Evaluation of a Small Scale Water Disinfection System using WFMF

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Department of Chemical Engineering,

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by

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Declaration

I hereby declare that this dissertation is my own work and to the best of my knowledge it neither contains materials previously published or written by another author and it has not been submitted in part or in whole for the award of another degree at Durban University of Technology (DUT) or any other educational institution. I also declare that the academic content of the dissertation is based on my work. All literature cited and contributions made by others have been acknowledged in this work.

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Signature Date

S. Rathilal

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Signature

Abstract

Provision of microbiologically safe drinking water for people living in the rural areas of developing countries remains a major challenge to date. One of the reasons is due to the inability to access potable water mainly because of poor existing water purification systems. Current measures have been put in place to address the challenges of rural water supply. Development of appropriate technologies such as decentralized water treatment supply in the form of point of use (POU) systems are been considered.

In lieu of the above, an appropriate POU system known as the Remote Rural Water Treatment System (RRWTS) was developed at Durban University of Technology (DUT). The RRWTS is polyester based locally sourced Woven Fabric Microfiltration (WFMF) membrane system. The unit is made up of flat sheet modules that are assembled into a pack. It is a robust gravity driven system with the ability to remove suspended solids and colloids in the form of turbidity. The system has high flux of 35 ± 7 LMH and turbidity below 1 NTU, it has the ability to remove pathogens well above 95%. However, this does not comply with WHO and SANS drinking water standards of zero *E. coli* count/100 ml of treated water. In order to bring the water treated by RRWTS to a satisfactory level for drinking, it is then necessary to add a separate disinfection step like chlorination step to further remove the remaining microbial contaminants.

Thus the main objective of the study was to evaluate the disinfection efficacy of two disinfectants namely waterguard and bromochlor tablet disinfectants and investigate their integration with the WFMF membrane. The study was categorised into three parts. The first part is the addition of disinfectants to unfiltered river water sources for the determination of residual chlorine and the most optimum dose that will yield effective disinfection and also evaluate the extent of *E. coli* removal by the disinfectants. The second stage was the filtration of four river water sources using the woven fibre membrane (WFM) to determine the efficiency of WFMF. Finally the effect of disinfection kinetics on disinfection was achieved by agitating the water

after disinfection and allowing it to stand at different contact times. Performance of the RRWTS was determined by the amount of *E. coli* and turbidity removed during filtration using WFMF and by chemical disinfectants after filtration.

The results on residual chlorine for different water sources showed that feed quality and disinfectant dose determines the quantity of residual chlorine on all the water sources. The effectiveness of chemical disinfectants in *E. coli* removal is affected by the quality of water to be disinfected. The study showed that turbidity plays a major role on disinfection by increasing chlorine demand on water sources with high turbidity levels. The WFMF demonstrated excellent filtration performance by producing permeates with turbidity less than 1 NTU for feed turbidities ranging from 10 to 200 NTU. The *E. coli* removal efficiency by WFMF was very high on all the water sources treated. There was 95-99.8% *E. coli* removal on raw feeds with influent *E. coli* ranging between 500 and 44500 CFU/100 ml.

It was seen that major benefits are derived from integrating the WFMF (RRWTS) with chemical disinfection. The benefits includes; better disinfection that meets drinking water set guidelines of zero *E. coli* and improved quality of water. The need for disinfection kinetics in order to obtain superior disinfection was eliminated. The possibility of disinfection-by-product formation was reduced as smaller quantities of chemical disinfectants were required for complete disinfection on the filtered water.

Dedication

This dissertation is dedicated to my late father Mr Elijah Halidu and my adopted parents Rev and Mrs J. Abechi who believed so much in my abilities and had always taught me to aim high in the midst of little. Finally, to my dear husband Kumnandi Pikwa for his tireless effort towards the completion of this work.

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Abbreviations

AIDS	Acquired immunodeficiency syndrome
DBP	Disinfection by products
BRMCH	Bromochlor tablet
CT	Contact time
DC	Developing countries
E .coli	Escherichia coli
BSF	Biosand filter
GAC	Granular activated carbon
HAAs	Haloacetic acids
HOCl	Hypochlorous acids
IC	Industrialised
LRV	Log removal value
MF	Microfiltration
MPN	Most probable number
NF	Nanofiltration
NTU	Nephelometric turbidity unit
PES	Polyester sulphone
POE	Point of entry
POU	Point of use

PVC	Polyvinyl chloride
PVP	Polyvinyl pyrrolidone
TMP	Transmembrane pressure
THMs	Trihalomethanes
RRWTS	Remote rural water treatment system
RO	Reverse osmosis
SWTR	Surface water treatment rule
SANS	South African national standards
SODIS	Solar disinfection
SSS	Small scale system
UNICEF	United nations children's fund
UNEP	United nations environmental protection agency
UN	United nations
UF	Ultrafiltration
UV	Ultra violet
WG	Water guard
WFM	Woven fibre membrane
WFMF	Woven fibre microfiltration
WHO	World health organisation

Chapter 1. **Introduction**

Safe drinking water is a basic human need that is increasingly getting scarce, and regrettably this resource is essential for continual existence. The depletion is not only due to reduced volumes of fresh water but also increased water pollution activities such as disposal of untreated waste into water bodies, inadequate sanitation and poor hygiene practices. These contribute to making the available water unsafe. Based on global assessments by the World Health Organisation (WHO) and United Nations Children's Fund (UNICEF), a huge percentage of the world's population does not have access to sufficient or microbiologically safe water for drinking (Mara, 2003). Water-borne diseases are therefore prevalent in areas where there is no microbiologically safe water due to insufficient water supply systems or the available water supply does not meet drinking water standards. Also water supply systems in many areas today are more concentrated in the urban regions using the centralized method of water supply. These facilities however cannot be accessed in the rural communities.

The major responsibility of water supply authorities is to provide consumers with drinking water that is microbiologically safe to prevent water borne diseases. Also there are certain standards and requirements that domestic water must meet in order to be generally accepted by the consumers, such as appearance, odour and taste of the water. Water with such quality can only be produced when the appropriate treatment systems are in place. According to Momba, Obi and Thompson (2008), implementation of multiple barriers to control microbiological pathogens and chemical contaminants that may enter into the water supply system is one of the ways to produce water of high and acceptable quality. While other factors like adoption of sound management practices, constant monitoring of the quality of treated water and the state of the distribution of infrastructures are vital in the production of potable water.

The consumption of water that is contaminated with microbial pathogens has been a major burden to water suppliers over the years. However there have been tremendous improvements in developing methods and processes that can be used to remove these contaminants. Traditional processes include coagulation; flocculation, sedimentation and filtration processes in which microbial pathogens like bacteria, viruses and protozoans are removed as particles (Peter-Varbanets *et al.* 2009; Cheremisinoff and Rosenfeld, 2009). Although these processes are capable of removing most pathogens, the application of disinfection becomes very critical as the turbidity removed by sedimentation and filtration does not completely remove all pathogenic organisms from the water.

Currently, available water disinfection systems are either in the form of centralized or decentralized treatment (Peter-Varbanets *et al.* 2009). In the urban areas of developing countries, centralized water supply systems are the major sources of water supply. This treatment method has thrived in the past in supplying safe drinking water using appropriate disinfection methods. The disinfection process is regarded as the last stage and the most powerful in the chain of water treatment processes; it has been in practise for a very long time and has contributed to the reduction of water borne diseases.

Chlorination is the commonly practised technology for water disinfection (Cheremisinoff, 2002). According to Solsona and Pearson (1995), disinfection by chlorination has proven to be reliable, appropriate and generally effective. Water free of pathogenic organisms that meet drinking water guidelines have been produced using chlorination worldwide. However some recent studies have shown that some small water supply plants and point-of-use systems (POU) do not produce the quality and quantity of water they are designed to produce despite the use of chlorination ((Mackintosh and Colvin, 2002)

From the findings of Swartz (2000) and Momba, Obi and Thompson (2008) small scale water treatment systems are faced with challenges like poor financial management, limited technical capacity and inadequate capital funding. These factors result in their inability to apply the paramount technology and comply with increasing regulations and guidelines. Hence it is possible to have the right disinfection method in place e.g. chlorination, and still produce water of poor quality if certain standards are not met.

On the other hand, rural communities of developing countries are faced with challenges in terms of access to drinking water. Other factors like rugged topography, low income, disperse settlement, lack of skills for operation and maintenance of water treatment systems, poorly developed infrastructure, custom and traditional beliefs contributes in making provision of drinking water supply difficult in rural communities (Pillay, Graham and Dlamini, 2009). While in cases where water treatment plants exist, some of these facilities have failed to achieve their aims in rural communities due to certain factors like political and socio-economical issues (Kyessi, 2005).

The major sources of drinking water in many rural communities are rivers, lakes, groundwater and rain harvesting. In many cases these available water sources are usually unprotected and are characterized by microbial and chemical pollutants. These pollutants are as a result of both point and non-point pollution sources that leads to contamination of drinking water with human and animal wastes that are either active cases or carriers of diseases (Gadgil, 1998; Peter-Varbanets *et al.*, 2009). Consumption of contaminated water from any of these sources without any form of disinfection or protection will definitely result in one form of ailment or another. It is in view of this that water treatment strategies particularly at household levels are being currently explored.

Small scale systems or POU systems has become the most suitable method of treatment in the rural areas as it has many advantages. The treatment can be done at the point of use. It does not require large volumes of water and is not affected by difficult topography or dispersed settlement. Most small scale systems may not require electricity (Sobsey, 2002). Although small scale systems have huge advantages, factors like lack of durability, short operational life span and lack of sustainability of the system has proven over the years to be major challenges in the implementation and survival of these systems in rural communities. In most rural communities where small water supply systems are provided, the systems are usually not effectively used as users get tired of the routine and they end up not following the proper operational instructions (Sobsey, 2002). This results in the consumption of water that is partially treated or not treated at all.

The most commonly used small scale and POU water treatment methods include: addition of alum, UV disinfection, boiling, solar disinfection and the use of chlorine and its derivatives like the popular bleach (NaOCl) and the use of filter cloth in areas with high guinea worm infestation and other types of filters like ceramic filters (Sobsey *et al.,* 2008). However it has been discovered that these treatment methods have major limitations and drawbacks although they have been in use for decades. For example boiling requires high thermal energy and the treated water can be easily re-contaminated; chlorine tablets are not readily available and direct chlorination can lead to formation of disinfection- by- product (DBPs) that are potentially carcinogenic to consumers particularly when used for a long time; solar disinfection cannot treat water with high turbidity and it requires long waiting periods while filters have low flow rates and lack durability as they can easily break (Sobsey *et al.*, 2008; Peter-Varbanets *et al.*, 2009).

The findings of Swartz (2000) also indicated that most existing POU systems have difficulty in adhering to the continuous increase in the number of guidelines. Also they are unable to apply the best available technology as a result of inadequate technical capacity, insufficient capital funding, poor financial management and they lack sustainability. Hence the application of these systems in the rural areas of developing countries will continue to be difficult, until other alternative methods such as membrane technology with the potential of overcoming these challenges is identified and implemented.

1.1 **Focus of the project**

This project focuses on evaluating the Remote Rural Water Treatment System (RRWTS) which is the combination of the WFM coupled with a disinfectant to produce drinking water that meets set standards at the point of use. Hence this project will assess the extent to which the membrane unit (WFM) can remove bacteria from different water sources while investigating available disinfectants and determining how the selected disinfectant can be integrated into the membrane unit to produce water that is microbiologically safe for drinking.

1.1.1 Project objective and approach

The overall goal of this research study is to develop and evaluate a small scale water disinfection system for integration with the RRWTS. The system should be effective and be implemented at the point of use particularly in the rural areas without requiring any additional energy.

The system should provide an alternative disinfection option for the reduction of water borne disease using the woven fibre membrane (WFM) and chemical disinfectants to produce the required disinfection residual.

Specific Objectives

- To evaluate the chemical and physical disinfection methods on *E. coli*removal, namely Waterguard disinfection, bromochlor tablet disinfection and woven fibre microfiltration (WFMF) disinfection

- To evaluate the effects of feed water characteristics on disinfection efficiency

- To determine the effect of disinfection kinetics such as disinfectant dosage, contact time and agitation on the overall disinfection process.

- To determine the effect of a pre-coat on the performance of the WFMF during disinfection.

- To integrate the disinfection methods into the RRWTS unit and evaluate its performance in terms of *E. coli* and turbidity removal.

1.2 **Approach**

The following disinfectants were evaluated in order to determine their efficiency and ease of integration into a RRWTS unit: nanosilver (silver nanoparticles in water), aqua surf (a synergy of zinc and activated carbon), liquid chlorine (sodium hypochlorite), iodine resin (iodine) and bromochlor tablets (bromine and chlorine combined). Both manual (offline) and automated (online) application techniques were evaluated for each of the disinfectants in order to mimic the practical application with the RRWTS unit.

Feed water of different qualities was acquired from various sources that represented variable water quality feeds. Natural raw water feeds were sourced from rivers while artificial feeds were made in the laboratory in order to standardise the concentrations. *E. coli* count was used as the main indicator of the unit's efficiency. Artificial feeds were made by spiking tap water with *E. coli* cells to produce water with varying concentrations.

The treatment process involved integrating a disinfectant to the unit where possible or manually adding the disinfectant to both unfiltered and filtered feeds. A feed was first applied to the membrane part of the unit and a filtered sample was collected and tested for E .Coli. Each of the disinfectants was then added to the membrane-filtered feed in order to determine the efficiency of the disinfectant on the filtered water. The same disinfectants were also tested for efficiency against the various unfiltered natural and artificial feeds. For both filtered and unfiltered feeds, the effect of disinfection kinetics like contact time and agitation on the rate of disinfection was also investigated. Performance of the WFMF was enhanced by pre-coating with lime.

Chapter 2. **Literature Review**

Introduction

This chapter presents a review of the literature and previous work that are relevant to this study. The information presented is divided into six sections, global water situation and problems associated with water supply are discussed in details in the first session, which was then followed by drinking water quality and guidelines recommended by WHO and SANS 241 for potable water. Centralised and decentralised water supply systems and available water treatment methods in rural areas are discussed. Thereafter an overview of water disinfection using thermal, physical and chemical processes is presented. Membrane technology as a physical process is elaborated with major focus on MF and UF membranes since these processes can be easily adoptable in rural areas. Furthermore, available decentralised MF and UF membranes are presented with advantages and challenges facing the use of current membrane systems in rural areas of developing countries.

Finally the summary of the gaps identified in the review are presented then the RRWTS is discussed in detail as an alternative POU water system for rural areas to bridge the gap that exist. Then integration of chlorine based disinfectants Waterguard and Bromochlor to the RRWTS to enhance effective disinfection is presented.

2.1 **Global water situation and problems associated with water supply.**

According to United Nations Environmental Programme (UNEP) about one third of the world's population are currently living in countries suffering from moderate to high water stress, where water consumption is more than 10% of renewable fresh water resources. Amongst these countries, Africa and Asia are the parts with tragically low water viability (UNEP, 2002). Findings by WHO and UNICEF also show that a large number of the world population cannot access adequate or microbiologically safe sources of water for drinking and other vital usage (Mara, 2003). Approximately 1.1 billion people were without access to adequate water supplies at the beginning of the 20^{th} century, and this has contributed greatly to the burden of water borne diseases. Moreover, 3.7 % of the global burden of diseases today is contributed by insufficient water supply, poor sanitation and hygiene (WHO, 2004b).

Target 7C of the millennium development goal is to half the proportion of people without access to sustainable safe drinking water and sanitation by 2015 raised a great concern to most people in the water sector. Remarkable progress has been made in this regard as more percentages of people now have access to safe sources of drinking water. From data collected, the percentage of people using drinking water from safe sources increased from 71% in 1990 to 80% in 2004. The percentage will continue to increase particularly if modern interventions are not ignored (WHO, 2004b; UN, 2006).

There are several factors that might impinge on the actualization of this goal by 2015. These factors include: population growth, which is a major factor in Africa and Asia; poor water management and supply which have accelerated the depletion of surface water and underground sources; improper infrastructure for sanitation in most places that has led to inadequate or microbiologically unsafe sources of water for drinking and other essential purposes. Finally, water quality has also been degraded by domestic and industrial pollutants, particularly for water meant for consumption. It has also been noted that disparities between urban and rural areas pose a major challenge to this goal (WHO, 2004b).

In most developed countries, measures have been put in place to curb the problems that may arise due to insufficient water supply. However, in the urban areas of developing countries the need for safe drinking water has been a major challenge due to the problems highlighted earlier in this chapter. Other factors like, industrial development, mechanized farming (e.g. irrigation farming) and inadequate water treatment facilities, cost of operation and maintenance contribute to making safe drinking water scarce. Also changes in climatic conditions such as rainfall patterns, flood cycles and drought affects the water cycle (UNEP, 2002).

Rural communities also face significant challenges in the provision of safe drinking water. For instance, they have scattered settlements and are situated far away from major centres, and cannot access centralized water supply systems due to their cost of putting up infrastructure. This often leads to consumption of untreated water. For such areas water is obtained by individuals from untreated sources like rivers and wells. The major challenge of these sources is poor water since it is always unprotected and are affected by microbial and chemical contamination resulting from poor sanitation (Gadgil, 1998). The quality and quantity of this water is usually critical particularly in arid areas. In cases where bore holes or wells are installed, access to water is a limiting factor, because the system is shared by many users hence the facility can easily go into despair (Lenton and Wright, 2004). Other major problems with rural water supply are the cost of installation of water treatment systems, operating cost, poor maintenance and lack of spare parts and technical skills, as well as poor institutional arrangement and beliefs may negatively affect their sustainability.

2.1.1 Drinking water quality and contaminants

One of the major causes of water borne diseases is microbial contamination; therefore effective microbial purification of drinking is an important part of any water treatment sector. Bacteria, viruses and protozoa are varieties of water borne pathogens that can be transmitted by water. Some have high levels of resistance while others do not. Therefore the choice of a disinfectant should be dependent on its ability to inactivate a certain range of bacteria, viruses and protozoa (Brick *et al.*, 2004).

Infectious diseases caused by pathogenic bacteria, viruses and parasites are the most common and wide spread health risk associated with drinking water. To prevent water borne diseases, drinking water must be free of both chemical and microbial contaminants, as breakdown in water supply safety may cause large scale contamination and even detectable disease outbreak. For example, in 1986-1988, there was a report of 50 out-breaks of illness in the United States as a result of drinking water that was regarded as safe; approximately 26,000 people were affected (Levine, Stephenson and Craun, 1990).

Contamination of water could either be at the source point (surface or ground water), or due to inadequate treatment techniques, storage facility deficiencies and the distribution network. When pathogens are transmitted by the faecal-oral route, drinking water is the only media for transmission. Although contamination of clothing, utensils, food, hands while eating can also enhance the rate of contamination particularly when sanitation and hygiene is compromised. Inhalation of water droplets in the form of aerosols can cause major illnesses in which the causative organism has multiplied because of warm temperatures and nutrients. Such major illnesses include *leginellosis* and *legionnaires*' diseases caused by *legionellae spp* and *amoebic* meningitis a pulmonary disease. Other illnesses transmitted due to faecal-oral contamination are cholera, typhoid, bacillary dysentery, infectious hepatitis, *leptospirosis, giardiasis, gastroenteritis*. Fungi, algae crustaceans and rotifers are other microorganisms found in water (Arnal *et al.*, 2001).

Good hygiene practises, improvement in the quality and quantity of water and proper excreta disposal are all important in reducing faecal-oral disease transmission (WHO, 2004b, 2004a). In most tropical and subtropical regions, *Schistosomiasis* is a major parasitic disease that is found in water particularly when the larva stage (*carceariae*) from the aquatic snail is released or comes in contact with water. For such regions, safe drinking water and water for bathing should be readily available without the need for contact with contaminated water sources. These parasitic worms are spread by water and have caused major havoc in many countries especially in Ghana where *schitstosomes* accounted for 1.3% of all deaths in Ghana in 2002 (Ashbolt, 2004). Water washed disease is another mode for disease transmission that is caused by insufficient quantity of water for proper maintenance of personal hygiene. Diseases associated with this situation is trachoma, (an eye infection), *leprosyscabies, conjuvtivitis, salmnellosis, ascaries,* hookworm and *trichuriasis* (Ashbolt, 2004).

The intensity of illnesses caused by the microorganisms above varies from person to person, and also depends on the immune defence mechanism of the affected individual. For people with impaired immunity, such as the elderly, or very young people, and those undergoing immune suppressive therapy or those with acquired immunodeficiency syndrome (AIDS), the minimum infectious dose is usually very low and depends also on the type of microorganism. For these categories of people, if their water for drinking or bathing contains a sufficient number of these organisms, various infections of the skin, and the mucous membranes of the eye, ear, nose and throat can be easily be contracted (Ashbolt, 2004).

Although typical waterborne pathogens are able to survive and persist in drinking water, most do not multiply in water. For instance, *E. coli* and *Campylobacter* usually accumulate in sediments after leaving the body of their host and become mobile when in contact with water flow. Most pathogens gradually become less viable and lose their ability to infect after leaving the body of their host. The rate of decay is usually exponential and they become undetectable after some time. Those with very low perseverance quickly find new hosts and are more likely to pass on from person to person due to contact or poor personal hygiene than by drinking water. Different factors affect the persistency of the pathogens with temperature being the most significant. At increased temperature, the rate of decay is faster and may be enhanced by UV radiation from sunlight acting on the surface of the water (Ashbolt, 2004).

Waterborne pathogens have different characteristics as discussed above, however the most common pathogens and parasites are those with very high infectivity ability and can multiply in water with very high resistance to decay when they are outside the body of their host. Most of the water borne pathogens mentioned above are present in most water sources of developing countries particularly in the rural areas (Sobsey, 2008). Treatment options like disinfection methods are not applied in most cases, however in cases where they are applied, their effectiveness cannot be guaranteed. The most frequently practiced method of disinfection in these areas is boiling and sometimes this is not sustainable because of the high thermal energy requirement and lack of energy sources (Sobsey *et al.*, 2008).

Drinking of untreated water may lead to severe illness, the study of Arnal *et al.* (2001) revealed that they can lead to major epidemic outbreak. Inactivation of pathogens is mostly achieved by the use of chemical disinfectants although the nature of the water to be disinfected can hinder the pathogens from being completely removed. The presence of suspended solids, colloidal matter (turbidity) can protect the bacteria from effective disinfection. It has to be assumed during disinfection that the pathogens are conceded by particles and could be possibly surrounded by a protective substance. This inhibits them from having a direct contact with the disinfectant. Also some of the water to be disinfected sometimes contains other substances which react with the disinfectant e.g. chlorine and thus reduces or prevents its disinfection ability (Schoenen, 2002).

When coliforms are found in drinking water it is an indication of faecal contamination. According to WHO the presence of coliform indicates the possibility of the presence of pathogens that are harmful to humans. Table 2-1 presents a list of harmful organisms that are easily transmitted by water. Although other disease causing organisms like enteroviruses and cysts of parasites are more resistant to disinfection than coliforms. It can then be deduced that, the absence of coliforms in drinking water, does not necessarily signify the absence of enteroviruses, cysts of *cryptosporidium, Giardia, amoeba* and other parasites (Sobsey, 2008; Gadgil, 1998).

Table 2-1 List of pathogenic organisms transmitted in water (WHO, 2011)

Bacteria	**Viruses**	**Protozoa**
Burholderia pseudomallei	Adenoviruses	*Acanthamoeba spp*
Campylobacter jejuni, E. coli	Astroviruses	*Crytosporidium hominis/Parvum*
Escherichia coli – Pathogenic	Ennteroviruses	*Cyclospora cayetanensis*
E .coli-Entherohaemorrhagic	Hepatitis A virus	*Entamoeba histolytica*
Francisella tularensis	Hepatitis E.virus	*Giardia intestinalis*
Legionella spp	Noroviruses	*Naegleria fowleri*
Mycobacteria (nontuberculous)	Rotaviruses	
Salmonella Typhi	Sapoviruses	
Shigella spp		
Vibrio Cholerae		

Apart from pathogenic contaminants, arsenide and fluorides are amongst the well-known and significantly naturally occurring waterborne chemical pollutants. Based on WHO statistics (WHO, 2011) water pollution differs from one place to another. These statistics confirm that with regard to water quality in developing countries microbial contamination of water supply is the major health risk. Although anthropogenic chemical contamination of drinking water is considered a more significant threat to human health in industrialized countries, the actual risks are minimal (Helmer., 1999; WHO, 2011).

2.1.2 Drinking water quality regulations

Lack of access to safe drinking water supplies has contributed greatly in putting lives at risk of water borne diseases. A clearer understanding of the advantages of supplying safe drinking water for human health and people's well-being, lead to developing new treatment options that can help alleviate the present water problem.

Table 2-2 displays major parameters and their standards according to WHO and SANS 241-1.

Different countries have their regulations of drinking water quality, e.g. the UK legislative under the water industry act 1991, states that all water supplied to the consumer must be "wholesome". Wholesomeness in this regard is defined by reference to the national and directive prescribed standards and requirements for microbiological, chemical and physical parameters. Indicator organisms including coliform bacteria, *Escherichia coli*, *Clostridium perfringens*, *enterococci* and colony counts are required by water supply (water quality) regulations. These organisms are used generally throughout the world as indicators. Certain organisms are also seen to pose a particular threat to the environment like *Cryptosporidium oocysts*. These are monitored in UK as a threat, to avoid exceeding the concentration level for these indicator organisms, each country has a prescribed concentration for them. The acceptable levels for the organisms are displayed in Table 2-2. According to water supply (water quality) regulations, drinking water should not contain any concentration of pathogens that is high enough to threaten public health (UNEP, 2002). SANS 241: 2011 states that the water shall comply with the following numerical limits for the microbiological determinands as specified in Table 2-2.

Table 2-2 Drinking water quality and standards (SANS, 2011; WHO, 2011b)

Parameter	Units	WHO Guidelines	SANS 241-1 standard
Physical quality requirements	mg/ℓ Pt	< 15	< 15
Colour	mg/ℓ	< 1000	< 1200
Dissolved solids	TON	< 5	< 5
Odour	pH units	6.5- 8.5	5.0 -9.7
pH value at 25^0C	FTN	< 5	< 5
Taste	NTU	< 1	< 1
Turbidity			
Chemical quality requirement – macro determined			
Ammonia as N	mg/ℓ	< 1.5	< 1. 0
Calcium as Ca	mg/ℓ	< 200	< 150
Chloride as Cl-	mg/ℓ	< 250	< 300
Fluoride as F	mg/ℓ	< 1.5	< 1.5
Nitrate as N	mg/ℓ	< 11	< 11
Silver as Ag	mg/ℓ	< 0.1	Not specified
Sodium as Na	mg/ℓ	< 50	< 200
Sulphate as SO_4^{2-}	mg/ℓ	< 250	< 250
Zinc as Zn	mg/ℓ	< 3	< 5
Chemical quality requirements – micro determinand			
Aluminium as Al	µg/ℓ	< 200	< 300
Antimony as Sb	µg/ℓ	< 20	< 20
Arsenic as As	µg/ℓ	< 10	< 10
Cadmium as Cd	µg/ℓ	< 3	< 3
Total Chromium as Cr	µg/ℓ	< 50	< 50
Copper as Cu	µg/ℓ	< 2000	< 2000
Cyanide (recoverable) as CN	µg/ℓ	< 500	< 70
Iron as Fe	µg/ℓ	< 2000	< 300
Lead as Pb	µg/ℓ	< 10	< 10
Manganese as Mn	µg/ℓ	< 400	< 100
Mercury as Hg	µg/ℓ	< 6	< 6
Nickel as Ni	µg/ℓ	< 70	< 70
Selenium as Se	µg/ℓ	< 40	< 10
Chemical requirement – organic determinant			
Total trihalomethanes		< 100	< 300
Phenols		< 9	< 10
Microbial safety requirement			
E. coli	Count/ 100 ℓ	0	0
Thermo tolerant (Faecal) coli bacteria	Count/ 100 ℓ	0	0

Table 2-3 Example of bacteriological guidelines in emergency situations (WHO, 2004a)

***E. coli* count/100 mℓ**	**Guideline**
0	Guideline compliant
1-10	Tolerable
10-100	Requires treatment
> 100	Unsuitable for consumption without proper treatment

2.2 Water treatment practices

2.2.1 Centralized water treatment and supply system

Centralized water supply which is also known as large scale water supply is one of the oldest conventional ways of treating and supplying drinking water. This method involves the use of multiple barriers such as coagulation, flocculation, sedimentation and filtration to produce water that is free of contaminants (Fig 2-1). Supply of drinking water has remained a major concern for most developing countries, as most governmental agencies see upgrading and innovation of new water treatment processes as a major objective (Mintz *et al.*, 2001). In most developing countries, a centralized water supply may be practicable because of their densely populated settlements. However the availability of these water supply networks depends on the economical standard of the area, although some may already have existing water treatment in the cities.

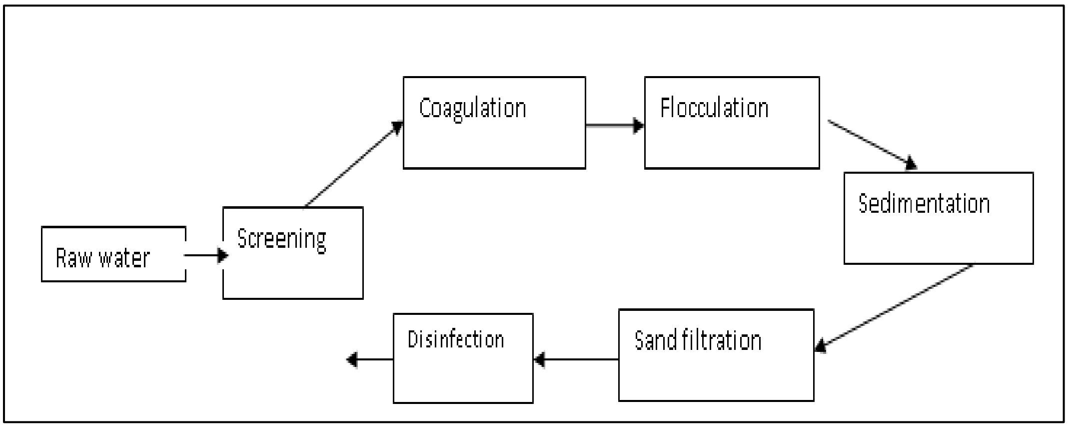

Figure 2-1 An Illustration of the conventional water treatment (Binnie, Kimber and Smethrust, 2009)

The steps followed during conventional water treatment are all aimed at bringing the water to a level where it can be easily disinfected to meet the drinking water standards. It's quite clear that water with high turbidity cannot be easily disinfected (USEPA, 2004). The presence of colloids and suspended matters reduces the efficiency of disinfection, increases the demand for disinfectants and can lead to the formation of disinfection by products. Also many pathogens and indicator organisms can be protected from being disinfected when the water has high turbidity as the organisms are shielded from having direct contact with the used disinfectant (Schoenen, 2002). It is then necessary to have all the steps followed during conventional treatment in order to remove most of the turbid substances that hinders disinfection efficiency. For effective disinfection to occur, water turbidity should be less than 1 NTU (WHO, 2004a; SANS-241, 2011).

Although it is necessary to follow all the steps on the treatment train as seen in Figure 2-1. The selection of the appropriate combination processes for the treatment of water from a certain source depends largely on the quality of the raw water to be treated. The presence of turbidity and the nature of the contaminants e.g. suspended solids that are present in the water will determine whether a certain process should be included or removed. For instance water with low suspended solids may not need to undergo coagulation but may require filtration to remove other smaller substances that are found in the water. The processes followed during conventional water treatment are detailed below.

Screening: This involves the use of strainers to remove larger solid particles such as stones and debris that are deposited in the water (Binnie, Kimber and Smethrust, 2009).

Coagulation: Coagulation is the addition of chemicals known as coagulants to water with the aim of destabilising the colloidal particles. Once the chemical is added to the water, the colloids become destabilized and begin to clog together. Ferric chloride and aluminium sulphate are very popular coagulants while others like hydrated lime and polyelectrolyte can also be used (Binnie, Kimber and Smethrust, 2009).

Flocculation: This process follows immediately after coagulation as it enhances the destabilized colloidal particles to collide with one another to form aggregates that can be easily removed. As the colloids grow bigger, they form sediments at the base or floats to the top (depending on their density compared to that of water) where they are then removed. To achieve proper flocculation, the water containing the coagulant is stirred slowly in order to form agglomerates. At high stirring rates the aggregates may break so it is important to keep stirring rates low (Binnie, Kimber and Smethrust, 2009)

Sedimentation: Sedimentation is that process where the aggregates from the previous process of coagulation and flocculation are allowed to settle at the bottom of the water before they are removed. During conventional treatment, the flocs are collected as sludge at the bottom of the sedimentation tanks where they are removed (Binnie, Kimber and Smethrust, 2009).

Sand filtration: This is another treatment step where different layers of sand are used as a filter to remove smaller flocs and other smaller materials that were not removed during the initial steps. The clean water which is referred to as permeate is then collected at the bottom of the sand. Pathogens such as *cryptosporidium* and

Giardia can be removed during sand filtration although the removal efficiency is dependent on the coarseness of the sands (Binnie, Kimber and Smethrust, 2009).

Disinfection: This is the last stage in the treatment train and is very important because it is the last barrier before the water is distributed to consumers. The process involves the addition of disinfectants for inactivation of pathogenic organisms. Chlorine, chloramines, chlorine dioxide, ozone, UV light, sodium hypochlorite are the basic disinfectants that are used on large scale water treatment (Peter-Varbanets *et al.*, 2009). Some of these disinfectants are also applicable on decentralized systems. Their methods of application are discussed in detail under decentralized systems for the purpose of this study.

The rural areas of developing countries often lack the capacity to invest in centralized systems due to the remoteness of the areas and lack of financial resources. In the event that centralized systems are installed, the system often fails as a result of poor management and unprofessional maintenance (Lenton and Wright, 2004). Therefore central water treatment and tap water from a supply network are generally unavailable in the rural areas (Peter-Varbanets *et al.*, 2009).

After much deliberation on the above, it can then be said that supplying of water using centralized approach may work in some urban regions of developing countries. However, government inability or refusal to introduce centralized water supply leads to provision of water by individual homes as well as intervention by private sectors which leads to decentralized water supply. Nevertheless, the theoretical principle of centralized systems remains prominent on the minds of the government while overlooking the support required for decentralized solutions (Peter-Varbanets *et al.*, 2009).

2.2.2 Decentralized water treatment and supply systems

There are cases where other problems like lack of knowledge, the danger of consuming partially treated water, inconsistency on the application of available treatment methods, cultural and traditional beliefs, and lack of adherence to stipulated rules and methods of application (e.g. over dosing or under dosing of disinfectants) can hinder proper application of decentralized water treatment systems. Many households in the rural areas source their water supply using any of the methods especially in cases where centralized water supply is inadequate. Also in places where there is no access to safe drinking water, decentralized water treatment allows for the improvement of quality of drinking water for underprivileged households to treat their water at the point of use or domestic level (Sobsey *et al.*, 2008). The available water sources for centralized water treatment are discussed below.

i. Ground and Surface water sources

Shallow wells and rivers are the major sources of water that poor households depend on where centralized water supply is unavailable or inadequate. Wells are preferred over rivers because their water is less polluted and are located near homesteads hence less travelling is required. Individual households build private wells to obtain water for their family needs at their own expense and can probably share with neighbours. In the urban areas of developing countries some upper class households who live within the same quarters may decide to make monthly contributions to build a well that will serve the people of that area. On the other hand rural communities may choose to build wells strictly for their personal usage as other households may not keep to their commitments for payment and maintenance of the well (Kyessi, 2005).

Water vendors and/or local authorities provide water to communities using wells (Kyessi, 2005). The use of wells as a source of decentralized water supply has contributed in reducing the problems of water scarcity in areas where centralized water supply is difficult. Although there are huge advantages of shallow wells, there are some constraints that are associated with the construction and use of ground wells. According to Charalambous (1982) and Schoeman and Steyn (2000) in cases where hydrological data are not available, it becomes extremely challenging to operate wells. Furthermore the location and depth of shallow wells are major challenges that affect both the quality and quantity of water obtained. Most often, shallow wells are located close to pit toilets of many households in rural areas which lead to microbial contamination from faecal waste. Continuous contamination and depletion can occur if there is a source of contamination nearby and as a result of overdraft Salinization is also common in cases where drainage systems are poor or inadequate (Konikow and Kendy, 2005; Schmoll *et al.*, 2006). Water from wells may require some additional treatment particularly in cases where the water quality is unsatisfactory due to industrial, agricultural and domestic pollution in the area. Apart from these pollutants, ground water is sometimes polluted by fluoride and arsenic in some countries. For instance arsenic is prevalent in Bangladesh and Nepal, while fluoride is commonly found in most ground water in South Africa, Tanzania, Sudan and Senegal (Schoeman and Steyn, 2000).

ii. Rain water harvesting

Rain water harvesting has been in existence for centuries particularly in semi-arid regions of the world. Most households collect a specified quantity based on their immediate requirement, while others store for future use. Fifty percent of places in the world like Tanzania depend on rain water for their survival (Mbilinyi *et al.*, 2005). Countries like Nigeria experiences heavy rain from late March to late October, although overall average rainfall has decreased over the years due to climatic change.

Rain harvesting eradicates the problems of operation and maintenance and it also reduces interferences with the water supply by non-family members. According to Gould and Nissen-Petersen (1999) some communities practise rain harvesting where water is collected from the field and used communally by family members. The advantage of rain harvesting is that it requires no capital such that people from low income areas can benefit at no cost. Also the water requires little or no treatment if the harvesting vessel or tank is properly cleaned before collection and storage. Some of the major limitations of rain harvesting are the uncertainty of rainfall, variability in seasonal supply and the unreliability of water quality because of infection and pathogen regrowth in storage vessels. Contamination may occur when harvesting water from fields, roads and roofs after dry seasons are over (Zhu *et al.*, 2004). Also rain water can become contaminated by users where proper sanitation and hygiene is inadequate.

There are three different categories of decentralized systems which are point of use (POU), point of entry (POE) and Small scale systems (SSS) (Peter-Varbanets *et al.*, 2009)**.** Another, which is the emergency systems, was developed to provide clean water in areas stricken by disasters to relief those affected.

The POU systems are used to treat all the water supplied to a household, its purpose is to meet all the water needs of the family. The operational capacity of this treatment is dependent on the size and general needs of the family.

2.3.2.1. Small Scale Systems (SSS)

These systems are smaller than the centralized water treatment systems, but have distinctly larger capacities than POU and POE systems. Although SSS cannot be defined exactly in terms of size, they can serve several families or a small village. The size range falls within 1000-10, 000 ℓ/day depending on the design and need. The term ‘‘household systems’’ can refer both to POU and POE systems, while ‘‘decentralized systems’’ can refer to POU, POE and SSS (Peter-Varbanets *et al.*, 2009).

2.3.2.2. POE

POE systems are mostly used in IC; their application in TC and DC is limited to the supplementary treatment of tap or good quality well-water for the homes of rich people and hotels as well as childcare and medical institutions. As they are often built on the basis of multi-stage treatment technology, qualified periodical control and maintenance are needed for their stable operation (Peter-Varbanets, *et al*., 2009).

2.3.2.3. Emergency systems

One of the major goals in emergency response is to provide potable water that is critical for the survival. Providing drinking water is the most challenging aspect of an emergency response for which there is no panacea. Due to the varying scenarios for different disasters, it is impractical to adopt the same solution for every disaster. The water treatment selection process is not straightforward. It depends on the emergency characteristics, source water quality, and the technical aspects of the water treatment. Some of the criteria set should include the speed of deployment, quantity and quality of treated water, and the cost of the treatment unit.

2.3.2.4. Point -of- use systems (POU)

POU systems are used to provide safe water that is required by individuals, households and for emergency relief. According to Sobsey (2002), the system is often referred to as household water treatment. Dated as far back as the early 19^{th} century, the impact of POU systems have been long understood with the Doulton filters being an example (Wagner and Lanoix, 1959). As a result of the cholera outbreak in the 1990s in Latin America, a renewed awareness of their application from a public health point of view came into recognition. Since then POU systems have become a topic of interest among many researchers till date (Ahammed and Chaudhuri, 1999). From an international point of view, the system has been adopted as a valuable policy option especially after the South Asia tsunami where it was estimated to have provided potable water to 3-5 million survivors of that disaster (WHO, 2004a).

In reality, most of the POU methods can also be applied for SSS and these technologies can be modified on a larger scale for decentralized or emergency reliefs. The modification can be in cases where liquid disinfectants like chlorine or chlorine dioxide dosage can be replaced by chlorine tablets or flocculants/coagulants.

Usually the treated water from POU systems are used for drinking, and as such, the required amount of water to be treated is dependent on the number of the users and the family size. Minimum amount required is about 2 ℓ per person per day whereas 8 ℓ is the maximum requirement for both cooking and drinking (DeZuane, 1997). Where larger volumes of drinking water are required, the system has to be designed to cater for such capacity to avoid system over use and break down.

The following criteria, simplicity of the system, environmental suitability, and availability of skilled personnel for both operation and repairs (maintenance), availability of spare parts and socio-cultural acceptability of the designed system are to be considered when developing a POU system.

According to Sobsey (2002), two major studies from different fields have revealed that POU systems become unsuccessful or unsustainable if they are installed or introduced without considering the criteria mentioned above. It was further stressed that decentralized systems are better or preferred if they are designed without pumps or pressure taps (Sobsey, 2002).

2.2.3 Available POU Filters

i. Biosand filter

Physical removal process uses different kinds of media including grains with varied sizes. One of such promising physical process for drinking water treatment technology at the household level is the biosand filter (BSF). Apart from the sand which is used as the filters, some additional biological materials are added as filtration media (Murcott, 2005). A large number of people depend on the BSF for treating their drinking water worldwide (about half a million). These mechanical processes have a high potential of becoming an attractive alternative or option for household water treatment because they can be produced at the point of use. Using locally available material the system is very simple to construct, easy to operate, potentially durable and can be used over a long period of time (Wagelin, Schertenlieb and Boller, 1991; Galvan and de Victorica, 1997; Lantagne, Quick and Mintz, 2007). Initial flow rates are usually high, however cleaning should be done frequently to maintain flow rates at the acceptable levels. Hence operators will require some skill and knowledge to operate and maintain the filters for optimum performance except if the filters are completely automated (Burch and Thomas, 1998). Based on laboratory and field tests, report show that BSF have high efficiency in bacterial removal on the average by 81-100% and 99.98% for protozoan, however the removal efficiency for viruses is very low (Kaiser *et al.*, 2002 ; Lantagne, Quick and Mintz, 2007).

ii. Fabric or paper filters

There are other filters that are presently available besides BSF that can be used at household levels such as fabric or paper filters. They are more effective in the removal of water borne pathogens that are larger in size like larva forms of *schistosomes* and *Faciola* species, guinea worm larvae within their intermediate crustacean host and bacterial pathogen (Huq *et al.*, 1996). Due to the large pore sizes of these filters they are not recommended for the overall treatment of household water as they are unable to retain viruses, bacteria and protozoan that are smaller than the pore sizes of these filters (Sobsey *et al.*, 2008).

In countries like Ghana and other African countries where Guinea worm is prevalent, fabric filters are used to treat water for household usage. Although this treatment does not give 100% removal efficiency, some degree of removal is usually achieved. Hence this type of filter can be recommended as a pre-treatment system for such areas before final treatment can be adopted.

iii. Activated carbon filter

Activated carbon filters, are found in most transitional countries as table top units, for additional treatment of tap water. These carbon filters are in the form of pressed blocks that may be pre-coated with silver (Ag) coatings or followed by UV disinfection (Abbaszadegan *et al.*, 1997; Ecosoft 2007). Their major disadvantage is the short operating life span of about six months. Its regular replacement escalates the cost and as such most households within the developing countries cannot afford them (Peter-Varbanets *et al.*, 2009).

iv. Ceramic filter

Ceramic filters are available in most developing countries. They are usually in pot forms and have larger pore sizes (0.6-3.0 mm) (Lantagne, Quick and Mintz, 2007). According to Wang *et al.* (2007) a filterable bacteria size has to be well below 0.6 mm, which then suggests that the principle of size segregation is not sufficient enough for this kind of filters to give a complete disinfection. To improve the efficiency of ceramic filter, most of the commercial ones are impregnated with colloidal silver which acts as a further disinfection step or additional barrier and assists in preventing biofilm on the filters (Sobsey, 2002) 2002).

Laboratory analysis carried out by potters for peace on the widely distributed ceramic filters shows that the bacterial removal rate by ceramic filters was 99.99%, however virus removal efficiency or inactivation is not yet known and the performance on field application has not been determined (Lantagne, Quick and Mintz, 2007).

Their major limitation is that they are relatively expensive, especially if all the materials of construction are not sourced locally. Most of the filters vary in their quality depending on the place of construction. They can easily break; and the coated nanosilver particles are easily removed during cleaning which then reduces the antimicrobial capacity of the filter. For non-turbid water, their flow is between 1-3 ℓ/h (Bang, Hein Phuong Do. and Dijakovic, 2011). Table 2-5 gives the summary of the advantages and disadvantages of POU filters.

2.2.4 Advantages of POU systems

The findings of Sobsey (2002), Ahammed and Chaudhuri (1999) and Mwabi *et al.* (2011) have shown the effectiveness of POU system particularly in removing suspended particles in the form of turbidity and in disinfecting microbiological contaminants such as bacteria, viruses and sometimes protozoa.. Also low income consumers are able to access potable water due to the low cost of emerging POU interventions (Hutton and Huller, 2004). The interest of these consumers in POU systems has raised a potential market for the products.

Since the discovery of POU systems, there has been a significant decrease on total dependency on centralized water supply. POU systems have been incorporated into the government health based programs and initiatives.

POU systems are seen as a strategy for modifying hygiene behaviour amongst water consumers and as an improved sanitation facility. POU systems are also used to mitigate recontaminations that usually occur during transportation, distribution and household storage of potable water. It promotes household water treatment and safe storage as drinking water contamination does not only occur (Trevett *et al.*, 2005; Lenton and Wright, 2004). In cases where water is drawn from a clean source point, such water is regarded as safe water for consumption but there are possibilities of infection which may occur during transportation to the home which are usually kilometres away. Also during the storage prior to consumption contaminated vessels or hands dipped into stored water can result in recontamination of clean water (Trevett *et al.*, 2005). Hence POU systems become an appropriate tool for treating water for immediate use.

a. Limitations and challenges of POU systems

POU systems are faced with a variety of challenges and have not been universally accepted as a solution to water treatment problems. According to Luby *et al.* (1999)

their effectiveness has not been established and the health benefits from these systems have been lost due to improper usage.

The taste and smell that usually comes with chemically purified water makes POU systems unacceptable hence people fail to adopt the process as a means of providing safe water for drinking. Also the impact of POU systems becomes insignificant as it addresses the problem of potable water alone without addressing other critical aspects like sanitation, personal hygiene, and good storage practices (Kirchhoff and McClelland, 1984). It is also believed that improving centralised water supply is far cost effective when compared with the distribution of POU systems to individual households.

According to the findings of Lantagne, Quick and Mintz (2007) POU systems are meant to be an interim solution to accelerate health gains associated with improved water supply until long term solution of centralized or piped water can be attained. The problem arises again on ethical grounds where finance that are meant for long term piped water may be directed toward POU solutions with a short term impact.

The most critical problem of POU systems is their lack of sustainability and the inability to scale up beyond a limited or project based application. In many cases, POU systems fail to achieve long term adoption. Their importance and acceptability does not go beyond the organization or public health initiative that promotes their usage. Water consumers are not willing to spend their money in purchasing POU systems except at subsidized rates; hence the penetration of the systems within a community cease once the project or subsidy supporting their use is withdrawn (Harris, 2005). Due to the challenges faced by POU systems, intensive research is required before designing and implementing POU systems.

The significance of disinfecting drinking water cannot be over emphasized as many water borne diseases are avoided today as a result of disinfection of water before consumption. In 1893, the importance of disinfection was discovered when two researchers Mills and Reincke discovered from their research that the general health of a community improved when their drinking water supply was replaced with purified water. Also morbidity and mortality resulting from water borne disease were reduced when bad drinking water was replaced with treated water (White, 1999).

Generally, disease causing organisms can be removed, inhibited, or killed at the POU using any of the treatment methods listed above; however the water disinfectant must be safe for human consumption with regards to both chemical composition and concentration (Brick *et al.*, 2004).

Table 2-4 Summary of advantages and disadvantages of POU filters

Filter	**Advantages**	**Disadvantages**
Biosand filter	Filter can be produced locally (local materials). The rate of treatment is fast and can be used for a long time (long life span)	Requires time for building of the biological phase for effective treatment. It is cumbersome.
Ceramic filter	Low cost of production (per cost of water filtered if locally produced). Long life span. Pathogenic removal is significant	Can easily break (fragile). Expensive during initial production. The treatment rate is slow. Filter design is not attractive. Pore sizes are not uniform.
Activated carbon filter	Effective in removing organic matter as well as chemical agents that are found in water. (e.g. excess chlorine). Economical and easy to maintain. Removes odour and taste from water. Does not remove important minerals like calcium and magnesium from drinking water.	Requires regular change of the filter cartridge. Could have large pore size depending on the manufacturer. Water may sometimes not be properly filtered, as flow could be channelled around the filter and not into the filter.
Fabric filter	Easy to use and affordable. Useable at household level if filter media is available.	Have wide range of filter media with varied pore size and formats. Its efficiency in microbe removal varies with filter media. It's better used to remove larger organisms.

2.3 Drinking Water Disinfection for Decentralized Water treatment Systems

2.3.1 Factors to consider in choosing a disinfection method for POU/small scale systems

Various water treatment technologies listed below for disinfecting water are applicable, however some degree of limitations are associated with these methods, hence before choosing any of the methods, the following criteria should be considered.

- ❖ Inactivation efficiency
- ❖ Potential for Disinfection by-product formation
- ❖ Toxicity of disinfectant
- ❖ Aesthetic water quality
- ❖ Cost
- ❖ Scalability
- ❖ Residual maintenance

a. Disinfection By-Product (DBP) formation

Huge amounts of DBPs have been identified over the years particularly in chlorinated water, with trihalomethanes (THMs) being the most common ones. Others are haloacetic acids (HAAs) chloral hydrate haloacetonitriles, haloketones and Chloropicrin (Singer *et al.*, 2002). A further study in the late 1970 through epidemiological research studies identified the potential formation of potentially carcinogenic by-products in chlorinated water during disinfection.

Factors like pH, organic carbon and bromide content of treated water and type of disinfectant used during disinfection determines the nature and type of DBPs that are later formed. In cases where water contains a high concentration of bromide, the DBP formed will be a large fraction of brominated DBPs.

b. Toxicity of disinfectant

The toxicity of any drinking water particularly at consumption level (tap) should be assessed before such water is regarded as wholesome. All substances that are present like chemicals, dissolved substances, disinfection by products, residual disinfectants and leachates from disinfection processes should be evaluated to verify their concentration and toxicity level (Brick *et al.*, 2004). The evaluation should be done with regard to the water supply regulations. Regulations 25-28 of the Water Supply (Water Quality) Regulations 2000, requires that all substances, product and processes that are used in the supply of public water must be approved. The approval of these substances is done on the basis of health standards by the committee on Products and Processes for use in Public Water Supply (CPP) (Brick *et al.*, 2004).

c. Aesthetic Water Quality

Taste, odor, and appearance are the aesthetic water characteristics that are very important in the consumer's perception of the drinking water. These three factors determine the reaction of water consumers at all levels, as most will prefer to drink odorless, tasteless and bright looking water that is not treated than to consume treated water with odor or taste (Brick *et al.*, 2004). The consumer market discovered that, 46% of those who do not drink tap water do not because of the taste and odor associated with drinking water. It has been discovered that chemical disinfectants like chlorine contributes greatly to problems of taste and odor in drinking water. Hence any technology that could serve as an alternative disinfection method should not have an adverse implication on the aesthetic quality of drinking water (Brick *et al.*, 2004).

d. Costs

It is likely that the costs of developing a technology from the point of conceptualization, to bench scale, to pilot scale and then finally to its operational stage should be calculated at each of these stages. It is vital to calculate the capital and operational cost of any treatment process before it can be actualized. Considering the scale of a particular technology is very important when comparing the capital and operational costs of a new technology. A large scale operational process will definitely cost far more than a bench scale technology. It therefore becomes a huge point of concern, when costs are transferred directly from bench scale and pilot scale to operational scale technologies without putting certain factors into consideration (Brick *et al.*, 2004). When selecting a new disinfection technology, its economic cost must be evaluated alongside the value and benefit that would be obtained from such a technology. Operational cost should be based on treated water and compared to established technologies such as chlorination. Although the capital costs of the new technology differs greatly it is also very important to consider the total costs which includes capital and operational costs (Brick *et al.*, 2004).

e. Scalability

Treatment technology may be received by a water supplier either at a bench, pilot or operational scale. In cases where the current disinfection technology is on a bench scale, it is very important that data is available based on the criteria of the initial technology. This can be used to indicate the possibility of developing a larger scale pilot and operational system. As technology develops, the data may vary, hence continuous evaluation is required in order to work within specification and obtain the desired results.

f. Residual maintenance

Disinfectant residual is an important part of any water supply network. Firstly to control the possibility of microbial regrowth in supply network and secondly to inactivate microbial contaminants that may enter into the system during distribution and storage (Le chevallier, 1998). According to Trussel (1999) residual disinfectant helps in the prevention of biofilm formation and gives an indication of whether the disinfectant is destroyed or no longer active. Different treatment systems achieve varying levels of residual; however, the required level is dependent on the nature and condition of the source water as well as the distribution system (Hydes, 1999).

Water quality parameters affects the stability of disinfectant residual, therefore it is important that water suppliers reveal the effect of different parameters on residual disinfectant. For instance, oxidant residuals are removed when organics and corrosion are present in water.

There are countries where the presence of residual is not a requirement. In the Netherlands only 21.2% of their drinking water undergoes final chemical disinfection. The rest of the drinking water is abstracted from groundwater that has special protections. Aquifers composing of different layers of sand, peat and clay are used to filter (treat) the drinking water using multi barrier treatment process before distributing in an uPVC distribution system. The entire process results in biostable drinking water without the need for residual disinfectant (Gale *et al.*, 2002). According to SANS-241 (2011), the required chlorine residual during distribution is 0.6-03 mg/l while 0.2-0.3 mg/l is required for POU systems (Mwabi *et al.*, 2011).

In order to design any system that will be sustainable, these factors must be put into consideration as most of the existing decentralized systems particularly those in the developing countries lack sustainability.

2.3.2 Review of available disinfection methods for decentralized systems

The available decentralized technologies for treating drinking water in most countries are designed using physical, chemical, biological and thermal processes.

2.3.2.1 Thermal Processes (Heat and UV-based systems)

i. Boiling

Boiling is one of the earliest and most used disinfection methods; however its cost of operation is a major concern (Sobsey, 2002). Although boiling with fuel may not be the optimal solution for treating drinking water, it is able to destroy all classes of water borne pathogens. Boiling becomes very easy in places where wood and other material for fuel are easily accessible, whereas in areas where wood and other source of fuels like fossils and biomass fuels are limited, or expensive to purchase, it becomes costly. Hence for a very poor household or population, boiling of water becomes unrealistic and inaccessible due to fuel scarcity and cost. Also sustainability of biomass or fossils in the community is another challenge of boiling water (Sobsey, 1989). Water can easily be re-contaminated after cooling due to the absence of residual protection and the risk of scorching that occurs a lot in children (Mintz *et al.*, 2001).

Although this technology has been in existence for decades it lacks sustainability due to the limitations highlighted above. Also for some households the process becomes monotonous and boring which then leads to discontinuity.

ii. SODIS system

SODIS is another system used in water treatment where heat is involved in the form of direct rays from the sun to the water that is to be treated. To achieve effective disinfection and treatment for this system, four basic steps have to be followed; solid removal from highly turbid water (> 30 NTU) using filtration or settling; adding water with low turbidity into clear PET bottles of 1-2 ℓ volume; aeration of the water by shaking it while in contact with air; and finally exposing the aerated bottle directly to sunlight for about 5 hours (Wagelin, Schertenlieb and Boller, 1991; Reed, Mani and Meyer, 2000; Mintz *et al.*, 2001). SODIS systems are more practicable for treatment of small amounts of water (<10 ℓ) particularly at a low turbidity (<30

NTU). The process has thrived well in producing drinking water particularly for emergency relief program.

The limitations of SODIS are that there is a total dependency on sunlight for disinfection and the process is laborious (e.g. filtration, aeration and bottling). The water has to be treated in PET bottles such that people are discouraged from using the water for other purposes besides drinking directly from the bottle. Finally it requires several PET bottles to cater for large families. Solar disinfection becomes an efficient POU system for developing economies when water turbidity is below 30 NTU.

iii. UV irradiation with lamps

Recently, the use of UV irradiation with lamps for water treatment has drawn great interest because of its ability to inactivate (*Cryptosporidium Parvum oocysts*) (>99.9%) and (*Giardia lambilia cysts*) at relatively low doses. These are water borne protozoan that are known to be resistant to chlorine. Despite the advantages of UV irradiation particularly in inactivating chlorine resistant protozoan, it also has some disadvantages. Certain substances like turbidity, suspended solids and particulates found in water can affect the performance of the lamps in inactivating microbial organisms. UV irradiation uses effective lamps that require consistent and an affordable source of electricity. Periodic cleaning is required to keep the lamps performing at their best particularly for submerged lamps that have fixed life spans and must be periodically changed (Gadgil, 1998). In order to make the cleaning and replacement possible, an efficient infrastructure is required and this may not always be available. As a result the operational cost of UV based systems becomes very high and this impacts on their sustainability.

2.3.2.2 Physical methods

Physical process is used in water treatment for the removal of water contaminants using physical methods such as clarification, sedimentation and filtration. The core aim of these processes is to provide safe water for drinking and other purposes. Although physical process are usually carried out in large scale systems, in recent times there have been a lot of modification in the processes such that they can also be achieved in small scale systems (Peter-Varbanets *et al.* 2009).

Filtration is one of the physical processes that have been modified for POU application. The filtration process is seen as a critical part of water treatment as it is able to remove contaminants like *Cryptosporidium* and *Gardia* which has high resistance to chemical disinfectants. It also reduces other contaminants like suspended solids and colloids thereby bringing the turbidity of water to a level where further disinfection can be easily achieved. Basically the process of filtration involves the passing of water through a granular bed of sand or any other suitable medium at low speed. While the media retains the solid matter, the clean water is permitted to flow to the other side as filtrate or permeate. A well performing filter will give a crystal clear filtrate with a turbidity of less than 1 NTU. For this high quality filtered water to be obtained, particles far smaller than the sizes of the opening between the filtering media have to be removed by the filter (Peter-Varbanets *et al.* 2009).

One major requirement of water treatment is to remove (*Cryptosporidium oocysts*) (dimension of 5 µm) during filtration since it is resistant to chemical disinfection and can cause a disease outbreak if consume. The effectiveness of filtration in reducing microbes varies widely depending on the type and size of the microbe. Filtration is not obtainable when the media particle size is 400-500 µm, however the process involved in granular filtration is far more complex than simple straining. Table 2-4 shows sizes of sand and different contaminants.

Table 2-5 Relative size of sand and suspended matter (Chris and Martin, 2009)

Materials	Particle diameter (approx) (μm)
Sand	800
Soil	1-100
Cryptosporidium oocysts	5
Bacteria	0.3-3
Viruses	0.005-0.01
Flocs Particles	100-200

There are basically three types of granular filters which are slow sand filter, rapid gravity filter and pressure filter.

i. Slow sand filters

Slow sand filters are the oldest form of filters. Their mode of operation is at low loading rates hence the word slow. This filter uses fine sand as a medium and the treatment processes are by physical straining and biological actions. The efficiency of slow sand filter is minimal until a biological phase has developed. Cleaning of the filter is carried out after several weeks and months of operation by scrapping off the biological growth and the upper part of the sand layer (Sobsey, 2002). Most modern days POU water treatment filters adopts the slow sand filter mode of operation.

ii. Rapid gravity filters

Rapid gravity filters operate at very high loading rates with more coarse media and higher permeability. The method of treatment is by the physical process alone, although in some cases granular activated carbon (GAC) may be the media which is used to absorb the chemicals that may be dissolved in the water. Rapid gravity filters maybe single media like sand or multimedia filters which combines two or more media for its operation. Backwashing is used to clean this type of filter (Sobsey, 2002).

iii. Pressure filters

Pressure filters are also another form of rapid filters. The only difference is that they operate under pressure in large closed vessels. Due to the nature of this filter pre-treatment like clarification may not be required particularly for groundwater. Direct pumping into filter and distribution can be achieved in the same unit.

2.3.3 Chemical Methods

This is the process of using chemical agents to enhance or achieve complete disinfection of water, some of which are coagulation, flocculation and precipitation, adsorption and ion exchange. Among the disinfection processes, chemical disinfection is the only process through which complete inactivation can be achieved. This process involves the use of chemical agents like chlorine and chlorine based compounds and other oxidizing agents for the purpose of disinfection.

Disinfection is one of the most critical processes. Disinfection involves two very important aspects which is the killing of pathogens that may have passed through the initial treatment processes and the production of residual disinfectant for the safety of the water leaving the treatment plants during distribution.

The efficiency of disinfection can be determined using equation 2-1. According to Baker (2004), disinfection efficiency can be expressed in terms of log removal values (LRV)

$$LRV = \log_{10} (C_f/C_p) \qquad (2\text{-}1)$$

Where,

C_f and C_p are the feed and permeate concentration in g/ℓ. A LRV of 4 or 5 is recommended during filtration for municipal water treatment (Momba, Obi and Thompson, 2008). Some of the chemical agents used for disinfection are discussed in the following sections.

2.3.4 Disinfection using chlorine and chlorine based compounds

In most large water works the commonly used chemical disinfectants are chlorine gas, chlorine dioxide, monochloamine and ozone; while in small water works, chlorine gas, hypochlorite, iodine, bromine, and mixed oxidant gases are normally the choice of disinfectant agents (Freese, Trollip and Nozaic, 2003).

Water disinfection using chlorine has been in practice for over a century. Its significance has been known for the treatment of water which have saved lives worldwide from water borne diseases. From a historical perspective, chlorine and its compounds are the most popular chemical disinfection agent, however, some special properties were also discovered in ozone that led to a rapid increase in its use as a chemical disinfectant worldwide (White, 1999). However for the purpose of this study chlorine and its compounds will be discussed in detail.

Chlorine is one of the most effective disinfectants. It is moderately easy to handle. The capital cost of chlorine installation is relatively low (cost effective). It is easy to dose, measure and control and has good residual effect. Furthermore, chlorine reduces objectionable taste and odour. It has the ability to oxidize most of the naturally occurring substances like foul–smelling algae secretions, sulphides and other odours from decaying vegetables and fresh plants (White, 1999).

Chemical compounds with unpleasant taste such as ammonia and other nitrogenous compounds and odour (hydrogen sulphide with rotten egg odour) can be removed by chlorine. However, some of the substances like ammonia and nitrogen compounds when found in water can hinder disinfection (Kerwick *et al.*, 2005).

Previous research has shown that there are other disinfectants like monochloamine, ozone and ultraviolet irradiation that are classified on the same level or even better than chlorine. But chlorine still remains the most widely used drinking water disinfectant particularly for the rural areas of developing countries (Momba and Brouckaert, 2005).

The method of chlorine application can be carried out using any of the following three: chlorine gas (elemental chlorine), sodium hypochlorite (bleach) and dry calcium hypochlorite (HTH). There are instances where chlorine is generated onsite. The locally available chemicals usually determine the form of chlorine to be added to water. Trained personnel are required for chlorination of water as solutions need to be prepared to have the required strength for disinfection. Also frequent checks are required to ensure that enough chemical is available (Momba, Obi and Thompson, 2008). In rural areas where chlorine application is in the form of bleach, proper adhesion to the user's guide is required and a single person may be selected per household to do the chlorine application.

Liquefied chlorination is most effective when considering cost per mass on an active chlorine basis. Accidental leakage of the gas is the risk that is associated with liquefied gas. This accounts for the reason why some plants will prefer a more expensive sodium hypochlorite solution. Hypochlorite can be generated on site located close to a cheap source of brine however; a source of electricity will be required (Momba, Obi and Thompson, 2008).

2.3.5 Chemistry of Chlorination

Two species known as free chlorine are formed when chlorine is added to water (Chlorine Chemistry Council, 2003). These are hypochlorous acid (HOCl, electrically neutral) and hypochlorite ion (OCl^- electrically negative).

$$Cl_{2\,(g)} + H_2O \rightarrow HOCl + H^+ + Cl^- \text{ ---------------------------- } (2\text{-}2)$$

Hypochlorous acid dissociates (splits up) to form hydrogen and hypochlorite ions (OCl^-)

$$HOCl \leftrightarrow H^+ + OCl^- \quad \text{----------------------------------- } (2\text{-}3)$$

The entire disinfection capability of the chlorine gas resides with either the undissociated HOCl or the OCl^- ions; however the ability of the chloride ion to kill microbes at the concentration it occurs in drinking water is limited. Whenever sodium or calcium hypochlorite is used as the source of chlorine, there will always be a yield of OCl^- ions dissociation in water. Hypochlorous acid is more reactive and is a stronger disinfectant and oxidant than the hypochlorite ions. The pH of the water determines the ratio of the hypochlorous acid to that of hypochlorite ion. In cases where the pH is low (higher acidity), hypochlorous acid dominates while at high pH, hypochlorite ion dominates. Hence disinfection efficacy of chlorine is higher and better in water with low pH than in water with high pH. In general, the rate of disinfection of pathogens using chlorine as a disinfectant may be affected by the pH of the water to be treated (Chlorine Chemistry Council, 2003).

Chlorination over a wide pH range makes bacteria and viruses an easy target for disinfection. For the treatment of raw water that is contaminated by parasitic protozoa (e.g. *Giardia)*, the system operators may take advantage by lowering the pH so they can be a more effective disinfection capability against *Giardia*, which is noted to have been resistant to chlorination than most viruses and bacteria . At the pH range of 6.5-9.5, disinfection occurs at its maximum, however, chlorine efficacy decreases as the pH increases. Hypochlorous acid is known to be a destructive, non-selective oxidant and can react with all biological molecules.

Bromo-chloro-dimethyl-hydantoin (BCDMH)

BCDMH falls under the family of chlorination but has Bromine as the additional active ingredient disinfectant combined in a single tablet. The tablet slowly releases bromine and chlorine when placed in water. BCDMH hydrolyzes in water into Hypobromous and Hypochlorous acids, the bromine release is immediate while chlorine release is slow as seen in equations 2-4 and 2-5 (Zhang and Matson, 1989).

$$\text{Bromochloro DMH} + H_2O \underset{\text{Rapid}}{\leftrightarrow} HOBr + \text{Monochloro DMH} \text{ ------------- } (2\text{-}4)$$

$$\text{Bromochloro DMH} + H_2O \underset{\text{Slow}}{\leftrightarrow} HOCl + \text{Monochloro DMH} \text{ -------------- } (2\text{-}5)$$

The monohalo-DMH products from equation 2-4 and 2-5 also can hydrolyze. The monobromo-DMH hydrolyzes much faster to release hypobromous acid (equation 2-8) than does the corresponding hydrolysis of the monochloro-DMH (equation 2-8), as shown. The hypobromous acid released in equations 2-5 and 2-7 can dissociate to the biocidally low active hypobromite ion (equation 2-8), but this reaction is much slower than the corresponding dissociation of the hypochlorous acid, especially in alkaline water, to formthe biocidally low active hypochlorite ion (equation 2-9)

Bromochloro DMH + H2O $\leftrightarrow$ HOBr + DMH------------------------------ (2-6)
Rapid

Bromochloro DMH + H2O $\leftrightarrow$ HOCl + DMH------------------------------ (2-7)
Slow

HOBr $\leftrightarrow$ OBr^- $\leftrightarrow$ Br^---- (2-8)
Slow Rapid

The reverse is true in the decomposition of the dissociated hypohalites, The hypobromite reacts rapidly to form bromide ion (2-7), whereas the hypochlorite ion reacts slowly to form the inactive chloride ion (2-8).

HOCl $\leftrightarrow$ OCl^- $\leftrightarrow$ Cl^- --- (2-9)
Rapid @ pH>7.5 Slow

HOCl + Br^- $\leftrightarrow$ HOBr -- (2-10)
Rapid

OCl^- + Br^- $\leftrightarrow$ HOBr $\leftrightarrow$ Cl^-
Rapid

One final, but very important set of reactions is that of bromide ion with hypochlorous acid or hypochlorite ion produced in some of the reactions. Bromide reacts rapidly with these chlorine compounds to form more of the biocidally active hypobromous acid (equations 2-9 and 2-10).

2.3.6 Limitation of chlorine

The relative short life of Hypochlorous acid in water is one of the major limitations of chlorine as this acid loses its residual contact time within 18 to 24 hours. Industries have to rely on the use of chloramines in order to increase the lifespan of combined chlorine residual from 24 hours to 3-7 days. In many cases chlorine requires constant monitoring to ensure its efficiency, however many treatment plants and small water supply schemes particularly those in the rural areas that uses chlorine are unreliable and often not monitored (Pearson and Idema, 1998; Momba *et al.*, 2004b). According to the studies done by Swartz (2000); Mackintosh and Colvin (2002); (Momba, Tafawa and Makala, 2004a); Momba *et al.* (2004b), it was discovered that most water treatment plants in South Africa uses chlorine for disinfection, however, most of the small water works have limitations in providing satisfactory treatment and disinfection, such that water consumers are at risk of contracting water borne diseases on consumption of the treated water.

Chlorine delivery and dosing remains a major challenge in most of the small rural water works. Improper chlorine dosing procedure and monitoring program leads to insufficient chlorine residual at the treatment point. An effective disinfection can be obtained when the ratio of chlorine is proportional to the plant flow rate. Hence before dosing chlorine, it is important to know the chlorine demand of the water to be treated. It can therefore be concluded that both human and technical factors are reported to be responsible for failure of small rural water treatment plants that uses chlorine as a disinfectant to provide potable water to consumers. Table 2-8 summarizes the advantages and disadvantages of chlorine.

a. Sodium hypochlorite

This liquid disinfectant is used in many small water treatment plants. The disinfectant is fed into the treatment plant by using a dosing pump or a constant head drip feeders. For most of the small treatment plants within the rural areas, one of the major advantages of the drip feeder is that they do not require electrical power;

however the limitation is that the solution cannot be introduced into the system under pressure.

In some developing countries, sodium hypochlorite is stored in small bottles of 150 mℓ and distributed to households to use for their water treatment with application procedures written on the bottles. Proper storage is required when using sodium hypochlorite as it easily decomposes when exposed to heat, light and other impurities. The stock solution should be used up quickly and maybe stored for over one month, if sealed and stored in a dark place (Momba, Obi and Thompson, 2008).

b. Waterguard

There are several disinfectants that are currently being used in many rural communities today. Waterguard is one such disinfectant. It is a one per-cent sodium hypochlorite disinfectant stored in 150 ml bottles. This disinfectant is sold at low prices in many stores of developing countries and is also distributed as part of the poverty relief program in many rural areas of developing countries for treatment of drinking water. A user manual is usually attached to the body of the bottle (UNICEF, 2013). The chemical reaction for this disinfectant is presented in equation (2-2) and (2-3).

Advantages of Waterguard

- Have advantages that are similar to that of chlorine.
- It is inexpensive
- Easily accessible from health centers for free or can be generated in the form of sodium hypochlorite
- The storage bottle is small and can be easily carried

It is a diluted form of chlorine hence will not easily form DBP which will have a negative effect on the health of users, particularly when used in a small amount.

Limitations of Waterguard

- ❖ Large amount may be required for highly contaminated water
- ❖ Users may deviate from their user manual as they come across water with different quality.
- ❖ Complete bacterial inactivation is not achieved with water with a higher turbidity.

c. Bromochlor tablet

Bromochlor tablets are chlorine based a solid disinfectant that is used mostly for large scale disinfection; however the tablet can be sized to suit small scale systems. One of the advantages of this tablet is that it does not dissolve or break easily on contact with water such that a small amount can be used to treat several volumes of water. Chlorine is the major active ingredient in this tablet (Zhang and Matson, 1989)

Advantages of Bromochlor tablets

- ❖ Minimal human interference that could lead to errors, once the bromochlor tablet is placed on the holder it can be used with no external interferences
- ❖ The water is ready for use the moment it comes out of the tap
- ❖ The tablet can last for a long period of time
- ❖ No mixing required
- ❖ Easy to handle and incorporate to other systems

Disadvantage of Bromochlor

- The tablet could run out unknown to the user if test for residual chlorine are not done regularly. This is because the sizes used in this study are quiet small and are fixed onto the permeate outlet.

- Resizing of Bromochlor tablet requires precision and this could be difficult for those in the rural areas (Zhang and Matson, 1989).

Table 2-6 Summary of advantages and disadvantages of chlorine (Momba, Obi and Thompson, 2008)

Advantages	**Disadvantages**
Inexpensive, well established, effective against a number of pathogens and can be dosed in a number of different forms.	Chlorine is highly corrosive, limits the material of use.
It is very flexible to apply to suit various circumstances	Shipping and handling and application have to be highly controlled and managed on a water works.
Has long lasting residual that can easily be measured using simple apparatus like pocket colorimeter.	Disinfection by products are formed which can be harmful to human health if consumed, however its advantages outweigh these disadvantages. Some pathogens are resistant to chlorine.

2.3.7 Chlorine Dose and Residual

Although chlorine is used to reduce or totally remove bacterial contamination, the mere use of chlorine does not give the assurance that total removal of microbiological pathogens will be achieved. It is very important to apply accurate dosage using the right frequency (Momba and Brouckaert, 2005).

Also the point of chlorine application must be such that it provides adequate contact time and mixing between chlorine and the water to be treated before it leaves the treatment plants. The required contact time is usually determined by the dose applied although there are cases where the quality of water to be treated plays a major role in determining the dose of chlorine and contact time that is required.

There are varieties of dosing methods that exist, but the following points must be considered when designing and controlling chlorine dosing systems to achieve maximum disinfection rates. These are uninterrupted dosing, even distribution of chlorine to all parts of the water, chlorine dose adjustment to the demand of water being treated and a dose that produces water that is safe without affecting the taste of the treated water (Swartz, 2000).

In most water treatment plants within the rural areas, chlorine demand measurement is done by the operators. These operators use a fixed amount for the chlorine dose not considering the changes in the chlorine demand, which then leads to over dosing or under dosing (Momba, Tafawa and Makala, 2004a).

2.4 Decentralized Drinking water treatment by Membrane filtration

2.4.1 Introduction

Globally, trends are now focusing on alternatives for producing high quality drinking water at all times especially as POU. Membrane technology has been seen to be one of such technology as disinfected water with constant high quality is now being produced using membrane technology as an alternative method. Madaeni (1999) explained that membranes can increase the safety of water in two ways: firstly, they can be used at the consumption point as a tool for increasing security and secondly they can be part of the water purification system.

The available categories of pressure driven membranes are microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO). However, MF and UF membranes and their application will be discussed in details in chapter two of this study.

Although membrane technology has been widely used in large scale water treatment, the application of current commercial membranes in rural areas is still questionable. This is because commercially available membranes are fragile and lack robustness. They can be easily damaged if left to dry. These membranes are relatively expensive and they require trained personnel both for their operation and cleaning. These challenges make the application and sustainability of commercial membranes in rural areas difficult (Pillay, Graham and Dlamini, 2009).

The use of membrane filtration process for the treatment of potable water at household levels has become more attractive recently due to increasing stringent rules in drinking water guidelines. Compared to conventional filtration processes, the use of membrane for smaller treatment units has become cost effective. Excellent separation capabilities have been achieved using membrane technology and this process has continued to show promising ability of meeting already existing and future drinking water standards (Baker, 2004).

Membrane technology has gained popularity in the field of water treatment both for centralized and decentralized systems. These processes are characterized by the use of a semi-permeable film otherwise known as the membrane and a driving force which can be in the form of differential pressure, concentration, temperature or electrical potential (Mulder, 1996; Baker, 2004). The majority of membrane processes are driven by pressure and are usually regarded as membrane filtration processes. Although in water treatment other methods like electrically driven (electrodialysis) and thermally driven processes (membrane distillation) are used for decentralized systems. Pressure-driven membrane processes are the most commonly used in water treatment. The hierarchy of pressure-driven membrane processes is illustrated in Figure 2-2.

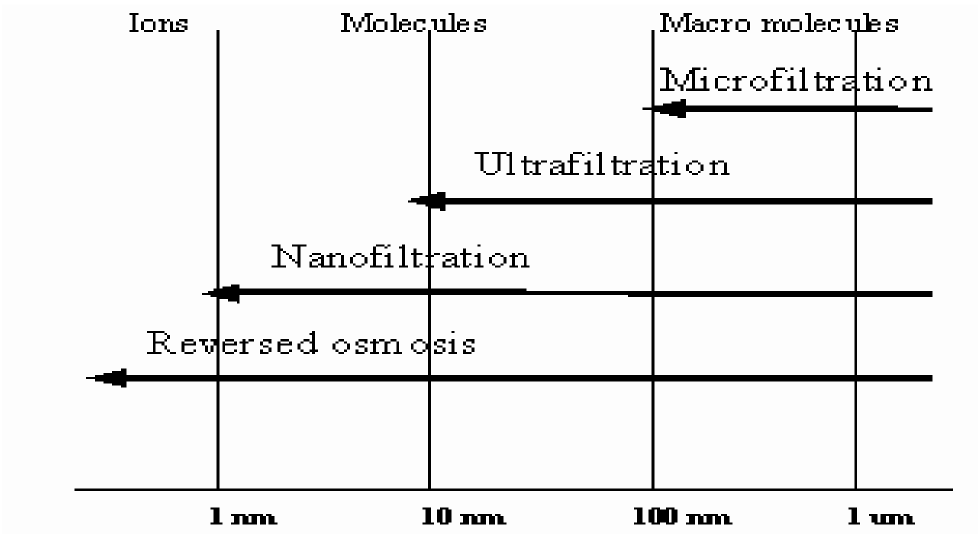

Figure 2-2 Hierarchy of pressure driven membrane processes (Baker, 2004)

Membrane technology present an alternative to disinfection processes which produces high quality effluent without requiring additional chemical reagents, hence problems such as formation of harmful disinfection by products are completely eliminated. Previously membrane technology has been viewed as unsuitable due to high operating costs and membrane fouling which tremendously affects the overall performance of the system. However, over the past 10 years membrane technology has expanded significantly in its application. This is because of technological advances, stringent discharge standards, drinking water quality guidelines and an enormous decrease in costs associated with membrane technology (Peter-Varbanets *et al.*, 2009).

2.4.2 Classification of membrane processes

Membrane processes are classified into 4 different categories which are;

Microfiltration (MF), Ultrafiltration (UF), Nanofiltration (NF) and Reverse Osmosis (RO). One of the most relevant areas for the application of membrane technology is in drinking water systems. Therefore it is important to evaluate the performance of membrane technology relative to waterborne pollutants.

This study will focus more on MF and UF as the aim of the study is to evaluate a membrane based POU system that can be applicable in the rural areas without requiring the use of electricity or pumps. MF and UF membranes are pressure driven membranes that meet these criteria hence they will be discussed in detail.

2.4.3 Microfiltration (MF) and Ultrafiltration (UF)

Microfiltration (MF) is of great interest among the categories of membranes, it is said to have similar properties to UF, however this membrane type has pore sizes of approximately 0.03 to 10 microns, a molecular weight cut-off (MWCO) of greater than 100,000 Da and a pressure of approximately 100 to 400 kPa (15 to 60 psi) that are slightly larger than that of UF (Mulder, 2000). Its bacterial removal efficiency may not be 100 per cent but it has high permeate flow rates and can be driven under gravity without requiring additional energy. Recently there have been some doubts with regards to its effectiveness because of bacterial retention (Wang *et al.*, 2007). However several studies have proven that MF membranes have high capability in bacterial and colloidal removal and are also used as pre-treatment for other systems like NF. Some of the materials removed by MF are sand, clay, *Giardia lamblia* and *cryptosporidium* cysts, algae and some bacterial species. Viruses are not removed by MF, however when used in combination with other disinfection processes, MF appears to be effective in controlling this pathogen in water (USEPA, 2004).

UF membranes have smaller pore size when compared to MF see Table 2-6. These pore sizes are capable of ensuring high removal of all types of microbiological hazard especially the likes of bacteria, *cryptosporidium* and *Giardia* which are known for their high resistance to chlorine (Hagen, 1998). Hence a significant amount of viruses can be removed using UF membrane rather than MF, being that viruses have their sizes within the range of 30-300 nm and UF membranes have poor sizes that are below these sizes.

While UF and MF are more effective in the removal of organic contaminants and colloids, nanofiltration (NF) and reverse osmosis (RO) can be used to remove inorganic contaminants from water. RO membranes are essential for the removal of monovalent ions like desalination of seawater or brackish water while NF membranes are efficient in removing bivalent ions with typical retention >90% (Peter-Varbanets *et al.*, 2009).

Table 2-7 Summary of membrane processes (Mulder, 1996)

	MF	**UF**	**NF**	**RO**
Membrane type	Symmetric microscopic	Asymmetric microscopic	Composite	Asymmetric or composite
Pore size	0.05-10 (μm)	1-10 nm	<2 nm (200-250 Da)	< 2 nm (100 Da)
Driving force (bar)	< 2	1-10	10-25	10-70
Separation principle	Sieving mechanism	Sieving mechanism	Solution-diffusion	Solution diffusion
Membrane material	Polymeric, ceramic	Polymer (polysulfone, polyacrylonitrile)	Polyamide (interfacial polymerisation)	Cellulose triacetate, aromatic polyamide, interfacial polymerisation

2.4.3.1 Rejection mechanism in UF and MF membranes

The rejection of particulates in the form of colloids either biological or non-biological using membranes depend on many factors which includes pore size. However for potable water disinfection, pore size is the most critical parameter. According to findings by Leahy and Sullivan (1978) membrane pore diameter should be smaller than the microorganism size. However for significant retention to occur, pore size can be greater than the particle size. There are cases where nominal pore size may be 2-3 times greater than the particle size. In UF and MF, membrane performance is by size exclusion rather than other operational parameters like pressure, influent concentration and operator's skill. Rejection is based on membrane pore size and product quality is determined by the membrane itself. It is determined by the use of the rejection equation as shown below.

$$R\ (\%) = 100\ (1 - C_p/C_f) \qquad (2\text{-}11)$$

Where,

C_f = Feed concentration (g/l)

C_p= Permeate concentration (g/l)

Adsorption, sieving retention and cake filtration have been identified as important mechanisms in the removal of particulates by UF and MF membranes (Baker, 2004).

i. Sieve Retention (straining)

This process is also known as straining and it involves the physical retention of particles on the membrane surface due to pore size. In this process, the porous media acts as a barrier to particle penetration such that the retained particles becomes a cake forming layer which increases proportionally with increased filtration time (Madaeni, 1999). During a sieving process, the particles that are larger than the pore size of the membranes are expected to be retained; however there is usually no complete retention of such particles. This could be due to the size distributions on the membrane matrix resulting from deformation or membrane imperfection; hence it is possible to allow the passage of larger particles in such cases.

ii. Adsorption

This mechanism results when material small enough to pass through pores are adsorbed onto the walls of the pores. If the particles and the membrane are oppositely charged or if their zeta potentials are appropriate, the particles will adhere to the membrane matrix resulting in the removal of the particles smaller than the pores of the membrane (Madaeni, 1999; Baker, 2004). This means that soluble materials may be rejected even though their physical dimensions are much smaller than that of the membrane retention rating. This will therefore, increase the ability of the membrane to retain smaller material by straining while increasing the chances of membrane fouling.

In terms of bacterial retention, the ability of bacteria to deform their shapes and assume a size smaller than that of the membrane pore size makes it difficult for retention to occur even in cases where pore size is greater than the actual size of the organism (Pall, Kirnbauer and Allen, 1980;Cheremisinoff, 2002). Also from previous studies it has been discovered that membranes are capable of removing biological colloids, either larger or smaller than the membrane pores. Rejection of bacteria is then possible through this process as bacteria have colloidal properties (Daniels, 1980; Cheremisinoff, 2002).

a. Transport in UF and MF

Transport processes in MF and UF membranes involve the application of pressure difference across the membrane in order to achieve separation of particulate matter from the feed. According to Cheryan (1986), the membrane properties are the major determinant of which components permeates through and also retained. The performance of MF and UF membranes is determined by the rate of solute or particle transported towards the membrane which is measured in terms of flux. Darcy’s law, is used to measure the permeate flow through the membrane, where the flux (J) is directly proportional to the applied pressure (Mulder, 2003).

$J = K.\Delta P$ (2-12)

Where,

J is the flux (LMH)

K is the permeability constant containing structural factors such as porosity and viscosity.

ΔP is the applied transmembrane pressure (TMP)

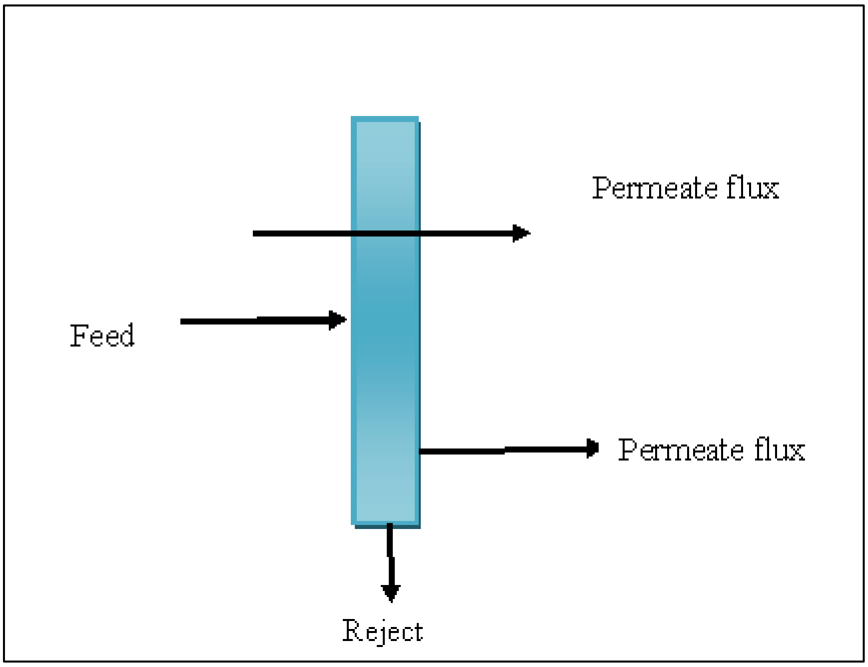

Figure 2-3 Schematic presentation of transport in MF and UF (Cheryan, 1986)

The flux or permeate rate of the membrane is obtained using the expression,

$J = V/ (A.\ t)$ (2-12)

Where,

V is the permeate volume (ℓ)

A is the membrane filtration area (m^2)

t is the period over which the permeate is collected (h)

The film theory shown in Figure 2-4 is one of the widely used theories for modelling flux in pressure-in dependent, mass transfer controlled systems. In this theory, as the feed is filtered, solute is brought to the membrane surface by convective transport at a rate; this is shown in equation 2-13.

$$J_s = J\,C_b \qquad (2\text{-}13)$$

Where,

J is the permeate flux (LMH)

C_b is the bulk concentration of the rejected solute (g/ℓ)

The resulting concentration gradient causes the solute to be transported back into the bulk of the solution due to diffusion effects (Cheryan, 1986). The rate of back-transport of solute (J_s) is given by,

$$J_s = D\,dc/dx \qquad (2\text{-}14)$$

Where,

D is the diffusion coefficient

dc/dx is the concentration gradient over a differential element in the boundary layer.

The rate of solute deposition at steady state is equal to the rate of solute back transport and the two mechanisms balance. On integration over the boundary layer, equation 2 and 3 can be equated to give,

$J = K \ln(C_g/C_b)$ (2-15)

Where,

K is the mass transfer coefficient

C_g is the gel concentration at the membranes surface

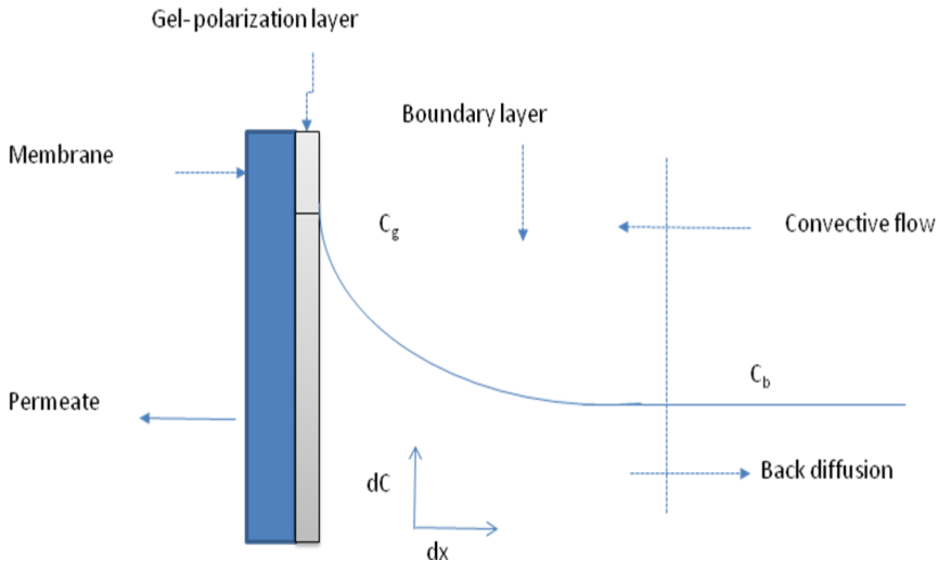

Figure 2-4 Schematic representation of concentration polarization showing the gel polarized layer and the associated boundary layer (Cheryan, 1986).

2.4.4 Membrane module configurations

Membrane modules are categorized into four: plate-and-frame, tubular, spiral wound, and hollow fibre, this is shown in Figures 2-4 to 2-7. The simplest module is the plate-and-frame. It consists of two end pates, the flat sheet membranes and spacers, while the tubular module is often on the inside of a tube, and the feed solution is pumped through the tube. The spiral wound module is the most popular one used in the industry for nanofiltration and reverse osmosis. It has a flat sheet membrane wrapped around a perforated permeate collection tube. The feed flows on one side of the membrane, while permeate is collected on the other side of the membrane and spirals in towards the centre collection tube (Ashbolt, 2004).

Hollow fibre modules used for seawater desalination consist of bundles of hollow fibres in a pressure vessel. They can have a shell-side feed configuration where the feed passes along the outside of the fibres and exits the fibre ends. Hollow fibre modules can also be used in a bore-side feed configuration where the feed is circulated through the fibres. Hollow fibres employed for waste water treatment and in membrane bioreactors are not always used in pressure vessels. Bundles of fibres can be suspended in the feed solution, and permeate is collected from one end of the fibres.

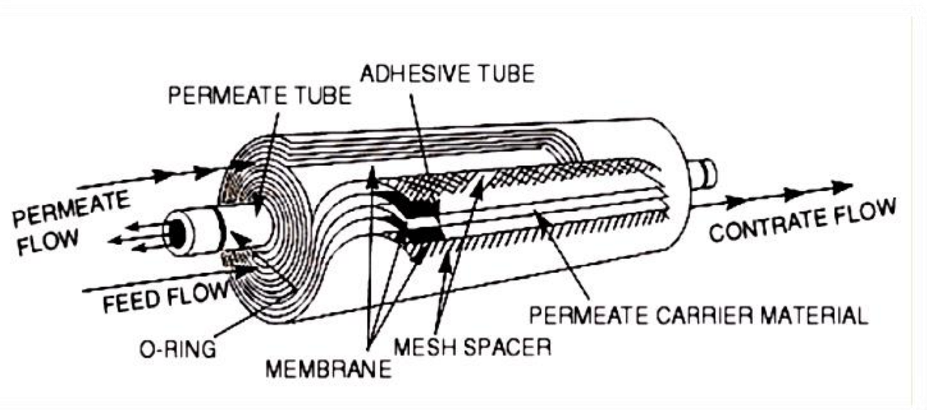

Figure 2-5 Spiral wound membrane module showing the filtration operation (Baker, 2004)

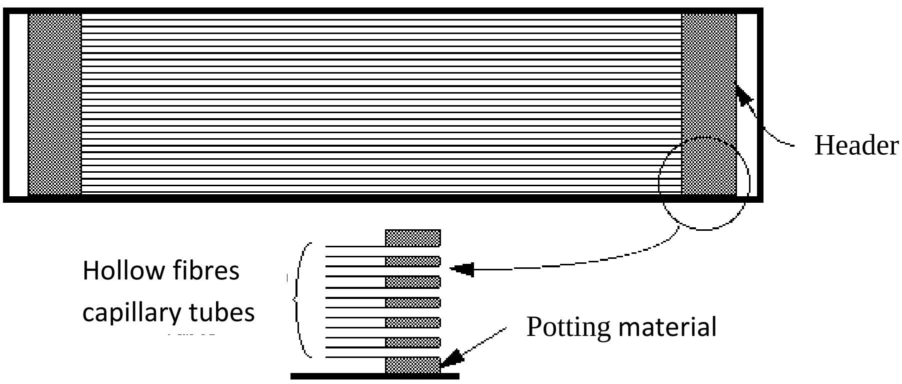

Figure 2-6 Schematic representation of hollow fibre membrane module (Baker, 2004)

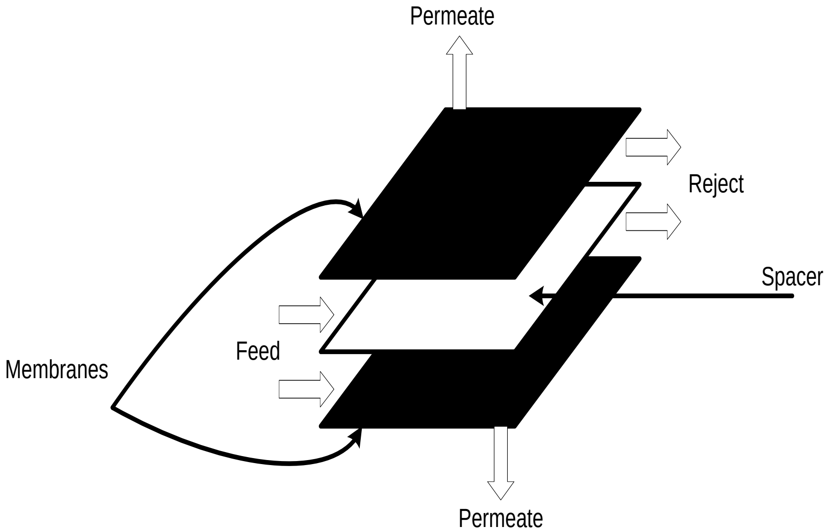

Figure 2-7 Plate-and-frame module showing system operation (Baker, 2004)

2.4.5 Membrane filtration modes

Pressure-driven membranes may be operated in the dead end filtration, cross flow filtration and immersed membrane filtration modes.

Dead end filtration

In this type of filtration, the entire feed flow is forced through the membrane under pressure as illustrated in the Figure 2-8 (A and C). On accumulation of particles on the membrane surface, the required pressure to maintain the flow increases due to increased cake formation. At constant pressure drop, the increased resistance to filtration causes the permeate flux rate to decline, or causes the pressure drop to increase if the flux rate is held constant. To reduce the effect of cake formation at some point the membrane must be cleaned or replaced due to the cake layer. Removal of cake layer is reduced by cleaning of the membrane. Figure 2-8 shows a schematic representation of the flux and cake thickness for constant pressure dead end (Ho and Sirkar, 2001). Figure 2-9 is a schematic diagram of TMP and cake thickness for constant flux dead end filtration (Ho and Sirkar, 2001)

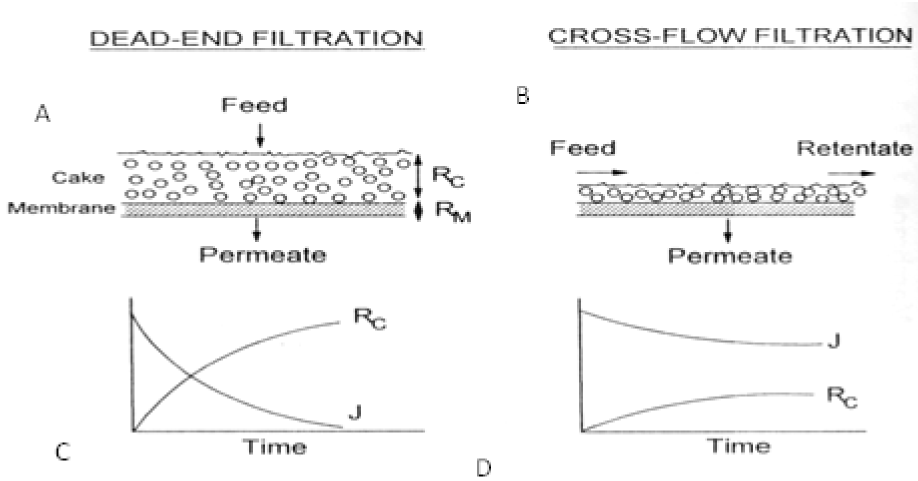

Figure 2-8 Membrane filtration modes; dead end (A) and (C), cross flow (B) and (D)

Figure 2-8 (B and D) represents the behaviour of ΔP and cake thickness for constant flux dead end and filtration. The ΔP increases with time as a result of increase in the resistance to filtration due to the increasing cake thickness. The ΔP decreases due to the low resistance to filtration when the membrane is cleaned and the cake layer is removed.

a. Cross flow filtration

In cross flow filtration, the feed solution is circulated across the surface of the filter at a high velocity parallel to the membrane surface. This behaviour is to reduce the collection of retained species at the membrane surface and hence the formation of a cake layer. At right angles to the permeate flow direction, the liquid being filtered is pumped tangentially across the membrane surface and filtration pressure. The solids deposited on the membrane surface are then sheared from the membrane surface and carried away with the feed solution. Thereafter two streams are produced which are permeate and a concentrated retentate containing the rejected particles. The findings of Baker (2004) reveals that the equipment for cross-flow filtration is more complex, however the membrane lifetime is longer than that of dead end filtration. Figure 2-8 (B and D) shows a schematic presentation of cross flow filtration.

The cake layer formation in cross flow filtration is not built up indefinitely like it is in dead end filtration. Here the high shear exerted by the feed flowing tangentially to the membrane surface sweeps the deposited particles towards the filter exit so that the cake layer remains thin. This occurrence makes it possible for high fluxes to be maintained over prolonged periods of time.

Immersed membrane filtration

The operation mode of immersed membrane filtration is commonly used in membrane bioreactors for treating waste water. The process involves immersing the membrane into the feed solution in the process tank. Filtration occurs either inside-out or outside in. Figure 2-9 illustrates the immersed membrane filtration using the principle of submerged gravity driven filtration.

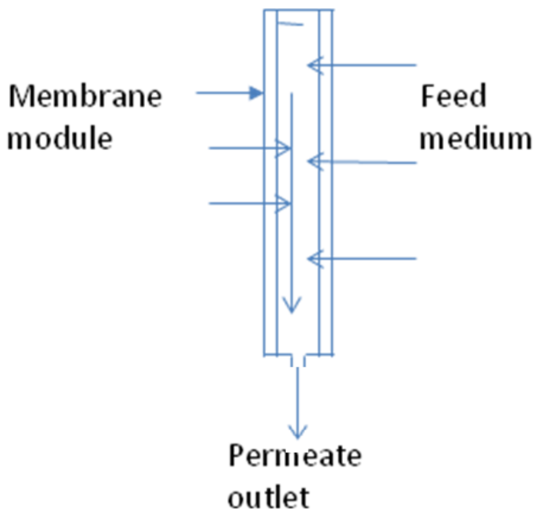

Figure 2-9 Schematic representation of outside-in-immersed membrane filtration (Crittenden *et al.*, 2005)

2.4.6 Advantages and limitations of membrane processes

The advantage of membrane processes when compared to conventional water treatment is that water treatment processes using membranes can be carried out in one stage and the desired quality of permeate is achieved without the need for chemicals or other utilities with a relatively small treatment footprint.

Over the years, membrane technology has experienced massive development and this has led to a major significant decrease of membrane costs and energy requirement (Churchhouse, 2000). Also membrane systems can be designed with different shapes and sizes e.g. flat sheet, hollow, and spiral membranes, with final product quality not being dependent on the performance of its operator. For instance, membrane systems that are built in a modular form enables easy adaptation of process scale (Peter-Varbanets *et al.*, 2009). The above advantages then support the possibilities of membrane systems being designed and applicable in decentralized water treatment in developing countries.

Membrane Fouling

Membrane fouling is one of the major limitations of membrane systems. It affects systems performance by clogging membrane surfaces and forming fouling layers which affects the flux of the system (Madaeni, 1999). Fouling reduces the effectiveness and performance of the membrane due to deposition of suspended or dissolved substances on the external surfaces, sometimes at its pores or within the pores. The major effect of fouling in membrane filter is the gradual deterioration of the system performance in terms of flux (Crittenden *et al.*, 2005).

Apart from clogging of the membrane pores which leads to reduction in flux, fouling has the other major implication on membrane performance. Such impacts are increased energy consumption due to higher transmembrane pressure (TMP), reduce operational time before cleaning is required and finally decrease membrane durability which affects the overall economy of the membrane process (Madaeni, 1999).

2.4.7 Membrane Cleaning

Fouling control is an important aspect of membrane technology and the following techniques can be used to alleviate it. In MF and UF, regular back flushing of approximately 30 minutes is required in large scale systems while for RO and NF, chemical cleaning is seriously required with a pre-treatment and the system operation should be in a cross flow mode. In other to actualize this fouling prevention measures, the system has to be operated in an automated process control with regulations which might lead to increased costs of investment (Peter-Varbanets *et al.*, 2009). The following below outlines some measures adopted to reduce fouling.

a. Feed pre-treatment to reduce the amount of particulate matter in feed before membrane filtration.

b. Fouling can be reduced by adjusting operating conditions, e.g. cross flow, pressure and backwashing velocity

c. Regeneration of the membrane can be achieved by cleaning with or without chemicals.

One of the physical processes to enhance membrane performance and reduce flux decline is membrane cleaning. Periodical cleaning of membrane to remove fouling is very important. One indicator of a cleaned membrane is to compare flux recovered to the initial pure water flux. When a membrane is able to recover its flux after cleaning, it indicates that the membrane is clean. Several factors determine the type of cleaning method to be used on a particular membrane which includes the type of membranes, configuration of the module, and the type of fouling matter in the feed and the chemical resistance of the membranes (Wenten, 2008).

2.4.8 Methods of membrane cleaning

i. Mechanical or physical method

A mechanical process is the physical removal of the fouling layer or matter that is deposited on the surface of the membrane. Air scouring, ultrasonic waves and oversized sponge balls are used to remove the fouling layer.

ii. Hydraulic cleaning

This method of cleaning is carried out during normal operation of the membrane system. The process includes back flushing, alternate pressurizing and depressurizing and changing the flow direction at a given frequency. Certain limitations are found in this method like the loss of permeate to feed solution and reduction in effective operation time (Wenten, 2008).

iii. Chemical cleaning

This involves the use of chemicals in cleaning the membrane. Chemicals like sodium hydroxide, sodium hypochlorite and other detergents and disinfectants can be used according to Madaeni (1999). This is the most common type of cleaning employed in reducing membrane fouling.

iv. Electrical cleaning

This cleaning method is achieved by applying an electric field across a membrane. The membrane becomes clean as the charged particles or molecules migrate in the direction of the electric field hence, separating them from the membrane (Wenten, 2008)

2.4.9 Available UF and MF membranes for POU water treatment.

Many point of use or point of entry (POU/POE) water purifiers are made of membranes that are of the same quality as the membranes used in large scale water treatment plants around the world today. These membrane systems were developed for residential and small commercial/industrial purposes. Although these systems were developed by industrialized countries for their use, they are increasingly being used in transition countries today for the improvement of their tap water or ground water.

In developing countries (DC), microfiltration is one of the few membrane technology systems that is used and recommended by WHO (Sobsey, 2002). These membranes have pore sizes that are about 0.2 µm and are presented in the form of monoliths or hollow cylindrical tubes (Wenten, 2008; Clasen *et al.*, 2004). Because of the pore sizes of such filters, bacteria are completely removed since they are bigger in size but only partial protection is obtainable from viruses due to their pore size in the range of 30-300 nm. Hence, in cases where virus removal is the target for a particular treatment or area, multiple barriers have to be put in place or another treatment option adopted.

For most MF systems, the formation of a cake layer can serve as an additional mechanism of pathogen removal, as the filtration process occurs in two stages whenever a cake layer is formed firstly by the layer and then the filter itself. So the configuration of the filter and mode of production determines the efficiency of bacterial removal (Sobsey *et al.*, 2008).

a. Ceramic membrane filter

According to Sobsey (2002), filters that are produced in IC have proven to perform better in removing bacteria and viruses than those DC. The use of microfiltration for POU systems is increasing particularly in the IC for their travellers. Katadyn in Switzerland is one of the best producers of ceramic filters. This filters consist of a ceramic membrane with 0.2 mm pore size, and are gravity driven or can be operated using a hand pump. The system is very portable and may be used to treat water that is polluted with organic matter and those with turbidity. Although the lifespan is limited to 20,000-100,000 ℓ of filtered water, this depends on the type and quality of raw water to be treated. These filters have relatively high costs of about US$ 250-600.

b. Filter Pen

The filter pen which is a microfiltration membrane is used in the form of a straw to suck water. A few examples are Filter Pen, manufactured by the Filter Pen Co of New Zealand and Filtrix Co of the Netherlands (Filtrix, 2007). The system is used mostly in the decentralized form. The average membrane pore size is about 0.15 mm with a surface area of 0.02 m^2. Initial flow rate for the clean water is approximately 0.1 ℓ/min at a pressure difference of 0.1 bars. The service lifespan of this filter is about 4 weeks or 100 ℓ of treated water which is equivalent to water production of 3.5 ℓ/day depending on the quality of water to be treated. Based on the manufacturer's data, the material used in manufacturing this membrane is a combination of different polymers like polyester sulphone, poly vinyl pyrrolidone (PES, PVP). The target market for this filter were travellers from industrialised countries (IC) going to DC, however it is now being used by the German military who are based in DC (Filtrix, 2007)

c. Life straw and Filter pen personal Life straw

Pathogenic organisms are known to be one of the major problems of water quality; however these pathogens can completely be removed by ultrafiltration membranes. Presently there are quite a few UF based POU systems that exist. One such is life Straw Family from Vestergaard Frandsen (LifeStraw, 2008). This system is made up of a UF module with a pore size of 20 nm with an attached pre- filter for reducing initial feed turbidity and a chlorine chamber. In other to create a pressure of 100-150 mbar, a feed water tank is connected to the module by a flexible hose pipe at an elevated direction. The cleaning of the module is by backwashing manually once in every 1-2 days. The first investigation on the performance of the life Straw Family was done by the University of Arizona and the results showed high stability of the system during operation and efficient bacteria and virus reduction during filtration of 18,000 ℓ of water, 100 NTU for turbidity with a TOC of 10 mg/ ℓ and a final flow rate of 16-8 ℓ/h. This system is presently being tested in Congo and China. A very large population in Kenya is presently using life straw family to treat their water (LifeStraw, 2008).

Life Straw Personal is a product for personal use for people living in the DC travelling to a faraway distance over a long period of time (e.g. Sheppard). The membrane filter was designed basically to prevent people from infestation of guinea worm diseases. The removal efficiency of pathogens by the filter was not only limited to guinea worm removal alone but had 6 log efficiency in removal of waterborne bacteria and 2 log removal for viruses. Life Straw has a life time which limits the filtration to about 1000 ℓ of water (LifeStraw, 2008).

d. Sky Hydrant unit

Sky Hydrant unit (SMF-1) is a decentralized filtration system developed by Sky Juice Foundation (Australia). It is intended for the supply of communities with water and as an emergency relief during disasters. This treatment option combines membrane filtration (MF) with chlorine disinfection. The membrane pore size is 0.1 μm and may be operated using a hydrostatic pressure of about 30 mbar. In order to maintain the performance of the system, manual back flushing of the membrane is required every 1-12 h with regular washing using 10% hypochlorite solution depending on the quality of water to be treated. Therefore, a skilled operator is required. The SMF-1 filter has been implemented in approximately 10 countries, central and south East Asia, and South America. It has the capacity of treating high turbid water (maximum 500 NTU) (SkyJuice, 2008).

A fast response emergency water treatment unit has been developed also at the University of Kassel (Frechen, 2007). The MF membrane module is driven by gravity, is chemical free, may be carried by one person (25 kg dry weight) and operated by non-trained persons. It is intended to treat highly polluted water for 200–500 people during the first 5–10 days after a disaster. The main idea behind this system is to provide simple water treatment to cover the time gap until disaster relief teams are able to deliver, install or repair long-term drinking water supply systems (Frechen, 2007).

e. Home spring

Home spring developed by Zenon is one of the POE systems developed using UF that is widely used in most IC and TC homes for tap water treatment. The system is suitable for treating a variety of feed water qualities. Being a POE system it provides water of good quality to the entire household, with a pre-treatment stage using an activated carbon filter. The key part of the system is the hollow fibre UF that removes the bacteria cysts and viruses. Surface water, well and/or tap water can be treated by the system without requiring additional pre-treatment. The system is designed to use existing pressures (e.g. tap water) and requires manual maintenance (Homespring, 2007). The limiting factor for the process capacity is the carbon filter which needs to be changed regularly (once a year). Continuous flow rate of 14-17 ℓ/min or approximately 840-1020 ℓ/h (20,160-24,480 ℓ/day) is expected. Other available UF membranes are those manufactured by MEMFIl and are is available in markets in Malaysia. Singapore and Malaysia has something similar to the Home spring UF membrane, however it has a higher flow rate of about 3000 ℓ/h and requires once off back flushing in a week which should be done manually by the household through opening and closing the control valves. Its limitation is the feed quality which should not exceed 20 NTU hence the system can be used only on tap water as an additional treatment or requires initial pre-treatment (Memfil, 2007).

f. UF low pressure membrane filters

According to Pryor *et al*. (1998) and Jacobs (2004), three UF membranes with low pressures were tested in South Africa for supply of water to some communities. These systems were tested on water containing different kinds of contaminants such as high levels of suspended matter, intermittent algal blooms and diffuse pollution resulting from surface runoff into the rivers. The expected daily supply output for the plant was 10,000 ℓ/day of treated water using cross flow mode with frequent cleaning.

Plant cleaning was carried out using detergent and complex agent when the feed used contained high organic load, while for low organic low, sodium hypochlorite was used. The ability of the system to operate under low pressures of 100-150 kPa was an advantage as it enhanced the application of the process in rural and peri urban areas by utilizing the water head without requiring additional pumping (Pryor *et al.*, 1998; Jacobs, 2004).

Ultrafiltration was proposed as an appropriate technology that can be used for urban water supply systems in developing countries (Arnal *et al.*, 2001; Arnal *et al.*, 2002). The membrane module proposed has a treatment ability of 1000 ℓ/h when the system is operating at its maximum efficiency with the ability to increase the number of modules as well as increasing the treated product flow under specific conditions and requirements. A polysulfide spiral wound membrane with a molecular weight cut off of 100 kDa is equipped on the module. Pre-treatment of the feed water is done before entering into the feed tank of the UF facility. The pre-treatment is carried out in a series of different filtration units like the coarse filter, micro filter (500 mm) and security filter (5 mm). System modification was carried out to supply water directly from a source to isolated communities that do not have a water source or electricity.

Energy was produced for the pump by rotation from the wheel when operating the modules manually. Water for direct consumption can be provided for about 300 persons when the manual ultrafiltration plant is operating at full capacity (Arnal *et* *al.*, 2001; Arnal *et al.*, 2002). Table 2-7 gives a brief summary of the advantages and disadvantages of the existing POU membrane system.

Table 2-8 Advantages and limitations of existing POU membrane systems

Products	**Advantages**	**Disadvantages**
Ceramic membrane filter	Its gravity driven, may require a pump if large a volume is required. Removes both bacteria and viruses than most membrane units in DC	It's expensive. Can clog easily
Filter pen	Used and maintained by an individual. Can remove most of the water contaminants	Can get lost during treatment. Treats small amounts of water.
Sky hydrant	It removes all pathogens. Can treat highly turbid water (500 NTU max). Produces large water volumes.	Requires regular cleaning. Needs chemicals and trained personal for cleaning.
Life straw personal/Family	Removes both bacteria and viruses. Treats large volume of water.	Requires pre-treatment and requires regular cleaning as well.
Emergency relief membrane	Gravity driven, trained personal is not required for operation. Treat large volumes of water within a short period of time	Short operational life span. It's used for emergency relief only.
Home spring	It's a POE system used to treat both tap and surface water. Removes both bacteria and viruses. High flow rates.	Requires a pre-treatment. Carbon cartridge has to be replaced regularly. Water with high turbidity could be a challenge.

2.4.10 The Remote Rural Water Treatment System

In order to exploit the advantages offered by membranes for rural use, it was then necessary to evaluate the membrane with respect to its capabilities on filtrating different water sources as well as its disinfection capability alone and on addition of a disinfectant.

The Remote Rural water treatment System (RRWTS) is a woven fibre microfiltration (WFMF) system developed by the Department of Chemical Engineering at Durban University Technology. It is a membrane based system utilizing a robust inexpensive woven fibre membrane. It is targeted for the rural areas in developing countries to reduce the health burdens caused by the consumption of contaminated water. This system is a simple gravity driven micro-filtration membrane unit aimed at point of use water treatment for remote rural households, and for emergency relief. The membrane unit removes suspended solids and colloids and gives a permeate (product) with a turbidity of less than 1NTU ((Pillay, Graham and Dlamini, 2009). Being a microfiltration membrane, it's able to remove 95-99 percentage of microbial contaminants e.g. E .Coli, however, 100% removal has not been proven hence it does not meet the set international standard for drinking water.

According to Baker (2004) removal of contaminants by MF is by size exclusion during which cake layers are formed on the membrane surface. This process leads to a better permeate quality as the formed layer becomes a secondary filter. However, permeate flow rates (flux) also decreases progressively due to membrane fouling. A previous study by Pillay (2006) revealed that the membrane can run for about 1 month at a flowrate of 45-60 l/hr before cleaning is required. Cleaning of the membrane is done to restore the flow rate using a very simple method of brushing the modules with bottle brush and soaking in hypochlorite to sterilize the membranes before another run. Unlike the commercial membranes where specialized chemicals and processes are required for cleaning, the WFMF cleaning process is very simple and less rigorous.

The RRWTS is able to produce drinking water that meets international guidelines and national standards. In terms of turbidity, the value produced by the RRWTS is less than 1 NTU. Microfiltration membrane is able to remove most bacteria and protozoa and whatever virus that escapes the membrane will be disinfected by the chlorine disinfectant (Mecha and Pillay, 2014). Hence the system is in the category of those that offers a multiple barrier approach to drinking water quality.

The findings of Sobsey *et al.* (2008) indicated that this type of POU (RRWTS) system is not common in developing countries. There are others which combine coagulant–flocculant tablets with chemical disinfectant that are presently used in South Africa for water treatment like those developed by Procter and Gamble (Sobsey, 2002). However, these processes do not use a membrane process which is viewed as a promising alternative for modern day water treatment based on the numerous advantages it offers.

Since the woven fibre is produced locally within the developing country, it gives it an edge over the other membranes. The four major drawbacks of the existing POU membranes are therefore eliminated. As the material of construction for the RRWTS is locally available, it does not incur the cost of transportation hence the system is inexpensive to produce and can be readily replaced or repaired should the need arise.

The WFM has very high mechanical strength and lasts for a long period of time since it does not wear and tear easily. According to the findings of Mecha and Pillay (2014), the membrane can be removed from the frame and reconstructed after several years of use. Long operational life span can be obtained by the RRWTS and the chlorine can be easily replaced since it's an easily available disinfectant.

a. Advantages of the RRWTS

The major advantages of WFMF are its robustness. It can be fixed easily if damaged and finally the product quality is high and the low cost of the system makes it attractive for developing economies (Pillay, 2006).

Cleaning can be carried out mechanically or by drying combined with mechanical cleaning, as the sheets are resistant to wear and insensitive to drying. Development and characterization of these sheets is currently in progress. The findings of Mecha and Pillay, (2014) prove that the WFMF is able to remove a large percentage of the contaminants bringing the water to a level where it can be easily disinfected.

b. Limitation of the RRWTS

Based on the findings of this work, the RRWTS overcomes most of the major drawbacks of other existing POU membrane systems for rural use. However the permeate from this system does not meet drinking water guidelines in terms of bacteriological compliance with SANS 241 which requires 100 per-cent E. coliremoval. In order to achieve complete compliance to the guidelines, an additional disinfection step is therefore necessary (SANS-241, 2011). Amongst the disinfection processes that were discussed in section 2.5, chemical disinfection using chlorine was selected as an additional disinfection step for the study.

Although a separate disinfection step may be a major challenge as users may forget to follow or ignore the step which then results in the consumption of partially treated water (Mecha and Pillay, 2014). However, many rural communities are very conversant with the use of other disinfectants particularly liquid chlorine (bleach) and Alum to disinfect their water before consumption. Although during this period, users who do not understand the dosing requirement may over dose leading to DBP formation or under dose which leads to partial disinfection. Hence these two factors impacts on the health of the consumers.

The problems highlighted above then calls for identification of ways to eliminate the risk associated with users adding disinfectant without the knowledge of the right dose. This can be achieved by identifying the right disinfectant and incorporating it into the membrane. Since chlorine is a familiar disinfectant amongst rural communities for water disinfection due to its low cost and ease of access it becomes the disinfectant of choice in this study. The major challenges will be on ways to dose such small amounts without overdosing or under dosing since most of the water contaminants are already removed by the WFM. Also identify a method in which solid chlorine can be integrated with the membrane online.

2.4.11 Summary of membranes

i. Cost

Most of the membranes are made in IC and TC which means bringing them to DC will require both the costs of purchase and transportation depending on the size of the item. Operational and maintenance costs are another challenge as most of the systems require chemical cleaning and trained personnel. Another cost is that of promotional awareness and campaigns for the adoption of the new systems (Serafini, 2005). Adding this cost into the overall cost of the POU system will definitely inflate and eliminate the potential for commercial sustainability.

ii. Material of construction

The materials like the membranes and other parts of the units are designed mostly in the IC, hence may not be readily available in DC should it require reconstruction or replacement. This then means that the same unit cannot be built should the need arise. The membranes used are usually fragile and may break easily requiring some level of care by a trained person. For a membrane material to function well in developing countries particularly in the rural areas, such membranes must be robust (tough mechanical strength), easy to clean and inexpensive.

iii. Operational life span

Since most people within the rural areas of DC are low income earners, they may not afford any system that requires regular replacement. Systems that are durable and a have long operational life span will strive more in the rural areas. In cases where such systems are found in DC they are used over a short period of time and are discarded hence the sustainability of such systems becomes questionable.

iv. Lack of awareness

Finally, one of the major factors that hinder the uptake of POU membrane system is the lack of awareness especially within low-income households of developing countries. Firstly most rural dwellers do not understand the impact of consuming contaminated water on their health and also the health benefit derived from using POU systems. According to Harris (2005), making a POU filter is technically easy, however to get the awareness and promotion aspect becomes difficult. Most people in the rural areas cannot afford the filter due to the cost while others do not understand the health benefits. In cases where awareness and promotion is done the supplier will have to deal with three major factors which are the difficulty to communicate to the people on filter importance, the promotional expenses and the sustainability.

The RRWTS as a membrane based system seems to have given an insight to the use of MF based membrane in rural communities because of it robustness. Although this membrane is limited due to its inability to completely remove pathogenic organisms that are found in water, all hope is not lost as this study is identifying ways to integrate another disinfection step to this existing one in order to produce drinking water of acceptable standard. Waterguard and Bromochlor tablet have been selected as the disinfectant of choice based on the advantages they offer. Hence the following investigation will be done to identify ways by which the selected disinfectants can be incorporated into the RRWTS.

The first investigation will be to identify the right concentrations of Waterguard and sizes of Bromochlor that will inactivate *E. coli*found in different rivers used and still maintain the required residual of 0.2-0.3 mg/ℓ for POU system (SANS-241, 2011).

Chapter 3. **Materials and methods**

3.1 **Introduction**

This chapter describes briefly the equipment and procedures that were used for the disinfection of the four different feed samples. The study is composed of three stages; the first stage was disinfection of the feed water using chlorine based disinfectants namely Waterguard and Bromochlor tablets and filtration by WFMF. The second stage is the optimization of the three disinfection methods and finally evaluation of the Remote rural water treatment system (RRWTS) on disinfection. RRWTS is WFMF combined with either bromochlor or waterguard disinfection. Disinfection in the study refers to either the physical removal of *E. coli* or inactivation by chemical disinfection.

Figure 3-1 provides an overall experimental frame work for three major steps that were involved in the disinfection process during this study. Different surface waters with varying characteristics were disinfected by manual addition of waterguard (offline process) without microfiltration. WFMF was also used to disinfect the same water by immersing the membranes completely into the feed water. It was a gravity driven process and was controlled by the feed head during the disinfection process. The overall frame work finally shows the online disinfection process (continuous flow) using Bromochlor tablets. Here the feed water flows over the tablets at varying flow rates without microfiltration. *E. coli* counts and turbidity were measured before and after disinfection for each sample. Chlorine residual was measured only for waterguard and Bromochlor tablet after disinfection.

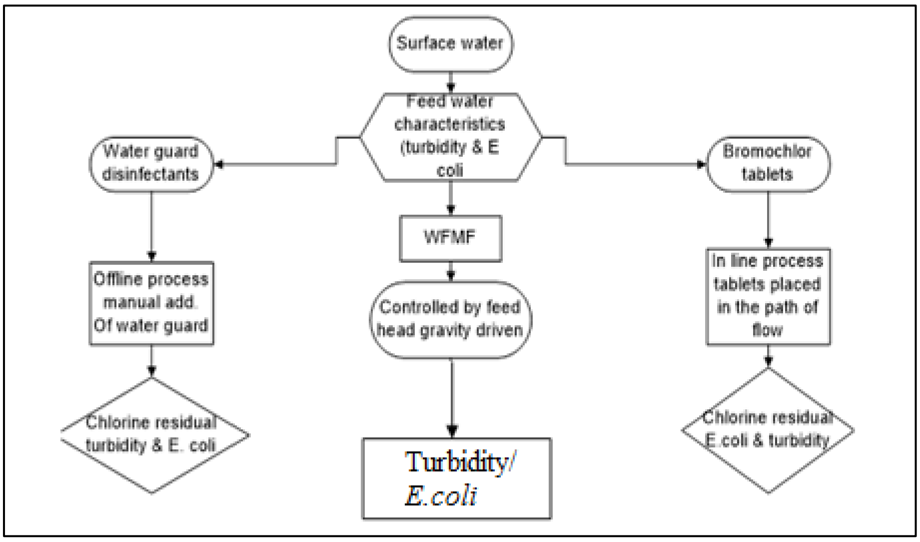

Figure 3-1 Overall experimental framework

3.2 **Materials and Analytical equipment**

3.2.1 Feed samples

Samples used in this study were selected in order to represent a wide range of scenarios, namely difficult, medium and fairly easy river to treat. Difficult water means water with high *E. coli* content, high turbidity and high concentration of other organic matters; medium water could have one of the contaminant as high concentrations while the others are low; and easy river had a low concentration of everything. Sampling was during the early hours of day from the middle part of the rivers.

Difficult River – Duzi River

Medium River – Umbilo River

Easy River - Town Bush River

3.2.2 River water characteristics

Town bush River: This is a small river that runs around the suburb of Pietermaritzburg (Formal settlement) and as expected this river is characterized by low turbidity and *E. coli* count within the range of 800 ± 300 *E. coli* count/100 mℓ and turbidity of 5 to 10 NTU. The test samples were taken from the bottom part of the river

Duzi River: This is one of the biggest rivers within the Pietermaritzburg area, it flows along different informal settlements where possibly domestic and biological waste end up contaminating this river. It is also used as a source for recreational activities within the area. During this study water quality tests showed that the river had an average turbidity of 150 NTU and *E. coli* counts averaged at 5000 ± 1500.

Umbilo River: It is found around the South coast of Durban. It runs along few industrial and domestic areas. This river had an average *E. coli* of 44,000 ± 2000 *E. coli* counts/100 mℓ and a turbidity of 30-40 NTU.

Table 3-1 Summary of characteristics of feed water sources

Feed water source	Turbidity	*E. coli* count/100 mℓ
Duzi River	100 ± 50	5000 ± 1500
Umbilo River	30 ± 10	44000 ± 2000
Town bush river	5 ± 5	800 ± 400
Synthetic feed	1 ± 0.8	36200 ± 1000

3.2.3 Preparation of synthetic feed

***E. coli* preparation**

E. coli was prepared in the microbiological laboratory in the Department of Biotechnology at Durban University of Technology. Agar nutrient was obtained from Prestige Lab Supplies cc (PLS).

Detailed procedure is shown below on how pure culture of *E. coli* was sub- cultured on nutrient agar slants.

I. Nutrient agar was dissolved in sterilized water using 3.1 g agar in 100 mℓ of water and autoclaved at 121ºC for 30 minutes in order to sterilize the media.

II. The media was cooled under a laminar flow to 40 ˚C and then poured into sterile glass bottles with each kept in a slanting position and allowed to solidify under laminar flow.

III. Pure culture of fresh *E. coli* was streaked on the slants and refrigerated at 4˚C. The *E. coli* was then used for subsequent experiments.

Preparation of pure culture

The procedure below was used to prepare pure *E. coli* in deionised water before spiking into the water.

I. Nutrient agar solution was sterilized by autoclaving and cooled to 50˚C.

II. 15 mℓ of the agar solution was poured into a Petri-dish under sterile conditions and allowed to solidify at room temperature.

III. A loop of culture was inoculated by streaking under a bunsen burner flame into the solidified nutrient agar in a Petri-dish. This was repeated for all the dishes.

IV. Before using the *E. coli* the plates were incubated for 24 hours at 35˚C before introducing to the water as synthetic feed.

Synthetic feed used in this study was prepared in the laboratory by inoculating 2 mℓ of *E. coli* that was prepared following the steps above into 200 ℓ of tap water. Subsequent concentration was prepared by using 1 and 3 mℓ in 200 ℓ of tap water. The tap water was exposed to direct sunlight a day before the injection of *E. coli* and residual chlorine was measured to ensure that no chlorine was present that could kill the *E .coli*. The reason for the synthetic feed was to determine two important aspects of this study which are;

a. To determine the effect of turbidity on WFMF process.

b. To determine disinfection efficiency in the absence of turbidity.

3.2.4 Selection of the indicator organism

For the ease of analysis certain organisms are used as indicators in determining the pathogenic quality of water. Hence microbial indicators are said to be those microorganisms that are not pathogenic themselves, but indicate the presence of potential threats to the microbiological quality of water. Examples of these organisms include, total coli forms, faecal coli forms and *E. coli.* According to Health (2005) and Cebral (2010), for an organism to be a good indicator of faecal pollution, it must fulfil the following criteria.

- The indicator organism should be present whenever a faecal pathogen is present.
- It should be relatively easy and quick to detect in environmental waters
- It should be found in faeces in large numbers so that the organisms can be easily detected.
- It should have high survival rate at least as long as waterborne pathogens of faecal origin.
- It should not be pathogenic to human beings but as sensitive to disinfection as the pathogen.

The findings of previous studies have shown that no indicator organism has all of these criteria, however the fact remains that the presence of indicators of faecal contamination implies an increased risk of water borne diseases. Most commonly used bacterial indicator organism for pathogenic contamination is *E. coli* which is used in quantifying the quality of feed waters in this study. WHO recommendation for *E. coli* in potable water is zero per 100 mℓ (WHO 2011b).

3.2.1 Criteria of selection of possible disinfectants

The selected disinfectant for integration should comply with drinking water disinfection standards and also be widely acceptable, easily assessable and inexpensive. It should be either in solid or liquid form for ease of storage as gaseous disinfectant might be difficult and risky to store and handle by untrained users. The disinfectant should be easy to integrate with other disinfection methods when required.

Hence liquid chlorine in the form of hypochlorite and chlorine tablets was selected for this study because of the above criteria.

3.2.2 Methods used to quantify microbes

Quantal or enumerative methods are ways in which bacteria are normally assayed (WHO, 2011). Quantal assays is achieved by making serial dilutions of a sample, inoculating the samples and estimating the bacterial density as a most probable number (MPN) per unit sample number. While enumerative methods are based on counting the bacteria colonies on a solid medium such as an agar medium, example is the standard plate count.

Most probable number method

This technique estimates microbial population sizes in a liquid substrate after dilution and incubation of the samples. The technique relies on presence or absence test. This tells you whether the test is negative or positive following inoculation of a suitable test medium (usually with a reagent) using tubes or micro well plates. Microbes are identified by observing the colour of the wells. In this method, the wells enumerated and the microbial population is read from statistical tables.

The collilert 18 method is an example of the MPN methods. The well plates hold the sample during incubation and detect both total coli forms and *E. coli*in water. The samples usually turns yellow when total coli forms metabolize Collilert 18's nutrient indicator, while it fluoresces for the presence of E. coliunder UV light to give a greenish blue colour. Below is the procedure for the Collilert 18 test.

i. Dilution of the sample containing the test organism is done by using sterile water to the required dilution level.

ii. The content of one sachet of the Collilert reagent is added to 100 mℓ of the sample in the sterile bottle.

iii. The bottle cap is replaced and the reagent is allowed to dissolve and mixed well.

iv. The sample is poured into a test bag known as a Quanti- tray.

v. The test bag is sealed using a Quanti- Tray sealer.

vi. The test bag is incubated at 37˚C for 18 hours.

vii. The test bag is bag is placed under a 6 watt, 365 nm UV light within 5 inches of the sample in a dark environment in order to count the wells containing *E .coli.*

viii. The amount of *E. coli* present is read from a standard statistical MPN table.

ix. To obtain the actual number of *E. coli* present in the sample, the number obtained from the table is multiplied by the dilution factor.

The standard plate count method is described in appendix A. In this study, the MPN method was selected in both laboratories where the test was done to quantify the concentration of the indicator organism (*E .coli*) in the feed and permeate samples. This method was used because it's more accurate in quantifying the numbers of microbes and also very convenient to use. It eliminates the errors that may be associated with the identification of *E. coli* colonies and the actual number of organism present in a sample.

3.2.1 Criteria of selection of possible disinfectants

The selected disinfectant for integration should comply with drinking water disinfection standards and also be widely acceptable, easily assessable and inexpensive. It should be either in solid or liquid form for ease of storage as gaseous disinfectant might be difficult and risky to store and handle by untrained users. The disinfectant should be easy to integrate with other disinfection methods when required.

Hence liquid chlorine in the form of hypochlorite and chlorine tablets was selected for this study because of the above criteria.

3.2.2 Determination of chlorine demand

The chlorine dose required for disinfection differs for different water sources. To determine the exact amount of chlorine it is then necessary to first find the chlorine demand of that particular water source. According to Momba, Obi and Thompson (2008) the following steps are to be followed;

Firstly divide a sample into six 100 ml sub-samples and put each in a different vessel.

Into these vessels add different amounts of 100 ppm chlorine. For instance, one could add increasing steps of 0.5 mℓ with this amount being added to the first, 1.0 mℓ to the second progressively. Proper stirring should be done after adding chlorine to the samples.

The samples should be left in a cool place out of direct sunlight for the required contact time.

Take a sample of water from the vessel after the contact time has expired and test for residual chlorine. If there is no presence of chlorine then keep testing the different vessels until residual chlorine is detected. The vessel in which the residual was detected indicates that the chlorine demand has been met. If for instance, it was first detected in the vessel to which 2 .0 mℓ of the solution was added but not found in the previous vessel to which 1.5 mℓ was added, then 1.5 mℓ is the least chlorine demand but less than 2 mg/ℓ.

Water sources will not always have a constant chlorine demand; it varies from one water source to another. For surface water the chlorine demand will depend on the recent pattern of rainfall run-off contributing to the source. Also the amount and type of materials that are directly deposited or washed into such surface water will affect its chlorine demand.

In instances where water to be treated is highly turbid, two things are bound to happen, 1) a larger amount of the chlorine will be wasted due to chemical reaction with the suspended materials particularly if there are organic substances and 2) most of the micro-organism will not be fully exposed to the germicidal activity of the chlorine because they are shielded by the suspended material (Nicholas 2002; Momba, Obi and Thompson, 2008). To achieve complete disinfection in this case, some form of prior treatment such as filtration or sedimentation is required before chlorination of unprotected surface water (Schoenen, 2002; Momba, Obi and Thompson, 2008).

3.2.3 Determination of disinfection efficiency

The efficiency removal of contaminants from the WFM was determined using equation 2-1:

$R (\%) = 100(1-C_p/C_f)$ --- (equation 2-1)

While disinfection efficiency which is expressed as the log removal value was determined by:

$LRV = \log_{10} C_f/C_p$ -- (equation 2-7)

3.2.4 Disinfectant specifications

I. Waterguard

1% sodium hypochlorite was used as the disinfectant of choice. The optimum waterguard concentration for disinfection was obtained by varying the dose of waterguard during disinfection. The doses used were 7.26, 14.52, 21.78, 29.04, 36.3 and 50.82 mg/ℓ. The effects of disinfection kinetics like contact time, and agitation on disinfection rate were also investigated.

II. Bromochlor

Bromochlor tablets were also used for the disinfection stage; the tablets were optimised by varying the tablet size and flowrate through the RRWTS system. The mass for the tablets used are as follows, 0.1, 0.2, 03, 0.4, 0.5, 0.6, 0.7 and 0.8 g.

III. Sodium Hypochlorite

Sodium hypochlorite was used as both a cleaning and sterilising chemical for the WFM. 25 ml of sodium hypochlorite was poured into 40 ℓ of tap water for the cleaning and sterilisation of the WFM.

3.3 Analytical Equipment

The work done in this study was to determine the disinfection abilities for waterguard, bromochlor and WFMF. Disinfection was measured by the ability of the disinfectants and WFMF to remove *E. coli* and turbidity. The parameters measured were turbidity, *E. coli* and residual chlorine. The equipments used are shown in below. The procedures for determining *E .coli*, turbidity and chlorine residual are described in appendix A and table 3-2 shows the equipment and methods used for the sample analysis.

Table 3-2 Equipment and methods used for analysis

Parameter	**Instrument used**	**Method (See appendix for method)**
E. coli and coliforms	Quanty Index	IDEXX Collilert reagent method.
Turbidity	HACH 2100N turbidity meter	Method 180
Temperature	HACH sensION	
pH	HACH sensION	Standard method
Total and free chlorine	HACH new 5870000 Pocket Colorimeter	Method 1111

3.3.1 Description of the RRWTS

The WFMF unit consists of a membrane pack of flat sheets (modules) made from woven polyester material. The effective pore size is 0.8-3 microns as shown in Figure 3-2. The construction of the module is by fabricating a rectangular PVC support frame with a permeate outlet incorporated on the inside. The WFMF membrane sheet is then glued to both sides of the frame and a mesh spacer is inserted between the sheets to enhance permeate flow to the outlet. A microscopic re-presentation of the woven fibre and a module is shown in Figure 3-2 and 3-3 below.

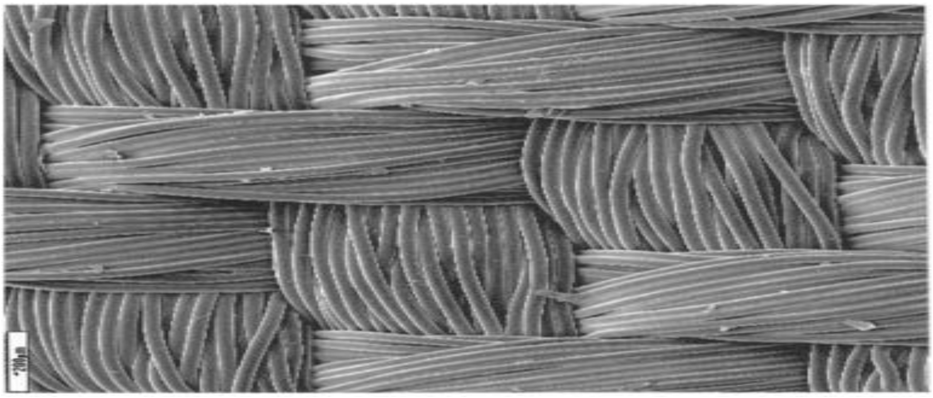

Figure 3-2 A microscopic representation of the woven fibre microfiltration membrane (16xmg)

Figure 3-3 Flat sheet WFMF module (Pillay, Graham and Dlamini, 2009)

The membrane modules have holes drilled through the corners. The modules are assembled together by inserting threaded rods to form a membrane pack as shown in Figure 3-4 below. The membrane pack contains 15 membranes joined together to the manifold, while the manifold combines permeate of each module (Figure 3-5) to the permeate outlet.

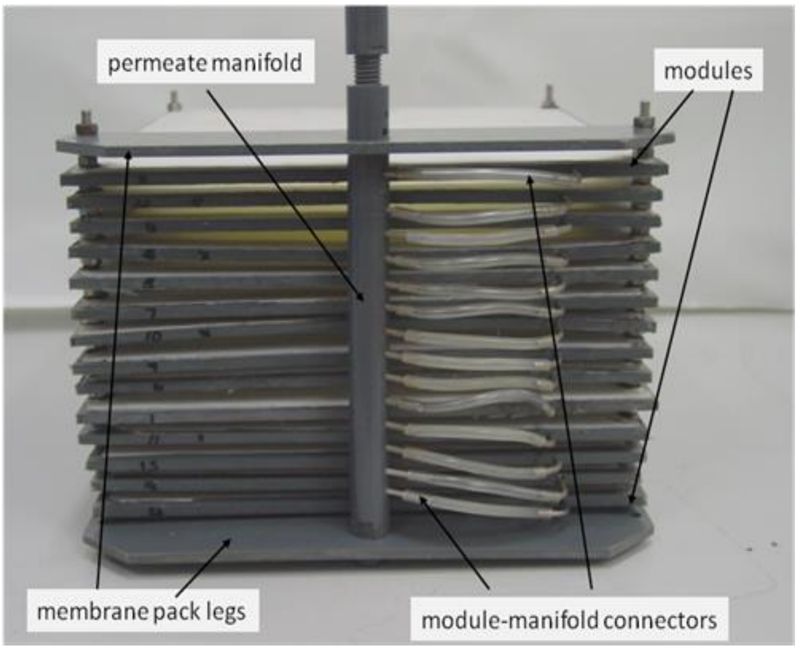

Figure 3-4 Bottom view of the RRWTS pack

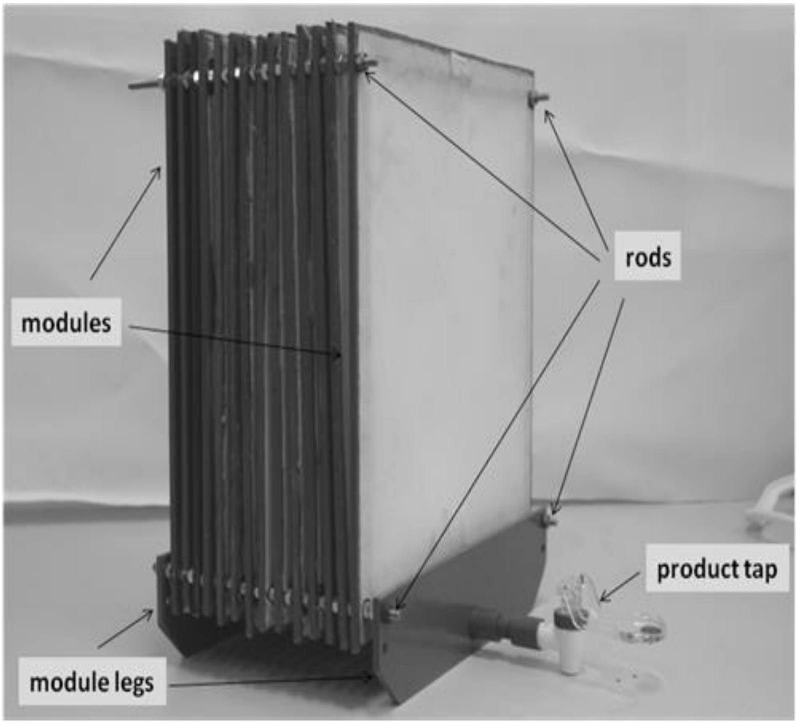

Figure 3-5 Side view of the RRWTS pack

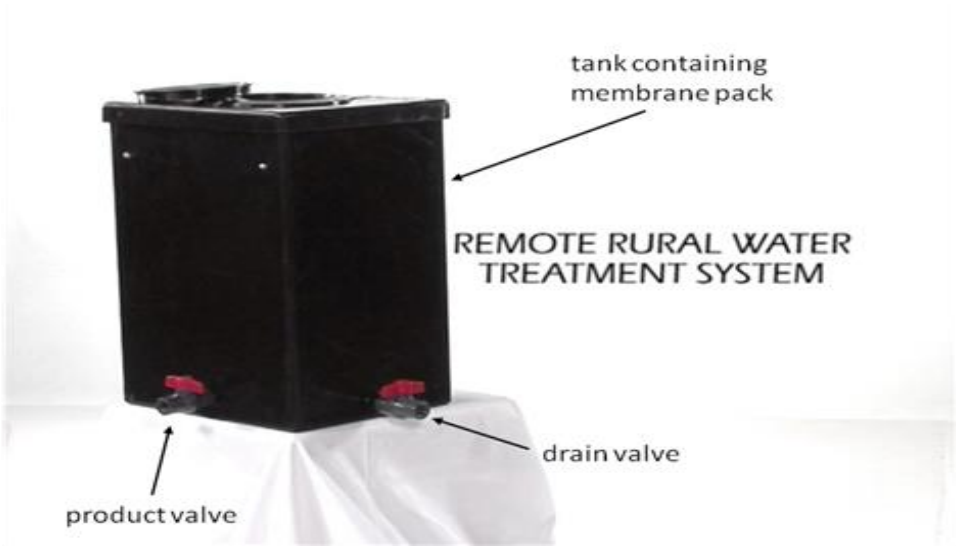

Figure 3-6 RRWTS showing the feed tank, drain valve, and permeate outlet valve when the system is assembled

3.3.2 Operation and Performance of the RRWTS

The studies carried out previously by Pillay, Graham and Dlamini (2009) shows that the RRWTS system is suitable for treating raw water of different quality in rural areas. Two major aspects were considered in terms of the performance of this system which are the permeate quality and product flow rate.

Permeate quality

The quality of permeate produced by the RRWTS during field trials was generally less than 1 NTU, for feed water ranging from 20 NTU to 300 NTU. Initial feed turbidity did not affect the permeate turbidity. Bacteriological removal by membrane alone was significantly high. About 80-99 % *E. coli* removal was obtained.

This brings the water to a level where it can be easily disinfected by an additional disinfection step to bring the water to the acceptable standards (Pillay and Kalu, 2010). Figure 3-7 gives a typical illustration of the feed and permeate after treatment with the RRWTS.

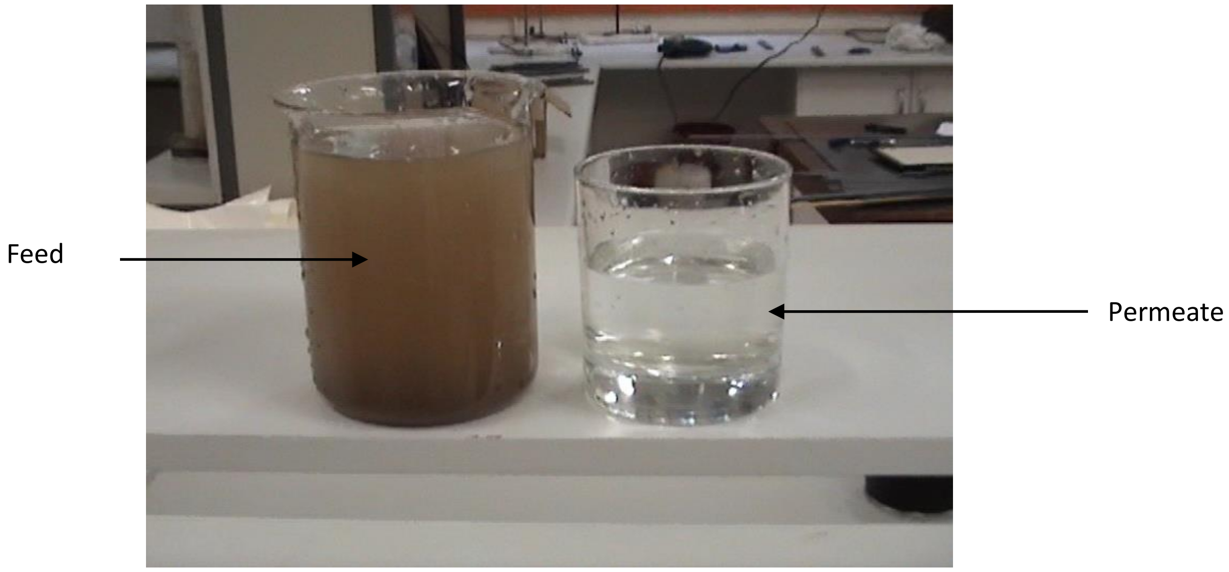

Figure 3-7 Initial feed and permeate sample after treatment with WFM

i. Product flow rate

Each module is 0.18 m^2 in area with a unit consisting of 15 modules. It removes suspended solids and colloids from raw water. The system is batch fed, 40 ℓ in capacity and has a permeate flow rate of 60-30 ℓ/h depending on the quality of the feed. The flowrate of the RRWTS is dependent on the cleaning of the system; flux is easily recovered immediately after cleaning and drops gradually as the filtration progresses due to membrane fouling.

ii. Cleaning of the RRWTS

Cleaning is an essential part of the RRWTS as membrane flux is immediately restored after every cleaning. Studies carried out by Pillay, Graham and Dlamini (2009) indicated that the RRWTS can operate effectively for a period of one month before requiring cleaning although this depends on the feed quality. The system can continue to run but at very low flowrate. During cleaning the membranes were dismantled from the pack of 15, soaked in 20 ℓ water, and then brushed with a scrubbing brush. Dish washing sunlight soup was used to assist in the removal of dirt from the membrane surface. The membranes manifold and the tanks were rinsed with tap water several times to remove all traces of dirt. Cleaning of membranes could also be done while the membrane was in place without dismantling as shown in Figure 3-8 below. Another option was to allow the membrane module to dry up and the fouling matter to fall off the membrane surface. In this study the, dismantling method was used because it proved to be more adequate as it exposes the entire membrane surface for cleaning and soaking in 3% sodium hypochlorite for 2-3 hours to inactivate any *E. coli* that may have clogged inside the membrane matrix.

Figure 3-8 Cleaning of the RRWTS system using brush

3.4 **Experimental procedures**

The experiments for this study were carried out in two major laboratories: the microbiological laboratory, in Umgeni water (Pietermaritzburg) and the microbiological laboratory at Durban University of Technology.

Materials and apparatus used in the experiments were autoclaved and sterilized. The entire procedures and tests were under sterilized conditions.

3.4.1 Procedure for Waterguard disinfection without WFM

Automatic or online dosing for waterguard disinfection was difficult because of the quantities used. Based on this, the addition of water guard was done manually by adding a controlled amount of waterguard measured by volume. The added volume was then converted to concentration.

$$C = M/V \text{ ....3-1}$$

Where,

C is concentration in milligram per litre (mg/ℓ)

M is mass in milligram (mg)

V is volume in litre (ℓ)

The experimental set up for Waterguard disinfection in Figure 3-8 consists of three major parts; the feed water tank where different feed samples were poured into the control valve and product tank which contains different concentrations of Waterguard.

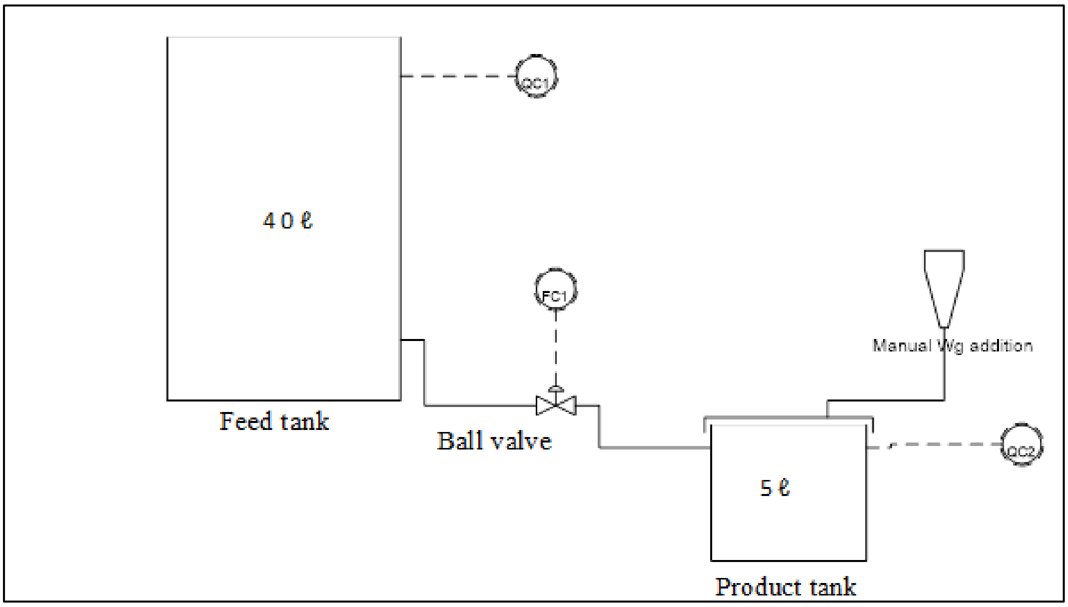

Figure 3-9 Schematic diagram of waterguard disinfection for different water sources

Where;

QC1= quality check of the raw feed water

FC1= flow control into the product tank

QC2= quality check of the product water

The following steps were followed for disinfection using Waterguard

- ❖ The raw water tank was filled with one of the feed waters and samples were taken for *E. coli* count, turbidity and chlorine residual tests.

- ❖ The required concentration (e.g. 7.2 mg/ℓ) amount of Waterguard was put into the product water tank.

- ❖ Through a hand valve FC1, the flow of raw water into the product tank was controlled to be between 1 ℓ/h and 45 ℓ/h. Addition of Waterguard prior to opening of FC1 was to facilitate inherent mixing required for uniform distribution of the disinfectant.

- ❖ Once the product tank was filled to the 5ℓ mark, it was allowed to stand, and then samples were taken and tested for *E. coli* after 5, 10, 20 and 30 minutes intervals.

- ❖ Another product tank was filled to 5 ℓ mark, the tank was agitated manually for 15 seconds; samples were then taken and tested for *E .coli*.

- ❖ The test was repeated for different concentrations.

- ❖ The entire test procedure was repeated for different feed water samples.

3.4.2 Procedure for Bromochlor tablets disinfection without WFM

In this study, the Bromochlor tablet was used as an online disinfectant. The experimental set up consists of four major parts; the feed water tank for different feeds, control valve, bromochlor tablet holder, and product tank. Here the tablet was placed in the flow path of raw water into the product tank thereby allowing contact between the tablet and the polluted water.

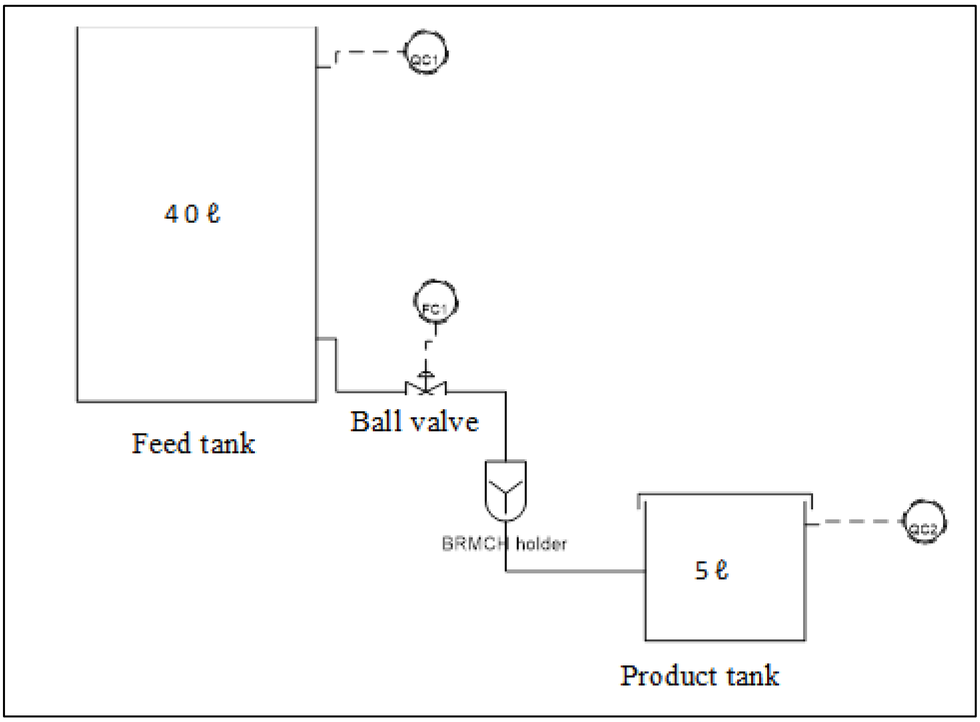

Figure 3-10 Schematic diagram of Bromochlor disinfection for different water sources

Where;

QC1= quality checks of the raw feed water

FC= flow control into the product tank

QC2= quality check in the product tank.

The following steps were followed.

- ❖ The feed water tank was filled with one of the water samples after testing for *E. coli* and turbidity.

- ❖ Through FC1 as shown in Figure 3-10, the flow to the product tank was controlled. As the water passes over the tablet, contact was made between the bromochlor tablet and water being disinfected. The disinfected water was collected in the product tank.

- ❖ From the product tank samples were taken and tested for *E. coli* and chlorine residual, for bromochlor tablet, it was not necessary to wait for the product tank to be completely full before tests were done. This was because the sample was already having direct contact with the feed before it is collected in the container.

- ❖ The experiment was repeated for all the other feed samples and different tablet sizes.

- ❖ Through FC1 the flow rate to the product tank was varied as 1, 5, 20, 30 and 45 l/h for different tablet sizes.

3.4.3 Procedure for Microfiltration without disinfectant

The effect of microfiltration on *E. coli* and turbidity removal from the different feed sources was investigated using the set up shown in Figure 3-10. The rig here consists of 15 flat sheet membrane modules that have been assembled using WFM.

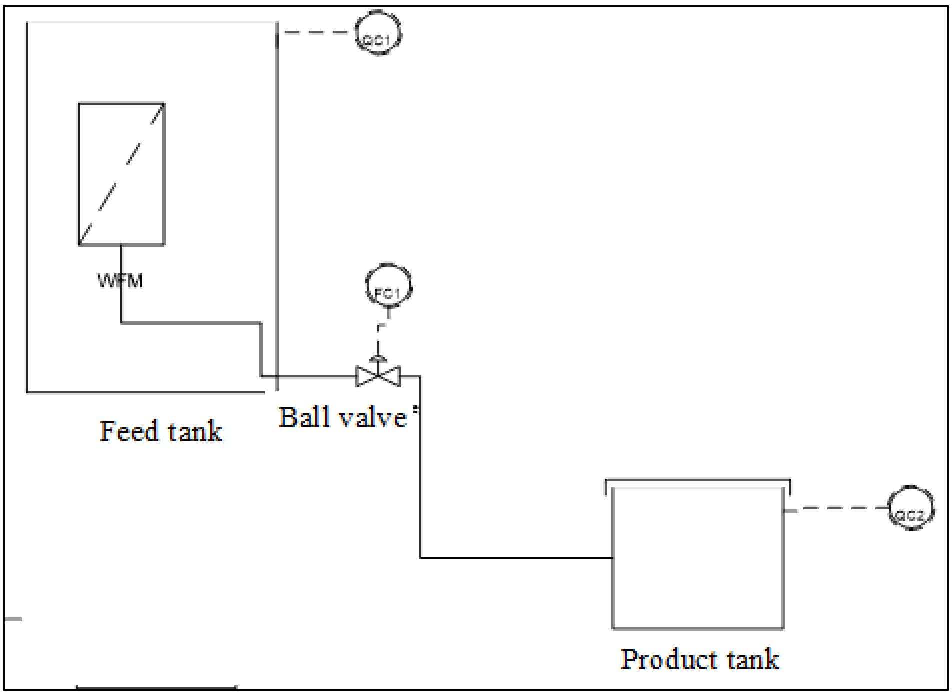

Figure 3-11 Schematic diagram for WFMF system

Where;

QC1= quality checks of the raw feed water

FC= flow control into the permeate tank

QC2= quality check of the permeate.

- ❖ WFMF permeate line was connected to feed tank outlet.
- ❖ Feed tank was filled with feed water to a level above the membrane
- ❖ FC valve was opened to allow permeate to flow.

- Once stable flow without air bubbles was achieved, a sample was taken for turbidity testing. After the above test was done, samples were taken for *E. coli* tests at different time intervals.

- The above procedure was repeated for the other feed samples.

3.4.4 WFMF Optimization

Optimization of the WFMF was done by coating the membrane surface with 2 micron lime. A leak test was carried out on the membranes. The test is to ensure that feed samples have not come into contact with permeates. If proper segregation is achieved turbidity should not be more than 1 NTU which indicates there are no leaks on the membranes. After which disinfection was carried out.

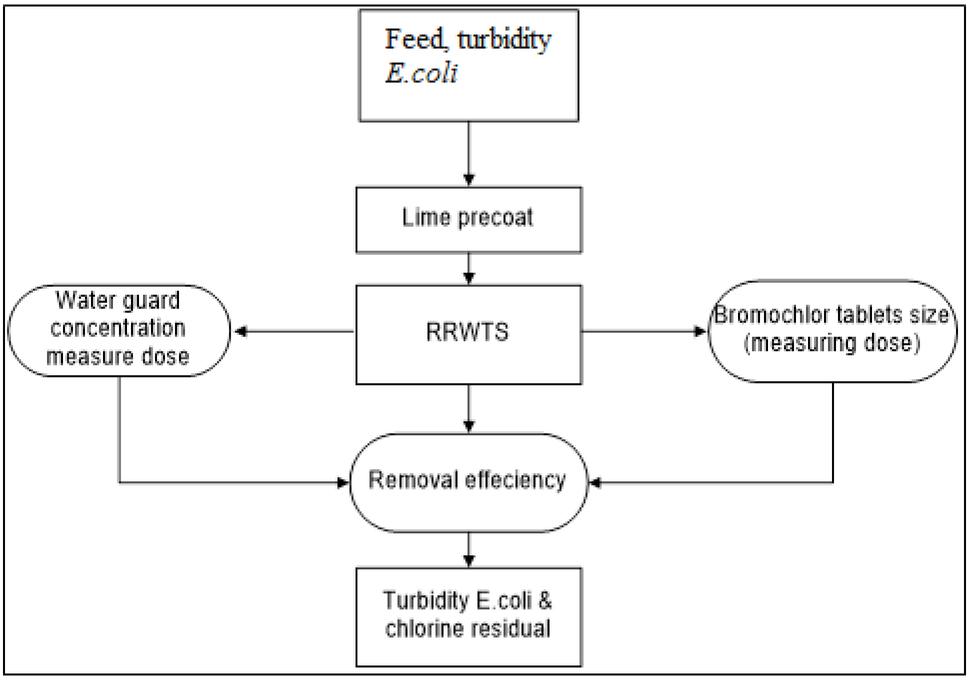

Figure 3-12 RRWTS test layout

- WFMF was connected to feed tank outlet.

- 2 g/ℓ of 2 microns lime was poured into the feed tank containing water. Lime was chosen because it has been used previously during the development of MFMF for leak checks.

- FC1 was opened to allow permeate to flow.

- Turbidity of permeate was checked after 5 minutes of operation. Obtained result was less than 1 NTU which indicates proper coating and absence of leaks.

- The experiment was allowed to run for 30 minutes for further coating

- Feed tank was drained of lime before operating with different feed water.

3.4.5 Procedure for RRWTS

RRWTS is a combination of WFMF with one of the disinfectants; the purpose of the experiment is to study the effect of WFMF while using the required disinfectant.

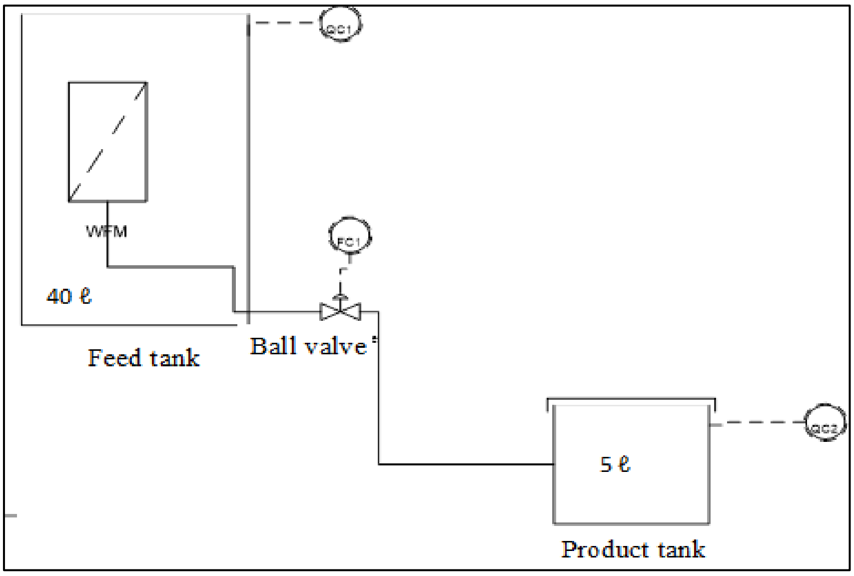

Figure 3-13 Schematic diagram for the remote rural water treatment system (RRWTS) and waterguard

Where;

QC1= quality checks of the raw feed water

FC1= flow control into the permeate tank

QC2= quality check 0f the permeate

3.4.6 Procedure for Waterguard with WFM

Repeat the procedure for WFMF under Figure 3-12

- Required amount of Waterguard was put into the permeate tank
- Through a hand valve FC1, the flow of raw water into the permeate tank was controlled to be between 1 ℓ/h and 45 ℓ/h.
- Once the product tank was filled to 5 ℓ mark, samples were taken and tested for *E. coli* and chlorine residual.
- The test was repeated for the incremental amounts of Waterguard.
- The entire test procedure was repeated for different feed samples with different *E. coli* levels and other contaminants

3.4.7 Procedure for Bromochlor tablets disinfection with WFM

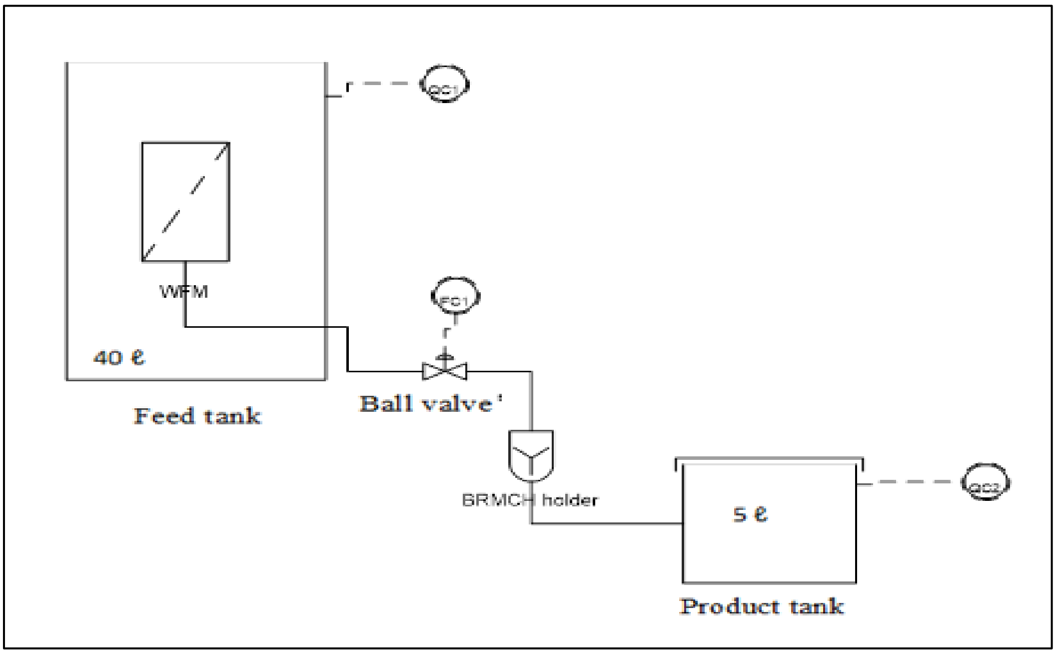

Figure 3-14 Schematic diagram on RRWTS with Bromochlor tablet

Where;

QC1= quality checks of the raw feed water

FC= flow control into the permeate tank

QC2= quality check of the permeate

The same procedure that was used for WFMF in Figure 3-10 and bromochlor disinfection in Figure 3-9 was combined to achieve disinfection by RRWTS using bromochlor. The experiment was repeated for all the other samples and different tablet sizes.

Chapter 4. **Results and Discussion**

4.1 **Introduction**

This chapter presents the results and findings obtained from the experiments of both Woven Fibre Microfiltration (WFMF) and the two selected disinfectants Waterguard (WG) and Bromochlor tablet operating with four water sources, Duzi River water, Town bush River water, Umbilo River water and synthetic feed water. The chapter is divided into four major parts; the first part is on the determination of residual chlorine on both disinfectants for all the water sources, followed by the evaluation of WFMF performance and its optimization. The third part is on the determination of the most optimum dose that will yield effective disinfection on all the water tested and the effect of disinfection kinetics is also evaluated. The results of combining the WFMF system with chemical disinfectants (RRWTS) are shown in the fourth part of this work.

4.2 **Effect of feed water quality on chemical disinfection**

The quality of feed to be disinfected plays a great role in the efficiency of disinfection. The major parameters considered are *E. coli* count and turbidity. Chlorine residual also known as free chlorine is the available chlorine after disinfection. This section investigates chlorine demand for the different rivers with varying characteristics with respect to *E. coli* and turbidity content. The stipulated value for chlorine residual according to SANS 241 is 0.2 mg/ℓ for point of use systems (SANS-241, 2011).

4.2.1 Feed water

Table 4-1 shows the characteristics of the different water sources investigated. Duzi River had the highest turbidity followed by Umbilo and then Town Bush River. In terms of *E. coli* count, Umbilo River had the highest *E. coli* count besides the synthetic feed. However, the ease of disinfection for all of these Rivers was more difficult on Duzi Rivers.

Table 3-3 Summary of feed characteristics

Feed	***E. colic*** **ounts/100 mℓ**	**Turbidity (NTU)**	**Residual Chlorine (mg/ℓ)**	**WHO Standards** **(0, <1 and 0.2 mg/ℓ)**
Duzi	2600±800	140 ± 60	-	
Town Bush	800±400	10± 4	-	
Umbilo	44500±2000	40±10	-	
Synthetic feed	2000± 1000	2±1	-	

4.2.2 Determination of chlorine residual using Waterguard disinfectant

Figure 4-1 shows the effect of waterguard on chlorine residual for various water sources. The results show an increase in residual chlorine with the increase of waterguard concentration as expected.

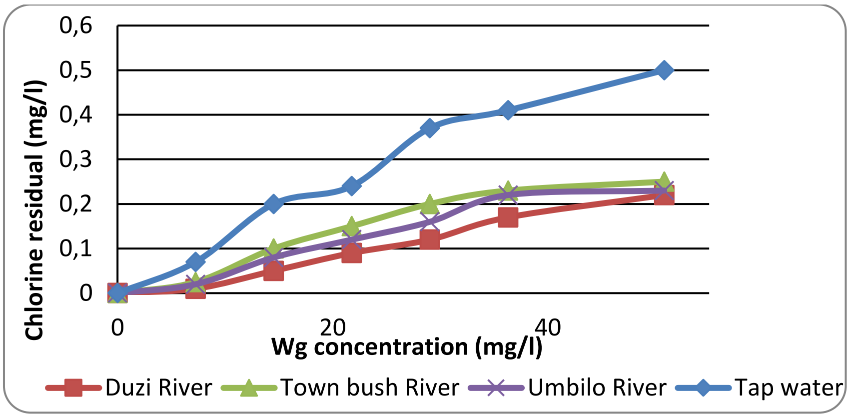

Figure 3-15 Comparison of WG concentration on chlorine residual for different rivers of varying feed quality (tap water is used as the standard for comparison).

Tap water and Town bush River, shows acceptable levels of residual chlorine with a small waterguard concentration. Although the same amount of disinfectant was used at the dosing point for the entire water source, Duzi and Umbilo River did not produce acceptable levels of chlorine residuals. This indicates that the chlorine demand for Duzi and Umbilo Rivers were higher which then resulted in low chlorine residual in the system. The required chlorine residual was only obtainable for these two rivers after the concentration of waterguard was increased above the limit used for tap water and Town Bush River.

The obtained chorine residual from the different Rivers was compared to the tap water residual which is used as a base case for this study. Hence the demand for waterguard concentration was according to the quality of each water source. Residual chlorine was more for waters with low contamination loads. In cases where contamination load is low, the added chlorine becomes available as free chlorine due to low chlorine demand. This was seen to be true with tap water and slightly with Town Bush River.

Residual chlorine is meant to protect against re-contamination of the water that is already disinfected. It is therefore expected that by increasing the Waterguard concentration (chlorine base disinfectant) the amount of chlorine residual would also increase. According to Nicholas (2002), Schoenen (2002) and Momba, Obi and Thompson (2008) pollutants that uses up much chlorine are metals such as iron and manganese, organic matter, pathogens (i.e. *E. coli* and other microorganisms) and turbidity. These metals and organic matter were suspected to be present in Duzi River and Umbilo River which explains the high chlorine demand for these rivers compared to the others. The phenomenon of how the chlorine gets used up in highly polluted water and how agitation plays a part in the loss of chlorine is explained in detail in 4.3.6.

The findings here signifies that water with a high contamination level will have higher chlorine demand (e.g. Waterguard) than less contaminated water to yield the required chlorine residual as seen with Duzi and Umbilo River. Effectiveness of disinfection depends greatly on the feed quality as seen from this finding. To achieve a high or complete disinfection rate and meet the standard for chlorine residual, the feed quality must be free of other contaminants. A small disinfectant concentration can yield the required chlorine residual on feed samples with little or no contamination like in the case of tap water and Town Bush River.

4.2.3 Determination of chlorine residual using Bromochlor tablet

Figure 4-2 shows the effect of increasing bromochlor amount on residual chlorine for different rivers whilst keeping flow rate constant at 20 ℓ/h. Figure 4-3 shows the effect of varying flow rate on chlorine residual while keeping a constant tablet size.

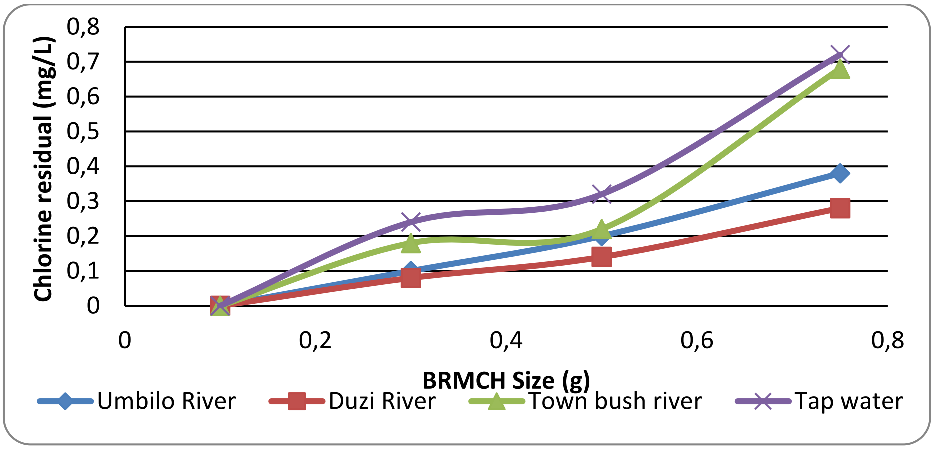

Figure 3-16 Effect of increased BRMCH size on residual chlorine

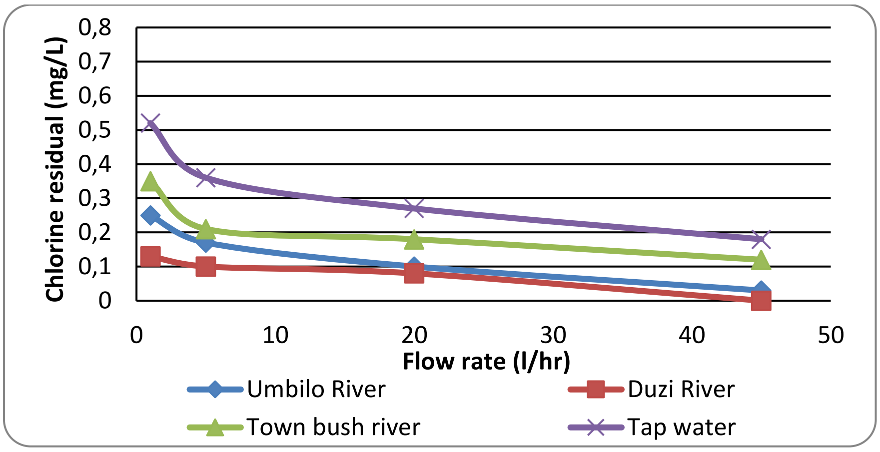

Figure 3-17 Effect of increasing flowrate on residual chlorine

Bromochlor tablet is a chlorine based disinfectant but in a solid form as opposed to the liquid based chlorine (Waterguard). The same effect seen with waterguard was seen with the Bromochlor tablet. The difference with the tablet was that the size was varied and not the concentration.

The results show a consistent decline in chlorine residual for higher flow shown in Figure 4-3. Again, Duzi and Umbilo were the worst in retaining residual chlorine. The reason for high residual chlorine at low flow rates is that, at low flow rates most of the water comes into contact with the tablet hence more chlorine is released. Also contact time is increased at low flow rates which results in higher chlorine residual.

At high flow rates such as 45 l/hr most of the water doesn't have contact with the tablet resulting in a reduction in residence time, hence little chorine residual is obtained.

Disinfection using the bromochlor tablets is achieved when contaminated water comes into contact with the tablets. A release of chlorine then occurs. Hence increasing the tablet size leads to an increase in the surface area available for contact. However according to manufactures of the Bromochlor tablet, the tablet only releases chlorine if the water that comes into contact with it is contaminated with microorganisms. This was found not to be true for this study because lots of chlorine was released when the tablet came into contact with tap water and Town Bush River water, (a river which had little microorganisms). The same observation made with waterguard was seen with the Bromochlor tablet; more chlorine residual was obtained for tap water and Town Bush River, while less chlorine residual was obtained for Duzi River because of the presence of high *E. coli* and other contaminants in the form of turbidity.

4.3 **Performance of WFMF without chemical disinfectant**

This section looks at disinfection abilities of the WFMF in the removal of *E. coli* and turbidity without chemical disinfection. The ability of the WFMF to remove contaminants with time based on quality of the different feeds was investigated.

4.3.1 Performance of WFMF on E. coliremoval

Figure 4-4 shows *E. coli* removal by WFMF over a period of 120 minutes for the rivers under this study which can also be seen in Table 4-2 at different phases of rejection. Figure 4-5 shows the effect of increase in operational time on flowrate.

Table 3-4 WFMF average percentage E. colirejection at three filtration phases

Water source	**Initial feed *E.coli* count**	**Rejection during pore clogging (%)**	**Rejection during transition phase (%)**	**Rejection at steady state phase (%)**
Duzi river	5402	98.1	99.3	99.6
Town bush river	448	75.2	89.8	98.8
Umbilo river	44500	99.0	99.7	99.8
Synthetic feed	35424	94.8	97.1	97.4

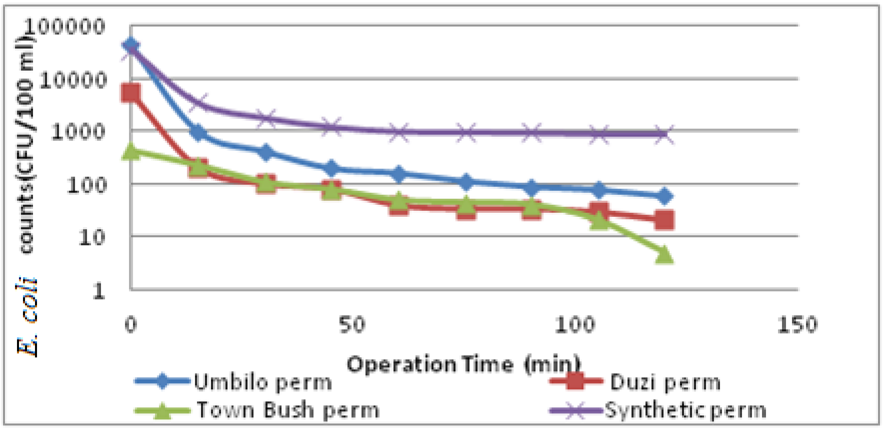

Figure 3-18 Performance of WFMF membranes in disinfection

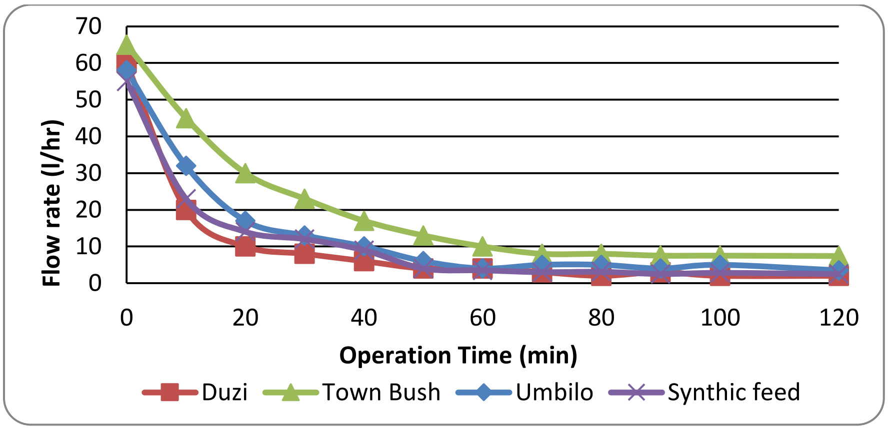

Figure 3-19 Flux time graph for WFMF

E. coli rejection was achieved for all the rivers but at different levels. The overall rejection for the period of experimentation for each water sample was 99.8%, 99.6%, 98.8% and 97.4% for Umbilo, Duzi, Town bush and synthetic feed water respectively. From Figure 4-4, the rejection profile starts off very strong in the first 20 minutes for all the rivers except town bush and then gradually slows down for the rest of the experimentation time. This could be explained by the fact that pore blocking and narrowing of the microfilter happens very quickly in the first 30 minutes of filtration of the contaminated fluids especially for water sources with high turbidity.

An important observation from Figure 4-4 is that WFMF does reject *E. coli* with a minimum rejection rate of 97.4% and 99.8% maximum for the waters used in the study. For coliform compliance, the WFMF complied with the South African drinking water recommended limits for total coliforms and faecal coliforms at the point of treatment (Momba, Obi and Thompson, 2008). Complete removal of *E. coli* by the WFMF was not achieved for all the rivers implying that further optimization is needed for complete removal of E .Coli. However the *E. coli* content on all the Rivers were brought to levels that could be easily disinfected with the addition of small disinfectant.

According to Tanny *et al.* (1979) different studies have revealed that membranes are effective in producing water with reduced bacterial level but the retentivity depends on the magnitude of the organism concentration levels. This was seen and proven when comparing Duzi River with Town Bush River. In this case, the *E. coli* content after filtration differs and this was due to the level of the magnitude of incoming *E. coli* on the feed side despite the use of the same filter on both rivers.

4.3.2 Pore blocking

Factors affecting the pore narrowing and pore blocking are the presence of fine particles smaller than the pore size of the membrane that gets stuck in the channel of the pore Madaeni (1999). This phenomenon is prevalent in membranes that are thick i.e. WFM. Another factor affecting pore narrowing is organic matter and microorganisms such as extracellular polymeric substances (EPS-these are the construction materials for microbial aggregates such as protein and polysaccharides) that get adsorbed into the pore of the membrane; narrowing the pore even more. This is also prevalent in thick membranes. The typical membrane thickness is less than 1 mm but WFM is 2 mm thick, hence WFM is more susceptible to pore blocking and narrowing due to its thickness. The strong rejection in the first 20 minutes for Duzi River and Umbilo could be explained by the presence of both colloidal matter and organic matter foulants that many researchers such as Madaeni (1999), Kim, and Park and Cho (2008) stated are responsible for the pore narrowing and blocking that takes place quickly in the filtration process.

4.3.3 Effect of feed characteristics on pore blocking

The improved rejection in the synthetic feed water could be attributed to pore blocking by *E. coli* itself and ESP adsorption which is present in the presence of *E .coli*. In addition to pore blocking another factor that could contribute to the rejection of *E. coli* in the synthetic feed water is the secretion of slimy biofilm by *E. coli* after death. According to the findings of membrane bioreactor by Simon (2010) this biofilm completely blocks the pores of the membrane because it coats the surface of the membrane and is usually very adhesive. This adhesiveness was seen in this study when the membranes were washed.

Pore blocking is seen in Figure 4-5 where a sharp decline in flux is seen for synthetic feed and Duzi River. The membranes that were used in the filtration of synthetic feed had to be soaked in sodium hypochlorite to recover the flux. This shows the adhesive nature of the *E. coli* bacteria on the WFM. Town Bush River did not exhibit the same trends as seen for other rivers. This was attributed to the fact that this river was not as highly contaminated as the others. In fact it simulated tap water with a sort of straight line rejection with time.

The second gradual *E. coli* rejection in microfiltration is attributed to cake filtration which results from rejected particulates that begin to build up on the surface of the membrane. Once a big layer has developed, the layer starts to act as the secondary filter. The filtration by this secondary layer is dependent on the porosity of the cake layer. The build-up of cake layer on the membrane surface together with pore blocking and narrowing is called membrane fouling (Kumar, Madhu and Roy, 2007). The effect of this fouling on the water sources is discussed in the section 4.3.4.

4.3.4 Effect of fouling on rejection

Membrane fouling is affected by many parameters like feed characteristics, operating conditions, membrane material, hydrodynamics, etc. The study focused more on feed characteristics and operation. The feeds characteristics was already explained above and operating conditions were limited only to pressure which declined with time. According to Madaeni (1999) higher operating pressure results in better rejection. The cause of this is that at high pressure operation transport towards the membrane is high hence pore blocking and cake layer formation is quickened. This also explained the good rejection in the first 20 minutes for all the rivers. For this study, the working tank is filled within the first 20 minutes and the maximum gravitational pressure was experienced by the membrane.

E. coli removal by membrane, in this study by a microfilter, is a physical removal where the membrane pore size determines the extent of separation. This size exclusion phenomenon is that smaller particles pass through the pores whilst bigger particles are retained (Madaeni, 1999). WFM pore size is between 0.4 and 1 micron, these sizes as stated in Chapter 3. According to Pillay, Graham and Dlamini (2009) separation by WFM is achieved by physical separation. Measuring of the physical pore for woven material proved to be challenging. *E. coli* size ranges from 0.2 to 1 micron in diameter and the length is usually much bigger.

4.3.5 Performance of WFM on turbidity removal

Figure 4-6 shows the turbidity profile of WFMF with time for different water sources.

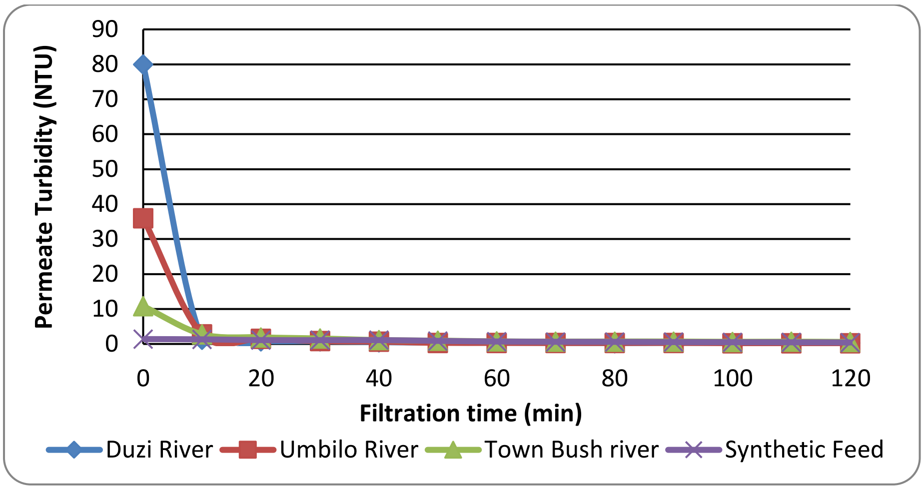

Figure 3-20 Performance of WFMF on turbidity removal

Removal of turbidity is an important part of disinfection as it helps in improving the appearance, taste and odour of the treated water. According to SANs 241, the stipulated standards for turbidity in drinking water should be below 1 NTU. Also turbidity hinders the effectiveness of chemical disinfection, if required. Hence it should be brought to levels were chemical disinfection can be easily and effectively achieved (SANS-241, 2011).

The turbidity removal profile in Figure 4-6 shows that as filtration time increases from 0 to 120 minutes turbidity rejection also improves. The turbidity rejection showed similar trends for all rivers. The highest turbidity rejection is observed in the first 30 minutes of filtration. Here the turbidities achieved for all the river sources were generally below I NTU irrespective of the initial feed water and therefore met the required guidelines for drinking water (WHO, 2011). It is noted that at about 90 minutes the rejection of turbidity no longer improves particularly for Duzi and Umbilo River. This could be due to the fact that the thickness of the cake, which is responsible for filtration after 45 minutes, has now reached its maximum and addition of the depositing particulates no longer plays any major role on filtration.

For rivers with initially low turbidities such as Town Bush and synthetic feed, the state of saturation in the cake thickness actually takes much longer since there was fewer suspended matter that builds up the cake layer. Figure 4-6 shows that WFMF is able to remove turbidity for the rivers studied and can be used for this purpose. This is in line with the previous study Mecha and Pillay (2014) where the performance of the WFM was found to be satisfactory. The WFMF filter is seen here to be an absolute barrier to substances that are larger than the equivalent pore size of the fabric. *E. coli* bacteria have a tendency to attach itself to suspended matter making it bigger and easier to reject by the WFMF. The findings of Ho and Sirkar (2001) further stressed that membranes are capable of removing most particles either biological or non-biological colloids that are smaller or larger than the pore size of the membrane. This could explain the good rejection of *E. coli* in section 4.2.1 and turbidity rejection in this section for water with both turbidity and *E .coli*.

4.4 **Efficiency of chemical disinfection without WFMF**

This section investigates the efficiency of chemical disinfectants in deactivating *E. coli* without the use of WFM. Different doses of disinfectant were used against the feed samples with different *E. coli* content.

4.4.1 Waterguard performance on disinfection

Figure 4-7 shows the effect of Waterguard concentration on *E. coli* removal for different rivers.

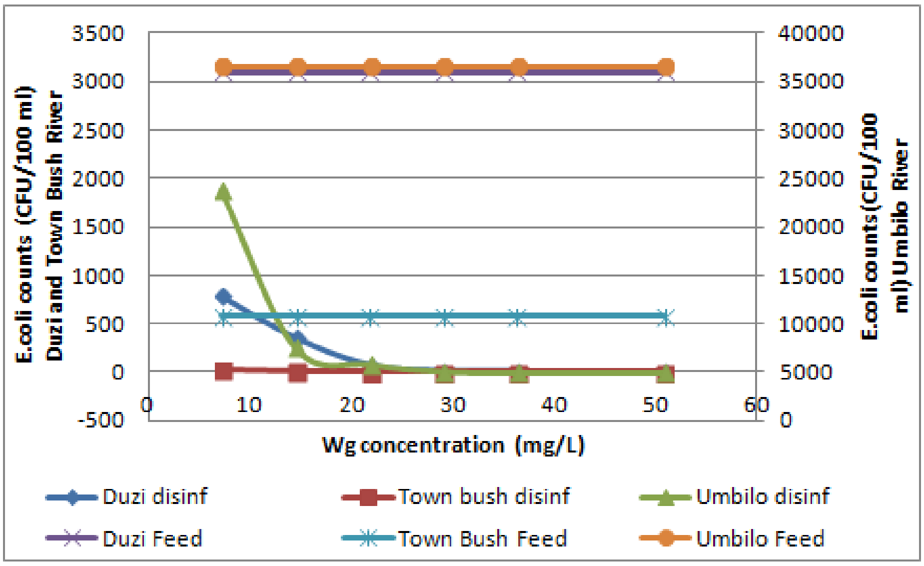

Figure 3-21 Effect of waterguard dose on disinfection

Table 3-5 Disinfection efficiency with waterguard

Water guard(Wg) Concentration(mg/ℓ)	Duzi disinfection (cfu/100mℓ)	Town bush disinfection (cfu/100mℓ)	Umbilo disinfection (cfu/100mℓ)
0	3102	581	36541
7.26	784	23	1875
14.52	352	4	254
21.78	68	2	85
29.04	12	0	11
36.3	5	0	0
50.82	0	0	0

The waters studied had different contaminant levels and hence had varying chlorine demand as discussed in section 4.2.2. For all the rivers irrespective of the contamination level, increasing waterguard concentration resulted in a decline in *E .coli*, meaning *E. coli* was being killed or deactivated. The improvement in disinfection on increasing waterguard concentration is expected, because for the same number of bacteria the concentration or strength of the disinfectant is then increased resulting in improved disinfection. This is in agreement with the findings of Nicholas (2002) which showed that when chlorine dosage is increased the amount of available chlorine to be used for oxidation or deactivation of bacteria is also increased.

This study revealed that initial concentrations of 7.26 and 14.52 mg/ℓ resulted in a greater impact on disinfection than on increased concentration from 21.78 to 50.8mg/ℓ. For example for Duzi River a Wg concentration of 14.52 mg/ℓ achieves 88.6% deactivation of *E. coli* whilst 36.3 mg/ℓ achieve 99.8% deactivation of *E .coli*. Further addition of disinfectant concentration from 14.52 to 36.3 mg/ℓ yielded only 11% increase in deactivation of *E .coli*. This amount is quiet small when compared to the initial value. The reason for this occurrence is unknown; however this finding could be due to resistance developed by the target organism on further addition of disinfectant. The difficulty to understand this phenomenon could also be due to the findings of Nicholas (2002) that the initial amount of chlorine dosed gets used up for oxidation of metals such as iron and manganese and organic matter present in the water before disinfection of bacteria occurs. Based on this reasoning the initial lower concentration should have minimal impact on deactivation of *E. coli* and upon increase of chlorine base disinfection then improvements should be significantly noted. This was not the case for this study or at least the improvement in deactivation/ removal of *E. coli* was not in accordance with the chlorine dose used.

Duzi River proved to be more difficult to disinfect by waterguard followed by Umbilo and the easiest was Town Bush River. The difficulty to disinfect Duzi River was due to high turbidity, organic matter and other pathogens competing for chlorine. Also according to Schoenen (2002) suspended matter or organic matter impedes disinfection by shielding pathogens or bacteria being disinfected. Only a concentration of 50.82 mg/ℓ of waterguard was able to completely disinfect Duzi River. These high dosages of chlorine according to Nicholas (2002) will need to be removed by activated carbon in order for the water to be palatable which may lead to further cost. The ease in disinfecting Town Bush River was linked to the absence of turbidity and organic matter in this water.

In conclusion from this study it was discovered that Waterguard concentration was able to deactivate to some degree the *E. coli* present in all the different water sources.

On increasing the disinfectant dose, the amount of *E. coli* also decreases, although there was no complete compliance to the set guidelines of zero *E. coli* for some rivers until high doses were used. These doses may impact on the taste and odour of the water which will incur additional costs for removal.

Rivers with low turbidities and *E. coli* count were easily disinfected using a small amount of disinfectant than those with high turbidities and *E. coli* count e.g. Duzi River. For such rivers to comply with the required guideline for drinking water, multiple barriers have to be employed to bring the water to a level where it can be easily disinfected (Nicholas, 2002).

Waterguard is an efficient disinfectant. However this study revealed that on further addition of this disinfectant with the aim of achieving complete deactivation of *E. coli* on difficult rivers, the amount of *E. coli* deactivated was found to be low when compared to the small amount initially used. This could be due to organism resistance or other chlorine loss.

4.4.2 Bromochlor tablet performance on disinfection

In this section bromochlor tablet was tested on all the water sources by varying the sizes and flow rates. The effect of tablet size was studied by varying the tablet size from 0.1, 0.3, 0.5 and 0.75 g whilst keeping a constant flow rate of 20 ℓ/hr. The effect of flow rate was determined by keeping a constant tablet size of 0.3 g and varying flow rates. The flows investigated were extremely low flows of 1 and 5 ℓ/hr and high flow rates of 20 and 45 ℓ/hr. Figure 4-8 shows the effect of tablet size on disinfection. This is also shown in Table 4-4. Figure 4-9 shows the effect of flowrate on *E. coli* removal with Bromochlor tablets.

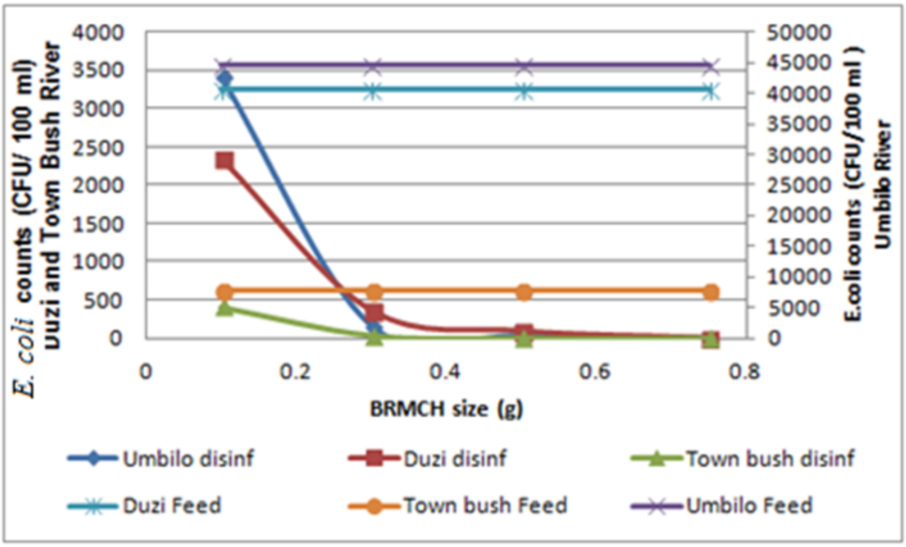

Figure 3-22 Effect of BRMCH size on *E. coli* removal

Table 3-6 Disinfection with BRMCH

Tablet Size (g)	Umbilo disinfection (cfu/100mℓ)	Duzi disinfection (cfu/100mℓ)	Town bush disinfection (cfu/100mℓ)
0	44500	3254	621
0.1	3412	2342	108
0.3	164	360	35
0.5	36	92	0
0.75	0	0	0

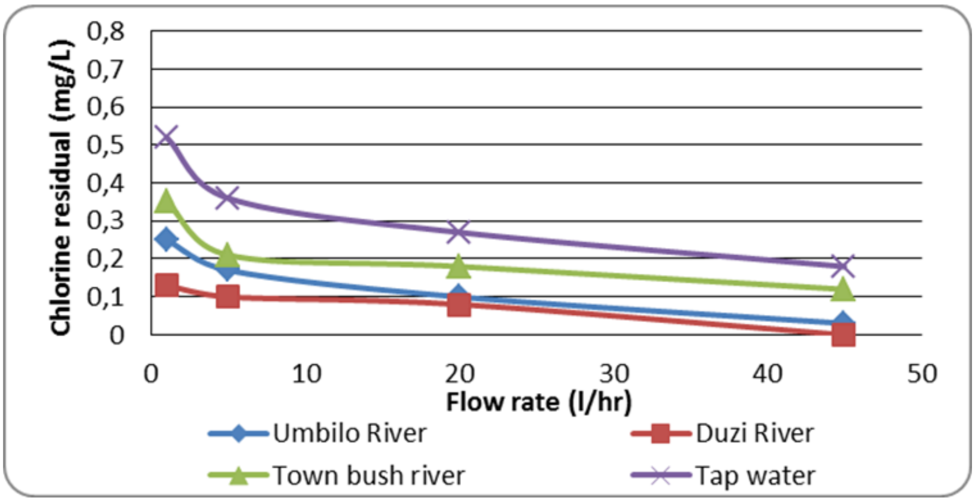

Figure 4-9 Effect of flowrate on *E. coli* removal by using 0.3g BRMCH

The results show that increasing the tablet size improves disinfection for all the rivers. This is because an increase in the tablet size increases the surface area of the tablet which in turn comes into contact with contaminated water and more chlorine is released. The increased contact between tablet and water being disinfected results in collision between disinfectant and the contaminant.

Table 3-7 Effect of flowrate on *E. coli* removal by using 0.3g BRMCH

Flowrate (l/hr)	**Umbilo disinfection (cfu/100mℓ)**	**Duzi disinfection (cfu/100mℓ)**	**Town bush disinfection (cfu/100mℓ)**
1	0	1	0
5	62	85	2
20	164	180	21
45	1523	897	103

This collision is necessary before any disinfection occurs. The effect of flow rate affects residence time or contact time and mixing. Figure 4-9 shows that at low flow rates more disinfection is achieved. This is because at low flow rates there is an increase in contact time which facilitates collision and also most of the fluid comes into contact with the tablet. Although high flow rate facilitate mixing, the increased flow rate reduces contact time and much of the fluid does not come into contact with the tablet hence no disinfection occurs. This explains the reason why less disinfection is achieved at high flow rates for highly contaminated feed water.

Hence for optimum disinfection to occur, the size of disinfectant, flow rate and quality of feed to be treated all play significant roles. For example, in Figure 4-8 and 4-9, it can be deduced that when flow rate is increased, the disinfectant size should be increased also for highly contaminated rivers, while for rivers like Town Bush with low contamination levels, disinfection can still occur at high flows and small disinfectant sizes.

In summary this study has revealed that flow rates, tablet size and water quality plays an important role in disinfection efficiency. Rivers with high contamination rate are best disinfected when the flow rates is low and at increased tablet size which provides more surface area for collision between the organism and disinfectant.

Bromochlor tablet releases more of its chlorine at low flow rate which then leads to an increased available chlorine for disinfection. In cases where flow rates are high, it is then necessary for the tablet size to be increased also as this will assist in increasing the amount of chlorine available due to increased surface area.

4.5 Enhancement of chemical and WFM disinfection processes

Pre-coating of the membrane surface was done to improve the performance of the membrane. For WFMF two microns lime was used as a pre-coat on the membrane to improve its filtration ability, while agitation and contact time were used to optimise chemical disinfection.

4.5.1 Enhancement of WFM performance by pre-coat with lime

The performance of WFM fitration was enhanced by precoating the WFM with lime before filtration of the feed water. Several information have shown that microfiltration effeciency is improved once a layer of cake is formed on the surface of the membrane acting as a secondary filter. Figure 4-10 shows the effect of pre-treating WFMF with 2 microns on *E. coli* removal while Figure 4-11 shows the effect of pre-treatment on turbidity.

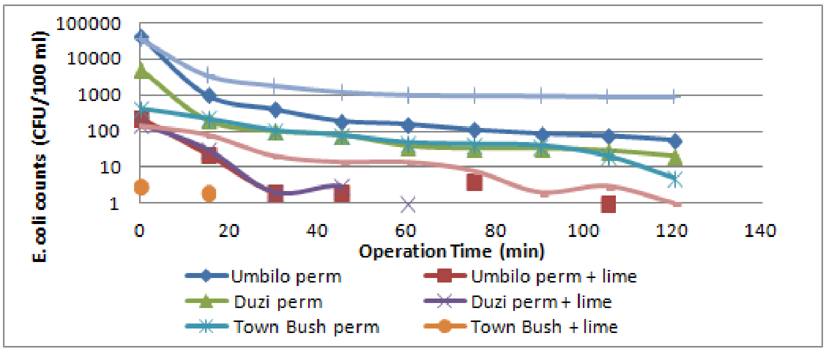

Figure 3-23 Effect of pre-coating WFMF with 2 microns lime

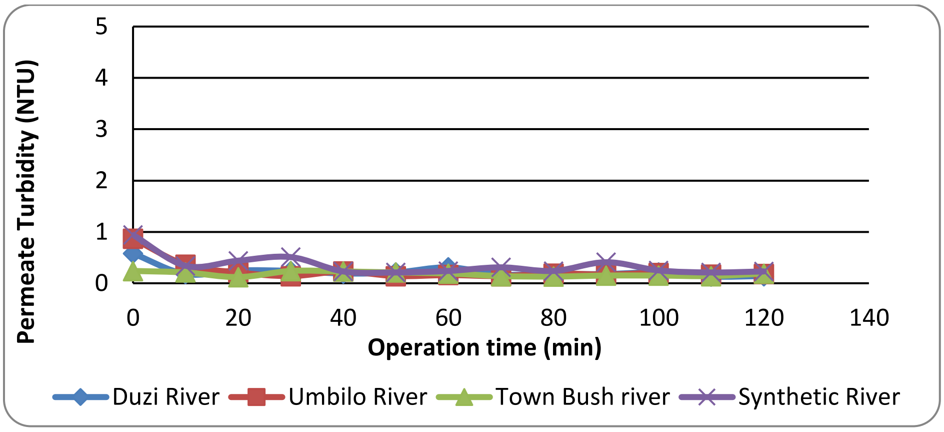

Figure 3-24 Effect of pre-coating WFMF with 2 microns lime

Precoated membranes showed at least a 3 log removal of E. coliwhen compared to no precoat on all the water sources used. This is solely due to the secondary filtration layer and the elimination of the initial filtration process during pore blocking. Here large volumes of particulates are transported to the membrane surface at a slightly higher pressure.

The findings of Pall, Kirnbauer and Allen (1980) suggests that bacteria like E. colican deform or change their shape. This enables them to pass through pores it would normally not be able to pass through and slightly high pressures are responsible for this passage. When membranes are precoated, primary layers are formed, which forces the filtration process to be more on the second steady state of filtration. During this time, cake layer is used for primary filtration and whatever break throughs this layer, gets caught by the membrane. This was so in this study especially for synthetic feed and Town Bush that had low feed turbidities. Turbibidity rejection in Figure 4-11 shows that turbidities of less than 1 NTU were for the first 20 minutes of filtration while with the coated membranes it was achieved in less than 5 minutes of filtration.

Precoating the WFM improves the surface performance of the membrane by forming a secondary layer which enhances the filtration process. This reduces the time required to obtain clarity on permeates (turbidity) and further improves membrane performance in rejection of *E. coli* on different water sources. The quality of permeates obtained on all the rivers after pre-coating with lime greatly improved irrespective of their initial feed quality.

In conclusion pre-coating the membranes with lime improves the surface performance of the membrane by foming an initial surface layer which enhances the general performance of WFM.

Permeates turbidities were easily reduced to less than 1 NTU after a short operational time on all the water sources in this study. Hence pre-coating reduces operational time and improves permeate quality. It brings the water to a complete compliance with drinking water standards at less operational time.

Rivers like Town bush and Synthetic feed produced permeate with turbidities less than 1 NTU in less than 5 minutes . This was not so for the uncoated membrane.

4.5.2 Optimization of chemical disinfection

Disinfection kinetics such as contact time and agitation were used as parameters in optimizing the performance of waterguard for removing *E .coli*. Figures 4-12, 4-13, and 4-14, shows the effect of agitation and contact time on waterguard disinfection for Duzi, Umbilo and Town Bush River.

Contact time is an important parameter during chlorine disinfection. It is used to determine the time required for direct contact between the organism and chlorine (disinfectant). Usually this parameter is dependent on other factors like chlorine concentration and quality of the water to be treated. The product of the concentration of chlorine in mg/ℓ and the contact time in minutes is called the CT value or exposure time. The amount of chlorine required deactivating a particular organism under specified conditions such as temperature and pH is sometimes specified by the CT value (Momba, Obi and Thompson, 2008).

Free chlorine of ≥ 0.5 mg/ℓ of at least 30 minutes of contact time in water at a pH of < 8.0 must be produced at disinfection point before distribution. While the required free chlorine for POU system is ≥ 0.2 mg/ℓ for at least 30 minutes contact time. Based on WHO (1993) the residual recommendation and contact time is to reduce the possibility of virus risk to a minimal value and the risk of the water transmitting parasites is reduced to a negligible value. After chlorination at the right CT value, organisms like Escherichia coli bacteria which are indicators of faecal pollution from humans or animals are not expected to be found in the disinfected water. The bacteriological quality of the water is determined by the number of organisms present in 100 mℓ of the water source (WHO, 2011)

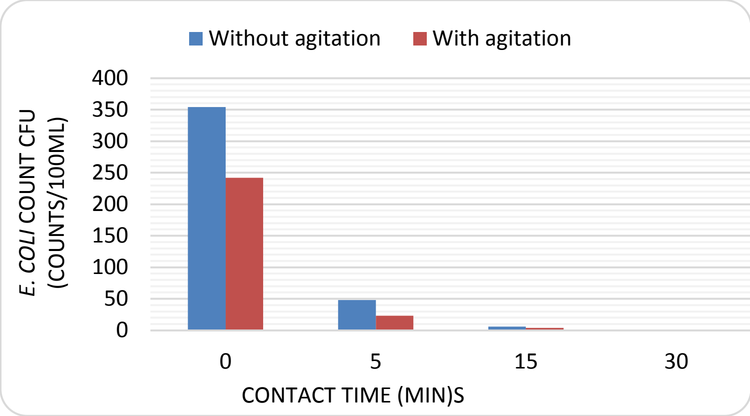

Figure 3-25 Effect of contact time and agitation on Umbilo River

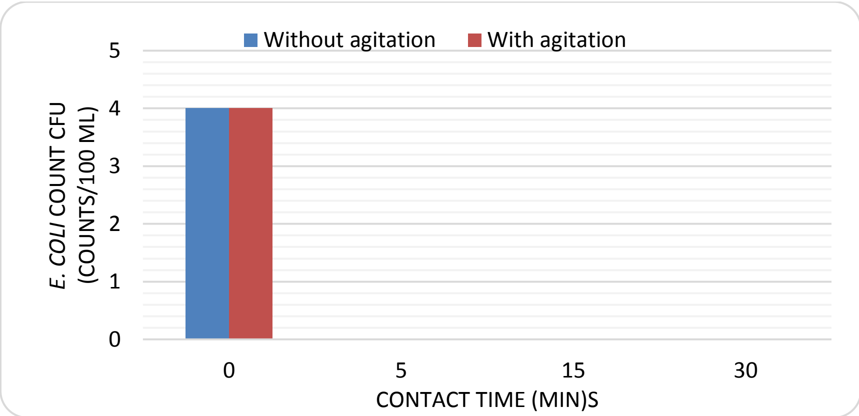

Figure 3-26: Effect of contact time and agitation on Town Bush River

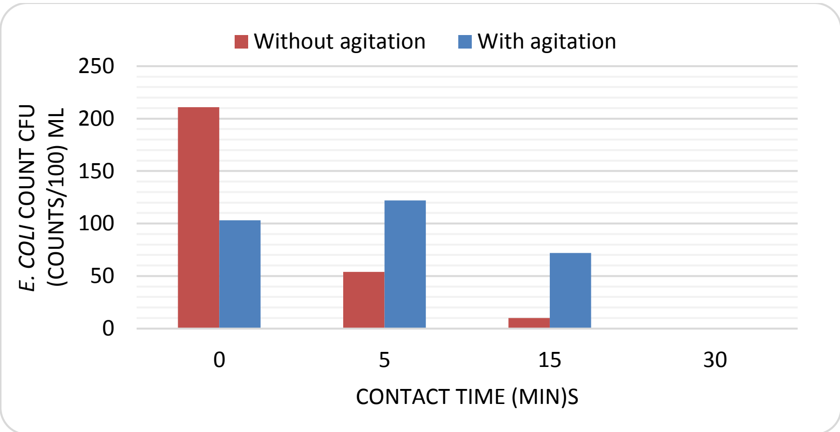

Figure 3-27 Effect of contact time and agitation on Duzi River

I. Contact Time

A constant waterguard concentration of 14.52 mg/ℓ was used for all the rivers. The results show that increasing the contact time from 5 to 30 minutes improves disinfection of water by waterguard. The biggest improvement was recorded for Town Bush River where a 10 minute increase in contact time produced 100% disinfection, followed by Umbilo with 85% then Duzi with 75% improvement. The improvement is attributed to increased time for collision between the pathogen and disinfectant. Disinfection or deactivation of pathogens only occurs when there is contact between the disinfectant molecules and the pathogen being disinfected.

During this study there was no additional mixing used when studying the effect of contact time besides the inherent mixing (mixing during collection from the tap into the permeate tank). Residence time which in this case was in the form of contact time became the only factor used to facilitate collision between Waterguard and pathogen i.e. E .Coli. Hence at increased contact time more *E. coli* was inactivated. This finding is in line with Nicholas (2002), which states that contact time increases disinfection efficiency.

II. Contamination load of different rivers

The efficiency of disinfection using Waterguard differs for different water source. Duzi River was the hardest water to disinfect in this study due to its high contamination. For this river, increased contact time improved the rate of disinfection. Whereas for a river like Town bush with less contamination load, disinfection was achieved in less than 30 minutes which is the requirement for many water treatment plants (Momba, Obi and Thompson, 2008). According to Nicholas (2002), chlorine tends to attach its self on the suspended matter and other microorganism present in water, which will then settle to the bottom leaving the rest of the water with less chlorine. Table 4-1, shows that Duzi River was the most polluted of the three rivers. Contaminants included different kinds of microorganisms and turbidity. This could explain the reason for the difficulty in the disinfection of

Duzi River even at increased contact time. The advantage that longer contact time also adds to water source such as Duzi River is that OCl^- which is the disinfecting part of waterguard can be detached with time from the organic matter it was originally attached. It therefore begins to move up the fluid because of the low density of the ion, hence increasing the chances of collision with the pathogen on its way up. However there are cases where disinfection by-products are formed during the attachment of chlorine to the organic matter.

III. Effect of agitation

The effect of agitation on disinfection is seen to improve disinfection as well, particularly for Umbilo and Duzi. Agitation effect did not consistently supersede the effect of contact time as one would have expected. Agitation impacts on disinfection by creating a chance for collision between the target organism and the disinfectant. According to other findings settling in sedimentation and clarification serves as part of disinfection of microorganisms such as *E .coli*. On the contrary, agitation prevents settling of heavy matter; however it assists collision before settling. In instances were settlement and clarification is involved, agitation and mixing should be done at slow rates to achieve optimum results (Chris and Martin, 2009). Although agitation significantly improves collision between bacteria and disinfectant, it also increases chlorine demand for the water. This is because the bacteria and suspended matter that would normally settle down at the bottom is now suspended and competes for the same chlorine. This explains the reason agitation did not show significant improvement over contact time in this study. The impact of agitation was insignificant for Town bush river, although it impacted slightly on Duzi River.

Another factor that makes agitation not to be as effective as it ought to be is that in the presence of air chlorine disinfection become less effective because it escapes with air. Agitation introduces air into the system and this was in line with the findings of Nicholas (2002).

In summary, contact time increases the rate of disinfection by creating sufficient time for exposure of the target organism to the disinfectant dosed. In this study, the effect of contact time was more significant on water sources with a high contamination level than on those with lesser contamination.

At increased contact time from 5 to 20 minutes, the quality of water sources with high contamination load e.g. Duzi River can be improved. The effect of contact time was insignificant for rivers with low contamination load.

Agitation had no impact on Town Bush River; however there was slight improvement on the Duzi river water quality after agitation at increased contact time. Hence contact time played a more significant role on disinfection than agitation in this study.

4.6 **Performance of RRWTS**

After the investigation of the WFMF and chemical disinfection, it was then necessary to investigate the efficiency of the disinfection on combining the two processes. The RRWTS's (combined filtration and disinfection) performance was evaluated on the basis of total removal of *E. coli* from the water.

4.6.1 RRWTS performance with Waterguard

Figure 4-15 and Table 4.6 represents the performance of the RRWTS in *E. coli* removal using different concentrations of waterguard disinfectant. Figure 4-16 and Table 4.7 shows the effect of pre-coating on RRWTS's removal of *E .coli*.

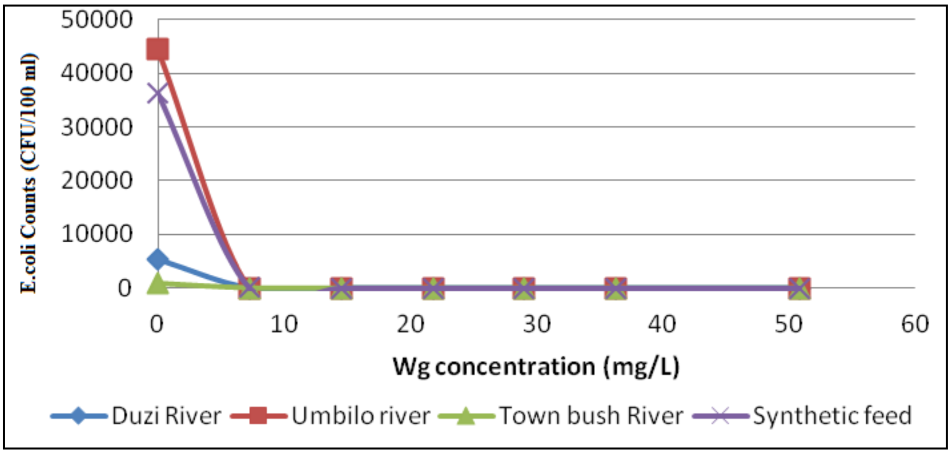

Figure 3-28 RRWTS evaluation with waterguard

Table 3-8 RRWTS evaluation with waterguard

Water Guard mg/ℓ	**Duzi disinfection (cfu/100mℓ)**	**Umbilo disinfection (cfu/100mℓ)**	**Town bush disinfection (cfu/100mℓ)**	**Synthetic disinfection (cfu/100mℓ)**
0	5402	44520	824	36214
7.26	12	25	21	72
14.52	5	1	0	15
21.78	0	0	0	5
29.04	0	0	0	0
36.3	0	0	0	0
50.82	0	0	0	0

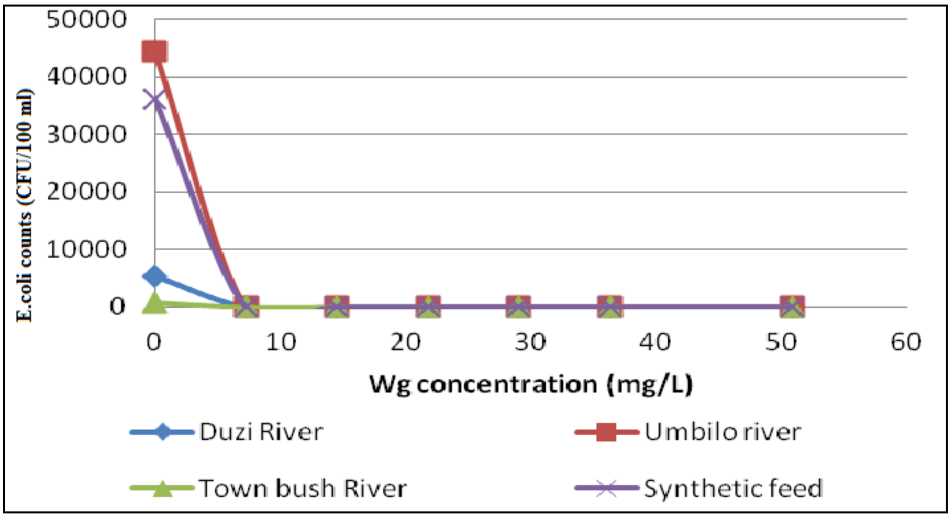

Figure 3-29 Effect of pre-coating RRWTS with lime on E. coliremoval (RRWTS+Wg)

Table 3-9 Effect of pre-coating RRWTS with lime on *E. coli* removal (RRWTS+Wg)

Water guard	**Duzi disinfection (cfu/100mℓ)**	**Umbilo disinfection (cfu/100mℓ)**	**Town bush disinfection (cfu/100mℓ)**	**Synthetic disinfection (cfu/100mℓ)**
0	5402	44520	824	36214
7.26	0	0	3	5
14.52	0	0	0	0
21.78	0	0	0	0
29.04	0	0	0	0
36.3	0	0	0	0

Figure 4-15 shows that after using 21.78 mg/ℓ of waterguard 100% disinfection was achieved on all the water tested irrespective of their initial feed water contamination level. Duzi River water was the most difficult water to disinfect, with a high concentration of 36.3 mg/ℓ of disinfectant, complete inactivation of E. coliwas not achieved without WFM.

Due to the presence of suspended matter in the form of turbidity and high *E. coli* level of this river water, total *E. coli* inactivation was obtained after using 50.82 mg/ℓ of Waterguard in Figure 4-16. This was at the expense of high chlorine residual which exceeded the required standard of 0.2 m/ℓ for POU systems and may render the water unpalatable. But with RRWTS, Duzi River was easy to disinfect using only 21.78 mg/ℓ of waterguard; a far smaller amount of disinfectant when compared to the quantity used in the unfiltered feed. This implies that WFMF improves the quality of highly contaminated river water bringing the water to a level where it can be easily disinfected while saving also on the disinfectant.

The need for extra disinfectant dose and contact time was not required as total disinfection was achieved immediately and at minimal disinfectant concentration. This was obtainable for all the rivers. RRWTS eliminates the need for disinfection kinetics that could be time consuming and costly in some cases.

The findings in this study tallies with the findings of Schoenen (2002), that filtration should be done prior to chemical disinfection to eliminate other unwanted particles that may shield the pathogen. On the basis of *E. coli* removal the RRWTS unit is a very effective tool requiring but minimal addition of disinfection.

Figure 4-16 and Table 4.7 show the effect of a pre-coat on RRWTS's removal of E .Coli. It can be seen that pre-coating the membrane with 2 microns lime improved disinfection efficiency. 7.26 mg/ℓ of waterguard was able to completely disinfect the all the water sources after pre-coating the membrane. Whereas without the pre-coat 21.78 mg/ℓ of waterguard was required for total inactivation. This study showed that combining WFMF with disinfectant (Wg) improves disinfection to a very satisfactory level. While introduction of pre-coat further improved the disinfection and saves on the quantity of disinfectant used.

4.6.2 RRWTS performance on bromochlor

Figure 4-17 shows the efficiency of the RRWTS in E. coliremoval with Bromochlor tablet.

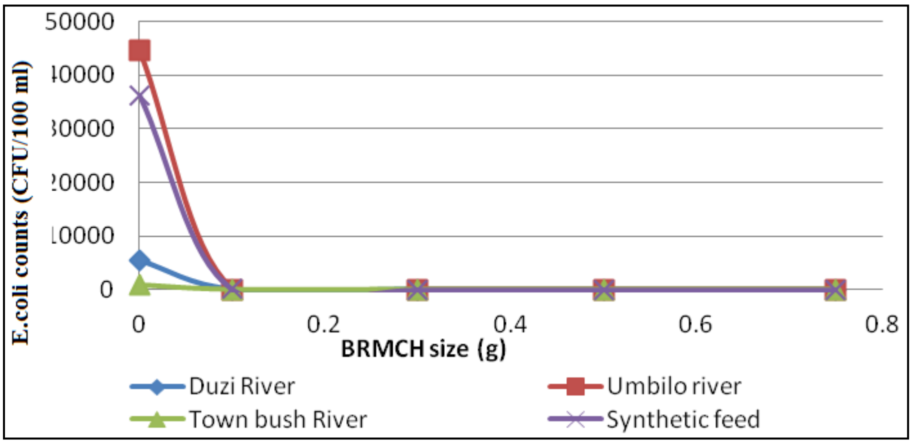

Figure 3-30 Evaluation of the effect of pre-coating RRWTS with lime on E. coliremoval (RRWTS+BRMCH)

Table 3-10 Evaluation of the effect of pre-coating RRWTS with lime on E. coliremoval (RRWTS+BRMCH)

BRMCH size (g)	Duzi disinfection (cfu/100mℓ)	Umbilo disinfection (cfu/100mℓ)	Town bush disinfection (cfu/100mℓ)	Synthetic disinfection (cfu/100mℓ)
0	5402	44500	824	36214
0.1	21	34	0	56
0.3	4	2	0	2
0.5	0	0	0	0
0.75	0	0	0	0

The *E. coli* removal efficiency on all the rivers by the RRWTS was significantly satisfactory at minimal bromochlor size. Rivers like Duzi and Umbilo that were difficult to disinfect in Figure 4-2 were easily disinfected using the RRWTS with 0.5g of bromochlor tablet. The same size of tablet was unable to disinfect Duzi and Umbilo River because of their high *E. coli* and turbidity levels.

The need for increasing tablet size was unnecessary while using the RRWTS as most contaminants that compete for chlorine during disinfection had been removed by microfiltration. Similar performance of RRWTS with waterguard in *E. coli* removal is seen with the Bromochlor tablet.

Figure 4-17 and Table 4-8 show the effect of pre-coat on RRWTS disinfection combined with BRMCH. From this Figure total *E. coli* removal was seen on all the water sources, however this was at a lesser amount of disinfectant. After pre-coating of the WFM, 0.3 mg of Bromochlor was sufficient to disinfect the entire *E. coli* count on all the water sources. Similar finding as those in section 4.4.1 were observed and are discussed in that section.

4.6.3 Effect of cleaning on flux recovery

The effect of cleaning on flux recovery and *E. coli* counts is illustrated in figure 4-18 and Figure 4-19 respectively. Duzi River with high *E. coli* and turbidity was used alongside synthetic feed with high *E. coli* and low turbidity for this investigation.

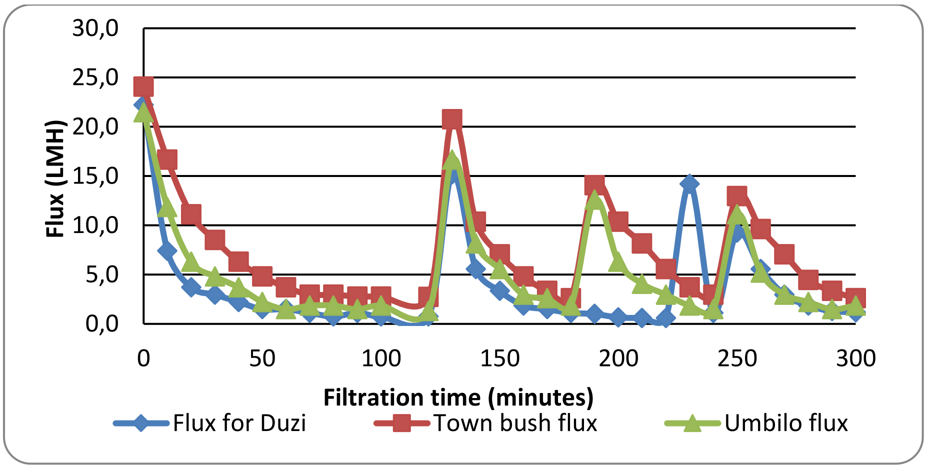

Figure 3-31 Effect of cleaning on flux recovery

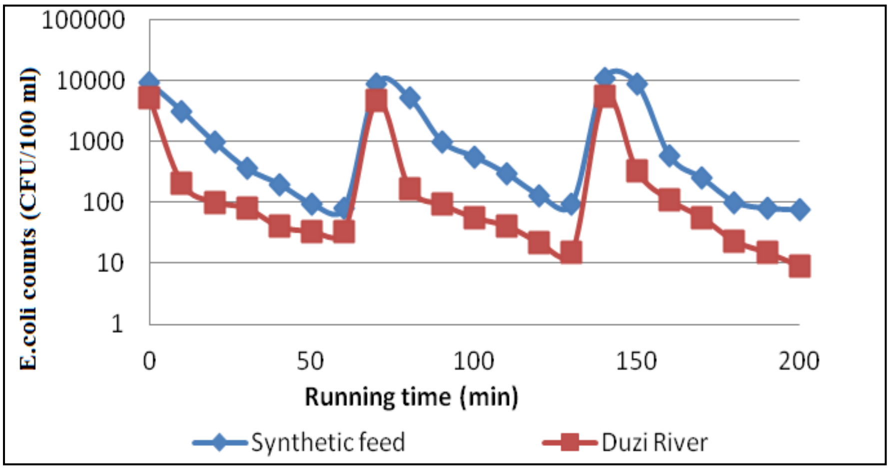

Figure 3-32 Effect of cleaning on *E. coli* removal

Figure 4-18 shows the effect of cleaning on flux recovery for all the water sources. It is seen from this study that cleaning improved the recovery of flux on all the water sources tested. Duzi River with an initial flux of 22.2 LMH later dropped to 1.5 LMH after 60 minutes of operation. The reduction in flux was due to membrane fouling. Duzi River had an initial high turbidity which necessitated the early formation of a cake layer on the membrane which resulted in the blockage of the membrane pores thereby leading to a reduction in flux. After 2 hours of filtration the flux had further dropped to 0.7 LMH, it was then necessary to clean the membranes. 15.2 LMH of flux was recovered after cleaning. Although 100% recovery of the initial flux was not achieved this could be due to inadequate cleaning or the type of foulant on the membrane surface.

Figure 4-19 shows that the initial value of *E. coli* for Duzi River feed was 5402 *E. coli* count/100 ml. The amount of *E. coli* dropped as the filtration process progressed. 34 *E. coli* counts/100 ml was found in the permeate after 1 hour of operation. The same trend was seen with the synthetic feed with an initial *E. coli* count of 9330 *E. coli* counts /100 ml which later reduced to 96 E. colicounts/100 ml. This showed that irrespective of *E. coli* concentration in the feed the filter was able to reduce the *E. coli* count, although the removal efficiency was higher for Duzi River than for the synthetic feed due to factors discussed earlier in Figure 4-10. The membranes were cleaned hourly. The permeate *E. coli* was found to be 5210 for Duzi and 8972 for synthetic feeds. This shows that the WFMF is a true example of a microfilter as it is able to recover its initial quality after cleaning. Also formation of the cake layer or coating of the membrane indeed assisted in the *E. coli* removal. This is seen as more *E. coli* was able to pass through the membrane after cleaning which had removed the entire fouling layers that were formed during filtration (Madaeni, 1999).

It is also seen that the *E. coli* removal efficiency by the WFMF was more rapid after cleaning for Duzi River than Town bush. This was due to the presence of turbidity in Duzi River which easily formed a cake layer that assisted in the filtration process.

In conclusion, during the filtration process, secondary layers are formed which assist in the permeate quality; however, the cake formation leads to a decrease in flux due to fouling.

Cleaning of the membrane removes the fouling layer which in turn assists in the recovery of flux during filtration. More frequent cleaning is required on rivers like Duzi than with the synthetic feed in order to recover flux. The effect of cleaning on *E. coli* removal was more significant immediately after membrane cleaning was done. *E. coli* removal efficiency improved immediately after cleaning on rivers with higher turbidity levels like Duzi than those with lower turbidity like synthetic feed.

4.7 **Comparison of disinfection processes.**

Table 4-9 shows the performance of the various disinfection processes and their effectiveness in *E. coli* and turbidity removal.

Table 3-11 Quantitative analysis on the results obtained from different unit operations

Disinfection processes	Quantity of disinfectant used	Regulated Chlorine residual met	Contact time requirement	Agitation requirement	Capability to Disinfect water
Waterguard (Wg) mg/ℓ on unfiltered feed	Large quantities	Disinfection occurs only at high doses such that removal of some of the added chlorine becomes a requirement	Yes	Yes	Total disinfection depends on the feed characteristics
Bromochlor Tablet	large size is required for more surface area	Disinfection occurs only at high doses such that removal of some of the added chlorine becomes a requirement	Yes	Yes	Total disinfection depends on the feed characteristics
WFMF	-	-	Permeate quality improved with filtration time	Not required	Partially (±70% removal) brings water to a level where chemical disinfection is easy
WFMF optimisation	-	-	Improved product time immediately	Not required	90% disinfection. Bring water to a level where fractions of chemical disinfection is required
RRWTS	Small amount is required	100% at very low chlorine dosage and small tablet size	Not required	Not required	100% disinfection

Chapter 5. **Conclusions and Recommendations**

In order to alleviate the problem associated with the provision of safe drinking to people with low income and those in the rural areas, deliberate efforts have to be put in place by all water suppliers and stake holders who are concerned with drinking water quality. POU systems have been identified as one of the means to supply potable water as it has the potential to improve water quality and reduce water borne diseases. In communities where POU systems are used as a means of water supply, water consumers are less at risk of health hazards associated with consuming untreated water. The RRWTS is a POU system with identified potential of providing microbiologically safe water and an interim solution to water supply in rural communities.

During this study, Waterguard (1% sodium hypochlorite) and Bromochlor tablet (chlorine based tablet) was integrated with the woven fibre membrane filtration (WFMF) membranes to produce water that meets drinking water standards. The integration resulted in an appropriate POU system that can treat water for people in the rural areas of developing countries who will ordinarily drink their water without any form of treatment. The major aim of the study identifies and evaluates chemical disinfectants that can be integrated with the WFMF in order to improve its disinfection capabilities.

Flat sheet woven fibre microfiltration membranes were used in this study with the overall focus on disinfection using both membranes and disinfectants. Major areas of investigation were: effect of chemical disinfectant dose on feed quality, performance of the WFMF in *E. coli* removal with time, filtration and disinfection efficiency of the RRWTS against *E. coli* and optimization of chemical and WFMF disinfection using disinfection kinetics and pre-coating.

The effectiveness of chemical disinfection (waterguard and Bromochlor tablet) in the removal of *E. coli* is affected by the quality of water to be disinfected. Duzi River could not achieve 100% *E. coli* removal or give the required residual chlorine until 50.7 m/l of Waterguard and 0.75g of Bromochlor was used. These doses of disinfectant used can affect the taste and odour of the treated water which may require additional costs to remove. The inability of this River to be disinfected using chemical disinfectants alone was due to high turbidity and *E. coli* counts, it was observed that turbidity plays a major role in hindering disinfection. Disinfection kinetics such as dose, contact time and agitation improves disinfection, however on highly polluted water the improvement was not to satisfactory levels.

WFMF turbidity removal was found to be very good and complied with the set guidelines of less than 1 NTU for feed turbidities ranging between 10-200 NTU. There was 95-99 % *E. coli* removal on all the water sources with influent *E. coli* ranging between 500 and 44500 CFU/100 ml. WFMF plays a major role in disinfection of *E .coli*, although the study showed that it does not completely removed but it brings the water to levels in which it could be easily disinfected.

It was seen that although turbidity is a major hindrance to disinfection it however helps to improve the WFMF effectiveness in *E. coli* removal. This was found to be due to pore blocking, narrowing and cake filtration which in turn improves disinfection by the WFMF. This was further proven by the excellent results obtained when the WFMF was coated with lime prior to *E. coli* removal.

The major benefit derived from integrating the WFMF with chemical disinfection included: better disinfection, improved quality of water both in health and appearance and elimination of the need for disinfection kinetics in order to obtain superior disinfection. This greatly reduced the use of huge amounts of chemicals because small quantities were able to disinfect the water and hence eliminating the possibilities of DBPs formation.

The RRWTS is in the category of those systems that offers a multiple barrier approach to drinking water quality and a good POU system that can be adopted in the rural areas of developing countries.

5.1 Limitations of the study and Recommendations

The following limitation where identified in this study

5.1.1 Waterguard dosing

The addition of waterguard in this study was based on manual addition which is a replicate of what is obtainable in most rural communities where sodium hydroxide is used. The drawback here is that users may not follow the required steps or forget to add the WG before collecting water from the RRWTS. In the future, modification and identification of online chemical dozers in small quantities should be considered.

5.1.2 Loss of Bromochlor tablet

The presence of Bromochlor tablet was determined by testing for residual chlorine after two weeks of operation. It was discovered that the residual had dropped significantly below the set standard of 0.2 m/l which is an indication that complete disinfection and protection of the water may not be achieved. Further studies should be carried out on how to determine if the tablet is still available and effective or not without necessarily putting the burden on users, e.g. regular residual chlorine test by a trained personnel or complete adherence to user's manual for the tablet.

5.1.3 Membrane fouling

Pre-coating of the membrane with lime showed an improved performance of the WFMF in *E. coli* removal and the overall removal efficiency of the RRWTS. However, its effect on the flux was not investigated in this study. Future work should include the effect of pre-coating the WFMF with 2 microns on flux recovery

5.1.4 Effect of agitation

Agitation was seen to have no significant impact on disinfection. Although the agitation done in this study was for a period of 15 seconds it was discovered not to improve disinfection on highly contaminated water. Further studies should be carried out to discover if longer agitation will improve disinfection on exposing the pathogens to the chemical disinfectants.

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Appendix A Determination of study parameters

Describes the methods used in the determination of parameters like chlorine residual, *E. coli* count and Turbidity test in this study.

Standard plate count method

Standard plate count is an example of enumerative method used to determine qualitatively a bacterial population.

The procedure is as follows:

i. Suspension of the bacteria is made from a fresh culture in liquid.
ii. Serial dilution of the suspension to approximately 300 CFU/ mℓ
iii. Sterile spreading of aliquots of the diluted sample over the surface of sterile nutrient medium such as solidified nutrient agar
iv. Incubation of the plates at appropriate conditions of temperature and for the required duration in order to induce the development of colonies
v. Counting of the resulting visible colonies
vi. Calculation of the number of CFUs in the original package or suspension from the number of colonies on the plate and dilution factor.

Turbidity- This is the measure of the amount of substances that are found in the water it could be in the form of suspended solids, colloids, and/or organic matter. A Hach turbidity meter was used to measure the turbidity in NTU

***E. coli* counts-** It is an indication organism for the presence of faecal and other coliforms present in water. The level of bacteriological contamination of a water source can also be determined by knowing its *E. coli* content. *E. coli* count tests were carried out on the feed and disinfected samples using the collilert method. Care was taken to ensure that there was no cross contamination of the samples.

Chlorine residual- This is the measure of the available chlorine after disinfection. It's also referred to as the free chlorine. Chlorine residual was measured using the Hach pocket colorimeter.

Appendix B *E. coli* and turbidity removal on WFMF

This appendix displays all the raw data on *E. coli* and Turbidity removal using the Woven Fibre Membrane.

***E. coli* and Turbidity removal on WFMF**

Table B-1: Performance of the WFM on *E. coli* removal for Duzi River

Time (min)	Run 1	Run 2	Run 3	Standard deviation
0	5402	5222	4370	551.2603741
15	208	202	205	3
30	102	103	100	1.527525232
45	81	80	79	1
60	40	42	40	1.154700538
75	34	32	34	1.154700538
90	34	32	34	1.154700538
105	30	29	29	0.577350269
120	30	27	28	1.527525232

Table B-2: Performance of the WFM on *E. coli* removal for Umbilo River

Time (min)	Run 1	Run 2	Run 3	Standard Deviation
0	44820	42123	36544	4220.806124
15	1035	1120	998	62.55397669
30	423	420	320	58.62024679
45	202	194	200	4.163331999
60	164	157	150	7
75	115	120	109	5.507570547
90	90	88	90	1.154700538
105	79	78	70	4.932882862
120	60	58	55	2.516611478

Table B-3: Performance of WFM on *E. coli* removal for town Bush

Time (min)	Run 1	Run 2	Run 3	Standard deviation
0	445	390	322	61.61439226
15	235	230	230	2.886751346
30	110	109	105	2.645751311
45	80	79	79	0.577350269
60	50	48	49	1
75	45	45	40	2.886751346
90	41	42	39	1.527525232
105	21	19	21	1.154700538
120	5	4	3	1

Table B-4: Performance of WFM on *E. coli* for synthetic feed

Time (min)	Run 1	Run 2	Run 3	Standard deviation
0	35424	38412	35349	1747.175721
15	3542	3459	3500	41.501004
30	1842	1851	1790	32.92921702
45	1245	1232	1198	24.2693222
60	1021	1021	998	13.27905619
75	994	987	992	3.605551275
90	967	968	970	1.527525232
105	921	918	918	1.732050808
120	902	900	903	1.527525232

The Woven fibre membrane was coated with 2microns lime to determine its efficiency on *E. coli* removal and the raw data collected are shown below.

Table B-5: Effect of lime coating on *E. coli* removal for Duzi River

Time (min)	Umbilo perm	Run 1	Run 2	Run 3	Standard deviation
0	44820	235	247	220	13.52774926
15	1035	23	18	20	2.516611478
30	423	2	2	3	0.577350269
45	202	2	1	1	0.577350269
60	164	0	1	2	1
75	115	2	1	2	0.577350269
90	90	0	0	1	0.577350269
105	79	1	2	1	0.577350269
120	60	0	0	0	0

Table B-6: Effect of lime coating on *E. coli* removal for Umbilo River using WFM

Time	**Duzi perm**	**Run 1**	**Run 2**	**Run 3**	**Standard deviation**
0	5402	156	162	149	6.506407099
15	208	32	40	28	6.110100927
30	102	2	3	1	1
45	81	3	2	1	1.527525232
60	40	1	2	0	1
75	34	0	0	0	0
90	34	0	0	0	0
105	30	0	0	0	0
120	21	0	0	0	0

Table B-7: Effect of lime coating on *E. coli* removal for Town bush River WFM

Time	**Town Bush perm**	**Run I**	**Run 2**	**Run 3**	**Standard deviation**
0	445	3	4	3	0.577350269
15	235	2	1	2	0.577350269
30	110	0	0	0	0
45	80	0	0	0	0
60	50	0	0	0	0
75	45	0	0	0	0
90	41	0	0	0	0
105	21	0	0	0	0
120	5	0	0	0	0

The table in B-8 to B-11 are raw data on performance of the WFM on turbidity removal on the water sources investigated.

Table B-8 Turbidity removal on Duzi River

Duzi River				
Time (min)	**Run 1**	**Run 2**	**Run 3**	**Standard deviation**
0	80	126	140	31.39001965
10	1.2	0.9	0.82	0.200333056
20	0.8	0.56	0.78	0.133166562
30	0.76	0.46	0.82	0.192873015
40	0.51	0.51	0.78	0.155884573
50	0.38	0.45	0.41	0.035118846
60	0.34	0.47	0.58	0.120138809
70	0.3	0.56	0.47	0.132035349
80	0.25	0.3	0.39	0.070945989
90	0.32	0.32	0.38	0.034641016
100	0.34	0.29	0.42	0.065574385
110	0.36	0.31	0.24	0.060277138
120	0.31	0.27	0.36	0.045092498

Table B-9 Turbidity removal on Town River

Town Bush River				
Time (min)	**Run 1**	**Run 2**	**Run 3**	**Standard deviation**
0	1.4	1.38	1.4	0.011547005
10	1.32	1.31	1.32	0.005773503
20	1.11	1.1	1.1	0.005773503
30	1.08	1.09	1.08	0.005773503
40	1.1	1.1	1.1	0
50	0.88	0.86	0.87	0.01
60	0.7	0.71	0.71	0.005773503
70	0.62	0.62	0.62	0
80	0.6	0.58	0.58	0.011547005
90	0.54	0.53	0.53	0.005773503
100	0.5	0.49	0.49	0.005773503
110	0.48	0.46	0.46	0.011547005
120	0.42	0.42	0.42	0

Table B-10 Turbidity removal on Town Bush River

	Town Bush River			
Time (min)	**Run 1**	**Run 2**	**Run 3**	**Standard deviation**
0	10.8	14	12.4	0.144222051
10	2.79	2.51	2.71	0.005773503
20	1.9	1.89	1.9	0.037859389
30	1.56	1.49	1.5	0.057735027
40	1.1	1.1	1.2	0.021213203
50	0.95	0.92	0.89.	0.011547005
60	0.74	0.74	0.72	0.04
70	0.68	0.64	0.6	0.01
80	0.7	0.69	0.71	0
90	0.7	0.7	0. 64	0.04163332
100	0.62	0.6	0.54	0.023094011
110	0.65	0.61	0.61	0.064291005
120	0.58	0.56	0.68	0.064291005

Table B-11 Turbidity removal on Umbilo River

Umbilo River				
Time (min)	**Run 1**	**Run 2**	**Run 3**	**Standard deviation**
0	36	40	55	10.0166528
10	2.76	1.5	1.78	0.661614188
20	1.53	0.98	1.03	0.304138127
30	0.82	0.78	0.98	0.105830052
40	0.66	0.56	0.67	0.060827625
50	0.32	0.47	0.6	0.140118997
60	0.31	0.32	0.58	0.1530795
70	0.28	0.3	0.39	0.058594653
80	0.29	0.24	0.31	0.036055513
90	0.31	0.41	0.4	0.055075705
100	0.23	0.39	0.37	0.087177979
110	0.21	0.34	0.38	0.088881944
120	0.18	0.3	0.36	0.091651514

Appendix C Determination of chlorine residual and *E. coli* using waterguard only

Appendix C displays all the raw data on residual chlorine and *E. coli* removal using Chemical disinfectants.

The major aim of this section is to determine the effect of feed water quality on chlorine residual after disinfection and to also determine the dose of disinfectant that will produce the required residual of 0.2mg/l for point of use systems

Table C-1: Data for Chlorine residual on Tap water and the standard deviation

Concentration (mg/L))	**Run 1**	**Run 2**	**Run 3**	**Standard deviation**
0	0	0	0	0
7.26	0.07	0.07	0.07	0
14.52	0.2	0.23	0.21	0.015275252
21.78	0.24	0.24	0.26	0.011547005
29.04	0.37	0.39	0.36	0.015275252
36.3	0.41	0.4	0.4	0.005773503
50.82	0.5	0.51	0.5	0.005773503

Table C-2: Data for Chlorine residual on Town Bush River and the standard deviation

Concentration (mg/L)	**Run 1**	**Run 2**	**Run 3**	**Standard deviation**
0	0	0	0	0
7.26	0.025	0.023	0.25	0.130484993
14.52	0.1	0.1	0.1	1.69967E-17
21.78	0.15	0.15	0.16	0.005773503
29.04	0.2	0.23	0.23	0.017320508
36.3	0.23	0.25	0.23	0.011547005
50.82	0.25	0.25	0.24	0.005773503

Table C-3: Data for Chlorine residual on Umbilo River and the standard deviation

Concentration (mg/L))	Run 1	Run 2	Run 3	Standard deviation
0	0	0	0	0
7.26	0.02	0.021	0.024	0.002081666
14.52	0.08	0.082	0.081	0.001
21.78	0.12	0.122	0.0124	0.062708213
29.04	0.16	0.162	0.163	0.001527525
36.3	0.22	0.224	0.221	0.002081666
50.82	0.23	0.23	0.231	0.00057735

Table C-4: Data for Chlorine residual on Duzi River and the standard deviation

Concentration (mg/L))	Run 1	Run 2	Run 3	Standard deviation
0	0	0	0	0
7.26	0.01	0.02	0.01	0.005773503
14.52	0.05	0.05	0.049	0.00057735
21.78	0.09	0.091	0.09	0.00057735
29.04	0.12	0.12	0.121	0.00057735
36.3	0.17	0.175	0.172	0.002516611
50.82	0.22	0.22	0.225	0.002886751

***E. coli* removal using waterguard**

Removal of E. colifrom the various water sources using different concentration of *E. coli* is shown in Table C-5 to C-7 waterguard

Table C-5 shows raw data collected on *E. coli* deactivation on Duzi River.

Concentration (mg/L))	Run 1	Run 2	Run 3	Standard deviation
0	3102	3110	3107	4.041451884
7.26	784	782	779	2.516611478
14.52	352	349	352	1.732050808
21.78	68	62	62	3.464101615
29.04	12	13	12	0.577350269
36.3	5	4	4	0.577350269
50.82	0	0	0	0

Table C-6 shows the raw data on deactivation of *E. coli* on Umbilo River

Concentration (mg/L))	Run 1	Run 2	Run 3	Standard deviation
0	36541	36544	42123	3221.903526
7.26	1875	1900	1795	54.84827557
14.52	254	245	253	4.932882862
21.78	85	89	92	3.511884584
29.04	11	10	11	0.577350269
36.3	0	0	0	0
50.82	0	0	0	0

Table C-7 shows the raw data collected on deactivation of *E. coli* on Town Bush River

Concentration (mg/L))	**Run 1**	**Run 2**	**Run 3**	**Standard deviation**
0	408	466	399	36.36390151
7.26	23	28	25	2.516611478
14.52	4	3	3	0.577350269
21.78	2	1	2	0.577350269
29.04	0	0	0	0
36.3	0	0	0	0
50.82	0	0	0	0

Effect of contact

The effects of contact time on *E. coli* deactivation in this study are shown in the tables below. Table C-8 to C-12 illustrated the raw data on the effect of contact time on *E. coli* deactivation using 7.9mg/l.

Table C-8: Effect of contact time on Town bush River using 7.9 mg/l

Contact Time (min)	**Run 1**	**Run 2**	**Run 3**
0	15	12	15
5	6	6	7
10	1	1	1
15	1	1	0
30	1	1	1

Table C-9: Effect of contact time on Town bush River using 14.5 mg/l

Contact Time (min)	Run 1	Run 2	Run 3	Standard deviation
0	0	0	0	0
5	0	0	0	0
10	0	0	0	0
15	0	0	0	0
30	0	0	0	0

Table C-10: Effect of contact time on waterguard disinfection for Duzi River using 7.2 mg/l

Contact time (min)	Run 1	Run 2	Run 3	Standard deviation
0	112	114	116	2
5	54	52	54	1.154700538
10	10	8	11	1.527525232
15	0	0	0	0
30	0	0	0	0

Table C-11: Effect of contact time on waterguard disinfection for Duzi River using 14.2 mg/l

Contact Time(min)	Run 1	Run 2	Run 3	standard deviation
0	211	213	223	6.429100507
5	74	76	78	2
10	68	66	66	1.154700538
15	47	50	45	2.516611478
30	2	2	4	1.154700538

Table C-12: Effect of contact time on waterguard disinfection for Duzi River using 21.9 mg/l

Contact Time (min)	Run 1	Run 2	Run 3	Standard deviation
0	7	8	10	1.527525232
5	3	4	2	1
10	0	0	0	0
15	0	0	0	0
30	0	0	0	0

Table C-13: Effect of contact time on waterguard disinfection for Duzi River using 29.0 mg/l

Contact Time (min)	Run 1	Run 2	Run 3	Standard deviation
0	52	49	50	1.527525232
5	21	23	22	1
10	0	0	0	0
15	0	0	0	0
30	0	0	0	0

Table C-14: Effect of contact time on waterguard disinfection for Duzi River using 36.6 mg/l

Contact Time (min)	Run 1	Run 2	Run 3	Standard deviation
0	7	8	10	1.527525232
5	3	4	2	1
10	0	0	0	0
15	0	0	0	0
30	0	0	0	0

Table C-15: Effect of contact time on waterguard disinfection for Duzi River using 50.8mg

Contact Time (min)	**Run 1**	**Run 2**	**Run 3**	**Standard deviation**
0	1	2	1	0.577350269
5	0	0	0	0
10	0	0	0	0
15	0	0	0	0
30	0	0	0	0

Table C-16: Effect of contact time on waterguard disinfection for Umbilo River using 7.9mg/l

Contact time	**Run 1**	**Run 2**	**Run 3**	**Standard deviation**
0	3642	3622	3522	64.29100507
5	2872	2882	2850	16.37070554
10	1674	1660	1674	8.082903769
15	1256	1259	1250	4.582575695
30	1012	1010	1012	1.154700538

Table C-17: Effect of contact time on waterguard disinfection for Umbilo River using 14.2mg/l

Contact time	**Run 1**	**Run 2**	**Run 3**	**Standard deviation**
0	22	20	24	2
5	20	18	20	1.154700538
10	15	16	17	1
15	0	0	0	0
30	0	0	0	0

Table C-18: Effect of contact time on waterguard disinfection for Umbilo River using 21.9 mg/l

Contact time	**Run 1**	**Run 2**	**Run 3**	**Standard deviation**
0	20	22	19	1.527525232
5	17	17	18	0.577350269
10	8	7	9	1
15	0	0	0	0
30	0	0	0	0

Table C-19: Effect of contact time on waterguard disinfection for Umbilo River using 29.9 mg/l

Contact time	Run 1	Run 2	Run 3	Standard deviation
0	20	22	19	1.527525232
5	17	17	18	0.577350269
10	8	7	9	1
15	0	0	0	0
30	0	0	0	0

Table C- 20: Effect of contact time on waterguard disinfection for Umbilo River using 36.6 mg/l

Contact time	Run 1	Run 2	Run 3	standard deviation
0	0	0	0	0
5	0	0	0	0
10	0	0	0	0
15	0	0	0	0
30	0	0	0	0

Table C-21: Effect of contact time on waterguard disinfection for Umbilo River using 50.82 mg/l

Contact time	Run 1	Run 2	Run 3	Standard deviation
0	0	0	0	0
5	0	0	0	0
10	0	0	0	0
15	0	0	0	0
30	0	0	0	0

Appendix D Performance of RRWTS on *E. coli* removal

This appendix shows the raw data on the efficiency of the RRWTS (Combination of WFMF and Chemical disinfection) to remove *E .coli*.

Table D- 1: Performance of the RRWTS on *E. coli* removal using different concentration of waterguard on Duzi River

Concentration (mg/l)	**Run 1**	**Run 2**	**Run 3**	**Standard deviation**
0	5402	5329	5402	42.14656965
7.26	12	14	11	1.527525232
14.52	5	3	5	1.154700538
21.78	0	0	0	0
29.04	0	0	0	0
36.3	0	0	0	0
50.82	0	0	0	0

Table D- 2: Performance of the RRWTS on *E. coli* removal using different concentration of waterguard on Umbilo River

Concentration (mg/l)	**Run 1**	**Run 2**	**Run 3**	**Standard deviation**
0	44520	44411	44520	62.93117934
7.26	25	22	25	1.732050808
14.52	1	1	0	0.577350269
21.78	0	0	0	0
29.04	0	0	0	0
36.3	0	0	0	0
50.82	0	0	0	0

Table D- 3: Performance of the RRWTS on *E. coli* removal using different concentration of waterguard on Town Bush River

Concentration (mg/l)	**Run 1**	**Run 2**	**Run 3**	**Standard deviation**
0	824	799	802	13.65039682
7.26	21	24	21	1.732050808
14.52	0	0	0	0
21.78	0	0	0	0
29.04	0	0	0	0
36.3	0	0	0	0
50.82	0	0	0	0

Table D- 4: Performance of the RRWTS on *E. coli* removal using different concentration of waterguard on Synthetic feed

Concentration (mg/l)	**Run 1**	**Run 2**	**Run 3**	**Standard deviation**
0	36214	36200	36159	28.58321186
7.26	72	69	70	1.527525232
14.52	15	14	15	0.577350269
21.78	5	4	5	0.577350269
29.04	0	0	0	0
36.3	0	0	0	0
50.82	0	0	0	0

Appendix E Effect of cleaning on *E. coli* and flux recovery with MFM

This section shows the raw data collected on the effect of cleaning on *E. coli* removal and flux recovery using the WFM.

Table E-1: Effect cleaning on *E. coli* removal and flux recovery using WFM

Running time (min)	Run 1	Run 2	Run 3	Standard deviation
0	5402	5229	5400	99.3092812
10	208	210	206	2
20	102	100	96	3.055050463
30	81	81	78	1.732050808
40	40	39	39	0.577350269
50	34	33	29	2.645751311
60	34	31	29	2.516611478
70	4682	4680	4682	1.154700538
80	168	170	165	2.516611478
90	92	89	87	2.516611478
100	56	53	55	1.527525232
110	41	39	39	1.154700538
120	22	21	22	0.577350269
130	15	13	14	1
140	5601	5600	5590	6.08276253
150	324	322	3200	1661.037025
160	110	109	112	1.527525232
170	56	52	54	2
180	23	22	19	2.081665999
190	15	15	16	0.577350269
200	9	9	9	0

Appendix F Performance of bromochlor tablets on residual chlorine and *E. coli* removal

This appendix shows the raw data on disinfection using bromochlor tablet both as a chemical disinfectant alone and in combination with WFM.

Table F-1-F-4: Raw data on residual chlorine using bromochlor tablet at an average flow rate of 20 l/h

Table F-1: Effect of tablet size on residual chlorine on Tap water

Bromo Size (g)	Run 1	Run 2	Run 3	Standard deviation
0.1	0	0	0	0
0.3	0.24	0.26	0.24	0.011547005
0.5	0.32	0.31	0.3	0.01
0.75	0.72	0.72	0.74	0.011547005

Table F-2: Effect of tablet size on residual chlorine on Town Bush River

Bromo Size (g)	Run 1	Run 2	Run 3	Standard deviation
0.1	0	0	0	0
0.3	0.18	0.18	0.19	0.005773503
0.5	0.22	0.24	0.25	0.015275252
0.75	0.68	0.7	0.68	0.011547005

Table F-3: Effect of tablet size on residual chlorine on Umbilo River

Bromo Size (g)	Run 1	Run 2	Run 3	Standard deviation
0.1	0	0	0	0
0.3	0.1	0.11	0.12	0.01
0.5	0.2	0.22	0.2	0.011547005
0.75	0.38	0.38	0.36	0.011547005

Table F-4: Effect of tablet size on residual chlorine on Duzi River

Bromo Size (g)	Run 1	Run 2	Run 3	Standard deviation
0.1	0	0	0	0
0.3	0.08	0.09	0.1	0.01
0.5	0.14	0.13	0.15	0.01
0.75	0.28	0.27	0.28	0.005773503

E. coli removal with Bromochlor tablets alone

Tables F-5 to F-7: Shows the raw data on *E. coli* disinfection using different sizes of Bromochlor tablets.

Table F-5 presents raw data obtained from disinfection of Town Bush River

Bromo size (g)	Run 1	Run 2	Run 3	Standard deviation
0	621	615	600	10.81665383
0.1	105	105	108	1.732050808
0.3	35	37	37	1.154700538
0.5	0	0	0	0
0.75	0	0	0	0

Table F-6 presents raw data obtained from disinfection of Umbilo River

Bromo size (g)	Run 1	Run 2	run 3	Standard deviation
0	44500	44325	44300	108.9724736
0.1	3412	3400	3410	6.429100507
0.3	164	160	164	2.309401077
0.5	36	34	37	1.527525232
0.75	0	0	0	0

Table F-7 presents raw data obtained from disinfection of Duzi River

Bromo size (g)	Run 1	Run 2	Run 3	Standard deviation
0	3254	3250	3200	30.08875759
0.1	2342	2339	2340	1.527525232
0.3	360	355	360	2.886751346
0.5	92	90	87	2.516611478
0.75	0	0	0	0

E. coli Removal using RRWTS with Bromochlor tablets

Tables F-7 to F10: Raw data on *E. coli* removal using the RRWTS with Bromochlor tablet as the chemical disinfectant.

Table F-7 presents raw data on *E. coli* removal using the RRWTS with Bromochlor tablet on Duzi River.

Tablet size (g)	Run 1	Run 2	Run 3	Standard deviation
0	5402	5329	5402	42.14656965
0.1	21	19	17	2
0.3	4	3	3	0.577350269
0.5	0	0	0	0
0.75	0	0	0	0

Table F-8: Raw data on *E. coli* removal using the RRWTS with Bromochlor as the chemical disinfectant on Umbilo River

Tablet size (g)	Run 1	Run 2	Run 3	Standard deviation
0	44500	44411	44520	58.02585631
0.1	34	28	35	3.785938897
0.3	2	2	1	0.577350269
0.5	0	0	0	0
0.75	0	0	0	0

Table F-9: Raw data on *E. coli* removal using the RRWTS with Bromochlor as the chemical disinfectant on Town Bush River

Tablet size (g)	Run 1	Run 2	Run 3	Standard deviation
0	824	799	802	13.6504
0.1	0	0	0	0
0.3	0	0	0	0
0.5	0	0	0	0
0.75	0	0	0	0

Table F-10: Raw data on *E. coli* removal using the RRWTS with Bromochlor as the chemical disinfectant on Synthetic feed

Tablet size (g)	Run 1	Run 2	Run 3	Standard deviation
0	36214	36200	36159	28.58321186
0.1	56	62	52	5.033222957
0.3	2	2	3	0.577350269
0.5	0	0	0	0
0.75	0	0	0	0