DESIGN AND EVALUATION OF A COST EFFECTIVE HOUSEHOLD DRINKING WATER TREATMENT SYSTEM

by

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DEDICATION

This work is dedicated to Overseer FD Ngwenya, and my parents, D Mahlangu and V Mahlangu.
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Presentations and Publications

This research work has been presented in regional, national and international conferences and some of it has been submitted for publication in peer reviewed journals.

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Publications:

1. JK Mwabi, FE Adeyemo, TO Mahlangu, BB Mamba, BM Brouckaert, CD Swartz, G Offringa, L Mpenyana-Monyatsi and MNB Momba. Household
water treatment systems: a solution to the production of safe drinking water by the low-income communities of Southern Africa. Accepted for publication in the Journal of Physics and Chemistry of the Earth and subject to correction.

2. TO Mahlangu, L Mpenyana-Monyatsi, MNB Momba and BB Mamba. A simplified cost-effective biosand filter (BSFZ) for removal of chemical contaminants from water. Accepted for publication in the Journal of Chemical Engineering and Materials Science and subject to correction.

3. TO Mahlangu, L Mpenyana-Monyatsi, BB Mamba and MNB Momba. Efficiency of SIPP for production of clean potable water at lower costs. Accepted for publication in the South African Journal of Science and subject to correction.

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ABSTRACT

The world is focusing on increasing the number of people who have access to safe drinking water due to the ascending numbers of drinking water related illnesses reported annually in rural areas where water is not treated before consumption. To meet this goal, household water treatment has to be introduced especially in places where homes are wide apart making centralised water treatment improbable. Most readily available household water treatment systems (HWTS) such as membrane filters may not be affordable in rural areas due to power requirements and degree of ability to use and maintain them. This study was therefore aimed at designing and constructing HWTS using readily available material such as sand, gravel, zeolites and clays. Five HWTS were designed, built, evaluated and compared based on their ability to remove chemical contaminants such as iron, arsenic and fluorides from drinking water. The types of filters that were used during this study are the biosand filter (BSF), a modified biosand filter with zeolites (BSFZ), a silver impregnated porous pot (SIPP) filter, a ceramic candle filter (CCF) and a bucket filter (BF). Effectiveness of the filters in reducing physical parameters such as turbidity and visual colour was also assessed. The water treatment devices had the following flow rates; 1.74 L/h – 19.20 L/h (BSFZ), 0.81 L/h – 6.84 L/h (BSF), 0.05 L/h – 2.49 L/h (SIPP) and 1.00 L/h – 4.00 L/h (CCF). The flow rates were high at the early stages of filter use and decreased with increase in the volume of water filtered through. The flow rates of the filters were affected by the turbidity of intake water which was between 1.74 NTU – 42.93 NTU and correlated to chlorophyll a concentrations. The household water treatment technologies reduced turbidity to levels less than 1 NTU (> 90% reduction) in the following order SIPP > BSFZ > BSF > CCF > BF. The filters achieved greater than 60% retention of calcium, magnesium, iron and arsenic. These contaminants with the exception of arsenic were reduced to acceptable levels of the South African National Standard of drinking water (SANS 241, 2004). Compared to the other filters, the BSFZ performed better in removing nitrates, phosphates and fluorides although the overall retention efficiency was low. Total organic carbon was removed greatly by the CCF (39%) and the least removal was by the BF. The overall performance of the filters in reducing contaminants from drinking water was in the order BSFZ > BSF > SIPP > CCF > BF. Filter washing
resulted in an overall increase in the flow rates of the filters but negatively affected turbidity reduction. The filters still removed contaminants after total cumulative volumes of 1200 L (BSFZ, BSF, CCF and BF) and 300 L (SIPP) were filtered through the devices. The five evaluated filters have several advantages to the readily available technologies and the advantages include ease of construction, operation and maintenance. The filters are gravity driven and work independent of temperature. These HWTS incorporate safe storages fitted with spigots to eliminate recontamination of water when it is drawn for use. The filters can produce enough drinking and cooking water for a family of six members due to their high flow rates. The BSFZ, BSF, SIPP, CCF and BF may therefore be considered for treating contaminated water at household scale in places where water is taken directly from the source without treatment.
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<td>HWTS</td>
<td>Household Water Treatment Systems</td>
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<tr>
<td>BSFZ</td>
<td>Biosand Filter with Zeolites</td>
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<tr>
<td>BSF</td>
<td>Biosand Filter</td>
</tr>
<tr>
<td>SIPP</td>
<td>Silver Impregnated Porous Pot</td>
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<tr>
<td>CCF</td>
<td>Ceramic Candle Filter</td>
</tr>
<tr>
<td>BF</td>
<td>Bucket Filter</td>
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<tr>
<td>NTU</td>
<td>Nephelometric Turbidity Units</td>
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<td>SANS</td>
<td>South African National Standard</td>
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<td>SA</td>
<td>South Africa</td>
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<tr>
<td>SADC</td>
<td>Southern African Developing Community</td>
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<tr>
<td>MDG</td>
<td>Millennium Development Goal</td>
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<td>TOC</td>
<td>Total Organic Carbon</td>
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<td>h</td>
<td>Hours</td>
</tr>
<tr>
<td>L</td>
<td>Litre</td>
</tr>
<tr>
<td>DC</td>
<td>Developing Countries</td>
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<tr>
<td>POU</td>
<td>Point Of Use</td>
</tr>
<tr>
<td>GAC</td>
<td>Granular Activated Carbon</td>
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<tr>
<td>ANOVA</td>
<td>Analysis Of Variance</td>
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<tr>
<td>DWAF</td>
<td>Department of Water Affairs and Forestry</td>
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<tr>
<td>WHO</td>
<td>World Health Organisation</td>
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<tr>
<td>AAS</td>
<td>Atomic Absorption Spectroscopy</td>
</tr>
<tr>
<td>UV</td>
<td>Ultra-violet</td>
</tr>
<tr>
<td>TISAB</td>
<td>Total Ionic Strength Adjuster Buffer</td>
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<tr>
<td>ISE</td>
<td>Ion Selective Electrode</td>
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TC  Total Carbon
IC  Inorganic Carbon
PFP  Potters For Peace
SODIS  Solar Disinfection
WADIS  Water Disinfection Stove
CFU  Coliform Forming Unit
RO  Reverse Osmosis
MF  Microfiltration
BOD  Biological Oxygen Demand
Eq.  Equation
SARA  South African Rural Areas
SSF  Slow Sand Filter
TUT  Tshwane University of Technology
Chl a  Chlorophyll a
SWL  Surface Water with Low turbidity
SWH  Surface Water with High turbidity
GWL  Ground Water with Low turbidity
GWH  Ground Water with High turbidity
BT  Before Treatment
AT  After Treatment
ICAITI  Central American Institute of Industrial Technology
FSF  Fast Sand Filter
CHAPTER 1
INTRODUCTION

1.1 Problem Statement
Water purity and scarcity are serious problems facing rural areas in developing countries (DCs). This is a surprising concern, considering that water is a primary necessity for all human beings, yet an estimate of about one billion people lack potable water globally.\textsuperscript{1,2} Industrialisation amongst other factors, has contributed to the scarcity of safe drinking water in developing countries.\textsuperscript{3} Chemical contaminants especially heavy metals get into water sources where people draw water for use as a result of acid mine drainage and industrialisation. This has resulted in water associated diseases that claim about two and a half billion death annually and approximately six thousand children daily from diarrhoea.\textsuperscript{4,5}

The escalating concerns about water purity have effected a significant growth in household water treatment systems (HWTS) in recent years.\textsuperscript{3,6} This has prompted the United Nations to set up a Millennium Development Goal (MDG) that will increase the number of people worldwide who have access to clean potable water.\textsuperscript{7} This goal was set to be accomplished by the year 2015; hence excessive research work is in progress to meet such a goal. Safe drinking water is essential in reducing the number of deaths due to exposure to contaminated water and where the local authority cannot provide clean drinking water to the community, home water treatment becomes an important factor.
Household water treatment ensures that the water drawn for consumption has reduced pollutants that are within tolerable levels. Through household treatment, one can be sure of scrapping off problems associated with drinking water pollution in rural areas of developing countries.

1.2 Justification
Household water treatment has become a major intervention in rural areas of developing countries since the introduction of HWTS. Van Halem adopted five criteria to investigate sustainability of HWTS and mentioned that these HWTS have contributed to reaching people in the short-term. A degree of expertise and commitment by users is a need for the success of these technologies. The adopted criteria include accessibility, water quality, water production, functionality and environmental foot print. Generally, application of traditional knowledge and practices may be a solution to clean drinking water in developing countries.

Household water treatment systems are considered cheap and effective in preventing or reducing waterborne diseases in rural areas of DCs. These HWTS would be an addition to other good practices such as improved hygiene, sanitation and improved water supply. Although there are a vast number of water treatment methods such as reverse osmosis and membrane filtration, these methods have been found to have some limitations and hence there is need for the development of a much efficient HWTS. Excessive research has been carried out to find the best method that can reduce colour and turbidity, with the removal of microorganisms such as Cryptosporidium and Giardia together with chemical contaminants. Due to the increase in the number of death reported every year as a result of drinking contaminated water, point of use (POU) water treatment systems are encouraged in rural areas of these DC. An ideal water treatment system for developing countries should be able to remove all chemical and microbial contaminants in one single filtration process. These filters should reduce contaminants to acceptable levels while retaining their permeability and efficiency over extended periods. Low cost and readily available materials which are efficient
in removing contaminants from drinking water are considered to be a solution for clean water in rural areas of DC. These materials include activated alumina, agricultural by-products (e.g. rice hulls), apatite, clay minerals, granular activated carbon (GAC), industrial by-products, iron oxide (coated sands), manganese oxide (coated sands), metallic iron (Fe), peat and peat moss, phosphate rocks, seaweeds and their derivatives, wood chips, and zeolites.11

This research study was aimed at designing and evaluating cost effective household water treatment systems (HWTS) using readily available material such as sand, gravel, clays and zeolites. The effectiveness of the designed HWTS was evaluated based on their ability to remove microorganisms such as pathogenic bacteria, protozoan parasites and viruses and chemical contaminants such as arsenic, fluorides, total organic carbon, nitrates, phosphates and iron from potable water. Based on the efficiency and limitations of the previously evaluated HWTS, a water purification system (which was a hybrid system) was designed and evaluated for treating typical rural water which contained pathogens and chemical contaminants.

In planning this study, the following points were taken into consideration:

1. Household water treatment devices such as solar cookers, bucket filters and clay pots have been proven to have limited efficiency in removing chemical contaminants such as arsenic, fluorides and nitrates. This study was aimed at evaluating, designing and constructing a more efficient HWTS for water purification in rural areas.

2. It is a fact that water purity is compromised in many developing countries which are associated with notorious waterborne diseases. Increasing HWTS’ efficiency will result in high water purity and if possible eliminate waterborne diseases through the removal of micro-organisms and chemical contaminants.
3. Most developing countries do not afford the HWTS that are in the market because they are expensive. The use of cheap but good quality (efficient) material such as very fine sand, gravel and zeolites for HWTS construction may result in excellent systems that may be affordable to the third world countries.

4. Maintenance and operational costs of most HWTS are too high due to high power requirements for functioning and have short life spans. This study was aimed at reducing these costs by selecting readily available HWTS, and modify their designs to come up with gravity operated filters with lengthened life spans.

Evaluation and selection criteria were developed to come up with HWTS that were tested in this study. These selection criteria encompassed availability and cost of construction material.

1.3 Evaluation and Selection Criteria
Due to the vast number of HWTS available in the market, it became a critical step to decide which devices would be evaluated for the purpose of this study. The following points were considered before the devices were selected:

1. The HWTS should produce water that complies with SANS, 241 limits. Microorganisms and chemical contaminants should be within the recommended limits after filtration and these limits should be comparable to local and international standards.

2. The HWTS should be user friendly in a way that putting water into the device and cleaning should be fairly simple.

3. Construction of the HWTS should be easy and construction material should be readily available and affordable to the rural people.
4. The HWTS should be cheaper to manufacture, run and maintain. This is important because cheaper devices can be afforded by the poorest of the poor. The HWTS should not require power and higher pressures for operation.

The HWTS should produce water enough for drinking and cooking, ideally the device should produce 25 L per day.

1.4 Aims and Objectives

The study was aimed at designing, constructing and evaluating a cost effective household water treatment system that could be used for water treatment in rural areas of South Africa. Specific objectives of this study were:

1. To select commercially available HWTS and evaluate their efficiency in purification or performance in eliminating chemical contaminants from drinking water.

2. To create a database collection of efficient HWTS which rural people can rely on for water treatment at homes.

3. To design and construct HWTS from cheap material with high effectiveness in removing chemical contaminants, and evaluate the efficiency of the constructed filters.

4. To select cheap material such as sand, gravel and clinoptilolite and use them in constructing HWTS. These treatment systems will be used in rural areas of developing countries.

5. To select and evaluate HWTS for various properties such as life span and maintenance costs. This will be achieved by carrying out successive field and laboratory tests. The filtration efficiency when the devices were new was compared with efficiency after the devices have been used for a certain period.
6. To evaluate the effectiveness of selected HWTS in reduction of physical parameters in contaminated water. These physical parameters included turbidity, visual colour and hardness.

7. To measure the level of water decontamination by the selected HWTS. Physical parameters together with the amount of chemical contaminants were determined before and after filtration.

8. To carry out laboratory tests on the selected HWTS and the modified and constructed filter. Results were used in carrying out statistical analysis such as analysis of variance (ANOVA). This was to determine whether there was a significant difference in effectiveness between the designed (modified) and standard HWTS.
1.5 Study Outline

Introduction of this dissertation with highlights on the need to improve water quality through household water treatment practices is done in Chapter 1.

Chapter 2 discusses health effects of contaminants in drinking water, their removal methods and advancements made on water treatment at household scale.

Chapter 3 describes a modified biosand filter, enhancement in contaminant removal efficiency as a result of adjustments, and cost and maintenance of the water treatment technology.

Chapter 4 presents results of the efficiency of a Silver Impregnated Porous Pot (SIPP) filter, difference of the SIPP to other clay pot filters, cost and maintenance practices.

Chapter 5 reports on a comparative study of three household water treatment systems, cost and maintenance procedures.

Chapter 6 discusses the overall conclusions and recommendations of the study.
1.6 References


2.1 Introduction
This chapter discusses related work that has been done on water quality, supply, missing gaps and advancements that could be taken into account to improve water quality in rural areas of developing countries.

2.2 Water Utilities in South Africa (SA)
The water purification and supply industry is important in maintaining community health and sustaining industry, business and agriculture. Present water reticulation systems depend on treated water. Smith and Ali predicted that water demand between countries is a function of culture, climate change and wealth. There is therefore fluctuation in water need between countries. The diurnal variation in water demand varies between peak and off peak usages and also with season of the year. Estimating water usage is a hard task to undertake as there are variations in water use and the sizes of households.

Municipalities and private companies are responsible for water treatment and supply in South Africa (SA). It is expected that municipalities and private companies provide clean potable water that has tolerable contaminant levels. Water has been found to be a limited resource in SA and hence there is need to conserve it. In SA, the Department of Water Affairs (DWA) has the responsibility of ensuring that people have access to safe drinking water. This is achieved through setting up municipalities in the nine provinces of SA. There are 262 municipalities in SA that ensure the provision of safe drinking water to communities. Table 2.1 shows the number of municipalities in each province. These municipalities are striving to provide clean drinking water to the nation in order to meet the
Millennium Development Goal of providing every individual with safe drinking water by the year 2015.

### Table 2.1 The 262 Municipalities in SA Provinces.\(^4\)

<table>
<thead>
<tr>
<th>Province</th>
<th>Number of Municipalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eastern Cape</td>
<td>43</td>
</tr>
<tr>
<td>Free State</td>
<td>21</td>
</tr>
<tr>
<td>Gauteng</td>
<td>11</td>
</tr>
<tr>
<td>Kwazulu-Natal</td>
<td>55</td>
</tr>
<tr>
<td>Limpopo</td>
<td>23</td>
</tr>
<tr>
<td>Mpumalanga</td>
<td>25</td>
</tr>
<tr>
<td>North West</td>
<td>23</td>
</tr>
<tr>
<td>Northern Cape</td>
<td>31</td>
</tr>
<tr>
<td>Western Cape</td>
<td>30</td>
</tr>
</tbody>
</table>

### 2.3 Challenges Faced with Water Quality and Scarcity

Most drinking water problems are associated with water contamination. These problems can be broken down into several categories which include infectious diseases and cancer. Waterborne infectious diseases are caused by pathogens such as helminths, protozoan parasites, bacteria and viruses. There are also aesthetic problems associated with drinking water, such as colour, odour and staining.\(^1\) Carcinogenic compounds in drinking water are classed into inorganic agents (e.g. nitrates, nitrites and cadmium), organic agents (e.g. polychlorinated biphenyls and dichromomethane), volatile organic compounds (e.g. benzene and vinyl chlorides) and other interim standards (e.g. alpha emitters and arsenic). Arsenic, nitrates and asbestos are some of the reported carcinogenic compounds in drinking water.\(^1\) Endocrine disrupting compounds together with organic and inorganic pollutants are also found in contaminated water. Presence of endocrine disrupting compounds in drinking water such as pesticides, results in a range of developmental, neuro-behavioural and reproductive problems. Inorganic compounds in drinking water such as calcium and magnesium cause water hardness (aesthetic, health, corrosion and scaling problems). The degree of
toxicity of organic compounds varies and these compounds are not easy to remove from drinking water.

2.3.1 Water Quality

One of the Millennium Development Goals (MDG) is to half the number of people, globally, who have limited access to safe drinking water.\(^5\) Due to the rising numbers of deaths reported every year, there is need to improve the quality of drinking water. Several factors affect the quality of potable water such as chemical and microbial contaminants, the nature of rain water which may be acidic due to excessive pollution, the nature of existing ground water, type of soil through which water percolates and the nature of the aquifer rock.\(^1\) Groundwater quality is also affected by the depth of the water table as ions tend to accumulate with increase in depth of groundwater sources.

The ability of water to absorb and dissolve substances makes it unsuitable to consume without treatment. Water colour, suspended matter, turbidity, pathogens, hardness and odour and harmful chemicals are nuisance substances when they are in excessive levels in drinking water. This, therefore, necessitates the need to purify natural and effluent water before use. Treated water must be palatable, safe, clear, colourless and odourless, soft, non-corrosive and low in organic content.\(^1\) Generally, treated water must comply with the South African National Standard (SANS 241)\(^6\) of drinking water or the World Health Organisation (WHO)\(^7\) standard. The SANS, 241 \(^6\) recommended limits for selected contaminants are given in Table 2.2.

The presence of a number of contaminants in drinking water such as arsenic and nitrates, has prompted investments in water treatment by governments that could be a solution to the elimination of these pollutants from water. A lot of research in most countries, South Africa in particular, has led to an overall improvement in water quality. These researches are aimed at reducing the cost of water treatment at household scale and hence are one of the strategies adopted by most developing countries in reaching the MDG by the year 2015.
Table 2.2 Contaminants Recommended Limits in Potable Water According to SANS, 241.

<table>
<thead>
<tr>
<th>Determinant</th>
<th>Units</th>
<th>Class I (Recommended Operational Limit)</th>
<th>Class II (Max. Allowable for Short Duration)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>pH units</td>
<td>5.0 – 9.5</td>
<td>4 – 10</td>
</tr>
<tr>
<td>Electrical conductivity</td>
<td>mS/cm</td>
<td>&lt; 150</td>
<td>150 – 370</td>
</tr>
<tr>
<td>Turbidity</td>
<td>NTU</td>
<td>&lt; 1.0</td>
<td>1 – 5</td>
</tr>
<tr>
<td>Calcium</td>
<td>mg/L</td>
<td>&lt; 150</td>
<td>150 – 300</td>
</tr>
<tr>
<td>Magnesium</td>
<td>mg/L</td>
<td>&lt; 70</td>
<td>70 – 100</td>
</tr>
<tr>
<td>Iron</td>
<td>µg/L</td>
<td>&lt; 200</td>
<td>200 – 2000</td>
</tr>
<tr>
<td>Arsenic</td>
<td>µg/L</td>
<td>&lt; 10</td>
<td>10 – 50</td>
</tr>
<tr>
<td>Phosphates</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Nitrates</td>
<td>mg/L</td>
<td>&lt; 10</td>
<td>10 – 20</td>
</tr>
<tr>
<td>Fluorides</td>
<td>mg/L</td>
<td>&lt; 1.0</td>
<td>1.0 – 1.5</td>
</tr>
</tbody>
</table>

2.3.2 Progress Made By Southern African Developing Community (SADC) Countries in Meeting the MDG.

The MDG of providing safe drinking water with improved sanitation has been set and progress in some developing countries in accomplishing this goal has been observed while in others the situation is becoming worse. This can be attributed to climate change which exasperates the situation. The current progress in accomplishing the MDG by SADC countries is shown in Figure 2.1. South Africa has made an average improvement of 8% between the year 1990 and 2008. More work has to be done to increase further the number of people having access to safe potable water. This is the reason that motivated investment in this study.
2.3.3 Common Contaminants in Drinking Water Contaminants

Drinking water has both microbial and chemical contaminants. These contaminants pose health risks to consumers who may not treat the water before consuming it.

2.3.3.1 Common Microbial Contaminants

Three groups of disease causing microorganisms namely bacteria, protozoa and viruses can be transmitted via drinking water. The mode of transmission by faecal oral route could be as a result of direct or indirect contamination of surface water sources by sewage or animal waste. *Cryptosporidium* (Cryptosporidiosis) and *Giardia lamblia* (Giardiasis) are the main protozoan parasites mostly found in water. Table 2.3 summarises common infections due to microbial contamination of drinking water.
Table 2.3: Waterborne Diseases as a Result of Microbial Contamination.

<table>
<thead>
<tr>
<th>Microorganism</th>
<th>Associated Diseases</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bacteria</strong></td>
<td>Shigellosis, Salmonellosis, Typhoid fever, Diarrhoea, Gastroenteritis</td>
</tr>
<tr>
<td><strong>Viruses</strong></td>
<td>Gastroenteritis, Hepatitis</td>
</tr>
<tr>
<td><strong>Protozoa</strong></td>
<td>Giardiasis, Amoebiasis, Cryptosporidiosis</td>
</tr>
</tbody>
</table>

2.3.3.2 Chemical Contaminants

A number of chemical contaminants have been discovered in contaminated drinking water. Sources of these pollutants include municipal and industrial discharges, natural geological formations, and urban and rural run-off. Soluble chemical compounds and elements are associated with various health effects which include cancer, adverse reproductive outcomes, cardiovascular diseases and neurological diseases. Some of the drinking water pollutants are discussed in this study.

a) Nitrates

Burning of fossil fuels, in addition to increment in fertiliser usage, has resulted in an overall increase in nitrates levels in drinking water. Nitrates and nitrites have accumulated in ground and surface water sources to levels greater by 30% to the amount that could be fixed by microorganisms. Nitrogen accumulation results in acid rain formation, global warming, ground level ozone, smog formation and increasing run off and leaching of nitrogen into water sources. There are various problems associated with high nitrates in drinking water such as the development of infantile methaemoglobinemia. Miscarriages and infant cyanosis are associated mostly with people who have nitrates consumptions higher than the recommended limit by SANS, which is 10 mg/L. A direct relationship between nitrate intake and N-nitroso compounds has been found by Moller et al. (1989) and these compounds are formed through nitrosation. N-nitroso compounds are carcinogenic and cause cancer of the oesophagus, stomach, colon, bladder and lymphatic. There is, therefore, demand to remove excess...
nitrates from drinking water. Nitrates can be removed from ground and surface water sources by biological denitrification, reverse osmosis and ion exchange.\textsuperscript{16} Natural clays have been found by Mena-Duran et al. (2007) to remove nitrates when they are modified by acid thermo-activation.\textsuperscript{17} In this study the removal of nitrates by selected household drinking water treatment systems was evaluated and alternative technologies proposed.

b) Iron
Iron is a common metal found in large amounts in soil and rocks. Iron is an essential element when consumed within acceptable levels as prescribed by SANS, \textsuperscript{241} but may cause problems such as high risks factor for coronary heart diseases due to elevated serum ferritin concentrations. Allowable level of iron by WHO is 0.3 mg/L\textsuperscript{18} and this agrees with the level set by SANS, \textsuperscript{241} which is 0.2 mg/L. Iron may be present in water as soluble ferrous iron or insoluble ferric iron.\textsuperscript{19} Higher concentrations make the water unusable due to metallic taste, odour and turbidity.\textsuperscript{20} Several methods for iron removal from contaminated water include ion exchange, oxidation\textsuperscript{21}, activated carbon, supercritical fluid extraction bioremediation and limestone purification.\textsuperscript{22,23,24}

c) Arsenic
Arsenic occurs in the environment as organic and inorganic arsenic. The inorganic form is known to be highly toxic than the organic one as it may cause arsenicosis.\textsuperscript{24,26} Arsenic poisoning from drinking water has been reported.\textsuperscript{20} An estimated 100 million people are exposed to arsenic contamination with Bangladesh, India, China and Taiwan being the most affected countries.\textsuperscript{1} Arsenic concentrations up to 2.04 mg/L in drinking water have been reported by Tondel et al. (1999)\textsuperscript{27} and in India (West Bengal), maximum concentrations of 3.7 mg/L in the wells were recorded by Bangla and Kaiser.\textsuperscript{28} Other high arsenic concentrations detected in water are 4.4 mg/L in Shanx, China,\textsuperscript{29} 1.82 mg/L in south west Taiwan\textsuperscript{30} and 3.59 mg/L in north-west Taiwan.\textsuperscript{31} Arsenic removal methods which are often expensive for rural people in developing countries include reverse osmosis and ion exchange,\textsuperscript{32} hence there is a need to come up with cheaper methods to solve the problem of arsenic poisoning associated with drinking water.
d) Fluorides

The world is faced with a problem of fluoride contamination of ground water as a result of natural causes and anthropogenic practices. These activities result in elevated fluoride concentrations in ground water. Fluorides are notorious for the health of humans and animals as they result in bone damage and lesions of the thyroid, endocrine glands and brain. Fluorides can be removed from water using physical and chemical treatment techniques such as chemical precipitation, ion exchange, reverse osmosis and nano-filtration, but none of these treatment methods have provided a permanent solution for fluoride removal from water sources. Coetzee et al. (2003) showed that South African clays can be used for de-fluoridation and this is made possible by sorption properties of clays.

e) Phosphates

Phosphates are one of the primary nutrients that cause eutrophication in water sources. Even when they occur in trace concentrations, phosphates cause eutrophication problems. Accumulation of phosphates in water bodies stimulates the growth of toxic cyanobacteria. Municipalities and industries have been found to be the main sources of phosphates in drinking water. Phosphorus in the form of phosphates could be removed by biological methods, chemical precipitation, crystallisation, tertiary filtration, ion exchange and adsorption. These removal processes are efficient but they may not be affordable to rural area people of developing countries. Cheaper adsorbents such as clays and natural zeolites which are abundant and readily available need to be evaluated as they may serve as solutions to phosphates contamination.

f) Magnesium

Magnesium is an essential element in the body of humans that plays a vital role in more than 300 known reactions. Magnesium is needed by the heart for functioning and muscles use magnesium for relaxing. Excessive intake of magnesium results in diarrhoea, hypotension and cardiac arrest.
g) Calcium

Calcium is an essential element in humans. According to Jackson et al. (2006), calcium is required for vascular contraction and vasodilation, muscle function, nerve transmission and intracellular signalling and hormonal secretion in the human body. Higher intakes of calcium than the recommended limit of less than 150 mg/L may result in renal insufficiency, vascular and soft tissue calcification, hypercalciuria and kidney stones. Other problems resulting from higher intakes of calcium than recommended limits include development of constipation and interference of calcium with iron and zinc uptake by the body. Ion exchange together with membrane technologies have been applied for the removal of calcium. Ion exchange has been found to be non economical for applications with highly concentrated water sources. Membrane filtration, on the other hand, is associated with fouling. Due to the limitations in calcium removal, there is a need to come out with a new system that could reduce high calcium concentrations to allowable levels in drinking water.

h) Chlorophyll a

During this study, chlorophyll a was determined but not as a health hazard but the interest was to investigate the effect of chlorophyll a on the flow rates of filters and correlate it with the turbidity of intake water.

Chlorophyll a being present in all flora including eukaryotic (algae) and prokaryotic organisms (cyanobacteria) is a reliable and commonly used proxy for the determination of total phytoplankton biomass. Most of the algae are harmless but their presence in water makes it look unpleasant for consumption. Quantification of chlorophyll a amount in raw water would help in making necessary recommendations on filter maintenance as high concentrations may clog filters.

i) Total Organic Carbon (TOC)

The amount of carbon bound to an organic compound is called the total organic carbon (TOC). Sources of TOC are both natural and synthetic organic matter. Total organic carbon is used as a measure of water quality, and in a sample TOC comprises of organic and inorganic carbon which have both aesthetic and health
effects. The allowable level of TOC is 10 mg/L. Total organic carbon is believed to be related to the levels of endotoxins and microorganisms in water, hence there is need to reduce it to low levels in contaminated water.

2.4 Detection of Contaminants in Drinking Water

There are several methods for determining contaminants in drinking water. The method to choose is influenced by the availability of equipment. For the purpose of this study, methods adopted will be discussed briefly.

2.4.1 Metal Determination by Atomic Absorption Spectrometry (AAS)

Atomic Adsorption Spectroscopy (AAS) is one of the familiar methods for metals and some metalloids determination. Some of the metalloids analysed using AAS are arsenic, antimony and selenium. Metals in their elemental forms absorb ultraviolet (UV) light when they are excited by heat. The absorbed wavelengths differ between metals. A beam of light is focused on a particular wavelength by an AAS instrument. This beam passes through a flame into a detector. A sample of interest is aspirated into a flame and atomised. The atomised element absorbs some of the light and results in an overall decrease in the intensity of the light beam. The amount of energy absorbed by the element is correlated to the concentration of the element. The absorbed energy is directly proportional to the concentration of the element in solution. Interferences sometimes occur during analyses of some metals as a result of the flame not hot enough to dissociate the molecules. Specific elements or compounds are normally added to the solution containing the metal of interest, to reduce interferences.

2.4.2 Nitrates Determination by the Salicylate Method

The principle behind the salicylate method involves developing colour (yellow) by adding sodium salicylate in samples containing nitrogen. The solution is then evaporated to dryness at high temperatures (105°C) in an oven for the conversion of NO$_3^-$ to NO$_2^+$. The formation of NO$_2^+$ takes place in acid conditions.
condition is reached by adding sulphuric acid ($H_2SO_4$). The acid ($H_2SO_4$) also dissolves all solids.

**Figure 2.2: An Atomic Absorption Spectrophotometer (220 FS)**

Deionised water is added to reduce the concentration of $H_2SO_4$ in the acid condition. The acid condition is neutralised upon addition of sodium hydroxide followed by colour development. Potassium tartrate is a complexing agent normally added to ward off the formation of insoluble hydroxides. The absorbance of UV light at 410 nm by the developed colour (Figure 2.3) is related to the concentration of nitrates in the sample. Standard solutions of known nitrate concentrations are made in a way that they bracket the nitrate concentration in the sample. The absorbance of the sample is related to the absorbance of the standard solution to get the concentration of the sample.$^{18}$

### 2.4.3 Phosphate Analysis by Ascorbic Acid Method

The principle of the Ascorbic Acid Method involves the reaction of ammonium molybdate ($([NH_4]_6Mo_7O_{24})$ and potassium tartrate with orthophosphate in acid medium normally sulphuric acid ($5N H_2SO_4$).$^{18}$ The reagents produce a heteropoly
acid called phosphomolybdic acid to an intensely coloured molybdenum blue solution (Figure 2.4) whose absorbance is examined at 880 nm using a spectrophotometer.

**Figure 2.3: Nitrate Samples Ready for analysis**

This method is suitable for the detection of orthophosphate in potable, surface and saline as well as domestic and industrial wastewaters. Concentrations higher than 10 mg P/L are diluted so that they are within the range of 0.001 and 10.0 mg P/L. 

**Figure 2.4: Phosphate Samples Ready for Analysis**
2.4.4 Fluoride Determination by the Ion Selective Electrode Method (ISE)

With the Ion Selective Electrode (ISE), an ion selective sensor which has high selectivity of one ion over others is used. The fluoride electrode comprises a laser-type doped lanthanum fluorides crystal. Different concentrations of fluoride solutions result in the development of a potential difference in the electrode. The fluoride electrode is a half cell and works with a reference electrode which could be a standard calomel electrode. Both the fluoride electrode and the reference electrode are connected to a pH meter that has a millivolt scale (Figure 2.5). In principle, the fluoride electrode measures the ion activity rather than the concentration.\(^\text{18}\) Due to the dependence of fluoride ions on the total ionic strength and pH, and fluoride complexing species, addition of total ionic strength adjuster buffer (TISAB) results in a uniform ionic strength background. The TISAB adjusts the pH of the solution and releases fluoride ions from its complexes by complexing interfering cations.\(^\text{18}\) A magnetic stirrer is normally used during fluoride analysis using the ion selective electrode (ISE) method.

![Figure 2.5: A General Setup for Fluoride Determination](image-url)
2.4.5 Spectrophotometric Methods for Chlorophyll a Determination

Chlorophyll a may be determined using spectrophotometric methods. To develop colour for detection by spectrophotometric methods, a known volume of sample with chlorophyll a concentration is filtered through a Whatman GF/F filter. The filter is then placed in a centrifuge tube. Acetone (90%) is added into the centrifuge tube followed by clarification using a centrifuge. The absorbance of the developed colour in samples is determined using a spectrophotometer (Figure 2.6) before and after acidification with hydrochloric acid.\(^\text{18}\) It is important to work with chlorophyll a samples under dark conditions.

![Figure 2.6: A Picture of a Spectrophotometer](image)

2.4.6 Detection of TOC

Analysis of TOC is performed using a TOC analyser (Figure 2.7) and the process involves three important steps which are acidification, oxidation and detection and quantification.\(^\text{18}\) To quantify the amount of TOC in a sample, a TOC analyser determines both the total carbon (TC) and inorganic carbon (IC). The TOC of the sample is then the difference between TC and IC.
2.5 Overview of Water Treatment Technologies
The need to control pathogens that cause diseases such as cholera and typhoid resulted in the development of water treatment systems towards the nineteenth and beginning of the twentieth century. Control of chemical contaminants in drinking water was realised early in the 1950s as some of the chemical contaminants were likely to cause medium to long term effects.\(^1\) Water treatment is, therefore, a solution to addressing water related maladies which result from pollution of water sources.

2.5.1 Water Treatment Methods
Water treatment methods include aeration (bubbling air through water), coagulation (addition of coagulants to water to destabilise particles and make them to aggregate into flocs)\(^48\), flocculation (aggregation of smaller particles to larger particles as a result of collision), clarification (flocs removal by settlement), filtration (downward passage of water through fine sand layers supported on coarse sand), and disinfection (sterilisation or killing of microorganisms in water through the use of chemicals, ozone or ultraviolet (UV) radiation). Chlorination is mostly used as a disinfection technique in water treatment. Although this process is effective in
destroying bacteria, viruses and amoeba, it is however costly and may not be affordable to rural areas of developing countries. The need to completely remove microorganisms has led to the development of membrane technology in the form of microfiltration as a replacement for coagulation, flocculation, clarification and filtration.\textsuperscript{49} According to several authors, reverse osmosis has been introduced to take the place of activated carbon adsorption.\textsuperscript{50,51} Membrane-based systems are also used for disinfection.\textsuperscript{49} Although there is a vast number of water treatment systems, most of them are costly and hence are unaffordable to rural area people or municipalities of developing countries. This calls for the design of cheaper treatment systems to reduce the number of waterborne diseases that could lead to death.

### 2.5.2 Water Treatment Technologies for Rural Communities

Due to the high rates of surface and groundwater pollution and failure by developing countries to provide communities with treated water, household water treatment is the only option rural area people have. Failure to come up with treatment options may result in an increase in the number of water related deaths reported annually. Decentralised systems of drinking water have been found by Peter-Verbanats et al. (2009) as a fundamental component of attaining the MDG of improving water quality and sanitation globally by the year 2015.\textsuperscript{52}

In rural areas where the population is sparse and homesteads are wide far apart, it becomes costly to the local authority to provide piped potable water to the people. These people end up relying on ground and surface water sources which may be microbially and chemically contaminated and thus exposing themselves to water related diseases. In the case whereby local authorities fail to provide safe drinking water, the people may be advised to set up a separate dual water supply system or ensure household treatment for potable water; otherwise they will bear the consequences of drinking contaminated water.\textsuperscript{52}

A number of household treatment systems are readily available in the market. They differ mainly in make and water purification mechanisms utilised. Most of the
available household treatment devices are costly and hence there is a need to come up with cheap or affordable treatment technologies.

2.5.3 Household Water Treatment Systems
An ideal water treatment system must produce quality water that complies with standards given by SANS, 241. Safe household water management to protect against microbiological contamination begins with safe storage. Safe storage is defined as a standard-sized container with (1) a narrow mouth or opening, (2) a lid and (3) a tap to access the stored water and to prevent contact with hands, cups or dippers.

Some of the available household water treatment devices available in the market are discussed in the report.

2.5.3.1 Porous Pot Filters
Porous ceramic filters made of clay, carved porous stone and other media have been used to filter water since ancient times. Modern accounts of ceramic filters for household use date back to at least the 18th century. Most modern ceramic filters are in the form of vessels or hollow cylindrical "candles". Many commercially produced ceramic filters are impregnated with silver to act as a bacteriostatic agent and prevent biofilm formation on the filter surface and excessive microbial levels in the product water. However, all porous ceramic media filters require regular cleaning to remove accumulated material and restore normal flow rate. Porous ceramic filters are made of various mineral media, including various types of clays, diatomaceous earth, glass and other fine particles. Ceramic filters have traditionally been used for water treatment throughout the world. Currently, the most widely distributed ceramic filter is the Potters for Peace (PFP) filter, which is shaped like a flowerpot and impregnated with colloidal silver. The filter removes 99.99% of protozoa by mechanical processes. However, the effectiveness of the filter in inactivating or removing viruses together with chemical contaminants is
unknown; hence this study will focus in evaluating the filter's efficiency in removing chemical contaminants discussed under section 2.3.3.2. Figure 2.8 demonstrates a complete porous pot filter with a collection vessel fitted with a spigot.

![Figure 2.8 Schematic Diagram of a Porous Pot Filter.](image)

2.5.3.2 Biosand Filters

The biosand filter (BSF) is a household slow sand filter originally from the University of Calcary, Canada. The BSF consists of a concrete-coated metal mould filled partially with one layer each of large gravel, small gravel, and clean medium-grade sand. A diffuser plate is placed on top of the sand and water is poured into the remaining space. Prior to use, the filter is filled with water each day for two to three weeks, until a biological layer of bacteria eating microorganisms resembling dirt develops on the surface of the sand. These microorganisms consume disease-causing viruses, bacteria, and parasites, while the sand traps organic matter and particles. Biosand filters have also been shown to remove 76 – 91% arsenic; reducing it to acceptable concentrations. Collins stated that BSFs reduce turbidity to levels lower than 1 NTU and have removal efficiency of other contaminants as follows: 15 – 25% dissolved organic carbon, 95 – 99% iron and 47% arsenic. Biosand filters have been found to remove bacteria to a great extent and the removal is between 81% and 100%. Protozoa are also removed greatly (99.98% to 100%). Biosand filters have limited virus removal efficiency as observed and reported by Lantagne et al. (2007) and Kaiser et al. (2002).
These filters do not sufficiently remove dissolved compounds such as salt and fluoride or organic chemicals such as pesticides and fertilizers. Due to the inefficiency of the BSF in removing chemical contaminants, modification of the filter for improved performance is fundamental. A standard biosand filter is presented in Figure 2.9.

![Figure 2.9 Schematic Layout of a Biosand Filter](image)

### 2.5.3.3 Activated Carbon Filters

Activated carbon filters are products of compacted blocks impregnated with silver and used for additional treatment of water in developing and transition countries. These filters have a short life span. Although these filters are very effective in removing organic and inorganic pollutants from contaminated water, their maintenance and operation costs are very high, making them cost ineffective to the majority of the population of rural developing countries.

### 2.5.3.4 Paper, Fiber and Fabric Filters

A fabric filter is made out of one or more compartments containing rows of fabric bags of cartridges. The cartridges may be round, flat, or pleated. Peter-Verbanats et al. (2009) reported that paper, fibre and fabric filters could be used as an
alternative for water treatment at household scale. Due to larger pore sizes of paper and fibre filters, their viral, bacterial and protozoan removal efficiencies are very poor. Larger waterborne pathogens such as guinea worm larvae and Vibrio cholera cannot be removed by these filters.

2.5.3.5 Household Sand Filters

Household sand filters (HSF) are one of the cheap water purification systems that have been used for ages. Mahmood et al. (2011) designed and constructed an HSF using a cylinder, gravel (15 mm) and sand obtained from local vendors (Figure 2.10). The gravel and sand were washed following standard methods and packed into the cylinder. The HSF slightly increased the pH of filtered water and this was believed to be due to the dissolution of anions from the packing materials of HSF. There was high reduction in turbidity by the filter (96%) and biological agents (> 90%).

![Figure 2.10 A Typical Household Filter Showing Different Filter Media Layers.](image-url)
2.5.3.6 Solar Disinfection

Solar Disinfection (SODIS) is an affordable method that is effective in peri-urban inhabitants.\textsuperscript{69} Solar radiation is used to kill pathogenic microorganisms. Contaminated water is filled in clear plastic bottles (normally 2 L) and then exposed to sunlight to heat up at temperatures between 60°C and 80°C for about 6 hours. A combination of radiation in the spectrum of UV-A and increased water temperature destroys most pathogenic microorganisms that may result in cholera, dysentery, typhoid, giardiasis, salmonella, gastroenteritis and polio.\textsuperscript{70} Solar disinfection systems do not remove chemical contaminants at all and treated water has high chances of recontamination if not handled well.\textsuperscript{69}

2.5.3.7 Water Disinfection Stove

The water disinfection stove (WADIS) is a household water treatment system used to kill thermo tolerant microorganisms. Christen et al. (2009) constructed the WADIS, using a lorena-stove fitted with a 2mm internal diameter and 3 m length galvanised iron water conduit pipe.\textsuperscript{71} The pipe was coiled helically around the three pot holes of the lorena-stove. The coiled conduit creates a flow through boiling water system as a result of exposure to the hottest zones in the combustion zones.\textsuperscript{71} A spigot fitted at the outlet of the conduit pipe of the water treatment system helps in regulating the flow rate. Approximate costs incurred in manufacturing and material for the WADIS stoves is around US$ 6 and therefore cost effective for water treatment in developing countries. The WADIS stove reduced thermo tolerant coliforms of initial concentrations as high as 87600 CFU per 100 mL (CFU/100 mL) to 0 CFU/100 mL. The WADIS has a flow rate of 1 – 3 L/h.\textsuperscript{71}

2.5.3.8 Membrane Filters

Membrane filters have a semi-permeable film and a driving force which may be in the form of pressure, concentration, temperature or electrical potential difference.\textsuperscript{72}
Thermally driven and electrically driven membrane filters are mostly used in water treatment. Some of the available membrane technologies are discussed in this study.

a) Ultra-Filtration Membrane Filters

Ultra-filtration and microfiltration membranes have high log removal of microbes due to their small particle sizes. In comparison to ultra-filtration membranes, microfiltration membranes have lower removal efficiencies of bacteria. Filters based on ultra-filtration are not extensively utilised for treatment of household water. LifeStraw Family has an ultra-filtration based water treatment device that consists of a 20 nm pore size ultra-filtration module, a turbidity reducing pre-filter and a chlorine chamber. The filter with flow rates between 6 and 8 L/h removes bacteria and viruses to a greater extent. The Homespring® filter was developed by Zenon and is currently being used in industrialised and transition countries to produce enough high quality water (840 – 1020 L/h) to several households. The filter has activated carbon and a hollow fibre ultra-filtration membrane.

Low pressure ultra-filtration membranes have been evaluated in South Africa, but the whole system required energy source for the production of up to 10 000 L/day to South African communities, hence cost ineffective for use in rural areas.

b) Nano-Filtration Membranes

Membrane filters which incorporate nano-filtration and reverse osmosis processes are used for the removal of inorganic contaminants from water. Nano-filtration membranes have greater than 90% removal efficiency of bivalent ions while reverse osmosis membranes are very good for monovalent ions. Membrane filters perform water treatment in a single purification step but they are mainly associated with fouling and operation and maintenance costs are high making them unsuitable for use in rural areas of developing countries.
c) **Reverse Osmosis Filters**

Reverse osmosis (RO) membranes are used in most available point of use (POU) systems in industrialised countries and these systems have multiple stages utilised during water purification.\(^7^9\) Reverse osmosis based systems require no energy for operation and they can be placed under the sink to treat water. Reverse osmosis based filters cost between US$ 200 to US$ 700 and have annual operation costs between US$ 85 – US$ 135. Generally, reverse osmosis based membrane filters are costly for rural area people of developing countries. Schafer and Richards\(^8^0\) developed a RO based water treatment system that could treat highly turbid and highly saline waters. The complexity of the system (i.e. has ultra-filtration, reverse osmosis and photovoltaic modules) makes the device costly and a qualified personnel is required for maintenance. Hence, this filter could not be used for water purification at household scale in rural areas of developing countries.

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**d) Microfiltration Membrane Filters**

Microfiltration (MF) based technologies such as ceramic microfiltration membranes which come in the form of hollow cylindrical tubes with 0.2 µm pore size\(^8^1\) are used in developing countries\(^5^2\) for the removal of bacteria and viruses by size exclusion. Microfiltration based filters used in rural areas of developing countries are in the form of clay pots with pore sizes of 0.6 to 3.0 µm.\(^6^0\) Silver nano-particles are incorporated in MF based clay pot for microbial disinfection\(^5^3\) and pore restriction in addition to cake layer formation is an additional mechanism of removal of microbial contaminants.

Some of the filters discussed above are not effective in removing microbial and chemical contaminants due to large pore size of the filter material or large particle size of the filter media used when making them. Some of the filter materials such as clay minerals need to be modified in order to remove certain contaminants. Clays used for the construction of porous pot filters are impregnated with silver to enhance removal of microbial contaminants. With all being said, there is therefore
need to change properties of some filter media or replace the media with another one which can perform better in removing contaminants from drinking water.

2.5.4 Household Filter Modification for Improved Performance
Filter modification is an important step in improving the performance of water purification filters. Filter operation is greatly impacted by the processes that precede it. There is a need to modify water treatment technologies due to changes in population, financial constraints, raw water quality and regulatory atmosphere. Modification of the technology results in improved water quality, improved reliability, reduced maintenance and reduced costs. Defects in household water treatment devices result in the need for modification to improve efficiency. Five techniques of modifying a filter have been identified by Smith et al. (2006), and include modification of chemical treatment, addition of rapid coagulant mixing, improving flocculation, improving sedimentation and modifying filtration processes. Filter modification can be done with the intention of improving flow rate or water quality.

2.5.4.1 Modification of Sand and Clay Filters
Modifying sand filters can result in improved effluent quality and flow rates. Fast sand filters are modified by changing the filter media to dual or mixed-media or replacing the top layer of sand with anthracite coal resulting in higher flow rates and improved quality effluent. River sand which forms the greatest part as the filter media in sand filters could be modified in various ways. Ahammed and Meera showed that manganese oxide-coated sand or iron hydroxide-coated sand dual media have increased the potential of removing bacteria, heavy metals and turbidity. Sharma modified a standard biosand filter by adding rusted iron nails for the removal of arsenic from drinking water. High arsenic removal efficiency was reported and the retention mechanism was believed to be through the adsorption of arsenic to ferric hydroxide.

Ahmad and Davra modified a biosand filter by adding a 10 cm thick layer of iron oxide-coated sand. The modified filter was evaluated and compared to the
standard biosand filters without the additional iron oxide-coated sand. The modified biosand filter performed better in removing microbial contaminants compared to the standard biosand filter. The modified biosand filter removed up to 92% turbidity and the removal efficiency improved with time.

A study to investigate the removal of organic carbon and nitrification of high strength waters using stratified sand filters was performed by Rodgers et al. (2005). Two stratified columns (0.425 m and 0.9 m deep and 0.3 m diameter) containing layers of coarse sand, fine sand and pea gravel were used. The columns removed low concentrations of biological oxygen demand (BOD), ammonium nitrogen and organic carbon effectively from wastewater. The stratified sand filters removed phosphates to a greater extent (96%) and the removal efficiency was higher at lower pH. Phosphates removal efficiencies by the filters decreased over time of filter use and the overall removal efficiency was 70%. Findings of the study done by Rodgers et al. (2006), revealed that stratified sand filters are effective in removing organic carbon, nitrogen in the form of nitrate ions and phosphorus in the form of phosphate ions.

The ceramic candle filter has been modified by impregnating with silver nanoparticles and evaluated for its performance in reducing microbial contaminants from drinking water. The silver impregnated ceramic pot filter produced high quality water compared to standard ceramic candle filters without silver nanoparticles. Mena-Duran et al. (2007) have modified natural clays by acid thermo-activation and the resultant modified clays were found effective in removing nitrates from contaminated water.

Since studies have shown that modification of the filter media results in an overall improvement in the performance of the filter, this study focused on modifying two filters namely the biosand filter and the porous pot filter. The biosand filter was modified by adding a layer of zeolites due to the high efficiency of zeolites in removing chemical contaminants. The clay used in the construction of the porous pot filter was modified by impregnating with silver nano-particles. Clays and
zeolites can become useful cheap adsorbents that could possibly solve the problem of heavy metal contamination in rural areas of developing countries.

2.6 Zeolites and Clays as Effective Adsorbents for Water Treatment
Zeolites and clays are natural adsorbents that can be used for water treatment. The advantages of using these minerals for water purification are that they are cheap and easy to modify. These advantages make zeolites and clays suitable for use in constructing household water treatment filters.

2.6.1 Zeolites
Zeolites are hydrated aluminosilicates. They comprise of symmetrically stacked alumina and silica tetrahedra which result in an open and static three dimensional honey comb structure with an overall negative charge neutralised by predominant exchangeable cations such as sodium.\(^{88,89,90}\) The large empty spaces or cages which reside in zeolites accommodate large cations such as Na\(^+\), K\(^+\) and Ca\(^{2+}\). Larger molecules and cationic groups such as ammonium ion, carbonate ions and nitrates are also accommodated.\(^{91}\) Zeolites provide a very good combination of ion exchange and molecular sieve properties, which can be modified with ease.\(^{92}\) Malion et al. (1992) found that the actual size of zeolites does not affect the actual metal uptake at equilibrium point but contact time becomes an important factor for wastewater treatment as there is more removal at longer contact times.\(^{93}\) Several other factors such as ion size and shape, ionic charge and concentration of the ion have an effect on the ion exchange behaviour of zeolites.

Several advantages of using zeolites for water treatment were discussed by Widiastuti et al. (2008) which include; the ability of zeolites to undergo ion exchange and adsorption, the ease of zeolites’ modification to remove certain chemical contaminants, zeolites’ abundance in nature and low costs and the regenerative properties of zeolites.\(^{94}\) Industrial applications of natural zeolites (clinoptilolite) in water treatment have been reported by Kallo et al. (2005) Clinoptilolite is the most abundant natural zeolite and it is widely used in water treatment.\(^{95}\)
Motsi et al. (2009) investigated the removal of heavy metals from acid mine drainage by natural zeolites. Results indicated greater reductions of 80%, 95%, 90% and 99% for $\text{Fe}^{3+}$, $\text{Mn}^{2+}$, $\text{Zn}^{2+}$ and $\text{Cu}^{2+}$ respectively and they concluded that the removal of these heavy metals was not only due to ion exchange but also as a result of precipitation of metal hydroxides from the solution.

Bowman et al. (1996) reported that natural zeolites can remove 10 – 90% iron and 95% arsenate. Nunez found that zeolites can remove up to 90% of phosphates from contaminated water. Phosphates and ammonium removal from water and wastewater by zeolites synthesised from coal fly ash has been reported by several authors. The mechanism of phosphates removal by zeolites is believed to be fixation of phosphates by ions of calcium and iron. Another mechanism of phosphates removal was through the formation of outer sphere complexes by phosphate ions such as $\text{H}_2\text{PO}_4^-$ with hydrolysed crystalline and isomorphous oxides or on the surface of the zeolites, when the hydroxyl groups are positively charged. The formed complexes are stable as a result of the primary bonding force in inner-sphere complexes being coordinate-covalent bonding.

2.6.2 Clays

Clays are one of the adsorbents that have been long used for water treatment. Most clay minerals have crystalline structures as a result of the combination of octahedral and tetrahedral sheets and exhibit properties of colloids. These sheets have inorganic structures arranged in a 1:1 or 2:1 layers. Substitution of one cation by another cation of comparable radii in the inorganic layer results in an overall negative charge which is counterbalanced by electrostatic adsorption of alkali and alkali earth cations. These cationic metals could be Ca, Mg or Na and this explains the removal of alkali and alkali earth metals by clays. Clay minerals are basically classed into two categories, the distinguishing factor being the number of tetrahedral and octahedral layers. In the 2:1 layer type, two silicon-oxygen tetrahedral sheets sandwich an alumina-oxygen-hydroxyl octahedral sheet. Permanent negative charges in clay minerals are as a result of the substitution of $\text{Al}^{3+}$ for $\text{Si}^{4+}$ in the tetrahedral sheet and $\text{Mg}^{2+}$ or $\text{Fe}^{2+}$ for $\text{Al}^{3+}$ in the
octahedral sheet. When in contact with water the layered structures of clays expand and this brings out an extra mineral surface capable of cation adsorption and this explains the removal of cationic species through adsorption and ion exchange by clays.

Clay minerals have been reported to adsorb cationic, anionic and neutral species from water. Geothite and kaolinite have been discussed by Mohan et al. (2007) to be good adsorbents of arsenic from waste water and they can remove up to 0.23 mg/g arsenic. Arsenic (III) and arsenic (IV) removal with bentonite, kaolinite and illite has been reported. Arsenate adsorption by kaolinite, montmorillonite and illite was observed to be affected by presence on phosphates as competing ions for the adsorption sites.

Clay minerals can remove phosphates when they are doped with lanthanum. Phosphates removal by clays could be as a result of inner sphere complexation of the phosphates on the clay surface via ligand exchange reaction mechanisms. It has been reported by Li that the use of pillared bentonite increases nitrates removal and these nitrates can at times be above maximum limit of 45 mg/L, allowable by WHO. Bentonite can also serve as a good adsorbent for ammonium due to the negative charge on the surface. Amongst the vast methods used for defluoridation such as ion exchange, precipitation and electrodialysis, adsorption is still extensively used and clay minerals are one of the adsorbents that are being used. Present exchangeable cations in clays such as Na\(^+\) and Ca\(^{2+}\) may form solid precipitates with F\(^-\) and result in effective retention of F\(^-\) by clays.

Since clay minerals are abundant, cheaper and harmless to the environment, they can act as potential ionic exchangers for heavy metals which cannot be destroyed chemically like organic pollutants.
2.7 Conclusion

The presence of chemical pollutants such as arsenic and fluorides in drinking water pose a health risk to consumers. These contaminants need to be removed using some of the available water purification techniques such as membrane filtration. Different household water treatment devices ranging from simple and low cost to complex and high cost filters are available in the market. The devices may not be affordable to rural area people of developing countries due to high operation and maintenance requirements. Hence there is need for designing cost effective water purification systems that can be used for the production of high quality water.

In this study five cost effective household water treatment systems were designed, constructed and evaluated for their efficiency in removing chemical contaminants. The filtration systems together with their retention efficiency of selected chemical pollutants are discussed in Chapter 3, 4 and 5 and the general summary of the study is presented in chapter 6.
2.8 References


CHAPTER 3
A SIMPLIFIED COST-EFFECTIVE BIOSAND FILTER (BSFZ) FOR REMOVAL OF CHEMICAL CONTAMINANTS FROM WATER

3.1 Introduction
Although access to safe potable water has recently become a human right, it is alarming to note that water quality and scarcity are serious problems, especially in the rural areas of developing countries (DC).

Approximately one billion people lack access to safe potable water globally and this situation has been brought about by industrialization resulting in safe drinking water being a scarce resource in the rural areas of most developing countries. This results in deaths estimated at 2.2 million annually, as a result of diarrhoea which is associated with water contamination. There has been a significant growth in household water treatment systems (HWTS) in recent years. These are considered cheap and effective in preventing or reducing waterborne diseases in rural areas of DC. These HWTS would be used in addition to other good practices such as improved hygiene, sanitation and improved water supply and quality. Although there are a vast number of treatment methods, they have been found to have some limitations and hence there is need for the development of a much more efficient HWTS.

Extensive research has therefore been conducted to develop an effective water purifier that can reduce colour and turbidity, while concomitantly removing microorganisms such as Cryptosporidium and Giardia as well as chemical contaminants. Due to the increase in the number of deaths reported every year as a result of drinking contaminated water, point of use (POU) water treatment systems are encouraged in rural areas of DC. An ideal water treatment system for developing countries should be able to remove all chemical and microbial contaminants in one single filtration process. These filters should reduce contaminants to acceptable levels while retaining their permeability and reactivity over extended periods. Low-cost and readily available materials which are efficient
in removing contaminants from drinking water are considered to be a solution for providing clean water in rural areas of DC. These materials include activated alumina, agricultural by-products (e.g. rice hulls), apatite, clay minerals, granular activated carbon (GAC), industrial by-products, iron oxide (coated sands), manganese oxide (coated sands), metallic iron (Fe), peat and peat moss, phosphate rocks, seaweeds and their derivatives, wood chips, and zeolites.\textsuperscript{7} Biosand filters (BSFs) form part of the many emerging technologies being developed from locally available materials, for the removal of contaminants from water in rural areas to make the water suitable for use by low-income rural people of DC. As BSFs are cheap to construct and maintain they could be promoted and utilised in the rural areas of many DC.

The BSF was developed by Dr Eric Manz (University of Calgary, Canada) and has been introduced to many countries\textsuperscript{6}, but this device is not in full use in South African rural areas (SARA). These SARA may be exposed to pollution by microbial and chemical contaminants. Before this system could be used in SARA, there is a need to evaluate its efficiency in removing chemical contaminants from drinking water. The BSF carries out various filtration processes which include settlement, straining, filtration, removal of organics, inactivation of micro-organisms and chemical change within itself.\textsuperscript{8} The BSF is gravity driven and no pre-treatment of water is required. The flow rate of the BSF (15 L/h to 20 L/h) is controlled by the height of the water above the sand bed together with the porosity of the sand.\textsuperscript{9} The BSF can remove up to <1 NTU turbidity\textsuperscript{10}, 15% to 25% (dissolved organic carbon), 90% to 95% iron\textsuperscript{11}, 50% to 90% organic and inorganic toxicants\textsuperscript{12} and <47% arsenic\textsuperscript{13}. Surface straining is a process whereby particles too large to pass through the interstices between the grains that form the filter media become trapped. This is the main mechanism of turbidity reduction by the BSF.\textsuperscript{14} Spherically shaped grains have been proposed to capture particles about 15% of the grain size.\textsuperscript{8} Muhammad\textsuperscript{14} and Collins\textsuperscript{13} predicted that modified BSFs may remove some heavy metals and their hypothesis was based on research carried out on slow-sand filters (SSF). On the whole, a complex biological layer (schmutzdecke) which is considered to be the most important component in BSFs provides effective purification, while the underlying sand provides the support
medium.\textsuperscript{8} The BSF has been shown to be effective in reducing turbidity and pathogens but the performance of the filter in terms of removing chemical contaminants as well as the amount of water that can be treated before the filter has to be cleaned is not well documented. The efficiency of the BSF was focused on the removal of microbial contaminants, yet there is a need to scale up the removal of chemical contaminants such as iron, due to the high rate of industrialisation which results in heavy-metal contamination of water sources.\textsuperscript{3}

Since some communities in the rural areas of DC may be exposed to heavy-metal water contaminants such as arsenic (As) and iron (Fe), we are proposing the design of a modified biosand filter containing zeolites (clinoptilolite) to serve as an alternative water purifier to many other designs which are complex and expensive. The BSF is one of the 5 filters that were selected by the study team (funded by the Water Research Commission, South Africa) to evaluate their efficiency and applicability in providing safe drinking water to people of SARA. The selection criteria were based on the cost-effectiveness of the filter, availability of construction materials, ease of construction, ease of operation, ease of maintenance, amount of purified water the filter can produce and durability of the filter. Modification of the standard BSF resulted in the filter being cheaper to construct and to maintain. This is because a plastic bucket was used as the filter house instead of concrete and the media bed was reduced. The size of the BSF was designed in a way that it could be located inside the house for the user’s convenience for use and maintenance.

The reasons for the choice of zeolite material to be incorporated in the BSF include the fact that zeolites occur as natural aluminosilicates which consist of a framework of tetrahedral molecules. Exchangeable cations present in zeolites counterbalance the negative charge on the zeolite surface generated from isomorphous substitution.\textsuperscript{16,17} Decreasing the particle size of zeolites increases their metal adsorption potential; however, particle size reduction often leads to the reduction in flow rate in the column due to reduced permeability of the column. It has been documented in the literature that zeolites provide a very good combination of ion exchange and molecular sieve properties, which can be
modified with ease. The predominant exchangeable cations for the natural zeolite are sodium (Na\(^+\)), potassium (K\(^+\)) and calcium (Ca\(^{2+}\)). In this study a natural zeolite (clinoptilolite) with a particle size of between 1 mm and 3 mm was used without any modification. It was conceptualised that a biosand filter with zeolites (BSFZ) would be developed that could efficiently and effectively remove chemical contaminants from raw water to produce potable water of acceptable quality in terms of the South African National Standard (SANS), Drinking Water Specification.

The specific objectives of the study were to evaluate the following:

- Removal efficiency of the BSFZ in removing chemical contaminants
- Effect of contact time on the removal of each chemical contaminant
- Effect of turbidity on the flow rate of the BSFZ
- Correlation of chlorophyll a concentrations with filter flow rate and turbidity of filtered water

The BSF was evaluated for performance in removing chemical contaminants, maintenance practices and lifespan. The acceptance of the BSFZ by South African people living in the rural areas is under investigation.

3.2 Experimental
3.2.1 Design and Description

The biosand filter with zeolites (BSFZ) was fabricated in the workshop of the Tshwane University of Technology, Pretoria, South Africa with minor modifications based on guidelines given in the literature.  

The BSFZ has six distinct zones: The first zone is the inlet reservoir zone where water is poured in during filtration. This was constructed by removing the lid of a 25 L new bucket. The second zone is the standing water zone. This zone came about as a result of elevating the under-drain pipe connected to the spigot, 5 cm above the top layer of sand (Figure 3.1). It is useful in that oxygen diffuses through this zone to the biological layer. The third zone is the bio-layer which develops a few centimetres (1 cm to 2 cm) above the top sand layer. This layer comprises
slime, sediments and micro-organisms. The fourth layer is the biological zone that develops at the top 5 cm to 10 cm of the sand surface and is useful for the removal of iron and microbial contaminants. The fifth layer is the clinoptilolite zone. This zone is 15 cm deep and forms the largest part of the filter media. The clinoptilolite zone is responsible for the removal of heavy metals. In standard BSFs, this layer is composed of sand. The sixth zone is the gravel zone composed of coarse sand (0.95 mm) and gravel (1 mm to 3 mm). The gravel layer (2.5 cm thick) is very useful in ensuring that there is an easy flow of water to the pipe that connects to the spigot. The coarse sand layer (also 2.5 cm deep) helps in retaining the clinoptilolite, and preventing it from being flushed down into the gravel layer. In order to prevent poured water from disturbing the biological layer, a diffuser plate was made from the lid of the bucket by trimming the lid radically until it fitted into the plastic bucket and resting it on top of short ledges made from PVC pipes. The diffuser plate was perforated by drilling circular holes (2 cm apart). The diffuser plate distributes water at a steady rate, maintains the flow rate of the BSFZ and also traps larger particles such as grass and leaves.

Figure 3.1: Illustration of the Four Layers within the BSFZ; A – Plumbing, Gravel and Coarse Sand Layers, B – Coarse Sand Layer and Zeolite Layer, C – Zeolite Layer and Fine Sand Layer, D – Fine Sand Layer with Supports for
the Diffusion Plate, E – Skeletal View of the BSFZ Showing the Internal Content.

3.2.2 Collection of Samples
Surface water samples of low turbidity were obtained from the Apies River in Hermanstad, Pretoria and high-turbidity surface water samples were obtained from Hartbeespoort Dam.

Low-turbidity and high-turbidity groundwater samples were collected from boreholes situated in two different areas, namely Delmas and Wallmannsthal, respectively. Water obtained from the Delmas Municipality constituted the low-turbidity groundwater. Water from a borehole situated in a security company compound in Wallmannsthal constituted the high-turbidity groundwater. The temperature, visual colour and odour of water were recorded on site. The turbidity and the pH were recorded immediately upon arrival at the Tshwane University of Technology (TUT) Water Research Group Laboratory. Water samples were collected 6 times from each site over each test period.

3.2.3 Filtration
The BSFZ was evaluated for its efficiency to reduce chemical contaminants from environmental water sources (surface water and groundwater) with low and high turbidity. Filtration was carried out in the laboratory (Tshwane University of Technology) in a manner that mimics the situation that would be taking place in homes in the rural areas. The collected water samples were filtered through the BSFZ upon arrival in the laboratory (TUT). Filtration was carried out for 3 h with the assumption that enough purified water would have been produced over this period of time for drinking and cooking. Different volumes of filtrates were collected at 1h intervals over the 3 h period of filtration. This was done to establish whether there was a difference in the reduction of chemical contaminants at different times and to make the necessary adjustments and recommendations. In cases where the pre-filtered raw water was found to have lower contaminant concentrations falling within the recommended limits, the water was spiked with the chemical of interest. This was mainly done to evaluate whether the BSFZ would reduce the
concentrations of the contaminants of interest to allowable levels recommended by SANS, 241. The collected samples were analysed in triplicate to determine the water quality after filtration. The quality of the water produced was compared to the SANS, 241 Drinking Water Guidelines for Chemical Contaminants.

3.2.4 Flow Rate and Turbidity Determination
The first step in evaluating the filter flow rate was to determine the flow rate of the filter using deionised water produced by an ultra-pure reverse osmosis unit (O Purite) with filter pore size of 0.2 µm. This would give the benchmark flow rate of the BSFZ expected when water samples with very low turbidity are filtered. Knowledge of this flow rate is fundamental in that it will allow filter users to know when the flow rate has declined significantly. Deionised water together with environmental water (surface water and groundwater with low and high turbidity) was filtered through the filter and the flow rate was measured every hour for 3 h. The flow rate was measured as the ratio of filtered water volume (L) per unit time (h) taken to filter it.

Turbidity in nephelometric turbidity units (NTU) for all samples was determined using a Eutech TN-100 turbidimeter calibrated with 0.2 NTU to 800 NTU calibration standards. Triplicate readings were taken for each sample for data validation.

3.2.5 Chlorophyll a Analysis
The main aim in the determination of chlorophyll a was to quantify the amount of chlorophyll a in unfiltered water samples and to correlate this with the filter flow rate and turbidity of the unfiltered raw water. Chlorophyll a concentrations were determined using Standard Methods. A Mixtacel CENTRO 8 centrifuge was used to centrifuge all samples at 3 600 r/min for 5 min and an ultrasonic cell disrupter (VIRSONIC 100 Ultrasonic Cell Disrupter) was used to disrupt chlorophyll a cells. Optical density was measured using a spectrophotometer (SPEKOL 1300 model) at 750 nm and 664 nm prior to acidification and at 750 nm and 665 nm after acidification of samples with 0.1 mL of 0.1 M hydrochloric acid.
3.2.6 Analysis of Metals

Chemical analyses of calcium, magnesium, iron and arsenic were performed by atomic absorption spectrophotometer (AAS) using a VARIAN 220 FS model with an air acetylene flame and nitrous oxide as a support gas for arsenic and calcium analysis.\textsuperscript{21} Pure metal standards of the ions (1 000 mg/L) were obtained from the Tshwane University of Technology chemical store and working standards were prepared from them.

3.2.7 Nitrate Analysis

To quantify nitrate removal by the filters, a calibration curve was drawn using results of 0 mg/L to 5 mg/L nitrate standards prepared from analytical reagent (AR) grade potassium nitrate (KNO$_3$) dissolved in deionised water. The salicylate method\textsuperscript{21} was used and the absorbance of standards and samples was determined at 410 nm using a spectrophotometer (SPEKOL 1300 Model).

3.2.8 Fluoride Analysis

The Metrohm 713 pH meter was used together with a fluoride electrode for all experimental measurements of fluorides from surface water and groundwater samples with low and high turbidity. An Ag/AgCl 6.0228.00 electrode was used as the reference electrode. Fluoride standard solutions (0.1 mg/L to 100 mg/L) were prepared using AR grade sodium fluoride (NaF) and a calibration curve was plotted as log concentration vs. potential difference (mV). Fluoride samples and fluoride standard solutions were diluted with TISAB II (total ionic strength adjuster buffer) in a 1:1 ratio. The ions (F$^-$) were then detected with the ion-selective electrode.\textsuperscript{22}

3.2.9 Analysis of Total Organic Carbon

A total organic carbon (TOC) combustion analyser (TEKMAR DOHRMANN APOLLO 9000 model) was used to analyse TOC in all filtered and unfiltered samples. Vials with penetrable Teflon septum were filled with 40 mL of samples to be analysed and placed into the TOC analyser auto-sampler rack. A calibration curve was prepared from results of a range of potassium phthalate standards (1.0
mg/L to 25.0 mg/L) and all sample concentrations were deduced from the calibration curve in triplicates.

3.2.10 Effect of Contact Time Between the Filter Media and the Contaminant
The effect of contact time between the contaminant/filter media was investigated by collecting water at different times (1 h intervals over a period of 3h) with the assumption that the filter media would have had enough contact time to act on the contaminated water.

3.2.11 Investigation of Cost and Maintenance of the Filter
It became a priority to investigate the cost and maintenance of each filter device. This was important in order to determine whether our device was cheaper in terms of construction and maintenance costs compared to other filters on the market. It was also imperative to establish the volume of water that the device could filter before cleaning needs to take place. Since this filter was designed for use in rural areas, we decided on two parameters that could be used to determine cleaning time, namely filter flow rate and visual observation of the dirty filter wall or media. The cost of the filter was investigated by recording the cost of each part used in the filter construction, repairs and maintenance. Volumes of filtered water before commencement of cleaning the filter were also monitored. This was useful in quantifying the cost effectiveness of the filter devices.

3.3 Results and Discussion
During this study period, 420 L of contaminated environmental water was filtered. Water from each water source was filtered six times and three replicate samples were taken at each hour of filter run. The first run of 120 L of contaminated water comprised the surface water with low turbidity (SWL); the second run of 140 L to 240 L comprised the groundwater with low turbidity (GWL); the third run of 260 L to 360 L comprised the groundwater with high turbidity (GWH); and the fourth run of 380 L to 420 L comprised the surface water with high turbidity (SWH).
3.3.1 Flow Rate and Turbidity

The BSFZ produced flow rates of between 1.74 L/h and 19.20 L/h (Figure 3.2). The flow rate of the BSFZ which was a function of the particle size of the media was higher in the first hour of filter run and decreased with time of filter run. This (*scenario) supported the observation made by Barnes et al. (2008), that a decrease in the height of the water above the sand bed results in a decrease in the flow rate. The flow rate of the BSFZ was within the recommended limit (15 L to 20 L) as given in the literature. The flow rate of the BSFZ decreased with an increase in volume of water filtered. Filter cleaning after 180 L of highly turbid water had been filtered resulted in an improvement in the flow rate which decreased again over time as more turbid water was filtered (Figure 3.2). Filter washing after 360 L had been filtered did not result in an overall increase in the flow rate of the BSFZ, but cleaning improved turbidity reduction by the filter. Lower flow rates were observed when water with higher turbidity levels (16.70 NTU to 42.93 NTU) was filtered (Figure 3.2). Higher turbidity levels were obtained from samples of SWH (Hartbeespoort Dam) and lower turbidity levels were obtained from samples of GWL (Delmas, Borehole 7). The BSFZ reduced turbidity greatly when the initial turbidity value in the untreated raw water was higher. The highest reduction in turbidity was 96% and this was obtained in the first hour of the filtration run with initial turbidity of 35.63 NTU (420 L). The lowest turbidity reduction (1%) was obtained in the first hour of filtering contaminated water with initial turbidity of 1.72 NTU (220 L). Higher turbidity reductions by the BSFZ were obtained on filtration of SWL (60 L to 100 L) and SWH (380 L to 420 L). As a generalisation, there was poor turbidity reduction by the BSFZ on filtering groundwater samples. The BSFZ reduced turbidity up to <1 NTU and this finding supported the observations made by Buzunis that BSFs have higher turbidity reduction efficiencies compared to fast sand filters. The major turbidity reduction mechanism is believed to be through surface straining as predicted by Haarhoff and Cleasby.
Figure 3.2: Results of Turbidity Removal from Environmental Water Sources (BT = Before Treatment; AT = After Treatment; FR = Flow Rate at 1, 2 and 3 h of Filter Run and SANS 241 = Limit According to the South African National Standard): Change of Flow Rate with Volume of Filtered Water. Effect of Turbidity in the Flow Rate of BSFZ and Effect of Filter Washing on Turbidity Reduction Efficiency.

3.3.2 Effect of Chlorophyll a on the Flow Rate of BSFZ

Chlorophyll a (chl a) which can be used as a measure of algal growth in the water was determined in the study. The effect of chl a on the flow rate of the BSFZ was studied. The relation between turbidity of intake water and chl a was also investigated. Figure 3.3 shows that higher chl a concentrations resulted in lower flow rates and higher turbidity in influent water. There was an inverse strong negative correlation between chl a and flow rate of the BSFZ ($r = -0.566$). The decrease in the flow rate could be as a result of the algal cells clogging the pores between the zeolite particles. Since algae add to the amount of suspended particles in the filtered water, it was expected that the turbidity of the water increases with increasing amounts of chl a (mg/m$^3$). There was a strong positive correlation between the chl a concentration and turbidity of the intake water ($r = 0.607$). The decrease in flow rate with an increase in both chl a concentrations and turbidity could be explained based on the fact that suspended particles result in fouling of the filter pores. Once the pores are clogged, the channels that allow
water molecules to pass become blocked. This results in a given volume of water taking longer to be filtered than it would have taken with lower levels of total suspended solids.\textsuperscript{23}

![Figure 3.3: Results of Turbidity Relation with Chlorophyll a and the Effect of Higher and Lower Chlorophyll a Concentrations on the Flow Rate of BSFZ.](image)

### 3.3.3 Removal of metals

The BSFZ achieved high removal efficiency of calcium and the reduction was greater during the first hour of the filter run and with higher initial concentrations (Figure 3.4). Calcium reduction efficiency by the BSFZ was between 50\% and 80\% at most during the study period. Higher reductions supported observations cited in the literature that zeolites provide a very good combination of ion-exchange and molecular sieve properties, which can be modified with ease.\textsuperscript{18} There was no significant difference in the reduction of calcium by the BSFZ between 1 h and 3 h ($p = 0.097$) and between 2 h and 3 h ($p = 0.821$) but there was a significant difference in the removal of calcium during the first and second hour of filter run ($p = 0.044$).

Higher magnesium reduction efficiency was achieved by the BSFZ. Magnesium was reduced greatly by the BSFZ regardless of whether the initial concentration in the untreated water was lower or higher. The highest initial magnesium concentration recorded was 108.48 mg/L (100 L) and the lowest initial concentration recorded was 21.34 mg/L (40 L).
Figure 3.4: Calcium Reduction by the BSFZ: Reduction from Environmental Water Samples with Low and High Turbidity. Hourly Reduction Efficiency and the Effect of Flow Rate on the Removal Efficiency of Calcium.

Figure 3.5 shows that at higher initial magnesium concentrations, the flow rates of the BSFZ were lower and when initial magnesium concentrations were lower, the flow rates were higher. The highest magnesium reduction efficiency achieved was 89% and this was obtained in the second hour of filter run (200 L) when GWL was filtered. The lowest recorded magnesium removal efficiency was 28% and this was obtained in the second hour of filter run when GWL was filtered (140 L). The average magnesium reduction efficiency by the filter was 63%, 59% and 57% for the first, second and third hour of filter run, respectively. Magnesium removal efficiency in 1 h, 2 h and 3 h of filter run was the same ($p \geq 0.05$). The reduction of magnesium by the BSFZ could be through ion exchange and precipitation of metal hydroxides from the solution as predicted by Motsi et al. (2009) in a study to investigate the removal of heavy metals from acid mine drainage by means of natural zeolites. Based on the fact that zeolites have an overall negative charge, it could be expected that zeolites have a higher affinity for positive cations such as magnesium ions and this would favour the removal of magnesium by the zeolites in the BSFZ.
BSFs have long been shown to remove 90% to 95% of iron from contaminated water.\textsuperscript{11} According to CAWST (2008), most iron in the contaminated water is removed in the biological zone of the filter. Our results also showed higher iron reductions by the BSFZ and iron was reduced greatly regardless of the initial concentration level (Figure 3.6). The highest iron reduction efficiency achieved was 99% and this was obtained during the second hour of the filter run when contaminated water with an initial iron concentration of 0.4 mg/L (220 L) was filtered. The average hourly reductions of iron by the BSFZ were 89%, 86% and 80% for filtration runs of 1 h, 2 h and 3 h, respectively. Analysis of variance in the mean reduction of iron by the BSFZ for filter runs of 1 h, 2 h and 3 h showed that there was no significant difference in the hourly reduction of iron between 1 h and 2 h ($p = 0.434$), 1 h and 3 h ($p = 0.117$) and 2 h and 3 h ($p = 0.406$). A mechanism of iron removal by BSFs was investigated and reported by Stumm and Morgan.\textsuperscript{25} The same mechanism is believed to be taking place in the reduction of iron by the BSFZ. It is believed that soluble iron (II) is oxidised and converted to insoluble iron (III) as a result of aeration. The process proceeds according to Eq. 3.1 and 3.2.\textsuperscript{25}

Figure 3.5: Magnesium Reduction by the BSFZ: Reduction from Environmental Water Samples with Low and High Turbidity. Hourly Reduction Efficiency and the Effect of Flow Rate on the Removal Efficiency of Magnesium.
Chapter 3: A simplified cost-effective biosand filter (BSFZ) for removal of chemical contaminants from water

\[ 4Fe^{2+} + O_2 + 4H^+ \rightarrow 4Fe^{3+} + 2H_2O \]  \hspace{1cm} (3.1)

\[ Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3 + 3H^+ \]  \hspace{1cm} (3.2)

Lower iron reductions were observed on filtration of 20 L (3 h) and 40 L (2 h and 3 h) of contaminated water. It was suspected that there was some recontamination of the filtered samples during sample collection and sample preparation for analysis.

There was greater removal of arsenic by the BSFZ on filtration of SWL (20 L to 120 L) and SWH (380 L to 420 L). Figure 3.7 shows that arsenic reduction by the BSFZ was greater when the initial concentration was lower. The highest arsenic reduction efficiency achieved by the BSFZ was 95% and this was obtained in the first hour (400 L) of the filter run during filtration of SWH (Figure 3.7). Arsenic reduction efficiency by the BSFZ was observed to be the same throughout the duration of the filter run. In short, there was equal removal of arsenic by the filter at

Figure 3.6: Iron Reduction by the BSFZ: Reduction from Environmental Water Samples with Low and High Turbidity. Hourly Reduction Efficiency and the Effect of Flow Rate on the Removal Efficiency of Iron.
all times of filter run ($p \geq 0.05$). The average hourly reductions of arsenic were 57%, 58% and 56% for filter runs of 1 h, 2 h and 3 h, respectively.

The BSFZ showed poor reduction of nitrates on filtration of all water sources (SWL, GWL, GWH and SWH). The average hourly removal was 37% (1 h), 50% (2 h) and 19% (3 h). Leaching of nitrates from the filter media was observed several times during the study period. There was no significant difference in the reduction of nitrates by the BSFZ at the different run times (1 h, 2 h and 3 h) of collecting filtered water ($p \geq 0.05$). Filter washing did not produce an overall improvement in the reduction of nitrates by the BSFZ. Poor reduction of nitrates by the BSFZ (Figure 3.8) could be accounted for by the overall negative charge of zeolites. Auerbach et al. (2003) predicted that zeolites would remove nitrates. They claimed that large empty spaces or cages which are found within zeolites accommodate large cations such as $\text{Na}^+$, $\text{Br}^-$, $\text{K}^+$ and $\text{Ca}^{3+}$ as well as larger molecules and cationic groups such as ammonia, carbonate ions and nitrates. Our results showed poor nitrate removal by the zeolite filter and nitrates retention could

![Figure 3.7: Arsenic Reduction by the BSFZ: Reduction from Environmental Water Samples with Low and High Turbidity. Hourly Reduction Efficiency and the Effect of Flow Rate on the Removal Efficiency of Arsenic.](image-url)
have been through biological mechanisms due to the presence of anaerobic denitrifying microorganisms in the filter.

Figure 3.8: Nitrate Reduction by the BSFZ: Reduction from Environmental Water Samples with Low and High Turbidity. Hourly Reduction Efficiency and the Effect of Flow Rate on the Removal Efficiency of Nitrate.

It was observed that the BSFZ was not able to remove fluorides from contaminated water on filtration of SWL (20 L to 100 L). Removal of fluorides was observed after the first filter washing at 180 L (Figure 3.9). The BSFZ had 42%, 37% and 54% average fluoride reduction efficiencies for filter runs of 1 h, 2 h and 3 h, respectively, but there was no difference in the overall hourly reduction of fluorides by the BSFZ ($p \geq 0.05$). The highest fluoride concentration recorded in the filtered water was 4.934 mg/L and this was obtained on filtration of SWL (120 L). The poor removal of fluorides by the BSFZ could be explained by the fact that zeolites have an overall negative charge. Due to the negative charge, the zeolites will therefore have poor affinity for fluorides resulting in poor removals being observed.
3.3.4 TOC Reduction

Table 3.1 shows results of TOC reduction by the BSFZ. Results show that the highest TOC concentration recorded in untreated water was 7.8567 mg/L and the lowest recorded concentration was 4.5927 mg/L.

![Fluoride Reduction by the BSFZ](image)

Figure 3.9: Fluoride Reduction by the BSFZ: Reduction from Environmental Water Samples with low and High Turbidity. Hourly Reduction Efficiency and the effect of Flow Rate on the Removal Efficiency of Fluoride.

The BSFZ achieved 41% TOC reduction efficiency and the lowest observed reduction was 2%. Total organic carbon removal by the filter was enhanced by the rejection of colloidal organic matter. Lower reductions in TOC were observed in the third hour of the filter run. The BSFZ removed TOC greatly when the initial TOC concentration in the untreated water was higher. Due to lower TOC reduction efficiency by the BSFZ, this filter is not recommended for use when TOC is the targeted pollutant. Total organic carbon reduction efficiency by the BSFZ was observed to decrease with filter usage as more volumes of contaminated water were filtered.
3.3.5 Effect of Contact Time

It has to be noted that in this study an attempt was made, as far as possible, to mimic the situation that would be taking place at household level when users use the BSFZ to filter their daily water. In investigating this effect, we had two assumptions in mind:

- Filter users fill up the BSFZ and collect filtered water after it has been allowed to collect in the collection vessel for 1 h

- Filter users fill up the BSFZ and collect filtered water after it had collected for 3 h in the collection vessel

Table 3.1: Results of Total Organic Carbon Removal by the BSFZ from Environmental Water with Hourly Percentage Reduction Efficiency.

<table>
<thead>
<tr>
<th>Water (L)</th>
<th>BT (mg/L)</th>
<th>AT 1 h (mg/L)</th>
<th>AT 2 h (mg/L)</th>
<th>AT 3 h (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>7.4769</td>
<td>4.5622 (39%)</td>
<td>5.8476 (22%)</td>
<td>6.1678 (18%)</td>
</tr>
<tr>
<td>40</td>
<td>7.8567</td>
<td>4.6416 (41%)</td>
<td>6.0772 (23%)</td>
<td>6.3474 (19%)</td>
</tr>
<tr>
<td>60</td>
<td>7.5484</td>
<td>4.5618 (40%)</td>
<td>6.1369 (19%)</td>
<td>6.4231 (15%)</td>
</tr>
<tr>
<td>80</td>
<td>7.6409</td>
<td>4.6279 (39%)</td>
<td>6.2465 (18%)</td>
<td>6.4273 (16%)</td>
</tr>
<tr>
<td>100</td>
<td>6.4082</td>
<td>5.5052 (14%)</td>
<td>5.4315 (15%)</td>
<td>5.6821 (11%)</td>
</tr>
<tr>
<td>120</td>
<td>6.5774</td>
<td>5.4319 (17%)</td>
<td>5.5102 (16%)</td>
<td>5.5698 (15%)</td>
</tr>
<tr>
<td>140</td>
<td>6.3757</td>
<td>5.3921 (15%)</td>
<td>5.5148 (14%)</td>
<td>5.5782 (13%)</td>
</tr>
<tr>
<td>160</td>
<td>6.4231</td>
<td>5.4838 (15%)</td>
<td>5.5312 (14%)</td>
<td>5.5205 (14%)</td>
</tr>
<tr>
<td>180</td>
<td>5.1311</td>
<td>4.6485 (9%)</td>
<td>4.2538 (17%)</td>
<td>4.4422 (13%)</td>
</tr>
<tr>
<td>200</td>
<td>4.9943</td>
<td>4.6585 (7%)</td>
<td>4.1644 (17%)</td>
<td>4.1655 (17%)</td>
</tr>
<tr>
<td>220</td>
<td>4.9229</td>
<td>4.5236 (8%)</td>
<td>4.19 (15%)</td>
<td>4.3757 (11%)</td>
</tr>
<tr>
<td>240</td>
<td>4.5927</td>
<td>4.4712 (3%)</td>
<td>4.1151 (10%)</td>
<td>4.4823 (2%)</td>
</tr>
</tbody>
</table>

Based on the results, advice needed to be given on whether or not there was a difference in the hourly removal of contaminants by the BSFZ so that special times could be set for collecting drinking water and for collecting water for cooking.
purposes. Therefore it had to be established whether there was a difference in the hourly removal of contaminants by the BSFZ; statistical results showed that the amount of time spent by the contaminant of interest in the filter media does not affect the removal of the contaminant. Removal of contaminants by the BSFZ, after allowing contaminated water to be filtered and collected every 1 h, showed equal removals ($p \geq 0.05$) for the 1 h collections, and throughout the duration of the filter run (3 h) for all contaminants investigated in the study. This implies that filter users can use the filtered water collected after a filter run of 1 h for drinking and cooking purposes equally as well as the 2 and 3 h collections.

### 3.3.6 Cost and Maintenance of BSFZ

In construction of the BSFZ, the following materials were used: two x 25 L plastic buckets (ZAR 25.58 each), 1 spigot (ZAR 49.99), 1 m clear tubing (ZAR 24.99), 2 insert elbows (ZAR 3.79 each), 1 thread tape (ZAR 6.49), 40 kg fine sand (ZAR 28.00), 40 kg gravel (ZAR 30.24), 40 kg coarse sand (ZAR 34.82) and 50 kg zeolites (ZAR 155.35). It was observed that the clear tubing and the thread tape could be used to construct 2 filters, fine sand (20 filters), gravel and coarse sand (40 filters) and zeolites (5 filters). This resulted in the cost of 1 BSFZ being ZAR 164.23 (< US$ 20.00). This price was observed to be reasonable for low-income SARA people compared to the price of a standard BSF which may cost over US$ 20.00 and require more labour for construction.

The sand filter can become clogged over time when solid materials accumulate within or on the sand surface. The filter is cleaned by removing the top 5 cm layer of fine sand, thoroughly washing the sand and replacing it. If new sand is available, it is recommended that it is used to replace the used sand. Clean filtered water must be used for cleaning the sand and the collection bucket. If the bed cannot be regenerated removal of the top few centimetres of the top sand bed is appropriate when it is clogged with fine particles and water cannot penetrate deep into the sand bed.\(^{27}\) Biosand filters have been designed to filter water with turbidity levels <50 NTU.\(^9\) Water with higher turbidity levels (>50 NTU) should be allowed to settle first before filtration. A standard to determine turbidity >50 NTU was given by CAWST.\(^{20}\) For rural people to test the turbidity of the raw water, it is advised that a
clear 2 L plastic soft-drink bottle is filled with water and placed on top of a piece of paper with large print. The more total suspended solids in the water, the murkier it seems and the higher the turbidity. If the print is not visible when looking down through the top of the bottle, then the water possibly has turbidity levels >50 NTU. The filter should not be moved after installation since this may disturb the biological layer. The filter should be kept out of the reach of children to avoid damage to the spigot and disturbance of the biological layer. Long pause periods (>48 h) should be avoided as the biological layer may die due to nutrient depletion. The recommended resting period is 6 h to 12 h.20

3.4 Conclusions
In conclusion, a modified biosand filter with zeolites (BSFZ) was designed, constructed and evaluated for chemical contaminant removal efficiency. The BSFZ is easy to construct, maintain and operate. The BSFZ is cost effective (ZAR 165.00) and could be afforded by most rural people in South Africa. The filter was observed to have high flow rates which make it suitable for use by a larger family for the production of clean water for both drinking and cooking purposes. The size of the filter makes it convenient for the users to position it in an area where food is prepared and hence encourages the use and maintenance of the filter. The BSFZ had higher removal efficiency of chemical contaminants and hence can be used for production of higher quality water at lower costs. If lower turbidity reductions during the first day of filter run are observed, it implies that the sand was not thoroughly washed. Removals of >90% are expected with time as the filter is continuously used. Cleaning the top layer of sand improves turbidity reduction by the BSFZ. High-turbidity water results in a significant drop in the flow rate of the filter. Highly turbid raw water needs to be left standing for a while to allow total suspended solids to settle before filtration. The flow rate of the BSFZ generally decreases with time of filter use and higher flow rates could be regained by filter washing. Reduction of chemical contaminants by the BSFZ was observed to be greatest when the flow rate was lower as this increased the contact time between the filtered water and the filter media, but the reduction was observed to be insignificantly different to those achieved at higher flow rates ($p \geq 0.05$). This means that BSFZ users can leave the filter filtering while doing some other
Chapter 3: A simplified cost-effective biosand filter (BSFZ) for removal of chemical contaminants from water

household chores and come and collect filtered water after 3 h. The BSFZ could be used for the removal of calcium, magnesium and iron to levels allowable by SANS, 241 but its use is not recommended for the removal of arsenic, total organic carbon and fluorides in highly contaminated water. Proper care needs to be taken when washing and moving the filter as there might be disturbance to the filter media and the biological layer.
3.5 References


CHAPTER 4

EFFICIENCY OF SIPP FOR PRODUCTION OF CLEAN POTABLE WATER AT LOWER COSTS

4.1 Introduction

Provision of adequate clean potable water to a nation is a complex social problem that calls for action across a broad front. There is lack of clean drinkable water supplies to communities of third world countries. Hence there is need for major initiatives to come out with engineering solutions to improve these suppliers. The lack of clean drinking water has led to crisis worldwide. Industrialisation is a major cause of water contamination of ground and surface water sources. These water sources contain cationic and anionic ions, oils and organics which could be removed by cost effective technologies. Clay minerals are one of the adsorbents that could possibly remove these contaminants. The porous clay pot household filter is one of the vast devices that use adsorption mechanism to remove chemical contaminants from contaminated water. The most common clay pot filter is the Potters For Peace (PFP) clay pot originally developed by the Central American Research Institute of Industrial Technology (ICAITI) in the 1980s. It has a volume capacity of 6–8 L and is made from natural materials. These cheap natural materials used in the manufacturing of the PFP include the likes of clay and fine sawdust which are mixed in a 1:1 ratio. The PFP filter could be easily constructed using hands but normally the PFP is constructed by wheel throwing. Silver which has antimicrobial properties is normally incorporated in these filters in the form of silver nitrate or colloidal silver solution. Incorporation of silver enhances the reduction of micro-organisms.

Ceramic candle filters such as the PFP filter, have filter pore sizes of 0.1 – 10 µm and have flow rates between 1 and 3 L/h. ICAITI noted that the flow rate declines over use and the decline rate could be up to 64%. Higher water turbidities result in higher decline in flow rate and the flow rates may decline to as low as 0.5 L/h according to van Halem. Ceramic filters remove contaminants mostly by size
exclusion and a large proportion of silts and solids are removed. The PFP has turbidity reduction range of 30–100% as reported by Lantagne. An increase in turbidity is also possible and this implies that the filter needs to be cleaned. Ceramic filters may have a life span of up to 7 years and still remove microbial and chemical contaminants from water, but the removal efficiency declines though. Ceramic filters have the advantage of producing quality water with good taste and they are easier to maintain. Some families would stop using the PFP filters due to reasons which included insufficient flow rate. Another reason would be that the men leave to work with all the filtered water.

Although a lot of research has been done on clay pots, there is lacking data on the removal of chemical contaminants and these filters have not been extensively tested in South African surface and ground water sources to evaluate if they produce water of good quality that complies with SANS, 241. Most of the researches concentrated in the removal of micro organisms such as viruses, protozoa, bacteria and helminths. Very little or nothing is said about the removal of cationic and anionic ions, oils and organics. The selection of the clay pot for evaluation of chemical contaminants removal from South African water sources was based on several selection criteria which include ease of construction, maintenance, use and cost effectiveness. The idea was to evaluate the removal efficiency of the Silver Impregnated Porous Pot (SIPP) filter in removing chemical contaminants. Specific objectives were to evaluate i) the removal efficiency of calcium (Ca^{2+}), iron (Fe^{3+}), magnesium (Mg^{2+}), arsenic (As^{3+}), total organic carbon (TOC) and fluorides (F^-) from contaminated water, ii) to determine the flow rate of the filter and compare with results given in literature, iii) to determine if the filter removes suspended particles (turbidity) from contaminated water and evaluate the effect of turbidity on the flow rate of the filter and, iv) to determine the effect of chlorophyll a on the flow rate of the SIPP filter.

4.2 Experimental
4.2.1 Filter Description
A similar filter was constructed in the laboratory (Tshwane University of Technology) and is called the Silver Incorporated Porous Pot (SIPP). It is a
product of the TUT Water Research Group. Brown clay was used in its construction and the clay was impregnated with silver nano particles. The main difference between the SIPP and other PFP filters is that AgNO$_3$ was impregnated before firing at 887 °C for 8–9 h. The filter has a capacity of 5–6 L. Figure 4.1 shows the complete SIPP filter. The filtering unit is the porous clay pot. Filtered water is collected in a clean collection bucket (25 L). The bucket was fitted with a tap where treated water is drawn to reduce recontamination of water when it is drawn for use.

The SIPP filter was evaluated for its efficiency to reduce chemical contaminants from environmental (surface and ground) water sources with low and high turbidities. These water sources were from three provinces of South Africa (Gauteng, Mpumalanga and North West).

Figure 4.1: Illustration of the SIPP Filter; A – The Silver Impregnated Clay Pot that Serves as the Filtering Unit, B – The Clay Pot Fitted into a 10 L Bucket and Placed on Top of a Collection Vessel, C – Skeletal View of a Complete SIPP Filter
4.2.2 Sample Collection and Filtration

Water samples were collected from Apies river (surface water with low turbidity), Delmas municipality borehole 7 (ground water with low turbidity), Wallmannsthal (ground water with high turbidity) and Hartbeespoort (surface water with high turbidity).

Filtration was carried out in the laboratory (Tshwane University of Technology). It was carried out in a manner that mimics the situation that would be taking place in rural areas. The collected water was filtered through the SIPP (5 L) filter upon arrival in the laboratory (TUT). Filtration was carried out for 3 hours and this was done so with the assumption that enough water would have been produced for drinking and cooking. Different volumes of filtrates were collected over the 3 hours of filtration at 1 h intervals. This was done to evaluate if there was a difference in chemical contaminants removal efficiency at different times and make necessary recommendations. In cases where the pre-filtered water was found to have lower contaminant concentrations that fall within the recommended limits by SANS, 241, the water was spiked with the chemical of interest. This was mainly done to evaluate if the filter would reduce the concentrations of the contaminants of interest to allowable levels recommended by the SANS, 241.

4.2.3 Flow Rate and Turbidity Analysis

Flow rate was determined by measuring the volume of water (L) collected per unit time (h). Deionised water with low turbidity and contaminant concentration was filtered first to establish a benchmark for the filter’s flow rate. It was later measured when environmental water with lower and higher turbidity was filtered. Turbidity determination was useful in accomplishing two interests. Firstly, we were interested in evaluating the filter’s turbidity removal efficiency. Secondly we needed to scale the effect of turbidity on the flow rate of the filter. Turbidity in nephelometric turbidity units (NTU), for all samples was determined using a Eutech TN-100 turbidimeter calibrated with 0.2 – 800 NTU calibration standards.
4.2.4 Determination of the Removal Efficiency of Metals

Chemical analysis of calcium, magnesium, iron and arsenic were performed by atomic absorption spectrophotometer (AAS) using a Varian 220 FS model with an air acetylene flame and nitrous oxide as a support gas for arsenic and calcium analysis. Working standards (200, 100, 10 and 5 mg/L for calcium, magnesium, iron and arsenic respectively) were prepared from the 1000 mg/L bulk standards. Deionised water was used in all experimental measurements. Accuracy of the Varian 220 FS was validated using a graphite furnace AAS (PERKIN ELMER, Analyst 600 model).

4.2.5 Fluoride Analysis

A Metrohm 713 pH meter together with a fluoride electrode was used for all experimental measurements of fluorides from surface and ground water with low and high turbidities. A Ag/AgCl 6.0228.00 electrode was used as the reference electrode. Fluoride standard solutions (0.1 – 100 mg/L) were prepared using analytical reagent grade sodium fluoride (NaF) and a calibration curve was drawn as log concentration versus potential difference (mV). Fluoride samples and fluoride standard solutions were diluted with TISAB II (total ionic strength adjuster buffer) in a 1:1 ratio. This buffer helps in the reducing the variation of the ionic strength in standards and samples. TISAB II was obtained from the Tshwane University of Technology Chemical Store. The buffer contains a product which forms a complex with all the ions that could result in interferences when determining fluorides and it decomplexes all complexed fluorides into free detectable fluoride ions. The ions (F⁻) can then be detected with the ion selective electrode.

4.2.6 Analysis of Total Organic Carbon

Total organic carbon (TOC) concentrations in all samples (filtered and unfiltered) was determined using a TOC combustion analyser (Tekmar Dohrmann Apollo 9000 model). A calibration curve was plotted using results of 1.0, 5.0, 10.0, 20.0 and 25.0 mg/L potassium phthalate standards. Vials with penetrable Teflon septum were filled with 40 mL of samples to be analysed and put into the TOC
analyser auto-sampler rack. Quadruplet readings deduced from the calibration curve were recorded for each sample.

4.2.7 Chlorophyll \( a \) Analysis
The main aim in the determination of chlorophyll \( a \) was to quantify the amount of algae in unfiltered water samples and correlate this with the filter flow rate. Briefly we were interested in finding out if higher concentrations of algae had an effect on the flow rate of the filters. Chlorophyll \( a \) concentrations were determined using standard methods. A CENTRO 8 centrifuge was used to centrifuge all samples at 3600 rpm for 5 minutes and an ultrasonic cell disrupter (Virsonic 100 model) was used to disrupt chlorophyll \( a \) cells. Optical density was measured using a spectrophotometer (SPEKOL 1300 model) at 750 and 664 nm prior to acidification and at 750 and 665 nm after acidification of samples with 0.1 mL of 0.1 M hydrochloric acid.

4.2.8 Statistical Analysis
The study also focused on carrying out statistical analysis to evaluate the performance of the filter on the reduction of different contaminants from surface and ground water with low and high turbidities, at 95% confidence interval. The Stata V10 statistical package (Tshwane University of Technology, Research Innovations) was used to evaluate if there was a significant difference in the reduction of chemical contaminants by the SIPP filter at the different times of filter run. Also investigated was the correlation between chlorophyll \( a \) and flow rates, turbidity and flow rate and chlorophyll \( a \) and turbidity.

4.3 Results and Discussion
During this study period, 105 L of contaminated water was filtered. Water from each water source was filtered six times and three replicate samples were taken at each hour of filter run. The first 30 L of contaminated water comprised the surface water with high turbidity (SWL), the 35 – 60 L comprised the ground water with low turbidity (GWL), the 65 – 90 L comprised the ground water with high turbidity (GWH) and the 95 – 105 L comprised the surface water with high turbidity (SWH).
4.3.1 Flow Rate and Turbidity Reduction

The flow rates of the SIPP were observed to be highest in the first hour of filter run and lowest in the third hour of filtration. The flow rate was observed to decrease with continuous use of the SIPP. The highest flow rate obtained was 1.52 L/h (95 L) and this was obtained after the second filter cleaning process at 90 L (Figure 4.2). Flow rates of the SIPP generally increased after cleaning. The lowest flow rate was 0.31 L/h (100 L) and it was obtained in the third hour of filter run. The SIPP’s flow rates were noticed to be lower at higher turbidity and higher at lower turbidity of filtered water but statistical results predicted a weak negative correlation between the filter’s flow rate and turbidity \( r = -0.1572 \). Higher turbidity was obtained on filtration of SWH. The highest recorded turbidity was 42.933 NTU (95 L) and the lowest turbidity recorded was 1.47 NTU (35 L). The highest turbidity reduction efficiency was 97% and it was obtained on filtration of 95 L of SWH (3h). The lowest turbidity reduction efficiency was 1% obtained on filtration of 5 L of SWL (3h). The SIPP filter reduced turbidity greater when the initial turbidity of the unfiltered water was higher. Filter washing resulted in an improvement in turbidity reduction by the SIPP filter (Figure 4.2). Filter washing improved turbidity reduction by SIPP filter as a reduction > 90% was recorded when SWH was filtered. Lantagne\(^6\) reported turbidity reduction efficiencies of 30 – 100% and this agrees with our results too where the reductions were 1 – 97%. Our results also showed that filtration of high turbidity reduced the flow rate of the filter and this agreed with findings reported in literature.\(^4\) There was a significant difference in the hourly reduction of turbidity by the SIPP filter \( p = 0.0004 \).

4.3.2 Reduction of Metals

The lowest calcium concentration recorded was on filtration of 95 L of contaminated GWH and the concentration was 12.711 mg/L. The highest calcium concentration detected was 195.000 mg/L and this was detected when 45 L of contaminated GWL was filtered. Calcium in SWL (filtration of 5 – 30 L) was removed by the SIPP filter at all volumes of water filtered. There was higher calcium reduction by the SIPP when the initial concentration was higher as it was on filtration of 20, 25, 30, 45, 50, 55 and 60 L of contaminated water.
Higher reductions of calcium by the SIPP filter were observed at lower calcium initial concentrations on filtration of SWH and GWH. Filter cleaning resulted in an increase in the reduction efficiency of Ca by the SIPP filter. The highest calcium reduction efficiency achieved by the SIPP filter was 93% and this was obtained in the first hour of filtering 100 L of contaminated water with initial concentration of 17.907 mg/L. The lowest reduction (1%) was obtained in the third hour of filtering 90 L of contaminated GWH with initial concentration of 30.333 mg/L (Figure 4.3). Statistical results indicated that there was no significant difference in calcium reduction by SIPP filter at 1, 2 and 3 h ($p = 0.8186$).
Figure 4.3: Calcium Reduction by the SIPP: Reduction from Environmental Water Samples with Low and High Turbidity. Effect of Contact Time on the Reduction Efficiency and the Amount of Contaminated Water that could be Treated before Leaching Occurs.

The SIPP filter was observed to remove magnesium at all volumes of water filtered. The flow rate of the SIPP also showed to decrease with an increase in the initial concentration of magnesium as it was on the filtration of 20, 25, 30, 50, 55, 60, 80, 85 and 90 L of contaminated environmental water. The highest magnesium reduction was observed in the first hour of filtering 95 L of contaminated water with initial concentration of 26.973 mg/L and this reduction was 98%. The lowest magnesium reduction was observed in the third hour of filtering 15 L (SWL) of contaminated water with initial concentration of 38.75 mg/L and the removal was 2% (Figure 4.4). There was equal reduction of magnesium by the SIPP filter throughout the 3 h duration of filter run ($p = 0.9758$). Greater reductions of Mg were observed on filtration of SWH and the higher reductions could be as a result of filter cleaning. Filter cleaning (at 45 L), also resulted in an increase in the reduction of Mg by SIPP as more reduction was observed on filtration of 50 – 90 L (Figure 4.4).
Figure 4.4: Magnesium Reduction by the SIPP: Reduction from Environmental Water Samples with Low and High Turbidity. Effect of Contact Time on the Reduction Efficiency and the Amount of Contaminated Water that could be Treated before Leaching Occurs.

Figure 4.5 shows that the SIPP filter reduced iron from all water sources. The results show that iron removal by SIPP was not dependent on the initial concentration of iron of the filtered water. The results show that the highest iron initial concentration was 1.632 mg/L and this was obtained on filtering 20 L of contaminated water. The lowest initial iron concentration detected was 0.19 mg/L and this was obtained when 75 L of contaminated water was filtered through the SIPP filter. Greater iron removal by the SIPP was observed when iron initial concentration was higher (Figure 4.5). Iron removal by the SIPP filter was not dependent on the contact time of the filtered water with the filter walls as statistical results predicted equal reduction of iron at 1, 2 and 3h of filter run (\(p = 0.912\)). The highest iron reduction efficiency was 98% and this was obtained in the third hour of filtration of 20 L of contaminated water with initial concentration of 1.632 mg/L. The lowest reduction efficiency was 4% and it was obtained in the first hour of filtering 10 L of contaminated water with initial concentration of 0.998 mg/L. The SIPP reduced greatly iron before and after cleaning (Figure 4.5).
The SIPP filter reduced arsenic but the reduction efficiency was poor at higher initial concentrations and it also decreased as more water was filtered. The flow rate of the SIPP was lower at higher arsenic initial concentrations (Figure 4.6). The lowest arsenic concentration detected was 3.09 mg/L and this was obtained on filtration of 10 L of contaminated SWH. The lowest arsenic reduction efficiency (1%) was obtained in the third hour of filtering 25 L of contaminated SWL with initial concentration of 6.082 mg/L (Figure 4.6). The highest arsenic reduction efficiency (98%) was obtained in the second hour of filtering 105 L of contaminated water with initial concentration of 4.5 mg/L. Arsenic was reduced greatly by the SIPP after the second cleaning process (Figure 4.6). The SIPP reduced calcium, magnesium, iron and arsenic greatly from all water sources. Statistical results showed that there was no significant difference in the removal arsenic at 1, 2 and 3 h of filter run ($p = 0.952$). The removals of calcium, magnesium, iron and arsenic by the SIPP and CCF were observed mostly to be greatest when the
contaminant's concentration in the unfiltered water is lower. At higher initial concentrations, the reduction of these contaminants was lower. Lower flow rates also favoured the reduction of these contaminants by the SIPP as more reduction was observed in the third hour of filter run where the lowest flow rate was observed. This could be as a result of increased contact time between the contaminated water and the filter. The removal of arsenic by the SIPP supports the hypothesis that clay minerals adsorb cationic, anionic and neutral metal species. Clays such as kaolinite, illite and montmorillonite have been found to remove arsenic from contaminated water. Due to sorption reactions of arsenic which releases OH\(^{-}\) from sorbents as a result of legand exchange, the pH of filtered water was observed to increased although the change was not significant.

![Figure 4.6: Arsenic reduction by the SIPP filter](image)

**Figure 4.6: Arsenic reduction by the SIPP: Reduction from Environmental Water Sample with Low and High Turbidity. Effect of Contact Time on the Reduction Efficiency and the Amount of Contaminated Water that could be Treated before Leaching Occurs.**

Filter washing also resulted in an increase in calcium, magnesium, iron and arsenic reductions by the SIPP filter as an increase in the reduction efficiency was observed throughout when surface water with high turbidity was filtered. It is
believed that soluble iron (II) is oxidised and converted to insoluble iron (III) as a result of aeration (see Eq. 3.1 and 3.2).

The same mechanism was believed to have taken place in the removal of iron by the SIPP. Clays are believed to constitute layers and in the case where by the layered material consists of one octahedral sandwiched by two octahedral layers, the oxygen atoms connects these sheets. Cationic substitution in either the tetrahedral or octahedral sites with cations of comparable radii results in residual negative charges which are counterbalanced by the electrostatic adsorption of alkali or alkali earth cations such as sodium, calcium and magnesium. This explains the removal of calcium, magnesium and iron by the SIPP filter.

4.3.3 Fluorides Reduction
The highest fluoride removal achieved by the SIPP was 97% and this was obtained in the first hour of filter run when 95 L (SWH) of contaminated water with initial concentration of 0.772 mg/L was filtered (Figure 4.7). The lowest fluoride reduction efficiency (1%) was obtained in the second hour of filter run on filtration of 10 L of contaminated SWL with initial concentration of 4.105 mg/L. Differences in fluoride reduction by SIPP at 1, 2 and 3 h was observed to be insignificant ($p = 0.5254$). The highest fluorides concentration was 4.934 mg/L and this was obtained on filtering SWL (10 L) and the lowest fluorides concentration detected was 0.263 mg/L which was obtained on filtration of GWL (60 L). Filter washing at 45 L and 80 L resulted in an overall increased in fluorides reduction efficiency by SIPP (Figure 4.7). Fluoride reduction by the SIPP and CCF was not surprising as Kau predicted clay minerals as one of the adsorbents that could possibly remove cations and anions from contaminated water.

4.3.4 Reduction of TOC
Results presented in Figure 4.8 show that the SIPP filter had very low TOC reduction efficiency. The highest initial TOC concentration was 7.857 mg/L obtained on filtration of 10 L of contaminated water and the lowest TOC initial
concentration (4.593 mg/L) was obtained on filtration of 60 L of contaminated water.

**Figure 4.7: Fluorides Reduction by the SIPP:** Reduction from Environmental Water Sample with Low and High Turbidity. Effect of Contact Time on the Reduction Efficiency and the Amount of Contaminated Water that could be Treated before Leaching Occurs.

The SIPP filter had the highest TOC reduction efficiency of 65% and this was obtained on filtration of 45 L (3h) of contaminated water with initial concentration of 5.131 mg/L. The lowest TOC reduction efficiency (4%) was obtained on filtration of 40 L (1h) of contaminated water (Figure 4.8). There was a significant difference in the reduction of TOC by the SIPP filter at the 0.05 level ($p = 0.042$).

### 4.3.5 Effects of Chlorophyll $a$ on the Flow Rate of SIPP

Figure 4.9 shows that the flow rate of the SIPP was negatively affected by chlorophyll $a$. At higher chlorophyll $a$ concentrations (70.49 mg/m$^3$ for example), the turbidity of the filtered water increased (43.8 NTU) resulting in a decrease in the flow rate of the SIPP (0.65 L/h). There was a weak negative correlation between the flow rate and chlorophyll $a$ concentration ($r = -0.2277$). Chlorophyll $a$ was noticed to have a positive correlation with turbidity ($r = 0.6070$) in a way that at
lower chlorophyll $a$ concentrations (11.214 mg/m$^3$), the turbidity of the water was low (2.55 NTU). Chlorophyll $a$ (algae) added to the amount of dissolved or suspended particles in the filtered water.

![Figure 4.8: TOC Reduction by the SIPP: Effect of Contact Time on the Reduction Efficiency and Change of the Reduction Efficiency with Volume of Filtered Water.](image)

**Figure 4.8:** TOC Reduction by the SIPP: Effect of Contact Time on the Reduction Efficiency and Change of the Reduction Efficiency with Volume of Filtered Water.

![Figure 4.9: Effects of Chlorophyll $a$ on the Flow Rate of SIPP: Relation of Chlorophyll $a$ with Turbidity.](image)

**Figure 4.9:** Effects of Chlorophyll $a$ on the Flow Rate of SIPP: Relation of Chlorophyll $a$ with Turbidity.
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4.4 Cost and Maintenance Guidelines of the SIPP filter
The total manufacturing cost price of a SIPP filter is between ZAR 150 and ZAR 200. It has to be noted that the SIPP filter was placed in a receptacle (10 L bucket costing ZAR 14.99) and the receptacle was put on top of a 25 L bucket (ZAR 25.58) fitted with a spigot (ZAR 49.99). The total cost of the housing and collection system was ZAR 90.56. The total price for a complete SIPP filter is between ZAR 240.56 and ZAR 290.56. The inside of the SIPP filter was thoroughly scrubbed using a brush and rinsed several times with clean water. The plastic receptacle and its lid was cleaned using soapy water and rinsed several times with clean water and they were left to air dry. The receptacle was cleaned once a week throughout the study period. It is recommended that a little household bleach (Jik) be added to the cleaning water for extra disinfection. The filter element was made of clay and is thus fragile. It must be handled with care to avoid cracks and breakage.

4.5 Conclusions
In conclusion a SIPP filter was evaluated for chemical contaminants removal efficiency. The filter was able to achieve the following removal efficiency; iron (90%), magnesium (60%), fluorides (90%) and arsenic (80%) from contaminated water. The SIPP also reduced turbidity by over 80% to levels allowable by SANS 241.\textsuperscript{7} Arsenic and fluorides were not reduced to levels allowable by SANS, 241\textsuperscript{7} which are 10–50 µg/L and 1.0–1.5 mg/L respectively. The recommended limits are 0.2–2 mg/L, 150–300 mg/L, 70–100 mg/L and 1–5 NTU for Fe, Ca, Mg and turbidity respectively. The SIPP has advantages over other household devices which include ease of construction, operation and maintain. The SIPP filter was observed to reduce TOC and turbidity from contaminated water. Chlorophyll a resulted in an overall decrease in the flow rate of the SIPP. Higher chlorophyll a concentrations in the unfiltered resulted in overall observation of higher turbidities in the contaminated water. Filtration of high turbidity water resulted in an overall decrease in the flow rate of the SIPP filter. The SIPP’s higher flow rate makes it suitable for use by a larger family for the production of drinking and cooking water.
Current work involves evaluating the SIPP’s life span and evaluation of the effect of initial concentration on the removal efficiency by the filter.
4.6 References


5.1 Introduction
There are vast numbers of problems associated with industrialisation which include high water pollution rate and lack of adequate potable water. Advanced treatment methods have been developed to treat microbial and chemical contaminants from polluted water. These treatment methods include membrane filtration, UV light and reverse osmosis. The drawback with these methods is that they are expensive and thus cannot be afforded by low income rural people. Therefore there is need for the design of cost effective household water treatment systems (HWTS). The design of the filters should take into account safe storage of the filtered water since treated water can be re-contaminated during transportation and storage. There are a number of HWTS that are already available to the market which include ceramic candle filters (CCF), slow sand filters (SSF), porous pot filters and bucket filters. A lot of research has been done in evaluating their efficiency at removing microbial contaminants but there is still a lack of data on their performance in removing chemical contaminants. This study presents results for the performance of three HWTS in removing chemical contaminants from drinking water. The filters were the biosand filter (BSF), the ceramic candle filter (CCF) and the bucket filter (BF).

Biosand filters are conventional slow sand filters which function with the aid of gravity. The design of a biosand filter comprises a concrete-coated metal mould filled partially with one layer each of large gravel, small gravel, and clean medium-grade sand. A diffuser plate is placed on top of the sand and water is poured into the remaining space. Prior to use, the filter is filled with water each day for two to three weeks until a biological layer of bacteria depleting microorganisms resembling dirt develops on the surface of the sand. These microorganisms consume disease-causing viruses, bacteria, and parasites, while the sand traps
organic matter and particles. Biosand filters have been shown to remove 76 to 91% of arsenic; reducing it to acceptable concentrations.  

Ceramic filtration has been reported to be one of the most popular methods of water treatment at household level. There are different types of ceramic filters which include ceramic candles and ceramic pot filters. All ceramic filters are known to greatly reduce turbidity and they can be impregnated with silver nano-particles and result in microbial disinfection. Another added advantage of silver impregnation is that bacteria are not able to develop resistance to silver.

Ceramic candle filters are made from clays mixed with saw dust or flour (combustible materials) to increase porosity. The clay and combustible materials are generally sieved through a fine mesh and mixed together with water to form a homogeneous mixture which is passed into shape using a mould. Fine pores for water to pass are retained after the filter is fired in an oven. Ceramic candle filters have flow rates between 1 L/h and 2 L/h. The flow rates may decrease relative to the lifetime of filter which can be affected by fouling. Porosity, filter thickness, filter surface area, water height and water quality have been discovered to be the main factors that affect the performance and flow rates of ceramic candle filters. Ceramic candle filters have micro pores (0.1 µm – 10 µm) and are effective at removing bacteria. Ceramic candle filters have pores ranging from 0.1 to 10 µm. Biological and physical processes are the main processes that occur during pathogen and turbidity reduction. Ceramic candle filters have been found to be effective in removing 83% – 99% turbidity, > 90% iron, 98% – 100% bacteria, 19% - 100% viruses, 100% protozoa and 100% helminths. Ceramic candle filters have advantages which include ease of operation, portable, carry out disinfection processes when coated with silver and greater reductions of turbidity. Water Filter Technologies have reported that improvement in chemical contaminants. Colour and odour removal by ceramic candle filters can be improved by the addition of activated carbon into the filter.

The bucket filter is fast or rapid sand filter that is used mostly by municipalities in water treatment. Coarse sand and fine sand is used in the construction of fast
sand filters (FSF) and these types of filters are gravity driven. Fast sand filters require frequent cleaning by back washing. Backwashing requires a lot of care as the media can be washed away. Fast sand filters have relatively high flow rates and these flow rates are not affected by the turbidity of the intake water.\textsuperscript{15} Fast sand filters do not have disinfection capabilities during the filtration process since they do not remove bacteria and other microbial contaminants; colour and odour reduction by FSF is also low.\textsuperscript{16}

The BSF and CCF have been extensively evaluated for microbial contaminants removal in most countries but to the best of our knowledge there is no evidence of their evaluation on chemical contaminants removal. These filters have not been tested in South African rural areas (SARA) to ascertain if they could be a solution for both chemical and microbial contaminant removal from drinking water. This study reports results on the removal efficiency by three filters (BSF, CCF and BF) of chemical contaminants. The choice of BSF and CCF was based on selection criteria that were formulated by the research team. These criteria included cost effectiveness, ease of construction, operation and maintenance of the filter devices. The availability of construction materials for these filters in SARA was considered as an important factor.

This study was aimed at designing and constructing cost effective household water treatment systems for microbial and chemical contaminants removal in SARA.

The main objectives of the study were to evaluate the following:

- Removal efficiency of heavy metals (calcium, iron, magnesium and arsenic), total organic carbon (TOC), nitrates, phosphates and fluorides from contaminated water

- Determination of the flow rates of the filters and find out if they are within the recommended limits.\textsuperscript{10,17}
• Determination if the filters can remove suspended particles (turbidity) from contaminated water and evaluate the effects of turbidity on the flow rates of the filters

• Investigation of the effects of chlorophyll a on the flow rates of the filters

5.2 Experimental
5.2.1 Description of Filters
5.2.1.1 BSF
The biosand filter (Figure 5.1A) was made in the workshop of the Tshwane University of Technology, Pretoria, South Africa with minor modifications based on guidelines given in the literature. The BSF consisted of six discrete zones (inlet, standing water, biolayer, biological layer, fine sand and gravel zone) which play an important role in the filtration process. The inlets zone is where water is poured for treatment and this is followed by the standing water zone which came about as a result of raising the outlet pipe (5 cm) above the top layer of sand. Oxygen diffuses through this zone to the third layer, the biolayer zone, which comprises slime, sediments and microorganisms. The biolayer zone develops 1 cm – 2 cm above the top layer of sand. The biological layer (the forth zone) develops at the sand-water interface and is useful in iron and microbial removal. The fifth zone (15 cm fine sand layer of particle size 0.15 mm) forms the largest part of the filter media. Gravel (2.5 cm thick) and coarse (2.5 cm thick) sand forms the sixth zone which plays an important role in preventing fine sand from flushing through the pipe connected to the spigot. A perforated diffuser plate was made from a lid of a 25 L bucket. Disturbance of the biological layer by newly poured water is facilitated by the diffusion plate. The diffusion plate also entraps suspended particles.

5.2.1.2 CCF
A complete ceramic candle filter has two buckets, a cylindrical hollow candle screwed at the base of the top bucket through the lid of the bottom bucket and a cloth which covers the cylindrical candle and prevents particles from clogging the filter (Figure 5.1B). The cloth plays a major role in turbidity reduction by trapping
Figure 5.1A: Illustration Showing Different Layers of the BSF; A – Gravel Layer (2.5 cm), B – Coarse Sand Layer (1 cm) together with the Gravel Layer, C – Fine Sand Layer (15 cm), D – Skeletal View of a BSFS Showing the Internal Content.

large particle sized suspended sediments such as grass and leaves. The lower bucket is fitted with a spigot where water is drawn. The ceramic candle filter is operated by removing the lid of the upper bucket with the cylindrical hollow candle, fill the bucket with contaminated water and draw filtered water from the spigot located in the lower bucket (Figure 5.1B).

5.2.1.3 BF

The bucket filter is a fast sand filter designed and built by the Tshwane University of Technology research group (Figure 5.1C) and consists of two buckets. The top bucket contains the filter media and the bottom bucket serves as a collection vessel. The base of the top bucket was perforated using a 2 mm drill bit through the lid of the collection bucket (bottom bucket). The seal between the lid and the bottom of the top bucket was ensured using PVC glue. Pressure exerted by the top bucket filled with media also ensured that the seal remained intact. The collection bucket was fitted with a spigot that was placed as low as possible at the base. The top bucket was then filled with filter media which comprised two layers.
Figure 5.1B: Illustration Showing CCF Filter; A – Outside View of the Filter with Inset (dome shaped filter covered with a cloth), B – Dome Shaped Filter, C – Skeletal View of CCF Showing the Internal Content of the whole Filter Unit.

The first layer was unmodified gravel with particle size of 5 mm – 7 mm while the second layer was unmodified fine sand of particle size 0.95 mm. The gravel layer thickness was 5 cm and its main purpose was to prevent the fine sand from going down through the pores during filter run. The gravel layer also allowed smooth flow of water during filtration. The fine sand layer thickness was 20 cm and this layer was responsible for most of the filtration process.

The main idea in designing the bucket filter was to evaluate the effect of flow rate and the presence of the biological layer in the reduction of microbial and chemical contaminants. The BSF was a slow sand filter while the BF was a fast sand filter (FSF) both having sand as the filtering media. The BSF had a biological layer which was absent in the BF and the CCF differed from both the BSF and BF since it had clay material and not sand. This study focused on comparing the BSF to BF (slow sand filter with biological layer vs. fast sand filter without a biological layer) and both the BSF and BF (sand filters) to CCF (clay) for the removal of chemical species relative to water flow in all the filters.
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5.2.2 Sample Collection

Water samples were collected from four different sites in three provinces of South Africa. Surface low turbidity water (SWL) was sourced from Apies River (Gauteng Province), ground low turbidity water (GWL) was sourced from Delmas (Mpumalanga Province), surface high turbidity water (SWH) was sourced from Hartbeespoort Dam (North West Province) and ground water with high turbidity (GWH) was sourced from Wallmannsthal (Mpumalanga Province). Collection of surface and ground water with low and high turbidities was done with the purpose of evaluating the effects of turbidity and chlorophyll $a$ concentrations on the flow rates of the filters and also to correlate chlorophyll $a$ concentrations with turbidity. Collected water samples were stored in 50 L containers and immediately transported to the laboratory where filtration and all analyses were performed. Sample collection was performed six times from each sampling site.

5.2.3 Filtration and Flow Rate Determination

Filtration was done upon arrival in the laboratory and lasted for 3 hours. Contaminated water was passed through the filters and allowed to collect in the collection vessels for 1 hour after which (first hour collection) analysis was done. The collection vessel was allowed to collect filtered water again for an additional
hour after which the filtered water was analysed (second hour collection). The third hour collection was obtained in the same manner as the first and second hour collections.

Multiple flow rates tests were performed in the event of collecting filtered water at each hour of filter run, by measuring the volumes of collected water at each hour of filter run for BSF and CCF. The flow rates (L/h) were expressed as the volume of filtered water (L) divided by the time taken to filter (h). In the event of measuring the flow rate, it was noted that the flow rate of the BF was too high and filtered water was collected before an hour had lapsed. The flow rate (BF) was then determined by measuring the volume of water collected in 1 minute (mL/min) and this was converted to (L/h).

5.2.4 Turbidity Testing
Turbidity tests were performed on all environmental water samples filtered through the BSF and CCF (1 h, 2h and 3 h collections) and BF (2 min, 4 min and 6 min collections). All turbidity values are reported in nephelometric turbidity units (NTU). A Cyber-Scan NTU-100 turbidity meter was used for all turbidity analysis. Clear vials were filled to the mark with water samples to be tested. The vials were then inserted into the turbidimeter slot and a black cap was placed on top of the slot to cover the vial and ensure there was no light coming externally. Triplicate readings of each sample were taken for statistical evaluation. The same turbidity determination method was applied for the evaluation of turbidity in unfiltered water. Turbidity reduction by the filters was obtained by comparing turbidity of unfiltered water with that of filtered water.

5.2.5 Removal of Chemical Contaminants
Standard methods were followed in the analysis of all chemical contaminants. A Varian 220 FS was used for calcium, magnesium, iron and arsenic analysis. The support gas for calcium and arsenic analysis was nitrous oxide. The ion selective electrode method\textsuperscript{20} was adopted for the analysis of fluorides and fluoride electrode was utilised together with a Metrohm 713 pH meter for the analysis. A SPEKOL 1300 was employed for nitrates, phosphates and chlorophyll \textit{a} analysis and
standard methods\textsuperscript{20} were followed when preparing samples for analysis. Total organic carbon (TOC) was analysed using a TOC combustion analyser (Tekmar Dohrmann Apollo 9000).

5.2.6 Statistical Analysis
All statistical analyses were performed using Stata V10 (Tshwane University of Technology, Research Innovations). Statistical analysis of chemical contaminants data was carried out on the removal efficiency of chemical contaminants (%) and results interpretation was performed at 95% confidence limit. One-way analysis of variance was used to compare more than two groups (e.g. comparing the flow rates (L/h) of BSF to CCF). Correlation between chlorophyll \(a\) and filter flow rates and/or turbidity was also determined using the Pearson correlation test.

5.3 Results and Discussion
5.3.1 Flow Rates
Figure 5.2 shows flow rates of filters. During the course of the study, the filters had flow rates between 0.8 L/h and 6.48 L/h (BSF) (Figure 5.2A), 0.05 L/h and 2.495 L/h (CCF) (Figure 5.2B) and 106.5 L/h and 160.5 L/h (BF) (Figure 5.2C). The flow rates of the BF were higher because the particle size of the filter media (sand) was larger than the particle size of the sand used as the filter media of BSF and the filter was designed in a way that it had higher flow rates. The lower flow rates of the BSF and CCF could be accounted for by the lower particle size of the sand (0.15 mm) used in construction of the BSF and the lower pore size (0.2 \(\mu\)m) of the clay used in the construction of the CCF. Elliot et al. (2008) stated that flow rate of filters is determined by the particle size of the filter media and this perfectly explains the higher flow rates by the BF compared to BSF and CCF.\textsuperscript{21} The design of the BSF also ensures that the flow rate of the filter remains minimal, to ensure enough contact time between the media and contaminated water. Standard biosand filters have flow rates up to 54 L/h.\textsuperscript{21} The flow rate of the biosand filter was lower than flow rates of standard biosand filters. This may be as a result of the smaller size of the filter and the very fine sand particles (0.15 mm) used in this study compared to 0.7 mm for standard biosand filters.\textsuperscript{17} The BSF was mainly different from standard BSFs in terms of the materials used for construction, size
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of the filter and the particle size of the media used. A plastic bucket (cheap and readily available in South African supermarkets) was used as a filter house instead of concrete. Ceramic candle filters generally have flow rates between 1 L/h and 3 L/h and these flow rates have been found by Shafiquzzaman et al. (2010) to be suitable enough for the production of drinking and cooking water for a family of six members. The flow rate of our CCF (0.05 L/h - 2.495 L/h) was within the recommended limit as given in literature (Figure 5.2B). Lower flow rates (< 1 L/h) were observed after the filter was used for some time. The flow rates of the BSF and CCF were observed to be significantly different ($p = 0.000$) and the BF had higher flow rates significantly different from both the CCF and BSF ($p = 0.000$). The flow rates of the filters were noticed to be higher when the filters were filled with water to be filtered and decreased with decrease in the volume of water in the filter. This observation was evaluated by comparing the flow rates during the first hour of filter run when the filters were full with flow rates of the third hour of filter run when the water head had dropped. There was a statistical significant difference between the first and third hour flow rates for BSF ($p = 0.000$) and CCF ($p = 0.000$). There was a significant difference in the flow rates of the BSF between the first and second hour of filter run ($p = 0.002$). There was a significant difference in the flow rates of CCF in the first and second hour of filter run ($p = 0.002$). The BSF and CCF have higher flow rates in the first hour of filter run and the flow rates decreased and became low in the third hour of filter run. It was believed that the flow rates depended on the degree of filter clogging and the level of water above the filter which dropped and became low in the third hour of filter run. The flow rates of the filters were observed to decrease with time of filter use and this could be as a result of persistent clogging each time the filter was used. Accumulation of microorganisms on the surface as biofilm resulted in sealing of the surface of the filters. Accumulated matter on the upper sand layer of the BSF and BF is believed to have undergone humification and gradually clog the pore space of the sand, hence reducing the permeability of the filter. Clogging of the BF was delayed possibly because of the larger sand bed and the larger particle size of the filter media. Filter cleaning was observed to result in an increase in the flow rates of the filters (Figure 5.2 A-C) as the finer particles resulting to clogging were removed when the sand was washed.
Figure 5.2: Flow Rates of BSF, CCF and BF; Effects of Filter Cleaning on Filter Flow Rates.
5.3.2 Turbidity Reduction

There was higher turbidity reduction by the filters (Figure 5.3) on filtering water with low and high turbidity (1.47 NTU – 42.93 NTU). There was on average 70%, 44% and 51% turbidity reduction by BSF (Figure 5.3A), CCF (Figure 5.3B) and BF (Figure 5.3C) respectively. Biosand and ceramic candle filters have been reported to greatly reduce up to 90% turbidity in contaminated water.\(^{10,11}\) Turbidity reduction by the filters was 19% - 98% (BSF), 5% - 99% (CCF) and 4% - 93% (BF). The higher turbidity reduction by the BSF compared to CCF and BF could be due to the smaller particle-sized sand (0.15 mm) used as the filter media that covered the largest area of the filter house. Contaminated water spent more time with the filter media before it came out of the spout hence there was higher reduction in turbidity. The lower turbidity reduction by the CCF and BF compared to the BSF could be accounted for by the smaller size of the filter (CCF), hence providing a smaller surface area for removal of particles and the large particle-size sand (0.95 mm) used as the filter media in the construction of the BF. Statistical results predicted that there was no significant difference in the hourly reduction of turbidity by the BSF (\(p = 0.514\)) but there was a significant difference in the hourly reduction of turbidity by CCF (\(p = 0.004\)) and BF (\(p = 0.001\)). There was a significant difference in overall turbidity reduction between BSF and CCF (\(p = 0.01\)), BSF and BF (\(p = 0.04\)) but there was equal removal of turbidity by CCF and BF (\(p = 0.41\)). Turbidity reduction (%) by the filters was in the order BSF (70%) > BF (51%) > CCF (44%) but statistical wise the order was BSF > BF = CCF. The turbidity of the water after filtration through the BSF was between 0.44 NTU and 15.61 NTU (Figure 5.3A). Out of 72 samples analysed after treatment, 33 samples (46%) had turbidity within the recommended limit.

The average turbidity readings of the water after filtration through the CCF were between 0.58 NTU and 36.43 NTU (Figure 5.3B). Only 18 samples (25%) out of 72 had turbidity readings within the SANS, 241 limit.\(^{26}\) Only 29% (21 samples) out of the 72 samples filtered through the BF had turbidity readings less than 1 NTU, a standard for turbidity of drinking water set by SANS, 241.\(^{26}\) The turbidity of the samples after filtration was between 0.46 NTU and 27.61 NTU (Figure 5.3C).
Washing of the filter media of BSF and BF together with the candle filter of CCF resulted in a slight increase in turbidity reductions by the filters although turbidity reduction efficiency was expected to decrease after filter washing as a result of the removal of particles that result to filter clogging. Turbidity reduction by filters is enhanced by filter clogging of the filter pores as a result of adsorption, attachment and sedimentation of particles.\textsuperscript{27} It may not be generalised that the improvement in turbidity reduction by the filters was due to filter washing solely because the source water filtered before and after washing were different. Generally the turbidity of the filtered water in the third hour (BSF and CCF) and sixth minute (BF) of filter run were high compared to turbidity of the first and second hour collections. This might be due to particles being concentrated in a smaller volume as the flow rates of the filters were lowest at most in the third hour (BSF and CCF) and sixth minute (BF) of filter run. Since the spigot of the collection vessel of CCF was closed during the filtration process and opened at the end of each hour when water was taken for analysis. It was assumed that particles were trapped in the spigot and released when it was opened hence an overall increase in the turbidity of the water with time of filter run.

### 5.3.3 Chemical Contaminants Removal

Figure 5.4, 5.5 and 5.6 show results of the three filters for the average reductions of contaminants from water on filtering environmental water samples where the average concentrations before treatment are presented as BT, average concentrations after treatment as AT, (1 h, 2 h and 3 h) and (2 min, 4 min and 6 min) were concentrations after treatment at 1 hour, 2 hour and 3 hour (BSF and CCF) and 2 minutes, 4 minutes and 6 minutes (BF) of filter run and SANS, 241 is the recommended limit by the South African National Standard.\textsuperscript{26}

Results showed that there was an average of 40%, 48% and 46% calcium reduction by BSF, CCF and BF on filtration of environmental water. The highest calcium reduction efficiency achieved by the filters was 93% (BSF), 99% (CCF) and 91% (BF). Results showed that there was no difference in the hourly removal
Figure 5.3: Turbidity Reduction by BSF, CCF and BF: Effects of filter cleaning on turbidity reduction.
of calcium by the BSF ($p = 0.96$), CCF ($p = 0.715$) and BF ($p = 0.948$). Calcium reduction by the filters was compared and results predicted equal calcium removal by the BSF and CCF ($p = 0.282$), BSF and BF ($p = 0.411$) and CCF and BF ($p = 0.708$). This means that any of the filters could be used for calcium removal from contaminated water. The filters were cleaned twice during the course of the study. The first cleaning was done after filtering a total cumulative volume of intake water of 980 L and the second cleaning was performed after filtering a total cumulative volume of 1100 L.

The BSF, CCF and BF were able to achieve 50% reduction of magnesium (Figure 5.4, 5.5 and 5.6). The average removal efficiency by the filters was 54% (BSF), 50% (CCF) and 51% (BF) and results showed that there was no significant difference in the removal efficiency by the filters ($p \geq 0.05$). There was also no significant difference in the hourly reduction of magnesium by the filters ($p \geq 0.05$). The performance of the filters in removing magnesium could be expressed as BSF = CCF = BF. During the course of the study, magnesium reduction > 90% was achieved by the filters (Figure 5.4, 5.5 and 5.6).

There was greater removal of iron by the filters as removal efficiency greater than 65% was achieved by all filters (Figure 5.4, 5.5 and 5.6). The highest iron concentration in intake water was 1.011 mg/L and the lowest concentration was 0.093 mg/L. The average reductions achieved by the filters (Figure 5.4, 5.5 and 5.6) were 73% (BSF), 70% (CCF) and 69% (BF). The BSF and BF were able achieve > 70% iron reduction. Iron retention by the BSF and BF could be through biological oxidation of soluble iron(II) by iron oxidising microorganisms such as Gallionella sp into poorly ordered insoluble iron(III) oxides. Soluble Iron(II) oxidation into insoluble iron(III) could also be through aeration. There was no statistical significant difference in the hourly reduction of iron by the filters ($p \geq 0.05$) and the three filters had equal removal efficiency of iron ($p \geq 0.05$). This indicated that any of the filters could be used for the removal of iron and water could be drawn for use at any time of filter run. The CCF evaluated in this study had a carbon fibre blanket with pore size of 0.2 µm and the ceramic component of the filter was 0.5 µm. Activated carbon filters have been found by Modin et al.
(2011) to be effective in removing more than 90% of cobalt, chromium, iron, lead and zinc.\textsuperscript{31} The activated carbon filter also removed calcium, cadmium, magnesium, mercury, manganese and molybdenum but not to the same extent. Removal of metals by activated carbon is believed to be through sorption processes whereby heavy metals are believed to form complexes with organic matter.\textsuperscript{32} The removal of magnesium, calcium and iron by the CCF could be through these processes.

The BSF, CCF and BF were able to achieve > 50% reduction of arsenic (Figure 5.4, 5.5 and 5.6). There was no difference in the average arsenic removal by the filters ($p \geq 0.05$) and the hourly reduction efficiency was observed to be statistically insignificant ($p \geq 0.05$). The average arsenic reduction efficiency by the filters throughout the filtration course was 55\% (72 samples for each filter). These filters (BSF, CCF and BF) were observed to remove arsenic greatly when the initial concentrations were low. Similar to the CCF evaluated in this study is a simple ceramic filter made from clay and rice bran available in rural areas of Bangladesh. The ceramic filter removes iron from contaminated water and arsenic to a lesser extent. Arsenic removal is believed to be through partial oxidation of arsenic (III) to arsenic (V) during physical-chemical oxidation of iron (II) to iron (III). This results in higher arsenic removal efficiency by the ceramic filter.\textsuperscript{33,34} This mechanism possibly explains arsenic retention by the CCF.

As mentioned earlier that biological oxidation of iron(II) is useful in arsenic removal, this process when coupled with ceramic filtration would be a worth alternative for arsenic removal from groundwater\textsuperscript{22}, because ceramic filters can be manufactured locally, using locally available materials at low costs. Inconsistency in the removal of contaminants by the BSF, CCF and BF showed dependence of the removal efficiency on the initial concentrations of contaminants.

On average, the BSF, CCF and BF did not remove fluorides from contaminated water. Poor fluorides reduction could be as a result of cracks in the CCF\textsuperscript{22} and the poor ability of sands to retain fluorides. Proposed mechanisms of fluorides removal include chemical precipitation, ion exchange, reverse osmosis, adsorption and
nanofiltration. None of these processes could be achieved through the use of sands regardless of the particle size.

There was poor reduction of nitrates by the filters as the average reduction efficiency was 8% (BSF), 17% (CCF) and 27% (BF). The mean nitrates hourly reductions together with the hourly reduction efficiency by the BSF, CCF and BF was not significantly different ($p \geq 0.05$). During the course of the study, the highest reduction efficiency achieved by the filters was 47% (BSF), 71% (CCF) and 92% (BF). Nitrates were often observed to leach from the filter media or walls as there were higher concentrations in the filtered water compared to the concentrations of unfiltered water. Achak et al. (2009) reported 81 – 99% nitrates reduction by sand filters and proposed that total nitrates removal was through anaerobic denitrification microorganisms when the filter was supplied by water. This process explains the removal of nitrates by the BSF, BF and other similar filters.

On average the BSF and the CCF did not remove phosphates from contaminated water. The BF was able to achieve on average 1% phosphates reduction but during the course of filter run, 6% reduction by the filter was achieved (Figure 5.6). The mean phosphates concentration in unfiltered water was 15.552 mg/L ± 10.969 mg/L and the highest concentration was 26.521 mg/L while the lowest concentration was 4.583 mg/L. Although on average the BSF did not remove phosphates, lower reduction efficiency (3%) was recorded during the course of the study. There was a significant difference in hourly reduction of phosphates by the BSF ($p = 0.02$). There was no significant difference in the hourly reduction of phosphates by the CCF ($p = 0.795$) and BF ($p = 0.553$). The performance of the filters in phosphates reduction was not significantly different ($p = 0.099$) and the filters failed to reduce phosphates from contaminated water. Phosphorus removal is a complex process that involves settlement, bacteria adsorption and substrate affinity. The removal of phosphates by the filters is believed to be through biological processes. Lower phosphates removals by the filters could be attributed to the particle size of the filter media as finer particle size materials have been reported to have higher phosphates sorption capacity. The slight
phosphates removal by the filters could also be through fixation of phosphate ions by ions of calcium and iron.\textsuperscript{47}

The BSF, CCF and BF cannot be used for the treatment of contaminated water with phosphates concentrations above the recommended limit by SANS, 241.\textsuperscript{26}

**Figure 5.4: Performance of BSF in Removing Chemical Contaminants from Surface and Ground Water Sources.**
There are literature reports on the removal of chemical contaminants by the BSF, CCF and BF devices. The BSF has been reported by CAWST\textsuperscript{17} to remove iron in the biolayer zone. Our BSF removed up to 90% iron and this could be attributed to the smaller particle size of sand used (compared to particle size reported in literature). Van Halem\textsuperscript{11} predicted > 90% reduction of iron by CCF devices and the CCF filter evaluated in this study was able to achieve 69% reduction efficiency. The failure to achieve 90% calcium reduction by our CCF could be due to the
Figure 5.6: Performance of BF in Removing Chemical Contaminants from Surface and Ground Water Sources.

larger pore size (0.5 µm) compared to the pore sizes of 0.2 µm reported in literature. The BF was designed and built by the TUT research group and hence evidence of chemical contaminants removal by this filter could be based on similar filters such as fast sand filters. The BSF, CCF and BF were able to achieve arsenic reduction efficiency > 40%. There are no reports on arsenic removal by the CCF and BF and/or fast sand filters reported in literature. In the case of BSFs,
Sharma$^6$ reported that these filters remove up to 90% arsenic. These filters evaluated in this study have been reported to have very poor removals of phosphates, nitrates and fluorides. Although the BF was classed as a fast sand filter, it has to be noted that the particle size of the sand used (0.95 mm) was much smaller than the conventional sand size of fast sand filters which is 2 mm – 8 mm$^{48}$ and this could explain why it removed some of the chemical contaminants. Greater reduction of contaminants by the BSF was noticed in the first hour of filtration. This could be explained based on the fact that the filter always had water to ensure the existence of the biological layer which is fundamental in the reduction of microorganisms from water. This implies that the first hour collection comprised greatly of the water that was left in the filter since the last filtration was done. This water had long contact time with the filter hence the greater reductions observed. The filters removed calcium, magnesium and iron to levels within the recommended limit by SANS, 241$^{26}$ but not arsenic, nitrates, fluorides and phosphates.

5.3.4 Removal of Total Organic Carbon (TOC)
The BSF, CCF and BF had very low TOC reduction efficiency (Table 5.1). The BSF had on average 17% TOC reduction (Table 5.1) while the CCF had 39% (Figure 5.5) and the BF had 11% (Table 5.1). The CCF was observed to have the highest TOC reduction efficiency compared to the BSF and BF. There was a significant difference in the hourly reduction of TOC by the BSF ($p = 0.049$) and CCF ($p = 0.00$) but there was no significant difference in the hourly reduction of TOC by the BF ($p = 0.153$). Statistical results showed that the CCF removed TOC better than the BSF ($p = 0.000$) and the BF ($p = 0.000$). There was equal removal of TOC by the BSF and BF ($p = 0.078$). The greater reduction of TOC by the CCF compared to BSF and BF shows that clay minerals perform better than sand in removing TOC from contaminated water. This higher removal could also be attributed to by the small pore size of the CCF (0.5 µm). TOC reduction by the filters was in the order CCF $>$ BSF = BF.
5.3.5 Effects of Chlorophyll $a$ on the Flow Rates of Filters and Turbidity of Intake Water.

The effects of chlorophyll $a$ on the flow rates of filters and the relationship between chlorophyll $a$ concentrations with turbidity of unfiltered water were evaluated and results are presented in Table 5.2. Results indicated that at higher chlorophyll $a$ concentrations, the flow rates of the filters decreased. Chlorophyll $a$ generally had an inverse relationship with the flow rates of BSF, CCF and BF as statistical results indicated correlation coefficients ($r$) of -0.556, -0.788 and -0.818 between BSF, CCF and BF respectively with chlorophyll $a$ concentrations. Higher chlorophyll $a$ concentrations in raw intake water resulted in observations of higher turbidities hence the filters clogged quicker resulting in the overall decrease in the flow rates of the filters. There was a positive correlation between chlorophyll $a$ in the unfiltered water with turbidity of the water ($r = 0.607$). This positive correlation could be explained from the fact that chlorophyll $a$ is used as a measure of the concentration of algae. Since turbidity is the measure of suspended particles in the water, algae also forms part of the suspended particles. An increase in chlorophyll $a$ concentration means an increase in the amount of suspended particles (turbidity). Uncles et al. (2000) investigated seasonal variation of salinity, temperature, turbidity and chlorophyll $a$ in the Tweet Estuary. Lower concentrations of chlorophyll $a$ were found to be lower together with turbidity. Although the interaction of light by suspended particles (high turbidity) limits phytoplankton growth resulting in low chlorophyll $a$ concentrations (inverse correlation) as reported by Boyd, Daly et al. (2001) and Moline and Prezelin, results of this study showed high chlorophyll $a$ concentrations at higher turbidity water sources and agreed with findings of Uncles et al. (2000).

Table 5.1: TOC Reduction by BSF, CCF and BF.

<table>
<thead>
<tr>
<th>Filter</th>
<th>BT (mg/L)</th>
<th>AT 1h (mg/L)</th>
<th>AT 2h (mg/L)</th>
<th>AT 3h (mg/L)</th>
<th>Av. % Reduction</th>
<th>(n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSF</td>
<td>6.329±1.173</td>
<td>5.213±0.781 (17%)</td>
<td>5.494±0.9 (13%)</td>
<td>5.204±1.566 (22%)</td>
<td>17%</td>
<td>12</td>
</tr>
<tr>
<td>CCF</td>
<td>6.329±1.173</td>
<td>5.167±0.308 (16%)</td>
<td>4.300±0.7 (32%)</td>
<td>1.759±1.560 (69%)</td>
<td>39%</td>
<td>12</td>
</tr>
<tr>
<td>BF</td>
<td>6.329±1.173</td>
<td>5.703±0.516 (5%)</td>
<td>5.671±0.4 (8%)</td>
<td>5.028±0.646 (20%)</td>
<td>11%</td>
<td>12</td>
</tr>
</tbody>
</table>
Table 5.2: Effects of Chlorophyll \(\text{a}\) on the Flow Rates of Filters and Turbidity of Unfiltered Water

<table>
<thead>
<tr>
<th>Chlorophyll (\text{a}) ((\text{mg/m}^3))</th>
<th>Turbidity ((\text{NTU}))</th>
<th>Flow rate ((\text{L/h}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BSF</td>
<td>CCF</td>
</tr>
<tr>
<td>28.321</td>
<td>0.84</td>
<td>1.35</td>
</tr>
<tr>
<td>34.172</td>
<td>2.00</td>
<td>1.11</td>
</tr>
<tr>
<td>39.142</td>
<td>1.26</td>
<td>0.70</td>
</tr>
<tr>
<td>33.642</td>
<td>1.50</td>
<td>1.31</td>
</tr>
<tr>
<td>14.418</td>
<td>2.40</td>
<td>2.30</td>
</tr>
<tr>
<td>11.214</td>
<td>1.92</td>
<td>3.02</td>
</tr>
<tr>
<td>28.84</td>
<td>1.16</td>
<td>0.95</td>
</tr>
<tr>
<td>92.92</td>
<td>1.18</td>
<td>0.59</td>
</tr>
<tr>
<td>94.92</td>
<td>0.96</td>
<td>0.31</td>
</tr>
<tr>
<td>70.49</td>
<td>1.6</td>
<td>0.69</td>
</tr>
<tr>
<td>49.66</td>
<td>0.79</td>
<td>0.65</td>
</tr>
<tr>
<td>95.02</td>
<td>0.82</td>
<td>0.33</td>
</tr>
</tbody>
</table>

5.3.6 Maintenance Guidelines of the Filters

Investigation of filters’ maintenance was fundamental in this study to make necessary recommendations on how the filters need to be handled for the production of good quality water and long life span.

Collection vessels for all the filters were cleaned thoroughly with deionised water and soap and sterilised with household bleach. It is recommended for rural households that have limited access to deionised water to use water filtered through the filter to wash collection vessels. In cases where household bleach cannot be afforded, thoroughly washed collection vessels may be left in the sun for sterilisation by drying and heating. The BSF, CCF and BF were cleaned when the flow rates were observed to have decreased significantly. In cases where the flow rates of the filters are observed to be high but the filters look dirty, it is recommended that the filters are washed as described in this study. Figure 5.7
shows how the BSF, CCF, BF and collection vessels looked like when they were dirty.

![Image of dirty filters and a collection vessel](image)

**Figure 5.7: Illustration Showing Dirty Filters and a Collection Vessel: A – BSF with Dirty Perforated Diffusion Plate; B – CCF with Candle Filter and Cloth; C – BF Showing Filter Media and Collection Vessel; D – Dirty Collection Vessel with a Spigot Fitted in a Socket.**

The BSF was cleaned by removing the top 5 cm layer of fine sand, thoroughly washed and replaced. It may be recommended that if new sand (with same particle size) is available, the old sand may be replaced with thoroughly washed new sand. When cleaning the sand, it is advised that filtered water is used to reduce the level of re-contamination. Removing the top few centimetres of the top sand bed was appropriate based from the observation that particles resulting to clogging could not penetrate deep into the sand bed.\(^{54}\)

Washing of the BF’s media was performed in the same manner as the BSF but the top 10 cm layer of sand was removed, washed and replaced. The reason for removing 10 cm could be justified based on the difference in the particle size of the sand used as the filter media being larger. Particles were observed to penetrate deeper into the sand.

Sludge or dirt on the filter (CCF) could be cleaned periodically when unsatisfactory flow rates are obtained as a result of filter clogging. Scribing with a cloth or soft brush, followed by rinsing with hot water once a week, is recommended.\(^{22}\) Care
must be taken not to cause cracks during cleaning. Dirt from the CCF was removed by scribing the candle filter with a soft brush followed by rinsing with deionised water.

The ceramic candle filter was easier to wash compared to the biosand filter and the bucket filter in the sense that lesser time and effort was spent.

These household filters have been invented in a way that they filter water with turbidities lower than 50 NTU. In cases where by the water to be filtered is highly turbid (> 50 NTU), the water must be left to settle before it is filtered. To test the turbidity of water, water to be filtered may be poured into a clean 2 L plastic bottle placed on top of a large print. Failure to see the large print when looking down through the top of the bottle indicates that the water has turbidity > 50 NTU.

Movement of the filters should be avoided since this disturbs the sand bed in the BSF and BF and the biological layer in the BSF might be disturbed too. Care needs to be taken when removing the top and bottom buckets of CCF and BF because the seal in the BF may be disturbed and the candle filter might be disturbed too. Care must be taken when opening the taps as leakages may results from detached taps.

The filters cost approximately US$ 16 (BSF), US$ 64 (CCF) and US$ 17 (BF). Low income rural people of South Africa may afford to possess one of these filters due to their low cost. The filters (BSF and BF) may be made at home at lower costs and construction materials are readily available.

5.4 Conclusions
Three filters were designed, constructed, evaluated and compared for their performance in removing chemical contaminants from contaminated water. The BSF, CCF and BF had flow rates within the recommended limits. Due to higher flow rates, these filters may be used for production of clean potable water for a family with a larger family number. The flow rates of the filters were significantly affected by the turbidity and chlorophyll a concentrations of raw intake water. The
filters were able to remove > 50% turbidity from contaminated water with turbidities > 40 NTU. The filters were observed to remove metals although the overall removal efficiency was not very high. The filters were observed to equally remove calcium, magnesium, iron and arsenic \( (p > 0.05) \). The performance of the filters in removing chemical contaminants was not affected by the contact time between the filter media and contaminated intake water. These filters may not be recommended for treatment of water highly contaminated with nitrates, fluorides and/or phosphates since they were not able to remove these contaminants to levels recommended by SANS, 241 (2006). The filters are cheaper to construct using readily available materials and easier to operate and maintain hence affordable to less income SARA people. The size of the filters is an added advantage since it makes it possible for household users to keep them where food is prepared. This will motivate users to continue using the filters and also maintain them.
5.5 References


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15 UNITED STATES ENVIRONMENTAL PROTECTION AGENCY (EPA). 1990. Cincinnati, OH. "Technologies for Upgrading Existing or Designing New Drinking Water Treatment Facilities."


Chapter 5: A comparative study of chemical contaminants removal by three household filter


6.1 General Conclusions

Five household water treatment systems were designed, constructed and evaluated for their efficiency in reducing chemical contaminants from drinking water. The filters were the modified biosand filter with zeolites (BSFZ), the standard biosand filter (BSF), the silver impregnated porous pot filter (SIPP), the ceramic candle filter (CCF) and the bucket filter (BF). The water treatment devices produced clear potable water having low concentrations of calcium, magnesium, iron, arsenic and total organic carbon. There was however low removal of nitrates, phosphates and fluorides.

The BSFZ had the following removal efficiency: 10 – 98% (Ca), 10 – 89% (Mg), 0 – 99% (Fe), 0 – 95% (As), 0 – 98% (NO$_3$), 0 – 98% (PO$_4$) and 0 – 96% (F).

Removal efficiency for BSF was: 6 – 93% (Ca), 30 – 99% (Mg), 40 – 99% (Fe), 7 – 96% (As), 0 – 90% (NO$_3$), 0 – 97% (PO$_4$) and 0 – 98% (F).

The removal efficiency of SIPP was: 10 – 95% (Ca), 15 – 98% (Mg), 70 – 98% (Fe), 5 – 98% (As), 0 – 97% (NO$_3$), 0 – 98% (PO$_4$) and 0 – 97% (F).

The CCF had removal efficiency in the range 13 – 99% (Ca), 5 – 99% (Mg), 14 – 98% (Fe), 0 – 98% (As), 0 – 96% (NO$_3$), 3 – 93% (PO$_4$) and 0 – 98% (F).

The BF had removal efficiency in the following ranges: 5 – 92% (Ca), 15 – 99% (Mg), 0 – 97% (Fe), 0 – 98% (As), 9 – 92% (NO$_3$), 0 – 99% (PO$_4$) and 0 – 98% (F).

Turbidity reduction by the filters was high and the removal was enhanced by clogging. The filters had the following turbidity reduction efficiency: 2 – 97% (BSFZ), 12 – 98% (BSF), 2 – 98% (SIPP), 2 – 99% (CCF) and 4 – 98% (BF). Filter washing resulted in a slight decrease in turbidity reduction as the particles which resulted in clogging were removed but the effect was insignificant. However filter washing resulted in an increase in the flow rates of the filters which were within the recommended limits given in literature. The flow rates of the filters during the course of the study were as follows: 1.74 – 19.2 L/h (BSFZ), 0.65 – 6.6 L/h (BSF),
0.31 – 1.52 L/h (SIPP), 0.05 – 4.2 L/h (CCF) and 106.5 – 160.4 L/h (BF). The high flow rates of the filters make them suitable for use by a family of six members for the production of drinking and cooking water. The flow rates of the filters were negatively affected by chlorophyll $a$ concentrations of the intake water but also the correlation was very weak. The correlation was strong between chlorophyll $a$ and turbidity of intake water ($r \geq 0.5$). The flow rates of the filters were in the order BF > BSF-Z > BSF-S > CCF > SIPP. The overall order of the reduction efficiency of chemical contaminants was BSFZ > BSF > SIPP > CCF > BF and the overall turbidity reduction efficiency was in the order SIPP > BAFZ > CCF > BSF and BF.

The manufacturing costs of the filters excluding labour were US $ 24 (BSFZ), US $ 16 (BSF), US $ 42 (SIPP), US $ 64 (CCF) and US $ 17 (BF). The filters may therefore be considered as cost effective as construction procedure was simple, no degree of expertise is required for operation and maintenance and they produce water at low costs. The filters can be used several times before the flow rates decrease significantly especially when low turbid water is filtered.

The difference between the BSFZ and BSF to standard biosand filters is the filter house. Standard biosand filters have concrete filter houses while the BSFZ and BSF had plastic filter houses. Most of the biosand filters do not have zeolites and the particle size of the media is much greater than the particle size of the fine sand used in the construction of BSFZ and BSF (0.15 mm).

The SIPP evaluated in this study is different from standard porous pot filters in a way that the silver nano-particles were incorporated before firing at high temperatures. Some porous pot filters are painted with the silver containing solution which leaches out of the filter wall after a certain period of use.

Most ceramic candle filters do not have a carbon blanket. The CCF evaluated in this study had a carbon blanket and this was useful in the removal of contaminants from water.
The bucket filter was a modification of a fast sand filter. The particle size of the filter media was smaller than the standard particle size of standard fast sand filters.

It may therefore be concluded that the study was successful and the filters may be recommended as household water treatment technologies in developing countries but concentrations of nitrates, phosphates and fluorides in the intake water must be within acceptable levels.

6.2 Recommendations
The following recommendations may be made to improve the removal efficiency of chemical contaminants by the filters.

1. The CCF may be improved by using activated carbon for its construction. This may result in better removal of chemical contaminants.

2. The combination of two filters, the BSFZ (made from zeolites and sand) and SIPP (made from clay) for example needs to be studied as there might be an enhanced improvement in the removal of chemical contaminants when these two filters are combined.

3. The volume of the SIPP may be increased by making a bigger pot to achieve higher flow rates.

The following recommendations may be made for the filters to last longer.

1. Filtration of highly turbid water must be avoided as this may result to rapid clogging of the filters.

2. The filters must be kept away from children’s reach as they may dismantle hanging spigots and re-contaminate purified water.
3. The filters, the biosand filters in particular (BSFZ and BSF), must be kept away from the sunlight to prevent evaporation of the 5 cm layer (the biological layer) where microorganisms reside.

4. Great care must be taken when moving and washing the filters to avoid the disturbance of the biological layer (BSFZ and BSF) and the development of cracks (SIPP and CCF) resulting in poor removal of contaminants.