sand. The ground charcoal therefore provided about 1.2 times more removal compared to sand. The removal in both ground charcoal and rapid sand fell with time to reach a final removal of about 42% and 39% in ground charcoal and sand , respectively. This is about 1.1 times more turbidity removal in ground charcoal compared to sand

Variation of head loss with depth

Figure 4.13 shows the results of terminal head loss with depth.

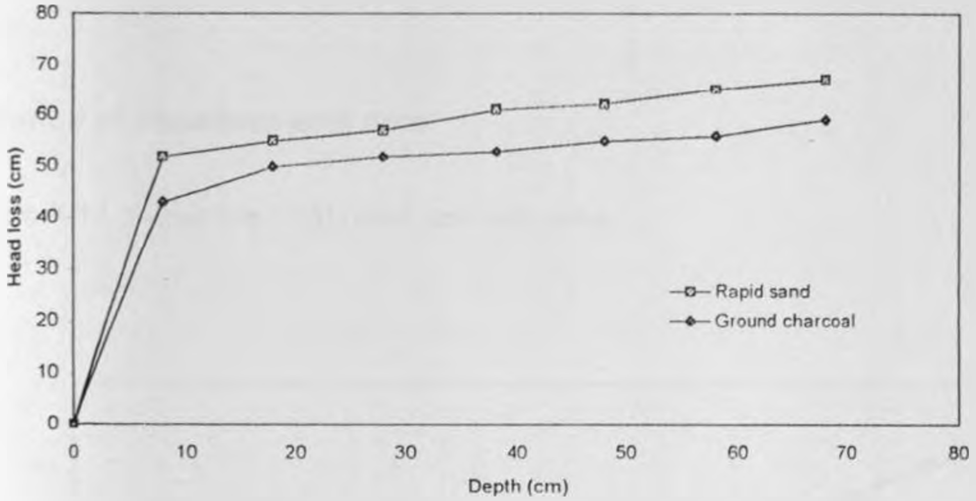

Fig. 4.13: Variation of terminal head loss with depth (high turbidity water)

From Figure 4.13 it is seen that the sand experienced a higher head loss development than ground charcoal throughout the depth of the filter bed. The head loss increased rapidly in both sand and ground charcoal to reach 52 cm and 43 cm , respectively within the top 10 cm. From 10 cm depth onwards, the head loss increased linearly at a small slope

The terminal head loss at the bottom of the media was 59 cm in ground charcoal and 67 cm in sand giving about 1.3 times head loss in rapid sand compared to ground charcoal.

Figure 4.11 is similar to Figure 4.10. Figure 4.10 showed that the highest turbidity removal took place in the top 10 cm depth of the filter bed. Therefore, this depth received the largest load of impurities and is therefore expected to develop the highest head loss (about 70 and 65 percent of the total head loss in sand and ground charcoal, respectively). A similar behaviour was observed by Ndiba (1992), where a head loss of 55 percent was in the top 10 cm sand layer when using a filter bed depth of 70 cm. After the filter bed attained a head loss of about 50 cm, it was observed to be constant with very little increase. This may be due to the fact that there was very little particulate removal in the rest of the depth after 10 cm due to limiting head loss development. The filter run was therefore terminated on the basis of turbidity breakthrough and did not attain a terminal head loss of 1.5 m.

Variation of head loss with time

Figure 4.14 shows the total head loss with time

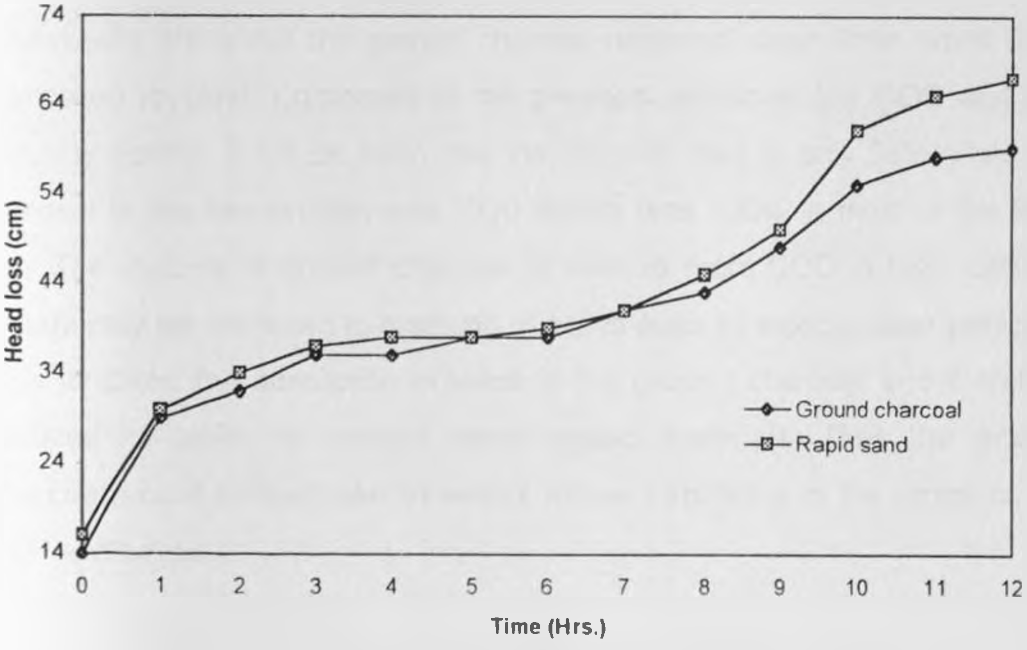

Fig. 4.14: Variation of total head loss with time (high turbidity water)

Figure 4.14 shows that the sand had a higher head loss than ground charcoal throughout the length of the filter run. The head losses increased linearly with time from 14 cm to 59 cm and 16 cm to 69 cm in ground charcoal and sand, respectively. These results shows 1.1 times head loss in sand compared to ground charcoal both at the beginning and at the end of the filter run.

COD Removal

The COD of the raw water was 168 mg/l The COD of the filtrate for this filter run was determined at the eighth hour after the beginning of the filter run. The results are summerised in Table 4 1 below

Table 4 1: Results of COD

Type of water	COD mg/l	% COD removal
Raw water	168	—
Filtrate (ground charcoal)	74	56
Filtrate (Sand)	138	18

The results show that the ground charcoal removed about three times COD compared to sand Compared to the previous results of low COD and low turbidity waters, it will be seen that the removal here is only 56% while the removal in the low turbidity and COD waters was 100% in most of the filter run. The inability of ground charcoal to remove more COD in high turbidity waters may be attributed to masking of active sites by muddy water particles. This inhibited the adsorption process in the ground charcoal and therefore reduced its ability to remove more organic materials Thus the ground charcoal would perform best in waters whose turbidity is in the range of 10 NTU and below

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Ground charcoal has the capacity to remove organic matter from water Ground charcoal therefore, has the potential for use in water treatment for the removal of organic matter in water Its ability to remove organic matter makes it more suitable to individual, small community and rural community water supplies where water contains organic matter, and chlorine is used as a disinfectant The ground charcoal provided a higher COD removal than sand and provided about 2 times COD removal in low turbidity waters compared to high turbidity waters This was attributed to masking of active sites and therefore no attachment between the carbon and humic acid Another reason is that the charcoal reached saturation and could not adsorb any more impurities.

Results of turbidity removal showed a superior performance by ground charcoal than sand filters by producing water of better quality The charcoal can therefore, replace sand in rapid sand filtration stage of a water treatment process for waters having turbidity amounts of up to 10 NTU. The turbidity removal by ground charcoal was between 40-52% in high turbidity waters and 41-65% in low turbidity waters This removal provided by a bed depth of 0.73 m is comparable to the removal provided by GAC where bed depths of 0.5-10 m have given 30-99% impurity removal The ground charcoal provided about 2 times more turbidity removal in low turbidity waters and 1.1 to 1.2 times more turbidity removal in high turbidity waters compared to sand.

Ground charcoal filters have the capacity to provide more filter run length compared to sand filters The ground charcoal provided 30% extra time of operation before the filter run was terminated based on head loss development. The development of head loss in low turbidity waters showed depth filtration while surface filtration was exhibited in high turbidity waters. Head loss development was high (1.2 to 2 times) in sand compared to that in ground charcoal.

5.2 Recommendations

The following recommendations have been suggested for further research on the applicability of ground charcoal as a filter media in waters containing organic matter:

1. Plain sedimentation should be assessed as a pre-treatment method with high turbidity waters. A research should also be done to establish practical rates of backwashing in ground charcoal filters treating high turbidity waters

2. Pilot plant studies should be done to establish the length of time the filter can operate before the charcoal is regenerated

3. The potential for regeneration of charcoal should be investigated.

4. Pilot plant studies should be done to establish the maximum filtration rates that can be applied to the filter while maintaining the acceptable drinking water quality standards.

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APPENDICES

APPENDIX 1

Media characteristics

APPENDIX IA THE WATTLE TREE

APPENDIX1A$_1$ MOISTURE CONTENT (MC) DETERMINATION

Sample	Initial wt. (g)	Final wt. (g)	Wt. of water (g)	mc %	Average mc
A	141.66	112.17	29.49	20.82	20.47
B	95.1	76.1	19	19.98	

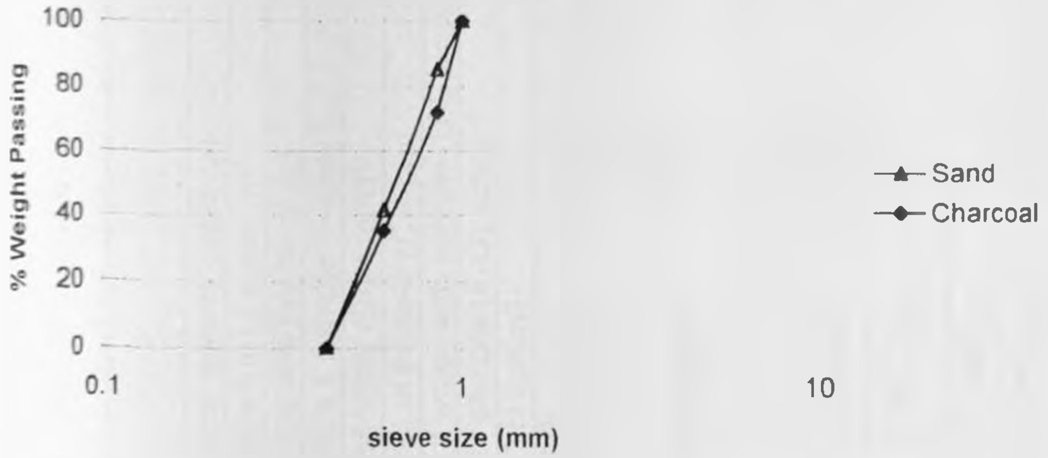
APPENDIX I A$_2$ SPECIFIC GRAVITY (Sg) DETERMINATION

Sample	Weight (g)	Volume (cm^3)	Sg (g/cm^3)	Avereage Sg
A	5.63	10	0.563	0.61
B	6.57	10	0.657	
C	6.11	10	0.611	

APPENDIX IB SIEVE ANALYSIS

Sieve size (mm)	Charcoal			Sand		
	Weight retained(g)	weight passing(g)	% weight passing	Weight retained(g)	weight passing(g)	% weight passing
0.42	3160.6	0	0	12590.4	0	0
0.6	3266.3	3160.7	35	13250	12590.4	41.44
0.85	2603	6427	71.71	4539.4	25840.4	85.06
1	0	9030	100	0	30379.8	100

Sieve analysis



APPENDIX 1C: SPECIFIC DENSITY

		Sand			**Charcoal (commercial)**			**Charcoal (laboratory made)**		
A	Wt. of empty density bottle (g)	50.2	50.80	36.2	52	36.3	51.65	50.9	35.5	36.15
B	Wt. of bottle full of water (g)	100.5	100.65	85.7	101.6	85.1	101.4	101.35	84.9	85.15
C	Wt. of bottle and dry sand (g)	77.85	86.80	85.75	60.1	51.4	68.25	59.8	49.45	46.25
D	Wt. of bottle + sample + water (g)	117.5	122.90	117.25	102.9	86.3	103.65	102.45	85.9	86.6
E	Volume of bottle (B-A) (cm3)	50.3	49.85	49.5	49.6	48.8	49.75	50.45	49.4	49
F	Wt. (mass) of sample (C-A) (g)	27.65	36	49.55	8.1	14.8	16.6	8.9	13.95	10.1
G	Volume of water with sample (D-C) (cm3)	39.65	36.1	31.5	42.8	34.9	35.4	42.65	36.45	40.35
H	Volume of sample (E-G) (cm3)	10.65	13.75	18	6.8	13.9	14.35	7.8	12.95	8.65
I	Density F/H (g/cm3)	2.596	2.618	2.753	1.191	1.065	1.157	1.141	1.077	1.168
	AVERAGE	2.656			1.138			1.129		

APPENDIX I D POROSITY

	Commercial charcoal			Laboratory made charcoal			Sand		
Density, ρs (g/m3)	1.138			1.129			2.656		
Volume V cm^3	45	33	37.5	42	39	41	45.5	41	95
Mass, M (g)	9.8	6.2	7.4	8.4	7.6	8.1	58.9	57.2	151.2
Porosity = $1 - M/P_s V$	0.809	0.835	0.827	0.823	0.827	0.825	0.466	0.475	0.401
Average porosity	0.824			0.825			0.447		

APPENDIX IE ACID SOLUBILITY TEST

	Ground charcoal	Sand
Wt. of crucible (g)	91.28	87.19
Wt. of sample + crucible before soaking in HCL (g)	106.28	137.19
Wt. of sample (g)	15	50
Observations	no effervescence	effervescence
Wt. of sample + crucible after soaking in HCL (g)	106.06	136.79
Wt. of sample (g)	14.78	49.6
Wt. loss (g)	0.22	0.4
% wt. loss	1.47	0.8

APPENDIX IF CARBON CONTENT DETERMINATION

Counter	Run	Weight (μg)	Sample identification
472	6	1303	commercial charcoal 1
473	7	1249	commercial charcoal 2
474	8	1552	Lab. made charcoal 1
475	9	1639	Lab. made charcoal 2

Counter	R_{-z}	Kc	Average Kc	Bc	Average (Bc)	Fill time (FT)
472	25128					19
473	24766	24 787	24 782	414	416.5	19
474	31543	24 777		419		18
475	32788					18

Counter	Raw results	% True Carbon (%C) %C=1/Kc*(R_{-z}-Bc)*100*1/wt	
		%C	Average %C
472	% C=83.526, %H=3.272, %N=-0.860, %Residue= 13.288	76.53	76.53
473	% C=85.866, %H=3.175, %N=-0.180, %Residue= 11.139	78.66*	
474	% C=88.258, %H=3.466, %N=-0.210, %Residue= 8.486	80.9	80.3
475	% C=86.905, %H=3.348, %N=-0.191, %Residue= 9.938	79.7	

* The results were affected by power blackout, and thus explains why they are very different from 76.53%. They were therefore not included in the calculation of the average carbon content.

APPENDIX 2

Filtration tests

DATE: 18.3.2000

APPENDIX 2A, FILTER RUN NO.1

MEDIA: GROUND CHARCOAL

FILTRATION RATE: 2m^3/m^2/hr

	TURBIDITY (NTU)										
Depth (cm)	0	8	18	8	18	28	38	48	58	68	73
Time (hr.)											
08:00	46	29	27	29	27	24.5	24	22	22	22	22
09:00	46	27	26	27	26	24	24	24	23	23	22
10:00	44	27	27	27	27	24.5	21	21	22.5	22	22
11:00	40	24	22	24	22	21	20	21	21	21	21.5
12:00	40	26	22.5	26	22.5	22	20	19	21	21	20
13:00	39	22	22	22	22	21	20	20	20.5	20.5	20
14:00	32	21	21	21	21	20.5	19.5	18	18	18	18
15:00	30	21	21	21	21	19	18	18	18	18	18
16:00	31	20.5	19.5	20.5	21	19	17.5	17.5	17.5	17.5	17.5
17:00	29.5	19.5	18	19.5	18	18	17	17.5	18	18	17
18:00	29.5	19.5	18	19.5	18	18	17	17	17.5	17.5	17
19:00	30	19.5	18.5	19.5	18.5	17.5	18	17.5	17.5	17.5	17
20:00	29.5	19	18.5	19	18.5	18.5	18	17.5	17	17	17

DATE: 18.3.2000

APPENDIX 2A, FILTER RUN NO.1

MEDIA: GROUND CHARCOAL

FILTRATION RATE: 2m^3/m^2/hr

	HEAD LOSS (cm)									
Depth (cm)	0	8	18	8	18	28	38	48	58	68
Time (hr.)										
08:00	124	120	119	120	119	118	117	114	113	110
09:00	122	111	104	111	104	101	100	97	96	93
10:00	117	100	93	100	93	91	90	88	87	85
11:00	117	99	91	99	91	88	87	85	84	81
12:00	120	101	94	101	94	91	90	88	87	84
13:00	120	100	93	100	93	90	89	86	85	82
14:00	120	98	91	98	91	88	87	85	84	82
15:00	119	95	88	95	88	86	85	82	81	78
16:00	118	90	83	90	83	81	80	79	77	75
17:00	113	81	74	81	74	72	71	69	68	65
18:00	113	74	67	74	67	65	64	62	61	58
19:00	113	73	64	73	64	62	61	59	58	55
20:00	118	75	68	75	68	66	65	63	62	59

DATE: 18.3.2000

APPENDIX 2A$_2$ FILTER RUN NO.1

MEDIA: RAPID SAND

FILTRATION RATE: 2m^3/m^2/hr

	TURBIDITY (NTU)										
Depth (cm)	0	8	18	8	18	28	38	48	58	68	73
Time (hr.)											
08:00	46	31	26	31	26	26	26	26	26	26	26
09:00	46	29	27	29	27	27	27	27	27	27	27
10:00	44	26	23	26	23	23	23	22.5	22.5	22.5	22.5
11:00	40	26	24	26	24	23	23	23	23	22	22
12:00	40	27	22	27	22	22	22	22	21	21	21
13:00	39	28	22	24	22	22	22	22	22	20.5	20.5
14:00	32	28.5	21	28.5	21	20	20.5	20.5	20	20	20
15:00	30	27.5	27.5	27.5	20.5	20.5	20.5	20.5	20	19	18.5
16:00	31	26	20	26	20	19.5	19.5	19.5	19	18	18
17:00	29.5	25.5	19.5	25.5	19.5	19.5	19.5	19.5	19	18	18
18:00	29.5	25	19.5	25	19.5	19.5	19.5	19.5	19	18	17.5
19:00	30	26.5	18.5	26.5	18.5	18.5	18.5	18.5	18.5	18	17.5
20:00	29.5	25	18.5	25	18.5	18.5	18.5	18.5	18	18	18

DATE: 18.3.2000

APPENDIX $2A_2$ FILTER RUN NO.1

MEDIA: RAPID SAND

FILTRATION RATE: $2m^3/m^2/hr$

	HEAD LOSS (cm)									
Depth (cm)	0	8	18	8	18	28	38	48	58	68
Time (hr.)										
08:00	117	113	111	113	111	110	107	104	102	101
09:00	111	90	89	90	89	88	86	85	83	81
10:00	104	79	78	79	78	76	74	73	72	70
11:00	104	79	76	79	76	75	73	70	69	67
12:00	106	76	75	76	75	74	72	70	69	68
13:00	106	75	74	75	74	74	71	69	68	68
14:00	106	78	75	73	75	74	71	69	68	67
15.00	102	72	70	72	70	69	67	64	63	61
16:00	102	64	63	64	63	62	61	59	58	57
17:00	104	64	63	64	63	61	59	57	56	54
18:00	104	58	56	58	56	54	50	49	46	43
19:00	108	57	54	57	54	52	49	48	45	43
20:00	110	58	55	58	55	53	49	48	45	43

DATE: 12.7.2000

APPENDIX $2B_1$ FILTER RUN NO.2

MEDIA: GROUND CHARCOAL

FILTRATION RATE: $2m^3/m^2/hr$

TURBIDITY (NTU)

Depth (cm)	0	8	18	28	38	48	58	68	73
Time (hrs.)									
9:00 AM	4.6	3.9	3.5	3.3	3.1	2.8	2.5	2	1.6
10:00 AM	4.6	3.9	3.5	3.2	3	2.8	2.6	2.2	1.9
11:00 AM	4.6	3.9	3.5	3.3	3.2	3	2.9	2.5	2.2
12:00 PM	4.7	4	3.6	3.4	3.3	3.2	3	2.8	2.5
1:00 PM	4.6	4.4	3.9	3.7	3.4	3.2	3.2	3.1	2.7
2:00 PM	4.6	4.5	3.8	3.5	3.4	3.3	3.2	3.1	2.8
3:00 PM	4.7	4.4	3.8	3.6	3.5	3.3	3.2	3.1	2.8
5:00 PM	4.6	4.5	3.9	3.7	3.5	3.4	3.3	3.2	2.8
7.00PM	4.6	4.5	3.9	3.7	3.5	3.4	3.3	3.2	2.8
9:00PM	4.5	4.4	4	3.9	3.8	3.6	3.5	2.8	2.5
11:00 PM	8.8	4.4	3.7	3.5	3.4	3.3	3.2	2.9	3.7
1:00AM	8.4	4.5	4.2	3.8	3.7	3.6	3.5	3.4	3.3
3:00AM	8.2	4.3	4.2	3.8	3.7	3.6	3.5	3.4	3.3
5:00AM	6.5	5.4	5.2	4.9	4.6	3.9	3.5	3.3	3.1
7:00AM	6.2	5.7	5.2	4.7	4.2	3.7	3.5	3.3	3.1
9:00AM	6.2	5.2	4.7	4.5	4.4	4.2	4	3.5	3
11:00AM	5.5	5.3	4.9	4.6	4.3	4	3.7	3.4	2.7
13:00:00	6.5	6.1	5.3	4.8	4.5	4	3.7	3.6	3
15:00:00	6.4	5.9	5.5	5.1	4.8	4.4	3.9	3.5	3.1
17:00	6.4	5.8	5.5	5	4.7	4.5	4.2	3.6	3.3

DATE: 12.7.2000

APPENDIX 2B, FILTER RUN NO.2

MEDIA: GROUND CHARCOAL

FILTRATION RATE: 2m^3/m^2/hr

HEAD LOSS (CM)

Depth (cm)	0	8	18	28	38	48	58	68
Time (hrs.)								
9:00 AM	144	143	142	141	139	138	137	137
10:00 AM	154	153	151	149	148	147	146	144
11:00 AM	157	153	150	148	147	145	143	141
12:00 PM	156	150	147	142	138	136	134	133
1:00 PM	154	148	145	141	139	138	133	127
2:00 PM	153	150	146	140	137	131	127	121
3:00 PM	146	145	143	132	125	118	113	109
5 00 PM	155	150	149	146	139	135	122	115
7:00PM	159	155	151	146	140	135	124	112
9:00PM	158	151	149	147	136	129	118	105
11:00 PM	158	152	148	146	142	127	110	96
1:00AM	158	156	150	143	138	125	107	81
3:00AM	160	157	145	136	129	117	98	66
5:00AM	160	155	142	128	121	115	96	50
7:00AM	163	156	140	129	119	112	93	42
9:00AM	181	166	155	144	132	121	107	54
11.00AM	173	158	147	130	123	111	107	38
13:00:00	172	158	145	128	121	109	88	33
15:00:00	157	143	135	124	105	92	59	11
17:00	176	162	148	129	105	83	59	25

DATE: 12.7.2000

APPENDIX $2B_2$ FILTER RUN NO.2

MEDIA: RAPID SAND

FILTRATION RATE: $2m^3/m^2/hr$

TURBIDITY (NTU)

Depth (cm)	0	8	18	28	38	48	58	68	73
Time (hrs.)									
9:00 AM	4.6	4.3	4.2	4	3.8	3.7	3.5	3.4	3.3
10:00 AM	4.6	4.4	4.2	4	3.9	3.8	3.7	3.6	3.5
11:00 AM	4.6	4.5	4.3	4	3.9	3.7	3.7	3.6	3.5
12:00 PM	4.7	4.6	4.2	4	3.9	3.8	3.7	3.6	3.4
1:00 PM	4.6	4.5	4.3	4.1	4	3.9	3.8	3.6	3.4
2:00 PM	4.6	4.4	4.2	4.1	4	3.9	3.8	3.7	3.5
3.00 PM	4.7	4.5	4.3	4	4	3.9	3.9	3.8	3.4
5:00 PM	4.6	4.4	4.2	4.1	4	3.9	3.7	3.5	3.4
7:00PM	4.5	4.4	4.3	4.2	4	3.8	3.6	3.4	3.2
9:00PM	4.5	4.4	4.3	4.1	3.9	3.6	3.4	3.1	2.9
11:00 PM	8.8	7.9	6.7	6.2	5.8	5.3	4.7	4.4	4
1:00AM	8.4	6.8	6.5	5.3	5.1	4.5	4	3.8	3.7
3:00AM	8.2	6.4	5.9	5.6	5.2	4.7	4.3	4.1	3.9
5:00AM	6.5	5.9	5.4	4.8	4.6	3.8	3.7	3.6	3.5
7:00AM	6.2	5.6	5.2	4.4	4	3.9	3.8	3.7	3.5
9:00AM	6.1	5.4	4.9	4.5	4.3	4	3.9	3.7	3.9
11:00AM	5.5	5.2	5.1	4.9	4.6	4.5	4.3	4.2	4.1

DATE: 12.7.2000

APPENDIX $2B_2$ FILTER RUN NO.2

MEDIA: RAPID SAND

FILTRATION RATE: $2m^3/m^2/hr$

HEAD LOSS (CM)

Depth (cm)	0	8	18	28	38	48	58	68
Time (hrs.)								
9.00 AM	137	133	130	129	126	125	123	122
10:00 AM	126	122	120	119	112	110	108	105
11:00 AM	121	117	116	114	105	104	103	95
12:00 PM	114	110	109	105	100	97	96	85
1.00 PM	113	106	103	102	100	97	94	78
2:00 PM	112	105	102	101	97	91	83	73
3 00 PM	113	106	103	100	98	90	80	69
5 00 PM	120	110	107	104	99	92	76	70
7 00PM	119	109	106	94	91	87	73	60
9 00PM	106	95	91	86	74	58	51	40
11 00 PM	106	95	90	82	73	58	44	29
1:00AM	113	99	93	84	71	60	49	21
3:00AM	130	115	102	81	73	63	41	20
5:00AM	136	117	99	72	64	55	37	14
7 00AM	141	118	101	74	63	54	36	10
9:00AM	147	122	102	75	67	56	39	6
11 00AM	161	133	113	91	71	51	30	6

APPENDIX 3

Results of filtration tests

Appendix 3A Low Turbidity Water

Appendix 3A$_1$ Residual Turbidity with depth

Depth (cm)	Residual Turbidity (NTU)			
	Ground charcoal (Beginning)	Ground charcoal (End)	Sand (Beginning)	Sand (End)
0	4.6	6.4	4.6	5.5
8	3.9	5.8	4.3	5.2
18	3.5	5.5	4.2	5.1
28	3.3	5.0	4.0	4.9
38	3.1	4.7	3.8	4.6
48	2.8	4.5	3.7	4.5
58	2.5	4.2	3.5	4.3
68	2	3.6	3.4	4.2
73	1.6	3.3	3.3	4.1

Appendix 3A$_2$Turbidity removal with depth

Depth (cm)	% Turbidity removal			
	Ground charcoal (Beginning)	Ground charcoal (End)	Sand (Beginning)	Sand (End)
0	0	0	0	0
8	15	9	7	5
18	24	14	9	7
28	28	22	13	11
38	33	27	17	16
48	39	30	20	18
58	46	34	24	22
68	57	44	26	24
73	65	48	28	25

Appendix 3A, Influent, residual turbidity and turbidity removal with time

Time (Hrs.)	Influent turbidity	Residual Turbidity (NTU)		% Turbidity removal	
		Ground chacoal	Sand	Ground charcoal	Sand
0	4.6	1.6	3.3	65	28
1	4.6	1.9	3.5	59	24
2	4.6	2.2	3.5	52	24
3	4.7	2.5	3.4	47	28
4	4.6	2.7	3.4	41	26
5	4.6	2.8	3.5	39	24
6	4.7	2.8	3.4	40	28
7	4.6	2.8	3.4	39	26
9	4.6	2.8	3.2	39	29
11	4.5	2.5	2.9	44	36
13	8.8	3.7	4	58	55
15	8.4	3.3	3.7	61	56
17	8.2	3.3	3.9	60	52
19	6.5	3.1	3.5	52	46
21	6.2	3.1	3.5	50	44
23	6.2	3	3.9	52	36
25	5.5	2.7	4.1	51	25
27	6.5	3		54	
29	6.4	3.1		52	
31	6.4	3.3		48	

Appendix $3A_4$ Distribition of Initial and terminal head loss

Depth (cm)	Head loss (cm)			
	Ground charcoal (Initial)	Ground charcoal (terminal)	Sand (Initial)	Sand (Terminal)
0	0	0	0	0
8	1	14	4	23
18	2	28	7	48
28	3	47	8	70
38	5	71	11	90
48	6	93	12	110
58	7	117	14	131
68	7	151	15	155

Appendix $3A_5$ Distribution of total head loss with time

Time (hrs.)	Head loss (cm)	
	Ground charcoal	Sand
0	7	15
1	10	21
2	16	26
3	23	29
4	27	35
5	32	39
6	37	44
7	40	50
9	47	59
11	53	66
13	62	77
15	77	92
17	94	110
19	110	122
21	121	131
23	127	141
25	135	155
27	139	
29	146	
31	151	

Appendix 3A_6 Residual COD with time

Time of sampling (hrs.)	Residual COD (mg/l)	
	Gound charcoal	Sand
0	0	8
4	0	8
8	0	8
12	0	8
16	0	8
20	0	9
24	4	10
26	4	10
28	4	
30	4	
31	4	

Note initial COD = 16 mg/l
initial COD was determined after the filtration system had stabilised

Appendix 3A_7 COD removal with time

Time of sampling (hrs.)	% COD removal	
	Ground charcoal	Sand
0	100	50
4	100	50
8	100	50
12	100	50
16	100	50
20	100	44
24	75	38
26	75	38
28	75	
30	75	
31	75	

Appendix 3B High Turbidity Water

Appendix $3B_1$ Residual turbidity and turbidity removal with depth of media

DEPTH (cm)	GROUND CHARCOAL				RAPID SAND			
	Beginning		End		Beginning		End	
	Turbidity (NTU)	% Turbidity removal	Turbidity (NTU)	% Turbidity removal	Turbidity (NTU)	% Turbidity removal	Turbidity (NTU)	% Turbidity removal
0	46	0	29.5	0	46	0	29.5	0
8	29	37	19	36	31	33	25	15
18	27	41	18.5	37	26	43	19	36
28	24.5	47	18.5	37	26	43	19	36
38	24	48	18	39	26	43	19	36
48	22	52	17.5	41	26	43	19	36
58	22	52	17	42	26	43	19	36
68	22	52	17	42	26	43	19	36
73	22	52	17	42	26	43	19	36

Appendix $3B_2$ Influent turbidity, turbidity remaining and turbidity removal with time

Time (hr.)	Influent turbidity	Turbidity remaining (NTU)		% turbidity removal	
		Ground charcoal	Rapid sand	Ground charcoal	Rapid sand
0	46	22	26	52	43
1	46	22	27	52	41
2	44	22	22.5	50	49
3	40	21.5	22	46	45
4	40	20	21	50	48
5	39	20	20.5	49	47
6	32	18	20	44	38
7	30	18	18.5	40	38
8	31	17.5	18	44	42
9	29.5	17	18	42	39
10	29.5	17	17.5	42	41
11	30	17	17.5	43	42
12	29.5	17	19.0	42	39

Appendix $3B_3$ Variation of terminal head loss with depth

Depth (cm)	Head loss (cm)	
	Ground charcoal	Rapid sand
0	0	0
8	43	52
18	50	55
28	52	57
38	53	61
48	55	62
58	56	65
68	59	67

Appendix $3B_4$ Variation of total head loss with time

Time (hr.)	Head loss (cm)	
	Ground charcoal	Rapid sand
0	14	16
1	29	30
2	32	34
3	36	37
4	36	38
5	38	38
6	38	39
7	41	41
8	43	45
9	48	50
10	55	61
11	58	65
12	59	67