Development and optimization of a combined small scale low cost point of use water treatment system

by

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Abstract

Access to safe drinking water is still limited in many rural and suburban areas of developing countries. Point-of-use (PoU) water treatment is the most feasible solution to fight waterborne diseases which pose a serious threat in such areas. Only user friendly, affordable and grid-independent but effective approaches are deemed feasible for poorer communities. Although efforts to develop cost-effective PoU technologies are underway globally, challenges still exist. This study was aimed at developing a combined small-scale low-cost gravity-driven PoU system able to provide bacteriologically safe and aesthetically acceptable drinking water.

A range of PoU system configurations were developed and tested. Knowledge gained culminated in the development of a final novel PoU system incorporating silver-coated ceramic granular media (SCCGM) for filtration and inbuilt disinfection, geotextile for pre-filtration (to significantly reduce particulate loads in the water before it passes through the SCCGM thereby increasing pathogen contact with the silver), granular activated carbon (GAC) as an adsorption media (for improving aesthetic aspects and removal of selected heavy metals), and a built-in storage compartment for treated water. No chemical addition is needed. It is a replicable, scalable, and user and environmentally friendly cost-effective technology primarily for particle and bacterial removal and aesthetic improvement. Geotextile and GAC filtration steps enhanced the system's ability to treat a broader variety of raw water and extended filter runs. Laboratory tests on the system showed high potential for significant *E.coli* and fecal coliforms removal (>99.99%) at an optimum flow of 2 L/h. In addition, the system exhibited substantial improvements of aesthetic aspects (color, odor and taste) with average turbidity removals of 99.2%.

Mathematical modelling was done using *E.coli* as an indicator organism to aid in optimization of the final novel PoU system and to support future research in terms of configuration, process combination, flow rate, material combination, etc. The system was modelled as a series of three compartments using suitable disinfection kinetic models for silver inactivation and specialized colloidal filtration theory models for fibrous and granular filtration. The modelling demonstrated that suitable removal mechanisms can be applied integrally to model a combined PoU system to predict overall effluent bacterial quality. Such modelling can be used to optimize similarly combined systems by allowing engineers to systematically vary design parameters until desired system effectiveness is attained.

The system was developed after investigation and evaluation of local treatment materials and approaches over a period of 18 months, which resulted in three simple, yet innovative water treatment systems namely the: (i) modified intermittently operated slow sand filtration system incorporating geotextile and GAC (ISSFGeoGAC), (ii) eight-layer four-pot bidim sequential filtration (BidimSEQFIL) system, and (iii) wood filtration system combined with GAC (WFSGAC). The ISSFGeoGAC and WFSGAC were designed for removal of bacteria, particles, color, taste, odor and selected heavy metals while BidimSEQFIL was designed for particle and bacterial removal. These were then comparatively evaluated alongside two commercially available PoU systems using a comparison framework developed in this study for evaluating low-cost PoU technologies.

The findings will be helpful to engineers, NGOs, etc. for possible application of the novel systems, modelling and optimization of combined PoU systems, and comparative evaluation of low-cost PoU systems.

Opsomming

Toegang tot veilige drinkwater is steeds beperk in baie landelike en stedelike gebiede van ontwikkelende lande. Gebruikspunt (GP) watersuiwering is die mees haalbare oplossing om wateroordraagbare siektes te beveg wat 'n ernstige bedreiging is in sulke areas. Slegs gebruikersvriendelike, bekostigbare en formele sisteem onafhanklike, maar effektiewe benaderings word as haalbaar beskou vir armer gemeenskappe. Hoewel pogings om kostedoeltreffende GP-tegnologieë wêreldwyd te ontwikkel tans bestaan, is daar steeds uitdagings. Hierdie studie was daarop gemik om 'n gekombineerde lae-koste swaartekrag-aangedrewe GP-stelsel op klein skaal te ontwikkel wat in staat is om bakteriologies veilige en esteties aanvaarbare drinkwater te voorsien.

‘n Reeks GP-stelsel konfigurasies was ontwikkel en getoets. Kennis hierdeer verkry was verder gebruik in die verdere ontwikkeling van ‘n nuwe GP-stelsel bestaande uit silwerbedekte keramiek granulêre media (SBKGM) vir filtrasie en ingeboude ontsmetting, geotekstiel vir prefiltrasie (om partikels in die water aansienlik te verminder voordat dit deur die SBKGM beweeg, waardeur die kontak met die silwer verhoog word), granulêre geaktiveerde koolstof (GAK) as 'n adsorpsiemedium (vir die verbetering van estetiese aspekte en verwydering van geselekteerde swaar metale), en 'n ingeboude stoorkompartement vir behandelde water. Geen chemikaliese toevoeging is nodig nie. Die ontwikkelde stelsel is 'n herhaalbare, skaalbare, gebruikersvriendelike en omgewingsvriendelike koste-effektiewe tegnologie. Dit kan hoofsaaklik vir verwydering van partikels en bakterieë sowel as estetiese verbetering van drinkwater toegepas word. Geotekstiel en GAK-filtrasiestappe het die stelsel se vermoë verbeter om 'n groter verskeidenheid rou water en uitgebreide filterlopies te behandel. Laboratoriumtoetse op die stelsel het 'n potensiaal uitgewys vir beduidende verwydering van *E.coli* en fekale koliforme (> 99,99%) met 'n optimale vloei van 2 L/h. Boonop het die stelsel aansienlike verbeterings aan estetiese aspekte (kleur, reuk en smaak) getoon, met 'n gemiddelde verwydering van troebelheid van 99,2%.

Wiskundige modellering is gedoen met gebruik van *E.coli* as 'n indikatororganisme om die finale nuwe GP-stelsel te optimaliseer en om toekomstige navorsing ten opsigte van konfigurasie, proseskombinasie, vloeitempo, materiaalkombinasie, ens. te ondersteun. Die stelsel is gemodelleer as 'n reeks van drie kompartemente met gebruik van geskikte ontsmettings kinetiese modelle vir inaktivering met silwer sowel as gespesialiseerde kolloïdale filtrasie teorie modelle vir vesel- en granulêre-filtrasie. Die modellering het aangetoon dat geskikte verwyderings meganismes integraal toegepas kan word om 'n gekombineerde GP-stelsel te modelleer om die uitvloeiwater bakteriele inhoud te voorspel. Hierdie tipe modellering kan gebruik word om soortgelyke gekombineerde GP-stelsels te optimaliseer deur ingenieurs in staat te stel om die ontwerpparameters stelselmatig te wissel totdat die gewenste stelseldoeltreffendheid bereik word.

Die finale GP-stelsel is ontwikkel na die ondersoek en evaluering van plaaslike behandelingsmateriaal en benaderings oor 'n periode van 18 maande. Dit het gelei tot drie nuwe eenvoudige, dog innoverende waterbehandelingstelsels, naamlik: (i) ‘n gewysigde, tussenpose bedryfde, stadige sandfiltrasiestelsel met geotekstiel en GAK (TSSFGeoGAK), (ii) ‘n ag-laag, vier pot “bidim” opeenvolgende filtrasie stelsel (BidimOFIL), en (iii) ‘n houtfiltrasiestelsel gekombineer met GAK (HFSGAK). Die TSSFGeoGAK en HFSGAK was ontwerp vir die verwydering van bakterieë, partikels, kleur, smaak, geur en geselekteerde swaar metale; terwyl BidimOFIL ontwerp is vir die verwydering van partikels en bakterieë. Hierdie sisteme was vergelykend geëvalueer saam met twee kommersieel beskikbare GP-stelsels met behulp van 'n vergelykingsraamwerk wat in hierdie studie ontwikkel is vir hierdie doel.

Die bevindinge is nuttig vir ingenieurs, NROs, ens. vir die moontlike toepassing van die nuwe GP-stelsels, modellering en optimalisering van gekombineerde GP-stelsels, en vergelykende evaluering van lae-koste GP-stelsels.

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May the Almighty JEHOVAH God Bless you All.

Dedication

This PhD dissertation is especially dedicated to Jehovah God Almighty for His Tender Mercies, Unmerited Favor, Gracious Love, Provision and Protection. 1 Chronicles 29:11-13.

And to

My wife and children for their love and support as well as for wholeheartedly and blessedly staying with me in South Africa throughout my study period. Jude 1:25.

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List of Abbreviations

BidimSEQFIL	Bidim sequential filtration
CAWST	Center for Affordable Water and Sanitation Technology
CCF	Ceramic Candle Filter
CFU	Colony Forming Units
CPF	Ceramic Pot Filter
DBPs	Disinfection by-products
DFS	Drip Filter System
DO	Dissolved oxygen
E. coli	*Escherichia coli*
EAWAG	Swiss Federal Institute of Aquatic Science & Technology
EBCT	Empty bed contact time
ES	Effective Size
GAC	granular activated carbon
Geo	Geotextile fabric
GWI	Gift of Water Inc.
GWS	Gift of Water System
HAAs	Halo acetic acids
HClO	Hypochlorous acid
HWTS	Household water treatment and safe storage
ISSF	intermittently operated slow sand filtration
ISSFGeoGAC	ISSF system incorporating geotextile fabric and GAC
IWA	International Water Association
JMP	Joint Monitoring Programme for Water Supply and Sanitation
LoD	Limit of Detection
LRV	Log removal value
NaDCC	Sodium Dichloroisocyanurate
NGOs	Non-governmental organizations

NOM	Natural Organic Matter
NTU	Nephelometric Turbidity Units
P & G	Procter and Gamble Company
PET	Polyethylene Terephthalate
PoU	Point of Use
PoUs	Point of Use systems
PSD	Particle size Distribution
PVC	Polyvinyl Chloride
RO	Reverse osmosis
RSF	Rapid Sand filter
SANDEC	Department of Water and Sanitation in Developing countries of EAWAG
SANS	South African National Standards
SCCGM	Silver-coated ceramic granular media
SCE	Single collector efficiency
SSF	Slow sand filtration
TDS	Total Dissolved Solids
TE model	Tufenkji and Elimelech model
THMs	Trihalomethanes
TSS	Total Suspended Solids
UC	Uniformity Coefficient
USD	United States dollars
WEF	Water Environment Federation
WFS	Wood filtration system
WFSGAC	Wood filtration system combined with GAC
WHO	World Health Organization
WISA	Water Institute of Southern Africa
ZAR	South African Rand

List of Symbols

c_s	Cunningham correction factor [-]
D_{BM}	Brownian diffusivity (m^2/s)
d_c	Collector diameter (m)
d_f	Fiber diameter (m)
d_p	Particle diameter (m)
H_a	Hamaker constant (J)
k_B	Boltzmann constant (1.381×10^{-23}J/K)
N_{pe}	Peclet number [−]
A_s	A hydrodynamic parameter for the Kuwabara cylinder-in-cell model
D_L	Diffusion coefficient (m^2/s)
N_A	Attraction number [-]
N_G	Gravitational parameter [-]
N_{LO}	London–van der Waals force parameter [-]
N_R	Interception parameter [-]
N_e	Effluent *E.coli* count [CFU/100 ml]
N_o	Influent *E.coli* count [CFU/100 ml]
N_{vdw}	*van der Walls number* [-]
V_F	GAC filtration rate (m/s)
V_s	Stokes' settling velocity (m/s)
a_p	Particle radius (m)
k_o	Mortality or inactivation rate (CFU inactivated/ min)
u_s	Geotextile filtration velocity (m/s)
η_D	Collection efficiency due to diffusion [-]
η_G	Collection efficiency due to gravity [-]
η_I	Collection efficiency due to interception [-]
ρ_p	Particle density (kg/m^3)
ρ_w	Density of water (kg/m^3)
ΔH	Total head loss in m
A	Filter cross-sectional area (m^2)

C	Concentration of disinfectant [mg/L]
C_1, C_2, C_3, C_4	hydrodynamic coefficients of the fibrous media stream function
C_e	Concentration of contaminant in treated water
C_i	Concentration of contaminant in untreated water
D	Internal pipe diameter in m
dx	Filter element length (m)
f	Darcy friction factor
g	Gravitational acceleration (m/s^2)
h	Filter bed height (m)
H	Head loss in m
K_{cw}	Specific lethality [L/(mg.min)]
L	Pipe length in m
L_f	Fibrous filter thickness (m)
N	*E.coli* count (CFU/100 ml)
P	Applied pressure in Pa
Q	Flow rate in m^3/s
Re	Reynolds number
T	Absolute temperature, K (273+^{o} C)
t	Contact time [s]
v	Filtration velocity (m/h)
V_{GAC}	Volume of granular activate carbon
V_{media}	Column volume occupied by filter media (m^3)
α	Attachment efficiency or adhesion probability [-]
γ	Porosity coefficient [-]
ε	Porosity of filter media [-]
η	Collector efficiency [-]
μ	Absolute viscosity of water (kg/m-s)
ρ	Density of water in kg/m^3
Φ	Solidity (packing density) (m^3/ m^3) = 1-ε
$\boldsymbol{\ell}$	Mean free path of water molecules (m)
λ	Filter coefficient (m^{-1})

Chapter 1: Introduction

1.1 Background and motivation

Availability of safe drinking water is a challenge in rural and suburban areas of developing countries (Pandit and Kumar 2019; Treacy 2019). Many such communities do not have access to safe drinking water supplies and fecal contamination is widespread (Gadgil 1998; Supong *et al.* 2017). Poor hygienic practices like open drainage systems, open defecation, careless garbage disposal, washing and bathing near or at drinking water sources are prevalent (Harvey *et al.* 2019; Kausley *et al.* 2015), causing a range of pollutants to enter water sources (Pandit and Kumar 2019; Treacy 2019). Mortality rates from contaminated water are correspondingly high, with communicable diseases a serious threat (Demena *et al*. 2003; Eitner and Kondruweit-Reinema 2019). Governments in developing countries worldwide struggle with inadequate resources and infrastructure to meet drinking water needs for all citizens (Savage 2018) and some people have to walk long distances to find drinking water (Savage 2018). Point-of-use (PoU) drinking water treatment technologies are a viable solution to fight waterborne diseases in under-resourced rural and suburban areas (Kausley *et al.* 2018).

While PoU systems are not a replacement for formalized provision of safe drinking water, they are considered to be important interim and immediate solutions for communities where centralized treatment systems are not feasible, difficult or costly (Brown *et al.* 2019; WHO 2016). Centralized treatment is usually expensive in rural areas due to remote locations, lack of trained personnel and skilled labour, as well as limited energy and financial resources (Baig *et al.* 2011; Pandit and Kumar 2019). Although some suburban areas in poor countries are serviced with piped water from centralized treatment systems, the quality of the supplied water is often suspect due to insufficient treatment or recontamination during distribution or storage (Chaudhuri and Sattar 1990). PoU systems are also valuable to areas with intermittent water supply (IWS) (Bivins *et al.* 2017). IWS systems are exposed to higher bacterial contamination and pose risk of waterborne diseases (Bivins *et al.* 2017). This is due to water intrusion from outside the supply pipes during low-pressure events, biofilm scouring during re-pressurization, bacterial regrowth during stagnant periods, and water storage due to erratic supply (Bivins *et al.* 2017; Kumpel and Nelson 2014). Additionally, PoU systems are useful during natural disasters such as floods, earthquakes, and hurricanes, which often damage water supply infrastructure and disrupt safe water delivery or impair its quality (Brown *et al.* 2019; Gerba and Naranjo 2000; Ray and Jain 2014).

Although the priority of most PoU water treatment systems is to produce microbiologically safe water (CAWST 2017a; McAllister 2005; WHO 2017a), the water must be aesthetically acceptable and therefore free from apparent turbidity, color, odor and objectionable taste (CAWST 2017a; Hammer and Hammer 2012; Nathanson and Schneider 2015). In addition, particles that cause turbidity often hinder bacterial disinfection (Nathanson and Schneider 2015; WHO 2017b). Furthermore, turbidity, color, odor and taste in water can motivate people to use water from sources that, while aesthetically more acceptable, may be of poorer quality and unsafe (CAWST, 2017a; WHO, 2017b, 2017a). Similarly, iron and manganese may not cause health problems but can impart a bitter taste or odor to treated water as well as discoloration (CAWST 2017a; Nathanson and Schneider 2015; WHO 2017a). Efforts should therefore be made to enhance PoU system removal of said contaminants by a careful combination of water treatment materials or steps that can remove them.

Some technologically advanced commercial PoU systems such as reverse osmosis, nanofiltration, ozonation, ion-exchange, pasteurization and ultraviolet disinfection exist (de Moel *et al.* 2007; Gadgil 1998; Lykins and Clark 1992; Pizzi 2010; Ritter 2010; WHO 2017a, 2016). They can treat various types of raw water but are expensive and often unsuitable for application in poorer communities (Chaudhuri and Sattar 1990; Kausley *et al.* 2015; McAllister 2005). These types of PoU systems normally require electricity and adequate tap water pressure, which are often unreliable or absent in poor communities. They are generally costly to run and difficult to operate and maintain (Kausley *et al.* 2015; Kim *et al.* 2016). Conversely, simple but effective, affordable, grid-independent and user friendly systems, such as PoU systems, can be more feasible for application in poorer communities (Kausley *et al.* 2018; Pandit and Kumar 2019).

A few promising PoU water technologies appropriate to poorer groups exist which have varying degrees of success (see CAWST 2017b; Kausley *et al.* 2018; Pandit and Kumar 2019; Treacy 2019; WHO 2017a). These include ceramic pot filters (CPFs), ceramic candle filters (CCFs), biosand filters (BSFs), boiling, chlorine tablets or liquids, cloth filtration, solar disinfection and sedimentation. However, these have been shown to have numerous limitations in consistently supplying safe water and are normally applied as singular steps, which reduces their contaminant removal potential. The recontamination potential for most of these systems is high especially in the absence of built-in storage. This minimizes the intended health impact. In addition, water treatment methods that chiefly rely on continuous chemical addition to deliver safe water pose a possible health hazard in most developing communities (Ellis 1991). Daily use of chemicals also increases running costs and presents a supply chain dependency (Harvey *et al.* 2019), which may not be sustainable in poorer groups. Therefore, a PoU system with an inbuilt disinfection step is preferred.

CPFs and CCFs vary in quality when made locally, are easily breakable, clog quickly and therefore, require frequent cleaning, have no residual disinfectant and their pathogen removal performance is often poor (Kausley *et al.* 2015, 2018). Turbid water slows down their filtration rates (Zinn *et al.* 2018). In addition, user education is vital for correct filter cleaning to minimize clogging and avoid biofilm buildup (Mihelcic *et al.* 2009; Zinn *et al.* 2018). Similarly, BSFs have various limitations such as (CAWST 2011, 2010; Lantagne *et al.* 2006; Singer *et al.* 2017): (i) there is a need for biolayer growth and its proper management, (ii) there is need for a 30 day waiting period for the biolayer to develop to maturity before significant pathogen removals, (iii) without a pause period bacterial removal rate is low, (iv) aesthetic improvement in the treated water is inconsistent, (v) virus removal is ineffective, (vi) scraping or “swirl and dump” cleaning techniques are quite tedious, (vii) after surface maintenance the filter takes some time before recovery in flow rate and bacterial removal efficiency (Singer *et al.* 2017), and (viii) recontamination potential is high if sand replacement is not done on time or if bacterial inactivation is insufficient (Zinn *et al.* 2018).

Boiling destroys nearly all pathogens. However, it uses a lot of energy (charcoal, wood or electricity), does not improve aesthetic aspects of water, and it is time consuming to boil and cool down the water (Backer 2002; Kausley *et al.* 2018; Sodha *et al.* 2011). Boiled water tastes flat and is susceptible to recontamination due to unsafe handling and need for separate storage (Jagals *et al.* 2003; Kausley *et al.* 2018; Supong *et al.* 2017; WHO 2016), and the water to be boiled needs to be clear, often necessitating pretreatment. Additionally, boiling uses stoves and fuels, which lead to environmental impacts including contribution to climate change (Sodha *et al.* 2011; WHO 2016). It also has high risk for burn injuries and respiratory diseases from indoor fires or stoves (Lantagne and Clasen 2009). Chances of incomplete pathogen removal increase if water is not brought to full boiling temperature (Lantagne and Clasen 2009).

Chlorine tablets or liquids used to disinfect water are appropriate to poorer communities. However, these (Backer 2000; Harvey *et al.* 2019; Kausley *et al.* 2015, 2018; Lantagne *et al.* 2006; Supong *et al.* 2017): (i) are not effective against protozoan cysts, (ii) require some level of education to ensure correct dosing, (iii) often impart unpleasant taste and smell to the water and the chlorinated water may therefore be rejected by users who have not been well informed, (iv) may at times cause some consumers to think a chlorine taste in the water signifies that it has been disinfected, while water can still taste of chlorine even if the chlorine amounts added are not enough to disinfect the water, (v) generally require water of low turbidity and organics to be effective, (vi) have running costs (i.e. need continuous supply of chemicals) and availability limitations, (vii) require proper storage and handling because chlorine is very toxic, hence might not be safe to uneducated users, and (viii) have potential for carcinogenic effects due to disinfection by-products especially if continuously overdosed (Kausley *et al.* 2018; Lantagne *et al.* 2006; Ray and Jain 2014).

Cloth filters such as cotton and silk are also applicable to poor communities and can be used to reduce turbidity and remove larger microbes (e.g. protozoa and helminths), thereby preventing illnesses such as cholera and Guinea worm (Mihelcic *et al.* 2009; Thompson 2014). However, cloth filters may possibly not reliably supply safe water due to pore sizes being too large to adequately remove bacteria and viruses (Mihelcic *et al.* 2009; Thompson 2014). In addition, cloth fabrics normally loosen significantly the more they are used and washed, increasing their pore size and becoming less effective (Mihelcic *et al.* 2009; Shrestha and Spuhler 2018; SWICH 2018). Cloth fabrics also have to be disinfected after every use and must be used with the same side up (Mihelcic *et al.* 2009) making it tedious for many users.

Solar disinfection is another technique applicable to poor communities. Plastic bottles are filled with water and exposed to sunlight for about six hours (CAWST 2011; Harvey *et al.* 2019; Kausley *et al.* 2018). The method has various limitations such as (CAWST 2011; Kausley *et al.* 2018; Lantagne *et al.* 2006): (i) it is only effective on clear water (even water that is slightly dirty has to be pretreated), (ii) it treats small volumes of water about 0.25-5 L over a long waiting period (Kausley *et al.* 2018), (iii) needs a continued supply of clean, intact and properly sized plastic bottles, (iv) it depends on sunshine intensity which differs across regions and seasons, (v) sunlight transmission and inactivation efficiency are reduced if the bottles are scratched, or due to labels on reused bottles or their remnants (Thompson 2014), (vi) bacterial regrowth and cross contamination if disinfection is weak (Thompson 2014), (vii) determination of the point at which the water treatment should end is difficult on cloudy days, (viii) treated water needs to be cooled before consumption, (ix) cannot be used during times of continuous rainfall, and (x) possible leaching of bottle material and introduction of photoproducts into treated water (Thompson 2014).

Sedimentation (or three-pot settling) is another water treatment method applicable to poorer groups whereby suspended particles able to settle by gravity (e.g., sand, silt, and large microbes) are removed from the raw water by allowing them to settle to the bottom of a water storage container (Backer 2002, Mihelcic *et al.* 2009). This is done by letting the container sit undisturbed for a minimum of one hour until a layer of sediment has formed at the bottom and decanting the supernatant (clear water) into a clean container (Backer 2002, Mihelcic *et al.* 2009). Usually three containers are used in which case the clarified water is decanted from the first through the second to the last container which then stores the treated (clear) water. However, the method (Backer 2002, Mihelcic *et al.* 2009): (i) does not reliably remove bacteria or small particles, (ii) requires a very long time (up to 48 hours) for appreciable amounts of suspended matter to settle out, (iii) usually requires transparent containers for easy process monitoring, (iv) needs frequent and proper cleaning of the containers; improper cleaning or disinfection may lead to recontamination, (v) requires careful handling to ensure that the layer of sediment is not disturbed so that settled particles are not resuspended, (vi) always requires disinfection by e.g. chlorination or boiling for its clarified water.

Since filtration based methods are generally cheaper, simpler, and more robust than other treatment techniques (Moran 2018), systems using appropriate combinations of filtration methods are attractive for applications in poor communities. Consequently, filtration based PoU systems are often more appropriate and preferable in poor communities. It was therefore decided to primarily investigate and optimize filtration based PoU systems in this research. Moreover, affordable materials such as sand, charcoal, biochar, rice husk ash, fly ash and cloth fabrics are feasible filtration media for water treatment in developing countries (Kausley *et al.* 2018). Additionally, ceramic granular media (Choi *et al.* 2014; Harvey *et al.* 2019), wood xylem filters (Boutilier *et al.* 2014; Sens *et al.* 2013; Siwila and Brink 2018a) and non-woven geotextile (Siwila and Brink 2018b) are emerging effective filter media with high potential for low-cost applications.

However, filter materials are generally more effective for removal of particles and less effective for removal of other contaminants (Kausley *et al.* 2018). Conversely, PoU systems made from impregnating effective filter media with metal disinfectants such as copper and silver (Bell 1991; Kausley *et al.* 2018; Rossainz-Castro *et al.* 2016; Singh *et al.* 2019) can conceivably be effective for combined removal of microbes and particles. Furthermore, it was thought in this study that, additional steps employing pre-filtration by fabrics such as bidim geotextile and further filtration by adsorption media such as granular activated carbon (GAC) can substantially improve aesthetic aspects (turbidity, color, taste and smell) and removal of other contaminants such as iron and manganese as well as excessive disinfectants added to water. It was consequently determined to incorporate the said materials and steps in the final developed system of this research. This was primarily based on knowledge gained from an intensive literature review on the applications as well as strengths and weaknesses of available low-cost PoU systems, laboratory comparisons of two similarly combined commercial PoU systems (presented in Chapter 2) and research on a wider range of local PoU filtration materials and methods (presented in Chapters 3, 4, 5 and appendix A).

The South African National Standards (SANS) 241 and the World Health Organization (WHO) guidelines recommend 0 CFU/100 ml of *E.coli* and fecal coliforms in drinking water. Therefore, an appropriately combined and optimized low-cost PoU system is expected to consistently and affordably supply water of good aesthetic quality with turbidity < 5 NTU and 0 CFU/100 ml *E.coli* and fecal coliforms.

Therefore, in this study, a range of low-cost treatment methods and technologies for application in Point of Use systems were investigated, specifically for application in the Southern African region. Local materials were sourced and different PoU system configurations were experimented with. Knowledge gained from these experiments was further used to develop a specialized comparison framework to aid in the choice of materials and systems to use depending on the application. The experimental work further led to the design, optimization and modelling of a final novel combined PoU system.

The experimental investigation of locally available materials and locally applicable processes initially resulted in the development of three simple, yet innovative water treatment systems namely the: (i) Modified intermittently operated slow sand filtration system incorporating geotextile and GAC for removal of bacteria, particles, color, taste, odor and selected heavy metals, (ii) eight-layer four-pot bidim sequential filtration system for bacteria and particle removal and, (iii) indigenous wood filtration combined with GAC for removal of bacteria, color, taste, odor, particles and selected heavy metals. These were then comparatively evaluated using the novel comparison framework developed in this study as mentioned above.

Finally, the knowledge gained in the experimental investigation and comparison framework results was further applied in developing a novel combined PoU system incorporating non-woven geotextile fabric, silver-coated ceramic granular media (SCCGM), Granular Activated Carbon (GAC) and a built-in safe storage compartment. It has been developed and optimized to produce bacteriologically safe water at an optimized filtration rate of 2 L/h. SCCGM was used for filtration and inbuilt disinfection; and non-woven geotextile fabric was used for pre-filtration (to remove debris and larger microbes e.g. helminths and protozoa) as well as reduce particulate loads in the water before it passes through the SCCGM, thereby increasing pathogen contact with the silver. GAC was used as an adsorption media for improving aesthetic aspects and possible removal of selected heavy metals. The storage compartment was used for storing treated water to minimize recontamination. A range of numerical modelling approaches were furthermore tested on the data generated by this system and applicable modelling approaches were presented.

1.2 Problem and Thesis statement

Problem statement

Access to safe drinking water is still limited in developing countries. Globally, around 780 million rural and 136 million urban dwellers lack access to improved drinking water supply (RWSN 2010). In sub-Saharan Africa, the discrepancy is even bigger with 272 million rural population lacking access to safe water, compared to 54 million in urban areas (RWSN 2010). Consumption of contaminated water can result in outbreaks of diseases such as cholera, dysentery, diarrhea, and typhoid. Point-of-use water treatment is a feasible solution to this problem. Furthermore, little investigation has been done towards improving low-cost PoU water treatment systems using locally applicable or available materials and process combinations in Southern Africa. Investigation towards development of optimized combinations of low-cost PoU systems for the Southern African region, using appropriate low-cost materials and locally applicable treatment steps coupled with inbuilt disinfection and safe storage could help increase bacterial and particle removal effectiveness and minimize post treatment recontamination. This can conceivably be more attractive to many users, avoid chemical use and improve the safety of drinking water, hence, make significant contributions to human health in poorer communities.

Thesis statement

The thesis statement reads as follows:

Optimized combinations of low-cost PoU methods using appropriate low-cost materials and locally applicable treatment methods coupled with an inbuilt disinfection step and safe storage could increase bacterial and particle removal effectiveness as well as substantially improve the aesthetic aspects of the treated water and minimize post treatment recontamination.

1.3 Research aim and objectives

The aim of this study was to develop and optimize a combined small-scale low-cost point-of-use system for water treatment in rural and suburban areas of Southern Africa. The specific study objectives included:

1. To comparatively analyze commercially available low-cost PoU systems with similar process and material combination and assess whether the quality of their treated water is sufficiently comparable to good quality tap water municipal supply.
2. To investigate and optimize simple, locally sourced low-cost water treatment materials and techniques for bacterial and particle removal in poverty stricken communities.
3. To develop and demonstrate a specialized comparison framework for qualitative and quantitative evaluation of low-cost PoU technologies.
4. To develop, evaluate and optimize a combined PoU system with an inbuilt disinfection step coupled with a safe storage compartment to avoid chemical addition by prospective users.

1.4 Research Significance

PoU systems that supply water with good aesthetic quality have higher acceptance potential, and hence present higher likelihood for achieving the desired health impact (CAWST 2017a; Nathanson and Schneider 2015; WHO 2017b, 2016). PoU methods that use safe storage are indicated to reduce waterborne disease occurrences (CAWST 2011; Lantagne *et al.* 2006; Luh and Bartram 2017). Therefore, combined low-cost PoU systems, which can remove particles and bacteria, improve aesthetic aspects and remove some additional pollutants e.g. iron and manganese (which impart taste and color to drinking water) coupled with safe storage are needed. Little investigation has been done towards improving low-cost PoU water treatment systems using appropriate material and process combinations in Southern Africa. In this research, a combined three-step low-cost gravity driven system able to substantially remove particles and bacteria, improve aesthetic aspects and substantially remove iron and manganese due to its material and process combination, was developed. The system also contained a built-in safe storage compartment for treated water to minimize recontamination which usually occurs when PoU methods are used as stand-alone items. No chemical addition was needed due to the presence of an inbuilt disinfection step provided by silver coating, thereby reducing running costs. It must be noted, however, that only indicator bacteria were tested. Viruses were not included in the study and may form part of future research. The developed system is replicable, scalable and environmentally friendly.

Low-cost PoU devices are normally not scalable due to various limitations. The developed system can be scaled up to serve institutions (e.g. rural health centers, rural schools, refugee camps, rural markets, etc.) or even larger groups of people with possible installation of multiple taps for drawing treated water from the system**.** The proposed novel system is scalable essentially because the ceramic media (SCCGM) which is the main disinfection step is granular thereby readily scalable to filter systems of any size. The SCCGM can be easily poured into a system containment of any shape and size made of PVC pipes, plastic lined concrete tanks, plastic buckets, etc. depending on the designer and needs of users (TAM ceramics 2019). By contrast all other existing ceramic based filter systems (e.g. CCFs and CPFs) are monolithic, which is to say, 'one piece.' Being one piece, implies that they must be mounted into filter systems of specific sizes and for this reason they are not so flexible to scaling (TAM ceramics 2019).

Similarly, most low-cost PoU systems (e.g. solar disinfection, boiling, etc.) including those investigated in Chapter 2 (the GWS and DFS) cannot be easily scaled up due to several technical limitations. Moreover, CCFs and CPFs have specified mould sizes for their production and due to their high susceptibility to breaking, large scale sizes are impractical. They are therefore limited to small sized units and are as a result only suited to household applications. Likewise, solar disinfection normally uses bottle sizes of only up to 5 L for effective bacterial inactivation and is therefore more appropriate to household level water treatment (Kausley *et al.* 2018). Boiling is energy intensive and is therefore more suited to household water treatment. Available institutional and community level water treatment systems such as the Lifestraw community level water filter and RO based community level water filters (Kausley *et al.* 2018) are technologically advanced and hence complex and expensive. Therefore, scalability of the designed system may make it more attractive for low-cost applications at institutional and community level. According to Luh and Bartram (2017), the sustainable development goals (SDGs) target on clean water and sanitation for all is not only confined to household sized water treatment systems, but also extends to institutional settings, such as rural health centers, rural schools, refugee camps, etc. The scalability of the developed system can therefore enhance its adoption and implementation potential by NGOs and engineers.

Geotextile and GAC filtration steps enhanced the system's ability to treat a broader variety of raw water and extended filter runs. The system is appropriate to rural and suburban areas due to its low-cost, simple design, ease of maintenance and user-friendliness. Modelling *E.coli* removal showed that suitable removal mechanisms can be applied integrally to model a combined PoU system to predict overall effluent bacterial quality. Such modelling can be used to optimize similarly combined systems by allowing engineers to systematically vary design parameters until desired system effectiveness is attained.

Additional to the final developed combined PoU system, three novel simple, yet innovative water treatment systems were designed and tested during the experimentation phase. These were the: (i) modified intermittently operated slow sand filtration system incorporating geotextile and GAC (ISSFGeoGAC), (ii) eight-layer four-pot bidim sequential filtration system (BidimSEQFIL), and (iii) wood filtration system combined with GAC (WFSGAC). ISSFGeoGAC and WFSGAC are for removal of bacteria, particles, color, taste, odor and selected heavy metals while BidimSEQFIL for particle and bacterial removal. The water treatment techniques designed and investigated in this research may find possible application in PoU water treatment implemented by governmental or non-governmental organizations for the rural and suburban poor of Southern Africa with little or no access to formal drinking water supplies. The systems were then comparatively evaluated alongside two commercially available PoU systems using a novel specialized comparison framework developed in this study for evaluating low-cost PoU technologies. Although it is difficult to choose which type of PoU technology is best for all applications due to many factors required for different situations and resource availability, the comparative evaluation showed that it is possible to qualitatively and quantitatively compare low-cost PoU technologies, thereby helping decision making.

Investigation of the ISSFGeoGAC demonstrated that modified ISSF systems incorporating pre-filtration by geotextile and further filtration by GAC can together with the other removal mechanisms by ISSF systems (predation, natural die-off, straining and adsorption), substantially enhance the removal effectiveness of multiple contaminants. Combined with a correct pause period, this can in turn enable the combined system to provide safe water of good aesthetic quality. Similarly, the gravity-driven wood filtration system using indigenous wood filters showed significant potential for turbidity and bacterial removal. The indigenous wood species studied were found to be a valid technological research area for low-cost water filtration and future research into this area is warranted, more so, when combined with GAC to further improve other aesthetic aspects (odor, color and taste) and selected heavy metals. Investigation of wood filtration also presented simple but valid and novel possibilities of using and preserving wood filters for drinking water treatment in rural areas of Southern Africa. The BidimSEQFIL is an optimized and very promising novel fabric filtration technology and recorded significant bacterial removals (>99.9%). Modelling of particle and bacterial removal on the geotextile and cloth fabrics presented a unique method of aiding fabric filtration optimization.

Adequate search for appropriate literature on the topics of interest was done, leading to a good understanding of the research topic, and identification of research gaps in utilization of low-cost PoU water treatment methods. Furthermore, critical evaluation of the literature was performed keeping the research aim in mind. Knowledge gained from literature and each research stage or case study was applied in the next research stages or case studies.

1.5 Delineations and limitations

This research was focused on combining appropriate locally applicable and available PoU water treatment materials and methods to improve drinking water quality in rural and suburban areas of Southern Africa. The developed system was optimized to remove indicator bacteria (*E.coli* and fecal coliforms), particles (turbidity and suspended solids), color, taste and odor. Although the investigated systems mostly had added benefits of being able to substantially remove iron and manganese, which impart taste and color to drinking water, they were not optimized towards removal of heavy metals. Additionally, other parameters like nitrate, nitrite, fluoride, chloride, alkalinity, and hardness may also affect drinking water quality but were beyond the scope of this study.

Although the WHO recommends testing three classes of pathogens in water (bacteria, virus and protozoa) for microbial safety (WHO 2017a, 2016), only fecal indicator bacteria (*E.coli* and fecal coliforms) were used in this study. This was mainly due to funding limitations. The choice was made to test for indicator bacteria over the other pathogens because *E.coli* and, to some degree fecal coliforms, are accepted to best meet the criteria for an ideal fecal contamination indicator (Cabral 2010; CAWST 2017a; Fewtrell and Bartram 2013; Gruber *et al*. 2014; Horan 2003; WHO 2017a). The presence of these signals that pathogens are present, and the water can therefore be regarded as being unsafe. Moreover, protozoa are indicated to be readily removed by filtration technologies such as those evaluated in this study (Cahoon 2019; DrinC 2017; Gift of Water Inc. 2017) and viruses can be inactivated by most disinfectants (WHO 2016). In addition, viruses have been associated with fewer health indices or lower illness rates to date than bacteria as a result of drinking untreated water (Ashbolt 2004; Hunter and Bartram 2015; McAllister 2005; WHO 2011). However, making use of surrogates (*bacteriophages* for viruses, *cryptosporidium* or *giardia* species for protozoan parasites and *E.coli* or *enterococcus* for bacteria) is still recommended for future tests on the investigated systems. This is because other organisms may respond differently as well as to fully comply with the WHO recommendations.

The study was limited to household sized PoU systems (i.e. for about 5 to 10 people) particularly low-cost systems appropriate to poor communities because they are: easily adoptable, more affordable, normally user friendly and more appropriate for treating smaller volumes of water. Additionally, it is theorized that users may take more ownership with cost-effective PoU systems than is usually the case with centralized or sophisticated water treatment systems.

Although the main study goal was to improve the quality of water for drinking purposes, the investigated PoU systems were envisioned to primarily be able to meet drinking water needs of 2.5–3 L/person/day and basic water needs of 7-15 L/person/day (The Sphere Project 2011). The developed systems were also expected to: (i) mainly use locally applicable or available materials, (ii) be user friendly, easy to construct with minimal training, grid-independent, and sustainable as well as affordable (costing ≤ 50 US$/unit).

The PoU system evaluation studies were done under laboratory conditions over specific time periods. Therefore, the results may not be directly transferable to field settings or other time periods. A combination of lab and field testing to ascertain removal performance sustainability and other criteria e.g. flow rates, user acceptability and maintenance requirements is recommended for future research. Although research outcomes for improving safe water needs in poor communities are primarily met by development of novel low-cost drinking water systems, field testing helps to establish suitability, field performance and sustainability of novel technologies in satisfying the needs of intended users.

Investigation of gravity driven wood filtration as a novel low-cost drinking water technology was done using Southern African indigenous tree species namely: *Combretum erythrophyllum*, *Tarchonanthus camphoratus*, *Leonotis leonurus* and *Salix mucronata.* Additionally, not all indigenous species were investigated due to time and resource constraints. Therefore, the results may not be directly transferable to tree species not investigated in this study. Similarly, BidimSEQFIL was tested using bidim geotextile manufactured by Kaytech Engineering, South Africa. Hence, the results may not be directly transferable to use of geotextile manufactured elsewhere.

The use of microscopy and image analysis equipment such as the scanning electron microscope (SEM) before and after filtration to: (i) visualize the longitudinal and cross-sectional characteristics (such as tracheids and vessels and pits and pit membranes) of the indigenous wood filters, (ii) approximate the pore diameter and densities of the investigated indigenous wood filters, and (iii) identify the actual filter features responsible for bacterial and particle removal) was not done to due to funding limitations. Identification of the main features responsible for contaminant removal and estimation of characteristics such as the pore diameter and pore densities for each species may help in comparative assessment of various indigenous wood species and in further optimization of the wood filters during future research.

Raw water samples for the evaluation tests were collected from the Kromrivier, a polluted urban river in Stellenbosch, Cape Town, during varying seasons. Although this river's water was considered representative of surface waters found in rural and suburban areas, which are typically contaminated with bacteria, suspended particles, color, taste and odor, the water quality results may not be directly transferable to other surface waters and seasons. Furthermore, chemicals and immiscible liquids (i.e. oil and grease) and emerging drinking water contaminants (e.g. disinfection byproducts (such as trihalomethanes), antibiotics, human hormones, pharmaceuticals, personal care products (PCPs), pesticides and polychlorinated biphenyls (PCBs)) were beyond the scope of this study.

Overall, the study limitations included (i) limited research funding, (ii) cost for raw materials which limited the number of experimental runs, (iii) cost of bacteriological and metal tests which to a large extent dictated the frequency of testing, (iv) limited time of carrying out the research, and (v) availability of literature on the subject, which was found to be highly limited.

1.6 Main assumptions

General assumptions are stated here, while assumptions specific to each research objective were stated within the relevant Chapters. It was assumed that the novel clay based silver-coated ceramic granular media currently produced by TAM ceramics in Niagara Falls, N.Y (TAM ceramics 2019) will in the near future be produced locally from existing raw material sources in Southern Africa and elsewhere when demand is established. This will in turn make the SCCGM media more affordable. This assumption was considered to be reasonable because clay is an abundant material found almost everywhere in the Southern African region and, according to TAM ceramics (2019), only small amounts of silver are needed. Pending determination of the actual price, there is an assurance that the cost of the SCCGM will be inexpensive (TAM ceramics 2019), especially when produced locally.

It was assumed that at an optimal flow rate of 2 L/h the developed system will consistently inactivate bacteria in the water through contact with silver and thereby prevent bacterial regrowth in the GAC column, which normally happens if bacterial inactivation is inadequate. It was also assumed that silver leaching from the SCCGM will be marginal, such that the material should not cause a silver toxicity problem in the produced water or reduce system efficacy.

In addition, the South African National Standards (SANS) 241 and the World Health Organization (WHO) guidelines recommend 0 CFU/100 ml of *E.coli* and fecal coliforms in drinking water. Therefore, the developed and optimized systems were assumed to be able to supply water of 0 CFU/100 ml *E.coli* and fecal coliforms and aesthetically acceptable with turbidity of < 5 NTU. However, in resource limited situations, water that is of reasonable quality (0-10 CFU/100 ml *E.coli levels*) and relatively safe (11-100 CFU/100 ml *E.coli* levels) may be consumed as is (CAWST 2013; Harvey 2007; WHO 1997). Additional solar and/or chemical disinfection according to WHO guidelines for drinking-water quality (WHO 2017a) is, however, still recommended to ensure complete elimination of pathogens.

Furthermore, for all the methods incorporating GAC, it was assumed that in areas where GAC is not available, normal charcoal may be a possible alternative with slightly deeper sections than GAC; however, further investigation of this application is warranted. It was further assumed that, in places where geotextile fabric is inaccessible, cloth material multiply layered e.g. folded about 6 to 8 times can be used in place of geotextile, future investigation into this application is needed.

With respect to wood filtration, it was assumed that enough safe indigenous wood species (species that may not introduce toxicity into the treated water) are found in many rural areas of Southern Africa and can be safely and sustainably accessed.

It was assumed that the raw water used in the experiments obtained from the Kromrivier stream could be used as a reasonable proxy for polluted surface waters. This assumption was supported by the high range of pollution parameters yielded by the stream including bacteria, suspended particles, color, taste and odor, which were deemed to cover the range of such parameters that may be expected in other areas.

It was assumed that the development of a well-functioning PoU system affordably producing water of good aesthetic quality and having a safe storage can increase adoptability and user acceptability of such a system. This reasoning is supported by literature indicating that PoU systems that supply water with good aesthetic quality have higher acceptance potential (CAWST 2017a; Nathanson and Schneider 2015; WHO 2017b, 2016), while PoU methods that use safe storage reduce waterborne disease occurrences (CAWST 2011; Lantagne *et al*. 2006; Luh and Bartram 2017).

1.7 Chapter overview

This dissertation is presented in manuscript format and consists of 5 papers published in peer-reviewed journals (Chapters 2, 3, 4, 5 and 6), 1 conference paper (Appendix A) and 2 unpublished works (Chapters 7 and 8). The manuscripts for Chapters 7 and 8 have been submitted for publication to the Journal of Water practice and Technology and are currently under review.

Chapter 1 presents the study background and highlights the major challenges, which limit or discourage the use of existing PoU technologies in poor communities of Southern Africa and other developing countries thus necessitating a need to develop locally viable affordable and sustainable PoU systems with user acceptability potential in such settings to achieve the intended health impact.

Chapter 2 presents study results on comparative analysis of two commercially available relatively affordable PoU systems. Most PoU technology studies focus on bacterial removal and generally neglect particle and aesthetic improvement. In addition to bacterial removal, PoU systems must make the water aesthetically acceptable so that users do not opt for water that looks aesthetically better but is actually contaminated. The study was therefore designed to compare the PoUs ability to improve the bacterial and aesthetic quality of water in addition to other factors such as cost, pore size, flow rate, operation and maintenance (O & M) needs, life span and installation difficulty. Additionally, the study assessed whether the quality of the PoU system's treated water was sufficiently comparable to good quality tap water municipal supply at Stellenbosch University over the study period. This can build user confidence for such systems and assess adoptability and acceptance.

Chapters 3, 4, 5 and 6 present results of broader investigation into simple, low-cost and novel water treatment materials and techniques that might be feasible for PoU applications in poorer groups based on the experimentations and appropriate literature. This was aimed at fulfillment of objective 2 as stated above.

Chapter 3 presents study results on two small-scale, low-cost, sand filtration systems incorporating GAC, non-woven geotextile and filter mats for removal of selected heavy metals, bacteria and particles from water. They were exposed to a single surface water source for five months and three weeks, a period that covered seasonal variations in the raw water quality, as it ran from winter through spring to summer. This Chapter was preceded by the work in the conference paper presented in Appendix A. The studies in Chapter 3 and Appendix A resulted in a simple, yet innovative combined PoU water treatment system namely the ISSFGeoGAC.

Chapter 4 presents results from an investigation on two engineered non-woven fabrics and five cloth fabrics that are locally available for low-cost PoU drinking water treatment. The focus was to attain the best process configuration to achieve the best possible contaminant removal, while preventing recontamination. Numerical models for predicting turbidity removal efficiency were developed for each fabric as support tools for selecting optimal process configuration. This study resulted in an optimized simple, yet innovative PoU water treatment system namely the eight-layer four-pot bidim sequential filtration system (BidimSEQFIL).

Chapter 5 presents investigation into a novel concept of drinking water treatment using indigenous wood filters combined with GAC as an appropriate PoU technology for the rural poor. A gravity-driven system was designed, tested and optimized. Four systems were assessed in respect of heavy metal, bacteria and particle removal when exposed to polluted river water with and without GAC. These were evaluated using fresh, wet preserved and dry preserved Southern African indigenous wood species namely: *Combretum erythrophyllum*, *Tarchonanthus camphoratus*, *Leonotis leonurus* and *Salix mucronata*. The study also presented simple but valid and novel possibilities of using and preserving wood filters for drinking water treatment in rural areas.

Chapter 6 presents and discusses a novel specialized comparison framework developed in this study for evaluating the low-cost combined PoU technologies developed and tested in this research. The comparison framework was demonstrated using three novel systems developed during this research (ISSFGeoGAC, BidimSEQFIL and WFSGAC) and two commercially available PoU systems. The comparison results and key features of the framework have been presented and discussed.

Chapter 7 presents optimization and contaminant removal performance of a final developed combined low-cost PoU drinking water treatment system as well as key system features. The developed system offers a novel concept of drinking water treatment primarily aimed at the rural and suburban poor of Southern Africa. This system was developed based on knowledge gained during the research previously done and as reported in Chapters 2 to 6.

In Chapter 8, mathematical modelling was done using *E.coli* as an indicator organism to aid in optimization of the final developed combined PoU system presented in Chapter 7, and to support further research in terms of configuration, process combination, flow rate, material combination, etc. The system was modelled as a series of three compartments using disinfection kinetic models for silver inactivation and specialized colloidal filtration theory models for fibrous and granular filtration. The modelling demonstrated that suitable removal mechanisms can be applied integrally to model the final developed combined PoU system to predict overall effluent bacterial quality.

Chapter 9 presents conclusions and summary of the study findings as well as summary of contributions to knowledge and recommendations for future research.

Appendix A presents research that was carried on PoU water treatment through use of activated carbon and geotextile layered within an intermittently operated slow sand filter. Three modified ISSF systems were investigated to: (i) evaluate contaminant removal performance of each system-i.e. their treatment effectiveness (to what extent the systems can purify water when needed), (ii) assess potential for improvement and, (iii) suitably optimize the systems. The laboratory scale systems were evaluated when exposed to polluted river water for 4 months. System 1 incorporated GAC, system 2 incorporated non-woven geotextile layers and filter system 3 incorporated both materials. In addition, a systematic design procedure for ISSF systems was presented as well as system optimization particularly on system 3 which had several O & M issues. This will be helpful to engineers for design and optimization of the investigated and similarly modified ISSF systems. This preliminary investigation led to the elimination of system 3 from the further study which was done in Chapter 3.

Chapter 2: Comparative analysis of two low cost point-of-use water treatment systems

This Chapter addressed the first study objective of this dissertation, which is "to comparatively analyze commercially available low-cost PoU systems with similar process and material combination and assess whether the quality of their treated water is sufficiently comparable to good quality tap water municipal supply."

The aim of this investigation was to firstly establish, at the outset of the research, how relatively affordable commercial PoU systems theoretically compare to other PoU systems made from locally sourced low-cost materials and technologies, which was later done in Chapter 6. It was additionally assessed whether the quality of PoU system's treated water is sufficiently comparable to good quality tap water municipal supply at Stellenbosch University such that user confidence in such PoU systems might be enhanced.

The results showed that the treated water from the two systems compared well with good quality tap water supplied to Stellenbosch University with respect to bacterial, turbidity and suspended solids content. Both systems produced bacteriologically safe drinking water (with an apparent 100% removal for *E.coli* and fecal coliforms) due to chlorine disinfection in the Gift of Water System (GWS) and silver disinfection in the Drip Filter System (DFS) and are relatively affordable water treatment options, with their own benefits and drawbacks, most of which are highlighted in this Chapter. The polypropylene string filter in the GWS was indicated to be able to pre-treat turbid water. Furthermore, the improvement of aesthetic aspects (turbidity, color, taste and odor) was generally good due to the presence of granular activated carbon in both systems. This may often enhance user acceptability of the two PoU systems. The main drawbacks with respect to the GWS are: (i) the need for regular filter replacement, and (ii) the potential for production of disinfection by-products (DBPs)-e.g., trihalomethanes-due to the use of Sodium Dichloroisocyanurate (NaDCC) tablets in both the top and bottom buckets, especially if the GAC, which removes excess chlorine, fails during use. The major drawbacks with the DFS are the ceramic candle filter being easily breakable, slow filtration rate and regular filter cleaning required to remove clogging.

The findings on the investigated commercial PoU systems in Chapter 2 led to the further investigation into performance improvement of an intermittently operated slow sand filtration (ISSF) system by incorporating geotextile fabrics for pre-filtration and GAC for aesthetic improvement. This was done in Chapter 3 together with a conference paper presented in Appendix A. ISSF systems are commonly used PoU configurations which are normally locally produced if clean suitable sand is available but have various limitations such as scraping or "swirl and dump" cleaning techniques being tedious, inconsistencies in producing water free of color, taste and odor as well as significant reduction in bacterial removals after cleaning (Singer *et al.* 2017). Appropriate modifications were therefore made as presented in Chapter 3 and Appendix A to enhance acceptability of ISSF systems for low-cost PoU applications.

Comparative analysis of two low-cost point-of-use water treatment systems

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ABSTRACT

The study examined two low-cost point-of-use water treatment systems developed in respect of bacterial and particulate removal when exposed to surface water for three months. Bacterial removal efficiency was estimated using *E.coli* and fecal coliforms, while particulate reduction efficiency was estimated by determining turbidity and total suspended solids (TSS). The systems investigated were the Gift of Water System (GWS) made in USA and the Drip Filter System (DFS) Model-JW-PD-1-70 made in South Africa. The study included seasonal water quality changes. Both systems recorded 100% bacterial removal throughout the study. Although results show that DFS was slightly better in terms of particulate reduction, both systems removed large proportions of particles from the water. On average TSS removals were 89% and 95%, while turbidity removals were 87% and 94%, by GWS and DFS respectively. The treated water from the two systems compared well with good quality tap water supplied to Stellenbosch University. The results show that both systems can treat the poor quality water used to meet the SANS 241 and WHO guidelines with respect to bacterial and suspended solids content.

Key words: Drip Filter system, Gift of Water system, low cost, PoU, potable water quality, surface water

INTRODUCTION

Water treatment systems, particularly, for developing nations, do not always need to be sophisticated or automated to be effective and useful, but should be able to produce bacteria free and aesthetically acceptable water. Hence, for point-of-use (PoU) water treatment systems, the safety of the water is of utmost concern. According to McAllister (2005), viruses and chemical pollutants cause far fewer problems as a result of drinking untreated water than bacteriological agents. The first and most important step in the battle against consumption of poor quality water is thus the elimination of bacteria (McAllister 2005) and particles, so that users do not opt for water that looks aesthetically better but is actually contaminated (CAWST 2011). PoU technologies have been proposed for providing safe water in developing countries (Sobsey 2002), as opposed to centralized water supply systems, since they minimize the risk of contamination between the water treatment plants and users. Many design guidelines and criteria exist for conventional water treatment systems (Davis 2010; Kawamura 2000), whereas PoU systems have varying guidelines making them vulnerable to quality and performance variability. There are very few low cost water systems that are well designed and produced, and give excellent sustainable performance. Comparative analysis on two, low-cost PoU water treatment systems was carried out in the water quality lab at Stellenbosch University, South Africa. The systems studied were the Gift of Water System (GWS) (Gift of Water Inc. USA) and the Drip Filter System (DFS) Model-JW-PD-1-70 (Headstream Water Holdings, South Africa). Both are relatively well produced and affordable (DrinC 2017; Gift of Water Inc. 2017).

A number of PoU systems worldwide can treat various types of contaminated water (McAllister 2005). However, most are expensive and fail to meet the specific needs of poor communities (McAllister 2005). The quality of many affordable PoU systems depends largely on the materials used and the fabricator's ability. In this study two, low-cost PoU technologies, developed and produced respectively in the USA and South Africa, were assessed by exposure to a single surface water source for three months. The comparison was based mainly on the efficiency of bacterial and particulate removal from poor quality urban stream water. Bacterial removal efficiency was estimated using *E.coli* and thermo-tolerant (fecal) coliforms as indicator organisms (Ritter 2010). Particulate reduction efficiency was tested using turbidity and total suspended solids (TSS) (Shammas and Wang 2015).

The cost of the PoU systems considered is relatively low compared to other modern PoU systems based on, e.g., ion exchange, reverse osmosis and other advanced technologies (de Moel *et al.* 2007; Ritter 2010; WHO 2011). An attempt was also made to determine the systems' effectiveness and how their treated outputs compare to good quality potable water produced by high-tech, or excellently maintained and operated, conventional water treatment systems (Howe *et al.* 2012). The systems' treated water quality was therefore compared to the good quality tap water municipal supply at Stellenbosch University. It is noted in this context that the municipal supply at Stellenbosch comprises: (i) screening at the reservoir, to remove suspended matter and floating debris, (ii) pre-chlorination, (iii) cascade aeration, (iv) pH correction with hydrated lime, (v) coagulation and flocculation with aluminum sulfate or sodium aluminate, (vi) sedimentation, (vii) rapid gravity sand filtration, (viii) stabilization with lime, and (ix) chlorination.

The potable water supplied to the university is obtained from surface water in the same catchment as Kromrivier stream, the raw water source for the Point of use systems (PoUs). The reservoir supplying water to the treatment plant receives some run-off from agricultural land and has recently recorded increases in algae and turbidity (Enviro Metsi (Pty) Ltd 2017), as does the Kromrivier stream.

The study was designed to compare the PoUs ability to improve both particulate and bacterial quality of water. Most PoU studies focus on bacterial removal and neglect the removal of particulates. According to CAWST (2011) PoUs must provide clear water (with little or no turbidity) so that users do not opt for water that looks aesthetically better but is actually contaminated.

MATERIALS AND METHODS

Source of untreated water

Raw surface water samples were obtained from Kromrivier, a small stream in Stellenbosch, South Africa, at 33°55'34.68"S and 18°51'40.56"E, next to the bridge between Ryneveld Street and Kromrivier Road, Stellenbosch-see **Figure 2-1**.

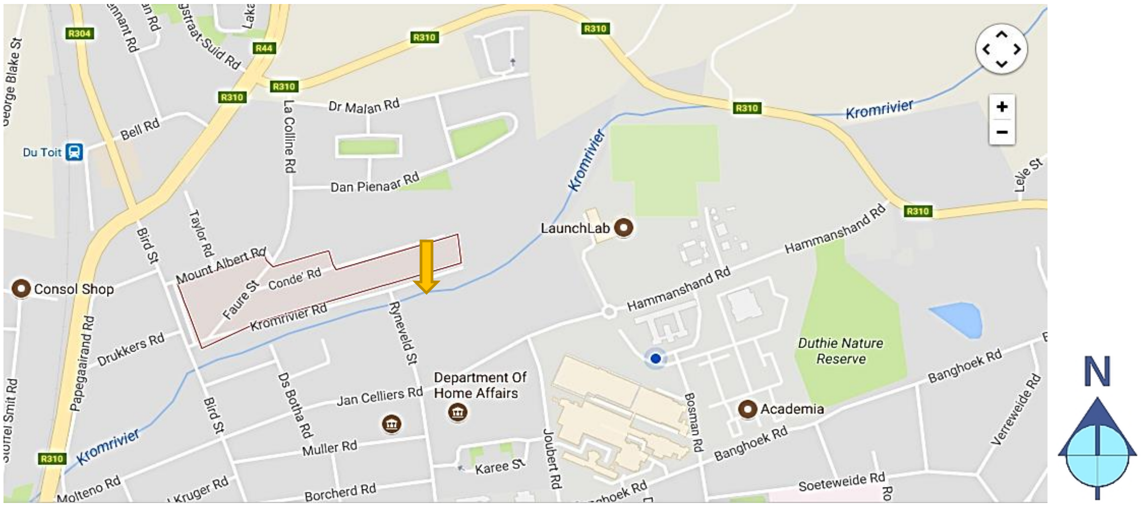

Figure 2-1: Kromrivier sampling point, Stellenbosch (Google Map 2017)

The Gift of Water System (GWS)

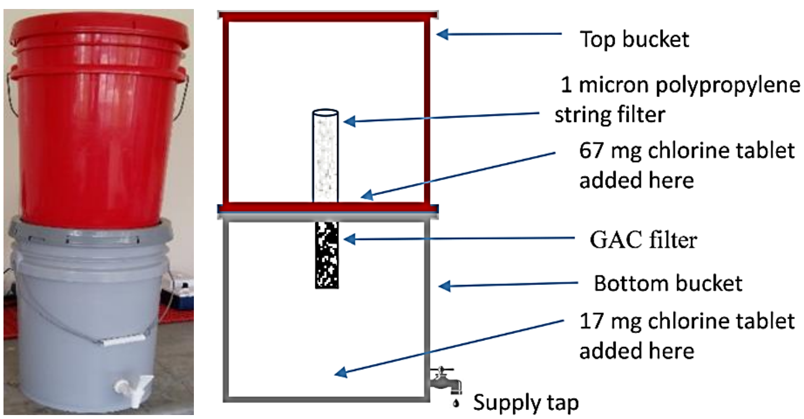

Figure 2-2: The GWS in operation (left) and schematic (right)

The GWS (**Figure 2-2**) comprises low-cost water treatment technology for developing countries. It was developed initially for use in Haiti to combat water-borne diseases and complications from malnourishment arising from drinking unsafe water (Gift of Water Inc. 2017). It is a two-bucket system that uses a 1 micron (µm) polypropylene string filter, a granular activated carbon (GAC) filter and chlorine tablets. The chlorine tablets are made of Sodium Dichloroisocyanurate (NaDCC) which dissociates in water to release hypochlorous acid (HClO) that kills microorganisms through oxidization (CAWST 2011; WHO 2016, 2003). Raw water is put into a 20-liter top bucket, with a 67 mg NaDCC tablet, and left for 30 minutes. A 17 mg NaDCC tablet is then added to the bottom bucket for post-chlorination, to ensure that the chlorine concentration remains high enough to prevent recolonization by (most) bacteria. The top bucket is placed on the bottom bucket, activating a check-valve enabling water to flow into the bottom bucket, passing in transit through the string and GAC filters. The former removes suspended solids and larger organisms like protozoa, the latter – the GAC filter – removes organic compounds and excess chlorine (Gift of Water Inc. 2017). Gift of Water Inc. (2017) recommends replacement of the GAC filter every 6 months. Treated water is available through a tap in the bottom bucket. The average flow through the GWS is estimated at 46.8 L/h (Gift of Water Inc. 2017), and the system costs 25 USD in the USA.

The Drip Filter System (DFS)

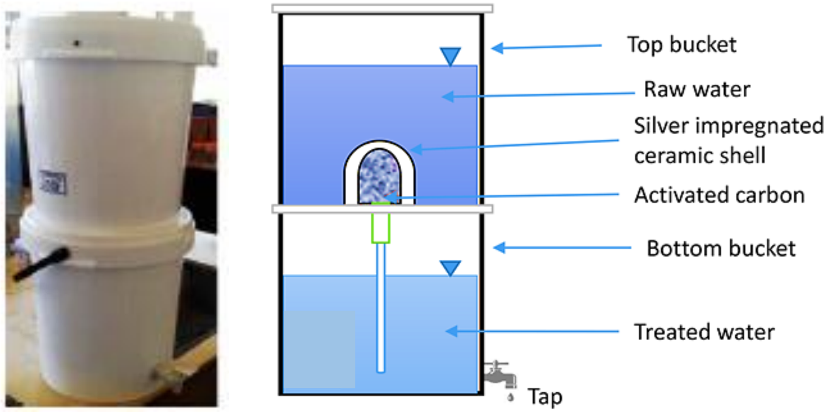

Figure 2-3: DFS in operation (left) and schematic (right)

The DFS (**Figure 2-3**) is a low-cost, two-bucket, ceramic candle, filter system distributed under the name DrinC. It costs about ZAR 600 (44 USD) in South Africa. The DFS candle filter, normally wedged between two 20-liter buckets, consists of a 0.2 μm, silver-impregnated ceramic shell containing activated carbon (charcoal) (DrinC 2017). The silver serves as a disinfectant. According to DrinC (2017), the ceramic shell sometimes has a fabric cover (filter sock) to remove larger debris (e.g. leaves and insects) from the source water. As water drips through the filter, suspended solids are removed, followed by bacteria and micro-organisms down to 0.2 μm. Raw water is put into the top bucket and drips through the filter into the bottom bucket, which is mainly for storage and is fitted with a tap. The GAC lasts for about 6 to 8 months and the filter must be replaced after one year's use (DrinC 2017), but it is advisable to shake it every 3 months to dislodge debris and extend its life, and ensure that the carbon stays loose. The DFS flow rate can be up to 13.26 L/h, when the system is new. During the study it was observed that the flow rate falls over time.

Tap water

The tap water used during the study was collected daily from the Civil Engineering Department water quality laboratory, Stellenbosch University. Samples were analyzed immediately after collection. The key treatment steps are outlined in the introduction, above, and shown in **Figure 2-4.**

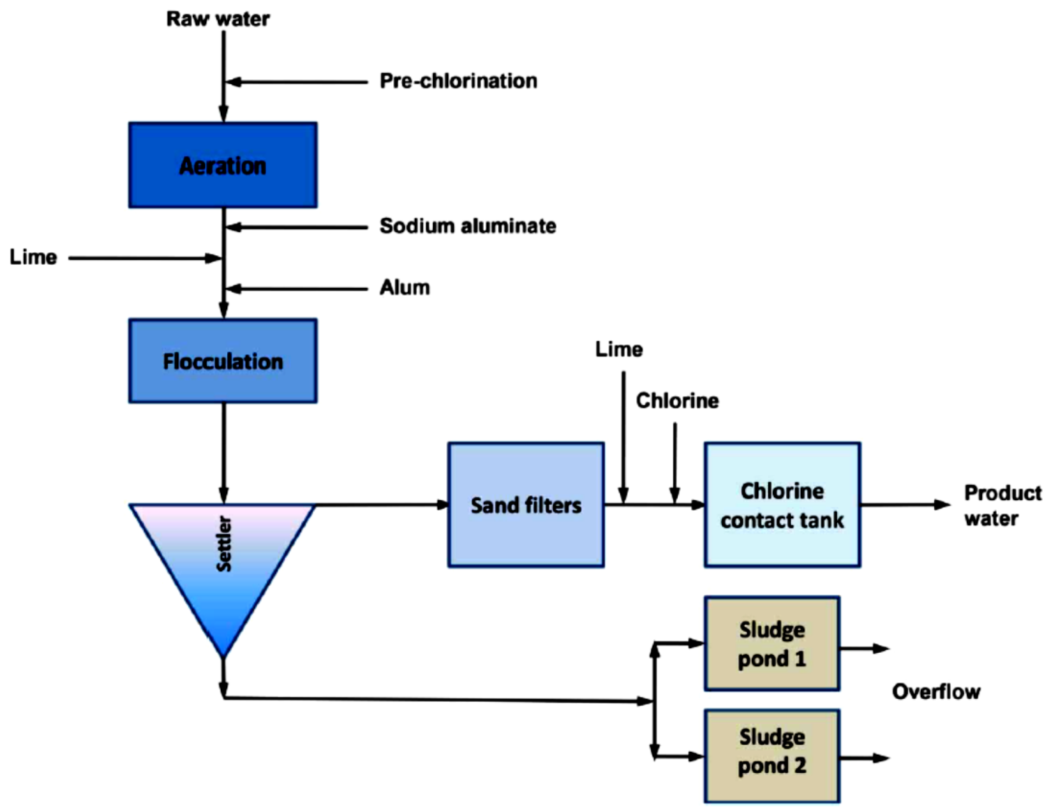

Figure 2-4: Key treatment steps for the tap water supply (adapted from Enviro Metsi Pty Ltd (2017))

Sampling and system evaluation

To ensure that the study's source water was contaminated with bacteria and particulate matter, raw water samples were collected and tested for at least two weeks before the evaluation tests started. In both weeks fecal coliforms reported more than 500 CFU/100ml and *E.coli* more than 400 CFU/100ml. TSS and turbidity were consistently above 14 mg/l and 10 NTU, respectively. The concentrations of fecal coliforms, *E.coli*, TSS, and turbidity were quantified before and after treatment by each system. Other parameters measured were electrical conductivity (EC), total dissolved solids (TDS), pH, and dissolved oxygen (DO).

The evaluation was done over a period of 3 months and 2 weeks. The raw water was passed through the PoU systems five days a week for 2 to 3 hours each day, to mimic normal daily use as closely as possible. Treated water was collected fortnightly for bacteriological tests and daily for physico-chemical tests. Tests for *E.coli* and fecal coliforms were done by Water Analytical Laboratory (WALAB) accredited to the South African National Accreditation System (SANAS), No: T0375 for microbiological analysis. Physico-chemical tests were done in the Water Quality Laboratory at Stellenbosch University. All tests were performed in accordance with the Standard Methods for the Examination of Water and Wastewater (APHA/AWWA/WEF 2012).

Percentage removal calculations

The percentage removals achieved by the PoU systems for *E.coli*, fecal coliforms, turbidity, and TSS were calculated using **Equation 2-1**:

$$\% \, removal \, of \, contaminant = \frac{C_i - C_e}{C_i} X \, 100 \tag{2-1}$$

Where: C_i = concentration of contaminant in untreated water C_e = concentration of contaminant in treated water

RESULTS AND DISCUSSION

Source (river) water quality

The source water was characterized initially and on every sampling day during the study for the selected parameters. The raw water characteristics were compared to the South African National Standards (SANS) 241 and the World Health Organization (WHO) guidelines for domestic and drinking water – see **Table 2-1.** In addition to high turbidity and suspended solids, the raw water was highly contaminated with fecal coliforms and *E.coli*.

Table 2-1: Source water quality compared to WHO and SANS 241 Standards

Parameter	***Source water***		***Drinking Water Standards***	
	Min	*Max*	*WHO*	*SANS 241*
pH (pH UNITS)	*7.47*	*8.76*	*6.5-9.0*	*≥ 5 to ≤ 9.7*
Conductivity (µS/cm)	*181*	*650*	*2500*	*≤ 1700*
TDS (mg/L)	*92*	*333*	*1500*	*≤ 1200*
TSS (mg/L)	*10*	*150*	*0.1*	*-*
Turbidity (NTU), Aesthetic	*6.25*	*93.75*	*5*	*≤ 5*
Fecal coliforms (CFU/100 ml)	*620*	*3800*	*0*	*0*
E.coli (CFU/100ml)	*460*	*3100*	*0*	*0*
DO (mg/L)	*9.07*	*11.70*	*-*	*-*

***E.coli* and fecal coliform removal**

The GWS and DFS were both very effective in bacterial removal, recording 100% in terms of both *E.coli* and fecal coliforms (**Figures 2-5 and 2-6).** The DFS gave similar results to those in a study by Adeyemo *et al.* (2015) and CAWST (2011) on bacteria removal by *silver*-coated ceramic candle filters (bacterial removals > 99% and > 99.95% of laboratory and field treatment efficiency, respectively). The GWS gave results similar to Lantagne *et al.* (2006) and Nath *et al.* (2006), who reported bacterial removal efficiencies for systems using combined filtration and chlorination > 99.99%. It is therefore clear that both systems can meet WHO and SANS 241 standards. The authors believe that the two PoU systems may often offer advantages over centralized water treatment systems by minimizing the risk of contamination between the source and the point-of-use, particularly in poor communities. In many countries, centralized systems commonly suffer from recontamination between water treatment plants and point-of-use, e.g., because of infrastructure failures connected with water storage and/or distribution. The bacteriological quality of the raw water improved by a factor of between about 2 and 3 during the course of the tests, and there was a noticeable surge in suspended solids concentrations around the middle of the tests, but this did not coincide with the bacterial count peaks, which were earlier. This was because the authors stirred the streambed gently for 3 weeks (31 July to 22 August) to collect water with higher particulate content to test the PoU systems. Most suspended solids comprise inorganic materials (clay, silt, sand, etc.), although bacteria and algae also contribute to suspended solids concentrations (Howe *et al.* 2012; Ritter 2010). The rather higher bacterial counts recorded earlier could be attributed to increased bacterial inflow from the storm drain that discharges about 20 m upstream of the sampling point, especially as the study area experiences winter rains at that time of the year. The storm drain is thought to collect fecal material from underneath the bridge (on Jan Celliers Road close by) where some homeless people find shelter. Evidence for this claim was noted on the day of the highest bacterial count (17 July) when the storm drain discharge looked and smelt like sewage.

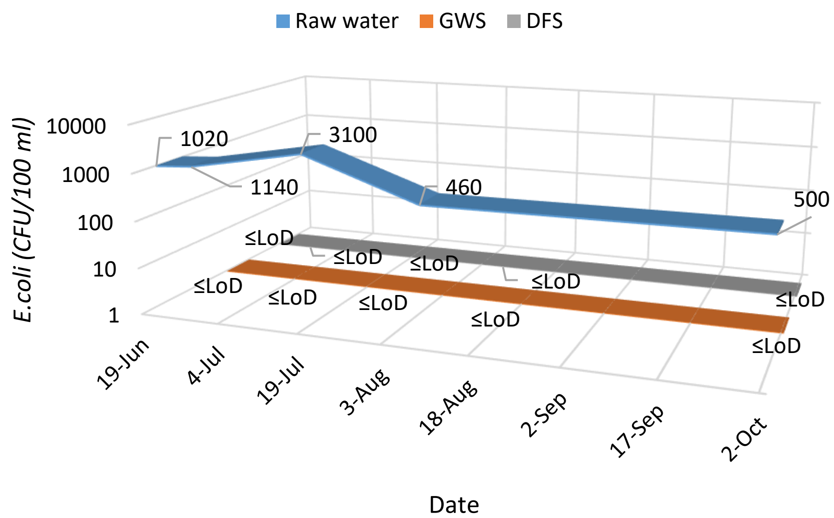

Figure 2-5: E.coli removal by the PoUs during the study

** Tests done by WALAB in Stellenbosch South Africa; accredited E.coli detection method used: Enzyme substrate, WAL M4; * LoD stands for limit of detection*

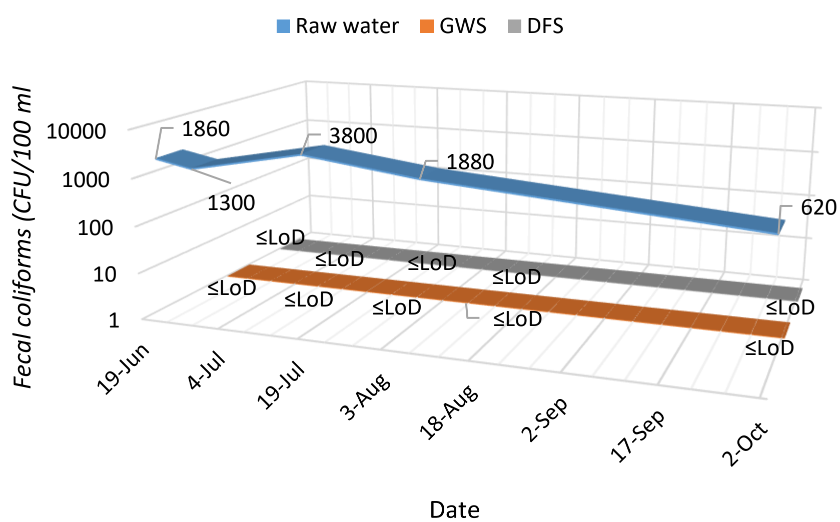

Figure 2-6: Fecal coliform removal by the PoUs during the study

** Tests done by WALAB in Stellenbosch South Africa; accredited fecal coliform detection method used: Biochemical method, WAL M3*

Particulate removal and comparison with tap water TSS and turbidity

There was substantial removal of TSS and turbidity from the raw water by both the GWS and DFS – see **Figures 2-7 to 2-10**. The DFS was slightly better than the GWS in TSS and turbidity removal, but particulate removal was highly significant by both. On average TSS reductions were 89 and 95% for the GWS and DFS, respectively, and 87 and 94% for turbidity. The higher particulate removals by the DFS could be attributed to the smaller pore size of its filter, which is 0.2 µm vs 1 µm for the GWS. While neither the GWS nor DFS met the WHO guideline level (0.1 mg-TSS/l) consistently, they always removed a very large fraction of the particles from the water and their effluent TSS values were little higher than those in the tap water – see **Figure 2-7**. The turbidity of the treated waters from both systems consistently met the WHO and SANS 241 level of 5 NTU, and compared well to that of the tap water.

There was a noticeable difference in performance between the two systems until around 19 July, after which, similarity was observed until almost the study end. The DFS performed better than the GWS at first, until, the coarser filter of the latter began to clog, when their performances became fairly similar. Additionally, comparative performance of the GWS and DFS in relation to turbidity was almost identical to that of the pair when removing TSS, which is not particularly surprising because turbidity and TSS complement each other, and are similar in the sense that both are measures of water clarity although they reflect different issues (Ritter 2010). Even though they cannot be directly correlated, turbidity and TSS overlap in the measurement of some particles such as bacteria, algae, clay, silt and non-settleable solids (Howe *et al.* 2012; Ritter 2010).

Since both systems contain a disinfection step and produce relatively clear water, they are good options for improving water security in poor communities, especially if produced locally and promoted by NGOs, who should ensure adequate user motivation and training.

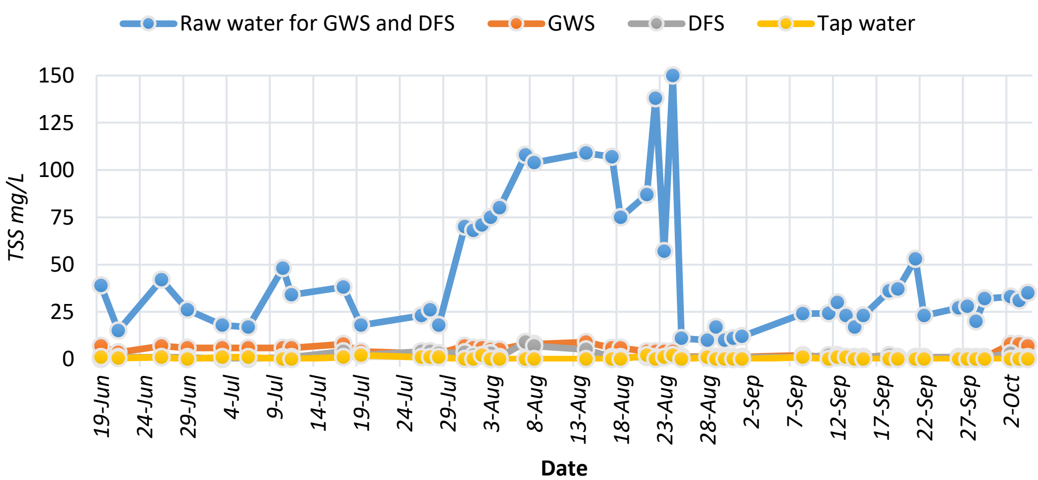

Figure 2-7: TSS removal by GWS and DFS, and comparison with tap water over the study period.

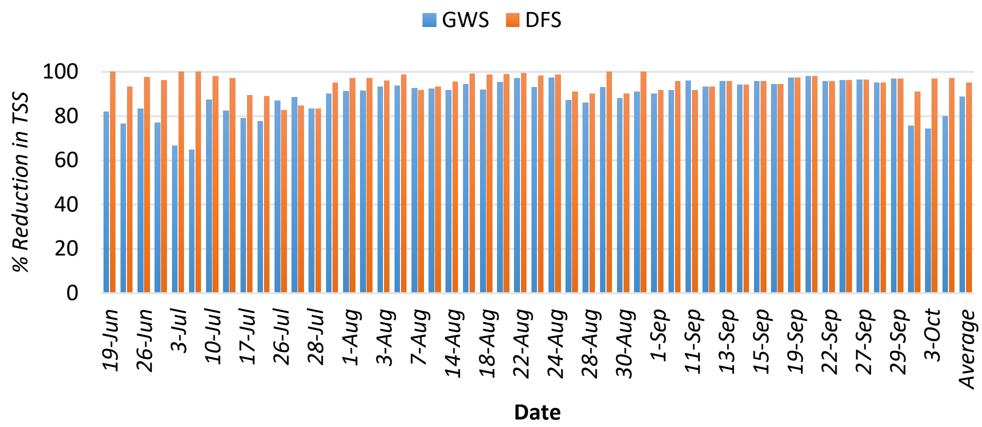

Figure 2-8: TSS removal percentage by GWS and DFS over the study period

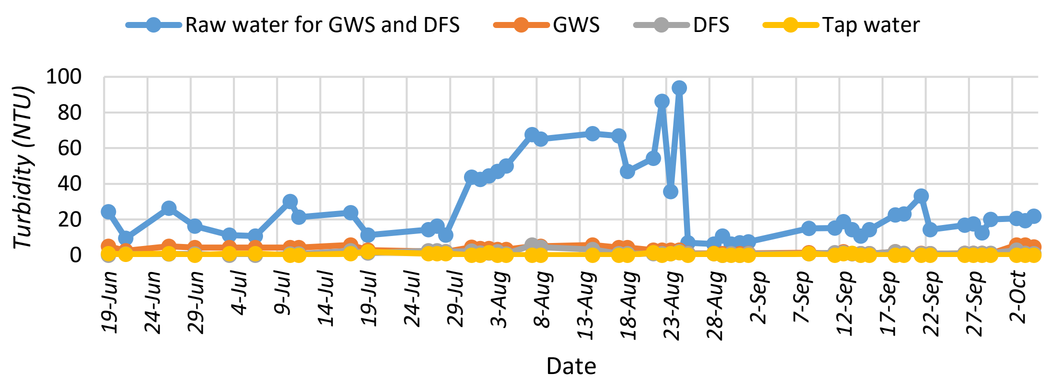

Figure 2-9: Turbidity removal by GWS and DFS, and comparison with tap water over the study period

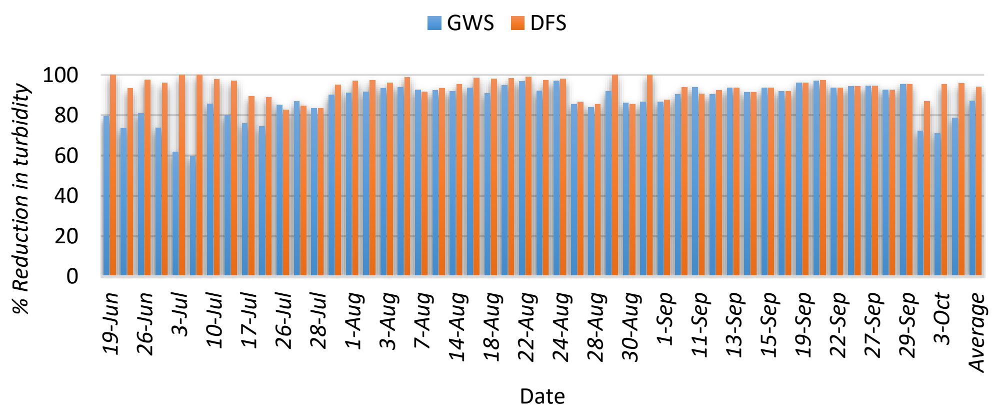

Figure 2-10: Turbidity removal percentage by GWS and DFS over the study period

pH and DO for the treated waters and comparison with tap water

Although DO levels in the DFS treated water were relatively low (**Figure 2-11**), both systems consistently met the SANS 241 and WHO guidelines– see **Table 2-1 –** in terms of pH. It was clear that the PoUs had little if any effect on the raw water's pH (**Figure 2-12**), EC or TDS, but they were not designed to do so. It is a good idea, therefore, to obtain raw water whose chemical content is reasonably close to the potable water guidelines when using these PoUs.

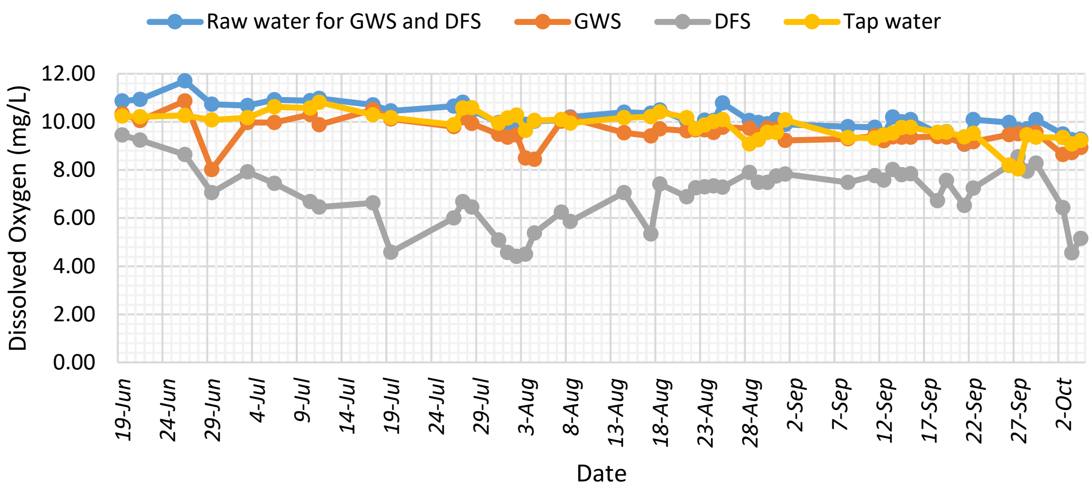

Figure 2-11: DO Trend for GWS and DFS effluent and source water, compared to tap water over the study period

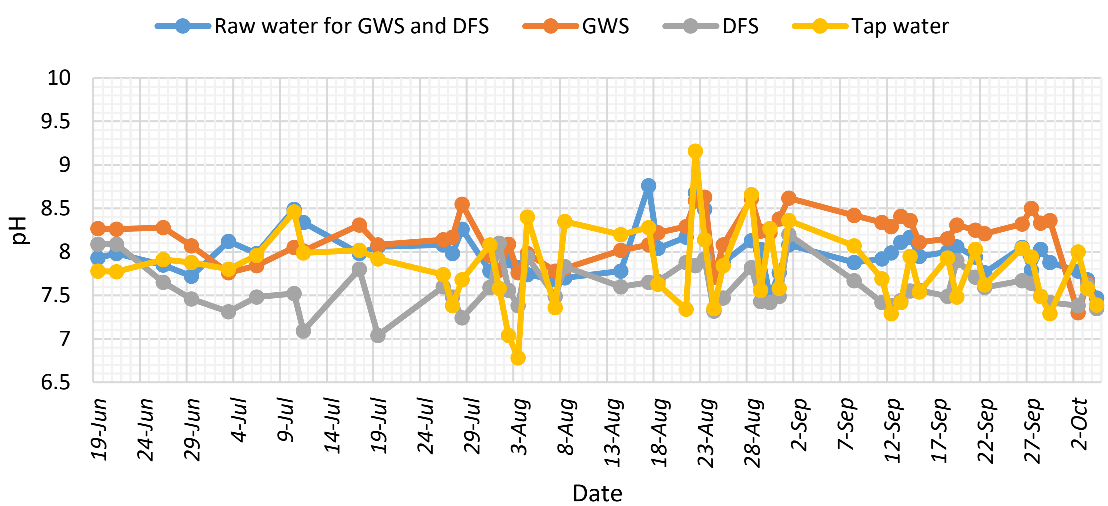

Figure 2-12: pH Trend for GWS and DFS effluent and source water, compared to tap water over the study period

Table 2-2 gives key comparisons between the GWS and DFS. The PoUs can both meet basic water needs of about 15 to 20 liters/capita/day (WHO 2016), particularly for poor communities. The main drawback with respect to the GWS is the potential for the production of disinfection-by-products – e.g., trihalomethanes – due to the use of NaDCC tablets in both the top and bottom buckets, especially if the

GAC, which removes excess chlorine, fails during use. The major drawback with DFS is the slow filtration flow rate and regular filter cleaning to remove clogging.

Key comparisons between GWS and DFS

Table 2-2: Comparative summary of GWS and DFS

	GWS	*DFS*
Capital Cost	*$25*	*$44*
Typical shipping cost to South Africa from USA	*$103*	-
Apparent removal of E.coli (%)	*100*	*100*
Apparent fecal coliform removal (%)	*100*	*100*
Range of turbidity removal (%)	*60.8-97.2*	*82.4-99*
Range of TSS removal (%)	*65.7-98.6*	*83-100*
Filter pore size	*1 µm*	*0.2 µm*
Maximum filter flow rate (L/h)	*46.8*	*13.26*
Minimum filter flow rate observed (L/h)	*20*	*3.4*
Water clarity (visual)	*Good*	*Good*
Major O & M needs	*GAC filter replacement & disinfection tablet costs*	*Filter replacement & regular cleaning of filter due to clogging*
Estimated life span	*More than 12 Months (Gift of Water Inc. 2017)*	*12 months (DrinC 2017)*
Installation difficulty	*minimal*	*minimal*
General benefits	*Include: High bacterial removal; residual protection against contamination; cotton filter able to pre-treat turbid water; user acceptability due to ease-of-use, fast filtration rate; acceptable taste; can yield clean water for a long time;*	*Include: High bacterial removal; user acceptability due to ease-of-use; long life if filter remains unbroken; if properly maintained, can yield clean water for a long time;*
General drawbacks	*Include: relatively high initial costs (including shipping) and ongoing maintenance costs; need for regular filter replacement; ongoing technical support; continuing education; concerns about potential long-term carcinogenic effects of disinfection-by-products.*	*Include: lack of residual protection can lead to recontamination; user education needed to keep the filter and receptacle clean; ongoing technical support; continuing education; may not be useable with very turbid waters due to potential clogging problems*

Average raw water quality for the PoUs and treated water quality vs Tap water

Table 2-3 gives average raw water quality for the PoUs vs treated water quality in comparison with tap water quality over the study period. There was no significant difference between the tap water quality and PoUs treated water quality in terms of pH, TSS or turbidity.

Table 2-3: Average raw water quality for the PoUs vs treated water quality (June 2017-October 2017)

Parameter	Recorded tap water values			Raw water for GWS and DFS			GWS treated water			DFS treated water			Potable Water Standards	
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	WHO	SANS 241
pH	7.8	6.8	9.2	8.00	7.5	8.8	8.2	7.3	8.6	7.6	7.0	8.2	6.5-9.0	≥ 5 to ≤ 9.7
TSS (mg/L)	0.4	0.0	2.0	44.6	10	150	4.0	1.0	9.0	1.8	0	9.1	0.1	-
Turbidity (NTU),	0.4	0.00	1.8	27.9	6.3	93.8	2.8	0.9	5.7	1.3	0	5.6	5	≤ 5
Fecal coliforms (CFU/100ml)	-	-	-	2043	620	3800	< LoD	≤ LoD	< LoD	< LoD	< LoD	< LoD	0	0
E.coli (CFU/100ml)	-	-	-	1398	460	3100	< LoD	≤ LoD	< LoD	< LoD	< LoD	< LoD	0	0
DO (mg/L)	9.8	8.0	10.8	10.2	9.1	11.7	9.6	8.0	10.9	7.0	4.4	9.5	-	-

CONCLUSIONS AND RECOMMENDATIONS

The results show that both the GWS and DFS can treat the urban stream water used, and produce water that meets the SANS 241 standards and WHO guidelines with respect to the parameters measured. The treated water from the PoU systems compared well with good quality tap water supplied to Stellenbosch University with respect to bacterial, turbidity and suspended solids content. Both systems are relatively low cost water treatment solutions, with their own benefits and drawbacks. Both can improve the quality of the raw surface water in terms of bacterial counts and clarity. The study also included seasonal variations in water quality to some extent, as it ran from winter through spring to summer. Since PoU systems (such as these) may often offer advantages over centralized water treatment systems by minimizing the risk of contamination between the source and the point-of-use, they are a good option to help improve water security in many communities over the world.

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Chapter 3: A small-scale low-cost water treatment system for removal of selected heavy metals, bacteria and particles

Chapter 3 and Appendix A (alongside Chapters 4 and 5) formed part of the work done to address the second objective of the dissertation, which was "to investigate and optimize simple, locally sourced low-cost water treatment materials and techniques for bacterial and particle removal in poverty stricken communities". The aim of this investigation was to develop a PoU system suitable to low-income areas, able to significantly remove particles and bacteria from water, improve aesthetic aspects and appreciably reduce concentrations of selected heavy metals and made from locally sourced materials.

Performance improvement of an ISSF system by incorporating filter mats made of geotextile fabric serving as a pretreatment step (to significantly reduce the particulate loads in the water before it passes through the sand body) and GAC as an adsorption media for improving aesthetic aspects (color, taste, odor) and for removal of selected heavy metals (arsenic, cadmium, lead, iron and manganese) was done. Placing filter mats on the sand surface also concentrates the major part of water purification in the filter mats and therefore less purification action happens within the sand body. In addition, the filter mats extended filter run times and offered easy filter cleaning by removal and washing of the fabric alone as opposed to "scraping" or "swirl and dump" in traditional ISSF systems. GAC enhanced the adsorption capacity and subsequently increased particle removals and aesthetic improvements by the ISSFGeoGAC as was seen in the turbidity results of system 1 (ISSF-1). Similarly, the geotextile within system 2 (ISSF-2) filter body was included to enhance particle capture and retention. However, this proved otherwise as depicted by the frequent particle breakthroughs in ISSF-2. It was therefore concluded that the use of geotextile layers within an ISSF may not be necessary. The use of filter mats was chosen with knowledge from Chapter 2 where polypropylene string filter in the GWS was indicated to be able to pre-treat turbid water. However, since polypropylene string filter may not be locally available and may not be affordable to the poorest groups, bidim geotextile which is locally produced in South Africa was chosen in its place. Similarly, GAC was included because it substantially improved the aesthetic aspects in both DFS and GWS and is locally produced in South Africa.

The studies in this Chapter and Appendix A resulted in a simple, yet innovative low-cost PoU water treatment system namely the ISSFGeoGAC. Sand is a robust natural material which is available in many parts of Southern Africa. This was used as a motivation to look into improvement of the ISSF system and then optimize it to reduce its current limitations. Therefore, enhancing ISSF system contaminant removal and improvement of the aesthetic quality of the treated water while extending filter runs is a novel initiative.

Based on comparisons of the commercial low cost PoU systems DFS and GWS (Chapter 2) and knowledge gained from a thorough review of literature (Binnie and Kimber 2013; CAWST and SPC 2017; Graham and Mbwette 1987; Jenkins *et al.* 2009; Manz 2004; Muhammad *et al.* 1996; NE-WTTAC 2014), the ISSFGeoGAC (system 1) was developed. Although there is still room for improvement, laboratory tests showed that the novel technology is expected to perform better than the traditional ISSF systems. Initial literature review on the applications as well as strengths and weaknesses of available low-cost PoU systems showed that ISSF systems particularly the institutional scale (CAWST and SPC 2017), still need further improvement in terms of cleaning frequency and removal of other contaminants such as metals. The traditional cleaning methods are somewhat tedious and tend to render the technology less acceptable to users. This is further worsened by inconsistencies in improving aesthetic aspects and significant reduction in bacterial removals after cleaning. Therefore, the innovative modifications mentioned above were made to address the said problems and increase the acceptability and adoptability potential of the ISSFGeoGAC.

A small-scale low-cost water treatment system for removal of selected heavy metals, bacteria and particles

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ABSTRACT

Two low-cost sand filtration systems incorporating granular activated carbon (GAC) and non-woven geotextile respectively were assessed for Point-of-Use water treatment. Laboratory scale models were evaluated in respect of selected heavy metals, bacterial and particulate removal when exposed to surface water for five months. System 1 (ISSF-1) incorporated GAC and system 2 (ISSF-2) incorporated non-woven geotextile. Filter-mats were placed on the filter surfaces of both systems. Flow rates ranged between 8 and 15 L/h for longer water contact with the GAC and bio-layer. On average, *E.coli* removals were 96% and 94%, while fecal coliform removals were 96% and 95%, by ISSF-1 and ISSF-2 respectively. Average TSS removals were 98% and 92%, while turbidity removals were 97% and 91%, by ISSF-1 and ISSF-2 respectively. Average metal removals were: Arsenic (21%), Cadmium (82%), Lead (36%), Iron (65%) and Manganese (94%) by ISSF-1, Arsenic (17%), Cadmium (<LoD), Lead (<LoD), Iron (92%) and Manganese (98%) by ISSF-2. Both models consistently met turbidity guideline (5 NTU) and can remove significant amounts of particles. Both systems can treat the poor-quality water used to provide relatively safe water and could be improved further for heavy metal removal. However, to guarantee continued safe-water supply, supplementary treatment by chlorination is recommended.

Key words: Drinking water, heavy metals, low cost, PoU, small-scale, surface water, water quality

INTRODUCTION

There is increasing recognition around the world that conventional piped systems are not the only solution for providing safe water. The traditional approach can be complemented by non-networked water supply and treatment systems to complete the service chain across urban, peri-urban, and rural contexts (CAWST 2017a). Colombia, for instance, has new legislation regarding universal access to basic services that recognizes that, to reach full water supply coverage for most vulnerable populations in peri-urban, rural and dispersed areas, centralized and traditional implementation mechanisms, for water quality assurance, are not sufficient. The new legislation prompts government agencies to acknowledge, evaluate and accept alternative, viable, context-appropriate solutions such as low-cost, point-of-use (PoU) water treatment technologies to improve water quality for underserved populations (op cit). Many poor communities, especially in sub-Saharan Africa, are underserved and below the global average for basic access, when it comes to providing people with safe water (WHO 2012). Lack of access can be fatal, particularly for the elderly, young children, pregnant women and people with HIV/AIDS (WHO 2017a). The absence of safe water is among the leading causes of child mortality in poverty stricken communities (WHO 2012). This study was undertaken to develop a low-cost, PoU water treatment system using easily accessible low-cost materials affordable to the poor of developing countries. Two low-cost, Intermittently-operated Slow Sand Filtration (ISSF) systems for PoU water treatment, incorporating GAC, non-woven geotextile and filter mats were designed and constructed from easily acquired materials locally available in South Africa.

The aim was to develop a PoU appropriate for low-income settings, and able to significantly remove turbidity and bacteria from water, and appreciably reduce concentrations of selected heavy metals. The system is also expected to treat enough water sufficiently quickly for point-of-use in households or small settings such as schools, etc. It must also be durable, requiring minimal frequency of cleaning and maintenance, easily assembled, low-cost, generally 'free-standing', and with little or no plumbing (WHO 2016). The main contaminants addressed in this study were bacteria *(E.coli* and thermo-tolerant (fecal) coliforms), particles (turbidity or suspended solids), and some heavy metals. While the water treatment focus for PoU applications must always be the microbial aspect (McAllister 2005), disease may also result from consuming water containing toxic levels of elements like arsenic and lead (WHO 2017a).

Many conventional methods exist for removal of heavy metals and other chemical contaminants, bacteria and particles, involving multiple steps such as tower aeration, lime softening and/or coagulation, followed by settlement of the insoluble precipitates, and rapid filtration and disinfection (de Moel *et al.* 2007; Mcghee 1991; WHO 2017a). In addition, high-tech water treatment technologies such as ultrafiltration, nanofiltration, ion exchange, flotation, ozonation, ultraviolet disinfection and reverse osmosis can treat various types of contaminated water (Mcghee 1991; Peavy *et al.* 1986; WHO 2017a). However, most of these are too expensive and fail to meet the specific needs of poor communities (McAllister 2005). Therefore, other small-scale, low-cost technologies are required. In this study, two low-cost filtration systems incorporating alternating layers of sand, gravel, GAC and non-woven geotextile with filter mats placed on filter surfaces, were investigated to assess their effectiveness in removing bacteria, particles and selected metals (arsenic, cadmium, lead, iron and manganese).

Bacterial removal was considered because infectious diseases caused by bacteriological agents are by far the most common and widespread health risk associated with drinking-water (McAllister 2005; WHO 2017a). Fecal coliforms and *E.coli* were used as indicator organisms, as their presence in water signals the presence of fecal contamination, and potentially, pathogens. The presence of coliform bacteria may indicate the presence of other pathogens that can lead to severe and sometimes life-threatening water borne diseases such as cholera, typhoid, dysentery, diarrhea, infectious hepatitis and giardiasis (de Moel *et al.* 2007; Ritter 2010; WHO 2017a).

Removal of turbidity was considered for aesthetic reasons because water that is aesthetically unappealing can lead to water use from sources that, while aesthetically more acceptable, may not be safe (WHO 2017a). There is a common perception that clear water is equivalent to safe water (Kotlarz *et al.* 2009). This view maybe somewhat justifiable, since pathogens are often attached or adherent to suspended particles (e.g. clay and silts) in water (CAWST 2011; WHO 2017a). According to WHO (2017b), the presence of particles can also indicate the presence of hazardous chemical and microbial contaminants, and increase chlorine demand. Reduced chlorine demand allows lower chlorine dosage (Kotlarz *et al.* 2009), which could increase taste acceptability and reduce water treatment costs. Apart from interfering with chlorination effectiveness, elevated particle concentrations in drinking water may produce disinfection byproducts (DBPs); the desired maximum particulate level for this purpose is 1.0 nephelometric turbidity units (NTU). Kotlarz et al (2009) showed that free chlorine residual was maintained at a significantly higher level in water passed through a sand filter before chlorination than in unfiltered water.

To enhance bacterial and particulate removal, filter mats (three geotextile layers each 0.60 cm thick) were employed, to augment mechanical trapping and support bio-layer growth. This was supplemented by sizing the fine sand layer according to recommendations by CAWST (2011) and Parsons & Jefferson (2006), with an effective particle size of 0.1 to 0.2 mm and uniformity coefficient of 1.5 to 2.5, giving a more tightly packed sand layer and, thus, more effective bacterial and particulate removal. This is expected to enhance surface straining and biological removal of contaminants, in addition to adsorption and natural bacterial death, which occur within the sand body.

An attempt was also made to enhance the systems' effectiveness in removing iron, manganese and other heavy metals. GAC was included mainly for this purpose, in addition to removal of color, taste and organic pollutants (McAllister 2005; WHO 2017a). Not all filters can remove heavy metals or other toxins from water, but incorporating GAC or bone charcoal, where appropriate, may help (Mihelcic *et al.* 2009). In regions where such contaminants are present in water, their removal is a good idea. The toxic elements considered were arsenic (As), cadmium (Cd) and lead (Pb), which are amongst the most common environmental pollutants (Turkez *et al.* 2012). According to Llobet et al (2003) these metals have no beneficial effects in humans and there is no known homeostatic mechanism for them. They are toxic and, when present in water supplies anywhere, require continued attention (Okun & Ernst 1987). It is noted, however, that inclusion of the metals in this study does not imply that all will necessarily be present or that other metals, not addressed, will always be absent.

Arsenic is highly poisonous and occurs naturally in many groundwaters, as well as some surface water sources. South Africa, where this research was done, is known to be affected by arsenic in drinking water (CAWST 2011; Mihelcic *et al.* 2009). According to Ahmed (2008), high arsenic doses are fatal immediately. Long-term consumption of arsenic in drinking water is often associated with increased risk of chronic diseases such as skin bulges (keratosis) on palms and feet, and cancer of the skin, lungs, bladder and kidney (WHO 2017a). Cadmium is classified as a human carcinogen known to cause deleterious effects to health and bone demineralization, either through direct bone damage or via renal dysfunction (Renu & Singh 2017). According to WHO (2017a), the kidney is the main target organ for cadmium toxicity, where it accumulates and has a long biological half-life of 10 to 35 years, in humans. Lead is found in many water supplies across the world, and is particularly important because it is highly toxic and has been shown to cause neurological damage in children, leading to intellectual and psychological impairment, even at extremely low exposures (Okun & Ernst 1987; Renu & Singh 2017). It is also associated with reduced fertility, impaired fetal development, impaired kidney function and increased blood pressure (WHO 2017a).

Iron and manganese removal were considered mainly for aesthetic reasons because these metals affect the acceptability of water. They occur naturally in ground- and surface- waters, in places where the rocks and sediments are high in iron and/or manganese (CAWST 2017b). Drinking water containing high concentrations of iron may not make people sick, but it affects the taste and gives it a reddish cast (CAWST 2017b). This makes the water less appealing to drink and can lead to indirect health impacts, if users lose confidence in treated water and either drink less, or opt for aesthetically better alternatives – i.e., without iron and/or manganese effects – that could be more harmful to health (CAWST 2017b; WHO 2017b). Since the raw water used in this study was collected from a point in the stream with noticeable mixing and turbulence, it was assumed that the iron and manganese were mainly in their oxidized forms.

Two small-scale, low-cost, sand filtration systems incorporating GAC, non-woven geotextile and filter mats for removal of selected heavy metals, bacteria and particles from water were designed, constructed, and evaluated for this study. They were exposed to a single surface water source for five months and three weeks, a period that covered seasonal variations in raw water quality, as it ran from winter through spring to summer.

MATERIALS AND METHODS

Setting

The research was conducted in the Water Quality Laboratory of the Department of Civil Engineering at Stellenbosch University in Cape Town, South Africa. Raw surface water samples were obtained from Kromrivier stream, at 33°55'34.68"S and 18°51'40.56"E, next to the bridge between Ryneveld Street and Kromrivier Road, Stellenbosch, South Africa.

Study design

Two small-scale, low-cost ISSF systems were evaluated for heavy metal, bacterial and particulate removal when exposed to surface water from 19 June to 8 December 2017. Both systems comprised columns 60 cm tall and of 10.5 cm internal diameter, and made of transparent Plexiglass. 1 mm perforated diffusers were fabricated for uniform and gentle water distribution onto the filter surface, and to prevent the schmutzdecke from being disturbed.

A 10 cm gravity water head was provided above the filter systems to drive water slowly through the filter media. The lower the gravity head, the less the pressure and the slower the flow rate, resulting in higher particulate and bacterial removal. The two ISSFs for PoU application were constructed with alternating filter media layers consisting of sand, gravel, GAC and geotextile. The main aspects included were: (i) filter mats (non-woven synthetic fabric) placed on the sand surface (ii) GAC layered within ISSF-1, and (iii) non-woven synthetic fabric layered within ISSF-2.

It is noted here that this research is ongoing and is expected to have two major phases. The phase, discussed in this paper, focused on evaluating the contaminant removal performance -i.e., their effectiveness - and assessed the potential for improvement. The next expected phase will involve constructing improved versions, and assessing their performance against an ordinary ISSF system having no GAC or geotextile, and, at the same time, duplicates of the two systems but without allowance for bio-layer growth. Construction of full-scale units is also anticipated, to check whether scale affects contaminant removal significantly. In the anticipated second phase units, there will also be a (standard) mechanism to maintain the recommended 5 cm standing water level automatically on the filter surface (CAWST 2011) and thus preserve the microbial community by preventing the bio-layer from drying out. In this phase, the standing water level was maintained manually to the labeled mark, which was rather laborious.

Table 3-1: *Filter material depths highlighted from top to bottom layers for each system*

Filter Material	*ISSF-1*	*ISSF-2*
Non-woven geotextile layers (≈75 µm pore size)	*1.80 cm*	*1.80 cm*
Fine sand (ES: 0.16 mm, UC = 2.0)	*14.5 cm*	*14.5 cm*
Coarse sand (ES: 0.30 mm, UC = 2.4)	*14.5 cm*	*14.5 cm*
GAC	*10 cm*	*-*
Non-woven geotextile layers (≈75 µm pore size)	*-*	*7 cm*
Gravel	*9 cm*	*9 cm*

System 1 (ISSF-1) incorporated GAC and system 2 (ISSF-2) non-woven geotextile layered within the filter media. Both had geotextile filter mats on top of the filter surface to offer some form of bacterial and particle removal, thereby serving as a pretreatment step. The mats are expected to provide longer filter run times and a simpler filter cleaning method than with ordinary ISSF systems. In this case, cleaning only involves the removal and cleaning of the filter mats. The GAC in ISSF-1 is expected to improve system adsorption capacity and help with metal removal. **Table 3-1** highlights the key filter materials, from top to bottom, in both systems. The silica sand and gravel were polished and graded at the University of Stellenbosch's Civil Engineering Geotechnics Laboratory. Fabrication was done in the Hydraulics Laboratory, and the systems were assembled and tested in the Water Quality Laboratory.

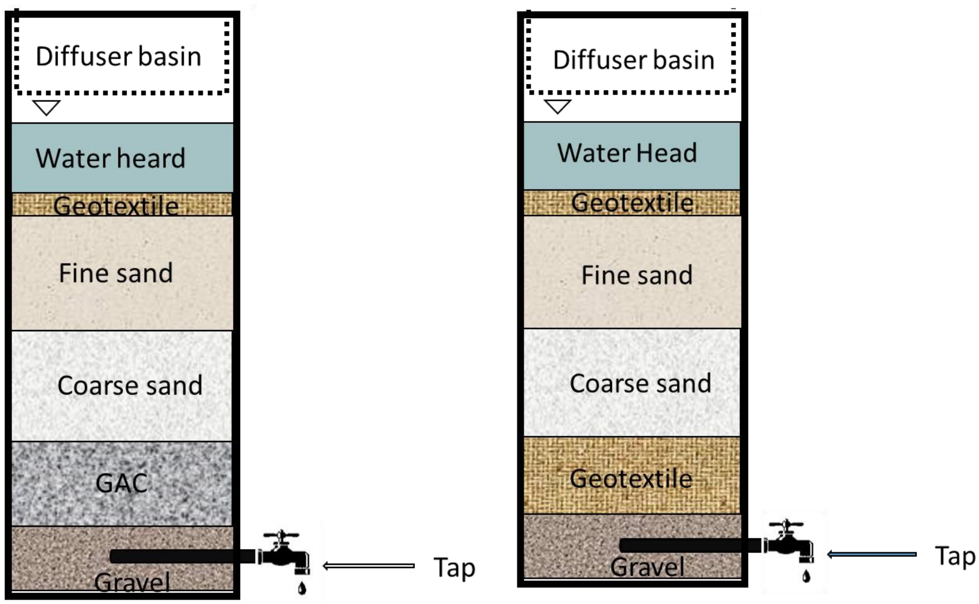

Figure 3-1: Schematic diagram of the laboratory scale systems; ISSF-1 (left) and ISSF-2 (right)

Figure 3-1 shows schematic diagrams of the systems. Each was provided with a tap for collecting treated water. GAC was purchased from a local pet shop in Stellenbosch making it relatively affordable and easy to obtain. Clean quarry sand was used in the study to ensure purity, with no fines, organics or pathogens, as recommended by CAWST (2011). The GAC was placed below the sand to inhibit particle clogging of the GAC, and also because it is recommended that the GAC not be used as a primary layer or filter (McAllister, 2005). It was also done on the assumption that this arrangement allows less contaminated water to pass through the GAC layer for removal of color, taste, some organics, certain pesticides and other micro-pollutants (Kawamura 2000; McAllister 2005) with less interference from particulate matter. In addition, it has been indicated by others (Mihelcic *et al.* 2009; Siabi 2003), that GAC can be used for removal of species like arsenic, iron and manganese.

Overview of ISSF systems in the study context

In an ISSF system raw water flows downwards by gravity, and pathogens and turbidity are removed by mechanical trapping primarily in the top few centimeters of the filter media (CAWST 2011; WHO 2017a). ISSF filter systems are operated intermittently as water becomes available, unlike ordinary slow sand filters, which are continuous filtration systems where water flows through at a slow but continuous rate (CAWST 2017a; Manz 2004). A bio-layer, commonly known as the "schmutzdecke", develops on the filter surface and helps in pathogen removal due to predation of pathogens by organisms living within it (CAWST 2011; WHO 2017a). Pathogens also die naturally deeper within the filter depth as oxygen, light and food become too scarce to sustain microbial life – most organic material is trapped on the filter surface. ISSFs are most effective in treating low-turbidity water or water that has been treated partially (WHO 2017a). When clogging occurs – i.e., when there is little or no flow – the top few centimeters of sand containing the accumulated solids are normally scraped off and replaced (CAWST 2011; WHO 2017a). ISSFs can remove algae and microorganisms, including protozoa, bacteria, helminths, and, if coupled with pretreatment, can reduce turbidity from very high levels (Manz 2004; WHO 2017a). Hence, filter mats were included to serve as a pretreatment to enhance performance, minimize clogging and reduce scraping requirements. Another removal mechanism by ISSFs is adsorption (or attachment), whereby pathogens and particles are adsorbed, or become attached to filter media. It was with respect to this aspect that GAC was included in ISSF-1, to augment adsorption capacity.

A household version of ISSF systems, normally called a biosand filter (BSF), was originally developed by Dr. David Manz, University of Calgary, in 1991 and has been further developed by CAWST to the current version 10 (CAWST 2011; Manz 2004). In 2012, Samaritan's Purse Canada and Clear Cambodia, used slow sand filtration and BSF principles to develop an ISSF system appropriate for institutional scale use, such as that of health centers, to improve water quality in rural schools in Cambodia, and included a float valve to control water level, filter hydraulic loading rate and flow rate (CAWST 2017a). The name commonly applied to this institutional-scale ISSF is "school biosand filter" (sBSF). The WHO refers to the BSF system as the 'household-level intermittently-operated slow sand filtration (hISSF)' (WHO 2017a). The filtration principle, and key contaminant removal mechanisms such as trapping, predation, absorption and natural bacterial death are the same. Both versions are primarily intended for bacteriological water quality improvement, although modifications can be made to allow removal of other impurities, e.g., arsenic (NE-WTTAC 2014). Some literature shows that both versions remove bacteria successfully (CAWST 2011; CAWST 2017a; Manz, 2004). While others report that the filters remove fewer bacteria, particularly in field settings, and their filtrate does not consistently meet potable water guidelines in removing bacteria and other pathogens (Nemade *et al.* 2009; Stubbe *et al.* 2016).

The ISSF-1 and ISSF-2 were designed to include materials highlighted earlier, to try to enhance performance so that a single system is expected to improve water quality with respect to bacteria, particulates and selected metals, thus increasing health benefits and filter run times, while reducing cleaning problems. In this context, some modifications to the hISSF system have been reported, focusing on improvements in the water's microbiological quality. For example, researchers at Massachusetts Institute of Technology have added a layer of sand above the diffuser basin, to provide a second biolayer (NE-WTTAC 2014). The TivaWater system, promoted in some African countries, is a lighter and more compact version of the BSF that includes integrated storage for filtered water (NE-WTTAC 2014). No literature on the performance impact of these modifications is available.

Flowrate and Raw water dosing

Each system was charged with at least 7.5 liters of water per day, fed in by pouring onto the filter surface to provide a maximum water head of 10 cm. Because the column reservoirs could not handle the full charge volume, they were filled to capacity and water was added when the head was low enough to accommodate more. The flow rate was measured using a 2 L jar and stopwatch at the fastest flow point in the filter, as this determines possible detachment of microbes and particles attached to filter media, and their subsequent flushing into the filtered water (NE-WTTAC 2014). The systems' initial flow rates were between 8 and 15 L/h, to ensure adequate empty-bed contact time (EBCT) for the GAC, and longer contact times between raw water and the bio-layer during the filtration run period. Flow rate was measured over the study period and decreased gradually with time, as expected. As the flowrate decreased the treated water quality improved, especially after filter ripening, for both systems, and particularly in terms of bacterial and particulate removal. The filters were not cleaned during the study, in order to reach the lowest possible flow rate. Initial observed flow rates were 10.08 and 9.97 L/h for ISSF-1 and ISSF-2, respectively, and 6.34 and 6.13 L/h at the study end. In other words, the two systems where still yielding appreciable volumes of treated water at the end of the study.

Water testing and system evaluation

To ensure that the source water was contaminated, raw water samples were collected and tested for two weeks before evaluation tests commenced. In both weeks more than 500 CFU/100ml of fecal coliforms and more than 400 CFU/100ml of *E.coli* were recorded. TSS and turbidity were consistently above 14 mg/l and 10 NTU, respectively. The concentrations of indicator bacteria (fecal coliforms and *E.coli)*, particles (TSS and turbidity) and metals (arsenic, cadmium, lead, iron and manganese) were determined before and after treatment by each filter system. Other parameters measured were pH, dissolved oxygen (DO), electrical conductivity (EC) and total dissolved solids (TDS). The two system models were flushed with potable tap water prior to use until the discharge was clear, to remove impurities.

Treated water was collected daily for physico-chemical tests and fortnightly for bacteriological tests, and only in the last two months for metal species. Tests for *E.coli* and fecal coliforms were done by Water Analytical Laboratory (WALAB) accredited to the South African National Accreditation System (SANAS), No: T0375 for microbiological analysis, whereas the metals were determined by the Central Analytical Facilities (CAF) of Stellenbosch university. The CAF operates state of the art equipment and provides analytical services to the Stellenbosch University research community and the rest of the South African research and development sector. Physico-chemical tests were done in the Water Quality Laboratory at Stellenbosch University. All tests were carried out in accordance with the Standard Methods for the Examination of Water and Wastewater (APHA/AWWA/WEF 2012).

Treatment effectiveness (percentage removal) calculations

The treatment effectiveness (percentage removal) achieved by each system for *E.coli*, fecal coliforms, turbidity, TSS and the selected metal species was calculated using **Equation 3-1***:*

$$\%\, removal\ of\ contaminant = \frac{C_i - C_e}{C_i} X\ 100 \qquad (3\text{-}1)$$

Where: C_i = concentration of contaminant in untreated water, C_e = concentration of contaminant in treated water

RESULTS AND DISCUSSION

Raw (river) water quality

The untreated river water was characterized initially and on each sampling day over the study period for the selected contaminants. Raw water quality was then compared to the South African National Standards

(SANS) 241 and WHO guidelines for potable water – see **Table 3-2.** In addition to the high particulate and iron contents, the raw water was highly contaminated with *E.coli* and thermo-tolerant (*fecal*) coliforms.

Table 3-2: Raw water quality compared to WHO guidelines and SANS 241 Standards

Parameter	*Untreated water*		*Drinking Water Standards*	
	Min	*Max*	*WHO*	*SANS 241*
pH (pH units)	*7.5*	*8.8*	*6.5-9.0*	*≥ 5 to ≤ 9.7*
Conductivity (µS/cm)	*140.9*	*650*	*2500*	*≤ 1700*
TDS (mg/L)	*71.9*	*332.6*	*1000*	*≤ 1200*
TSS (mg/L)	*10*	*150*	*0.1*	*-*
Turbidity (NTU), Aesthetic	*6.3*	*93.8*	*5*	*≤ 5*
Fecal coliforms (CFU/100 ml)	*620*	*3800*	*0*	*0*
E. coli (CFU/100ml)	*460*	*3100*	*0*	*0*
DO (mg/L)	*8.3*	*11.7*	*-*	*-*
Arsenic (µg/L)	*1.0*	*5.6*	*10*	*≤10*
Cadmium (µg/L)	*<0.01*	*0.01*	*3*	*≤3*
Lead (µg/L)	*0.22*	*1.4*	*10*	*≤10*
Iron (µg/L), Aesthetic	*1030.3*	*1349.6*	*300*	*≤300*
Manganese (µg/L), Aesthetic	*29.4*	*66.1*	*100*	*≤100*

E.coli and fecal coliform removal

The results (**Figures 3-2** and **3-3)** show that ISSF-1 and ISSF-2 were both significantly effective in bacterial removal, and recorded respective *E.coli* removal ranges of 87.3 to 99.9% and 84.1 to 100%, as well as achieving fecal coliform removal of 88.5 to 99.9% and 85.0 to 99.8% . The average *E.coli* removal rates (96% for ISSF-1 and 94% for ISSF-2) are slightly higher than those typically reported for ISSFs, e.g. 90% (WHO 2017a).

As shown in **Figures 3-2** and **3-3**, bacterial removal became much more pronounced and consistently exceeded 95% after a month's operation, signifying the importance of *schmutzdecke* growth on systems of this kind. According to CAWST (2011), filter ripening – i.e., *schmutzdecke* development – which considerably improves bacterial removal, takes about 4 weeks. After filter ripening, the recorded average *E.coli* counts were 1233 CFU/100 ml for the raw water, and 6 and 17 CFU/100 ml, respectively, for the treated waters from ISSF-1 and ISSF-2. So, both units yielded drinking water of reasonable quality before chlorination. According to various authors (e.g., CAWST 2011; Harvey 2007; WHO 1997), water of this quality may be consumed as it is. This is especially true during emergencies or for those not yet serviced with good quality piped supplies. Even before filter ripening, however, bacterial removal by both systems was high, with ISSF-1 and ISSF-2, respectively, reporting fecal coliform removal of up to 93.6 and 89.1%, and *E.coli* removal of up to 89.2 and 84.4%. This could be attributed to presence of filter mats on the filter surfaces, and of GAC in ISSF-1 and geotextile layers in ISSF-2.

Both systems can produce relatively high-quality water, and can meet WHO and SANS 241 drinking water guidelines and standards of 0 CFU/100 ml for *E.coli* and fecal coliforms, if combined with chlorination. This claim was tested on ISSF-1, when its effluent was chlorinated to give 0 CFU/100 ml, using a low chlorine dose (1.875 mg/L) due to the low organic content, as recommended by Kotlarz et al (2009).

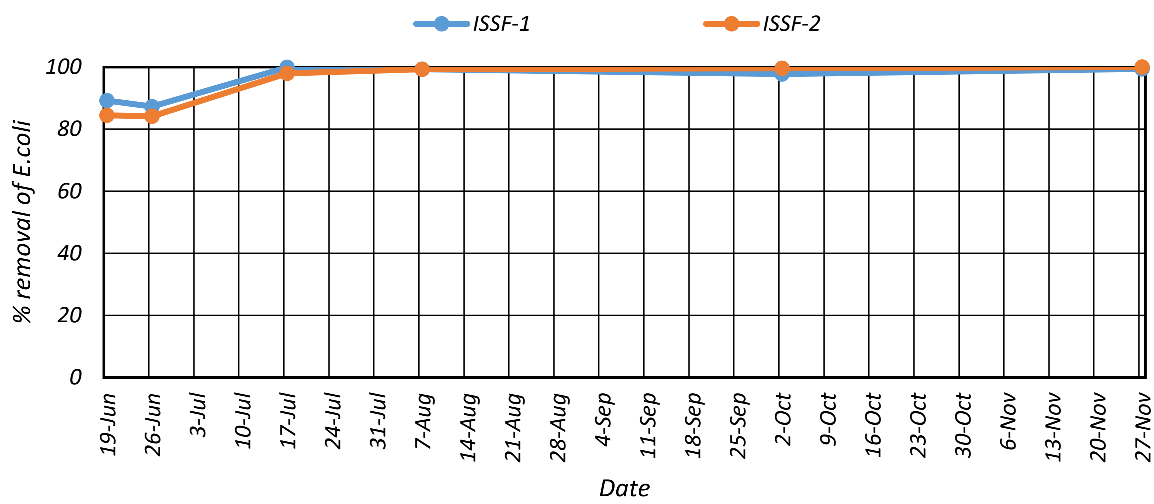

Figure 3-2: E.coli removal proportions by the two filter systems

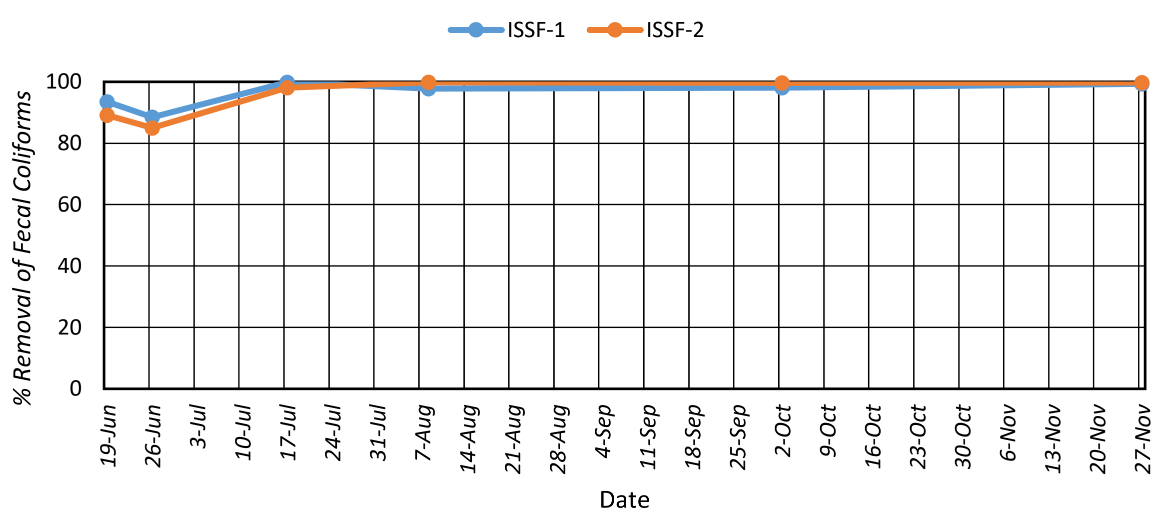

Figure 3-3: Fecal coliform removal proportions by the two filter systems

Particulate removal (TSS and turbidity)

There was substantial particle removal from the raw water by both ISSF-1 and ISSF-2 – see **Figures 3-4** and **3-5**. The ISSF-1 was generally better than the ISSF-2 for both TSS and turbidity removal, but particulate removal was significant by both systems. TSS removal was between 88.9 and 100% and 70.0 and 100%, respectively, for ISSF-1 and ISSF-2, whereas turbidity removal was between 87.3 and 100% and 65.8 and 100%. The higher particulate removal by ISSF-1 could be attributed to the presence of the GAC, which, to some extent, increased the filter's adsorption capacity. Although only ISSF-1 consistently met WHO's TSS guideline (0.1 mg-TSS/l) from 17 July to 13 October **(Figure 3-4)**, both consistently met both the WHO and SANS 241 turbidity guidelines (5 NTU) and removed very large proportions of particulate materials from the raw water, possibly due to the combined effect of the filter mats and bio-layers, coupled with other removal mechanisms.

There was a noticeable difference in particulate removal efficiency between ISSF-1 and ISSF-2 until after 13 October, when both systems began to perform similarly, perhaps indicating that the GAC in ISSF-1 had reached saturation, reducing its effectiveness, and required replacement. In general, the TSS and turbidity removal efficiencies were almost identical for the two systems. Although they cannot be directly correlated, TSS and turbidity are both measures of water clarity, and overlap in the measurement of particles like clay, silt, algae, bacteria, and non-settleable solids (Peavy *et al.* 1986; Ritter 2010) although they reflect different things (Peavy *et al.* 1986).

Since both systems can produce clear water, and remove iron and manganese, with significant efficiency – **Table 3-3** – they can improve water security in poor communities, particularly if combined with chlorination to guarantee continued supply of safe water. Both systems are affordable.

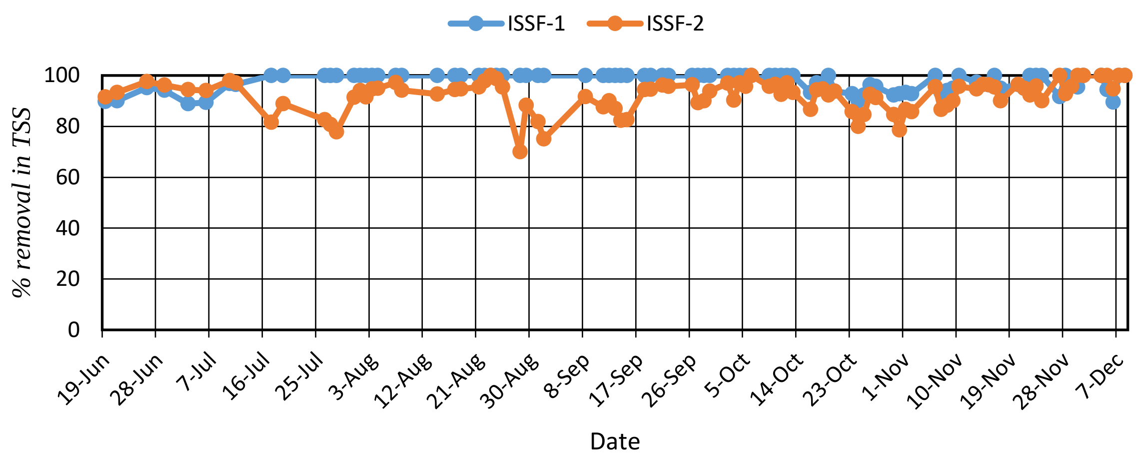

Figure 3-4: TSS removal proportions by ISSF-1 and ISSF-2

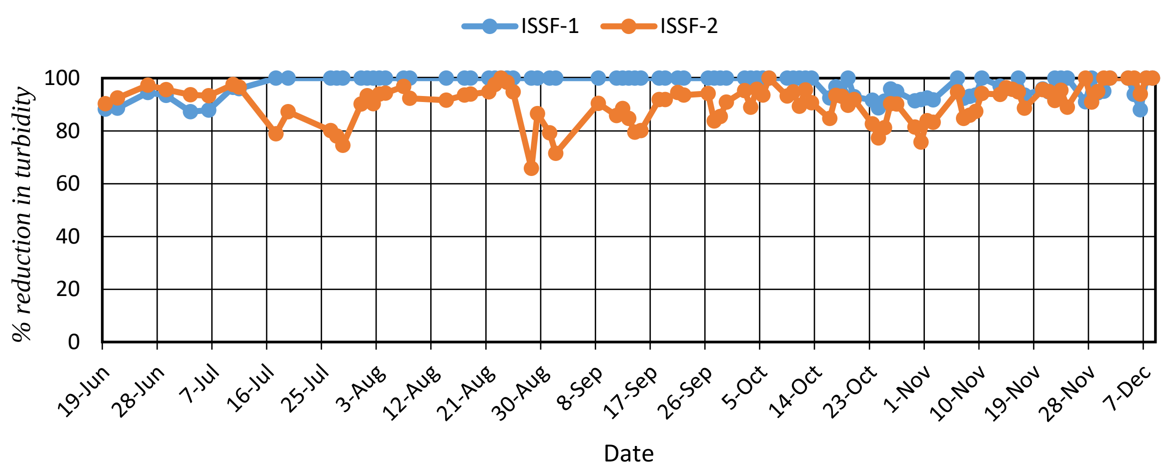

Figure 3-5: Turbidity removal proportions by ISSF-1 and ISSF-2

Metal species removal

Results shown in **Table 3-3** indicate removal of arsenic (up to 30.3%), cadmium (93.9%), lead (63.1%), iron (70.5%) and manganese (94.1%) for ISSF-1, and arsenic (29.3%), cadmium (<LoD), lead (<LoD), iron (92.1%) and manganese (97.7%) for ISSF-2. Iron and manganese removal was substantial by both systems and, since these parameters affect the acceptability of water, their removal is important where they occur. Although ISSF-2 was on average slightly more efficient than ISSF-1 with respect to removing these two species, it did not remove either cadmium or lead.

The slightly better performance of ISSF-2 with respect to iron and manganese probably arose from algal growth observed in the standing water of ISSF-2 (in the last two months of the study), which may have led to increased oxygen release – **Figure 3-7 –** and subsequent further oxidation and increased precipitation of the two species, leading to improved capture. Both filter columns were transparent and uncovered, attracting algae and plant growth. The ISSF-1 had marginal algal growth as it was more "inside" the laboratory, while the ISSF-2 was much closer to the laboratory window and generally recorded higher temperatures.

Table 3-3: Heavy metal removal by the two units on the sampling days

			25/10/2017					***24/11/2017***				
Metal	***Unit***	***LoD***	*Raw water*	*ISSF-1*	*ISSF-1 (%removal)*	*ISSF-2*	*(ISSF-2 %removal)*	*Raw water*	*ISSF-1*	*ISSF-1 (%removal)*	*ISSF-2*	*(ISSF-2 %removal)*
As	*µg/l*	*0.02214*	*5.63*	*5.00*	*11.13*	*5.31*	*5.57*	*0.99*	*0.69*	*30.30*	*0.70*	*29.29*
Cd	*µg/l*	*0.00061*	*0.01*	*≥LoD*	*69.08*	*0.15*	****	*0.01*	*≥LoD*	*93.9*	*0.18*	****
Pb	*µg/l*	*0.00545*	*1.37*	*0.51*	*63.10*	*7.69*	****	*0.22*	*0.20*	*9.09*	*1.48*	****
Mn	*µg/l*	*0.16406*	*66.05*	*3.92*	*94.07*	*1.53*	*97.68*	*29.41*	*1.93*	*93.44*	*0.66*	*97.76*
Fe	*µg/l*	*0.41529*	*1349.64*	*398.76*	*70.45*	*106.27*	*92.13*	*1030.29*	*423.33*	*58.91*	*77.20*	*92.51*

LoD = Limit of Detection; ** = increase in concentration over influent level

Equally, the better removal of the other metals by ISSF-1 could be attributed to adsorption by the GAC layer, although the effect was minimal due to their low concentrations in the raw water. Use of water with relatively higher/synthetic concentrations of the metals concerned is proposed for testing water treatment systems such as these. According to Mihelcic et al (2009), activated carbon adsorption is a proven process used to remove metals like arsenic and could be feasible for use by poor communities. Better technologies exist but are too costly or still being developed.

The ISSF-2 recorded higher cadmium and lead concentrations in its effluent than were found in the raw water influent **(**entries marked ** in **Table 3-3).** It is not clear whether these metals leached from the filter media – e.g., with initial capture and subsequent release.

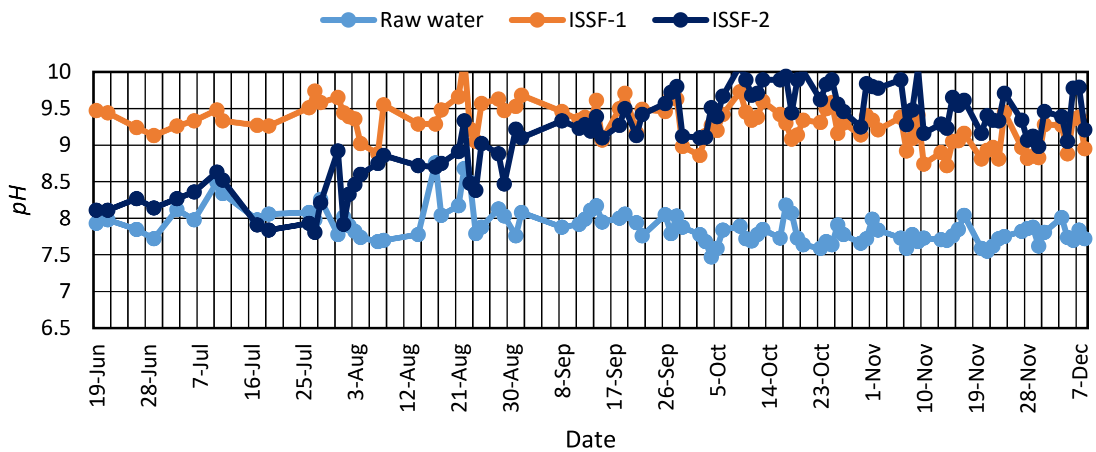

Figure 3-6: pH for ISSF-1 and ISSF-2 effluents, and raw water

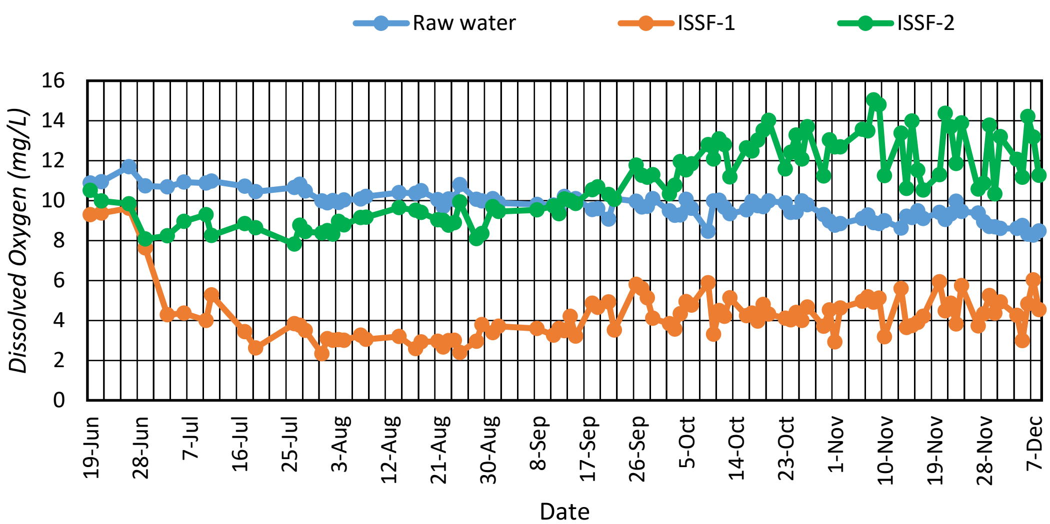

Figure 3-7: DO concentration of ISSF-1 and ISSF-2 effluents, and raw water

pH, DO, EC and TDS

Although the DO level in the ISSF-1 effluent was low most of the time (***Figure 3-7***), both systems consistently met the SANS 241 and WHO guidelines in terms of TDS and conductivity – see **Table 3-1.** Their effect on water quality was marginal, however, with respect to these parameters **(Figures 3-8** and **3-9)**.

Effluent pH values from the two systems **(Figure 3-6)** were generally above the WHO guidelines but within the SANS 241 limits. The high pH values recorded by both systems contributed somehow to the removal of iron and manganese. Tyrrel (1997) says that iron and manganese can be removed by raising the pH of the water, leading to the formation of insoluble metal precipitates that can be removed by filtration. In addition, de Moel *et al.* (2007) report that the oxidation and hydrolysis rates of iron and manganese depend on the pH – i.e., at low pH the rate of reaction for iron and manganese removal processes is slower than at high pH (Mcghee 1991; de Moel *et al.* 2007). Thus, de Moel *et al.* (2007) recommend that, when treating water with low pH for iron and manganese, aeration is used to remove much of the carbon dioxide, so that a higher pH is achieved.

As the raw water for this study was collected from a point where there was noticeable mixing and turbulence, it was assumed that the iron and manganese were sufficiently aerated and mainly in oxidized form. This may be supported by the raw water DO levels recorded, which exceeded 8.30 mg/l throughout the trials. The higher DO concentrations recorded by ISSF-2 **(Figure 3-7)**, started around 15 September and could have been caused by the algal growth observed – algal blooms were seen then in the raw water source and subsequently in ISSF-2. ISSF-1 had marginal algal growth as it was more "inside" the laboratory, while ISSF-2 was much closer to the laboratory window and generally recorded higher temperatures. It was also observed (**Figures 3-8** and **3-9**) that both the EC and TDS concentration of raw water dropped significantly from around 29 September, as did those of the treated effluent. This is likely due to the onset of summer, with reduced dissolved pollutant loads – the latter arising mainly from stormwater inflows. (The study area normally experiences winter rains from around June to September of each year, while very little or no rain is expected at other times.)

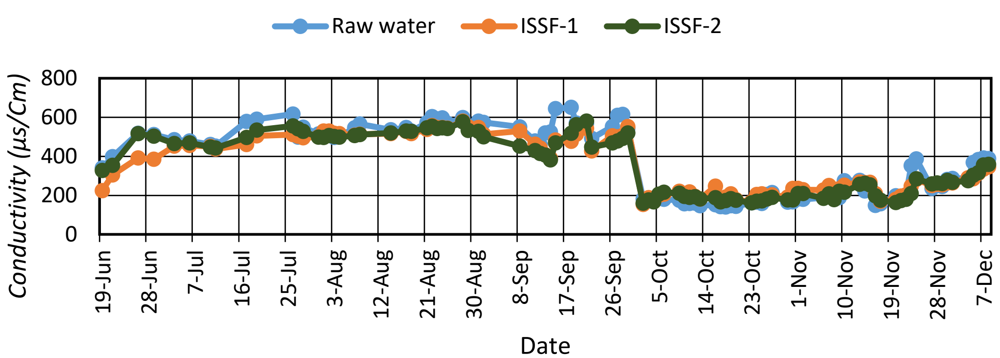

Figure 3-8: Conductivity of ISSF-1 and ISSF-2 effluents, and raw water

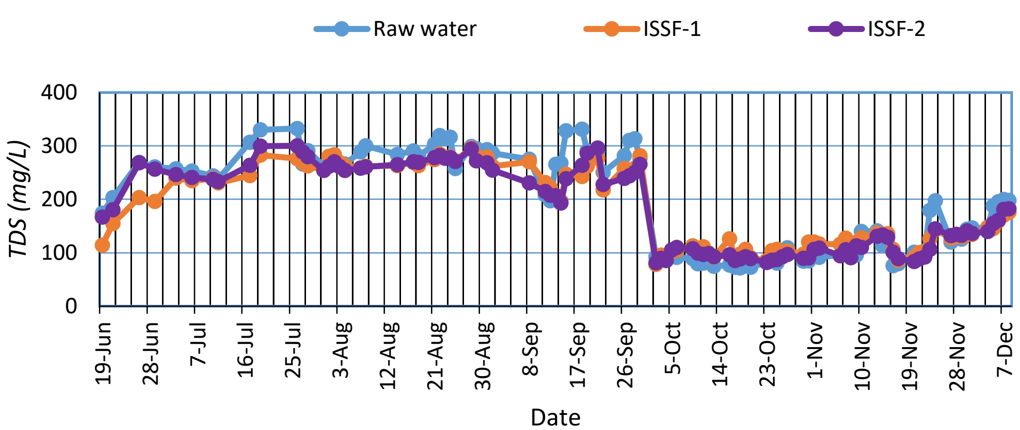

Figure 3-9: TDS of ISSF-1 and ISSF-2 effluents, and raw water

CONCLUSIONS AND RECOMMENDATIONS

Both ISSF-1 and ISSF-2 can meet basic water needs of about 7.5 to 15 liters/capita/day (The Sphere Project 2011). They will be particularly useful for poor communities and in emergencies. The systems can treat poor-quality water sufficiently well to produce relatively safe water. Both can improve water security affordably in poor communities, especially with respect to bacterial counts and acceptability aspects (turbidity, suspended solids, iron and manganese). Bacterial removal efficiency was substantial, and it may be possible to reduce pathogenic loads below infectious levels so that human health is no longer endangered. However, to guarantee the continued supply of water meeting the SANS 241 standards and WHO guidelines for drinking water, supplementary treatment by chlorination is recommended. The inclusion of filter mats, GAC and geotextiles in both systems is a small-scale, low-cost option for high quality filtration, possibly improving PoU treatment efficiency in underserved communities and minimizing cleaning problems.

System costs are approximately US$24 for ISSF-1 and US$20 for ISSF-2. They are easy to fabricate, assemble, operate and maintain. They could be very useful in homes, small communities, schools, refugee camps, prisons, markets, and/or health centers, where there is no access to safe drinking water sources, and, perhaps even more, where surface water is abundant or there are unprotected water wells.

Low-cost PoU water treatment systems may often offer advantages over networked water supply and treatment systems, by minimizing the risk of contamination between the source and the point-of-use.

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Chapter 4: Low cost drinking water treatment using nonwoven engineered and woven cloth fabrics

Chapter 4 (alongside Chapters 3 and 5) formed part of the work done to address the second objective of the dissertation, which is “to investigate and optimize simple, locally sourced low-cost water treatment materials and techniques for bacterial and particle removal in poverty stricken communities”.

The aim of this study was to investigate fabric filtration for low-cost PoU drinking water treatment by testing two nonwoven engineered and five woven cloth fabrics in respect of particle and bacterial removal. The best performers of each fabric type were then optimized for bacteria and turbidity removal. An optimized fabric filtration technique was developed and tested. The emphasis was to attain the best process configuration to achieve best possible contaminant removal while preventing recontamination. Numerical models for predicting turbidity removal efficiency were developed for each fabric as support tools for selecting optimal process configuration.

The use of nonwoven geotextile fabric as filter mats in Chapter 3 was found to be an interesting water treatment material particularly that the filter mats extended filter run times and offered easy filter cleaning by removal and washing of the fabric alone as opposed to “scraping” or “swirl and dump” in ordinary ISSF systems. This led to an investigation into possible use of nonwoven bidim engineered fabric for possible drinking water treatment in low-resource settings which was done alongside locally sourced cloth fabrics in this Chapter (Chapter 4). The use of nonwoven geotextile fabrics for drinking water treatment is an uncommon and simple method applicable to low-resource settings. It has the advantage of easy removal and washing to remove trapped dirt and once again improve flow rates.

The study in this Chapter resulted in an optimized simple, yet innovative low-cost PoU water treatment system namely the “eight-layer four-pot bidim sequential filtration system (BidimSEQFIL)”. The optimized fabric filtration technique was constructed and tested. It was found that BidimSEQFIL can substantially remove indicator bacteria (*E.coli* and fecal coliforms) up to 3 log removal value (LRV). The bacterial removal performance by BidimSEQFIL is much better than both ordinary fabric filtration and three-pot settling methods and has minimal recontamination potential. Additionally, bidim geotextile has comparative advantages for drinking water treatment over cloth fabrics as it is stronger and can be reused more often with less cleaning needs. Furthermore, bidim fabric is easy to wash without significant fabric loosening by normal hand wash. It can be disinfected in ordinary utility ovens at around 100 to 200°C and is structurally stable up to 200°C (Kaytech Engineering 2018).

Realizing that although geotextile fabric is cost-effective and can be readily sold and easily transported in bulk with sufficient roll dimensions, it might not be readily available to some remotest rural areas of Southern Africa. It was decided to investigate water filtration using indigenous wood species which are a natural material available in most rural areas of Southern Africa. This was done in Chapter 5.

Low cost drinking water treatment using nonwoven engineered and woven cloth fabrics

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ABSTRACT

The study investigated two engineered fabrics and five cloth fabrics for low cost drinking water treatment. An optimized fabric filtration method has been developed and tested. Numerical models for predicting particulate removal efficiency have been developed for each fabric as support tool for selecting optimal process configuration. Both engineered fabrics showed better performance and achieved the most effective particulate removal for the highest number of layers used. Sequential filtration was done on eight layers for representative fabrics of each type and recorded higher contaminant removal than one filtration run. Geotextile 1 was better than geotextile 2 in particulate removal and recorded *Escherichia coli* removals of up to 1.4 log removal value (LRV) for eight-layer normal filtration and 3.0 LRV for four-pot sequential filtration. Brushed cotton was best among the cloth fabrics in particulate removal but performed below expectation in bacterial removal. It recorded *E. coli* removals of only 0.04 LRV and 0.2 LRV for eight-layer normal filtration and four-pot sequential filtration, respectively. Effluent turbidity decreased exponentially with number of fabric layers, in line with porous media filtration theory. The optimized filtration method produced very clear drinking water of relatively safe quality using geotextile 1. Appropriate disinfection is still recommended to ensure continued water safety.

Key words | bacteria, drinking water treatment, engineered fabrics, fabric filtration, sequential filtration, turbidity

INTRODUCTION

Drinking water can be treated using many different methods or a combination thereof (Parsons &nd Jefferson 2006; Davis 2010; MWH 2012; WHO 2017a). The use of contaminated water from unprotected sources such as streams, rivers, shallow wells, etc. without any form of treatment for drinking or in the preparation of food can lead to acute and chronic diseases with devastating public health implications (Demena *et al.* 2003; WHO 2017a). Outbreaks of waterborne diseases such as cholera and typhoid are a widespread problem and a major cause of death in many places of the world (WHO 2012). Such diseases occur in all countries, but are five to six times more common in developing countries (Demena *et al.* 2003). The problem is especially acute in less privileged communities, where hygiene and environmental sanitation are generally poor, and is exacerbated by inadequate supplies of safe water (Demena *et al.* 2003; WHO 2012). It is possible for certain individuals to become immune to some waterborne bacteria by continued consumption of contaminated water, but high bacteria levels can still pose a serious threat to life in combination with other infections (Vishwanath 2010). Drinking water that has been treated effectively at point-of-use (e.g., through filtration and chlorination) and stored in clean containers can help reduce the problem (WHO 2017a).

This study optimized fabric filtration initially for particle and then for bacterial removal using two nonwoven engineered and five woven cloth fabrics for drinking water treatment. The degree to which the fabrics can remove impurities from a surface water source was assessed. Experiments were done to investigate best material and process combination for best possible removals while preventing recontamination. Bacterial removal efficiency was estimated using *E. coli* and fecal coliforms (Ritter 2010; WHO 2017a). This is because *E. coli* and fecal coliforms are indicators of the level of fecal contamination in water and signal the presence of pathogens. If these are present, the water should be treated (Mihelcic *et al.* 2009; WHO 2012). Viruses and chemical pollutants cause far fewer problems because of drinking untreated water than bacteriological agents (McAllister 2005). Hence, the first and most important step in the fight against drinking poor quality water is the elimination of bacteria (McAllister 2005) coupled with removal of turbidity so that consumers do not choose to use lower turbidity alternatives that may not be safe (Kotlarz *et al.* 2009; WHO 2017b).

Fabric filtration using cloth fabrics (e.g., nylon and cotton) has been used for water treatment in many poor communities since ancient times (SWICH 2018), mainly, for removing particles (Swick & Jensen 2015). However, little work has been done to optimize fabric filtration using the principles of science and engineering (Swick & Jensen 2015). Additionally, and to the authors' knowledge, no study has been done to date on use of bidim engineered nonwoven geotextile for point-of-use (PoU) drinking water treatment. Published literature generally show studies focused on use of geotextile for storm water pollution reduction (Franks *et al.* 2012; Paul & Tota-Maharaj 2015) and as biofilm attachment media in wastewater treatment (Yaman *et al.* 2008). In drinking water treatment, nonwoven geotextile has generally been used for improving the efficiency of other methods like slow sand filtration (Graham & Mbwette 1987) and in some cases, in advanced high cost standalone systems e.g., drinking straw (Mihelcic *et al.* 2009).

Much published research on fabric filtration has focused on cloth fabrics (Mihelcic *et al.* 2009; CAWST 2011; Swick & Jensen 2015; Shrestha & Spuhler 2018; SWICH 2018), while little research has been done to investigate and optimize bidim fabrics for low cost PoU water treatment. Cloth fabric studies, to date, have largely focused on removal of particles to improve clarity, enhance acceptability (Swick & Jensen 2015), and reduce chlorine requirements in order to reduce costs and improve taste (Kotlarz *et al.* 2009). In this study, nonwoven engineered bidim fabrics for PoU drinking water treatment were assessed and optimized – in addition to cloth fabrics – for both bacteria and particle removal. Cloth fabrics normally loosen significantly the more they are used, increasing their pore size and becoming less effective (Shrestha & Spuhler 2018; SWICH 2018). Therefore, engineered fabrics like bidim have relative advantages for drinking water treatment since they are stronger and can therefore be reused more often. Bidim, for instance, can easily be washed without significant fabric loosening by normal hand wash. It can also be disinfected in ordinary utility ovens at temperatures of around 100 to 200 °C, as was done in this study, and is structurally stable up to 200 °C (Kaytech Engineering 2018).

Bidim is a "food grade" geotextile manufactured by Kaytech Engineering, South Africa, in accordance with ISO 9001:2008, Registration No: LS1176 (Kaytech Engineering 2018). It is a nonwoven, continuous filament, needle punched, A-grade polyester geotextile for general civil engineering applications. The A-grade geotextile has nine sub-grades ranging from A1 to A10 (Kaytech Engineering 2018), from which two were chosen for this research (A8 and A10) based on availability, mechanical, and hydraulic properties. Bidim is normally applied in hydraulic applications, e.g., for erosion control, filtration and drainage, water and waste containment, hydraulic and retaining structures, and as a turbidity curtain during bay constructions (Kaytech Engineering 2018). The woven fabrics (polycotton, cotton wool, brushed cotton, 100% polyester, and 55% polyester45% cotton) included in this research were purchased in Stellenbosch, South Africa. These were selected based on availability and affordability to indigent groups.

International research on woven cloth filtration has shown promising results. For example, Sari cloth filtration is used by women in India to improve water quality (SWICH 2018). If folded 3–8 times, sari cloth provides a filter of about 20 µm mesh size which increases to 100–150 µm in older cloth that becomes loosened (Colwell *et al.* 2003; Mihelcic *et al.* 2009). The initial pore size of 20 µm is small enough to remove all zooplankton, most phytoplankton, and all *Vibrio cholerae* (the bacteria that causes cholera) attached to the plankton as well as other particulates larger than 20 µm (Colwell *et al.* 2003; CDC 2015; Shrestha & Spuhler 2018; SWICH 2018). Studies done by Colwell *et al.* (2003) showed that cholera risk can be reduced by about 50% using sari cloth folded three times to produce an eight-layer filter. Another example is the guinea worm cloth used in Ghana for preventing PoU transmission of Guinea worm disease. It is a tightly woven monofilament cloth filter manufactured by Vestegaard, a Swiss company and has pore sizes of 100–150 micron and a 200 mm × 200 mm nylon center (CDC 2015). The cloth filters out the predatory genus Cyclops, a vector of the guinea-worm larvae which cause dracunculiasis (guinea worm disease) (Mihelcic *et al.* 2009; CDC 2015).

The assessment and optimization process elaborated in the methodology section, included measurement of turbidity, *E. coli* and fecal coliforms of raw and treated water. It was also assessed whether the filtered water can be consumed without additional treatment methods such as sand filtration, chlorination, solar disinfection, and boiling. That is, can the improved water quality meet safe levels of being consumed as is (WHO 1997, 2017a; Harvey 2007) and for which optimized process configuration and material combination. According to Shrestha & Spuhler (2018), fabric filtration has two important applications, namely, (i) as a drinking water improvement method for people with limited choices, i.e., the less privileged who cannot afford treating water another way; have a "*better than nothing"* option, and (ii) used as first treatment stage from which water can then be disinfected or passed through additional treatment methods such as biosand filters. Although the technology might equally well apply in times of emergencies, it is primarily aimed at poor communities in developing countries due to prevalent levels of poverty and vulnerability in such settings (Demena *et al.* 2003; WHO 2012).

The focus of this research was therefore to investigate fabric filtration for low cost PoU drinking water treatment by testing two nonwoven engineered and five woven cloth fabrics in respect of particle and bacterial removal. The best performers of each fabric type were then optimized for both bacteria and turbidity removal. An optimized fabric filtration technique was also developed and tested. The emphasis was to attain the best process configuration to achieve best possible contaminant removal while preventing recontamination.

MATERIALS AND METHODS

Setting

This research was conducted in the Water Quality Laboratory of the Department of Civil Engineering at Stellenbosch University in Cape Town, South Africa. Raw surface water samples were obtained from Kromrivier stream, at 33°55′34.68″S and 18°51′40.56″E, next to the bridge between Ryneveld Street and Kromrivier Road, Stellenbosch, South Africa.

Study design

Laboratory experiments were conducted to optimize fabric filtration for removal of bacteria and particles (turbidity) by testing two nonwoven engineered fabrics and five woven cloth fabrics for PoU drinking water treatment. Initially, the extent to which all the fabrics can remove particles from water was assessed. More experiments were then systematically conducted on the best two of each fabric type for both bacteria and particle removal. The tests were done with a view to attaining best material combination and process configuration to give best possible contaminant removals while preventing recontamination. This was done with an assumption that fabrics producing the clearest water would be more acceptable to users as opposed to the ones producing water of marginal clarity (Kotlarz *et al.* 2009; CAWST 2017; WHO 2017b). In addition, fabrics removing most particles were assumed to also remove the most bacteria. Numerical models for estimating the optimal number of fabric layers were derived and tested for each fabric. These models may possibly serve as a support tool for costing and selection of optimal process configuration and material combination. Flow rates for each number of layers were measured for the two representative fabrics.

Sequential filtration was carried out in two different ways to decide on the best configuration with highest convenience and least recontamination potential. Optimization was done to produce drinking water with lowest possible bacterial counts and particulate concentrations in the easiest possible way. The first type of sequential filtration, whereby filtered water was re-filtered through eight layers of fabric multiple times (Swick & Jensen 2015) was performed up to 15 runs. In the second type – developed during this research based on the three-pot settling method (Mihelcic *et al.* 2009; CAWST 2011) – water was filtered through a set of four pots with eight fabric layers. Possible relationship between effluent turbidity and bacteria was assessed for the best configuration and is discussed in the results section.

Baseline study (turbidity removal only)

Initially, 300 mL water samples were filtered through a number of fabric layers ranging from one up to eight layers as proposed in various literature (e.g., Colwell *et al.* 2003; Mihelcic *et al.* 2009; Swick & Jensen 2015) where eight-layer cloth filters were used for cloth filtration. The baseline tests were done for turbidity removal only. Each filtration run was done using a new water sample and a new number of layers for each of the seven fabrics. Ten runs were conducted on each layer combination culminating into 80 runs for each fabric. Raw water and effluent turbidity were measured in duplicate for each run, thereafter percent removal values were averaged for reporting purposes. Water of low turbidity, generally <30 NTU, was used for the tests. Low turbidity is technically more difficult to remove without coagulation. For example, a study by Kotlarz *et al.* (2009) showed lower removals for lower turbidities and higher removals for higher turbidities. Additionally, various authors (e.g., Parsons & Jefferson 2006; Davis 2010; MWH 2012) recommend turbidities of ideally up to 10 NTU and not exceeding 20 NTU in raw water influent for direct filtration. From the initial (baseline) runs, the best performing fabrics were chosen for further experimentation.

Set up and apparatus

The general filtration set-up as shown in **Figure 4-1** comprised: (i) a water column, (ii) the respective fabric layer combination, and (iii) a clean beaker to collect the filtered water. The fabric was gently tied over the beaker without stretching and the column was then gently secured in place. Everything was conducted in a manner to mimic as closely as possible how the filtration can be done in poor communities. The fabric materials used in the study are highlighted in **Table 4-1**.

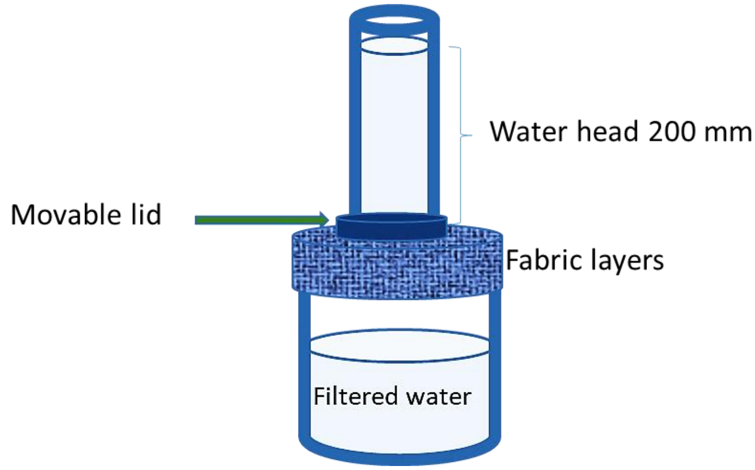


Figure 4-1: General filtration set-up (left) and schematic with movable lid added for flow rate measurement (right).

Ordinary sequential filtration (refiltering through the same layers of fabric)

This part of the study involved filtering 750 mL of water through an eight-layer combination of geotextile 1 (bidim A8) and cotton cloth, respectively. The effluent (filtered water) was then re-filtered several times through the same eight layers of fabric as proposed by Swick & Jensen (2015). Geotextile 1 was chosen because it had the highest performance in filtration efficiency among all the fabrics and was more efficient than geotextile 2 (bidim A10). Brushed cotton fabric recorded the highest particle removal efficiency among the cloth filters and was therefore chosen for further experimentation. The bacterial and particle contents were measured for the raw water and before and after sequential filtration. The filtration set-up as depicted in **Figure 4-1** was used.

Four-pot sequential filtration (filtering through a four-pot treatment system)

In this part of the study, filtration runs involved eight independent layers of geotextile 1 and brushed cotton tied over four clean beakers. The experimental set-up comprised four pots like the one shown in **Figure 4-1**. It essentially consisted of: (i) a moveable water column (ii) an eight-layer fabric combination wrapped over each beaker, and (iii) four clean beakers to collect the filtered water. Effluent from the first eight-layer set was filtered through the second set, then through the third set, and finally through the last (fourth) set. Turbidity was measured for raw water and filtered water (effluent) after each step. Only geotextile 1 had bacterial counts tested after each step whereas cloth fabric had only the first and last set effluent tested for bacteria. Testing geotextile 1 for all treatment steps was done to check if bacterial removal had a similar pattern to particle removal and to assess possible relation between effluent turbidity and bacteria (CAWST 2013).

This filtration method was adapted from the three-pot treatment system (Mihelcic *et al.* 2009; CAWST 2011). The three-pot method is used for particle settling and requires a minimum of 24 hours waiting period (Mihelcic *et al.* 2009). The eight-layer four-pot sequential filtration only required a 2 hour retention time for the first pot. According to SDWF (2018), 2 hours is adequate for most particles to settle out, after which the remaining particles will require 8 days or more to settle. It was thought that four pots with eight fabric layers would remove a large proportion of contaminants from water. According to SDWF (2018), the average settling times of selected particles in water through 1 m are as follows: (i) colloids and viruses: 2 to 200 years, (ii) bacteria: 8 days, (iii) clay, algae, protozoa, and helminths: 2 hours, (iv) fine sand: 2

minutes, and (v) gravel: 1 second. This indicates that settling alone is probably not adequate. Therefore, the four-pot sequential filtration method may provide a better solution for removing more particles than the ordinary three-pot settling method.

Preparation of water of varying turbidity values for turbidity removal testing

The principal of mass conservation was applied to estimate varying water turbidities using source and filtered water, more especially, for the baseline studies, as follows:

$$C_3V_3 = C_2V_2+C_1V_1 \tag{4-1}$$

Where: C = solids concentration (mg/L); V = volume (L); C_1 and C_2 are solids' concentrations in the mixed samples of volume 1 and 2, respectively; and C_3 is concentration of the resulting mixture.

$$V_3 = V_2 + V_1 \tag{4-2}$$

According to Walski *et al*. (2017) the solids' concentrations can be related to turbidity according to a generalized function:

$$C = f(T) \tag{4-3}$$

Where: T is turbidity in NTU.

Substituting Equation (4-3) into Equation (4-1) and solving for turbidity (T) yields a generalized Law of Conservation of Turbidity (Walski *et al*. 2017):

$$T_3 = f_3^{-1}\left(\frac{f_1(T_1)V_1+f_2(T_2)V_2}{V_3}\right) \tag{4-4}$$

Assuming a linear relationship between turbidity and solids' concentration (i.e., C = kT) in the mixed samples and resulting mixture (Walski *et al*. 2017), Equation (4-4) was reduced to Equation (4-5) and used to estimate resulting mixture turbidities for fabric testing.

$$T_3 = \left(\frac{T_1V_1+T_2V_2}{V_3}\right) \tag{4-5}$$

Roughly only water blends with turbidity values within ±0.5 NTU of the estimated turbidity values were used in the tests. Mixtures with turbidity deviation above this were discarded. This was done to rationally keep as close as possible to the intended turbidity values.

General properties of the fabrics

Table 4-1 provides some typical properties (thickness, pore size, permeability, tensile strength, and static puncture strength) of each fabric material used. The values for geotextile 1 and geotextile 2 – except for thickness – were extracted from a technical data sheet provided by the manufacturer Kaytech Engineering, South Africa. The geotextile fabrics are food grade, nonwoven, continuous filament, needle punched, polyester geotextile normally used in civil engineering applications (Kaytech Engineering 2018). The cloth fabrics (polycotton, cotton wool, brushed cotton, 100% polyester, and 55% polyester45% cotton) were generally coarser (>150 µm) and thinner (<1.5 mm) than the geotextile fabrics (see **Table 4-1**). Apparently, the cost per m^2 of cloth fabrics was generally higher than that of the geotextile fabrics (**Table 4-1**), probably because geotextile fabrics are mainly sold in bulk with sufficient roll dimensions.

Table 4-1: Properties of the nonwoven engineered and woven cloth fabrics

Fabric type	*Thickness (mm)*	*Pore size (µm)*	*Permeability (m/s × 10^{-3})*	*Tensile strength (kN/m)*	*Static puncture strength (kN)*	*Availability in South Africa*	*Estimate Cost (USD/m^2)*
Geotextile 1	*6.1*	*<75**	*3.1**	*50.0**	*9.5**	*Available*	*1.76**
Geotextile 2	*5.8*	*<75**	*2.6**	*56.0**	*11.7**	*Available*	*2.31**
Polycotton	*<1.5*	*>150*	*NA*	*NA*	*NA*	*Available*	*2.35*
Cotton wool	*<1.5*	*>150*	*NA*	*NA*	*NA*	*Available*	*6.46*
Brushed cotton	*<1.5*	*>150*	*NA*	*NA*	*NA*	*Available*	*2.35*
100% Polyester	*<1.5*	*>150*	*NA*	*NA*	*NA*	*Available*	*2.35*
55% Polyester 45% Cotton	*<1.5*	*>150*	*NA*	*NA*	*NA*	*Available*	*2.35*

*Reference (Kaytech Engineering 2018); NA = data not available.

Turbidity removal efficiency prediction models

Numerical models were developed from baseline data using multiple linear regression (MLR) analysis (Juntunen *et al.* 2012) for predicting turbidity removal percentage by each fabric. The regression analysis was done using Analyse-it® (version 4.96.4) and Tool Pak VBA statistical software add-ins for Excel 2016. Model fitting was done using the least squares technique that minimizes the sum of squares of discrepancies between observed and predicted values (Juntunen *et al.* 2012). **Table 4-2** contains a compilation of the developed models with selected model performance indicators. Seventy-two pairs of data from ten runs on each fabric were used to develop the models from 80 pairs of observed data. The remaining data set was used for model verification. The 72 turbidity removal data points were averaged across number of layers to get layer-turbidity removal data sets which were then used in the multiple linear regression (MLR) analysis to generate the models. The models were thereafter used to estimate the maximum number of layers required to achieve a possible 100% turbidity removal (**Table 4-2**).

An MLR model of the general form given in Equation (4-6) with N observations and P variables (Juntunen *et al.* 2012) assisted in the stepwise derivation of the models for each fabric.

$$y_i = \beta_0 + \beta_1 x_{1i} + \beta_2 x_{2i} + \ldots\ldots\ldots + \beta_p x_{pi} + \varepsilon_i, \text{ for } i = 1, 2, \ldots, N \quad (4\text{-}6)$$

Where y = value of the response variable (turbidity removal efficiency); x = value of the predictor (explanatory) variable (number of fabric layers); β_0 = a constant; $\beta_1 \cdot \cdot \cdot \beta p$ = model coefficients to be estimated; ε = random error term (uncontrolled factors and experimental errors in the model); i indexes the N observed data.

The performance of each numerical model on turbidity removal was assessed by calculating the following (Gikas & Tsihrintzis 2012; Chen & Liu 2015):

$$R^2 = 1 - \frac{SSE}{SST} \quad (4\text{-}7)$$

Where R^2 = coefficient of determination; SSE = sum of squared errors; SST = total sum of squares.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(P_i - O_i)^2}{N}} \quad (4\text{-}8)$$

where *RMSE* = root mean squared error; *N* = total number of observations; P_i = model predicted value; O_i = observed value.

$$\text{Nash–Sutcliffe model efficiency coefficient } (NSE) = 1 - \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}(O_i - O_{mean})^2} \quad (4\text{-}9)$$

Where *NSE* ranges between −∞ and 1.0, and the best value of *NSE* is 1.0; P_i = model predicted value; O_i = measured value; O_{mean} = mean of observed values.

Sampling and filtration evaluation

At the baseline stage, only turbidity was quantified before and after fabric filtration. Thereafter, the concentrations of indicator bacteria (*E. coli* and fecal coliforms) and turbidity were quantified before and after filtration for geotextile 1 and brushed cotton only. Raw water was passed through the fabrics in a manner simulating as closely as possible PoU water treatment practices by users in poor communities (**Figure 4-1**). Tests for *E. coli* and fecal coliforms were done by Water Analytical Laboratory (WALAB) accredited to the South African National Accreditation System (SANAS) No: T0375 for microbiological analysis. The accredited fecal coliform detection method used is the biochemical method, WAL M3 while the accredited *E. coli* detection method used is the enzyme substrate, WAL M4. Physico-chemical tests were done in the Water Quality Laboratory at Stellenbosch University with the test apparatus being calibrated daily. All tests were performed in accordance with the *Standard Methods for the Examination of Water and Wastewater* (APHA/AWWA/WEF 2012).

Removal effectiveness calculations

The removal percentages for turbidity were calculated using Equation 4-10**:**

$$Turbidity\ removal\ effectivenss\ (\%) = \left[\frac{Influent\ turbidity - Effluent\ turbidity}{Influent\ turbidity}\right] x100 \quad (4\text{-}10)$$

Log removals for bacteria (*E. coli* and fecal coliforms) were calculated using Equation 4-11:

$$LRV[-] = log_{10}(B_{in}) - log_{10}(B_{out}) = log_{10}\left[\frac{B_{in}}{B_{out}}\right] \quad (4\text{-}11)$$

Where *LRV* = log removal value; B_{in} = concentration of bacteria in influent; B_{out} = concentration of bacteria in effluent.

RESULTS AND DISCUSSION

Baseline study (turbidity removal only)

Average percentage turbidity remaining of the ten runs on each fabric’s layer combination were calculated and plotted as a function of number of layers (see **Figure 4-2**). The characteristics of the fabrics are as shown in **Table 4-1**. Geotextile 1 performed exceptionally well and consistently recorded the lowest remaining turbidity for each number of layers used. Although geotextile 2 and brushed cotton had slightly higher remaining turbidity than geotextile 1, they also recorded appreciable removals. The superior turbidity removals by geotextile 1 **(Figure 4-2)** could be attributed to its smaller pore sizes coupled with its thickness (**Table 4-1**). Geotextile 2’s lower removals than geotextile 1 could be due to being slightly thinner than geotextile 1 (**Table 4-1**). Also, geotextile 2 had some observed minor loose fibers on its fabric surface, few of which were probably released into the water during filtration. The slightly higher turbidity removals by brushed cotton among the cloth fabrics could be attributed to its being a bit tighter than the others.

Polycotton and 100% polyester recorded roughly the same percent removals in each layer's effluent and constantly recorded the highest remaining turbidity. The pair generally had the largest pore sizes and slightly higher than 55%polyester45%cotton. 55%polyester45%cotton had remaining turbidity roughly equal to that of cotton wool and higher than that of brushed cotton. Cotton wool was expected to provide the best performance among the cloth fabrics but was generally loose and clearly released fibers into the treated water. It is possible that cotton wool may work more reliably if packed in a filter bag to prevent fibers from escaping into the water. Overall, the best performance in filtration efficiency was achieved using the highest number of layers of geotextile 1. This is not particularly surprising and fits well with filtration theory where more and thicker filter layers are expected to be more efficient in trapping particles than thinner and fewer layers (Parsons & Jefferson 2006; Davis 2010; MWH 2012). Likewise, filter media with smaller pore size are expected to be more efficient (Parsons & Jefferson 2006; Davis 2010; MWH 2012).

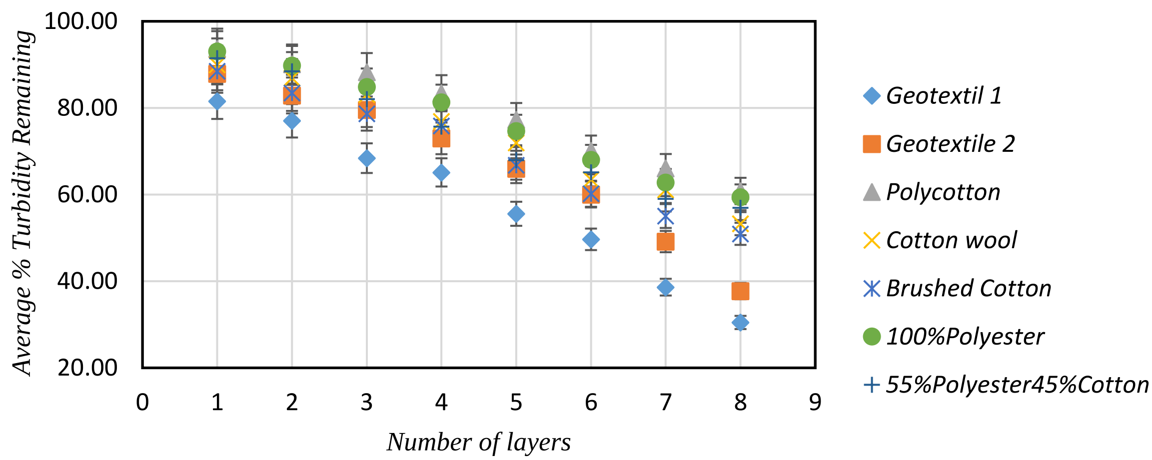


Figure 4-2: Average percentage turbidity remaining in the effluent from each fabric during the baseline study.

Turbidity removal prediction models

The mathematical models giving the best fit of each fabric's observed data were derived and are as listed in **Table 4-2**. **Figure 4-3** shows each fabric's model verification plots respectively for observed and predicted turbidity removals. The estimated removals using the developed models are within sufficient accuracy of measured values, that is, the models were verified and found to generate reasonable predictions of turbidity removal efficiencies from the raw water used (**Table 4-2** and **Figure 4-3**). These models may be helpful as a support tool for costing and selection of optimal process configuration and material combinations and may help the user to estimate the optimal number of layers for a given fabric and, correspondingly, the cost. Depending on available resources and required filter surface area the choice of fabric and material combination can then be made.

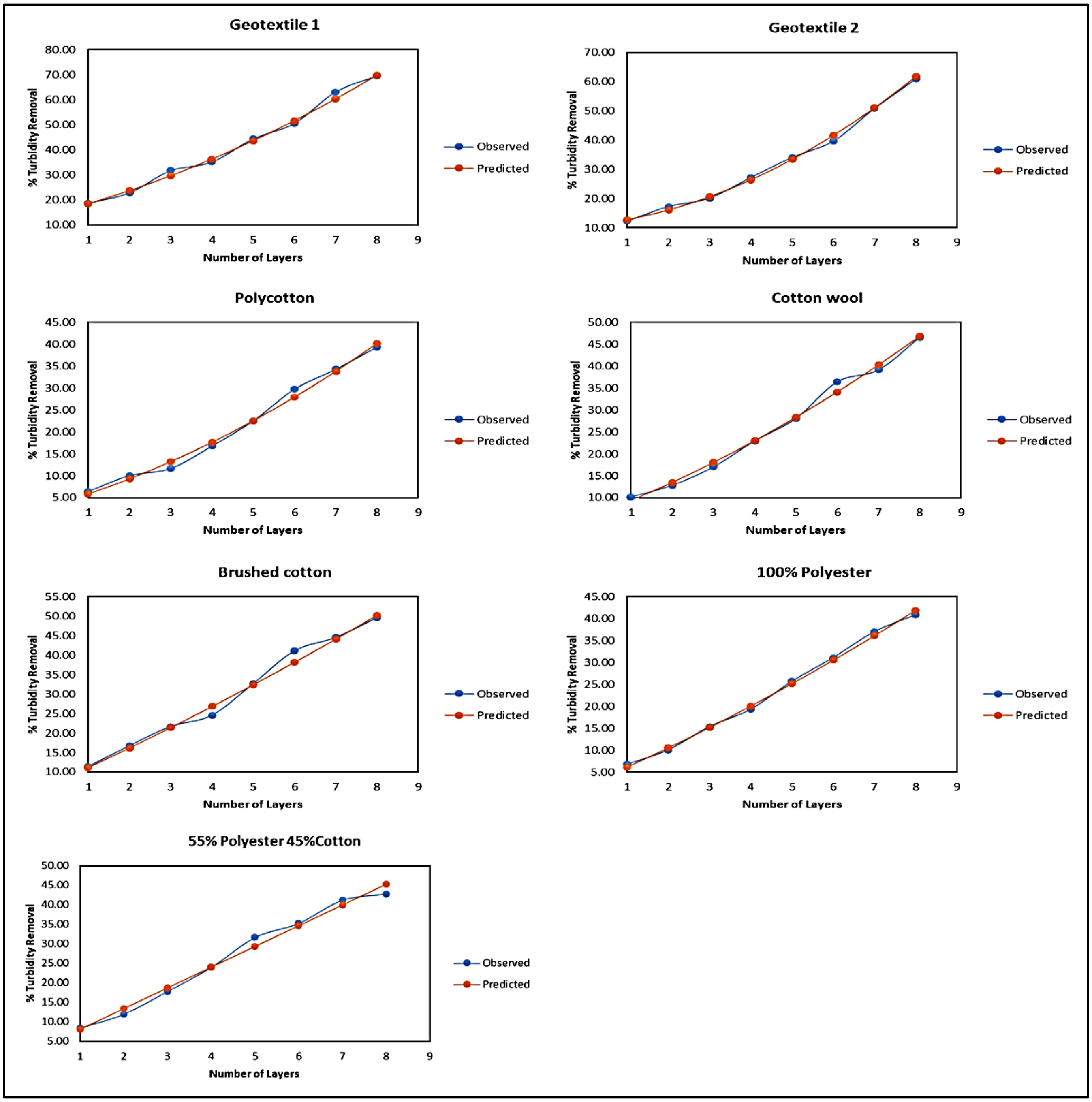


Figure 4-3: Model verification plots: observed and predicted turbidity removal percent values as a function of number of layers.

Table 4-2: Turbidity removal prediction models for each fabric

Fabric	*Numerical model*	R^2	*RMSE*	*CL*	*NSE*	*Number of layers for E = 100*
Geotextile 1	$E = 13.90 + 4.22\ \eta + 0.344\ \eta^2$	0.996	1.3738	95%	0.993	11
Geotextile 2	$E = 10.74 + 1.48\ \eta + 0.6119\ \eta^2$	0.997	1.0445	95%	0.996	11
Polycotton	$E = 2.93 + 2.70\ \eta + 0.2425\ \eta^2$	0.991	1.3254	95%	0.992	16
Cotton wool	$E = 5.59 + 3.55\ \eta + 0.1993\ \eta^2$	0.992	1.4077	95%	0.993	15
Brushed cotton	$E = 6.25 + 4.78\ \eta + 0.0901\ \eta^2$	0.990	1.6000	95%	0.989	16
100% Polyester	$E = 2.04 + 4.06\ \eta + 0.1158\ \eta^2$	0.993	1.2805	95%	0.997	17
55% Polyester45% Cotton	$E = 2.68 + 5.32\ \eta - 0.0010\ \eta^2$	0.985	1.6415	95%	0.987	19

E = turbidity removal efficiency in %; η = number of fabric layers; *CL* = confidence level.

Ordinary sequential filtration (turbidity removal performance)

Ordinary sequential filtration was done using geotextile 1 and brushed cotton and the results for turbidity removal are as shown in **Figure 4-4**. The filtration was done using 750 mL of raw water with an initial turbidity of 18 NTU through eight layers of each fabric. There was a noticeable decrease in effluent turbidity after every run until the fourth run, after which, minimal decrease was observed until the last run. Generally, turbidity decreased after each run and by the tenth run reduced to 0.8 NTU for geotextile 1 and 3.8 NTU for brushed cotton. The values are well within the recommended turbidity level (≤5 NTU) for household settings and small-scale water supplies (CAWST 2013; WHO 2017b). The exponential decrease in turbidity is not particularly surprising and is consistent with filtration theory through porous media (Davis 2010; MWH 2012; Swick & Jensen 2015).

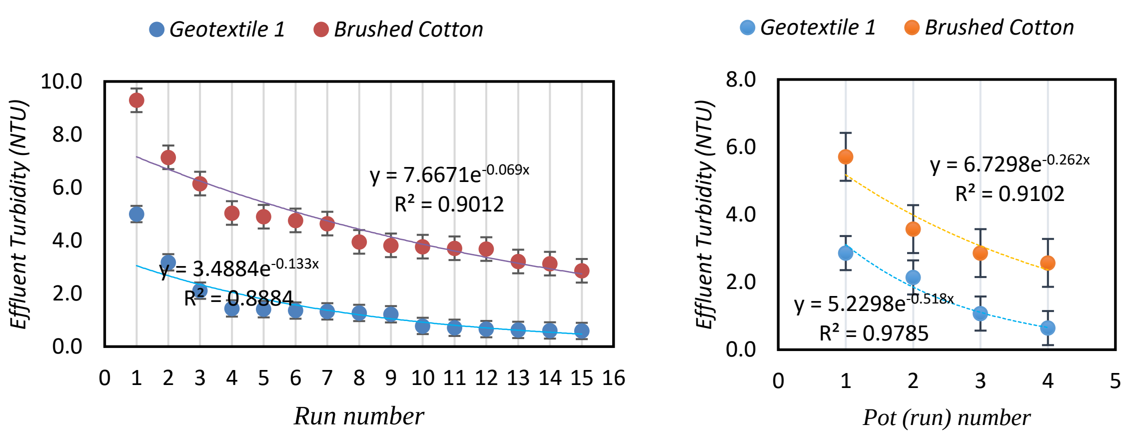


Figure 4-4: Ordinary (left) and four-pot (right) sequential filtration effluent turbidity as a function of run number.

Geotextile 1 performed better than brushed cotton throughout the tests. The higher particulate removals by geotextile 1 could be attributed to the smaller pore size of its filter, which is <75 μm (Kaytech Engineering 2018) vs >150 μm (Mihelcic *et al.* 2009) for brushed cotton and to its layer thickness of about 6 mm compared to brushed cotton with layer thickness of ≤1.5 mm. Geotextile 1 was able to meet WHO and SANS 241 standards for turbidity (≤5 NTU) after the first run while brushed cotton only met the turbidity standard after the fourth run of sequential filtration. Therefore, the eight-layer filtration for geotextile 1 may be more beneficial for small scale drinking water treatment than brushed cotton. Only geotextile 1 met the turbidity requirement (≤1 NTU) for best disinfection performance after the tenth run (WHO 2017b) to use the least possible chlorine dosage with minimal potential for disinfection by-products (CAWST 2017;

WHO 2017a) and this may ably enhance taste acceptability for treated water (Kotlarz *et al.* 2009; WHO 2017a).

Ordinary sequential filtration: Bacterial removal

The results in **Table 4-3** show that brushed cotton could not reduce the bacteriological loads to safe levels even after 15 run cycles implying that its effluent may not provide safe drinking water, and if used, may require thorough disinfection to make the water safe. On the other hand, geotextile 1 significantly reduced bacterial loads just with one run of an eight-layer normal filtration and its effluent may require minimal disinfection. Generally, a high level of caution should be observed when using ordinary sequential filtration as some recontamination was noticed during sequential filtration. For instance, geotextile 1 recorded more bacteria in the effluent than the single run (normal) eight-layer filtration. This was noted as a disadvantage for using ordinary sequential filtration as compared to the four-pot sequential filtration method which by far gave better removals (**Table 4-4**). The four-pot sequential filtration may often perform better and need less caution and effort while ordinary sequential filtration was noted as a highly laborious and very delicate filtration process.

Table 4-3:Bacterial removal by geotextile 1 and brushed cotton (normal eight-layer and ordinary sequential filtration)

Parameter	*Raw water*	*Effluent from the tested fabrics and associated filtration process*				*Potable Water Standards*	
		Geotextile 1 normal filtration	*Geotextile 1 sequential filtration*	*Brushed cotton normal filtration*	*Brushed cotton sequential filtration*	*WHO*	*SANS 241*
Fecal coliforms (CFU/100 mL)	*970*	*41*	*192*	*870*	*570*	*0*	*0*
E. coli (CFU/100 mL)	*870*	*36*	*178*	*800*	*520*	*0*	*0*
LRV (fecal coliforms)		*1.37*	*0.70*	*0.05*	*0.23*		
LRV (E. coli)		*1.38*	*0.69*	*0.04*	*0.22*		

Four-pot eight-layer sequential filtration performance (turbidity removal)

Turbidity removal trends for the four-pot eight-layer sequential filtration was much better than that of the ordinary eight-layer sequential filtration (**Figure 4-4**). The four-pot sequential filtration method achieved effluent turbidity of 0.6 and 2.6 NTU for geotextile 1 and brushed cotton, respectively, after only four cycles (**Figure 4-4**). In contrast, it took about 10 to 15 runs to reach similar turbidity levels in the ordinary eight-layer sequential filtration (**Figure 4-4**). This could be attributed to higher recontamination potential in the latter method. Therefore, the authors recommend the use of four-pot method for sequential filtration. A tap for drawing water may also be fixed on each filtration vessel so that the fabrics can be kept intact and only untied for cleaning purposes. **Figure 4-5** gives a visual comparison of the four-pot sequentially filtered water by geotextile 1. The figure depicts significant improvement in water's clarity from the raw water through the first to the last filtration set (pot).

Figure 4-5: Visual comparison of four-pot sequentially treated water by geotextile 1; from raw water through first to last set.

Four-pot eight-layer sequential filtration performance (bacterial removal)

There was a consistent trend of bacteria counts decreasing after each four-pot filtration set with only 1 *CFU*/100 mL fecal coliforms and 1 *CFU*/100 mL *E. coli* remaining in geotextile 1's fourth pot effluent (**Table 4-4).** This was a noticeable improvement in the bacteriological quality from the raw water (influent) bacterial levels which were 1110 *CFU*/100 mL and 960 *CFU*/100 mL, respectively (**Table 4-4**). Therefore, the four-pot eight-layer process configuration for geotextile 1 was shown to provide relatively safe water (WHO 1997; Harvey 2007; CAWST 2013) even without disinfection (**Table 4-5**). This can possibly be improved and made more convenient if a tap is provided for each pot in the proposed four-pot method. The WHO and SANS 241 potable water standards recommend 0 *CFU*/100 mL for both *E. coli* and fecal coliforms. In contrast to geotextile 1's removals, brushed cotton unsatisfactorily recorded 740 *CFU*/100 mL and 620 *CFU*/100 mL in its fourth-pot effluent for fecal coliforms and *E. coli*, respectively. This shows that fabric choice is important regardless of the process configuration used. In this case, geotextile 1 was shown to be the best performing fabric.

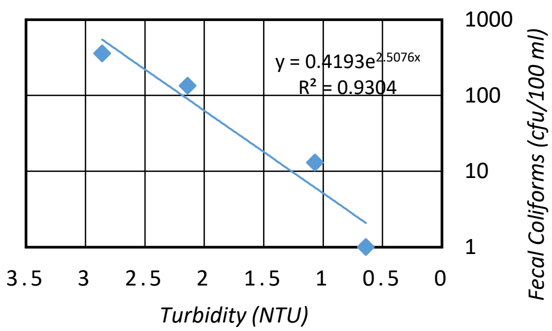
Table 4-4: Bacterial removal by the four-pot eight-layer sequential filtration method

Parameter	***Pot number***	***Geotextile 1***			***Brushed cotton***		
		Influent	***Effluent***	***LRV***	***Influent***	***Effluent***	***LRV***
Fecal coliforms (CFU/100 mL)	*Pot 1*	*1110*	*360*	*0.49*	*1110*	*1100*	*0.004*
E. coli (CFU/100 mL)		*960*	*310*	*0.49*	*960*	*860*	*0.048*
Fecal coliforms (CFU/100 mL)	*Pot 2*		*134*	*0.43*		–	–
E. coli (CFU/100 mL)			*122*	*0.41*		–	–
Fecal coliforms (CFU/100 mL)	*Pot 3*		*13*	*1.01*		–	–
E. coli (CFU/100 mL)			*13*	*0.97*		–	–
Fecal coliforms (CFU/100 mL)	*Pot 4*		*1*	*1.11*		*740*	*0.176*
E. coli (CFU/100 mL)			*1*	*1.11*		*620*	*0.142*
Total (fecal coliforms)	*4 Pots*	*1110*	*1*	*3.05*	*1110*	*740*	*0.18*
Total (E. coli)	*4 Pots*	*960*	*1*	*2.98*	*960*	*620*	*0.19*

"-" not tested.

Relationship between turbidity and presence of bacteria

Figure 4-6 shows that there was some form of relationship between bacterial counts and turbidity in the effluent after each pot filtration. According to various authors (e.g., WHO 1997, 2017b; CAWST 2013), higher turbidity levels are most often associated with higher levels of pathogens (viruses, protozoa, bacteria, helminths, etc.). The pathogens are often attached to particles (e.g., clay and silts) in water (Ritter 2010; CAWST 2013; WHO 2017b). The presence of particles can also indicate the presence of hazardous chemicals and increased chlorine requirements (Kotlarz *et al.* 2009; WHO 2017b). This result supports the importance of turbidity removal by PoU methods. The WHO (2017b) recommends that in lower resource settings and small-scale water supplies turbidity should be kept below 5 NTU. The four-pot eight-layer sequential filtration method using geotextile 1 met this recommended value. It is therefore recommended for use in poor communities.



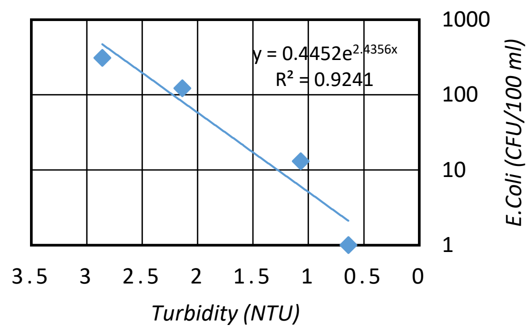


Figure 4-6: Correlation between bacteria and turbidity in treated effluent for geotextile1 four-pot sequential filtration.

Table 4-5: Associated risk for fecal contamination in drinking water (CAWST 2013)

***E. coli* level (CFU/100 mL sample)**	***Risk (CAWST 2013; Harvey 2007; WHO 1997)***	***Recommended action (Harvey 2007)***
0–10	*Reasonable quality*	*Water may be consumed as it is*
11–100	*Polluted*	*Treat if possible, but may be consumed as it is*
101–1000	*Dangerous*	*Must be treated*
>1000	*Very dangerous*	*Rejected or must be treated thoroughly*

Flow rate variation with number of layers for the representative fabrics

Filtration flow rates for geotextile 1 and brushed cotton were estimated by filtering 300 mL of potable tap water through each layer combination in a manner mimicking low cost PoU water treatment. This was done to assess the usability of the fabrics with respect to filtration time and convenience. Tap water was initially filtered through each layer combination before commencing measurements to remove any captured air, flush out any dirt, and ensure uniform initial moisture content. The time taken for 300 mL of tap water to filter through was noted and flow rate was estimated using Equation 4-12. The flow rate tests were done in triplicate for each layer combination to ensure accuracy using the **Figure 4-1** set-up with a movable lid for temporarily holding water in place. Average values were then calculated for reporting purposes. The initial maximum head in a cylinder of about 43 mm diameter was 200 mm. It is worth noting, that as the water volume reduced the head also reduced. Hence, the actual flow rates may be slightly higher than measured.

However, in actual applications, flow rate is expected to reduce with time as a function of solids' accumulation on each filter surface (Franks *et al.* 2012). **Table 4-6** shows estimated flow rates in L/h as a function of the number of fabric layers. Flow rate was measured in mL/s and thereafter converted to L/h. It was observed that flow rate decreased with increase in the number of layers. It should be noted that when raw (untreated) water is used, flow rate will reduce faster as solids get captured on and within the fabrics (Franks *et al.* 2012). However, the use of fabrics has the advantage of easy removal and washing to remove trapped dirt and once again improve flow rates.

There was a noticeable significant difference in flow rate between the two fabrics particularly from two layers upwards. This could be attributed to the observed rapid clogging exhibited by the brushed cotton fabric. The rapid clogging could possibly be due to brushed cotton being woven resulting in rapid caking and consequently fast clogging. According to Mulligan *et al.* (2009), woven fabrics are more susceptible to rapid clogging than nonwoven fabrics. Woven fabrics generally clog quickly due to accumulation of captured particles on the first layers. Nonwoven fabrics are expected to allow for more depth filtration than woven fabrics Mulligan *et al.* (2009). Higher flow rates by geotextile 1 could hence be attributed to the probable depth filtration due to being nonwoven and thicker. Therefore, use of geotextile 1 would be more practical for fabric filtration due to comparatively less cleaning or replacement frequency than brushed cotton.

Table 4-6: Estimated flow rate values for geotextile 1 and brushed cotton as a function of the number of layers

Number of layers		*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
Geotextile 1	*Flow rate (L/h)*	*425.20*	*300.84*	*253.52*	*216.87*	*207.29*	*204.55*	*200.74*	*183.99*
Brushed cotton	*Flow rate (L/h)*	*375.00*	*173.91*	*167.44*	*158.36*	*108.76*	*83.53*	*60.61*	*53.31*

$$Q = \frac{V}{t} \tag{4-12}$$

Where: Q = flow rate (L/h); V = volume of filtered water (L); t = filtration time (hours).

CONCLUSIONS AND RECOMMENDATIONS

Due to its low cost and simple operation, fabric filtration using authentic nonwoven engineered fabrics is a promising technology that can improve water security in poor communities, especially when using an optimized process such as the developed four-pot system. The representative cloth fabric (brushed cotton) performed comparatively poorly when compared to the geotextile for bacterial removal. It may therefore not be reliable due to pore sizes being too large to remove microbes. *E. coli* and fecal coliform levels in the brushed cotton effluent exceeded WHO drinking water guidelines and SANS 241 standards throughout the study. The nonwoven bidim fabrics performed exceptionally well and successfully removed most bacteria, especially when multiple layered and with the four-pot system.

Multiple layered fabrics recorded higher turbidity and bacterial removals compared to single layered fabrics. Sequential fabric filtration was more effective than normal (single) filtration in turbidity removals and produced clear water of acceptable turbidity (CAWST 2017; WHO 2017b). However, the ordinary sequential filtration encountered some recontamination on bacterial removals. The optimized four-pot sequential filtration method with eight layers of bidim A8 (geotextile 1) produced very clear drinking water of relatively safe quality (WHO 1997; Harvey 2007; CAWST 2013). However, an appropriate disinfection step, e.g., solar disinfection or chlorination, is still recommended to ensure continued water safety. Bidim

A10 (geotextile 2) also performed remarkably well and is generally easier to wash by hand than geotextile 1. It should therefore also be considered in future applications. Both the ordinary and four-pot sequential filtration methods should be subjected to field testing using bidim geotextile to assess acceptability, sustainability, and long-term performance.

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ADDITIONAL CONTENT TO CHAPTER 4:

Bacterial removal model for the BidimSEQFIL system

This section presents the bacterial removal model for the BidimSEQFIL system. This was not included in the published paper of this Chapter. The mathematical model for *E.coli* removal by the system was derived using multiple linear regression analysis based on the *E.coli* removal data on the four-pot eight-layer sequential filtration (BidimSEQFIL) method (**Table 4-4**). The developed model is given as Equation 4-13 below**.** The modelled remaining fraction of *E.coli* (N_e/N_o) by geotextile was then used to estimate the effluent concentration. **Table 4-7** below gives a summary of the model performance as assessed using model performance equations (Equations 4-7 to 4-9).

$$\frac{N_e}{N_o} = k_1 - k_2\beta + k_3\beta^2 \qquad (4\text{-}13)$$

Where: N_o = Initial E.coli concentration [CFU/100 ml]; Ne = Effluent E.coli concentration [CFU/100 ml]; (N_e/N_o) fraction of influent E.coli [CFU/100 ml] remaining in the effluent; β = number of fabric layers; k_1 = 0.61510 is a constant; k_2 = 0.04214 and k_3 = 0.00072 are estimated model coefficients

Table 4-7: Model performance of the Bacterial removal model for the BidimSEQFIL system

Model performance	*R^2*	*RMSE*	*CL*	*NSE*
Geotextile model	*0.999*	*0.21*	*95%*	*0.999*

Chapter 5: Drinking water treatment using indigenous wood filters combined with granular activated carbon

This Chapter (alongside Chapters 3 and 4) formed part of the work done to address the second objective of the dissertation, which is "to investigate and optimize simple, locally sourced low-cost water treatment materials and techniques for bacterial and particle removal in poverty stricken communities".

The aim of this study was to research the feasibility of using Southern African indigenous wood filters under low water pressure for low-cost water treatment and to demonstrate possibilities of using the wood filters in combination with GAC (and potentially charcoal). Thus, this study examined and optimized gravity driven wood filtration using indigenous tree species native to Southern Africa; incorporating GAC for water treatment as a novel low-cost water treatment technology. The study in this Chapter resulted in an optimized simple, yet innovative low-cost PoU water treatment system, namely the "wood filtration system combined with GAC (WFSGAC)".

Since the initial tests in this Chapter on the wood filters alone produced water with objectionable aesthetic aspects (color, odor and taste) which may discourage many potential users of the technology, it was decided to combine the wood filters with GAC to enhance aesthetic improvement. The initiative to incorporate GAC was made using the knowledge gained from the research done in Chapters 2 and 3 where GAC incorporation showed high potential for producing aesthetically acceptable water.

In areas where GAC is not available, normal charcoal may be used possibly with slightly deeper sections than GAC, however further investigation in this application is warranted. It is worth noting that in as much as research into possible use of ordinary charcoal as a substitute for GAC is encouraged, the wood and GAC combined filter system is meant to be low-cost i.e. not necessarily that people can build it themselves, but so that NGOs could possibly make use of the knowledge towards application on site. The NGOs are expected to be able to source GAC at a reasonably low-cost.

The gravity driven system was chosen for research over a mechanical pressure system because: (i) a gravity driven wood filter system does not require electricity or tap pressure for its operation and is expected to be easier to operate, appropriate and affordable to the rural poor, and (ii) to the author's knowledge no gravity driven wood filtration has been presented in any published literature particularly using Southern African indigenous species. In other words - because pressure filtration requires pumps / high heads research into the possible use of an even simpler - gravity driven (low pressure) wood filter system was warranted to see if it could be at all feasible.

Evaluations were done using fresh, wet preserved (cured) and dry preserved (cured) Southern African indigenous wood species namely: *Combretum erythrophyllum*, *Tarchonanthus camphoratus*, *Leonotis leonurus* and *Salix mucronata*. The study also presented simple but valid and novel possibilities of using and preserving wood filters for drinking water treatment in rural areas. The indigenous wood species were found to be a valid technological research area for low cost water filtration and future research into this area is warranted. The novel WFSGAC showed high potential for significant *E.coli* removals (>99.9%), and up to 100 % TSS and turbidity removals. Fecal coliforms and *E.coli* removals are normally expected to be similar, but interestingly System 1 (WFS1) recorded very low removals for fecal coliforms but much higher *E.coli* removals (**Figure 5-4**) for the wet preserved pieces. This is probably due to observed signs of filter decay in the wood filter pieces during the 7-day wet preservation (curing) period indicating suspected growth of coliforms in the wood pieces. On the other hand, System 4 (WFS4) performed less than expected for the wet preserved pieces though it exhibited similar removal trends for fecal coliforms and *E.coli* (**Figure 5-4**). The reason for this was not clearly established. However, WFS4 was expected to perform like WFS3 and WFS2 but generally had larger pore sizes as visually observed which most probably caused its slightly higher flow rates.

The developed WFSGAC presented in this Chapter was afterwards comparatively evaluated in Chapter 6 together with the systems investigated in Chapters 2, 3, and 4.

Although a few aspects remain to be investigated, some practicalities such as filtration rates by each wood species, possible bacterial and metal removals as well as aesthetic improvements by adding GAC (and potentially charcoal) have been demonstrated, as research contribution on the feasibility of using Southern African wood filters under low water pressure for low-cost water treatment.

Drinking water treatment using indigenous wood filters combined with granular activated carbon

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ABSTRACT

A gravity-driven wood filtration system, incorporating granular activated carbon (GAC) as an appropriate point of-use technology for the rural poor, has been designed, tested and optimized. Four systems were assessed in respect of metal, bacteria and particle removal when exposed to polluted river water with and without GAC. These were evaluated using fresh, wet preserved and dry preserved Southern African indigenous wood species. Initially, all filter systems with the following indigenous wood species *Combretum erythrophyllum* in System 1, *Tarchonanthus camphoratus* in System 2, *Leonotis leonurus* in System 3 and *Salix mucronata* in System 4 did not incorporate GAC. The systems recorded 83.3, 85.4, 94.3 and 57.3% *E.coli* removals, respectively, for fresh filters. Incorporation of GAC in Systems 1 and 4 showed high potential for significant *E.coli* removals (>99.9%). Particulate removals were: 97% TSS (total suspended solids) and 96% turbidity removals by System 1; and 100% TSS and 100% turbidity removals by System 4. Metal removals by the combined systems were noteworthy and in the following order: Fe > Pb > Ni > Al > Zn > Cu > As > Cr > Cd > Mn (with average removals for the first five >90% and the last five >50%). Each combined system consistently met turbidity guidelines (≤5 NTU) and produced water with pleasant aesthetic aspects.

Key words: aesthetic aspects, bacterial removal**,** drinking water, heavy metals, indigenous wood filters, water quality

INTRODUCTION

Poor communities across the world are affected by waterborne diseases. Affordable and appropriate point-of-use (PoU) water treatment technologies are needed to reduce the prevalence of water borne diseases in developing communities (Kausley *et al.* 2018; McAllister 2005; Supong *et al.* 2017). Many technologically advanced water treatment technologies, for example, pasteurization, ultrafiltration, nanofiltration, reverse osmosis, ion exchange, ozonation, water softening, and ultraviolet disinfection exist (Binnie and Kimber 2013; Kim *et al.* 2016; WHO 2017a) to treat various types of contaminated water. However, most of these technologies fail to meet the needs of the poor (Binnie and Kimber 2013; Kim *et al.* 2016; McAllister 2005). The advanced technologies are costly and suffer from high power usage, expensive running costs, and complexity (Kausley *et al.* 2018; Kim *et al.* 2016, McAllister 2005; Supong *et al.* 2017).

Therefore, there is a need to establish low-cost, simple and effective techniques for improving the quality of drinking water based on resources available to poor communities. To this effect, this study examined and optimized gravity driven wood filtration systems using indigenous tree species native to Southern Africa; incorporating GAC for water treatment as a novel low-cost water treatment technology. In areas where GAC is not available, normal charcoal may be a possible alternative with slightly deeper sections than GAC, however further investigation in this application is warranted. Gravity driven wood filtration as an alternative to pressure-driven wood filtration and the resulting flow rates was investigated for each indigenous wood species. A gravity driven wood filter system does not require electricity or tap pressure for its operation and is expected to be easier to operate, appropriate and affordable to the rural poor (Kausley *et al.* 2018; Kim *et al.* 2016, McAllister 2005). To the author's knowledge no gravity driven wood filtration using Southern African indigenous species has been presented in any published literature.

Studies by Boutilier *et al.* (2014) and Sens *et al.* (2013) suggest that the use of wood filters as renewable materials could lead to a new generation of potentially low cost water filters and could therefore improve water security in developing communities. However, their work was done principally using white pine (a wood species not indigenous to Southern Africa) and did not incorporate GAC or charcoal.

Wood filters remove bacteria by size exclusion using pit membranes as was demonstrated by Boutilier *et al.* (2014). Additionally, Choat *et al.* (2003) showed that inter-tracheid pit membranes removed particles within 200 nm range, sufficient for bacterial removal. Wood filters, as shown by Boutilier *et al.* (2014) may not eliminate the smallest viruses (< 20 nanometers in size). However, viruses cause fewer health problems as a result of drinking contaminated water compared to bacterial diseases (McAllister 2005; WHO/UNICEF 2004).

In addition, it was decided to use and assess some wood species with reported medicinal properties. Three of the four wood species used in this study namely *Tarchonanthus camphoratus (System 2)*, *Leonotis leonurus (System 3)* and *Salix mucronata (System 4)* are reported to contain medicinal properties in their stems (SANBI 2018; SUBGSA 2018). For instance, *Leonotis leonurus* contains a chemical constituent *leonurine* that has been reported to be used in traditional medicine for curing a wide range of ailments including headaches, coughs, fever, asthma, haemorrhoids and dysentery (SANBI 2018; SUBGSA 2018).

Although the main objective of PoU drinking water treatment is to produce microbiologically safe water (CAWST 2017; McAllister 2005; WHO 2017a), the water must be aesthetically acceptable and therefore free from apparent turbidity, color, odor and objectionable taste (Hammer and Hammer 2012; Nathanson and Schneider 2015). Particles that cause Turbidity shield disease causing microbes against disinfection (Nathanson and Schneider 2015; WHO 2017b). Additionally, turbidity, color, odor and taste in water can motivate people to use water from sources that, while aesthetically more acceptable, may be of poorer quality and unsafe (CAWST 2017; WHO 2017a). Similarly, iron (Fe) and manganese (Mn) may not cause health problems but can impart a bitter taste or odor to drinking water as well as cause discoloration (CAWST 2017; Nathanson and Schneider 2015; WHO 2017a). An attempt was therefore made to enhance removal of the said contaminants by using wood filtration in combination with GAC.

Toxic metals assessed for removal due to inclusion of GAC were As, Cd, Pb and Hg, which are amongst the most common environmental pollutants (Turkez *et al.* 2012). According to (Llobet *et al.* (2003), these elements are not beneficial to humans and there is no known means of removing them from the human body. They are toxic and, when present in water supplies require removal (Okun and Ernst 1987). Other heavy metals evaluated were Al, Cr, Cu, Fe, Mn, Ni and Zn. According to literature (see Binnie and Kimber 2013; Kearns 2007; Mihelcic *et al.* 2009; Siabi 2003) these can be removed by GAC filtration.

MATERIALS AND METHODS

Study design

Laboratory experiments were conducted using four identical systems made of transparent Perspex columns, each 60 cm long and of 10.5 cm internal diameter. Each column was mounted to the laboratory wall and connected to a 200 cm long flexible transparent silicon pipe of 2.54 cm internal diameter. During operation, peeled wood filters of 2.54 cm length and 2.54 cm diameter from indigenous tree species were firmly clamped in a 10 cm flexible pipe. Each 10 cm flexible pipe containing wood filter elements was then connected to the end of the 200 cm flexible pipe via PVC connectors (see **Figure 5-1**). A leak-tight seal was provided between the flexible pipe and filter by firmly clamping the wood using tube fasteners to prevent water flow between the wood and the pipe wall as mentioned by Boutilier *et al.* (2014). To confirm the seal was secure, it was continually checked if there was leakage or presence of water between the transparent pipe and the wood filter. The filter systems were fed with contaminated river water and operated under gravity head. The raw water was collected daily from the river and was fed into the systems as obtained. Fresh filters were kept moist until usage.

A gravity head of 2.6 m was selected based on Boutilier *et al.* (2014) who, based on their applied pressures of 6894.8 - 34473.8 Pa, proposed that corresponding gravitational pressure heads of 0.7 - 3.5 m could be used. This is a simpler and cheaper alternative to mechanical pressure-driven wood filtration (see Boutilier *et al.* 2014). The gravity head values were estimated and confirmed as falling within the pressures range during system design using **Equation 5-1**. The Darcy-Weisbach head loss formula (**Equation 5-2**) and Hagen–Poiseuille formula (**Equation 5-3**) for estimating Darcy friction factor were assumed to be applicable and used to assess whether the 2.6 m head was adequate. Taking flow rate to be 4 L/d ($4.6*10^{-8}$ m^3/s) based on the average value obtained by Boutilier *et al.* (2014), the estimated head loss was 0.049 m. This gave an expected net gravity head of about 2.551 m, sufficiently within the desired range.

$$h = \frac{P}{\rho g} \tag{5-1}$$

Where: h = gravitational pressure head in m; P = applied pressure in Pa; ρ = density of water ≈ 1000 kg/m^3 g = gravitational acceleration ≈ 9.81 m/s^2

$$\Delta H = H_{friction\ losses} + H_{minor\ losses} = \frac{8fLQ^2}{\pi^2 g D^5} + H_{minor\ losses} \tag{5-2}$$

Where: ΔH = total head loss in m; f = Darcy friction factor; L = pipe length in m; D = internal pipe diameter in m; Q = average flow rate in m^3/s; $H_{minor\ losses}$ = 0.026 m (i.e. assumed to be 1 % of the static head)

$$f = \frac{64}{Re} \tag{5-3}$$

Where: f = Darcy friction factor for laminar flow; Re (Reynolds number) < 2,000, assuming laminar flow and that pipe roughness is not a factor.

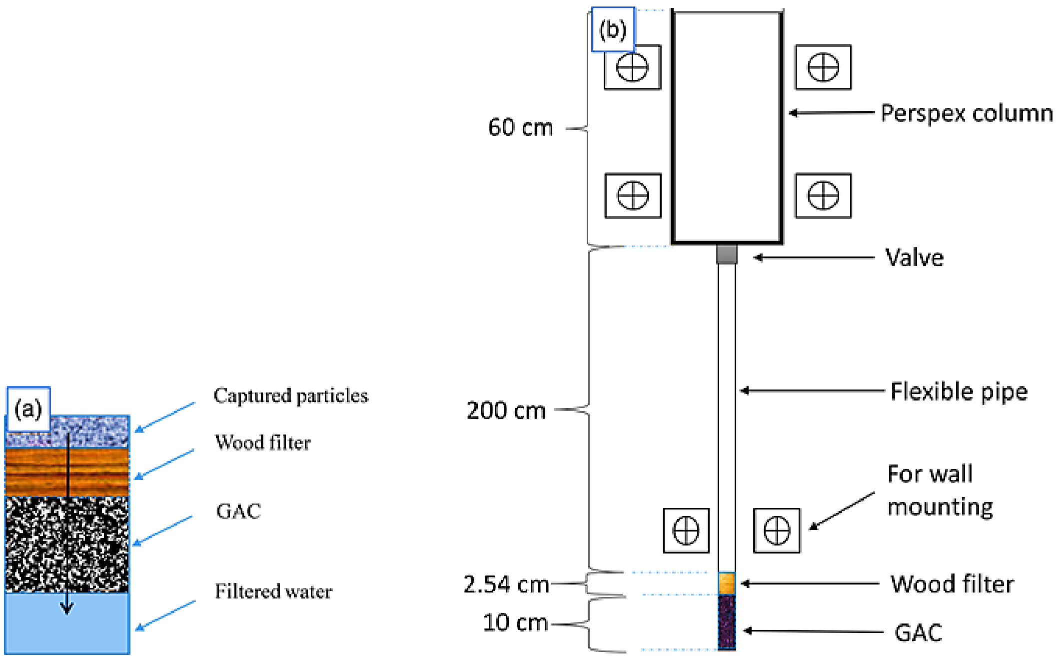

Figure 5-1: Combined wood and GAC filtration: (a) process schematic diagram, and (b) designed filter system

Baseline study

Parallel experiments were performed on fresh, wet preserved and dry preserved wood filters. The four indigenous wood species used (**Table 5-1**) were obtained from the Stellenbosch University Botanical Garden. Although the final design included GAC (**Figure 5-1**), the initial tests were carried out using wood filters only to assess their effectiveness without GAC. Two species were then selected and further tested to examine the effects of incorporating GAC.

Choice of wood species

An initial field visit was made to the Stellenbosch University botanical garden where 55 tree species where physically viewed/inspected. Species attributes were reviewed using the Botanical Garden website (see SUBGSA 2018) and published literature (ispotnature 2018; SANBI 2018). Advice from staff at the botanical garden helped to inform the final choices. Four species where finally selected for this study based on characteristics such as medicinal properties (indicating safety for general consumption), nativity (endemic to the Southern African region) and general uses (indicating the plant is known to local communities). The selected species are as highlighted in **Table 5-1**.

Table 5-1: Wood filter systems and corresponding wood species used (SANBI 2018; SUBGSA 2018):

Filter system Name	***Wood species common names***	***Scientific name***
System 1 (WFS1)	*river bushwillow (Eng.); umhlalavane (Zulu)*	*Combretum erythrophyllum*
System 2 (WFS2)	*Canfer bush (Eng); igqeba emlimhlophe (Zulu)*	*Tarchonanthus camphoratus*
System 3 (WFS3)	*Lion's ear (Eng.); imunyane, (Zulu)*	*Leonotis leonurus*
System 4 (WFS4)	*Cape Willow (Eng.); Umzekana (Zulu)*	*Salix mucronata*

Baseline study: performance of fresh, wet preserved and dry preserved wood filter elements

Comparative analysis on the performance of each indigenous wood species with respect to fresh, wet preserved and dry preserved wood filter pieces was carried out with respect to removal of various contaminants. Preservation was done to try and preserve structural integrity of the sapwood membrane without compromising filter performance. Water samples were collected after 24 hours operational time to ensure adequate representation of the water treatment process. **Figure 5-2** depicts the wood species *Combretum erythrophyllum*, *Tarchonanthus camphoratus*, *Leonotis leonurus* and *Salix mucronata* shown respectively from left to right on top right and bottom images of **Figure 5-2.** The respective effluents are depicted in **Figure 5-3**.

Figure 5-2: Fresh wood (top left), wet preserved wood (top right) and dry preserved wood (bottom); Combretum erythrophyllum, Tarchonanthus camphoratus, Leonotis leonurus and Salix mucronata left to right respectively.

Figure 5-3: Raw water and corresponding treated effluents: (a) fresh wood, (b) wet preserved wood and, (c) dry preserved wood

Fresh wood filter testing: Testing on **fresh wood filters** was done as replicates over two testing periods (**Figures 5-5 to 5-6**). The testing period on the first set of fresh filters was 2 days (from 15th August 2018 to 16th August 2018). At that stage only sampling for physical-chemical tests was done for both days. New **fresh wood pieces** were then collected and tested over seven days (from 21st August 2018 to 27th August 2018). Sampling for physical-chemical tests was done for four days only (see **Figures 5-5 to 5-6**), while sampling for *E.coli* and fecal coliforms removals by fresh filters was done on 21st August 2018.

Wet preserved filter testing: Wet preservation was done by leaving fresh wood pieces submerged in distilled water for seven days under room temperature and afterwards used as filters in the designed system. Testing on **wet preserved filters** was also done as replicates over two testing periods (**Figures 5-5** to **5-6**). The first testing on the first set of **wet preserved filters** was over 4 days (from 17th August 2018 to 20th August 2018). At that stage only physical-chemical tests were done for three days only (**Figures 5-5 to 5-6**). Then new **wet preserved filters** were tested for one day only (on 28th August 2018). Sampling for *E.coli*, fecal coliforms and physical-chemical tests was done only on 28th August 2018 (**Figures 5-5** to **5-6).**

Dry preserved filter testing: Dry preservation was done by keeping unpeeled wood pieces away from direct sunlight under room temperature which was generally between 8 and 20^{o}C during the study. The **dry filters** were only peeled before testing. **Dry preserved filters** were tested over a 6 days period (from 29th August 2018 to 3rd September 2018). Sampling for physical-chemical tests was done for two days only (**Figures 5-5** to **5-6**), while sampling for *bacterial* removals by dry filters was done only on 29th August 2018. Dry filters were tested only for one testing period and only on two sampling days due to their very low recorded flowrates.

Performance effect of GAC on the quality of produced water

The performance effect of combining wood filtration with GAC was assessed using fresh wood filters of two species *Combretum erythrophyllum* (WFS1) and *Salix mucronata (WFS4)*. Each species was tested in duplicate with and without GAC. These species recorded higher values of bacteria in the filtered water during the baseline study. In addition, *Combretum erythrophyllum* generally recorded the most objectionable colour in the filtered water seconded by *Salix mucronata*. Also, *Combretum erythrophyllum* yielded the lowest flow rates while *Salix mucronata* recorded the highest filter flow rates.

Testing of **the combined wood and GAC system**s and the respective controls was done over one testing period (**Figure 5-7**) for eight days (from 4th September 2018 to 11th September 2018). Sampling for physical-chemical tests was done for five days only (see **Figure 5-7**), while sampling for *E.coli* and fecal coliforms removals by fresh filters was done only on 4th September 2018. It was also assessed as to how long the wood filters could remain in operation before deteriorating in quality and subsequently reducing the quality of produced water.

150 cm Flexible pipes containing 10 cm GAC and 2.54 cm wood filter elements were connected to the end of the 200 cm flexible pipe via PVC connectors (see **Figure 5-1**). The GAC weighed approximately 80 g and may be reused during wood filter replacement. 1 mm Perforated PVC end plugs were inserted at the base of the 150 cm pipe to hold the GAC in place. The GAC used was the ProCarb-900 produced by Rotocarb South Africa with an effective size of 0.8-1.0 mm (Rotocarb 2018). Removal of contaminants by GAC is largely dependent on empty bed contact time (EBCT). EBCT was assessed using **Equation 5-4** for an anticipated flowrate of about $4.6*10^{-8}$ m^3/s (Boutilier *et al.* 2014) and found to be about 20 min; enough to remove most contaminants that can be removed by GAC (Binnie and Kimber 2013; Pizzi 2010).

$$EBCT = \frac{V_{GAC}}{Q_v} = \frac{V_{GAC}}{v.A} = \frac{h.A}{v.A} = \frac{h}{v} \quad \textbf{(5-4)}$$

Where; Q_v = flow rate (m^3/h); A = cross sectional area of the filter bed (m^2) of diameter d (m) $\left(A = \frac{\pi d^2}{4}\right)$

V_{GAC} = volume of granular activate carbon (m^3); v = filtration velocity (m/h); h = GAC bed height (m)

Water testing and treatment effectiveness

Fecal coliforms, *E.coli*, TSS (total suspended solids) and turbidity, pH, electrical conductivity (EC), total dissolved solids (TDS), color, odor, taste, and metals (Al, As, Cd, Cr, Cu, Fe, Hg, Pb, Mn, Ni, and Zn) were tested before and after treatment for each sampling. The bacteriological tests were done by the Water Analytical Laboratory (WALAB) accredited to the South African National Accreditation System (SANAS), No: T0375 for microbiological analysis, while the metals were tested by the Central Analytical Facilities (CAF) of Stellenbosch University. The physico-chemical tests were done in the Civil Engineering Department's Water Quality Laboratory at Stellenbosch University. All tests were done in compliance with the Standard Methods for the Examination of Water and Wastewater (APHA/AWWA/WEF 2012).

The four filter systems correspond to the four wood species which were used as defined in **Table 5-1.** The treatment effectiveness achieved by each filter system for *E.coli*, fecal coliforms, turbidity, TSS and metals was calculated using **Equation 5-5**:

$$\%\ \boldsymbol{removal\ of\ contaminant} = \frac{\boldsymbol{C_i - C_e}}{\boldsymbol{C_i}} \boldsymbol{X\ 100} \qquad (5\text{-}5)$$

Where: C_i = concentration of contaminant in untreated water, C_e = concentration of contaminant in treated water

RESULTS AND DISCUSSION

Baseline bacterial removals: fresh versus preserved wood filter elements

E.coli removals for fresh wood filters were 83.3, 85.4, 94.3 and 57.3% by *Combretum erythrophyllum* (WFS1), *Tarchonanthus camphoratus* (WFS2), *Leonotis leonurus* (WFS3) and *Salix mucronata* (WFS4) respectively, while fecal coliform removals were 78.9, 78.5, 91.7 and 58.7 % respectively. WFS1, WFS2 and WFS3 recorded higher *E.coli* removals than WFS4 in terms of fresh and wet preserved filter elements (**Figure 5-4**). WFS4 recorded higher *E.coli* removals than WFS1 and WFS2 for the dry preserved filter elements. A similar trend was observed for particle and fecal coliform removals (**Figures 5-4** and **5-5**). WFS1 and WFS4 recorded their lowest fecal coliform removals as wet preserved filters. WFS3 exhibited superior performance throughout with *E.coli* removals being 94.3, 99.4 and 96.5% respectively for fresh, wet preserved and dry preserved filter elements. *Leonotis leonurus* may therefore be a preferable and very valuable species for water filtration in areas where it is found.

WFS2 was the second best performer recording *E.coli* removals of 85.4, 97.0 and 83.1% by fresh, wet preserved and dry preserved filter elements respectively. The higher bacterial removals by *Leonotis leonurus* and *Tarchonanthus camphoratus* may be attributed to their medicinal properties (SANBI 2018; SUBGSA 2018) and observed smaller xylem pore sizes. The authors believe that the "medicinal properties" may be anti-bacterial. *Salix mucronata* was expected to perform like *Leonotis leonurus* and *Tarchonanthus camphoratus* but generally had larger xylem pore sizes as visually observed which most probably caused its slightly higher flow rates. Poor fecal coliform removals by *Combretum erythrophyllum* in wet preserved state could be attributed to absence of medicinal properties in its xylem. Signs of filter decay were observed during the preservation period for the wet preserved *Combretum erythrophyllum* and after four days of fresh filter use.

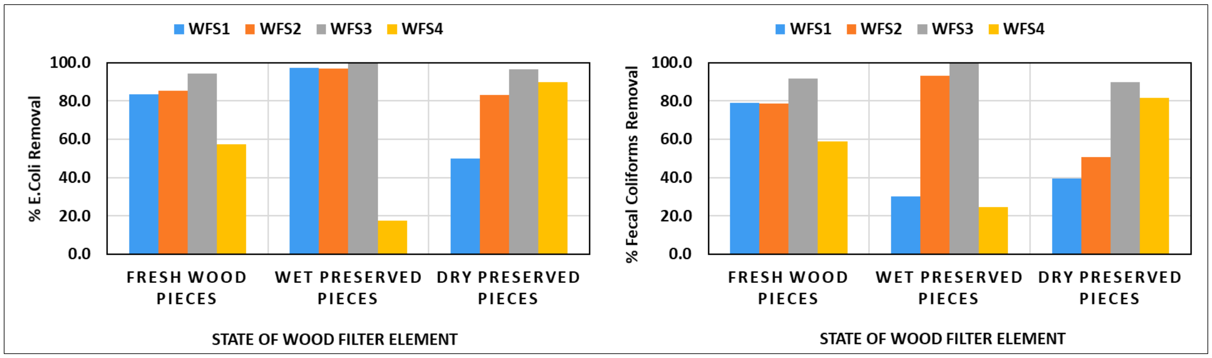

Figure 5-4: Baseline study: Bacterial removals by fresh and preserved wood filters

Baseline particle, color, odor and taste removals: fresh versus preserved wood filter elements

Though color, odor and taste were not adequately removed at this stage, particle removals were still appreciable **(Figure 5-5** to **5-6).** The fresh and wet preserved filters produced water of low turbidity with WFS4 giving the best TSS (96.5%) and turbidity (95.7%) removals for fresh filters. WFS1 recorded its least particle removals for fresh and dry preserved filters (**Figures 5-5** to **5-6**) with worst removals being TSS (-18.7%) and turbidity (-45.0%) for dry preserved filters. That is, *Combretum erythrophyllum* performed far below expectation for dry preserved filters such that the water produced was highly colored, smelly and very turbid. *Combretum erythrophyllum* may not be a good candidate for dry preserved filter applications exacerbated by its very low flow rates when dry preserved. WFS1 and WFS2 gave their best particle removals as wet preserved filters recording 86.0 & 97.3% TSS removals and 82.9 & 96.7% turbidity removals respectively. Whereas WFS3 and WFS4 gave their best particle removals as fresh filters recording 95.4 & 96.5% TSS removals and 94.4 & 95.7% turbidity removals respectively (**Figures 5-5** to **5-6)**. *E.coli* removals by fresh and wet preserved filters corresponded very well with particle removals by WFS1, WFS2 and WFS3 but oddly not so for WFS4. The poor removals in color, odor and taste confirmed the need for combining wood filters with GAC.

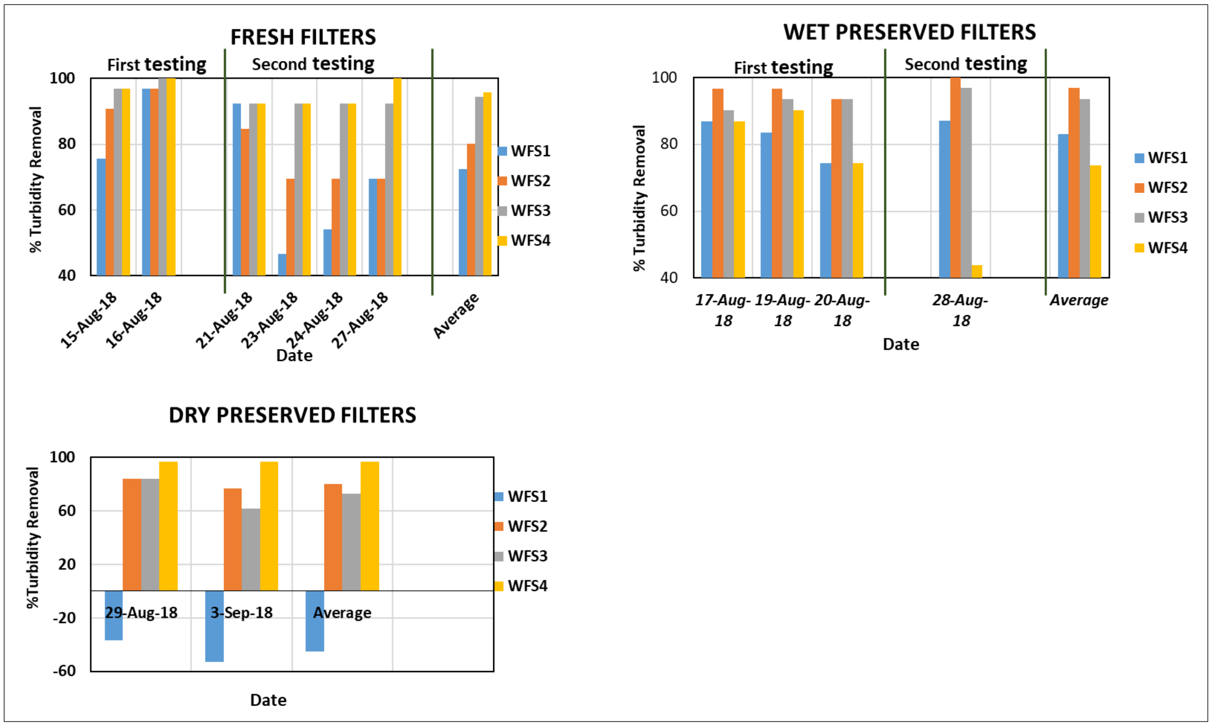

Figure 5-5: Baseline study: Percentage turbidity removals by fresh, wet preserved and dry preserved wood filters

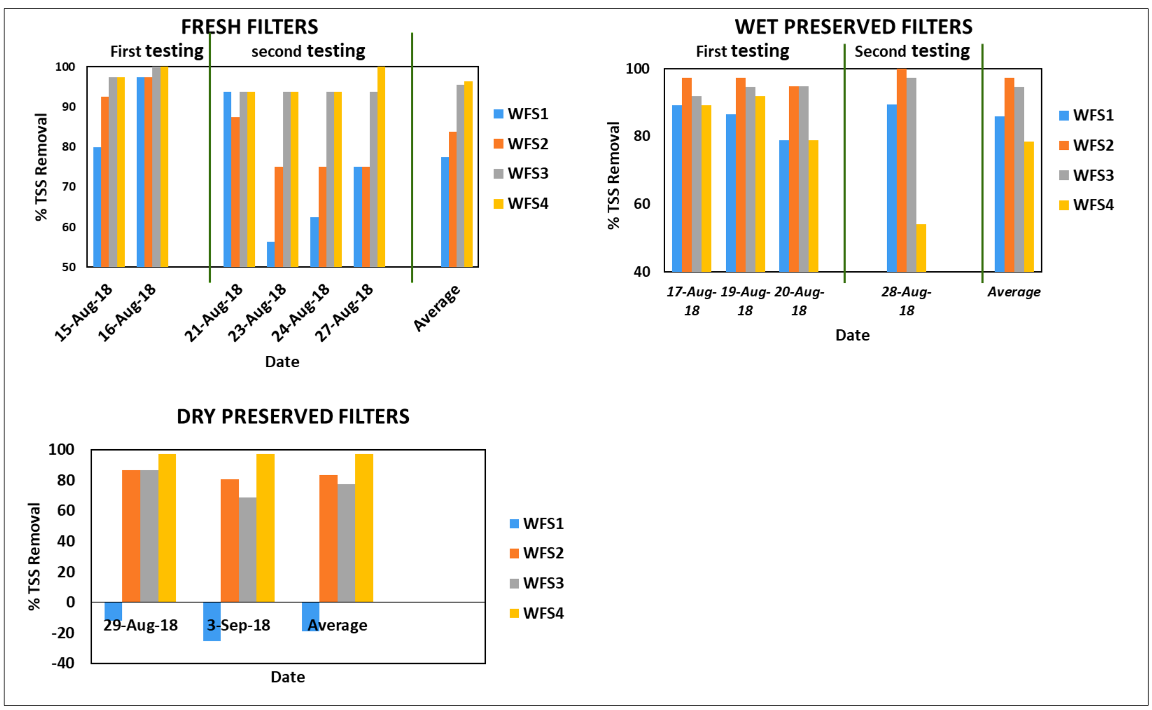

Figure 5-6: Baseline study: Percentage TSS removals by fresh, wet preserved and dry preserved wood filters

Baseline heavy metal removal: fresh versus preserved wood filter elements

Heavy metal removal performance by fresh and preserved filters was generally similar. All the filters (fresh and preserved) substantially removed Al and Fe. With fresh filters recording removals of up to 99.3 and

90.1% respectively **(Table 5-2)**, while wet preserved wood filters recorded up to 99.9 and 99.8% Al and Fe removals respectively (**Table 5-3a**). Dry preserved wood filters recorded up to 99.9 and 91.1% Al and Fe removals respectively (**Table 5-3b**). All the filters (fresh and preserved) generally caused an increase in Cu, Mn and Zn. The increase could be attributed to leaching of these metals from the filter elements due to natural plant uptake of metals and other nutrients (DalCorso *et al.* 2014; Roy and McDonald 2015; Sumiahadi and Acar 2018). According to DalCorso *et al.* (2014) metal nutrients, such as Cu, Mn, Ni and Zn, are essential plant nutrients and are utilized in various cellular functions including energy metabolism, regulation of gene expression, hormone synthesis and perception. The sampling and tests for metals was done on three separate days.

Table 5-2: Baseline: average heavy metal removal by fresh wood filters

Fresh Wood Filters Average Metal Removals (Sampling done on 16th and 21st August 2018)											
		LoD	*Raw water*	*WFS1*		*WFS3*		*WFS4*		*WFS5*	
			Influent Conc.	*Effluent Conc.*	*%removal*	*Effluent Conc.*	*%removal*	*Effluent Conc.*	*%removal*	*Effluent Conc.*	*%removal*
Al	*ug/l*	*1.67*	*244.6*	*13.9*	*93.6*	*1.7*	*99.3*	*23.9*	*90.5*	*28.7*	*86.8*
Cr	*ug/l*	*0.18*	*<LoD*	*<LoD*	*<LoD*	*<LoD*	*<LoD*	*<LoD*	*<LoD*	*<LoD*	*<LoD*
Cu	*ug/l*	*1.69*	*15.0*	*25.8*	****	*53.1*	****	*22.9*	****	*28.1*	****
Fe	*ug/l*	*0.97*	*699.0*	*57.1*	*90.1*	*62.0*	*89.6*	*123.8*	*81.8*	*106.8*	*83.5*
Mn	*ug/l*	*0.29*	*24.0*	*39.4*	****	*33.5*	****	*21.8*	*9.2*	*67.0*	****
Ni	*ug/l*	*0.05*	*<LoD*	*<LoD*	*<LoD*	*<LoD*	*<LoD*	*<LoD*	*<LoD*	*<LoD*	*<LoD*
Pb	*ug/l*	*0.01*	*<LoD*	*<LoD*	*<LoD*	*<LoD*	*<LoD*	*<LoD*	*<LoD*	*<LoD*	*<LoD*
Zn	*ug/l*	*0.16*	*<LoD*	*24.6*	****	*19.7*	****	*<LoD*	****	*25.5*	****

LoD = Limit of Detection; **= increase in concentration over influent level.

Table 5-3:Heavy metal removal by wet and dry preserved wood filters

(a)			Wet Preserved Wood Filters (Sampling done on 28th August 2018)								
			Raw water	WFS1		WFS2		WFS3		WFS4	
Metal	unit	LoD	Influent Conc.	Effluent Conc.	%removal	Effluent Conc.	%removal	Effluent Conc.	%removal	Effluent Conc.	%removal
Al	µg/l	1.67	1275.0	<LoD	99.9	<LoD	99.9	<LoD	99.9	977.9	23.3
Cr	µg/l	0.18	<LoD	<LoD	<LoD	<LoD	<LoD	<LoD	<LoD	<LoD	<LoD
Cu	µg/l	1.69	<LoD	<LoD	<LoD	11.4	**	11.2	**	13.8	**
Fe	µg/l	0.97	619.0	<LoD	99.8	13.6	97.8	15.2	97.5	445.0	28.1
Mn	µg/l	0.29	<LoD	38.4	**	22.1	**	<LoD	<LoD	18.1	**
Ni	µg/l	0.05	<LoD	<LoD	<LoD	<LoD	<LoD	<LoD	<LoD	<LoD	<LoD
Pb	µg/l	0.01	<LoD	<LoD	<LoD	<LoD	<LoD	<LoD	<LoD	<LoD	<LoD
Zn	µg/l	0.16	<LoD	12.8	**	35.1	**	2512.0	**	846.1	**
(b)			Dry Preserved Wood Filters (Sampling done on 29th August 2018)								
			Raw water	WFS1		WFS2		WFS3		WFS4	
Metal	unit	LoD	Influent Conc.	Effluent Conc.	%removal	Effluent Conc.	%removal	Effluent Conc.	%removal	Effluent Conc.	%removal
Al	µg/l	1.67	1252.0	<LoD	99.9	<LoD	99.9	<LoD	99.9	<LoD	99.9
Cr	µg/l	0.18	<LoD	<LoD	<LoD	<LoD	<LoD	<LoD	<LoD	<LoD	<LoD
Cu	µg/l	1.69	<LoD	33.9	**	21.8	**	18.0	**	21.5	**
Fe	µg/l	0.97	1251.0	111.2	91.1	141.8	88.7	111.2	91.1	101.4	91.9
Mn	µg/l	0.29	<LoD	21.1	**	12.6	**	14.0	**	75.2	**
Ni	µg/l	0.05	<LoD	<LoD	<LoD	<LoD	<LoD	<LoD	<LoD	<LoD	<LoD
Pb	µg/l	0.01	<LoD	<LoD	<LoD	<LoD	<LoD	<LoD	<LoD	<LoD	<LoD
Zn	µg/l	0.16	6.0	1392.0	**	82.4	**	1021.0	**	27.5	**

LoD = Limit of Detection; **= increase in concentration over influent level.

Observed filter flow rates: fresh versus preserved wood filter elements

Observed fresh wood flow rates were 0.8, 1.5, 2.2 and 3.6 L/d for WFS1, WFS2, WFS3 and WFS4 respectively. The wet preserved filter flow rates were higher producing 1.0, 2.0, 3.3 and 7.6 L/d respectively for WFS1, WFS2, WFS3 and WFS4. The wet preserved filters recorded higher flow rates probably due to their initially being saturated with water. Dry preserved filters recorded very low flow rate values giving respectively 0.2, 0.2, 0.3 and 0.5 L/d for WFS1, WFS2, WFS3 and WFS4. Overall, the flow rate values were in the following order: WFS1<WFS2<WFS3<WFS4. Therefore, in terms of flow rate *Leonotis leonurus* and *Salix mucronata* are the most promising species for the designed gravity-driven filter system. Flow rates for fresh and wet preserved *Leonotis leonurus* and *Salix mucronata* are high enough for a simple gravity-driven small scale PoU filter of this kind and may deliver enough drinking water for an individual, the more so if a few filters are run in parallel.

Wood filters combined with GAC: Effect on quality of produced water

High pollutant removals were recorded by the combined system (**Tables 5-4 & 5-5)**. This may be attributed to the low flow rates and large EBCT >20 min which was adequate for removal of most contaminants removable by GAC (Binnie and Kimber 2013; Pizzi 2010). It is worth noting here that the improved performance by the wood filters combined with GAC is due to the combined effect of the filter materials. For example, the low flow rates and large EBCT through the system were due to wood filter elements which then enhanced GAC removals. Also, the results from the baseline studies (**Tables 5-3 & 5-4**) and control filters used here (**Tables 5-4 & 5-5**) depict some appreciable contaminant removals by wood filters alone.

Wood filters combined with GAC: Removal of TSS, Turbidity, color, odor and taste

Figure 5-7 shows that wood filters combined with GAC caused high particle removals respectively recording up to 97% TSS and 96% turbidity removals by WFS1, and 100% TSS and 100% turbidity removal by WFS4 in the first four days of filter operation. The treated water met turbidity requirements (≤5 NTU) for small water supply systems (WHO 2017b) and gave better results than the use of wood filters alone. Higher particulates removal was attributed to the presence of the GAC, which increased the system's adsorption capacity. The results also showed that filter elements of WFS1 combined with GAC may remain in operation for four days and still produce clear drinking water and can then be replaced. On the other hand, WFS4 was still producing very clear water up to the last (8^{th}) day of operation. In general, TSS and turbidity removals were almost identical. Although they reflect different aspects, TSS and turbidity both indirectly measure water clarity and overlap in measurement of particles like bacteria, algae, silt, clay, and non-settleable solids (Nathanson and Schneider 2015).

The combined systems removed color, odor and taste remarkably well (**Table 5-5**),further improving acceptability of the treated water. Improving aesthetic characteristics of water (TSS, turbidity, color, odor & taste) is key to acceptability of a low cost water treatment system (CAWST 2017; McAllister 2005; WHO 2017b) and can improve water security in many poor communities (Mihelcic *et al.* 2009). Water that is free from apparent turbidity, color, odor and objectionable taste is always more acceptable to users (Hammer Sr and Hammer Jr 2012; Nathanson and Schneider 2015; WHO 2017a). While poor acceptability can lead to indirect health impacts if consumers lose confidence in the produced water and drink less water or opt for alternatives that may not be safe (McAllister 2005; Sullivan *et al.* 2005; WHO 2017b). Therefore, use of wood filters combined with GAC may often be a better option for producing drinking water than wood filter elements alone.

Wood filters combined with GAC: Bacterial removals

Bacteria removal for the combined wood and GAC system was high recording >99.9% *E.coli* removals by both WFS1 and WFS4 (**Table 5-5**). Likewise, fecal coliform removal was >99.9% by WFS1 and ≥99.9% by WFS4 (**Table 5-5**). This is a notable contribution to the need for combining wood filter systems with GAC. The results are supported by Hijnen *et al.* (2010) whose findings on GAC filters as barriers for pathogens in water treatment reported up to 92 % *E.coli* removals. Inclusion of GAC is therefore required to not only improve removal of organics, heavy metals, color, odor and taste (see Binnie and Kimber 2013; CAWST 2017; Kearns 2007; Pizzi 2010; WHO 2017b), but may also enhance bacterial removals. The reason as to why "WFS1 gave higher fecal coliform concentration in its effluent" is not clear but suspected recontamination or bacterial regrowth during sample handling is a possible cause.

According to Ellis (1991), it is essential to understand that the disinfection stage can be vulnerable to malfunctioning. Therefore, low cost water treatment systems must be primarily aimed at inactivation or removal of pathogens. That is, even without a functional disinfection step, a PoU water treatment system should be able to produce water virtually free of pathogens (Ellis 1991). Additionally, a water treatment technology that mainly relies on chemical use to deliver safe water clearly poses a possible health hazard in most developing communities (Ellis 1991). Hence wood filters combined with GAC will be very useful in much of the developing world for producing safer water. However, due to the possibility of re-contamination after filtration in rural settings, some form of disinfection applicable to the local context before consumption is still recommended.

Wood filters combined with GAC: Heavy metal removals

The combined effect of wood filters with GAC produced notable heavy metal removals (**Table 5-4**) with a removal trend generally in the following order: Fe>Pb>Ni>Al>Zn>Cu>As>Cr>Cd>Mn (with average removals for the first five above 90% and the last five above 50%). Removals by WFS1 combined with GAC were 99.8, 96.4, 93.2, 90.4, 87.6, 82.6, 64.1, 62.8, 45.8 & 0.0% for Fe, Pb, Ni, Al, Zn, Cu, As, Cr, Cd and Mn, respectively. Whereas metal removals by WFS1 without GAC were 98.7, 79.9, 0.0, 96.2, 0.0, 47.4, 6.9, 21.9, 0.0 & 0.0% for Fe, Pb, Ni, Al, Zn, Cu, As, Cr, Cd and Mn, respectively. Similarly, Metal removals by WFS4 combined with GAC were respectively 99.4, 93.8, 88.6, 92.4, 93.7, 94.3, 65.1, 62.8, 73.7 & 0.0% for Fe, Pb, Ni, Al, Zn, Cu, As, Cr, Cd and Mn. The removals by WFS4 without GAC were 94.5, 71.9, 0.0, 96.2, 0.0, 5.2, 11.1, 31.4, 0.0 & 0.0% for Fe, Pb, Ni, Al, Zn, Cu, As, Cr, Cd and Mn. These results demonstrate that the combined systems performed well in metal removals compared to the systems without GAC.

An odd result was observed whereby all filter systems with or without GAC recorded an increase in Mn concentration over influent level (entries marked ** in **Table 5-4**). It is not clear whether Mn leached from the filter media or not e.g., with initial capture and subsequent release. According to literature (see bin Jusoh *et al.* 2005; Binnie and Kimber 2013; Siabi 2003), GAC is expected to remove Mn. For instance, Siabi (2003), reported 75-92% Mn removals respectively by GAC. bin Jusoh *et al.* (2005), however, cautioned that GAC has higher adsorption capacity for Fe(II) than for Mn(II) because electronegativity of Fe(II) is higher than that of Mn(II). Overall, wood filter systems without GAC performed less efficiently than the combined systems. The systems without GAC could not remove Cd, Mn, Ni and Zn and gave very low As, Cr and Cu removals. Therefore, the incorporation of GAC is indicated especially in places where toxic metals are present in water and in the root zone soil.

Table 5-4: Effect of GAC on heavy metal removal by the filter systems

Metal	Unit	LoD	Raw water	WFS1 with GAC		WFS1 without GAC		WFS4 with GAC		WFS4 without GAC	
			Influent Conc.	Effluent Conc.	%removal	Effluent Conc.	%removal	Effluent Conc.	%removal	Effluent Conc.	%removal
As	µg/l	0.05	0.52	0.19	64.09	0.49	6.85	0.18	65.05	0.46	11.11
Al	µg/l	1.67	46.87	4.50	90.40	1.80	96.16	3.56	92.40	1.81	96.15
Cd	µg/l	0.002	0.012	0.007	45.77	0.036	**	0.003	73.65	0.089	**
Cr	µg/l	0.18	0.27	<LoD	62.80	0.21	21.85	<LoD	62.80	0.18	31.35
Cu	µg/l	1.69	10.44	1.82	82.57	5.49	47.39	0.60	94.26	9.91	5.15
Fe	µg/l	0.97	331.80	0.68	99.80	4.26	98.72	2.00	99.40	18.43	94.45
Pb	µg/l	0.01	0.25	<LoD	96.39	0.05	79.90	0.02	93.83	0.07	71.94
Hg	µg/l	0.02	<LoD	<LoD	<LoD	<LoD	<LoD	<LoD	<LoD	<LoD	<LoD
Mn	µg/l	0.29	0.69	108.18	**	31.53	**	147.89	**	95.18	**
Ni	µg/l	0.05	0.80	0.05	93.21	4.39	**	0.09	88.62	11.36	**
Zn	µg/l	0.16	2.52	0.31	87.64	3.36	**	<LoD	93.65	534.66	**

LoD = Limit of Detection; **= increase in concentration over influent level.   Metal sampling done on 5th September 2018

Wood filters combined with GAC: Effluent pH, Conductivity, TDS, TSS and Turbidity

Both combined systems of WFS1 and WFS4 recorded higher pH, TDS and conductivity values (see **Table 5-5 & Figure 5-7**) in their effluent compared to the systems without GAC. However, they were well within South African National Standards (SANS) 241 and WHO potable water guidelines (**Table 5-5**). Higher pH values in the effluent of WFS1 and WFS4 could be attributed to the presence of the GAC. According to Fanner *et al.* (1996), typical activated carbon has a pH of about 8.5-10. This claim was also confirmed by the product data sheet provided by Rotocarb (2018) for the GAC used in this research reporting pH of 10.2. Fanner *et al.* (1996) also indicated that GAC can act as an ion exchange type media and contribute to increase in pH. This effect is more pronounced in new GAC filters and ranges from several hours to several days Fanner *et al.* (1996). This may also be the reason for increase in TDS and conductivity. If GAC is reused-as expected-in combination with a new wood filter element, this effect may be negligible. Additional explanations may include changes in pH, TDS and conductivity due to GAC reacting with chemicals from the wood sap. Further research into this possibility is required. As the filters stayed in use for several days the effect decreased probably due to substances causing high pH, TDS and conductivity being flushed out of the filter systems.

TSS and turbidity removals were generally similar and indicated improvements in clarity and particle removals. Removals of these and other aesthetic parameters (color, odour and taste) by the combined filter systems were significantly higher than removed by wood filters alone. It is worth noting that in as much as research into possible use of ordinary charcoal as a substitute for GAC is encouraged, the wood and GAC combined filter system is meant to be low-cost not necessarily that people can build it themselves, but so that NGOs could possibly make use of the knowledge towards application on site. The NGOs should be able to source GAC at reasonably low cost.

Table 5-5: Bacteriological and physical parameters raw water, systems with and without GAC, and drinking water standards

Bacteriological and physical parameters	***N***	***Raw water***	***Gravity-driven filter systems with and Without GAC***				***Drinking Water Standards***	
			WFS1 with GAC	***WFS1 without GAC***	***WFS4 with GAC***	***WFS4 without GAC***	***SANS241***	***WHO 2017a***
Color	*5*	*Yellow to Brownish*	*Pleasing & clear*	*objectionable*	*Pleasing & clear*	*objectionable*	*≤ 15 mg/l Pt-Co*	*≤ 5 Hazen units*
Odor	*5*	*Odorous*	*odorless*	*objectionable*	*odorless*	*objectionable*		*Unobjectionable*
Taste	*5*	*Sour*	*acceptable*	*objectionable*	*acceptable*	*objectionable*		*Unobjectionable*
Fecal coliforms (CFU/100 ml)	*1*	*1420*	*0*	*2200*	*1*	*5*	*0*	*0*
E.coli (CFU/100 ml)	*1*	*620*	*0*	*260*	*0*	*3*	*0*	*0*
pH (pH UNITS)	*5*	*7.8±0.03*	*8.7±0.06*	*7.8±0.06*	*8.2±0.33*	*7.8±0.05*	*≥ 5 to ≤ 9.7*	*6.5-9.0*
Conductivity (µS/cm)	*5*	*255.3±4.0*	*487.7±17.6*	*287.0±10.6*	*343.7±14.0*	*258.7±5.5*	*≤ 1700*	*2500*
TDS (mg/L)	*5*	*163.4±2.1*	*312.1±9.2*	*183.7±5.5*	*219.9±7.3*	*165.5±2.9*	*≤ 1200*	*1000*
TSS (mg/L)	*5*	*32.0±0.0*	*2.0±1.4*	*8.3±1.7*	*0.3±0.01*	*1.3±0.02*		*0.1*
Turbidity (NTU), Aesthetic	*5*	*19.9±0.0*	*1.5±0.03*	*6.3±0.5*	*0.3±0.01*	*1.0±0.01*	*≤ 5*	*5*

± = standard deviation

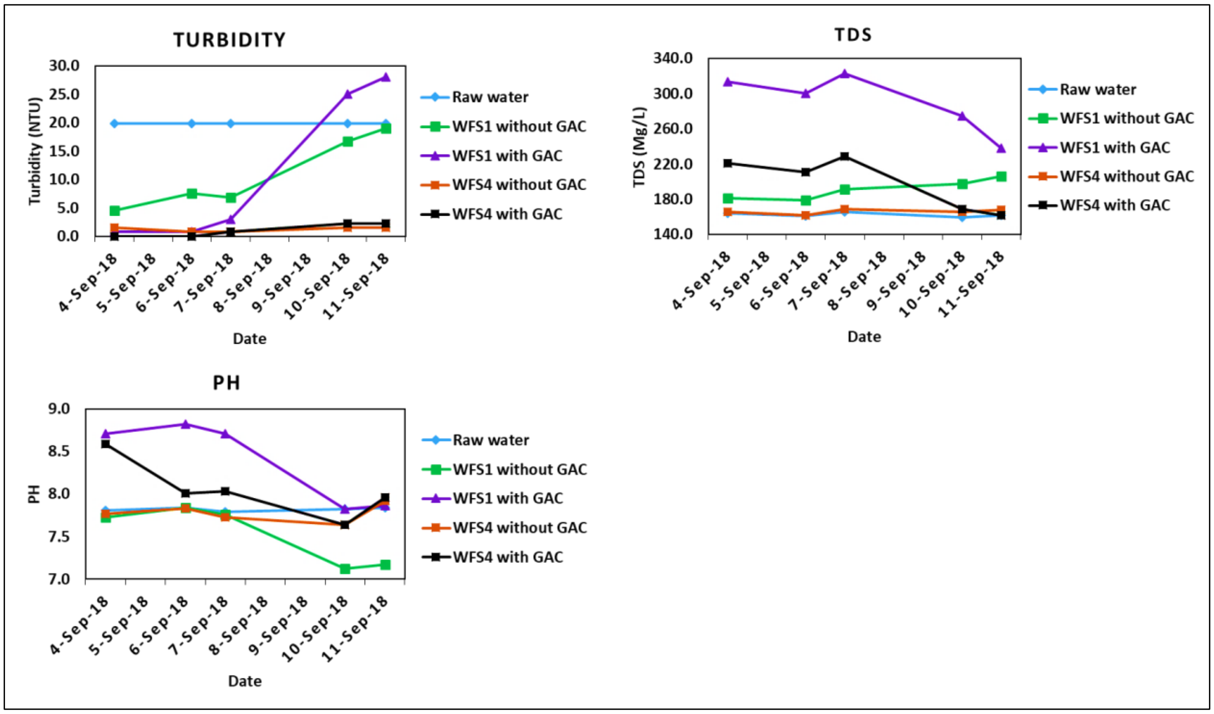

Figure 5-7: GAC effect on produced water and assessment of the period after which the filter elements should be replaced

CONCLUSIONS AND RECOMMENDATIONS

The findings of this research have demonstrated that wood filters combined with GAC are a better option than separate wood or GAC alone for drinking water production. The indigenous wood species studied were found to be a valid technological research area for low cost water filtration and future research into this area is warranted. *Salix mucronata* and *Leonotis leonurus* recorded the highest flow rates of 3.6 and 2.2 L/d respectively for fresh wood filters and 7.6 and 3.3 L/d for wet preserved wood filters. However, it is possible that each of the investigated systems could, with a higher gravity head say 3.5 to 4 m and parallel units, conceivably deliver adequate drinking water amounts. The designed gravity-driven combined wood and GAC system was found to be of relative low cost (< 4 US$) and can be easily constructed and fabricated. This technology therefore finds possible application in Point of Use drinking water systems implemented by governmental or non-governmental organizations for the rural poor with little or no access to formal drinking water supplies.

The designed system was indicated to be able to supply relatively safe water when considering bacterial indicator species, even if further disinfection malfunctions. It may be particularly useful for application in rural areas especially where enough safe wood species are found. Wood filters coupled with GAC can therefore affordably improve water security in many developing communities. In places where GAC cannot be obtained, it is possible that ordinary charcoal may be used with slightly deeper sections than GAC, however further research in this application is recommended. Longer term research is also recommended to assess how long *E.coli* removal could be sustained before filter disintegration in order to recommend filter replacement times. Additionally, further research for application in a specific rural area should consider local wood species coupled with a large sample size of filters per wood species to investigate possible variation within the chosen species.

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Chapter 6: Comparison of five Point of Use drinking water technologies using a specialized comparison framework

This Chapter addressed the third study objective of this dissertation, which is "to develop and demonstrate a specialized comparison framework for qualitative and quantitative evaluation of low-cost PoU technologies."

The aim of this work was to develop and demonstrate a specialized comparison framework by applying it to the five investigated technologies in Chapters 2, 3, 4 and 5. This was done to ascertain the most suited material and process configuration for further research towards production of an optimized final product developed and presented in Chapter 7 and then modelled in Chapter 8.

A range of low-cost treatment methods and technologies for application in low-cost PoU systems were investigated specifically for application in the Southern African region in Chapters 3, 4 and 5. Local materials were sourced and different PoU system configurations were experimented with. Knowledge gained from the experiments in Chapters 2, 3, 4 and 5 was used in this Chapter to develop the specialized comparison framework presented here. The experimental work in Chapters 3, 4 and 5 initially resulted in the development of three simple, yet innovative water treatment systems namely the: (i) ISSFGeoGAC, (ii) BidimSEQFIL, and (iii) WFSGAC. These were then comparatively evaluated alongside two commercially available PoU systems (researched in Chapter 2) using the comparison framework developed in this Chapter as mentioned above. This led to the design, optimization and modelling of a novel combined PoU system as presented in Chapters 7 and 8.

Although there is room for refinement on the developed comparison framework depending on the application or situation being investigated probably in consultation with interested stakeholders, the study in this Chapter indicated that it is possible to qualitatively and quantitatively compare low-cost PoU technologies, thereby helping decision making. The novel comparison framework finds possible application by engineers and implementers for comparatively assessing low-cost PoU systems. This can also assist engineers to improve and modify or innovate even further on low-cost PoU systems.

Based on the study in this Chapter and various issues identified in Chapters 2, 3, 4 and 5, it was decided to incorporate the following in the design of the final product as initiatives towards possible alleviation of certain identified issues: (i) safe storage compartment to minimize recontamination, (ii) GAC filtration for aesthetic improvement and enhancing additional removal of other contaminants such as iron and manganese which impart color and taste to water, (iii) inbuilt disinfection provided by the silver in the clay based SCCGM to avoid further treatment by disinfection (e.g. chlorination which imparts smell and taste to water) thereby enhance acceptability of the treated water. According to literature (e.g. Pandit and Kumar 2019), silver concentrations needed for bacterial inactivation in water do not impart color, taste or odor to water. This is also expected to avoid DBPs by chlorination such as trihalomethanes and Halo acetic acids (HAAs) which are suspected carcinogens, and (iv) pre-filtration by the nonwoven bidim geotextile as a form of pretreatment to remove debris and larger microbes (e.g. helminths and protozoa) and reduce particulate loads in the water before it passes through the disinfection step. This enhances disinfection efficiency by increasing bacterial contact with the silver in the SCCGM. Furthermore, pre-filtration was proposed to enhance the system's ability to treat a broader variety of raw water and extend filter runs and to cater for fluctuations in suspended particle concentrations in the surface waters of rural and suburban communities of Southern Africa.

Comparison of five Point of Use drinking water technologies using a specialized comparison framework

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ABSTRACT

Three novel and two commercially available low-cost Point-of-use (PoU) water treatment technologies were comparatively evaluated using a specialized comparison framework targeted at them. The comparison results and specialized framework have been discussed. The PoU systems were evaluated principally in terms of performance, flow rate and cost per volume of water treated (quantitatively), ease of use, potential acceptability and material availability (qualitatively) with main focus on rural and suburban settings. The three novel systems assessed were developed in an ongoing research project aimed at developing a multi-barrier low-cost PoU water treatment system. The comparative evaluation and analysis revealed that the commercially available systems may often produce water free of pathogens (with an apparent 100 % removal for *E.coli* and Fecal coliforms) but may not be affordable for application to the poorest groups in much of the developing world. The novel systems, which were principally constructed from local materials, were more affordable, can supply relatively safe water and can be constructed by users with minimal training. Overall, bacterial removal effectiveness, ease of use, flow rate, material availability, cost and acceptability aspects of water were identified as key to potential adoption and sustainability of the evaluated low-cost PoU systems.

Key words: Drinking water, low-cost, point-of-use, specialized comparison framework, novel technology, water treatment

INTRODUCTION

Provision of safe drinking water in developing countries can be best achieved by avoiding sophistication in technological design. Simplicity and reliability must be the key words in the minds of designers and implementers of low cost drinking water technologies (Ellis 1991). Although Point of Use (PoU) water treatment is not a replacement for formal provision of safe drinking water; it serves as a valuable interim measure for reducing the risk of waterborne diseases for about 660 million people with no access to improved supplies (WHO 2016). When the absence of fecal contamination is considered, the population in need of safer water increases to 1.9 billion (WHO 2016). According to the World Health Organization (WHO 2016), to realize health gains, PoU technologies must produce microbiologically safe drinking water and be correctly and consistently utilized. Furthermore, the systems must be able to produce aesthetically acceptable drinking water so that users do not opt for aesthetically better alternatives that may be unsafe (CAWST 2017; Hammer Sr and Hammer Jr 2012; WHO 2017a).

Safe drinking water is a significant problem in many poor communities due to widespread poverty and vulnerability levels. Boiling is often used in such settings and can be efficient at elimination of waterborne pathogens. However, boiled water is not aesthetically acceptable to most people and is susceptible to recontamination due to unsafe handling and storage (Genthe *et al.* 2013, Jagals *et al.* 1997; 2003; Kausley *et al.* 2018; Potgieter *et al.* 2009; Supong *et al.* 2017; WHO 2016). It is time consuming to boil and cool down the water, and the water to be boiled needs to be clear, often necessitating pretreatment. Additionally, boiling is energy intensive and uses stoves and fuels, which lead to environmental impacts including contribution to climate change (WHO 2016). Therefore, developing and optimizing low-cost PoU systems that can efficiently remove pathogens from drinking water and improve acceptability aspects is warranted.

Although most PoU water treatment systems work primarily like centralized water treatment systems (Peter-Varbanets *et al.* 2009), quality, performance and sustainability varies significantly across these technologies. Many design guidelines and criteria exist for centralized water treatment systems (Davis 2010; Kawamura 2000), while PoU water treatment systems have varying guidelines and criteria. Most available low-cost systems may not be well designed and produced and may therefore be unable to give excellent sustainable performance. Comparative evaluation (quantitatively and qualitatively) of PoU systems is therefore necessary to ascertain the most apt system to use in a specific situation.

Three novel and two commercially available low-cost PoU water treatment systems were compared by means of a comparison framework developed specifically for them. The three novel systems assessed were developed by the authors in an ongoing research aimed at developing and optimizing a low cost multi-barrier water treatment system. This specialized comparison framework has been developed based on the WHO Scheme for Evaluating PoU Water Treatment Technologies and reports by various water treatment researchers. Various performance criteria for low-cost PoU water treatment systems were comprehensively explored based on findings and recommendations by a number of authors see (Adeyemo *et al.* 2015; CAWST 2011; Ellis 1991; Lantagne and Clasen 2009; Loo *et al.* 2012; McAllister 2005; Nath *et al.* 2006; Peter-Varbanets *et al.* 2009; Sobsey *et al.* 2008; Stubbe *et al.* 2016; WHO 2016).

The three novel and two commercially available systems were assessed both quantitatively and qualitatively using the developed comparison framework. Bacterial diseases e.g. acute gastroenteritis, cholera, diarrhoea, dysentery, typhoid, etc. cause far more health problems than viruses or chemicals as a result of drinking untreated water (McAllister 2005; WHO/UNICEF 2004). Therefore, bacterial removal was afforded high priority in the evaluation criteria. Special attention was given to application of the comparative framework in evaluating low-cost filtration technologies. This is because the evaluated PoU technologies were mainly filtration based.

The two evaluated commercial PoU systems were the gift of water filter system (GWS) and drip filter system (DFS) manufactured in the USA and South Africa respectively; and previously researched by the authors (Siwila and Brink 2018a). The three novel systems evaluated in this study were the: (i) Modified intermittently operated slow sand filtration system (ISSFGeoGAC) incorporating geotextile and granular activated carbon (GAC) for removal of bacteria, particles, color, taste, odor and selected heavy metals (Siwila and Brink 2018b), (ii) the four pot 8-layer sequential bidim filtration system using bidim geotextile (BidimSEQFIL) for removal of bacteria and particles (Siwila and Brink 2018c) and, (iii) the wood filtration combined with GAC (WFSGAC) for removal of bacteria, color, taste, odor, particles and heavy metals (Siwila and Brink 2018d). These filtration technologies were developed and tested as contribution to research on affordable PoU water treatment systems appropriate to poor communities producing water with a high degree of acceptability.

It is hoped that the developed comparative framework presented here will support the WHO PoU evaluation scheme and promote adoption of novel PoU technologies. It is further envisaged that such an exercise may bring out new research insights. That is, researchers and implementers may be encouraged to carry out studies aimed at optimizing novel technologies e.g. in terms of pollutants of interest, ease of use, maintenance requirements, etc.

For instance, based on a preliminary evaluation using various published literature (Binnie and Kimber 2013; CAWST and SPC 2017; Graham and Mbwette 1987; Jenkins *et al.* 2009; Manz 2004; Muhammad *et al.* 1996; NE-WTTAC 2014; Stauber *et al.* 2006) the first of the three novel technologies being evaluated, was developed. Although there is still room for improvement, laboratory tests by Siwila and Brink (2018b) showed that the novel technology is expected to perform better than the traditional ISSF systems. Meanwhile, initial literature review showed that ISSF systems particularly the institutional scale (CAWST and SPC 2017) still need further improvement in terms of cleaning frequency and removal of other contaminants such as metals, color, taste and odour. GAC was therefore added to improve contaminant removal (Siwila and Brink 2018b). Geotextile filter mats were placed on the sand surface to minimize the cleaning frequency whereby the filter mats are to be cleaned instead of the traditional sand removal scraping, or “swirl and dump” (surface agitation and stirring) cleaning techniques (CAWST 2011; Singer *et al.* 2017). The traditional cleaning methods are somewhat tedious and tend to render the technology less acceptable to users. This is further worsened by inconsistencies in producing water free of color, taste and odor as well as significant reduction in bacterial removals after cleaning (Singer *et al.* 2017).

Therefore, in this study a specialized comparison framework for low-cost PoU water treatment systems was developed and used to evaluate five low-cost PoU systems. Though particular emphasis was placed on elimination of bacteria, improvement of the acceptability aspects of water was also given high priority so that users do not opt for water that seems more acceptable but is contaminated.

MATERIALS AND METHODS

Design Considerations and Evaluation criteria

A thorough review of published literature was done and showed that there is currently no documented standard on design and suitability of low cost PoU systems based on quantitative specifications. The quality of many low cost PoU technologies relies primarily on the materials used and the fabricator’s skill. There is a gray area in which scientific and engineering judgement must be employed to determine the level to which a PoU technology is suitable. Studies and field experiences by various authors on various PoU water treatment technologies showed suggested guidelines and criteria (see Loo *et al.* 2012; McAllister 2005; Nath *et al.* 2006; Peter-Varbanets *et al.* 2009; Sobsey *et al.* 2008; WHO 2016). **Table 6-1a** shows that contaminant removal performance, ease of use, social acceptability, cost, flow rate, implementation potential (i.e. training, technical personnel for installation and repairs, availability of spare parts, energy requirements, chemical requirements, etc.), pore size, brushing and removing silver from ceramic candles are among the main criteria which affect effectiveness as proposed by various authors.

Principally, the table was generated qualitatively through thorough content and text analysis of the referenced literature. The extracted criteria were then logically arranged. Thereafter, the criteria for the specialized comparison framework were developed (**Table 6-1b**). Definitions of the comparison framework evaluation criteria, some of which are adapted from **Table 6-1** references, were then provided (**Table 6-2**).

PoU technology suggested guidelines and evaluation criteria

Various PoU technology evaluation criteria have been suggested by different authors as summarized in **Table 6-1**. For example, CAWST (2011) noted five main criteria for evaluating PoU water treatment technologies namely: (1) effectiveness (the quality and quantity of the water that can be treated), (2) appropriateness (availability, time for treatment, work involved and estimated lifespan of the technology), (3) acceptability (the ease of use and the acceptability of the users or user perception and buy in), (4) cost to user (capital/initial costs, maintenance and ongoing costs), and (5) implementation (what is required to get the technology into people's homes e.g. training for users to properly use the technology, monitoring required for the technology, additional support, etc.). McAllister (2005) proposed the following guidelines in order to achieve sustainable low cost PoU technologies: (1) little or no use of non-renewable energy during the production or technology use, (2) minimal environmental impact during the production or technology use (3) selected materials should be readily available and/or easy to manufacture, (4) manufacturing processes should be safe and efficient, and (5) technology should regard cultural principles, practices, or customs. Published criteria, therefore, vary in terms of content and importance given to different elements.

Most suggested criteria were scattered with no provided definitions and systematic guidance for technology evaluation. In addition, most of the proposed criteria were generalized not necessarily focused on low-cost systems. The criteria adapted and proposed in this study were chosen to be suited specifically to low-cost systems.

Therefore, this study is aimed towards the provision of necessary detailed guidance (**Figure 6-1**), definitions (**Table 6-2**), a background compilation of criteria suggestions by various authors (**Table 6-1**), quantitative comparisons (**Table 6-4**), qualitative comparisons (**Table 6-5**) and a decision matrix (**Table 6-6**) for low-cost PoU technology analysis and assessments. In addition, the criteria for the developed comparison framework also emphasizes factors such as system durability and acceptability potential of treated water. Product durability may promote adoption of a novel technology by users. Drinking water of high acceptability will certainly prevent users from opting for more appealing water that may not be safe (CAWST 2017; WHO 2017a).

Although acceptability aspects of water may have little health significance, their presence could reflect treatment malfunction and the likely presence of other contaminants (WHO 2017a). Some technologies such as those based on chemical treatment may produce water which is virtually free of pathogens but has a bitter taste or color. Such types of water may in some cases not be acceptable to various consumers, minimizing its health impacts. This can also be supported by published work from various authors' who have done PoU water and health related work in South Africa and other regions of the world (e.g. Ashbolt 2004, Curry *et al.* 2015, Genthe *et al.* 2013, Gundry *et al.* 2004, Jagals *et al.* 2003, Momba *et al.* 2013, Potgieter 2007, Potgieter *et al.* 2009, Singer *et al.* 2017, Sobsey *et al.* 2008), where social and aesthetic acceptability were investigated and found to be vital to acceptance and sustainability of various low-cost PoU systems. For instance, Potgieter *et al.* (2009) indicated that people associated chlorine smell and taste of water with cholera outbreaks as it was recommended to add bleach to their drinking water after boiling during cholera outbreaks in rural areas of South Africa's Limpopo Province. That is, water that tasted of chlorine was only consumed during the outbreak, and rarely afterwards even where people suspected that their water quality was not good.

Table 6-1: (a) Summary of key PoU technology characteristics and evaluation criteria as extracted from content and text analysis of various literature and, (b) the framework evaluation criteria

(a). Extracted/ suggested PoU water treatment technology evaluation criteria											Reference/Source
Investment cost $US	Operational cost $US	Performance	Ease of use	Maintenance	Sustainability	Energy requirement	Social acceptability				Peter-Varbanets *et al.* 2009
Cost ($US)	Environmental Impact	Performance	Ease of use &deployment	Maintenance	Life span	Energy requirement	Social acceptability	Water production rate (L/h)	Supply chain		Loo *et al.* 2012
Manufacturing cost $US	Environmental Impact	Pollutant removal	Locally Made	Manufacturing Time	Material Availability	Filter pore size (microns)	Socially acceptable	Capacity (liters/h)			McAllister 2005
Capital/initial costs $US	Ongoing costs $US	Pollutant removal	Ease of use	Maintenance	Estimated lifespan	Locally Made	Socially acceptable	Quantity treated (L/h)	Training needs		CAWST 2011
Cost ($US)		Pathogen removal		generally, 'free-standing'	Material availability	Local availability	Appropriate	Quantity treated	Training needs		WHO 2016
Capital costs $US	Running costs $US	Pollutant removal	Ease of operation	Storage ability	Robustness/ durability	Sustainability & maintenance	Social acceptance	Quantity treated	Training needs		Adeyemo *et al.* 2015
Price ($US)	Retail Price ($US)	Effectiveness	Price/m^3	Locally produced	Life span	Maintenance cost	Acceptability	Flow rate (L/h)	Training and monitoring needs		Stubbe *et al.* 2016
Cost ($US)	Running costs $US	Performance	Ease of use	Environmental Impact	Availability	Energy requirement	Improves taste	Time efficient	Replicable		Sharma and Sood 2016
Cost ($US)	Running costs $US	Performance	Ease of use	Public health hazard	Local materials	Energy requirement			Technical assistance		Ellis 1991
Cost ($US)	Running costs $US	Performance	Ease of use	Maintenance	Sustainability	Treatment robustness	Health impacts	Time treating water	Supply chain		Sobsey *et al.* 2008
Cost ($US)	Running costs $US	Performance	Ease of use	Maintenance	Local availability	Life span	User acceptability	Flow rate (L/h)	Supply chain		Lantagne and Clasen 2009
Cost ($US)	Running costs $US	Performance	Ease of use	Maintenance	Availability	Energy requirement	Practicality	Flow rate (L/h)	Supply chain		Nath *et al.* 2006
Cost ($US)	Running costs $US	Performance	Ease of use	Maintenance	Sustainability	Energy requirement	Social acceptability	Volume treated	Supply chain		Mac Mahon and Gill 2018
(b) Developed framework evaluation criteria: listed from most critical to least critical (left to right)											
Performance	Ease of use	Water throughput	Acceptability potential	Energy requirement	Cost	Ease of deployment	Durability	Maintenance	Environmental impact		Supply chain

Table 6-2: Score definitions with respect to each of the PoU specialized comparison framework's evaluation criteria[a]

Evaluation criteria	Meaning of scores used in the comparison				
	1	2	3	4	5
Performance	Fair pathogen removal (1 to 2 LRVs); treatment efficiency affected by variations in raw water quality; cannot remove color, taste, odor and turbidity	Fair pathogen removal (1 to 2 LRVs) ; treatment efficiency affected by variations in raw water quality; can remove color, taste, odor and turbidity	Good pathogen (2 to 3 LRVs) removal; treatment efficiency not affected by variations in raw water quality; cannot remove color, taste, odor and turbidity	Excellent (4 to 5 LRVs) pathogen removal; treatment efficiency not affected by variations in raw water quality; can remove color, taste, odor, turbidity	Exceptional pathogen removal (6 to 8 LRVs); treatment efficiency not affected by variations in raw water quality; can remove color, taste, odor and turbidity and various chemical contaminants
Ease of use	Needs very skilled operators; complex system design; difficult to operate	Needs skilled operators and/or operation is laborious	Needs some form of user training; relatively easy to operate	Needs very little user training; very easy to operate	Virtually no user training needed; very easy to operate
Water throughput	Very low flow rate (<7.5 L/d)	Low flow rate (< 15 L/d);	Flow rate is fair (> 15 L/d)	High flow rate; can meet drinking water needs of a household, small community or institution	High flow rate; can meet drinking water needs of a large community or institution
Acceptability potential	No improvement in appearance, smell, and taste of the treated water; difficult to use	No improvement in appearance of the treated water; treated water has acceptable taste and smell; difficult to use	Improved appearance in the treated water; acceptable taste and smell; relatively easy to use	Improved appearance in the treated water; acceptable taste and smell; easy to use, may not be user friendly to everyone	Improved appearance in the treated water; acceptable taste and smell; very easy to use, acceptable among many user groups
Energy requirement	Substantial quantities of energy required and does not run on renewable energy	Substantial quantities of energy required; can run on renewable energy	Minimal energy requirement or uses tap pressure	Tap pressure or gravity fed; no electricity needed	Gravity-driven; no dependence on utilities
Cost	>US$10/m^3	US$5/m^3- US$10/m^3	US$1/m^3- US$5/m^3	<US$1/m^3	One off cost needed (0-50 US$/unit); no operational costs required
Ease of deployment	Too heavy or delicate to be transported; has to be constructed or assembled at the point of use	Heavy or delicate; major parts require expert assembly at the point of use	Heavy but not delicate; system set up at the point of use is relatively easy	Light, small and not delicate; Very easy to assemble; can be transported in large numbers	Light, small and not delicate; ready to use; can be transported in large numbers
Durability	Easily breakable and requires frequent repairs	Cannot break easily but requires frequent repairs	Made of durable materials; repairs are often needed	Made of durable materials and requires periodical repairs	made of durable materials and virtually requires no repairs
Maintenance	Maintenance is complex, frequently performed and takes a lot of time	Maintenance is complex, frequently performed but takes little time	Maintenance is easy, takes little time but is performed frequently	Maintenance is easy, takes little time and performed periodically	Virtually no need for maintenance
Environmental impact	Can pollute or cause damage to the environment; e.g. can release Green House Gasses; uses fossil fuels	Little pollution or damage to the environment; uses fossil fuels and nonrenewable materials	No pollution or damage to the environment; uses gravity or renewable energy; partly made of nonrenewable materials	No pollution or damage to the environment; mainly made of renewable materials and gravity fed	No damage or pollution to the environment; fully made of renewable materials and gravity fed
Supply chain	Nonstop supply of consumables needed whose stocks are only obtainable from certain dealers	Nonstop supply of consumables needed; but consumables can be easily obtained	Needs timely replacement of some parts obtainable from certain dealers only	Needs timely replacement of some parts; spare parts can be easily obtained	Everything is locally available or easily obtainable

[a]Key references for this table are those listed in **Table 1 .** LRVs = Log removal values **(**mainly targeted at bacterial removal).

The WHO PoU Evaluation scheme

The WHO evaluation scheme for PoU drinking water technologies focuses primarily on reference pathogens (**Table 6-3**). According to WHO (2016), priority PoU technologies selected for evaluation are those that are: (1) low cost; (2) appropriate for low-income communities; (3) generally, ‘free-standing’ and do not require being plumbed in; and (4) only treat sufficient water to serve a small number of users a day, for households or small settings such as schools, health care centers, etc. The Water, Sanitation, Hygiene and Health Unit of the WHO coordinates the scheme. The unit (WHO 2016): (1) reviews and assigns testing labs, (2) develops testing procedures and report formats, (3) manages PoU technology testing, (4) reviews test results, and (5) conveys PoU evaluations results to Member States.

Table 6-3:Test organisms of the WHO Scheme and recommended microbiological performance criteria (WHO 2016)

Pathogen class	Organism	Key considerations in PoU water technology evaluation	Recommended targets for microbiological reduction by PoU water treatment systems (LRV)		
			Comprehensive protection: very high pathogen removal	Comprehensive protection: high pathogen removal	Targeted protection
Bacteria	*Escherichia coli*	• Well characterized fecal indicator organism; frequently found in raw water sources • most sensitive organism to disinfection	≥ 4	≥ 2	Achieves “ protective” target for at least two classes of pathogens.
Virus	*MS2 and phiX174* *(*human viral surrogates*)*	• Widely used surrogates for human viruses •Broad variety of traits and subsequent variations in sensitivity to water treatment •Well characterized susceptibility to various disinfectants	≥ 5	≥ 3	
Protozoa	*Cryptosporidium parvum* *oocysts*	• Relatively resistant to chemical disinfectants but sensitive to UV irradiation • Readily removed by physical processes e.g. filtration	≥ 4	≥ 2	

1 log removal value (LRV) = 90 %; 2 LRV = 99%; 3 LRV = 99.9 %, 4 LRV = 99.99%; 5 LRV=99.999%

Suggested Test organisms for the specialized comparison framework

Although the WHO evaluation scheme recommends testing three classes of pathogens in water (bacteria, virus and protozoa) for microbial safety (**Table 6-3**), only fecal indicator bacteria (*E.coli* and *fecal coliforms*) were used in this study. *E.coli* and to some degree *fecal coliforms* are accepted to best meet the criteria for an ideal fecal contamination indicator (Ashbolt *et al.* 2001; Cabral 2010; Fewtrell and Bartram 2013). The presence of these signals that pathogens are present, and the water can therefore be regarded as being unsafe. Moreover, protozoa are readily removed by filtration technologies such as those being evaluated (DrinC 2017; Gift of Water Inc. 2017) and viruses can be inactivated by most disinfectants (WHO 2016). In addition, viruses have been associated with fewer health indices or lower illness rates to date than bacteria (Ashbolt *et al.* 2001; Bartram & Hunter 2015; McAllister 2005; Sobsey 1989; USEPA 1987; WHO/UNICEF 2004; WHO 2011). However, making use of surrogates (*bacteriophages* for viruses, *cryptosporidium* or *giardia* species for protozoan parasites and *E.coli* or *enterococcus* for bacteria) is still recommended for future application of the developed framework. This is in order to be in harmony with the WHO evaluation scheme which suggests the use of three classes of pathogens. This can be done in places where testing for the mentioned surrogates, is relatively simple, available and cost effective.

The specialized comparison framework vs The WHO PoU Evaluation scheme

As stated above, the WHO evaluation scheme requires testing for three classes of pathogens (bacteria, viruses and protozoa) using challenge test waters. This is more ideal but may not be feasible in many poor communities especially in rural and remote areas. The framework developed in this study recommends testing for indicator bacteria (*E.coli* and/or *fecal coliforms*) while other pathogens can be tested if resources allow. In addition, the WHO evaluation scheme procedure mainly stresses on evaluating pathogen removal performance, while the developed comparison framework emphasizes assessing both bacterial removal performance and the acceptability aspects of water. Furthermore, the WHO evaluation scheme has not distinctively provided defined scores and a corresponding decision matrix for possible comparisons such as included in the specialized comparison framework. In addition, the WHO evaluation scheme is mainly suited to PoU technologies that can primarily eliminate all pathogens. These include membrane ultrafiltration, flocculation-disinfection, UV disinfection, chemical disinfection and solar disinfection (WHO 2016); most of which are relatively expensive to poor communities. In resource limited situations, water that is of reasonable quality (0-10 CFU/100 ml *E.coli* levels) and relatively safe (11-100 CFU/100 ml *E.coli* levels) may be consumed as is (CAWST 2013; Harvey 2007; WHO 1997). Additional solar and/or chemical disinfection according to WHO guidelines for drinking-water quality (WHO 2017b) is, however, still recommended to ensure the complete elimination of pathogens.

Comparison framework evaluation procedure

Highlighted in **Figure 6-1** are the key steps of the specialized comparison framework evaluation procedure. Screening is done to identify the low cost PoU water technologies to be evaluated in **Step 1**. This is essentially based on availability, user needs and engineer/implementer interests. Data needs are defined, and quality of available data is assessed (**Step 2)**. In **Step 3**, if data is unavailable then adequate testing of the novel technology should be done. If data is available, comprehensive review and analysis should be done followed by quantitative and qualitative performance assessment of each PoU technology (**Tables 6-4** and **6-5**). WHO drinking water guidelines and local potable water standards can be used in assessing the safety of water. In **Step 4** technologies meeting potable water standards are noted and respective scores for each evaluation criteria are defined (**Table 6-2**). The criteria in **Table 6-2** have been ranked in order of most critical to least critical.

In **Step 5** a decision matrix is generated**.** Criteria scores are then categorized as being least favorable (bad) to most favorable (excellent) (**Tables 6-5** and **6-6**). Weighting factors are assigned to each criteria based on a three-point scale (**Table 6-6**). Each technology is then assessed and scored using a five-point scale (**Table 6-6**). The sum of the unweighted and weighted scores of each technology are then calculated using

Equations 6-1 and **6-2** respectively**.** In **Step 6** the technologies are comparatively ranked and compared from the most favorable to the least favorable using the weighted scores (**Figure 6-6**). **Step 7** essentially involves discussing and reporting the evaluation findings in terms of features such as design, contaminant removal effectiveness, raw material availability, social acceptability, technical needs, etc. **Conclusions and** r**ecommendations** are then made on whether the novel low-cost technology can be adopted as it is or needs further improvement.

$$\delta_{uw} = \gamma_1 + \gamma_2 + \gamma_3 + \cdots + \gamma_n = \sum_{k=1}^{n} \gamma_k; \quad \textit{for } k=1,2, \ldots\ldots, n \tag{6-1}$$

$$\delta_{w} = \beta_1\gamma_1 + \beta_2\gamma_2 + \beta_3\gamma_3 + \cdots + \beta_n \gamma_n = \sum_{k=1}^{n} \beta_k\gamma_k; \quad \textit{for } k=1,2, \ldots\ldots, n \tag{6-2}$$

Where: δuw = sum of unweighted criteria scores; δw = sum of weighted scores; β = weighting factor; $\gamma 1 \cdots \gamma n$ = respective criteria scores; γk = score for the k^{th} criteria; k indexes the n- criteria

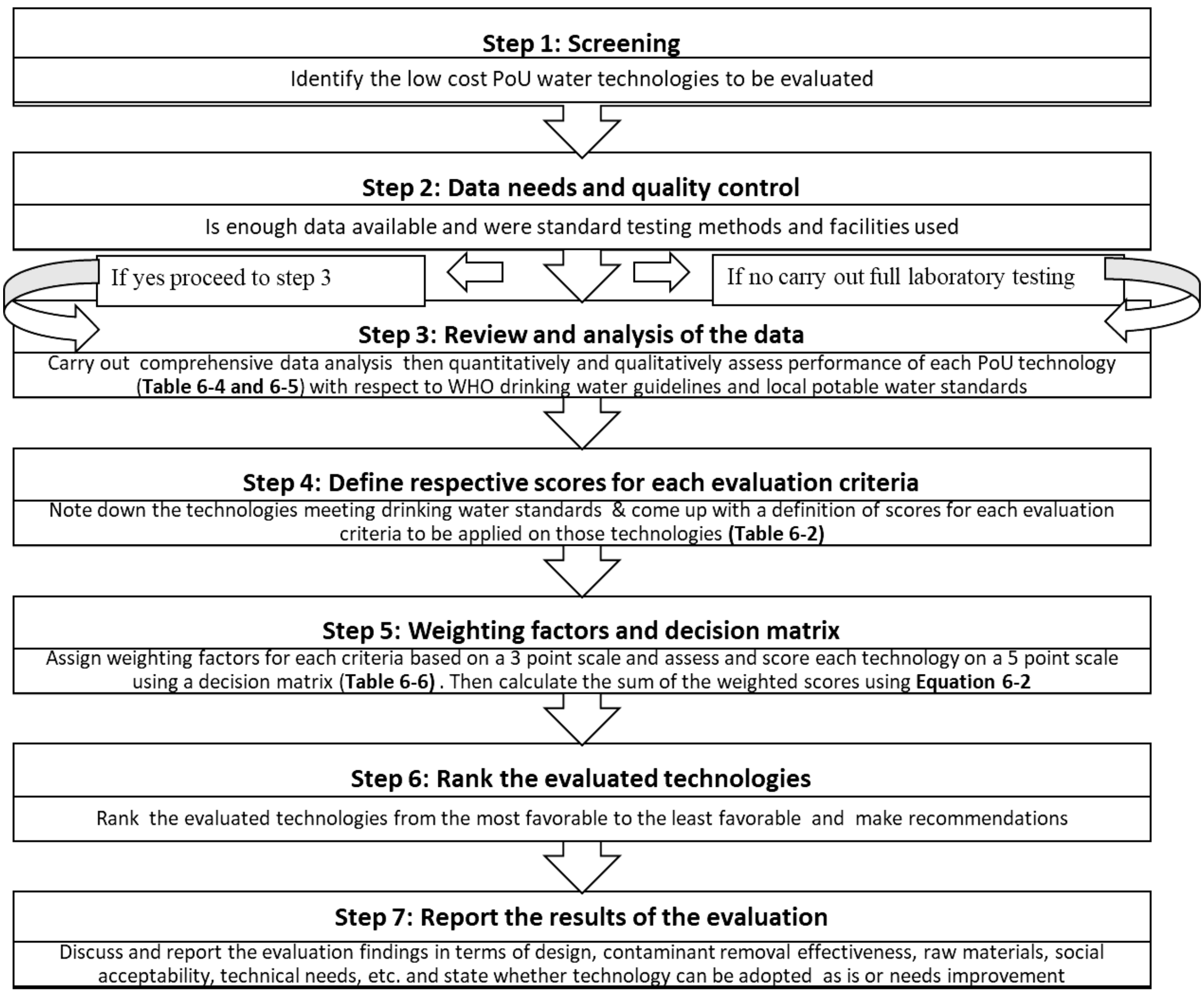

Figure 6-1: An overview of the specialized comparison framework evaluation procedure

RESULTS AND DISCUSSION

Description and analysis of the five point-of-use technologies

The individual PoU technologies which were evaluated are briefly discussed below in terms of system description, application, advantages, disadvantages, etc. The qualitative and quantitative comparative performance for each system is presented in **Tables 6-4** and **6-5**. For more information on each system, the reader is referred to the respective cited work.

Modified intermittently operated slow sand filtration system (ISSFGeoGAC)

Developed by the authors, ISSFGeoGAC (**Figure 6-2**) is a novel gravity-driven intermittently operated slow sand filter incorporating geotextile and GAC for removal of bacteria, particles, color, taste, odor and selected heavy metals (Siwila and Brink 2018b). It's gravity head is 10 cm. It uses fine sand of effective size (ES) = 0.16 mm and uniformity coefficient (UC) = 2.0 and depth of 14.5 cm. The coarse sand size is of ES = 0.30 mm and UC = 2.4 with a depth of 14.5 cm. The GAC is of depth 10 cm and gravel layer depth is 9 cm. During filtration, particles and pathogens are physically and biologically removed from water as it passes through the system. The key contaminant removal mechanisms which take place in the biolayer and within the filter body are trapping, predation, absorption and natural bacterial death (CAWST 2010). Filter mats have been included to serve as a pretreatment to enhance performance and reduce clogging.

The geotextile fabric also concentrates the major part of water purification within the mats and therefore less purification action happens within the sand (Graham and Mbwette 1987). The filter mats are also expected to extend filter run times and offer easy filter cleaning by removal and washing of the fabric alone as opposed to "scraping" or "swirl and dump" in ordinary ISSF systems (Graham and Mbwette 1987). GAC has been included to supplement adsorption capacity and allow removal of other contaminants, e.g., arsenic (As), cadmium (Cd), lead (Pb), mercury (Hg), iron (Fe) and manganese (Mn) (Siwila and Brink 2018b). The system has been designed to include the mentioned materials, to enhance performance so that the system is expected to improve water quality with respect to bacteria, acceptability aspects (turbidity, color, taste and odor) and the said heavy metals, thus increasing health benefits and filter run times, while minimizing the cleaning frequency.

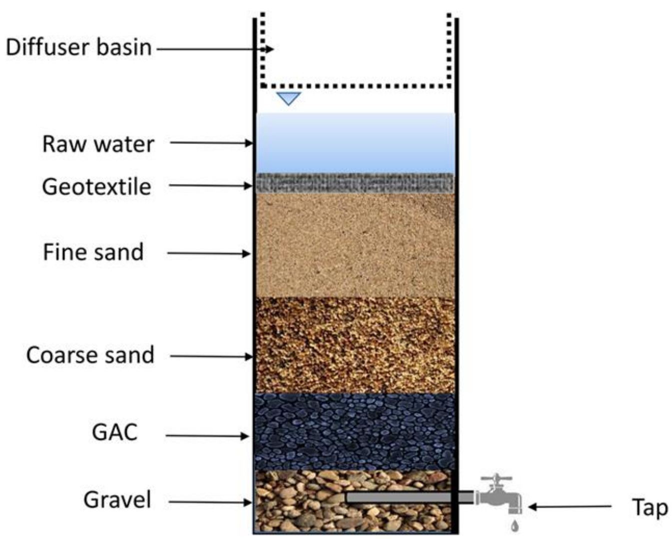

Figure 6-2: Schematic diagram of the ISSFGeoGAC filter system

Advantages

(i) easy to use, (ii) enhanced acceptability of treated water, (iii) can be produced locally, (iv) added benefit of removing heavy metals, (v) extended filter run times, (vi) reduced cleaning frequency and subsequent biolayer disturbance, (vii) uses local and easily accessible materials, (viii) low-cost, (ix) gravity driven, and (x) it is replicable.

Limitations

(i) No protection against recontamination except if treated water is safely stored, (ii) periodical replacement of GAC attracts some running costs, and (iii) relatively heavy for distribution.

Sequential bidim filtration system (BidimSEQFIL)

The sequential bidim filtration system (**Figure 6-3**) is an optimized fabric filtration method developed by the authors for low-cost water treatment (Siwila and Brink 2018c). The optimized 8-layer four-pot sequential filtration method using Bidim A8 can produce very clear drinking water of reasonable quality (0-10 CFU/100 ml *E.coli* levels) that may be consumed as is (CAWST 2013; Harvey 2007; Siwila and Brink 2018c; WHO 1997). Bidim A8 has an average pore size of <75 µm (Kaytech Engineering 2018) and layer thickness of about 6 mm (Siwila and Brink 2018c). The fabric costs about 1.76 US$/m^2. It is a nonwoven, engineered fabric, continuous filament, needle punched "food grade" geotextile manufactured by Kaytech Engineering, South Africa. It is normally applied in hydraulic applications such as for erosion control, filtration and drainage, hydraulic and retaining structures, water and waste containment and as a turbidity curtain during bay constructions (Kaytech Engineering 2018). As water is filtered through the first to fourth pot set (**Figure 6-3**), impurities (bacteria, turbidity and suspended solids) are removed. Clean water is stored and obtained from the fourth pot. When pores become clogged the bidim fabrics needs to be washed. The fabric can be easily removed and washed to remove trapped dirt thereby ensuring adequate flow rates.

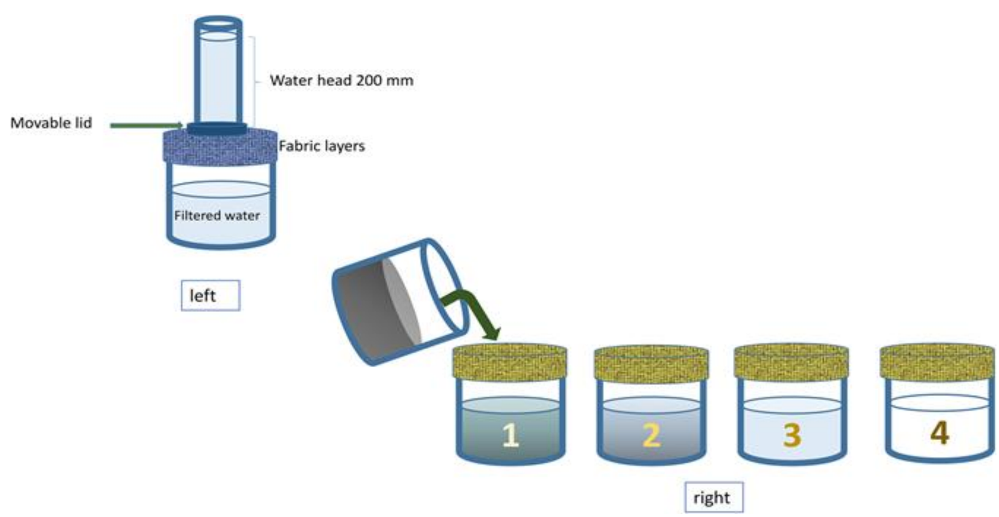

Figure 6-3: General filtration Setup with movable lid for flow rate measurement (left); four-pot Sequential Filtration (right)

Advantages

Bidim has comparative advantages for drinking water treatment over cloth fabrics as it is stronger and can be reused more often with less cleaning needs. BidimSEQFIL can substantially remove indicator bacteria up to 3 LRV. This is much better than both ordinary fabric filtration and three-pot settling methods. The fabric is easy to wash without significant fabric loosening by normal hand wash. It can be disinfected in ordinary utility ovens at around 100 to 200ºC and is structurally stable up to 200ºC (Kaytech Engineering 2018).

Limitations

(i) Relatively laborious compared to other filtration methods, (ii) periodical washing of the bidim fabric, (iii) user training on how to correctly use and maintain the technology is vital, and (iv) the fabric may not be easily accessible in some rural areas.

Wood filtration combined with GAC (WFSGAC)

WFSGAC (**Figure 6-4**) is a novel low cost gravity-driven drinking water technology developed and optimized by Siwila and Brink (2018d). The system uses 2.54 cm long wood filter elements of 2.54 cm diameter from indigenous tree species coupled with GAC for PoU water treatment under a 2.6 m gravity head. During operation, peeled wood filters are firmly clamped in a 10 cm flexible pipe which is then connected to the end of the 200 cm flexible pipe via connectors (**Figure 6-4**). The system uses about 80 g GAC normally reused during wood filter replacement. It is fed with raw water from a Perspex column, 60 cm long and of 10.5 cm diameter. The combined system consistently produces very clear drinking water of turbidity (<5 NTU) with pleasant color, odor and taste. When tested using *Combretum erythrophyllum* (umhlalavane) and *Salix mucronata* (Umzekana) tree species, it recorded 100% removal for indicator bacteria. The combined system can also significantly remove heavy metals: Fe, Pb, Nickel (Ni), Aluminium (Al) and Zinc (Zn) above 90%, and: Copper (Cu), As, Chromium (Cr), Cd and Mn above 50%.

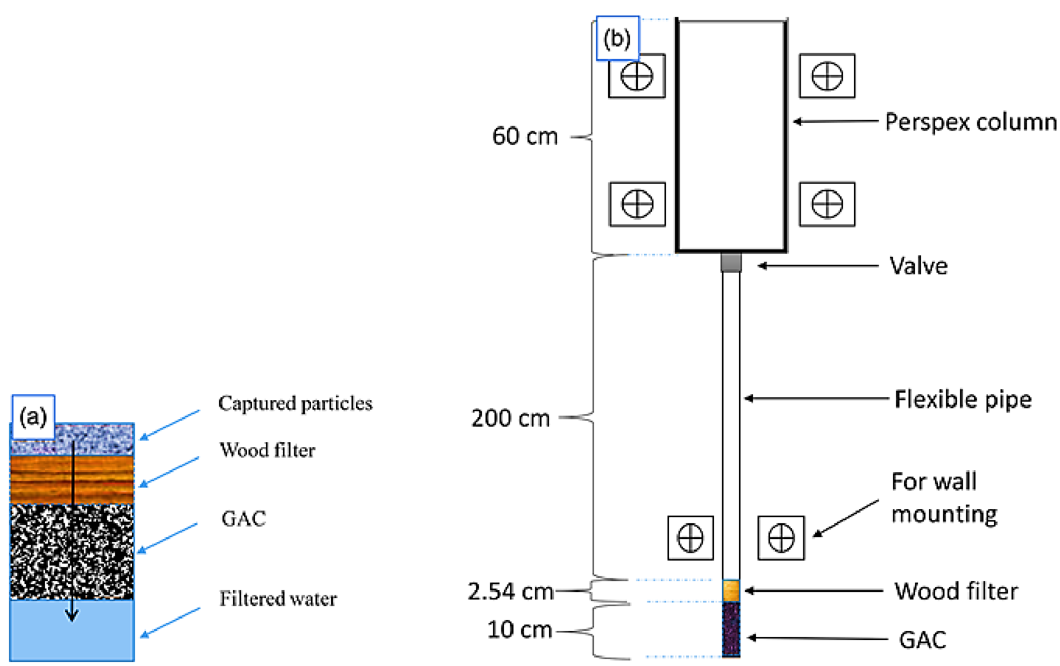

Figure 6-4: Combined wood and GAC filtration: (a) process schematic diagram, and (b) designed filter system

Advantages

(i) Made from small easily replaceable wood pieces, (ii) locally available, (iii) easy to fabricate, (iv) wood is a renewable material, (iii) significant bacterial and particle removals, (iv) significant improvement in treated water's acceptability aspects, and (iv) added benefit of heavy metal removal.

Limitations

(i) Relatively laborious to operate and maintain, (ii) low flow rates, (iii) user training on how to correctly cut, preserve and fix the wood pieces is necessary, and (iv) potential of introducing harmful substances into the water especially if the GAC malfunctions.

The Drip filter system (DFS)

Distributed under the name DrinC, the DFS (**Figure 6-5a**) is a low-cost, ceramic candle filter system. The filter is normally wedged between two 20 L buckets and has a 0.2 µm, silver-impregnated ceramic shell containing activated carbon (DrinC 2017). The treated water gets disinfected through contact with silver. The ceramic candle is sometimes covered with a filter sock to trap some particles and larger debris (e.g. leaves and insects) from the raw water. Particles and debris are removed, followed by microbes down to 0.2 µm as water flows through the system. Raw water from the top bucket drips through the ceramic candle into the bottom bucket, fitted with a tap for drawing drinking water. According to DrinC (2017), the candle filter must be replaced after one year's use. It is advisable to shake it every 3 months to dislodge debris and prolong its life and ensure that the carbon stays loose. Furthermore, the activated carbon lasts for about 6 to 8 months. The system flow rate can be up to 318.24 L/day, when the system is new, but it falls over time (Siwila and Brink 2018a). The DFS costs around 600 South African Rand (ZAR) (44 US$) within South Africa.

Advantages (DrinC 2017; Siwila and Brink 2018a)**:**

(i) High user acceptability due to ease-of-use, simple installation and significant visual improvement in treated water, (ii) high bacterial and particle removal, (iii) long lifespan if filter remains unbroken, and (iv) can yield clean water for a long time if properly maintained.

Limitations (DrinC 2017; Siwila and Brink 2018a)**:**

(i) User education is needed to keep the filter and receptacle clean, (ii) ongoing technical support needed, (iii) may not be useable with very turbid waters due to potential clogging problems, (iv) lack of residual protection can lead to recontamination, and (v) continuing user education is needed.

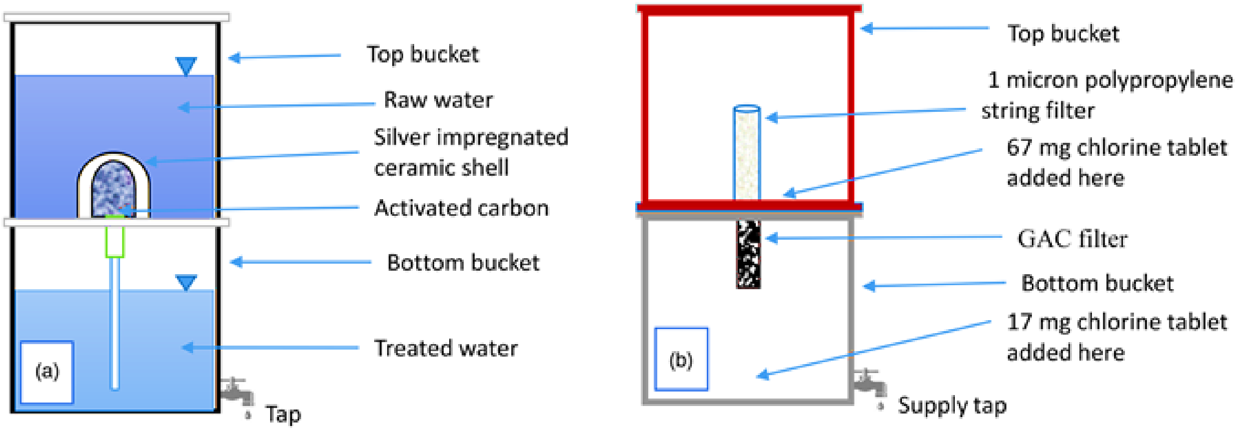

Figure 6-5:PoU system schematic drawing: (a) DFS and (b) GWS

The gift of water system (GWS)

The GWS (**Figure 6-5b**) is a low-cost PoU technology primarily developed to combat water-borne diseases and health related problems in Haiti (Gift of Water Inc. 2017). The two-bucket system employs a 1 micron (μm) string filter, a GAC filter and Aquatabs. Aquatabs are chlorine tablets made of Sodium Dichloroisocyanurate (NaDCC) which dissolves in water to release hypochlorous acid (HClO) that disinfects the water (CAWST 2011; WHO 2003). A 20 L top bucket, with a 67 mg Aquatab tablet, is filled with raw water and left for 30 minutes. Then a 17 mg Aquatab tablet is added to the bottom 20 L bucket for post-chlorination, to prevent recolonization by most bacteria (Siwila and Brink 2018). Placing the top bucket on the bottom bucket activates a check-valve. This enables water to flow into the bottom bucket, moving in transit via the string and GAC filters. The string filter removes particles and larger microbes like protozoa, while the GAC filter removes organic compounds and excess chlorine (Gift of Water Inc. 2017). Users obtain treated water through a tap fixed near the base of the bottom bucket. Gift of Water Inc. (2017) recommends replacing the carbon filter every 6 months. The GWS system costs 25 US$ in the USA, and its estimated flow rate is 1123.2 L/day (Gift of Water Inc. 2017).

Advantages (Gift of Water Inc. 2017; Siwila and Brink 2018a)**:**

(i) Includes a string filter able to pre-treat turbid water, (ii) high bacterial elimination, (iii) chlorine concentration remains high enough to prevent recontamination, (iv) can yield safe water for a long time, and (v) user acceptability due to ease-of-use, fast filtration rate and acceptable taste.

Limitations (Gift of Water Inc. 2017; Siwila and Brink 2018a)**:**

(i) High initial costs due to shipping requirements, (ii) continuing user education needed, (iii) ongoing technical support needed, (iv) ongoing maintenance costs, (v) concerns about potential long-term carcinogenic effects of disinfection-by-products, and (vi) need for regular filter replacement.

Comparison and evaluation of the PoU technologies

This section gives a comparative analysis of each system based on the comparison framework. Although the comparative analysis of the drinking water technologies shows that none can totally remove all pollutants (**Table 6-4**), they can all improve drinking water security in many parts of the world. It is necessary to appreciate that most PoU technologies are normally not meant for removal of chemicals

(Siwila and Brink 2018a). This may not be ideal everywhere but there is enough room for improvement particularly on the three novel technologies.

Removal of indicator bacteria

All of the five evaluated PoU technologies can remove over 96% of *E.coli* and *fecal coliforms* from water **(Table 6-4).** Only GWS, DFS and WFSGAC can completely eliminate indicator bacteria. With proper technology use and maintenance, these may affordably supply safe water in various settings. Long term sustainable bacterial removals are technically more assured for GWS due to the use of chlorine tablets in both the top and bottom buckets. The drawback with GWS is the potential for the production of disinfection-by-products and objectionable taste especially if the GAC, which removes excess chlorine, fails during use (Siwila and Brink 2018a). Bacterial diseases (Cholera, Acute Bacterial Gastro Enteritis, Dysentry, Meningitis, Typhoid, etc.) cause the most deaths. According to WHO (2016), about 502000 diarrhoea deaths occur each year in much of the developing world due to consumption of contaminated water. This is roughly 58% of the total deaths caused by poor water, sanitation and hygiene as a whole (WHO 2016). Therefore, the first and most important step in the battle against consumption of contaminated water is removal of all bacteria (McAllister 2005) and improvement of acceptability aspects of water, so that users do not opt for water that is more appealing but is actually unsafe (CAWST 2017; Siwila and Brink 2018a; WHO 2017a). Removal of other contaminants (viruses, chemicals, heavy metals, etc.) can be considered based on resource availability and technology advancement (McAllister 2005) as well as some regional needs or situational analysis.

Improvement of acceptability aspects of water

Another important consideration in evaluating performance of PoU drinking water systems is the ability to improve the acceptability aspects of water (suspended solids, turbidity, color, odor and taste). Poor acceptability of water can lead to indirect health impacts if consumers lose confidence in the treated water and drink less water or opt for options that may not be safe (McAllister 2005; Sullivan *et al.* 2005; WHO 2017a). All the five evaluated PoU technologies can substantially improve the acceptability aspects of water (**Table 6-5**). The best performance in this regard was depicted by ISSFGeoGAC, WFSGAC and DFS **(Table 6-5).** For ISSFGeoGAC this is most probably due to combined removal mechanisms as highlighted earlier. Whereas for WFSGAC the excellent improvement in the acceptability aspects could be due to the low flow rates (**Table 6-4**) provided by the wood filter elements and subsequent large empty bed contact time > 20 min (Siwila and Brink 2018d). Likewise, DFS exhibits relatively low flow rates (**Table 6-4**) allowing more contact time between water and the GAC.

Heavy metal removal

Table 6-4 shows that ISSFGoeGAC, WFSGAC and DFS can appreciably remove heavy metals. Although heavy metal removal may still be enhanced, it is an added benefit and may make the PoU systems more feasible in many places. It is perceived that due to presence of GAC, the GWS is likewise able to remove heavy metals. BidimSEQFIL may not remove metals due its material combination. Generally, heavy metal removal without inclusion of advanced processes or adsorption materials e.g. GAC is difficult for most low-cost methods.

Table 6-4: Quantitative comparison of the PoU water treatment systems

PoU Technology	E.coli removal(%)	Fecal coliforms removal (%)	Turbidity removal (%)	TSS removal (%)	Heavy metal removal (%)					Flow rate (L/day)		Cost (US$)		Reference
					As	Cd	Pb	Fe	Mn	Max	Min	Capital	Operation (per m^3)	
ISSFGeoGAC	96	96	89-100	87-100	30	94	63	71	94	242	152	24	0	(Siwila and Brink 2018b)
BidimSEQFIL	99.9	99.9	95	95	d.n.a	d.n.a	d.n.a	d.n.a	d.n.a	4416	n.t	1.76/m^2	0	(Siwila and Brink 2018c)
WFSGAC	100	100	100	100	65	74	94	99	n.d	7.6	3.6	<0.5	<0.1	(Siwila and Brink 2018d)
GWS	100	100	61-97	66-99	d.n.a	d.n.a	d.n.a	d.n.a	d.n.a	1123	480	25	1.25	(Gift of Water Inc. 2017; Siwila and Brink 2018a)
DFS	100	100	82–99	83-100	99	d.n.a	98	96	d.n.a	318	82	44	0	(DrinC 2017; Siwila and Brink 2018a)

n.d = not detected; d.n.a: data not available, 0 = no running costs, n.t = not tested

Flow rates

With the exception of the WFSGAC, all the evaluated technologies can treat water >240 L/day **(Table 6-4)**. This is satisfactory for point-of-use purposes in homes or small settings such as health centers, schools, etc. (WHO 2016). Though flow rates for WFSGAC may not deliver enough drinking water for a small setting, it can meet drinking water needs for a couple of people, the more so if two or three systems are run in parallel (Siwila and Brink 2018d). According to The Sphere Project (2011), basic water needs are about 7.5 to 15 liters/capita/day. Therefore, all the evaluated systems with exception of WFSGAC can meet basic water needs. However, if a few units are operated in parallel WFSGAC may also meet basic water needs (Siwila and Brink 2018d).

Table 6-5: Qualitative comparison of the PoU water treatment systems

PoU Technology	Locally Made	Ease of use	Improvement of acceptability aspects				Material Availability		Environmental Impact
			turbidity	color	taste	smell	Urban areas	Rural areas	
ISSFGeoGAC	yes	3	5	5	5	5	4	3	3
BidimSEQFIL	yes	2	5	3	4	3	4	2	4
WFSGAC	yes	2	5	5	5	5	3	5	3
GWS	no	3	4	3	4	4	3	2	3
DFS	yes	4	4	4	4	5	3	2	3

5 = excellent; 4 = good; 3=average; 2 = poor; 1 = bad

Quantitative and qualitative comparison

The comparison framework decision matrix (**Table 6-6**), qualitative comparison (**Table 6-5**) and quantitative comparison (**Table 6-4**) clearly show that all the PoU technologies are viable for adoption depending on a combination of most desired and least desired factors. Good judgement by the engineers or implementers is henceforth critical for a PoU technology to be adopted or further improved. The specialized comparison framework is useful to low cost PoU water treatment implementers to determine the level to which a PoU technology is suitable in relation to other viable options. The weighted scores indicated that the five evaluated technologies can be ranked from most promising to least promising as follows: (1) ISSFGeoGAC, (2) DFS, (3) GWS, (4) BidimSEQFIL, and (5) WFSGAC. Therefore, DFS ranked higher than GWS between the commercial PoU systems this is especially true in relation to sub-Saharan Africa due to the shipping cost associated with GWS. The ISSFGeoGAC is the best option amongst the three novel technologies though it still requires further optimization in terms of ease of use, ease of deployment and cost (all these factors are mainly dependent on system configuration and material combination). The WFSGAC is least favorable due to the observed very low flow rates while BidimSEQFIL is relatively laborious.

Table 6-6: Comparison framework decision matrix

	Criteria scores for comparison of the PoU water treatment technologies												
	Performance	*Ease of use*	*Water throughput*	*Acceptability potential*	*Energy requirement*	*Cost*	*Ease of deployment*	*Durability*	*Maintenance*	*Environmental impact*	*Supply chain*	*Comparative score*	
Weighting factor⇨	*3*	*3*	*2*	*3*	*3*	*2*	*2*	*2*	*2*	*1*	*1*	*unweighted*	*weighted*
ISSFGeoGAC	*5*	*3*	*4*	*4*	*5*	*3*	*3*	*4*	*4*	*3*	*4*	*42*	*94*
BidimSEQFIL	*3*	*2*	*4*	*2*	*5*	*4*	*4*	*4*	*3*	*4*	*4*	*39*	*82*
WFSGAC	*5*	*2*	*2*	*2*	*5*	*4*	*2*	*3*	*3*	*3*	*3*	*34*	*76*
GWS	*5*	*3*	*4*	*3*	*5*	*3*	*4*	*4*	*3*	*3*	*3*	*40*	*90*
DFS	*5*	*4*	*3*	*4*	*5*	*3*	*4*	*3*	*3*	*3*	*3*	*40*	*92*

Evaluation criteria: 5 = excellent; 4 = good; 3=average; 2 = poor; 1 = bad

Weighting factors: 3 = most critical; 2= moderately critical; 1 = least critical

Evaluated novel PoU technologies: potential for adoption

The novel technologies were comparatively ranked from best to least promising as shown in **Figure 6-6**. The advantages and limitations of each evaluated low-cost and non-advanced PoU technologies have been highlighted. The ISSFGeoGAC was found to be the most promising amongst the three novel technologies. Further optimization of such a combined system might result in an efficient and user friendly PoU technology useful to many communities and situations. The weighted scores were principally based on **Table 6-2** definitions, comparisons in **Tables 6-4** and **6-5,** process and material combinations of each evaluated system, and reports by various researchers (most of which are referenced in **Table 6-1**) as well as the author's experience during the technology installations and application tests.

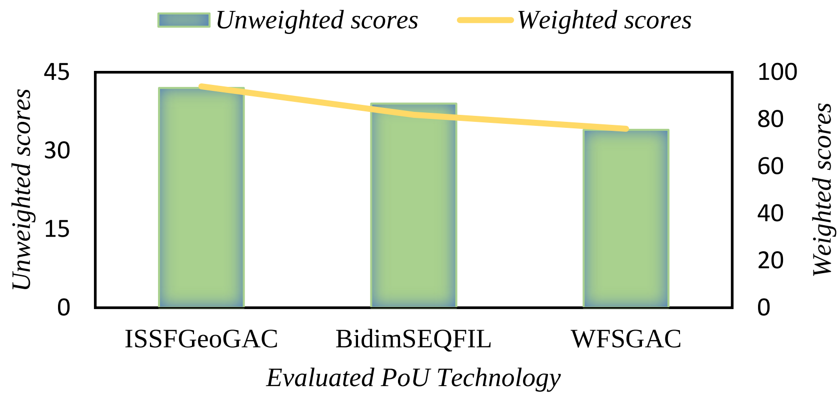

Figure 6-6: The evaluated novel technologies comparatively ranked from best to least promising (left to right)

CONCLUSIONS AND RECOMMENDATIONS.

The ISSFGeoGAC has been identified as the most viable for adoption amongst the three novel technologies. This is because of its simple and robust design coupled with contaminant removal effectiveness, raw material availability and acceptability of its treated water. The novel technology can be adopted as is, but further improvement is suggested. The proposed improvements include addition of a treated water storage compartment and an inbuilt disinfection step to prevent recontamination. Improper storage of treated water has been reported to cause recontamination (Curry *et al.* 2015; Potgieter *et al.* 2009; Jagals *et al.* 2003). The two commercially available PoU systems evaluated have shown similar performance and acceptability potential. These may help improve water security in much of the third world, especially if manufactured locally and materials (spare parts, chemicals, etc.) are guaranteed near or around the places of use. In general, the novel low-cost water treatment systems can reduce (≥87%) particles and eliminate (≥ 96%) *E.coli* and *fecal coliforms* from drinking water by physical, biological, adsorption, and chemical processes or a combination thereof. Performance depends largely on filter media, pore sizes and additional treatment processes.

Although it is difficult to choose which type of PoU technology is best for all applications due to many factors required for different situations and resource availability, this study has demonstrated that it is possible to qualitatively and quantitatively compare low-cost PoU technologies. If resources allow, each technology being comparatively evaluated should be tested under similar conditions e.g. using same test water characteristics and all three test organisms recommended by the WHO evaluation scheme and those proposed in this study. A combination of lab and field testing to ascertain removal performance sustainability and other criteria e.g. flow rates, social acceptability and maintenance requirements is recommended. Although research outcomes for improving safe water needs in poor communities are primarily met by development of novel low-cost drinking water systems, field testing helps to establish suitability and sustainability of novel technologies in satisfying the needs of intended users. Adequate training is also proposed wherever the evaluated technologies are to be used so that users can correctly use and maintain the devices.

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Chapter 7: A novel low-cost multi-barrier system for drinking water treatment in rural and suburban areas

This Chapter (together with Chapter 8) addressed the fourth study objective of this dissertation, which is "to develop, evaluate and optimize a combined PoU system with an inbuilt disinfection step coupled with a safe storage compartment to avoid chemical addition by prospective users."

The aim of this study was to develop a combined small-scale low-cost gravity-driven PoU system able to provide bacteriologically safe and aesthetically acceptable drinking water with an inbuilt disinfection step and a safe storage compartment to avoid chemical addition and recontamination respectively.

The knowledge gained in the investigations of Chapters 2, 3, 4 and 5 and comparison framework results in Chapter 6 led to the development of the novel combined PoU system presented in this Chapter. This system was chosen for optimization and for detailed modelling done in Chapter 8. It consisted of non-woven bidim geotextile fabric, SCCGM, GAC and a built-in safe storage compartment. It was developed and optimized to produce bacteriologically safe water at an optimized filtration rate of 2 L/h. SCCGM was used for filtration and inbuilt disinfection; and non-woven bidim geotextile fabric was used for pre-filtration (to remove the debris, larger microbes e.g. helminths and protozoa) and reduce particulate loads in the water before it passes through the SCCGM thereby increasing pathogen contact with the silver. This makes the raw water fit for silver disinfection and reduces clogging especially in that bidim geotextile is a robust fabric and can be easily washed by hand. Thus, for silver disinfection to be consistently effective, most of the particulates in the raw water need to be removed thereby necessitating adequate pre-filtration. GAC was used as an adsorption media for improving aesthetic aspects and possible removal of selected heavy metals. Since GAC was expected to be used for about 6 months and thereafter changed, it was decided to contain it in an easily removable side column fastened with clamps. The storage compartment was used for storing treated water to minimize recontamination and contained a tap near its base for drawing treated water. The lab tests showed high potential for significant *E.coli* and fecal coliforms removal (>99.99%) at an optimum flow of 2 L/h. The system exhibited substantial improvements of aesthetic aspects with average turbidity removals of 99.2% and removed selected heavy metals like iron (>97.6%) and manganese (>83.2%).

It should be noted here that ISSFGeoGAC was identified in Chapter 6 as the most promising PoU system with higher adoptability and acceptability potential amongst the three investigated novel technologies in Chapters 3, 4 and 5. This is because of its simple and robust design coupled with contaminant removal effectiveness, raw material availability and high acceptability of its treated water as well as potential for removal of selected metals. However, ISSFGeoGAC still had some limitations such as: (i) potential for recontamination due to absence of inbuilt safe storage, (ii) need for a properly managed biolayer and a pause period of up to 48 hours between filter runs for significant contaminant removals, (iii) need for further treatment by disinfection due to absence of an inbuilt disinfection step, (iv) difficulty of GAC replacement due to its placement under the sand body, (v) manual control of the standing water level which was rather laborious and posed threat to potential bio-layer drying out, and (vi) need for properly cleaned sand and recontamination potential is high if sand replacement is not done on time or if bacterial inactivation is insufficient (Zinn *et al.* 2018). The sand cleaning process may not be appealing to some users and clean water for cleaning the sand may not be readily available in some areas. Therefore, the combined system presented in this Chapter was designed, constructed and tested to address the highlighted problems.

A novel low-cost multi-barrier system for drinking water treatment in rural and suburban areas

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ABSTRACT

A low-cost multi-barrier drinking water system incorporating geotextile fabric for pre-filtration, silver-coated ceramic granular media (SCCGM) for filtration and disinfection, granular activated carbon (GAC) as an adsorption media and a safe storage compartment for treated water has been developed and tested. The developed system offers a novel concept of point-of-use drinking water treatment in rural and suburban areas of developing countries. The system is primarily aimed at bacterial and aesthetic improvement and has been optimised to produce >99.99% *E.coli* and fecal coliforms removal. Although particular emphasis was placed on the elimination of bacteria, improvement of the acceptability aspects of water was also given high priority so that users are not motivated to use more appealing but potentially unsafe sources. This paper discusses key system features and contaminant removal performance. A control system using SCCGM only was also tested alongside the multi-barrier system. Strengths and weaknesses of the system are also presented. Both the developed and control systems consistently provided >99.99% *E.coli* and fecal coliforms removal at an optimum flow of 2 L/h. The developed system significantly recorded improvements of aesthetic aspects (turbidity, color, taste and odor). Average turbidity removals were 99.2% and 90.2% by the multi-barrier and control systems respectively.

Key words: aesthetic aspects, bacterial removal**,** drinking water, combined system, silver-coated granular media

INTRODUCTION

Access to safe drinking water is often limited in rural and suburban areas of developing countries (Chaudhuri and Sattar 1990; Savage 2018; Supong *et al.* 2017). Safe piped water is sometimes unavailable in such settings and many water sources contain pathogens (Chaudhuri and Sattar 1990). Mortality rates from contaminated water are correspondingly high, with communicable diseases a threat (Demena *et al.* 2003; Eitner and Kondruweit-Reinema 2019). Governments in the developing world struggle with inadequate resources and infrastructure to meet drinking water needs for all citizens (Savage 2018). Some people have to walk long distances to find drinking water (Savage 2018). Point-of-use (PoU) drinking water treatment technologies are the most feasible solution to fight waterborne diseases in many rural and suburban areas (Kausley *et al.* 2018). A number of PoU systems exist for treating various types of raw water but are expensive and often unsuitable in poorer communities (Chaudhuri and Sattar 1990; Kausley *et al.* 2015; McAllister 2005). This is particularly true for systems based on advanced technologies like ozonation, ion exchange, reverse osmosis, ultrafiltration membranes, etc. (de Moel *et al.* 2007; Gadgil 1998; Lykins and Clark 1992; Pizzi 2010; Ritter 2010; WHO 2017a, 2016a). These normally require electricity and adequate tap water pressure, which are often unreliable or absent in rural and many suburban areas. They are generally costly to run and difficult to operate and maintain (Kausley *et al.* 2015; Kim *et al.* 2016).

There is therefore a need to develop sustainable, affordable, grid-independent, low maintenance, and easy to use point-of-use (PoU) water treatment technologies to provide comparably safe drinking water in poor communities of developing countries (Kausley *et al.* 2015; Supong *et al.* 2017). This study was aimed at developing a multi-barrier low-cost small-scale, gravity-driven PoU system able to provide potable and aesthetically acceptable water with an inbuilt disinfection step. The developed system consists of geotextile fabric for pre-filtration (to significantly reduce the particulate loads in the water before it passes through the silver-coated ceramic granular media (SCCGM) and increase pathogen contact with the silver), SCCGM for filtration and inbuilt disinfection and granular activated carbon (GAC) as an adsorption media for improving aesthetic aspects (color, taste, odor) and possible removal of some heavy metals. No chemical addition is needed. It is a user and environmentally friendly low-cost technology primarily for particle and bacterial removal and aesthetic improvement. The pre-treatment by geotextile is expected to enhance the ability of the system such that it may treat a broader variety of raw water. According to Tobiason *et al.* (2011), adding a pre-treatment and/or post-treatment step extends filter runs and enhances the performance of filter systems. Additionally, for silver disinfection to be consistently effective, the debris and most suspended particles in the raw water need to be removed thereby necessitating adequate pre-filtration.

The adequacy of a PoU water treatment system is determined by how well it can maintain or improve aesthetic aspects of water (Gadgil 1998; WHO 2017b). This is important so that users do not opt for aesthetically appealing alternatives which may be contaminated (CAWST 2017; Gadgil 1998; Sullivan *et al.* 2005; WHO 2017b). Although the system was primarily designed and optimised for bacterial removal and aesthetic improvements, an attempt was made to assess possible removal of heavy metals. The heavy metals assessed for removal were iron (Fe), manganese (Mn), cadmium (Cd), mercury (Hg) and lead (Pb). Iron and manganese affect the acceptability of water by imparting color and taste and their removal is therefore important where they occur. Cd, Hg and Pb are amongst the most common environmental pollutants and are toxic (Turkez *et al.* 2012). Other metals tested were Aluminium (Al), Chromium (Cr), Copper (Cu), Nickel (Ni) and Zinc (Zn). According to various authors (see Binnie and Kimber 2013; Mihelcic *et al.* 2009; Pizzi 2010; Siabi 2003), these can potentially be removed by GAC.

SCCGM is a promising novel clay based filter media produced by TAM ceramics in Niagara Falls, N.Y (TAM ceramics 2019). At an optimal flow rate, it is able to disinfect water through contact with silver. Pending determination of the actual price, there is an assurance that the cost of the SCCGM will be inexpensive (TAM ceramics 2019). In addition, the goal of TAM ceramics (2019) is to eventually have the SCCGM produced locally from existing raw material sources in sub-Saharan Africa and elsewhere when demand is established. TAM ceramics anticipates SCCGM life expectancy to be substantial depending on use and overall water quality. Their aim is to achieve a 10 year life expectancy (TAM ceramics 2019). The pre-filtration geotextile used in this study costs about 1.76 US$/m^2 (Kaytech Engineering 2018). It is a nonwoven continuous filament, needle punched "food grade" fabric manufactured by Kaytech Engineering, South Africa. The engineered fabric is normally applied in hydraulic applications such as filtration and drainage, erosion control, water and waste containment, retaining and hydraulic structures, and as a turbidity curtain during bay constructions (Kaytech Engineering 2018). The GAC used was ProCarb-900 produced by Rotocarb South Africa with an effective size of between 0.6 -1.0 mm and costs < 2.5 US$/kg (Rotocarb 2018).

The closest documented alternative technologies to the designed multi-barrier system are the ceramic pot filters (CPFs), ceramic candle filters (CCFs) and bio-sand filters (BSFs). These are generally made of low-cost materials. CPFs and CCFs are specifically designed for low-income settings (CAWST 2011), however they are easily breakable, they clog quickly, and their pathogen removal performance is often poor (Kausley *et al.* 2015; 2018). BSFs are a promising technology for providing drinking water to poor communities, but have various limitations such as (CAWST 2011, 2010; Lantagne *et al.* 2006; Singer *et al.* 2017): (i) there is need for bio-layer growth and for its proper management, (ii) there is need for a 30 day waiting period for the bio-layer to develop to maturity before significant pathogen removals, (iii) without a pause period bacterial removal rate is low, (iv) aesthetic improvement in the treated water is inconsistent (v) virus removal is ineffective, (vi) scraping or "swirl and dump" cleaning techniques are quite tedious and, (vii) after surface maintenance the filter takes some time before recovery in flow rate and bacterial removal efficiency (Singer *et al.* 2017).

Boiling is another low-cost alternative and destroys nearly all pathogens. However, it uses a lot of energy (charcoal, wood or electricity), does not improve aesthetic aspects of water and can be laborious if done daily over longer periods (Backer 2000; Kausley *et al.* 2018). The other effective low-cost water treatment method is the use of chlorine tablets or liquids to disinfect water. However, these (Backer 2000; Harvey *et al.* 2019; Kausley *et al.* 2015, 2018; Lantagne *et al.* 2006; Supong *et al.* 2017): (i) are not effective against protozoan cysts, (ii) require some level of education to ensure correct dosing, (iii) often impart unpleasant taste and odour to the water, (iv) generally require water of low turbidity and organics to be effective and (v) have potential for carcinogenic effects due to disinfection by-products especially if continuously overdosed (Kausley *et al.* 2018, Lantagne *et al.* 2006).

Solar disinfection is another low-cost water treatment alternative. Plastic bottles are filled with water and exposed to sunlight for about six hours (CAWST 2011; Harvey *et al.* 2019; Kausley *et al.* 2018). However, the method has limitations such as (CAWST 2011; Kausley *et al.* 2018; Lantagne *et al.* 2006): (i) they are only effective on clear water (water that is slightly dirty has to be pretreated), (ii) treats small volumes of water about 0.25 – 5 L over a long waiting period (Kausley *et al.* 2018), (iii) needs a continued supply of clean, intact and properly sized plastic bottles, and (iv) depends on sunshine intensity and differs across regions and seasons.

The most significant drinking water problem in many rural and suburban areas of developing countries is the prevalence of pathogenic contamination from poor sanitation, resulting in frequent waterborne disease outbreaks (Harvey *et al.* 2019; Kausley *et al.* 2015; Supong *et al.* 2017). Many of these communities do not have access to safe drinking water supplies and fecal contamination is widespread (Gadgil 1998; Supong *et al.* 2017). Poor hygienic practices like open drainage systems, open defecation, careless garbage disposal, washing and bathing near or at the drinking water sources are highly prevalent (Kausley *et al.* 2015). Therefore, the first priority for PoU drinking water treatment in such settings is the effective inactivation of waterborne pathogens (Chaudhuri and Sattar 1990; Gadgil 1998; Kausley *et al.* 2015; McAllister 2005). Therefore, PoU systems with an inbuilt disinfection step such as the designed multi-barrier system may be more effective and attractive.

The multi-barrier system developed in this project is a promising and appropriate technology expected to affordably supply potable water in rural and suburban areas. It can be easily scaled up to any desired size. More so, when production of the disinfection media (SCCGM) is started near or around intended areas. Strengths and weaknesses of the system are presented in the results and discussion section to help potential implementers and users make informed decisions. Additionally, one of the key issues in the design of a water treatment system is the need to predict the performance of the system (Metcalf & Eddy 2014).

Therefore, the work presented in this paper was used as a basis for mathematical modelling of *E.coli* removal performance prediction to be published at a later stage.

MATERIALS AND METHODS

Setting

This study was conducted in the Water Quality Laboratory of the Department of Civil Engineering at Stellenbosch University in Cape Town, South Africa. Raw surface water samples were obtained from Kromrivier stream, at 33°55'34.68"S and 18°51'40.56"E, Stellenbosch, South Africa.

Study design and technical considerations

The designed multi-barrier system is 'on demand', such that it is operated intermittently when water for treatment is available. Although intended for about 5 to 10 users, it can be easily scaled up to serve e.g. 100, 1000, 2000 etc. persons or for institutional use e.g. in schools, clinics, refugee camps, etc. (TAM ceramics 2019). It is therefore expected to serve as a prototype. The research was conducted using the designed multi-barrier system and a control system (**Figure 7-1**). Affordability, user friendliness, easy engineering, easy maintenance, water safety and acceptability aspects were among key driving factors in the design.

The designed system (**Figure 7-1a**) comprises 86 mm internal diameter and 800 mm length upper and bottom reservoirs. A 200 mm long flexible pipe of 40 mm internal diameter connected the two reservoirs and housed the GAC. The underdrain system below the filter media consisted of an end plug with 1 mm drilled small holes and was inserted at the inside end of a pipe section which also had 1 mm drilled small holes (**Figures 7-1a**). This underdrain type is different from most low-cost filter systems, which use unperforated pipes with one open end in a layer of gravel below the filter media (CAWST 2010; NE-WTTAC 2014). It was expected to slow the flowrate and keep a more even distribution of flow through the SCCGM, thereby enhancing filter efficiency (NE-WTTAC 2014). Small pieces of cotton cloth were placed above and beneath the GAC filter column to ensure that any fines from the GAC did not clog the flow in the 40 mm side pipe. The whole system was disinfected using chlorine before introducing the filter media.

During operation, raw water first passed through 6 layers of geotextile fabric (each 6 mm thick and 75 μm pore size) where any debris (e.g. leaves and insects), suspended solids and larger organisms e.g. protozoa and helminths were removed. Thereafter, the water flowed through the SCCGM for disinfection and further filtration. The silver in the SCCGM served as a disinfection medium. The water then flowed into the bottom reservoir, passing in transit through the GAC filter. GAC removes color, odor and taste and is thought to augment turbidity removal. Since GAC was expected to be used for about 6 months and thereafter changed, it was decided to contain it in an easily removable column fastened with clamps. The bottom reservoir served as the safe storage compartment and contained a tap near its base for drawing water.

The control system (**Figure 7-1b**), used SCCGM only and consisted of top and bottom reservoirs 500 mm and 300 mm in height respectively. A removable screen was placed on the media surface and a fixed screen underneath the media. The surface screen prevented large particles from entering the filter bed. The bottom screen held the media in place and prevented particles from flushing out into the treated water. The control system design was recommended to serve as a cheaper alternative in places where the water contains waterborne pathogens but is aesthetically acceptable. Both systems were mounted to the laboratory wall and fed with polluted urban stream water. They were operated with 55 cm and 25 cm water head for the multi-barrier and control systems respectively.

The 20 cm depth for GAC was chosen based on Binnie and Kimber (2013) who recommended a 20 cm GAC layer for similar low loading rate filtration systems. The SCCGM bed height was 20 cm in both the designed multibarrier and control systems. The 25 cm water head for the control was calculated based on TAM ceramics (2019) who recommend the water column depth to be approximately 1.25 times the SCCGM bed height. Likewise, water head for the GAC was estimated to be 25 cm. The total water head for the multi-barrier system was then taken to be 55 cm to cater for SCCGM and GAC water column requirements as well as the head loss in the pipe fittings connecting the GAC column.

According to Harvey *et al.* (2019) and TAM ceramics (2019), SCCGM (**Figure 7-2a**) is manufactured by treating fired ceramic granules with silver solution and firing them again to bond the silver. The presence of bonded silver on the granules was confirmed using X-ray energy dispersive spectroscopy (**Figure 7-2b**). Triaxial diagrams e.g. **Figure 7-3** are proposed by (Harvey *et al.* (2019) and TAM ceramics (2019) to help in the design and optimization of filter systems using SCCGM. Depending on the design and size of the filter system, one can carefully select the filter media height, amount of silver and residence time. Therefore, within the working (shaded) area the values can be adjusted such that one can still get a viable filter (Harvey *et al*. 2019). Particle size distribution is another important variable in the filter system design and determines flow rate. Although not explicitly shown in the triaxial diagram (**Figure 7-3**), if the fine granules are insufficient the flow rate is very high and if coarse granules are insufficient the flow rate is too low. This is to a large extent taken care of by the residence time which is approximately equal to contact time in this case and is largely dependent on the flow rate and media depth (see **Equation 7-2**).

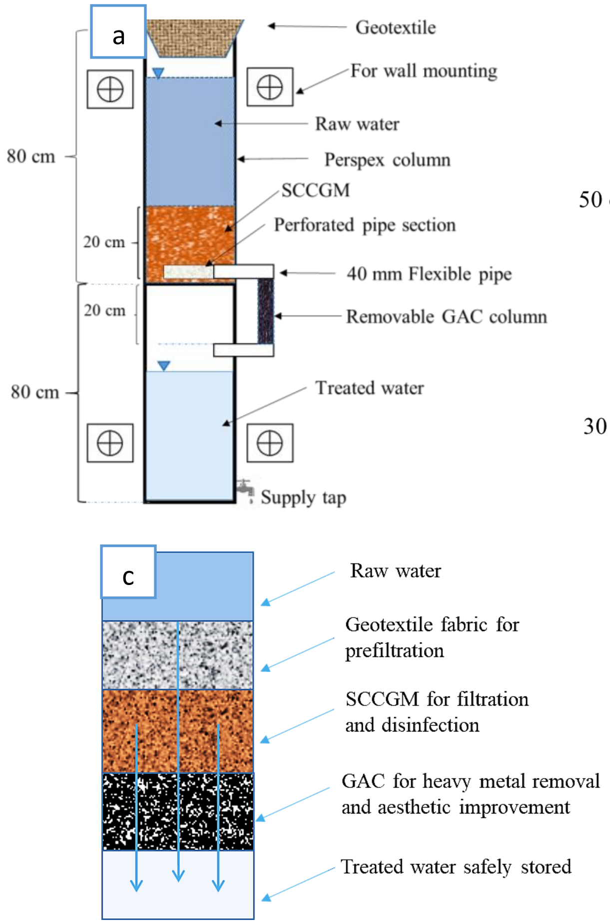

Figure 7-1: Novel filter system: (a) designed multi-barrier system, (b) control system, and (c) process schematic diagram

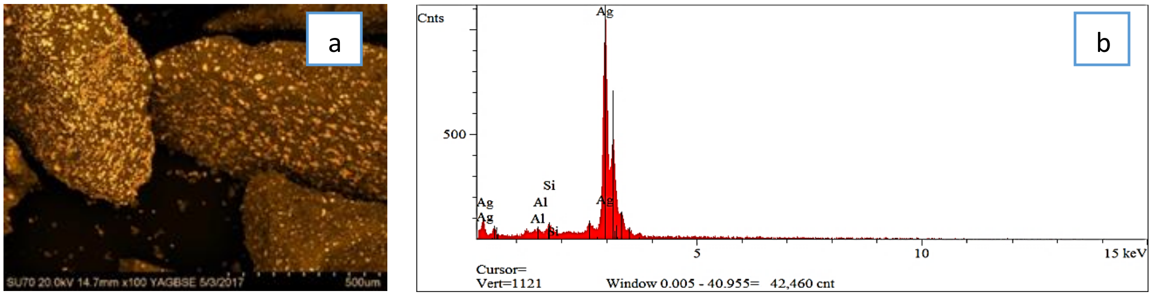

Figure 7-2: (a) Scanning electron micrograph showing silver deposits on SCCGM, (b) Energy dispersive spectroscopy X-ray spectrum showing localized silver deposits on a clay particle; source (TAM ceramics 2019)

The desired working area for the designed system are represented by the shading in **Figure 7-3** which is typical for most low-cost small scale PoU systems. The shaded area is adequate for a household system using (i) 20 to 50 cm media depth, (ii) 0.15 to 0.40 % weight percent of silver, and (iii) residence time of 0.4 to 0.7 hours. The values are read in a manner similar to the reading of basic soil texture classification triangles. A horizontal line is first drawn starting at the desired bed length. Then the other variables are read using slanted vertical lines drawn with respect to desired weight percent of silver and corresponding residence time. The numbers in this case are read in increasing order for each variable from left to right for the weight percent silver and bottom to up for the bed length and top to bottom for the residence time.

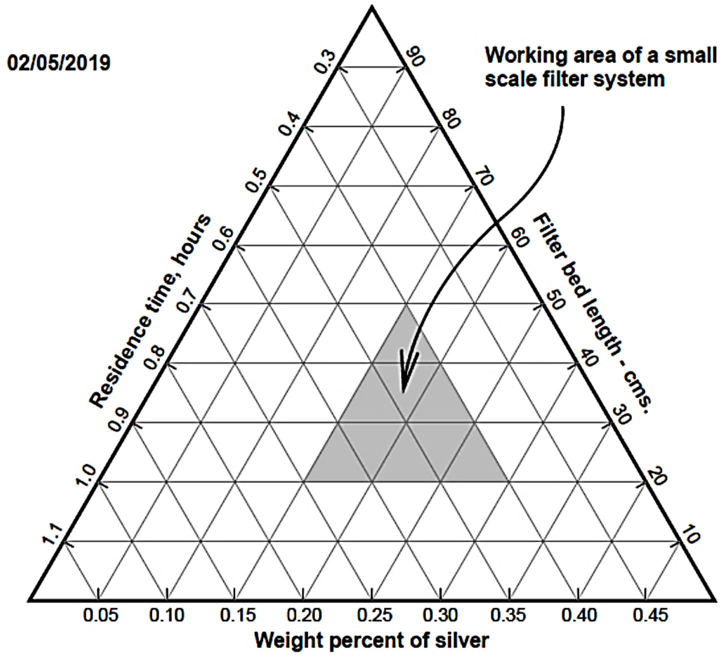

Figure 7-3: Triaxial diagram working area for the designed small scale PoU system

Flow rate measurement and sample collection

Flow rate was estimated for each system by recording the volume of water collected over a given time and using **Equation 7-1**. The flow rate measurements were done in triplicate for each system to ensure accuracy, then averaged for reporting purposes. The flow rate values were initially measured in mL/s and thereafter converted to L/h and were roughly within ±0.5 L/h.

$$Flow\ rate,\ Q = \frac{V}{t} \qquad \textbf{(7-1)}$$

Where: Q = flow rate (L/h); V=volume of filtered water (L), t = filtration time (hours)

The systems were flushed with distilled water during each run before start of testing until the discharge was clear to remove impurities. Sampling was done after at least 7.5 liters of water was passed through each system before sample collection **(Table 7-1)** during each run**.** Since the column reservoirs could not handle 7.5 L volume at once, they were filled to the maximum design head and water was added when the head was low enough to accommodate more.

Sampling was done at varied flow rates for the first 9 runs and at 2 L/h for the last 3 runs (**Table 7-1**). The first four runs for the multi-barrier system were done at maximum possible flow rate 10 L/h (**Table 7-1**). For the control system, only the first two runs were done at maximum flow rate 20 L/h (**Table 7-1**). Thereafter, flow rates at each run were controlled using the valve (supply tap) to obtain the desired value. The flow rates were varied from 10 L/h to 2 L/h and 20 L/h to 2 L/h for the multi-barrier and control system respectively (**Table 7-1**). Varying the flow rate was done to arrive at an optimal flow rate and yield varied contact time to provide data for further modelling in future research. The optimal flow rate in this case was the flow rate required to produce 0 CFU/100 ml for *E.coli* and fecal coliform in the effluent. Since the World Health Organization (WHO) guidelines and South African National Standards (SANS) 241 recommend 0 CFU/100 ml of both *fecal coliforms* and *E.coli* in drinking water **(Table 7-3**), flow rates where staggered from the highest obtainable by each system to an optimal 2 L/h were >99.99% removals of the indicator bacteria were consistently achieved. Three runs were thereafter done at 2 L/h flow rate to assess removal consistency.

Table 7-1: Flow rate used, and volume of water treated for each run

Run number	*Date of testing*	*Volume of water treated*	*Multi - barrier system flow rate (L/h)*	*Control system flow rate (L/h)*
1	*4/2/2019*	*7.5*	*10*	*20*
2	*4/2/2019*	*7.5*	*10*	*20*
3	*4/2/2019*	*7.5*	*10*	*15*
4	*4/2/2019*	*7.5*	*10*	*13*
5	*5/2/2019*	*7.5*	*8*	*8*
6	*5/2/2019*	*7.5*	*8*	*8*
7	*5/2/2019*	*15*	*7*	*7*
8	*6/2/2019*	*15*	*5*	*5*
9	*6/2/2019*	*15*	*3*	*3*
10	*11/2/2019*	*7.5*	*2*	*2*
11	*12/2/2019*	*7.5*	*2*	*2*
12	*13/2/2019*	*7.5*	*2*	*2*

Contact time estimation

Empty-bed contact time (EBCT) is a key factor in the performance of GAC and similar granular media (Binnie and Kimber 2013;Pizzi 2010). Sufficient contact time is also very important for adequate contact between the bacteria and the silver. EBCT at each flow rate was estimated using **Equation 7-2**.

$$EBCT = \frac{V_{media}}{Q_v} = \frac{V_{media}}{v.A} = \frac{h.A}{v.A} = \frac{h}{v} \qquad \textbf{(7.2)}$$

Where: EBCT = empty bed contact time (h); Q_v = flow rate (m^3/h); A = cross sectional area of GAC or SCCGM filter bed (m^2) of diameter d (m) $\left(A = \frac{\pi d^2}{4}\right)$; V_{media} = column volume occupied by GAC or SCCGM (m^3); v = filtration velocity (m/h); h = height of GAC or SCCGM bed (m)

Testing for contaminant removal

The following water quality parameters were analyzed during each sampling before and after filtration through each system: indicator bacteria (fecal coliforms and *E.coli*), turbidity, pH, electrical conductivity (EC), Dissolved oxygen (DO), color, odor, taste, and metals (Al, Cd, Cr, Cu, Fe, Hg, Pb, Mn, Ni, and Zn). Samples were analyzed immediately after collection to ensure accurate results. The bacteriological tests were done by the Water Analytical Laboratory (WALAB) accredited to the South African National Accreditation System (SANAS), No: T0375 for microbiological analysis. The accredited fecal coliform detection method used is the biochemical method, WAL M3. In this method fecal coliforms ferment lactose when incubated at 44.5°C for 24 hours to form blue colonies on m-FC agar containing aniline blue. m-FC Agar is a selective membrane filtration medium used for culturing and enumeration of fecal coliforms. Non-fecal coliforms will be colorless or various shades of cream or yellow. The accredited *E.coli* detection method used is the enzyme substrate, WAL M4. In this method, the membrane filter is transferred from the m-FC culture plate to a culture plate containing Nutrient Agar with MUG (4-methylumbelliferyl-ß-D-glucoronide) and is then incubated for two more hours. The presence of a blue fluorescence under longwave UV on the outer edge of a colony, is considered a positive response for *E.coli*. *E.coli* is therefore defined as any coliform that produces the enzyme ß-glucoronidase and hydrolyses the MUG substrate to produce a blue fluorescence around the periphery of the colony.

Metals were determined by the Central Analytical Facilities (CAF) of Stellenbosch University. The CAF analyses for major and trace elements using inductively coupled plasma mass spectroscopy (ICPMS) and Agilent 7900 as the analytical instrument. The Agilent 7900 is used for trace analysis for samples ranging from sub parts per billion (ppb) to mid parts per million (ppm) levels. Unknown samples are analysed against traceable standards and independent quality control solutions. Physico-chemical tests were done in the Civil Engineering Water Quality Laboratory at Stellenbosch University with the test apparatus being calibrated daily. Turbidity was measured using a handheld HI-93703 Microprocessor Turbidity Meter purchased from Hanna Instruments. pH was tested using pH Tester PH-107 a pocket-sized digital pH Meter. Conductivity and DO were measured using the Hach HQ440d benchtop Multi-Parameter Meter. All tests were done in accordance with the Standard Methods for the Examination of Water and Wastewater (APHA/AWWA/WEF 2012).

Treatment effectiveness calculations

Contaminant removal efficiencies for turbidity, *bacteria* and metals were calculated using **Equation 7-3*:***

$$contaminant\ removal\ efficiency\ (\%) = \frac{C_i - C_e}{C_i} X\ 100 \qquad \textbf{(7-3)}$$

Where: C_i *= influent contaminant concentration;* C_e *= effluent contaminant concentration*

It is worth noting that there were a number of cases in which metals tested < LoD in the raw water as well as in the designed (multi-barrier) and control system effluents. In such cases, the limit of detection (LoD) value was used in the calculation of percentage removals as an indicator of the minimum percentage removal of the system.

Statistical analysis

Statistical analysis was done using Tool Pak VBA, a statistical software add-in for Excel 2016 at 95% confidence level for all the 12 runs. Included in **Table 7-3** are the following statistical parameters: sample number (N), mean, range of values (minimum - maximum) and Standard error (SE) of the mean. SE refers to the standard deviation of the estimation of the mean for all the experimental runs (N = 12) (Montgomery and Runger 2018) and was used as a statistical measure of the accuracy of the mean. It provides a rough indication of the range within which the population mean is likely to fall. In Excel, the SE is calculated as the Standard Deviation (σ) divided by the square root of the sample size (N) (**Equation 7-4**) (Montgomery and Runger 2018).

$$SE = \frac{\sigma}{\sqrt{N}} \qquad \textbf{(7-4)}$$

Where: σ = Standard Deviation; N = sample size; SE = Standard error

The SE of the mean percentage metal removals were additionally calculated as described above. Here, the SE refers to the standard deviation of the estimation of the mean percentage removals (**Equations 7-3** and **7-4**) for all metal removals in all the experimental runs (N = 12) (Montgomery and Runger 2018) and was used as a statistical measure of the accuracy of the mean metals percentage removals.

RESULTS AND DISCUSSION

Aesthetic improvements: removal of Turbidity, color, odor and taste

There was substantial removal of turbidity from the raw water by both the designed and control systems particularly after the fourth run **(Figure 7-4)**. The results show that the designed multi-barrier system caused significant particle removals recording up to 99.9% turbidity removals. The multi-barrier system's effluent consistently met turbidity requirements for small water supply systems (WHO 2017b) and SANS 241 drinking water standard of ≤ 5 NTU. After the fourth run, at which point similar and lower flow rates were used for both systems, the control system recorded up to 95.5% turbidity removal. It also, thereafter, consistently met turbidity requirements of ≤ 5 NTU. Turbidity levels in the raw water were generally high and ranged from 40.3 to 77.7 NTU, with an average of 67.6 NTU (**Table 7-3**).

The multi-barrier system significantly improved the other aesthetic aspects (color, odor & taste) of water (**Table 7-3**) and performed much better than the control system in this regard. As previously mentioned, improving aesthetic characteristics of water is critical to the acceptability of a PoU drinking water system (CAWST 2017; McAllister 2005; WHO 2017b) and can increase the systems' potential to improve water security in many places (Mihelcic *et al.* 2009). If treated water displays objectionable levels of turbidity, colour, taste and odor, users may opt for alternative water sources which may be contaminated (CAWST 2017; McAllister 2005; Sullivan *et al.* 2005; WHO 2017b). PoU systems should therefore produce water that is aesthetically appealing if the desired health gains are to be achieved. Higher particulate removal and aesthetic improvements by the multi-barrier system compared to the control was probably due to pre-filtration by the geotextile layers and augmented removals by the GAC (Tobiason *et al.* 2011). With correct use and maintenance, the designed multi-barrier system may often enhance aesthetic improvements of the water being treated. Therefore, the designed multi-barrier system may often be a better option in this respect than the control system.

Raw water versus treated water quality: pH, DO and Conductivity

In general, both the designed and control system produced water with higher pH and conductivity values in relation to the raw water (**Figure 7-4**). However, the parameters were well within SANS 241 drinking water standards (**Table 7-3**). The higher pH values in the designed multi-barrier system's effluent could be attributed to GAC presence. According to Fanner *et al.* 1996, typical GAC has a pH of between 8.5-10. This claim was also confirmed by the data sheet from Rotocarb (2018) the suppliers of the GAC used in this study stating a pH of 10.2. Fanner *et al.* (1996) also reported that GAC can act as an ion-exchange media thereby contributing to increase in pH. The effect is more pronounced in new GAC media and can range from several hours to several days (Fanner *et al.* 1996). This effect is also probably the reason for higher effluent conductivity values. After several days of system use, the effect is expected to decrease. However, this depends on whether or not the materials causing high pH and conductivity are being accumulated or flushed out of the system. Increase in pH in the control system could be attributed to possible reaction between silver and the water or substances in the water. In addition, silver coating is normally done using compounds such as silver chloride ($AgCl$), silver bromide ($AgBr$) or silver iodide (AgI) which are alkaline in nature.

According to literature e.g. Bell (1991), disinfection action by silver is most efficient at higher pH values (> 8) and higher temperatures (>20ºC). Since the anti-microbial action of silver increases with increase in pH (Bell 1991), the recorded higher pH values were likely beneficial for optimal disinfection of the water by both systems. Both the multi-barrier and control systems had little if any effect on the raw water's DO levels (**Figure 7-4**). This suggests that the effluent DO levels were mainly dependent on the raw water DO values.

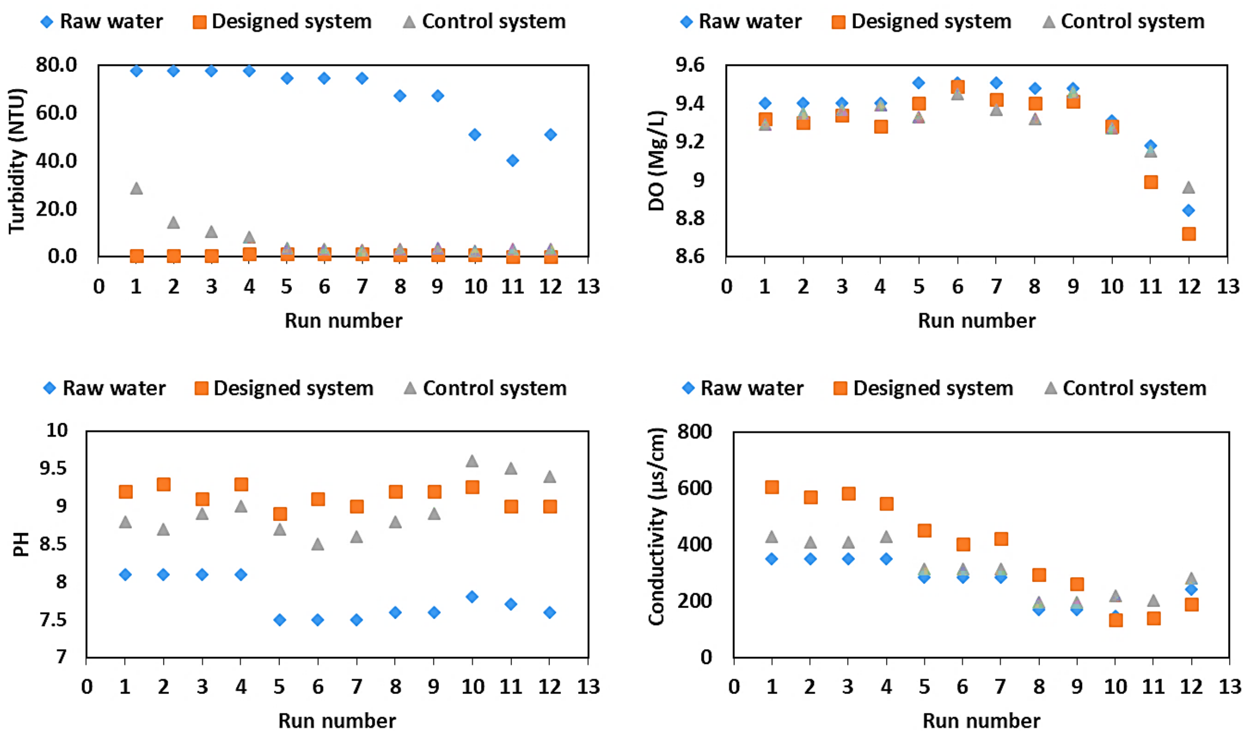

Figure 7-4: Raw water versus treated water quality: Turbidity, pH, DO and Conductivity for the multi-barrier (designed) and control systems.

Removals for indicator bacteria: fecal coliforms and *E.coli*

The designed multi-barrier and control systems both recorded significant bacterial removals (Table 7-2). *E.coli* removal ranged between 98.7 and >99.99% and 51.7 and >99.99%, respectively, for the designed and control system, whereas fecal coliform removal ranged between 98.3 and >99.99% and 49.6 and >99.99%. Both systems consistently recorded an apparent 100% removal efficiency for *E.coli* and fecal coliforms when operated at 2 L/h meeting both the SANS 241 and WHO guidelines for potable water. This finding therefore suggests that 2 L/h is the optimal flow rate for both configurations. This result supports findings by TAM ceramics (2019), who recommend flow rates close to or around 2 L/h for adequate bacterial inactivation by systems using SCCGM.

Table 7-2: Bacterial removal by the designed (multi-barrier) and control systems

Run number	Raw water (Influent)		Multi-barrier system				Control system			
	E.coli (CFU/ 100 ml)	Fecal coliforms (CFU/ 100 ml)	Effluent E.coli (CFU/ 100 ml)	% removal	Effluent fecal coliforms (CFU/ 100 ml)	% removal	Effluent E.coli (CFU/ 100ml)	% removal	Effluent fecal coliforms (CFU/ 100ml)	% removal
1	2600	2600	7	99.73	7	99.73	70	97.31	108	95.85
2	2600	2600	33	98.73	35	98.65	77	97.04	131	94.96
3	2600	2600	29	98.88	34	98.69	103	96.04	122	95.31
4	2600	2600	3	99.88	4	99.85	81	96.88	123	95.27
5	610	640	7	98.85	11	98.28	146	76.07	172	73.13
6	610	640	6	99.02	14	97.81	142	76.72	150	76.56
7	610	640	2	99.67	3	99.53	148	75.74	190	70.31
8	420	500	1	99.76	1	99.80	172	59.05	180	64.00
9	420	500	0	>99.99	0	>99.99	203	51.67	252	49.60
10	400	430	0	>99.99	0	>99.99	0	>99.99	0	>99.99
11	580	920	0	>99.99	0	>99.99	0	>99.99	0	>99.99
12	1240	1480	0	>99.99	0	>99.99	0	>99.99	0	>99.99

It is worth noting however that, the designed multi-barrier system still produced relatively safe water (≤10 CFU/100 mL) even at flow rates higher than 2 L/h. This could be attributed to the multi-barrier effect due to material combinations in its configuration (Tobiason *et al.* 2011) and higher contact time as it initially had lower flow rates particularly in the first four runs. According to literature e.g. (Binnie and Kimber 2013; de Moel *et al.* 2007; Pizzi 2010), contact time is a key factor for significant contaminant removal by granular media. It is still possible that with further optimization-e.g. by use of finer sizes of SCCGM and GAC and more layers of geotextile, the designed multi-barrier system could be operated at higher flow rate say 3 to 7 L/h. Early bacterial breakthrough was exhibited by the control system (**Table 7-2**) due to high turbidity levels in the influent (**Table 7-3**) as well as higher initial flow rates (**Table 7-1**). Therefore, the top 10 cm of the SCCGM in both systems was cleaned then replaced and were then flushed with distilled water before the 2 L/h runs. Problems in complete removal of bacteria can arise from an overload of particles and suspended bacteria in the raw water. Therefore, use of source water with turbidity 40±10 NTU (WHO 2016) would be more preferred to prevent early bacterial and particle breakthroughs. Since there are usually many classes of waterborne pathogens (bacteria, viruses, protozoa, helminths, etc.), in areas where systems such as the proposed would be used. Assessing the removal efficiency of other waterborne pathogens (e.g. viruses and protozoa) not tested in this study is recommended.

Possible heavy metal removals

Although the designed multi-barrier system generally showed higher heavy metal removal potential than the control system (**Figure 7-5**), the removals for Al, Fe, Mn, Ni and Zn were relatively significant by both systems. Average heavy metal removals by the multi-barrier system were 87.5, 59.2, 34.0, 80.7, 97.6, 83.2, 73.3, 89.1, 88.6 and 1.5 % for Al, Cd, Cr, Cu, Fe, Mn, Pb, Ni, Zn and Hg respectively. While average removals by the control system were 85.2, 38.9, 48.1, 58.2, 82.9, 95.7, 58.2, 56.7, 88.8 and 15.7 % for Al, Cd, Cr, Cu, Fe, Mn, Pb, Ni, Zn and Hg respectively. The designed multi-barrier system performed comparatively better than the control system in the removal of many metals viz: Fe, Ni, Al, Cu, Pb and Cd, probably due to presence of GAC. However, both systems were not optimised towards heavy metal removal. They were consequently inconsistent on the removal of Cd, Cr, Cu and Pb (**Figure 7-5**) and were essentially not able to remove Hg (**Figure 7-5**). Overall, the control system (SCCGM only) performed less well for heavy metal removals as mentioned above.

Although both systems were capable of removing some of the heavy metals mentioned above, the SCCGM was not produced with this intended purpose in mind (TAM Ceramics 2019). Similarly, the multi-barrier system was designed and optimised for bacterial removal and aesthetic improvements only as mentioned earlier. Both systems should therefore be primarily used in places where there is no suspected presence of toxic elements in water.

It is worth noting here that, since substantial and consistent removal (>80% on average) of Fe and Mn was indicated by both systems, they are potentially useful in areas with Fe and Mn. Since Fe and Mn affect aesthetic aspects of water by imparting color and taste, their removal is vital where they occur (CAWST 2017; Nathanson and Schneider 2015; Sullivan *et al.* 2005; WHO 2017a).

Table 7-3: Bacteriological and physical parameters: raw water vs multi-barrier (designed) and control system effluents

Parameter	Risk (SANS241)	N	Raw water (influent)			Multi-barrier system effluent			Control system effluent			Drinking Water Standards	
			Range	Mean	SE	Range	Mean	SE	Range	Mean	SE	SANS241	WHO 2017a
Color	Aesthetic	12	Yellow to Brownish			Pleasing & clear			Slightly objectionable			≤ 15 mg/l Pt-Co	≤ 5 Hazen units
Odor	Aesthetic	12	Odorous			Very acceptable			acceptable				Unobjectionable
Taste	Aesthetic	12	Sour			Very acceptable			acceptable				Unobjectionable
pH (pH UNITS)	Operational	12	7.5-8.1	7.8	0.1	8.9-9.3	9.1	0.0	8.5-9.6	9.0	0.1	≥ 5 to ≤ 9.7	6.5-9.0
Conductivity (µS/cm)	Aesthetic	12	139.9-350	259.9	24.3	132.5-605.0	383.6	50.7	196.0-429.0	309.5	26.7	≤ 1700	2500
Turbidity (NTU)	Aesthetic	12	40.3-77.7	67.6	3.7	0.0-1.0	0.5	0.1	2.3-28.4	7.1	2.2	≤ 5	5
Dissolved oxygen (DO)	Operational	12	8.8-9.5	9.4	0.1	8.7-9.5	9.3	0.1	9.0-9.5	9.3	0.0		
E.coli (CFU/100 ml)	Acute health	12	400-2600	1274.2	289.5	0.0-33.0	7.3	3.3	0.0-203.0	95.2	20.1	0	0
Fecal coliforms (CFU/100 ml)	Acute health	12	430-2600	1345.8	278.7	0.0-35	9.1	3.7	0.0-252	119.0	23.5	0	0
Al (µg/l)	Operational	12	620.7-8813.3	3498.0	905.1	86.9-295.5	172.2	21.5	159.9-312.1	236.4	12.2	≤ 300	300
Cd (µg/l)	Chronic health	12	0.01-0.11	0.1	0.01	0.00-0.2	0.0	0.0	0.01-0.1	0.0	0.0	≤ 3	3
Cr (µg/l)	Chronic health	12	0.22-13.5	4.2	1.3	1.06-15.0	3.9	1.2	0.3-4.4	1.1	0.3	≤ 50	50
Cu (µg/l)	Chronic health	12	0.1-43.5	19.2	4.5	0.3-2.0	1.3	0.2	2.6-7.3	4.1	0.4	≤ 2000	2000
Fe (µg/l)	Aesthetic	12	722.5-6891.7	2766.6	696.9	4.7-107.2	41.1	9.1	147.4-454.8	300.2	27.7	≤ 300	300
Mn (µg/l)	Aesthetic	12	21.4-278.5	112.7	28.2	2.0-24.8	7.6	2.2	1.06-7.33	2.8	0.5	≤ 100	100
Pb (µg/l)	Chronic health	12	0.01-38.1	14.9	4.8	0.001-0.15	0.0	0.0	0.01-1.4	0.3	0.1	≤ 10	10
Hg (µg/l)	Chronic health	12	<0.01-0.01	0.01	0.0	0.009-0.06	0.02	0.006	0.006-0.06	0.03	0.006	≤ 6	6
Ni (µg/l)	Chronic health	12	0.3-9.2	2.7	0.9	0.02-0.3	0.2	0.0	0.21-1.04	0.5	0.1	≤ 70	70
Zn (µg/l)	Aesthetic	12	3.5-57.9	24.2	5.8	0.1-3.9	2.0	0.4	0.27-3.2	1.5	0.3	≤ 5000	5000

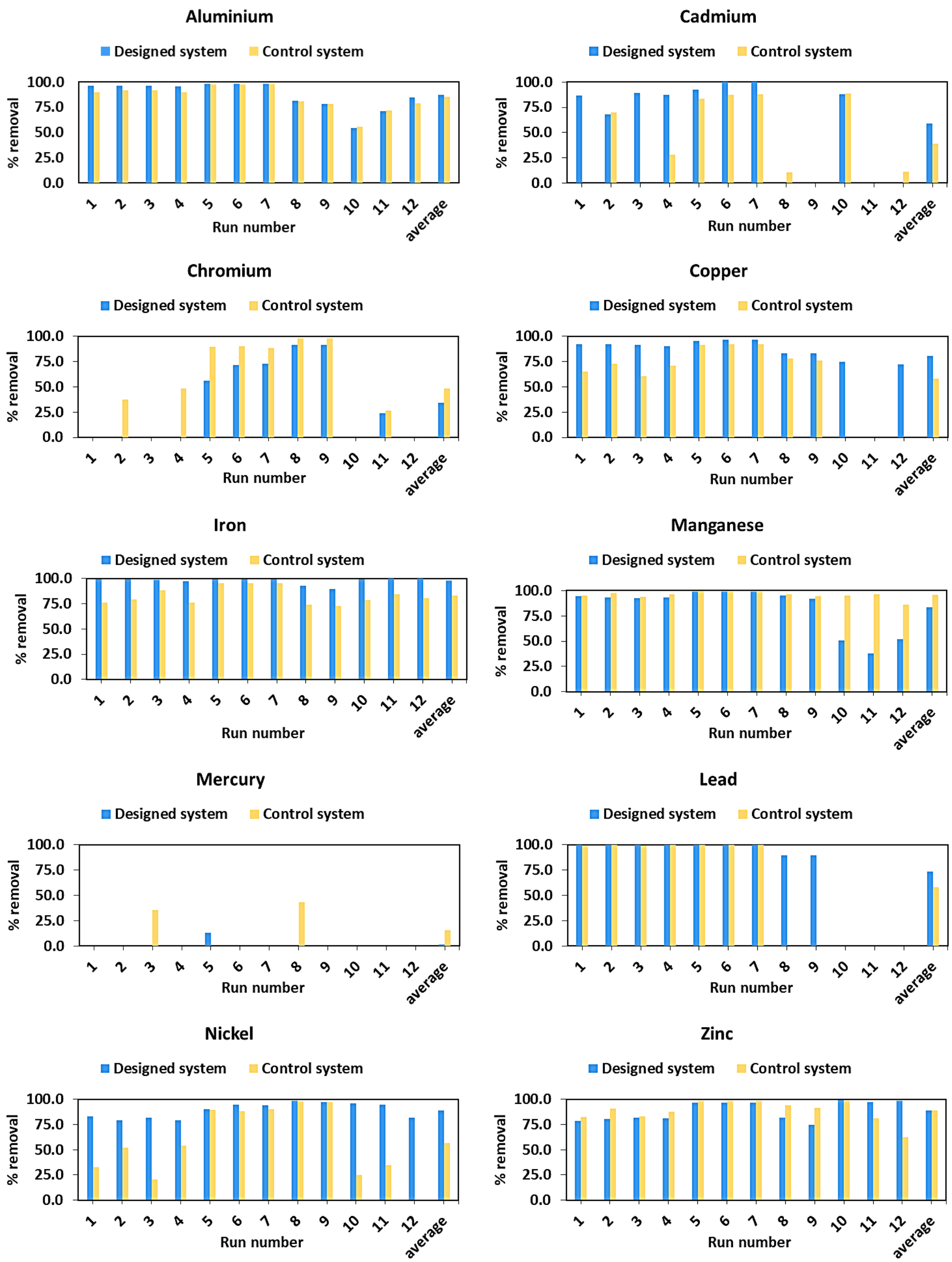

Figure 7-5:Heavy metal percentage removals by the multi-barrier (designed) and control systems for each run number

Advantages of the designed multi-barrier system

The developed system showed several advantages, including: (i) significant improvement in treated water's acceptability aspects, (ii) contains safe storage to minimize recontamination, (iii) easy to clean by washing the pre-filtration geotextile only, (iv) extended filter run times, (v) gravity driven, (vi) no need for chemical addition, (vii) long expected SCCGM life span (TAM ceramics 2019), (viii) the clay based filter media is highly replicable (TAM ceramics 2019), (ix) easy to maintain, (x) it is simple in design and user friendly, (xi) low cost especially when performance and SCCGM life span are considered, (xii) it is potentially sustainable in comparison with other PoU techniques, (xiii) it is robust and can be easily fabricated, (xv) it is appropriate for low-income settings, and (xiv) it can be easily scaled up to larger sized systems.

Limitations of the designed multi-barrier system

The limitations included: (i) height of the system is relatively high, (ii) potential for microbial regrowth on the GAC in case of bacterial breakthrough, (iii) periodical replacement of GAC attracts some running costs, (iv) relatively heavy for distribution, (v) user training on how to correctly use and maintain the technology is vital, (vi) high cost of silver if one desires to use higher flow rates which demand higher weight percent of silver, (vii) slow bactericidal action requiring higher contact time necessitating low optimal flow rates.

Cost and practical aspects of the multi-barrier and control systems

The geotextile used in the study costs around 1.76 US$/sqm (Kaytech Engineering 2018), while the GAC (ProCarb-900) costs ≤ 2.5 US$/kg (Rotocarb 2018). Pending determination of the retail price by the company in future, there is an assurance that the cost of the SCCGM will be affordable (TAM Ceramics 2019). When production of SCCGM using local raw material sources in sub-Saharan Africa and elsewhere is established as anticipated by TAM Ceramics (2019) after the market for the media is established, the cost of SCCGM based systems is expected to be cost-effective.

Practically, the filter systems are easy to use, water is easily dispensed, and the systems can be easily maintained. The geotextile fabric used in the multi-barrier system is easy to wash and reuse without significant fabric loosening by normal hand-washing. It can be disinfected in ordinary utility ovens at around 100-200ºC and is structurally stable up to 200ºC (Kaytech Engineering 2018). The main limitation of the control system configuration was a need to settle out any particles due to turbidity. A further challenge for both systems may be virus removal. It is possible that viruses may bypass the filter media, including the silver in the SCCGM, especially if the contact time and silver concentrations are insufficient. Testing the systems for virus removals is therefore recommended for future research.

According to TAM Ceramics (2019), to enhance durability, the ceramic granules need to be fired at a sufficiently high temperature to ensure that their strength and durability will resist wear and tear under normal use. Additionally, leaching may occur with silver coated materials such as the SCCGM. The USA Environmental Protection agency states the maximum allowable silver concentration is 100.0 micrograms per liter. Initial tests on the SCCGM by TAM Ceramics (2019) indicated 5.0 micrograms per liter of silver leaching indicating that the material should not cause a silver toxicity problem in the produced water.

CONCLUSIONS AND RECOMMENDATIONS

The designed multi-barrier system showed a potential to supply bacteriologically safe and aesthetically acceptable drinking water. The system is a low-cost technology with an estimated cost of about US$25. It has good potential for improving water security in poor communities, especially when production of the disinfection media (SCCGM) is implemented in developing countries. Since it can be easily scaled up to serve a larger population due to the robustness of the SCCGM (TAM ceramics 2019), the system will also be very handy to middle income urban communities in developing countries. Although many such communities are serviced with piped water from centralized treatment systems, the quality of the supplied water is often suspect due to insufficient treatment or recontamination during distribution or storage (Chaudhuri and Sattar 1990). In areas where GAC is unavailable, it is suggested that with careful assessment, ordinary charcoal be used, probably with slightly deeper sections and/or thicker sections. Additionally, in places where geotextile fabric is inaccessible, cloth material folded about 6 to 8 times can be used in place of geotextile. Both systems can meet basic water needs of about 7.5 to 15 liters/capita/day (The Sphere Project 2011), particularly for rural and suburban areas. If source water primarily requires bacterial inactivation the control system configuration will be preferable, probably with fabric pre-filtration- and costs around US$10.

If resources allow, running 4 to 5 systems concurrently for the designed and control system while varying filtration rates and other parameters of interest over a longer period is proposed for future research. Feasibility of: (i) sandwiching the GAC in the side column between small equal layers of SCCGM, (ii) use of silver impregnated GAC in the side column, and (iii) use of more geotextile layers for pre-filtration are suggested for further studies. Since limitations of the designed multibarrier system include the system height being relatively high, future investigation into reducing the system height by e.g. use of larger diameter PVC pipes could mitigate this limitation. Also, in places where the water is generally aesthetically appealing, investigating the possibility of leaving out the GAC column from the system could reduce system costs and avoid GAC replacement costs further minimizing potential for bacterial regrowth in the system. Use of challenge test water with characteristics outlined in the WHO evaluation scheme for PoU drinking water systems (WHO 2016) is also recommended (e.g. testing for three classes of pathogens and using raw water turbidity levels of 40±10 NTU). Furthermore, long term (multiyear) and field testing of both systems at the optimized flow rate of 2 L/h to assess acceptability, pollutant breakthrough, system lifespan, field performance and sustainability is recommended.

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The authors wish to acknowledge: (i) the help of the Hydraulics laboratory technical staff at Stellenbosch University during the fabrication and set up of the experiments, (ii) Kaytech Engineering South Africa for providing the geotextile, (iii) TAM ceramics LLC, Niagara Falls, N.Y for providing the SCCGM as well as helpful information, valuable discussions and suggestions towards the system design, and (iv) Rotocarb South Africa for providing the GAC.

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Chapter 8: Modelling of *Escherichia coli* removal by a low-cost combined drinking water treatment system

This Chapter (alongside Chapter 7) addressed the fourth study objective of this dissertation, which is "to develop, evaluate and optimize a combined PoU system with an inbuilt disinfection step coupled with a safe storage compartment to avoid chemical addition by prospective users."

This study modelled and assessed bacterial removal performance prediction by the developed combined three-stage low-cost PoU drinking water system (presented in Chapter 7) using specific removal mechanisms for each stage with *E.coli* as an indicator bacteria. This was done to aid in optimization of the designed multi-barrier system and similarly combined PoU systems and to support future research in terms of configuration, process combination, flow rate, material combination, etc. as a decision support tool. The system was modelled as a series of three compartments using suitable disinfection kinetic models for silver inactivation and specialized colloidal filtration theory (CFT) models for hydrosol deposition in fibrous media and CFT models for removal of colloidal particles by granular media. Suitable parameter values were estimated and applied to the models. The theoretically combined models demonstrated that suitable removal mechanisms can be applied integrally to model a combined PoU system to predict overall effluent bacterial quality. The mathematical modeling was useful in e.g. predicting that the main bacterial removal mechanism in the final PoU system was inactivation by silver in the SCCGM. This kind of modelling can be used to optimize the developed system and to design and optimize similarly combined PoU systems by allowing engineers to systematically vary design parameters until desired system effectiveness is attained. An attempt was also made to assess the effect of various factors that affect bacterial removal performance e.g. collector diameter, particle size, contact time, media depth and filtration rate.

This study also indicated that each barrier or treatment stage contributes to the overall *E.coli* removal. Consequently, the bacterial load on the SCCGM (which is the main disinfection stage due to the silver coating) can be significantly reduced by optimizing all components of the multi-barrier (combined) system, especially the pre-filtration stage. The model predictions also confirmed the 2 L/h as being an optimal flow rate due to the resulting adequate contact time between the silver and the bacteria. The modelling together with the comparison framework in Chapter 6 can sufficiently help decision making during the innovation and adoption of combined PoU systems such as the system proposed in Chapter 7 and can inform the kind of experimentations such as done in Chapters 2, 3, 4 and 5.

Future users of the mathematical modelling developed in this chapter, are advised to carefully consider and calibrate the models according to the various scenarios being investigated and actual application context. Additionally, it should be ensured that all the key input parameters such as those listed in **Table 8-1** are correctly obtained or calculated. Furthermore, the experiments used to generate the data for calculating the input parameters should be adequately representative of the system being modelled. Also, any data obtained from literature should possibly be calibrated by further experimentation before being applied. Although the developed models are primarily limited to the developed and similarly combined PoU systems, they could with careful considerations and modifications be applicable to similarly combined large scale systems. The parameters identified as most sensitive in the presented mathematical models include particle diameter, collector/fiber diameter, particle density, filter media porosity, fluid temperature, filtration rate, contact time, filter media depth, attachment efficiency, disinfectant concentration, inactivation constant and coefficient of specific lethality.

Modelling of *Escherichia coli* removal by a low-cost combined drinking water treatment system

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ABSTRACT

This work presents mathematical modelling of *Escherichia coli (E.coli) removal* by a multi-barrier point-of-use drinking water system. The modelled system is a combination of three treatment stages: filtration by geotextile fabric followed by filtration and disinfection by silver-coated ceramic granular media (SCCGM) then granular activated carbon (GAC) filtration. The presented models accounted for removal mechanisms by each treatment stage. *E.coli* was modelled as a microbial particle. *E.coli* inactivation by SCCGM was modelled using the Chick's, Chick-Watson, Collins-Selleck and complete mix system bacterial inactivation kinetic models, which were considered adequately representative for describing the removal. Geotextile removal was modelled using colloidal filtration theory (CFT) for hydrosol deposition in fibrous media. The filtration removal contributions by the SCCGM and GAC were modelled using CFT for removal of colloidal particles by granular media. The model results showed that inactivation by silver in the SCCGM was the main bacterial removal mechanism. Geotextile and GAC also depicted appreciable removals. The theoretical modelling approach used is important for design and optimization of the multi-barrier system and can support future research in terms of material combinations, system costs, etc. Collector diameter, particle size, filtration velocity and contact time were identified as critical parameters for *E.coli* removal efficiency.

Key words: Combined system, CFT models, disinfection models, *E.coli* removal modelling, SCCGM, system optimization

INTRODUCTION

Availability of safe drinking water is a major challenge in many rural and suburban areas of developing countries (Pandit and Kumar 2019; Treacy 2019). Globally, around 780 million rural and 136 million urban dwellers lack access to improved drinking water supply (RWSN 2010). In sub-Saharan Africa, the discrepancy is even bigger with 272 million rural population lacking access to safe water, compared to 54 million in urban areas (RWSN 2010). Consumption of contaminated water can result in outbreaks of diseases such as cholera, dysentery, diarrhea, and typhoid. Safe drinking water provision through point-of-use (PoU) water treatment is among the key measures required to prevent such outbreaks. While centralized piped water supply is the ideal solution for meeting drinking water needs in many communities worldwide (Lantagne and Yates 2018; Pandit and Kumar 2019; Smieja 2011), PoU water treatment has been shown by various authors (CAWST 2011; Kausley *et al.* 2015, 2018; Lantagne and Yates 2018; Pandit and Kumar 2019, 2015; Treacy 2019) to improve drinking water safety and reduce the burden of waterborne diseases. It is sometimes the only cost-effective option in many rural and suburban areas of developing countries.

Although efforts to develop simple yet effective low-cost PoU technologies for rural and suburban areas have intensified globally (Pandit and Kumar 2015; Treacy 2019), challenges still exist (Treacy 2019). Therefore, there is still need for development and/or optimization of more PoU techniques appropriate to poor communities. Mathematical modelling may assist in the design and optimization (costs, material combination, etc.) of various PoU systems and can support further research in terms of configuration, flow rate, media combination, etc. while also serving as a decision support tool.

Low-cost PoU water treatment technologies can be broadly classified into five groups (Lantagne and Yates 2018): (1) chemical disinfection (e.g., chlorine disinfection); (2) disinfection by heat (e.g., boiling), ultraviolet or solar radiation; (3) coagulation, flocculation, and sedimentation; (4) filtration (e.g., slow sand filtration); and (5) combined (multi-barrier) systems (CAWST 2011; Nath *et al.* 2006; Pandit and Kumar 2019). The priority of most PoU systems is to make water bacteriologically safe (CAWST 2017, 2011) and aesthetically acceptable (WHO 2017a). Good aesthetic quality promotes health gains from drinking safe water (Lantagne and Yates 2018; WHO 2016). Water of poor aesthetic quality, although safe, is often avoided (Nathanson and Schneider 2015; WHO 2017a). Additionally, particles that contribute to poor aesthetic quality hinder bacterial inactivation (WHO 2017a).

A thorough review of literature showed that modelling of PoU and similar systems for contaminant removal or system optimization has mainly been done on uncombined systems e.g.: (i) intermittently operated slow sand filters (Fulazzaky *et al.* 2009; Jenkins *et al.* 2011), (ii) disinfection by using chlorine (Lee and Nam 2002), (iii) disinfection by natural herbs (Somani and Ingole 2012), (iv) disinfection by silver or silver coated materials (Chong *et al.* 2011; Rossainz-Castro *et al.* 2016; Singh *et al.* 2019), (v) granular activated carbon filtration (Hijnen *et al.* 2010), (vi) filtration by geotextile fabrics and other fibrous filter media (Choo and Tien 1991; Li and Park 1999; Siwila and Brink 2018a), and (vii) ultraviolet disinfection (Brownell *et al.* 2008), etc.

This paper presents modelling of *E.coli* removal by a combined drinking water system developed by the authors (Siwila and Brink 2019) as a contribution to research and development on low-cost PoU drinking water treatment. The combined system consists of three treatment stages: pre-filtration by geotextile fabric followed by filtration and disinfection by SCCGM then GAC filtration (Siwila and Brink 2019). Each of these steps were modelled as a series of compartments by using specialized theoretical removal mechanisms for each barrier. *E.coli* was modelled as a microbial colloid or particle as proposed in literature see (Harvey and Garabedian 1991; Hijnen *et al.* 2010; Khatiwada and Polprasert 1999; Tufenkji *et al.* 2003).

E.coli inactivation by SCCGM was modelled using Chicks, Chick-Watson, complete mix system and Collins-Selleck disinfection models (Metcalf & Eddy 2014; MWH 2012; Qasim and Zhu 2018), which were considered sufficiently representative to describe the removal. The Chick's and Chick-Watson models have been applied by various authors (Rossainz-Castro *et al.* 2016; Shimabuku *et al.* 2018; Singh *et al.* 2019) to model bacterial removal by silver and other metals. Additionally, Chick worked with silver nitrate among other disinfectants and *E.coli* among other organisms (MWH 2012). Geotextile removal was modelled using colloidal filtration theory (CFT) models for removal of hydrosols by fibrous media developed by Guzy *et al.* (1983) and Choo and Tien (1991) as presented by Tien (2012). The filtration removals by the SCCGM and GAC were modelled using the Yao CFT model for removal of colloidal particles from liquids by granular media developed by Yao *et al.* (1971) then refined by Rajagopalan and

Tien (1976) (the RT model) and expanded further by Tufenkji and Elimelech (2004) (the TE model) (MWH 2012). The highlighted removal theories, governing equations and respective modelling procedure are explained in the methodology section of this paper.

Applied modelling of multi-barrier systems such as presented here can be helpful to system design and optimization (MWH 2012). This can help engineers understand the governing characteristics and contribution of each barrier to the effluent quality, subsequently enabling them to make informed decisions on the appropriate optimization measures. The importance of each treatment stage and associated removal mechanisms can be assessed as a function of system parameters (MWH 2012). This can allow engineers to vary design parameters until the desired system effectiveness and cost are achieved. For example, modelling may assist in minimizing cost while ensuring the system is effective while deciding on which component needs more attention to increase removal efficiency of the water quality parameter of interest.

Waterborne pathogens are generally grouped into four major classes (MWH 2012; Pandit and Kumar 2019; Qasim and Zhu 2018; WHO 2017b): (i) bacteria, (ii) viruses, (iii) protozoa, and (iv) helminths. Each class has numerous members with varying degrees of pathogenicity and cause various diseases in humans (MWH 2012; Pandit and Kumar 2019). Bacteria form a major and critical class and require careful attention (Pandit and Kumar 2019). Bacterial diseases, such as cholera, typhoid, dysentery, acute gastroenteritis, diarrhea, leptospirosis, legionnaires' disease, campylobacteriosis, etc. cause far more health problems than viruses or chemicals as a result of the drinking of untreated water (WHO/UNICEF 2004; McAllister 2005). Testing for every possible pathogen in water is difficult, time consuming, and expensive. Therefore, indicator organisms are often employed to assess bacteriological safety of drinking water (CAWST 2017; WHO 2017b). The presence of indicator organisms in water signals fecal contamination and the likely presence of pathogens (CAWST 2017; Pandit and Kumar 2019). Therefore, bacterial removal by use of *E.coli* was chosen for modelling in this research. Future research should expand to include the other pathogen classes.

The South African National Standards (SANS) 241 and the World Health Organization (WHO) guidelines recommend 0 CFU/100 ml of *E.coli* and fecal coliforms in drinking water. Therefore, an optimised system is expected to consistently supply water of 0 CFU/100 ml *E.coli* and fecal coliforms. Although over 95% of fecal coliform bacteria are primarily *E.coli* (Ballance and Bartram 1998; Horan 2003), some non-fecal coliforms may grow at 44-45ºC (Horan 2003). Hence, *E.coli* which is exclusively of fecal origin, is the most preferred fecal indicator bacteria (Brandt *et al.* 2017; Foppen and Schijven 2006; Horan 2003). Thus, the presence of *E.coli* is definitive evidence of fecal contamination (Brandt *et al.* 2017; Horan 2003). If *E.coli* is detected in treated water, it indicates the presence of fecal matter and potentially pathogens (CAWST 2017; WHO 2017b). This signals potential malfunctioning in the responsible water treatment system posing a health risk requiring urgent action. In addition, *E.coli* has been indicated to be a better indicator for predicting diarrhoeal and gastrointestinal disease-causing pathogens than fecal coliforms particularly when detected in tropical drinking waters (Brandt *et al.* 2017; Horan 2003; Qasim and Zhu 2018).

MATERIALS AND METHODS

The general experimental methodology aspects (study setting, design aspects, set up, sampling, etc.), are presented in Siwila and Brink (2019). The methodology for the present work primarily presents the mathematical modelling approach for prediction of *E.coli* removal by the modelled system. The schematic diagram of the combined system that is modelled is given in **Figure 8-1.** The system consisted of geotextile fabric for pre-filtration, SCCGM for filtration and disinfection, GAC filtration and a safe storage compartment for treated water. The key system parameters, particularly, those applied directly to the modelling done in this paper are included in **Table 8-1**.

Sampling was done after at least 7.5 liters of water was passed through the system and at varied flow rates for the first 9 runs and at 2 L/h for the last 3 runs (Siwila and Brink 2019). The first four filtration runs were done at the maximum obtainable flow rate of 10 L/h (**Table 8-4**), while subsequent flow rates were varied from 8 L/h to 2 L/h (**Table 8-4**). Varying the flow rate was done to arrive at an optimal flow rate and produce varied contact time, and provide data for the modelling done in this paper. The optimal flow rate in this case was the flow rate required to produce 0 CFU/100 ml for *E.coli* and fecal coliform in the effluent recommended by SANS 241 and WHO guidelines as mentioned above. Thus, flow rates where staggered from the highest obtainable by the system to an optimal 2 L/h were 0 CFU/100 ml for *E.coli* and fecal coliform in the effluent (>99.99% removal) were consistently achieved. Thereafter, three runs were done at 2 L/h flow rate to assess the removal consistency at the optimal flow rate.

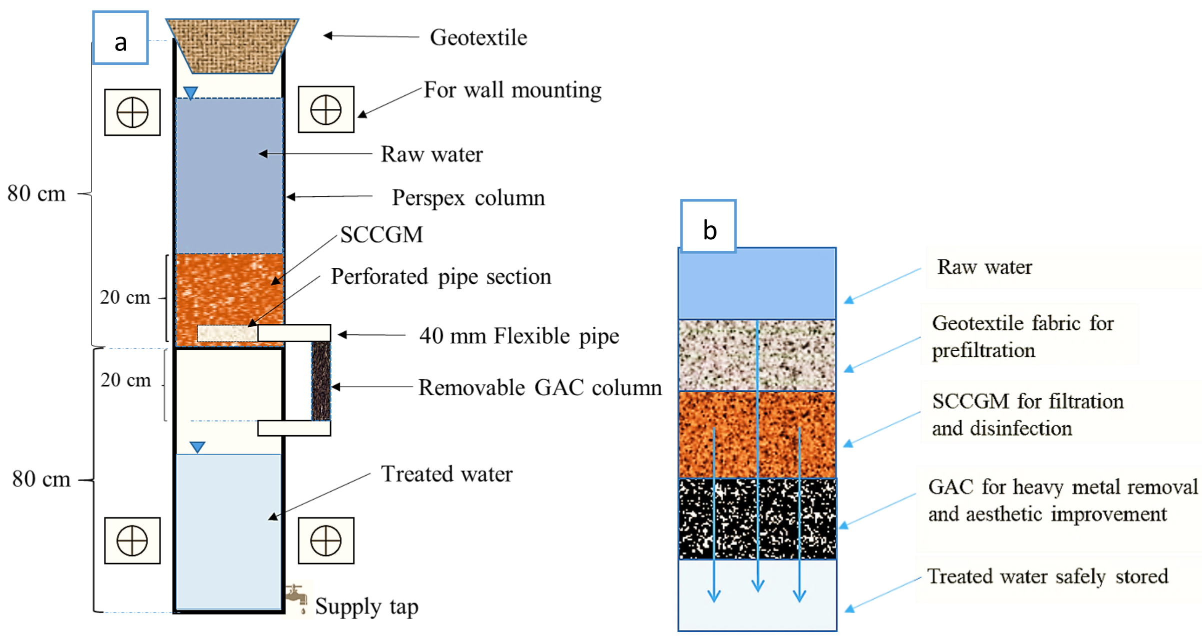

Figure 8-1 Novel multi-barrier filter system, (a) designed system, and (b) process schematic diagram (Siwila and Brink 2019)

***E.coli* removal performance modelling procedure**

One of the key issues in the design of a water treatment system is the need to predict the performance of the proposed design (Metcalf & Eddy 2014). To demonstrate the importance of this, mathematical modelling was done on *E.coli* removal performance prediction. The overall *E.coli* removal by the combined system was modelled as a series of three compartments. The models were coupled as depicted in **Figure 8-2,** whereby the effluent from the geotextile was modelled as the influent to the SCCGM and effluent from SCCGM was modelled as influent to the GAC. Thus, the effluent of one compartment was modelled as influent to the next (Masters and Ela 2014). This modelling approach was derived from the works of (i) Metcalf & Eddy (2014) who modelled a number of wastewater reactors in series for pollutant removal, (ii) Rietveld (2019) who modelled a large scale multi-barrier water treatment plant comprising ozone and sand filtration for *E.coli* reduction as units in series, as well as (iii) Masters and Ela (2014) who modelled a four-chamber tank for large scale drinking water disinfection as tanks in series.

E.coli removal was calculated using numerical models appropriate to each compartment. Input parameters (**Table 8-1**) used in the mathematical calculations were obtained using experimental data and from literature. The modelled removals were then calculated using **Equation 8-1** adapted from de Moel *et al.* (2007) and Tien (2012) while log removal values (LRV) were obtained using **Equation 8-2** adapted from MWH (2012). The total removal efficiency for each experimental run was calculated using **Equation 8-3** (Tien 2012) and was then applied to the influent *E.coli* counts for each run. Computation and integration of removal efficiencies by each stage (**Figure 8-2** & **Table 8-3**) and respective removal mechanisms was done in Microsoft Excel 2016. Statistical analysis was done using Tool Pak VBA a Microsoft Excel 2016 add-in.

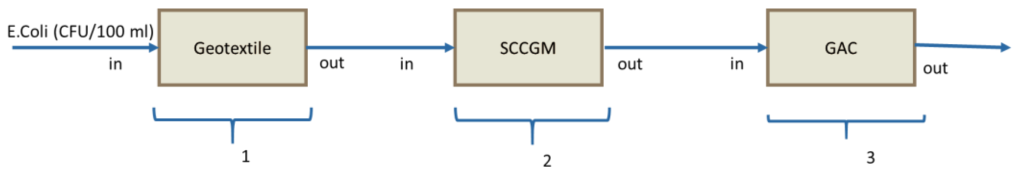

Figure 8-2: Definition sketch for modelling the multi-barrier system's E.coli removal using compartments in series

$$\text{Removal}_{predicted} = \left(1 - \frac{N_e}{N_o}\right) \tag{8-1}$$

Where: N_o = Influent *E.coli* count [CFU/100 ml]; N_e = Effluent *E.coli* count [CFU/100 ml]; $\text{Removal}_{predicted}$ = Predicted removal fraction

$$LRV_{predicted} = -log_{10}\left(\frac{N_e}{N_o}\right) \tag{8-2}$$

Where: $LRV_{predicted}$ = Predicted log removal value

$$\eta_{total\ efficieny} = 1 - \left[\left(1 - \eta_{geotextile}\right)(1 - \eta_{SCCGM})(1 - \eta_{GAC})\right] \tag{8-3}$$

Where: $\eta_{geotextile}$ = geotextile removal efficiency; SCCGM removal efficiency; GAC removal efficiency

Remembering that the length of the filter bed and the residence time play key roles in determining bacterial removals (Jenkins *et al.* 2009; Muhammad *et al.* 1996; TAM ceramics 2019), contact time between *E.coli* and silver was estimated using **Equation 8-4** adapted from Metcalf & Eddy (2014) for each run and flow rate

$$EBCT = \frac{V_{media}}{Q_v} = \frac{V_{media}}{v.A} = \frac{h.A}{v.A} = \frac{h}{v} \tag{8-4}$$

Where: EBCT = empty bed contact time (h); Q_v = flow rate (m^3/h); A = cross sectional area of GAC or SCCGM filter bed (m^2) of diameter d (m) $\left(A = \frac{\pi d^2}{4}\right)$; V_{media} = column volume occupied by GAC or SCCGM (m^3); v = filtration velocity (m/h); h = height of GAC or SCCGM bed (m)

A total of eight combined mathematical models (see **Table 8-3**) were tested using combinations of disinfection and filtration modelling approaches as given below. The respective disinfection and filtration modelling approaches alongside the various *E.coli* removal mechanisms and parameter equations are explained below. Thereafter, the eight combined models as were used in the numerical calculations of this study were summarized in **Table 8-3** and the associated text just above **Table 8-3**.

Modelling *E.coli* removal by the SCCGM

E.coli removal by SCCGM was first modelled using disinfection kinetics in the first four combined models (see **Table 8-3**). The removal was thereby modelled as being only due to bacterial inactivation by the silver coating of the media. The inactivation by silver was modelled using Chick's, Collins-Selleck, complete-mix system (CMS) model and the Chick-Watson bacterial inactivation models (de Moel *et al.* 2007; Metcalf & Eddy 2014) explained below. Thereafter *E.coli* removal contribution by SCCGM filtration (**Table 8-3**) was included in the last four combined models using the colloidal filtration theory (CFT) numerical modelling procedure explained under *E.coli* removal by GAC filtration, but using appropriate SCCGM characteristics as given in **Table 8-1.**

Chick's and Plug flow model

Assuming that for any length, dx, and throughout the corresponding cross section (i) mixing of the microbial particles is ideal (**Figure 8-3),** (ii) flow rate is constant, and (iii) no storage exists in the SCCGM filter bed, mass balance was done as follows (de Moel *et al.* 2007):

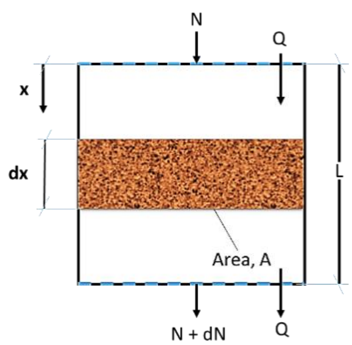

Figure 8-3: Schematic element for the plug flow model

Inlet = outlet + decay

$$QN = Q(N + dN) + k_o NAdx \tag{8-5}$$

Where: Q = flow rate, N = *E.coli* count (CFU/100 ml), dx = length; k_o = mortality or inactivation rate (CFU inactivated/ min), A = cross-sectional area

Simplifying **Equation 8-5** gives E**quation 8-6:**

$$\frac{1}{N} dN = -k_o \frac{A}{Q} dx \tag{8-6}$$

Applying the following boundary conditions to the SCCGM filter bed: (i) at x = 0; $N = N_o$, and (ii) at x = L; $N = N_e$, and remembering that $\frac{AL}{Q} = \frac{V}{Q} = t$; yields **Equation 8-7** (de Moel *et al.* 2007):

$$\Rightarrow \frac{N_e}{N_o} = exp\,(-k_o t) \tag{8-7}$$

Where: N_o = Influent *E.coli* count [CFU/100 ml]; N_e = Effluent *E.coli* count [CFU/100 ml]; $(\frac{N_e}{N_o})$ = fraction of influent *E.coli* [CFU/100 ml] remaining in the effluent, t = time (in this study, t ≈ EBCT (de Moel *et al.* 2007)). k_o $(CFU\ inactivated/\ min)$ was estimated by plotting $-\,ln\left(\frac{N_e}{N_o}\right)$ versus contact time, where k_o is the gradient of the best fit line (Metcalf & Eddy 2014).

Since the form of **Equation 8-7** is exactly like the Chick's model (Chick 1908; Metcalf & Eddy 2014; MWH 2012; Qasim and Zhu 2018) for disinfection, it was handled as such to simplify the theoretical approach. The Chick's model (**Equation 8-7**) and Chick-Watson model (**Equation 8-11**) were also used by Rossainz-Castro *et al.* (2016) to model *E.coli* and *Candida albicans* inactivation by silver and copper coated granular zeolite, by Singh *et al.* (2019) to model *E.coli* inactivation by silver and other metals as well as by Somani and Ingole (2012) for kinetic modelling of water disinfection by natural herbs.

Complete mixing system (CMS) model

The SCCGM bed was modelled as having a volume V (m^3) fed by a flow rate Q and an *E.coli* count N_o and with effluent *E.coli* count of N_e and flow rate Q same as the influent flow rate. Steady state mass balance for the filter bed was as follows (de Moel *et al.* 2007; Masters and Ela 2014):

Inlet = outlet + decay

$$QN_o \ = \ QN_e + \ k_o V N_e$$

$$\Rightarrow 0 = \ QN_o - QN_e - \ k_o V N_e \tag{8-8}$$

Solving for N_e and remembering that $t = \frac{V}{Q}$, then rearranging gives **Equation 8-9**

$$\Rightarrow N_e = \frac{QN_0}{Q + Vk_o}$$

$$\Rightarrow \ \frac{N_e}{N_0} = \frac{1}{1 + k_0 t} \tag{8-9}$$

Where: N_o = Influent *E.coli* count [CFU/100 ml]; N_e = Effluent *E.coli* count [CFU/100 ml]; k_o = mortality or inactivation rate; t = contact time (in this study, t ≈ EBCT (de Moel *et al.* 2007)).

The Collins-Selleck model

The Collins-Selleck model **Equation 8-10** (Metcalf & Eddy 2014) was developed by Collins for chemical disinfection of coliform bacteria in domestic wastewater (MWH 2012). The model has overtime been proven valuable for modelling bacterial inactivation by various alternative disinfectants as well (MWH 2012).

$$\frac{N_e}{N_0} = \frac{1}{(1+0.23Ct)^3} \tag{8-10}$$

Where: C = concentration of disinfectant, mg/L; t = contact time (in this study, T ≈ EBCT (de Moel *et al.* 2007)).

Table 8-1: Key input parameter values used in the numerical computations

Parameter	*Units*	*Value*	*Source of parameter and/or data used to calculate the parameter*
Microbial particle (E.coli) size (dp)	m	0.0000015	(Medema *et al.* 1998; Qasim and Zhu 2018)
Diameter of the collector (dc) for GAC	*m*	*0.0006*	*Siwila and Brink (2019)*
GAC media porosity (ε)	*-*	*0.34*	*Siwila and Brink (2019)*
Attachment efficiency (α) for GAC	*-*	*0.57*	*Hijnen et al. (2010)*
Absolute temperature (T) of water	*K*	*298.15*	*Siwila and Brink (2019)*
E.coli density (ρ_p)	*kg/m^3*	*1100*	*Bouwer and Rittmann (1992)*
Acceleration due to gravity (g)	*m/s^2*	*9.81*	*MWH (2012)*
Density of water (ρ_w)	*kg/m^3*	*997*	*Metcalf & Eddy (2014)*
Dynamic viscosity (μ)	*kg/m·s*	*0.00089*	*Metcalf & Eddy (2014)*
Filtration rate (v_f) for GAC and SCCGM	*m/h*	*0.34-1.72*	*Siwila and Brink (2019)*
GAC bed depth (L)	*m*	*0.2*	*Siwila and Brink (2019)*
Hamaker constant (H_a) for E.coli PVC water interface	*$kg{\cdot}m^2/s^2$*	*9.72E-20*	*Rijnaarts et al. (1995)*
Boltzmann constant (k_B)	*$kg{\cdot}m^2/s^2{\cdot}K$*	*1.381E-23*	*(MWH 2012; Tobiason et al. 2011)*
Empty bed contact time (EBCT)	*h*	*0.12-0.58*	*Siwila and Brink (2019)*
Chick's model inactivation constant, k_o	*min^{-1}*	*0.21*	*Siwila and Brink (2019)*
Chick-Watson coefficient of specific lethality, K_{cw}	*L/mg.min*	*0.103*	*Tam Ceramics (2019)*
Range of Ct values for Chick-Watson model	*mg.min/L*	*13.9-69.7*	*Siwila and Brink (2019)*
Geotextile fabric porosity (ε)	*(-)*	*0.75*	*Kaytech Engineering (2018)*
Geotextile single fiber diameter (df)	*µm*	*25*	*Kaytech Engineering (2018)*
Geotextile total thickness (h)	*mm*	*36*	*Siwila and Brink (2019)*
Geotextile solidity (Φ)	*-*	*0.25*	*Siwila and Brink (2019)*
Filtration rate (v_f) for the Geotextile	*m/s*	*0.0098*	*Siwila & Brink (2018)*
Hamaker constant (H_a) for E.coli geotextile water interface	*$kg{\cdot}m^2/s^2$*	*6.48E-20*	*Rijnaarts et al. (1995)*
diameter of the collector (dc) for SCCGM	*m*	*0.0005*	*Tam Ceramics (2019)*
SCCGM bed depth (L)	*m*	*0.2*	*Siwila and Brink (2019)*
SCCGM porosity (ε)	*-*	*0.30*	*Tam Ceramics (2019)*
Hamaker constant (H_a) for E.coli SCCGM water interface	*$kg{\cdot}m^2/s^2$*	*8.10E-20*	*Rijnaarts et al. (1995)*
Attachment efficiency (α) for SCCGM	*-*	*0.10*	*Tufenkji et al. (2003)*

The Chick–Watson model

The Chick-Watson model **Equation 8-11** is a refined version of the Chick's model and emphasizes that time required to achieve a certain inactivation level is related to the disinfectant concentration (Metcalf & Eddy 2014; MWH 2012).

$$\frac{N_e}{N_0} = exp\,(-K_{cw}Ct) \tag{8-11}$$

Where: N_o = Influent *E.coli* count [CFU/100 ml]; N_e = Effluent *E.coli* count [CFU/100 ml]; C= concentration of disinfectant [mg/L]; t = contact time [s]; Kcw = specific lethality [L/(mg.min)] and was estimated by plotting *-ln(Ne/No)* versus Ct (concentration x contact time) and obtaining the slope for the best fit line (Metcalf & Eddy 2014; MWH 2012; Qasim and Zhu 2018) using experimental data; Ct was calculated by multiplying C by t (Metcalf & Eddy 2014; MWH 2012).

E.coli removal modelling by the GAC filtration

Microbial particle removal mechanisms by granular media

In granular filtration, water is passed through granular media such as GAC or sand, which filter out the pollutants allowing clean water through. Particles in water only strike the collectors (grains) after deviating from the streamline (Wood *et al.* 2019). Thereafter, the particles stick to the collectors by van der Waals forces, which hold them at collector surfaces after contact has been made (Wood *et al.* 2019). According to Wood *et al.* (2019), intermolecular binding forces such as van der Waals forces, are likely the key means for bacterial removal.

The main particle removal mechanisms in the Yao CFT model are interception, sedimentation and diffusion (MWH 2012). Interception happens once a particle following a streamline hits the collector and gets captured because of its own size (Tufenkji and Elimelech 2004). Sedimentation occurs when particles with densities higher than water settle vertically onto the collector due to gravity (MWH 2012; Tufenkji and Elimelech 2004). Diffusion occurs when particles move in Brownian motion then deviate from the streamlines and contact the collector (MWH 2012). The removal efficiencies by each mechanism are assumed as additive and are accounted for in the single collector efficiency (SCE) (**Equation 8-14)** (MWH 2012; Tufenkji and Elimelech 2004). The efficiencies depend on a number of factors such as filtration rate, particle diameter, collector diameter, fluid viscosity, etc. (Wood *et al.* 2019). According to Yao *et al.* (1971) diffusion dominates the removal of particles of diameter < 1 μm, while removal of particles with diameter > 1 μm is dominated by sedimentation and interception.

In the classical CFT model, particle removal from water is modelled based on the single collector efficiency (SCE) model (**Equation 8-14**). SCE is defined as the ratio of the amount of particles contacting the collector to the amount of particles approaching the collector (MWH 2012). The attachment efficiency (**Equation 8-15)** shows that only a fraction of particles contacting the collector stick to the collector (MWH 2012). Consequently, the fraction of particles that actually get captured by a single collector is a product of the SCE (η) and the attachment efficiency (α) (**Equations 8-12** & **8-13**).

E.coli removal by GAC modelling approach

The removal of *E.coli* as microbial particles by GAC was therefore modelled using the CFT approach (MWH 2012; Tobiason *et al.* 2011; Yao *et al.* 1971) by relating the *E.coli* removal performance of the GAC column of depth L to the SCE of GAC (**Equation 8-12)**. Doing a mass balance on a small differential element and integrating over the entire depth **Equation 8-12** gives **Equation 8-13** which is the classical Yao CFT model (MWH 2012; Tobiason *et al.* 2011; Yao *et al.* 1971).

$$\frac{\partial N}{\partial L} = -\lambda N = -\left(\frac{3}{2}\frac{(1-\varepsilon)}{d_c}\alpha\eta\right) N \quad (8\text{-}12)$$

Where: λ= filter coefficient, ε = porosity of GAC, L = column depth (m), α = attachment efficiency which reflects the chemistry of the system, η = SCE, d_c= diameter of collector (m), N = concentration of microbial particles (*E.coli*).

$$\frac{N_e}{N_0} = \exp\left[\frac{-3\ (1-\varepsilon)\alpha\eta L}{2d_c}\right] \tag{8-13}$$

Where N_e = effluent concentration of *E.coli* (CFU/100 ml); N_o= influent concentration of *E.coli* (CFU/100 ml);

Table 8-2: Definitions of the TE model SCE equations and parameters adapted from MWH (2012) and Tobiason et al. (2011)

Parameter	*Definition equation*		*Parameter*	*Definition*
N_R (relative size group, dimensionless)	$N_R = \frac{d_p}{d_c}$		d_p	*Particle diameter (m)*
N_G (gravity number, dimensionless)	$N_G = \frac{V_S}{V_F} = \frac{g(\rho_p - \rho_w)(d_p)^2}{18\mu V_F}$		d_c	*Collector diameter (m)*
N_A (attraction number, dimensionless)	$N_A = \frac{N_{vdw}}{N_R P_e} = \frac{H_a}{3\pi\mu(d_p)^2 V_F}$		k_B	*Boltzmann's constant, (1.381 × 10^{-23}J/K)*
***N_{vdw}** (van der Walls number, dimensionless)*	$N_{vdw} = \frac{H_a}{k_B T}$		ε	*Filter media porosity, dimensionless*
***N_{pe}** (Peclet number, dimensionless)*	$N_{pe} = \frac{V_F d_c}{D_L} = \frac{3\pi\mu d_p d_c V_F}{k_B T}$		g	*Gravitational acceleration (m/s^2)*
***A_s** (porosity dependent function, dimensionless)*	$A_s = \frac{2(1-\gamma^5)}{2-3\gamma+3\gamma^5-2\gamma^6}$		H_a	*Hamaker constant (J)*
***D_L** (diffusion coefficient, m^2/s)*	$D_L = \frac{kT}{3\pi\mu dp}$		T	*Absolute temperature, K (273+° C)*
γ (porosity coefficient, dimensionless)	$\gamma = (1-\varepsilon)^{\left(\frac{1}{3}\right)}$		V_F	*Filtration rate (m/s)*
			ρ_p	*E.coli (particle) density, (kg/m^3)*
***V_s** (Stokes' settling velocity, m/s)*	$V_s = \frac{g(\rho_p - \rho_w)(d_p)^2}{18\mu}$		μ	*Absolute viscosity of water (kg/m-s)*
			ρ_w	*Density of water (kg/m^3)*

The η and α respectively give the fractions of *E.coli* contacting and being retained by the GAC grains as defined by **Equations 8-14** and **8-15**. SCE (η) was computed using the optimized SCE model (**Equation 8-14)** presented by Tufenkji and Elimelech (2004). The Tufenkji and Elimelech (TE) model for SCE computation (**Equation 8-14)** is a semi-empirical expression that was derived using results of numerical simulations (MWH 2012). It is an expansion on the Rajagopalan and Tien's SCE model and fully integrates hydrodynamic and van der Waal forces interactions into all particle removal mechanisms (MWH 2012). The parameters in the TE model are defined in **Table 8-2** while the summary of the input values for the present study are given in **Table 8-1.**

$$\eta\ (SCE) = \frac{E.coli\ bacteria\ contacting\ the\ GAC\ collector}{E.coli\ bacteria\ approaching\ the\ GAC\ collector} = \eta_D + \eta_I + \eta_G$$

$$=2.4A_s^{\left(\frac{1}{3}\right)} N_R^{-0.081} N_{pe}^{-0.715} N_{vdw}^{0.052} + 0.55 A_s N_R^{1.675} N_A^{0.125} + 0.22 N_R^{-0.24} N_G^{1.11} N_{vdw}^{0.053} \tag{8-14}$$

Where: η_D= transport due to diffusion, η_I = transport due to interception, η_G = transport due to gravity

$$\alpha\ (attachment\ efficiency) = \frac{E.coli\ bacteria\ sticking\ to\ the\ collector}{E.coli\ bacteria\ contacting\ the\ collector} \tag{8-15}$$

Theoretically α ranges between 0 and 1 from poor to optimal sticking conditions respectively (Parsons and Jefferson 2006; Tobiason *et al.* 2011; Tufenkji and Elimelech 2004).

E.coli **removal modelling by the geotextile fabric**

Microbial particle removal mechanisms by fibrous media

Similar to the SCE models applied in granular filtration (Tufenkji and Elimelech 2004), the theoretical filtration efficiency of fibrous media is predicted based on single fiber collector efficiency (SFCE) models (Bulejko 2018; Graham and Mbwette 1987). SFCE is the ratio of the number of particles captured by a single fiber collector to the number of particles flowing toward the collector in a cylindrical pore. The actual fraction of particles captured by a single fiber collector is the product of the SFCE and the particle-fiber attachment efficiency (Bulejko 2018; Graham and Mbwette 1987). In the present study the SFCE mechanisms accounting for particle removal (i.e. gravitation, interception, the London–van der Waals forces and diffusion) are assumed adequately incorporated in the filter coefficients given by **Equations 8-16** and **8-19a** as presented by Tien (2012). A large filter coefficient signifies high particle removal rate and correspondingly high single fiber collector efficiencies (Li and Park 1999).

Brownian motion causes particles < 1 μm to strike the collector fibers and eventually get captured (Bulejko 2018; Guzy *et al.* 1983). For particles > 1 μm, the removal is mainly by interception and gravitational settling (Graham and Mbwette 1987). Gravitational force governed by **Equation 8-17b** acts on colloidal particles which are principally heavier than water causing them to settle onto the collector fiber. Interception governed by the interception parameter (**Equation 8-17a**) happens when a particle following a streamline comes within a distance of one particle radius from the collector fiber, and gets attached due to attraction forces (Bulejko 2018). The net effect of the London-van der Waals attraction forces governed by **Equation 8-17c** between the fibers and particles, and resistive forces determines the actual particle-fiber attachment efficiency (Graham and Mbwette 1987).

E.coli **removal modelling approach**

The prediction of *E.coli* removal as a microbial particle by the geotextile was therefore modelled using CFT filter coefficients for hydrosol deposition in fibrous media (Tien 2012). The correlations were originally derived by Guzy *et al.* (1983) and Choo and Tien (1991) who assumed that removal of hydrosols in fibrous media is due to combined effects of gravitational settling, interception and the London-van der Waals force (Tien 2012). Guzy *et al.* (1983) and Choo and Tien (1991) did trajectory analysis using various cylinder-in-cell models to obtain filter coefficient correlations under conditions of favorable surface interactions (Tien 2012). They considered molecular dispersion, electro kinetic and hydrodynamic forces on the hydrosol using Swarm theory for flow through a system of fibers (Guzy *et al.* 1983). Using results from their application of Kuwabara's cylinder-in-cell model, Choo and Tien (1991) derived the correlation applied in the present study as given by **Equation 8-16** (Tien 2012).

$$\lambda_1 = \left(\frac{6}{\pi}\right)\left(\frac{1-\varepsilon}{d_f}\right)A_s\left[0.216 \text{ x } 10^{-0.41\varepsilon}{N_R}^{1.55}{N_{LO}}^{0.1542} + 2.99 \text{ x } 10^{-4}\text{x } 10^{3\varepsilon}{N_G}^{1.1}{N_R}^{-0.3}\right] \quad (8\text{-}16)$$

For $10^{-3} < N_R < 10^{-1}$;
$10^{-4} < N_G < 10^{-1}$;
$10^{-8} < N_{LO} < 10^{-3}$;
$0.01 < \Phi < 0.65$;

Where: λ_1 = filter coefficient, ε = porosity, N_R = Interception parameter defined by **Equation 8-17a** N_G = dimensionless gravitational parameter defined by **Equation 8-17b;** N_{LO} = London–van der Waals force parameter defined by **Equation 8-17c;** A_s = a hydrodynamic parameter for the Kuwabara cylinder-in-cell model defined by **Equation 8-18a;** Φ = solidity (packing density) = 1-ε, ε = geotextile porosity;

$$N_R = \frac{\mathrm{d}_p}{\mathrm{d}_f}; \quad (8\text{-}17a)$$

$$N_G = \frac{2\mathrm{g}(\rho_p - \rho_w){a_p}^2}{9\mu u_s}; \quad (8\text{-}17b)$$

$$N_{LO} = \frac{\mathrm{H}_a}{9\pi\mu {a_p}^2 u_s} \quad (8\text{-}17c)$$

Where: d_p= particle diameter (m), d_f= fiber diameter (m); μ= absolute viscosity of water (kg/m-s), u_s= filtration velocity (m/s); a_p= particle radius (m); ρ_p= particle density (kg/m^3), ρ_w= density of water (kg/m^3), H_a= Hamaker constant (J).

$$\mathrm{A_s} = \frac{(\frac{2}{3})(4\mathrm{C_1} + \mathrm{C_4})}{\mathrm{C_1}\left(\left(\frac{1}{\Phi}\right) - 2 + \Phi\right) + \left(\frac{\mathrm{C_4}}{2}\right)(\Phi - 1 - \ln\Phi)} \quad (8\text{-}18a)$$

$$\mathrm{C_1} = -\Phi\frac{\mathrm{C_4}}{4} \quad (8\text{-}18b)$$

$$\mathrm{C_2} = -\mathrm{C_1} - \mathrm{C_3} \quad (8\text{-}18c)$$

$$\mathrm{C_3} = \mathrm{C_1} + \left(\frac{\mathrm{C_4}}{2}\right) \quad (8\text{-}18d)$$

$$\mathrm{C_4} = \frac{-4}{2\ln\Phi + 3 - 4\Phi + \Phi^2} \quad (8\text{-}18e)$$

$$\Phi = 1 - \mathcal{E} \quad (8\text{-}18f)$$

Where: Φ = solidity (packing density) (m^3/ m^3), ε = porosity

To cater for the SFCE by Brownian diffusion, which is not accounted for in **Equation 8-16**, the filter Coefficient accounting for Brownian Diffusion (λ_{bm}) was calculated by **Equation 8-19a** (Tien 2012) and was then added to λ_1 (**Equation 8-20**) assuming additivity (Tien 2012; Tien and Ramarao 2007). **Equation 8-19a** was established by Choo and Tien (1991) to account for hydrosol deposition by Brownian motion based on results of the convective diffusion equation solutions.

$$\lambda_{bm} = \left(\frac{9.2}{\pi}\right)(C_1 + C_3)^{\left(\frac{1}{3}\right)}\left[\frac{(1-\mathcal{E})}{d_f}\right]{N_{pe}}^{\left(\frac{-2}{3}\right)} \quad (8\text{-}19a)$$

$$N_{pe} = \frac{d_f u_s}{D_{BM}} \quad (8\text{-}19b)$$

$$D_{BM} = \frac{c_s K_B T}{3\pi\mu d_p} \quad (8\text{-}19c)$$

$$c_s = 1 + \frac{\ell}{a_p}\left[1.23 + 0.41 exp\left(\frac{-0.88a_p}{\ell}\right)\right] \quad (8\text{-}19d)$$

$$\ell = \frac{\mu}{\sqrt{\frac{(2\rho_W P)}{\pi}}} \quad (8\text{-}19e)$$

Where: N_{pe} = Peclet number, dimensionless ; D_{BM} = brownian diffusivity (m^2/s); ε = porosity c_s = Cunningham correction factor, k_B= Boltzmann constant (1.381×10^{-23}J/K), d_f= fiber diameter (m); μ= absolute viscosity of water (kg/m-s), u_s= filtration velocity (m/s); d_p= particle diameter (m), a_p= particle radius (m); ρ_w= density of water (kg/m^3); P = pressure (pa) assumed equal to atmospheric pressure (Tien (2012); T = temperature (K); C_1 and C_3 are as defined in **Equation 8-18** above; ℓ = mean free path of water molecules (m).

Adding λ_1 and λ_{bm}; we obtain a geotextile filter coefficient (λ) that was used in **Equation 8-23**:

$$\lambda = \lambda_1 + \lambda_{bm} \quad (8\text{-}20)$$

Assuming further that the geotextile filter has the same porosity and uniform collector size distribution throughout its depth, the filter coefficient (λ) is defined in **Equation 8-21** (Wakeman and Tarleton 2005):

$$\lambda = -\left(\frac{\delta_N}{N}\right)\left(\frac{1}{\delta L}\right) \quad (8\text{-}21)$$

Where: -δ_N is the reduction of the concentration of *E.coli* as microbial particles passing through a layer of thickness δL. Rearranging the above equation yields **Equation 8-22** (MWH 2012; Wakeman and Tarleton 2005).

$$-\frac{\mathrm{dN}}{\mathrm{dL}} = \lambda N \quad (8\text{-}22)$$

Representing the influent concentration of the microbial particles by N_0 and integrating **Equation 8-22** with L = 0 (as initial conditions) at filter inlet, we obtained **Equation 8-23** which was then used to estimate the fraction of microbial particle concentration remaining in the effluent.

$$\frac{N_e}{N_0} = \exp(-\lambda L) \quad (8\text{-}23)$$

Where: N_e = effluent concentration of *E.coli* (CFU/100 ml); N_o= influent concentration of *E.coli* (CFU/100 ml); L = fibrous filter thickness, L_f (m)

Definitions of the combined system mathematical models

Overall, eight combined mathematical models as defined below and summarized in **Table 8-3** were used in the numerical calculations of the present study. It is worth noting here that most of the model equations used are associated with the various removal mechanisms and parameter equations explained above.

Model 1 refers to the modelled combined removals starting with geotextile filtration governed by **Equation 8-23** coupled to SCCGM disinfection removals modelled by Chick's model **(Equation 8-7)** followed by GAC filtration removals modelled by **Equation 8-13**. **Model 2** refers to the modelled combined removals starting with geotextile filtration governed by **Equation 8-23** coupled to SCCGM disinfection removals modelled by the complete mixing system model **(Equation 8-9)** followed by GAC filtration removals modelled by **Equation 8-13**. **Model 3** refers to the modelled combined removals starting with geotextile filtration governed by **Equation 8-23** coupled to SCCGM disinfection removals modelled by the Collins-Selleck model **(Equation 8-10)** followed by GAC filtration removals modelled by **Equation 8-13**. **Model 4** refers to the modelled combined removals starting with geotextile filtration governed by **Equation 8-23** coupled to SCCGM disinfection removals modelled by Chick-Watson model **(Equation 8-11)** followed by GAC filtration removals modelled by **Equation 8-13**. **Model 5** refers to the modelled combined removals of **Model 1** plus SCCGM filtration contribution modelled by **Equation 8-13**. **Model 6** refers to the modelled combined removals of **Model 2** plus SCCGM filtration contribution modelled by **Equation 8-13**. **Model 7** refers to the modelled combined removals of **Model 3** plus SCCGM filtration contribution modelled by **Equation 8-13**. **Model 8** refers to the modelled combined removals of **Model 4** plus SCCGM filtration contribution modelled by **Equation 8-13**. Model calculations for each run begun with *E.coli* counts in the influent then integrated removal efficiencies (**Equation 8-3**) by each stage (**Figure 8-2** & **Table 8-3**) were applied successively to the influent counts to get effluent *E.coli counts* and respective LRVs (**Table 8-4**). Thus, for given influent *E.coli* counts (N_o) the models predicted effluent *E.coli* counts (N_e) and correspondingly the predicted LRVs were calculated.

Table 8-3: Summary of the E.coli removal prediction combined mathematical models

	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Model 6**	**Model 7**	**Model 8**
E.coli counts	*Influent*	*Influent*	*Influent*	*Influent*	*Influent*	*Influent*	*Influent*	*Influent*
	↓	↓	↓	↓	↓	↓	↓	↓
Geotextile E.coli removal governed by:	*Equation 8-23*	*Equation 8-23*	*Equation 8-23*	*Equation 8-23*	*Equation 8-23*	*Equation 8-23*	*Equation 8-23*	*Equation 8-23*
SCCGM E.coli removal governed by:	*Equation 8-7*	*Equation 8-9*	*Equation 8-10*	*Equation 8-11*	*Equation 8-7 plus, Equation 8-13*	*Equation 8-9 plus, Equation 8-13*	*Equation 8-10 plus, Equation 8-13*	*Equation 8-11 plus, Equation 8-13*
GAC E.coli removal governed by:	*Equation 8-13*	*Equation 8-13*	*Equation 8-13*	*Equation 8-13*	*Equation 8-13*	*Equation 8-13*	*Equation 8-13*	*Equation 8-13*
	↓	↓	↓	↓	↓	↓	↓	↓
E.coli counts	*Effluent*	*Effluent*	*Effluent*	*Effluent*	*Effluent*	*Effluent*	*Effluent*	*Effluent*

Model performance assessment

The *E.coli* removal performance of each model was assessed using the following statistical techniques (Chen and Liu 2015; Gikas and Tsihrintzis 2012; Krause *et al.* 2005; Moriasi *et al.* 2007):

$$R^2 = 1 - \frac{SSE}{SST} = \left(\frac{\sum_{i=1}^{N}(O_i - O_{mean})(P_i - P_{mean})}{\sqrt{\sum_{i=1}^{N}(O_i - O_{mean})^2}\sqrt{\sum_{i=1}^{N}(P_i - P_{mean})^2}} \right)^2 \quad (8\text{-}24)$$

Where: R^2 = coefficient of determination; SSE = sum of squared errors; SST = total sum of squares. P_i = model predicted value; O_i = observed value. P_{mean} = mean of predicted values; O_{mean} = mean of observed values. R^2 values range between 0.0 and 1.0. The ideal value of R^2 is 1.0 which signifies a perfect match between the predicted and measured values, while, R^2 values larger than 0.5 are generally considered acceptable and indicate an acceptable fit. An R^2 value of 0.0 indicates there is no correlation between predicted and measured values.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(P_i - O_i)^2}{N}} \tag{8-25}$$

Where: RMSE = root mean squared error; N = total number of observations; P_i = model predicted value; O_i = observed value. The smaller the RMSE, the better the model predictions.

$$NOF = \frac{RMSE}{O_{mean}} \tag{8-26}$$

Where: NOF = normalized objective function, and O_{mean} = mean of observed values. The optimal value of NOF is 0.0. However, the model is acceptable if NOF values range between 0.0 and 1.0. The smaller the NOF, the better the model predictions.

$$PBIAS = \left[\frac{\sum_{i=1}^{N}(O_i - P_i) * (100)}{\sum_{i=1}^{N}(O_i)}\right] \tag{8-27}$$

Where: PBIAS = Percent bias, and measures the average deviation between predicted and observed values expressed as a percentage; P_i = model predicted value; O_i = observed value. The ideal value of PBIAS is 0.0, with smaller absolute values signifying more accurate predictions. Positive values signify model underestimation bias, while, negative values indicate model overestimation bias.

Sensitivity analysis

Sensitivity analysis was carried to test (i) the effect of neglecting the filtration removal component by the SCCGM to the models, (ii) the effect of modelling *E.coli* removal by disinfection alone, (iii) the sensitivity of contact time, filtration rate, collector diameter and microbial particle (*E.coli*) size to the models. Condition (i), was assessed by essentially comparing the predicted *E.coli* removals by models 1 to 4 with the corresponding removals by models 5 to 8 (**Figure 8-4**), while, conditions (ii) and (iii), were tested using models 3 and 8 to test the sensitivity of simulated *E.coli* removal to each condition or parameter (**Figures 8-5** and **8-6**). The results of the sensitivity analysis are given and explained below under results and discussion.

RESULTS AND DISCUSSION

Comparison of measured and predicted effluent *E.coli* removals

Predicted *E.coli* removals were calculated using the coupled models presented above, which are based on the removal mechanisms elaborated on earlier. **Figure 8-4** gives comparative plots of theoretically predicted and measured *E.coli* Log Removal Values (LRVs) for each run and model respectively. The results (**Figure 8-4** and **Tables 8-4** to **8-5**) show that the coupled models-except for models 2 and 6-reasonably described the combined *E.coli* removals by the multi-barrier system. Although models 1, 4, 5, and 8 gave slight underestimations for runs with lower contact time, their predictions were considered satisfactory as also shown by the model performance criteria in **Table 8-5.** Models 3 and 7 gave the closest predictions of *E.coli* removal values with respect to the measured values, but generally overestimated the LRVs. The appreciable performance by models 1, 3, 4, 5, 7 and 8 signifies they simulated the combined physical and chemical *E.coli* disinfection mechanisms by the multi-barrier system relatively well.

The silver disinfection component by these models was theoretically within the findings by Singh *et al.* 2019), who indicated that about 24 mg.min/L of Ct (silver concentration multiplied by time) value is required to eliminate 99% of *E.coli* from natural stream waters. The calculated Ct values in this study, which corresponded to approximately 99% (≈ 2 LRV) and higher, were >20 mg.min/L. These were from runs 8 to 12 (**Table 8-4** and **Figure 8-4).** Further improvement of the models, particularly in terms of the input parameter values obtained or calculated from literature, could conceivably minimize the underestimations (by models 1, 4, 5 and 8) and overestimation (by models 3 and 7) of *E.coli* removals. Long term experimentation is therefore recommended to improve or calibrate the model input parameter values (especially those obtained from literature). Thus, long term experimentation may possibly help in calibrating model parameters to achieve the best fit between the modelled and measured *E.coli* counts and thereby improve the model performance. Additionally, quantification of measured influent and effluent *E.coli* counts using particle counting techniques may help characterize the modelled *E.coli* microbial particle diameter (dp) better and may significantly enhance the model predictions.

Models 3 and 7 may prompt the design engineer to under design the system, since the expected removals were higher than the measured. Conversely, models 1, 4, 5 and 8 may prompt the design engineer to over design the system. This shows that different model and removal mechanism combinations can produce different bacterial removal predictions. Therefore, using an array of models coupled with larger experimental data sets may help minimize under and over predictions and correspondingly minimize over and under designs of multi-barrier PoU water treatment systems such as the modelled system. Despite the uncertainty involved in mathematical models it can be seen that understanding the theory behind, careful selection and application of removal mechanisms is important for system optimization studies.

In general, the simulated *E.coli* removal trends by models 1, 4, 5 and 8 were relatively similar and consistent with the measured *E.coli* removals for each run, while, the simulated removals by models 3 and 7 showed a slightly better consistency with measured *E.coli* removal trends. The higher removals by models 3 and 7 could be attributed to the silver disinfection by the Collins-Selleck model which generally gave higher predictions for *E.coli* inactivation rates. On the other hand, silver disinfection by models 1 and 5 was simulated by the Chick's model while silver disinfection by models 4 and 8 was simulated by the Chick-Watson model. The Chick's and Chick-Watson models generally under predicted the *E.coli* inactivation rate. However, with further refinement models 1, 4, 5 and 8 are tentatively expected to give a better match since their removals showed a more realistic gradual increment in *E.coli* removals, which closely corresponded to the contact time as is theoretically supposed to be the case.

Figure 8-4 shows that models 2 and 6 were essentially unable to predict the *E.coli* removals. The weak predictions of the two models could be attributed to the CMS model (**Equation 8-9**) being weak at simulating *E.coli* inactivation by silver in the SCCGM which is the main disinfection step in the multi-barrier system. The CMS model, predicts microbial inactivation by using natural die-off kinetics assuming microbial die-off with time (de Moel *et al.* 2007; Qasim and Zhu 2018). It may thus need higher contact time for substantial removals. Better estimates of the mortality rate using more data might help improve the predictions. In addition, the CMS model is principally applicable to bacterial die-off in non-disinfection treatment processes like natural treatment reservoirs (Qasim and Zhu 2018).

Table 8-4: Measured and predicted E.coli log removal values for each run number

Run number	Date of testing	Flow rate (L/h)	Estimated contact time (h)	Measured LRVs	Predicted LRVs							
					Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
1	4/2/2019	10	0.12	2.57	1.21	0.97	2.46	1.21	1.26	1.02	2.51	1.26
2	4/2/2019	10	0.12	1.90	1.21	0.97	2.46	1.21	1.26	1.02	2.51	1.26
3	4/2/2019	10	0.12	1.95	1.21	0.97	2.46	1.21	1.26	1.02	2.51	1.26
4	4/2/2019	10	0.12	2.94	1.21	0.97	2.46	1.21	1.26	1.02	2.51	1.26
5	5/2/2019	8	0.15	1.94	1.38	1.05	2.70	1.39	1.44	1.11	2.76	1.44
6	5/2/2019	8	0.15	2.01	1.38	1.05	2.70	1.39	1.44	1.11	2.76	1.44
7	5/2/2019	7	0.17	2.48	1.51	1.10	2.86	1.51	1.57	1.16	2.92	1.57
8	6/2/2019	5	0.23	2.62	1.90	1.24	3.27	1.91	1.97	1.31	3.33	1.97
9	6/2/2019	3	0.39	4.00	2.82	1.50	3.94	2.82	2.91	1.59	4.03	2.91
10	11/2/2019	2	0.58	4.00	3.95	1.74	4.52	3.95	4.07	1.86	4.64	4.07
11	12/2/2019	2	0.58	4.00	3.95	1.74	4.52	3.95	4.07	1.86	4.64	4.07
12	13/2/2019	2	0.58	4.00	3.95	1.74	4.52	3.95	4.07	1.86	4.64	4.07

Table 8-5: Model performance assessment for measured vs predicted values

Mathematical model	R^2	RMSE	NOF	PBIAS
Model 1	0.822	0.887	0.309	25.4
Model 2	0.828	1.717	0.599	56.3
Model 3	0.826	0.520	0.181	-12.9
Model 4	0.820	0.885	0.309	25.3
Model 5	0.821	0.839	0.293	22.8
Model 6	0.825	1.639	0.572	53.7
Model 7	0.825	0.580	0.202	-15.5
Model 8	0.821	0.839	0.293	22.8

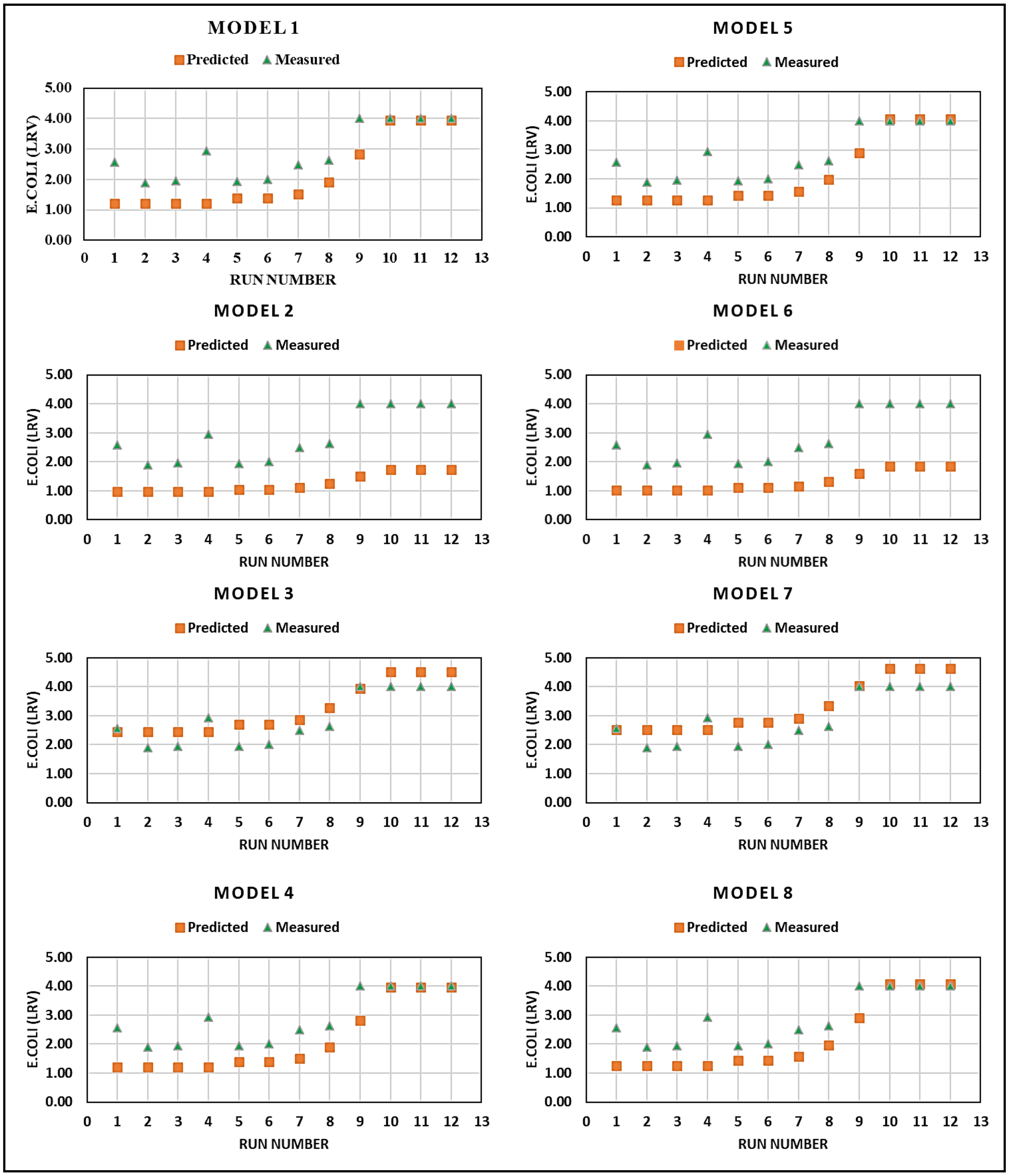

Figure 8-4 Graphical visualization of predicted and measured E.coli log removal values

Effect of neglecting the filtration contribution by the SCCGM

The effect of neglecting filtration contribution by the SCCGM was assessed by essentially comparing the predicted removals by models 1 to 4 with the corresponding removals by models 5 to 8 (**Figure 8-4**). Modelling the additional removal contribution by SCCGM had minimal effect on the predicted overall removal (**Figure 8-4** and **Tables 8-4** to **8-5**). This was not surprising because, except for advanced technologies such as reverse osmosis and iodine resin filters (Backer 2000), bacterial removal by fabric and granular filtration alone is primarily most efficient for suspended solids removal, not for removal of bacteria due to large pore sizes (Backer 2002, 2000; Kausley *et al.* 2018; Siwila and Brink 2018a). Therefore, fabric and granular filtration are normally used as a first stage before other treatment steps (Kausley *et al.* 2018; Shrestha and Spuhler 2018). The need for an in-built disinfection step by silver in the SCCGM is therefore indicated. It should also be noted that without any silver impregnation, granular media may trap, but not inactivate bacteria (Backer 2002), which may potentially get dislodged and subsequently flushed into the treated water (NE-WTTAC 2014). If disinfection is absent or inadequate, bacteria may readily colonize the porous media such as GAC (Backer 2002). This finding is supported by literature from various authors where bacterial removal by silver impregnated filter media (Chong *et al.* 2011; Rossainz-Castro *et al.* 2016; Shimabuku *et al.* 2018) was satisfactorily modelled by considering silver disinfection only without consideration of physical removal by filtration. Thus, porous media impregnated with silver or other metal disinfectants have been shown to be efficient at bacterial inactivation (Chong *et al.* 2011; Rossainz-Castro *et al.* 2016). However, disinfection may also be improved if fabric pre-filtration is provided to increase bacterial contact with the metal disinfectant (Tobiason *et al.* 2011) while GAC post filtration is provided to make the water more acceptable (Backer 2002; Siwila and Brink 2018b; Tobiason *et al.* 2011).

Effect of modelling *E.coli* removal by disinfection only

It was assessed whether *E.coli* removal could be modelled by disinfection kinetics only (**Figure 8-5**) using two models (models 3 and 8) representing possible overestimation and underestimation. Thus, the removal of the coupled models was contrasted with removal by SCCGM disinfection alone. Model 3 was selected for this purpose over model 7 because it showed better performance statistics than model 7 (**Table 8-5**). Similarly, model 8 was chosen over models 1, 2, 4, 5 and 6 since it also depicted better statistics (**Table 8-5**). It can be seen from **Figure 8-5** that, although, *E.coli* removal prediction by SCCGM alone seemed to be a good representation, modelling additional removal by other treatment steps (i.e. geotextile and GAC removals) was still important for the models to be fully representative of the multi-barrier system. Thus, from the results shown in **Figure 8-5**, it can be seen that disinfection removal alone could not fully describe the *E.coli* removals giving predicted LRVs below measured values for both models.

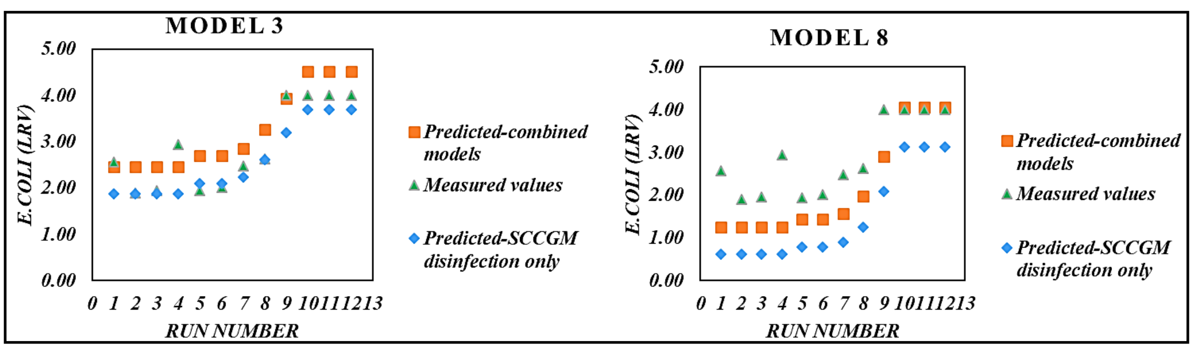

Figure 8-5 Effect of modelling E.coli removal by disinfection only

Effect of contact time, filtration rate, collector diameter and microbial particle *(E.coli)* size

The effect of contact time, filtration rate, collector diameter and microbial particle size on *E.coli* removal was assessed using models 3 and 8 (**Figure 8-6**). Both models indicated that larger contact time (**Figure 8-6(i))** resulted in higher *E.coli* removal. Since contact time is dependent on filter media depth and filtration rate (see **Equation 8-4**); optimizing either or both of the parameters optimizes contact time and subsequently enhances *E.coli* removals. Each of the models used in this study were affected by contact time and hence by media depth (h) and filtration rate (v). For instance, as filtration rate increases (**Figure 8-6(ii)),** *E.coli* removal by both models decreases. Therefore, careful optimization of these parameters is expected to enhance *E.coli* removal performance. It is worth noting that, filtration rate is affected by various factors, of which particle size distribution is the key factor (Siwila and Brink 2019). Therefore, to optimise contact time it is necessary to not only look at filtration rate, but also at factors affecting it such as particle size distribution. If fine granules are insufficient in a filter media the filtration rate is very high leading to lower contact time, while, if coarse granules are insufficient the filtration rate is too low leading to higher contact time. The collector diameter (d_c) depends on particle size distribution and subsequently affects *E.coli* removal prediction.

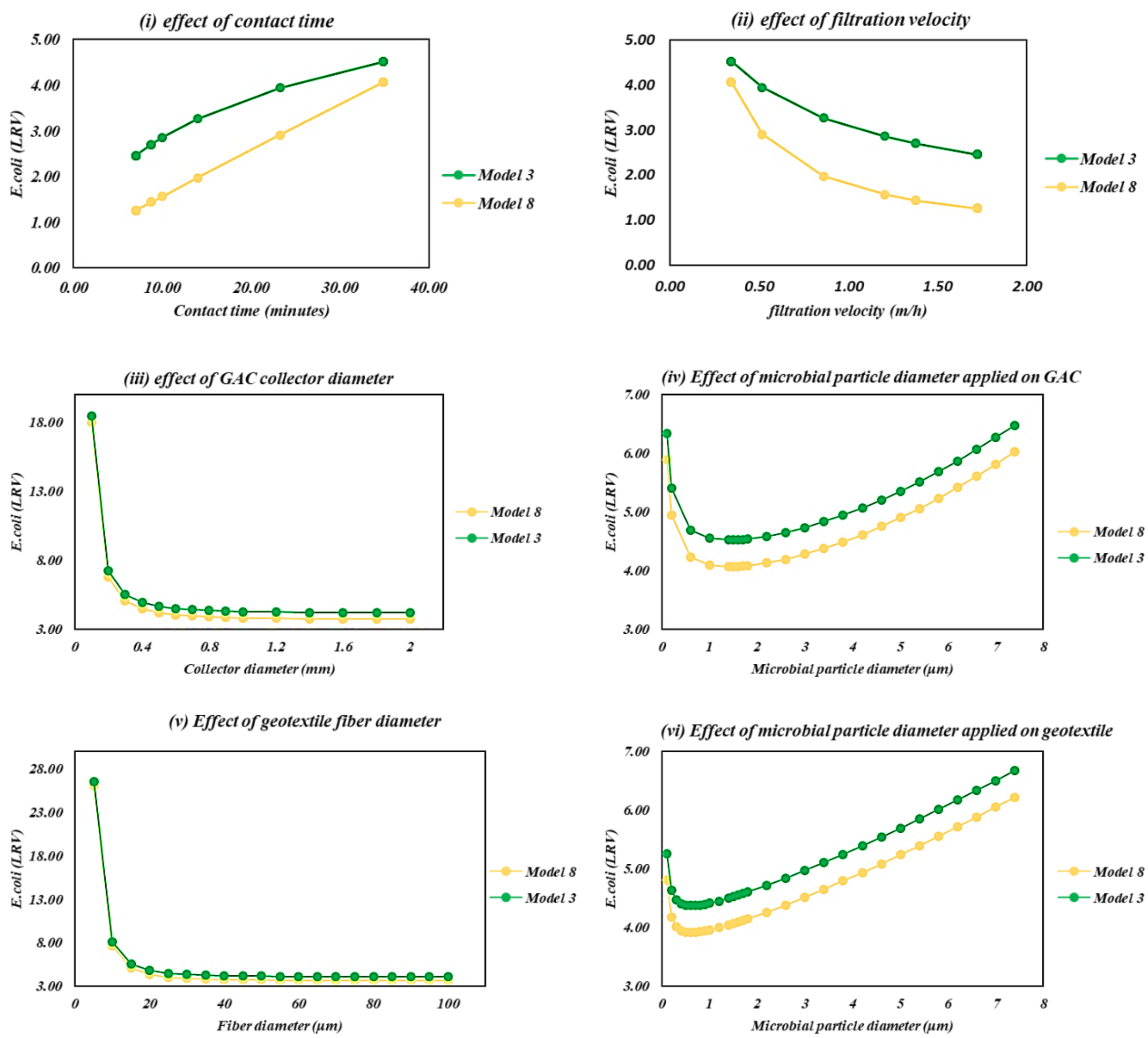

Figure 8-6 Effect of contact time, filtration rate, collector diameter and microbial particle (E.coli) size

The sensitivity of models 3 and 8 to collector and fiber diameter is shown in **Figure 8-6(iii)** and **8-6(v).** The smaller the collector or fiber diameter the higher the removals (**Figures 8-6(iii)** and **8-6(v)**). The sensitivity of microbial particle (*E.coli*) size was also assessed (**Figure 8-6(iv)** and **8-6(vi)).** The effect of the collector/fiber diameter and microbial particle diameter were assessed by applying the varied particle sizes on the geotextile and GAC CFT models which are directly affected by particle size. This analysis was done using the input parameters listed in **Table 8-1** but keeping the optimal flow rate (2 L/h) constant. It can be seen from **Figure 8-6(iv)** and **8-6(vi)** that the microbial particle diameter having the least removal efficiency by GAC and geotextile in both models is somewhere between 1 and 2 µm. Removal of microbial particles below this range increases with decreasing particle diameter because removal is primarily by diffusion (Tufenkji and Elimelech 2004; Yao *et al.* 1971), while, removal of bacteria with diameters larger than 2 µm increases with particle diameter and removal is mainly by sedimentation and interception (Tufenkji and Elimelech 2004; Yao *et al.* 1971). This explanation consequently entails that removal of microbial particles by porous media filtration alone is a huge challenge. This finding is important because it further supports the need for a carefully optimized inbuilt disinfection step to ensure continued safety of the produced water. Overall, the sensitivity analysis results of predicted *E.coli* removals by models 3 and 8 were significantly similar for each parameter assessed (**Figure 8-6**).

CONCLUSIONS AND RECOMMENDATIONS

The modelling exercise has demonstrated that suitable removal mechanisms can be integrally used to model a combined PoU system to predict the overall effluent bacterial quality. This kind of modelling can be used to optimize system design by allowing the engineer to systematically vary design parameters until the desired system effectiveness is attained. This research has also indicated that each barrier or treatment stage contributes to the overall *E.coli* removal. Therefore, the bacterial load on the SCCGM (which is the main disinfection stage) can be significantly reduced by optimizing all components of the multi-barrier (combined) system, especially the pre-filtration stage. Some reasons for differences between predicted *E.coli* inactivation and actual inactivation by models such as the Chick's and the Chick-Watson models include (Qasim and Zhu 2018): (i) disinfectant residue may not be constant or uniform throughout the system and filter runs, (ii) pH changes may affect the inactivation rate, (iii) variations in the incoming suspended particle loads of the water being treated, and (iv) the disinfectant may be consumed by other competitive reactions.

It is recommended that future research should keep the obtained optimal flow constant then model the breakthrough of *E.coli* for several runs ensuring water is passed in triplicate for each run. Furthermore, modelling of data obtained from field testing to assess possible applicability of the mathematical models on field data is proposed. Also, concurrent modelling of *E.coli* and turbidity is proposed since performance of filter systems is usually monitored by measuring effluent turbidity (MWH 2012). Additionally, since the proposed multi-barrier water treatment design, is scalable such that the capacity is flexible and can be increased to serve more consumers, modelling the effect of scalability is proposed. Long term (multiyear) experimentation is also recommended to further calibrate the input parameter values. Quantification of measured influent and effluent *E.coli* counts using particle counting techniques is also recommended. This may help characterize the modelled microbial particle diameter (dp) better.

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Chapter 9: Conclusion

9.1 Summary of findings

Access to safe drinking water remains a challenge in many rural and suburban areas of developing countries (RWSN 2010; Treacy 2019). Mortality rates from contaminated water are correspondingly high, with communicable diseases a serious threat (Demena *et al*. 2003; Eitner and Kondruweit-Reinema 2019). Governments in developing countries worldwide struggle with inadequate resources and infrastructure to meet drinking water needs for all citizens (Savage 2018). PoU water treatment has been shown by various authors (CAWST 2011; Kausley *et al.* 2018; Lantagne and Yates 2018; Pandit and Kumar 2019; Treacy 2019) to improve drinking water safety and reduce the burden of waterborne diseases. It is an interim measure to drinking water provision and sometimes the only option in many rural and suburban areas of developing countries with little or no access to formal drinking water supplies. Although efforts to solve drinking water problems in poor communities are underway globally, challenges still exist (Lantagne and Yates 2018; Pandit and Kumar 2019; Treacy 2019).

The aim of this research was to develop and optimize combined small-scale low-cost gravity driven PoU systems for water treatment (able to provide bacteriologically safe and aesthetically acceptable drinking water) in rural and suburban areas of Southern Africa. A final optimized novel combined small scale low-cost (about 25US$) PoU system for drinking water treatment in the rural and suburban areas of Southern Africa has been proposed in the final Chapters. The final system was developed after development, evaluation and optimization of a range of PoU system configurations. The final system offers a promising and viable method for safe drinking water provision in poor communities of the Southern African region.

Additional to the final optimized combined PoU system, during the course of the research, a range of low-cost treatment methods and technologies for application in low-cost PoU systems were investigated specifically for application in the Southern African region in Chapters 3, 4 and 5. Local materials were sourced and different combined PoU system configurations were designed, constructed and experimented on. Knowledge gained from the experimentations in Chapters 3, 4 and 5 alongside that gained from Chapter 2 was further used in Chapter 6 to develop a specialized comparison framework to aid in the design and choice of materials and systems to use depending on the application. The experimental work further led to the design, optimization and modelling of the final developed system.

The experimental investigation on locally available materials and locally applicable processes in Chapters 3, 4 and 5 initially resulted in the development of three novel and simple, yet innovative water treatment systems namely the: (i) Modified intermittently operated slow sand filtration system incorporating geotextile and GAC (ISSFGeoGAC) for removal of bacteria, particles, color, taste, odor and selected heavy metals, (ii) eight-layer four-pot bidim sequential filtration (BidimSEQFIL) system for bacteria and particle removal and, (iii) indigenous wood filtration combined with GAC (WFSGAC) for removal of bacteria, color, taste, odor, particles and selected heavy metals; as presented in Chapters 3, 4 and 5. These were then comparatively evaluated alongside two commercially available PoU systems (investigated in Chapter 2) using the novel comparison framework developed in Chapter 6 as mentioned above.

This further led to the design, optimization and modelling of a novel combined PoU system as presented in Chapters 7 and 8. Thus, the knowledge gained in the experimental investigations of Chapters 2, 3, 4 and 5 and the comparison framework results in Chapter 6 was further applied in developing the proposed novel combined PoU system presented in Chapter 7. It has been developed and optimized to produce bacteriologically safe water at an optimized filtration rate of 2 L/h. This system was subsequently chosen for optimization and the detailed modelling which was done in Chapter 8.

Based on the study in Chapter 6 and various issues identified in Chapters 2, 3, 4 and 5, it was decided to incorporate the following in the design of the final product as initiatives towards possible alleviation of certain identified issues: (i) safe storage compartment to minimize recontamination, (ii) GAC filtration for aesthetic improvement and possible enhancement of additional removal of other contaminants such as iron and manganese which impart color and taste to water, (iii) inbuilt disinfection provided by the silver in the SCCGM to avoid further treatment by disinfection (e.g. chlorination which imparts smell and taste to water) and thereby enhance acceptability of the treated water. The more so that, silver concentrations needed for bacterial inactivation in water do not impart color, taste or odor to water (Pandit and Kumar 2019). This is also expected to avoid DBPs by chlorination such as trihalomethanes and Halo acetic acids (HAAs) which are suspected carcinogens, and (iv) pre-filtration by the nonwoven bidim geotextile as a form of pretreatment to remove debris and larger microbes (e.g. helminths and protozoa) and reduce particulate loads in the water before it passes through the disinfection step. This makes the raw water fit for silver disinfection and reduces clogging especially in that bidim geotextile is a robust fabric and can be easily washed by hand. Thus, pre-filtration removes most of the suspended particles and enables silver disinfection to be more effective.

Furthermore, pre-filtration was included to enhance the system's ability to treat a broader variety of raw water and extend filter runs and to cater for fluctuations in suspended particle concentrations in the surface waters of rural and suburban communities of Southern Africa. SCCGM is a replicable filter media produced by TAM ceramics (2019) based on "red firing clays" with many advantages, such as no need for pause (waiting) period or biolayer development which are required in ISSF systems and are difficult to manage by many users. Also, red firing clays can be found nearly anywhere in Southern Africa. Laboratory tests on the system in Chapter 7 showed high potential for significant *E.coli* and fecal coliforms removal (>99.99%) at an optimum flow of 2 L/h. The system exhibited substantial improvements of aesthetic aspects (color, odor and taste) with average turbidity removals of 99.2%.

The work in Chapter 8 presented mathematical modelling of *E.coli* removal of the developed multi-barrier PoU drinking water system. The system was modelled as a series of three compartments integrating the removals by geotextile filtration, SCCGM filtration and disinfection and GAC filtration. The individual models used accounted for removal mechanisms by each treatment stage. *E.coli* inactivation by SCCGM was modelled using the Chick's, Chick-Watson, Collins-Selleck and complete mix system bacterial inactivation kinetic models, which were considered adequately representative for describing the removal. Geotextile removal was modelled using colloidal filtration theory (CFT) for hydrosol deposition in fibrous media. The filtration removal contributions by the SCCGM and GAC were modelled using CFT for removal of colloidal particles by granular media. In the CFT models *E.coli* was modelled as a microbial particle. Suitable parameter values were estimated and applied to the models. The theoretically combined models demonstrated that suitable removal mechanisms can be applied integrally to model a combined PoU system to predict overall effluent bacterial quality. This kind of modelling can be used to optimize the developed system and to design and optimize similarly combined PoU systems by allowing engineers to systematically vary design parameters until desired system effectiveness is attained. An attempt was also made to assess the effect of various factors that affect bacterial removal performance e.g. collector diameter, particle size, contact time, media depth and filtration rate.

In addition, a novel specialized comparison framework was developed and demonstrated in Chapter 6 for evaluating low-cost PoU technologies as mentioned above. Although it is difficult to choose which type of PoU technology is best for all applications due to many factors required for different situations and resource availability, the comparison framework results in Chapter 6 showed that it is possible to qualitatively and quantitatively compare low-cost PoU technologies, thereby helping decision making. A recent study by Stubbe *et al.* (2016) concluded that insufficient reliable information is available for a straightforward recommendation for the most effective and affordable PoU system/device. Therefore, the specialized comparison framework finds possible application by engineers and implementers for comparatively assessing low-cost PoU systems. This can also assist engineers to improve and modify or innovate even further on low-cost PoU systems.

The study in Chapter 2 comparatively analyzed two commercially available low-cost PoU systems with similar process and material combination namely the GWS and DFS and assessed whether the quality of their treated water is sufficiently comparable to good quality tap water municipal supply. It showed that the treated water from the two systems compared well with good quality tap water supplied to Stellenbosch University with respect to bacterial, turbidity and suspended solids content. Both systems produced bacteriologically safe drinking water (with an apparent 100% removal for *E.coli* and fecal coliforms) due to chlorine disinfection in the gift of water system (GWS) and silver disinfection in the drip filter system (DFS) and are relatively affordable water treatment options, with their own benefits and drawbacks, most of which are highlighted in Chapter 2. The polypropylene string filter in the GWS was indicated to be able to pre-treat turbid water. Furthermore, the improvement of aesthetic aspects (turbidity, color, taste and odor) was generally good due to the presence of GAC in both systems. This may often enhance user acceptability of the two PoU systems. The main drawbacks with respect to the GWS are the need for regular filter replacement, and potential for production of DBPs-e.g., trihalomethanes-due to the use of NaDCC tablets in both the top and bottom buckets, especially if the GAC, which removes excess chlorine, fails during use. The major drawbacks with the DFS are the ceramic candle filter being fragile, slow filtration rate and regular filter cleaning to remove clogging. The findings on the investigated commercial PoU systems in Chapter 2 led to the further investigation into performance improvement of an ISSF system by incorporating geotextile fabrics for pre-filtration and GAC for aesthetic improvement which was done in Chapter 3.

Overall, the study in Chapter 3 and Appendix A which resulted in the ISSFGeoGAC as mentioned earlier, demonstrated that modified ISSF systems incorporating pre-filtration by geotextile and further filtration by GAC can together with the other removal mechanisms in ISSF systems (predation, natural die-off, straining and adsorption) substantially enhance the removal effectiveness of multiple contaminants. Combined with a correct pause period, this can in turn enable the combined system to provide safe water of good aesthetic quality. After filter ripening, the *E.coli* removals by the ISSFGeoGAC recorded up to 99.9% *E.coli* and fecal coliforms removal. However, even before filter ripening, bacterial removal by ISSFGeoGAC was high, reporting fecal coliform removals of up to 94% and *E.coli* removals of up to 89%. In addition, the average *E.coli* removal rates (96%) by the ISSFGeoGAC were slightly higher than those typically reported for traditional ISSF systems, e.g. 90% (WHO 2017a). These findings could be attributed to the presence of the geotextile filter mats on its filter surface and enhanced adsorption by GAC presence in its system. This may considerably offer advantages over traditional ISSF systems which before filter ripening (full development of biolayer) only remove about 30-70% of bacteria through adsorption and mechanical trapping (CAWST 2010). It was noted, however, with the gained knowledge from the study in Appendix A that, physical removal alone is not adequate in ISSF systems. Table 3-3 indicated reasonable iron removals by ISSF-1, but the effluent iron concentrations were slightly above the criteria value of 300 μg/L given in Table 3-2. Possible explanation for this could be that at the time of sampling for metals the GAC which enhanced Iron removals had probably reached saturation as indicated by figures 3-4 and 3-5 for turbidity and TSS removals. Metal sampling was only done after 5 months of filter operation while GAC saturation was observed to have occurred after 4 months of operation during data analysis.

The study in Chapter 4 on "Low cost drinking water treatment using nonwoven engineered and woven cloth fabrics" resulted in an optimized simple, yet innovative low-cost PoU water treatment system namely BidimSEQFIL. BidimSEQFIL is a promising technology for low-cost water treatment in poor communities. In addition, numerical models for predicting turbidity removal (presented in Chapter 4) were developed for each fabric as support tools for selecting optimal process configuration. The bacterial removal numerical model for the BidimSEQFIL system was presented as additional content to Chapter 4. The optimized fabric filtration technique was constructed and tested. It was found that BidimSEQFIL can substantially remove indicator bacteria (*E.coli* and fecal coliforms) up to 3 log removal value (LRV). The finding is important because bacterial removal performance by BidimSEQFIL is much better than both ordinary fabric filtration and three-pot settling methods and has minimal recontamination potential. Additionally, bidim geotextile has comparative advantage for drinking water treatment over ordinary fabrics as it is stronger and can be reused more often with less cleaning needs. It is cost-effective and can be readily sold and easily transported in bulk to many parts of Southern Africa. Furthermore, bidim fabric is easy to wash without significant fabric loosening by normal hand wash as opposed to cloth fabrics which loosen significantly over time further reducing their contaminant removal. The fabric can also be disinfected in ordinary utility ovens at around 100 to 200^{o}C and is structurally stable up to 200^{o}C (Kaytech Engineering 2018).

The study in Chapter 5 on "Drinking water treatment using indigenous wood filters combined with granular activated carbon" resulted in a simple, yet innovative low-cost PoU water treatment system, namely the WFSGAC as mentioned above. The technology is appropriate for the rural poor. The study demonstrated the possibility of using Southern African indigenous wood filters under low water pressure for low-cost water treatment and use of wood filters in combination with GAC (and potentially charcoal). The indigenous wood species were found to be a valid technological research area for low cost water filtration in rural areas of Southern Africa and future research into this area is warranted. The case study also demonstrated simple but valid and novel possibilities of using and preserving the indigenous wood filters for drinking water treatment in the rural areas of Southern Africa using available resources. Although a few aspects remain to be investigated, some practicalities have been demonstrated such as gravity driven wood filtration, filtration rates by each wood species, effect of GAC incorporation on the quality of produced water, initial assessment of the period after which the filter elements should be replaced, significant bacterial removals and possible heavy metals removal.

Since the initial tests in Chapter 5 on using wood filters alone produced water with objectionable aesthetic aspects (color, odor and taste) which may discourage many potential users of the technology, it was decided to combine the wood filters with GAC to enhance aesthetic improvement. In areas where GAC is not available, normal charcoal may be used possibly with slightly deeper sections than GAC, however future investigation in this application is warranted. When tested using *Combretum erythrophyllum* and *Salix mucronata* tree species, the gravity driven WFSGAC recorded 100 % removal for indicator bacteria (*E.coli* and fecal coliforms). The combined system also significantly removed heavy metals: Fe, Pb, Ni, Al and Zn above 90%, and: Cu, As, Cr, Cd and Mn above 50%.

The gravity driven wood filtration system was chosen for research over a mechanical pressure system because: (i) a gravity driven wood filter system does not require electricity or tap pressure for its operation and is expected to be easier to operate, appropriate and affordable to the rural poor, and (ii) to the author's knowledge no gravity driven wood filtration has been presented in any published literature particularly using Southern African indigenous species. In other words - because pressure filtration requires pumps / high heads research into the possible use of an even simpler - gravity driven (low pressure) wood filter system was warranted to see if it could be at all feasible. The gravity driven WFSGAC technology finds possible application in PoU drinking water systems implemented by governmental or non-governmental organizations for the rural poor with little or no access to formal drinking water supplies.

The research done forms a strong basis for further studies to conduct field trials and optimize practical PoU water treatment systems for wider application, which could realize an important contribution to human health especially for those with little or no access to formal drinking water supplies. The study resulted in useful findings potentially beneficial to the water treatment sector. It provides significant contributions and insights towards decision making and application of low-cost PoU water treatment methods.

9.2 Recommendations

General recommendation include the following:

1. In places where GAC cannot be obtained, it is possible that ordinary charcoal may be used with slightly deeper sections than GAC; therefore, further research in this application is recommended. This recommendation applies to all investigated systems that incorporated GAC including the final system.

2. Long-term research is recommended on all the investigated wood filters with and without GAC to ascertain how long *E.coli* removal could be sustained by the filters before filter disintegration, in order to recommend filter replacement times. Additionally, further research for application in a specific rural area should consider local wood species coupled with a large sample size of filters per wood species to investigate possible variation within the chosen species.

3. Users of the developed WFSGAC technology should ensure safe indigenous wood species are used in consultation with native people or trained plant specialists with sufficient knowledge on each tree species. Additionally, regular replacement of the GAC or charcoal is recommended to avoid bacterial regrowth on the GAC.

4. Since there is a synergy between pause (waiting) period and contaminant removal efficiency by the developed ISSFGeoGAC technology, to ensure consistent and substantial bacterial inactivation and particle removal and adequate aesthetic improvement, the ISSFGeoGAC system should be used with a 24 hour residence time (pause period) for each filter run. A short pause period reduces removal efficiency therefore adequate pause period up to a maximum of 48 hours (CAWST 2010) should be considered for best possible bacterial inactivation and particle removal. It is also recommended that GAC or charcoal be replaced after every 4 months. Additionally, when the flow rate becomes too low, the geotextile filter mats should be removed and washed and a recovery period of at least 14 days should be allowed after that for substantial bacterial inactivation to be revived. Just like required during the biolayer development after filter commissioning, chlorination of the filtered water during the recovery period after system cleaning is a must.

5. To ensure dependable application of the developed BidimSEQFIL system, potential users are advised to wash and disinfect the bidim fabrics as well as the treatment and storage vessels after each use. This will enable consistent bacterial and particle removal performance and minimize recontamination. Similarly, potential users of the WFSGAC and ISSFGeoGAC systems are advised that any container used to collect, and store raw water should be used for raw water only, while, vessels used for storing purified water should not be used for collecting or storing raw water and the containers should be regularly disinfected with a cleaning detergent or chlorine. Also, an appropriate disinfection step, e.g., solar disinfection or chlorination, is still recommended on the treated water by the said three systems to ensure continued water safety.

6. Since silver bactericidal action is generally slow, which requires higher contact time thereby necessitating low optimal flow rates, the developed multi-barrier system should be operated within ± 0.5 L/h of the optimized flow rate (2 L/h) for consistent bacterial removal. In addition, daily cleaning of the pre-filtration geotextile is proposed to avoid breakthrough of originally captured particles. Regular replacement of GAC is also proposed to prevent any possible bacterial regrowth in the GAC column of the developed system. In addition, feasibility of: (i) sandwiching the GAC in the side column between small equal layers of SCCGM, (ii) use of silver impregnated GAC in the side column, and (iii) use of more geotextile layers for pre-filtration are suggested for further studies on the developed system. Furthermore, long term (multiyear) and field testing of the developed system at the optimized flow rate of 2 L/h to assess adoptability, acceptability, pollutant breakthrough, system lifespan, field performance and sustainability is recommended.

7. Adequate training is also proposed wherever the investigated systems are to be used so that users can correctly use and maintain the technologies. Implementers should ensure adequate training of the users. Furthermore, advantages and limitations for the developed and each investigated system should be jointly considered. Depending on the raw water quality, user needs and practicality, careful selection, adoption or necessary improvement can then be done to supply safe and aesthetically acceptable drinking water.

8. Long term experimentation and extensive testing is recommended to improve or calibrate the model input parameter values (especially those gotten from literature) and to further calibrate the mathematical models used in Chapter 8. Thus, long term experimentation may help in calibrating model parameters to achieve best fit between the modelled and measured *E.coli* counts and thereby improve the model performance. Additionally, quantification of measured influent and effluent *E.coli* counts using particle counting techniques is proposed and may help characterize the modelled *E.coli* microbial particle diameter (dp) better. Modelling of the final system's *E.coli* breakthrough for several runs by keeping the obtained optimal flow rate constant is also recommended for future research. Furthermore, modelling of data obtained from field testing to assess possible applicability of the mathematical models on field data is recommended.

9.3 Research Contributions

The following contributions towards new knowledge, practical application and choice of Point of Use systems were made:

1. The study on "Drinking water treatment using indigenous wood filters combined with granular activated carbon" is a new application of natural materials in the Southern African setting and is an inimitably new contribution to science unique to this dissertation. The study demonstrated the possibility of using Southern African indigenous wood filters under low water pressure for low-cost water treatment and use of wood filters in combination with GAC (and potentially charcoal). Although a number of aspects remain to be investigated, some practicalities have been demonstrated such as gravity wood filtration, filtration rates by

each wood species, effect of GAC incorporation on the quality of produced water, initial assessment of the period after which the filter elements should be replaced, significant bacterial removals and possible heavy metals removal. The work resulted in an optimized simple, yet innovative gravity driven low-cost PoU water treatment system namely the "wood filtration system combined with GAC (WFSGAC) able to improve water security in rural areas of Southern Africa. The WFSGAC showed high potential for significant *E.coli* and fecal coliforms removals. Evaluations were done using fresh, wet preserved and dry preserved Southern African indigenous wood species namely: *Combretum erythrophyllum*, *Tarchonanthus camphoratus*, *Leonotis leonurus* and *Salix mucronata*. The indigenous wood species studied were found to be a valid technological research area for low-cost water filtration and future research into this area is guaranteed. Inclusion of GAC for improvement of aesthetic aspects (color, smell and taste), which may discourage potential users of the wood filtration technology is new and has not been presented before to the author's knowledge.

2. The study on wood filtration additionally presented simple but valid and novel possibilities of using and preserving wood filters for drinking water treatment applicable to rural areas namely dry and wet preservation. Additionally, gravity driven wood filtration was chosen for research over a mechanical pressure system because: (i) to the author's knowledge no gravity driven wood filtration system has been presented in any published literature particularly using Southern African indigenous species, and (ii) a gravity driven wood filter system does not require electricity or tap pressure for its operation and is expected to be easier to operate, appropriate and affordable to the rural poor. One of the main challenges to safe water provision in most rural areas of Southern Africa is the energy required to purify water, therefore a gravity driven system would be most preferable. In other words - because pressure filtration requires pumps / high heads research into possible use of an even simpler - low pressure (gravity driven) wood filtration was warranted to establish whether it could be at all feasible as further contribution to knowledge. The gravity driven WFSGAC technology finds possible application in PoU drinking water systems implemented by governmental or non-governmental organizations for the rural poor with little or no access to formal drinking water supplies.

3. The study on "Low cost drinking water treatment using nonwoven engineered and woven cloth fabrics" resulted in an optimized simple, yet innovative low-cost PoU water treatment system namely the "eight-layer four-pot bidim sequential filtration system (BidimSEQFIL)". BidimSEQFIL is unique to this study and a promising technology for low-cost water treatment in poor communities. In addition, numerical models for predicting turbidity removal efficiency were developed for each fabric as support tools for selecting optimal process configuration. The optimized fabric filtration technique was constructed and tested. It was found that BidimSEQFIL can substantially remove indicator bacteria (*E.coli* and fecal coliforms) up to 3 log removal value (LRV). The finding is important because bacterial removal performance by BidimSEQFIL is much better than both ordinary fabric filtration and plain sedimentation (or three-pot settling) methods and has minimal recontamination potential. Additionally, bidim geotextile has comparative advantage for drinking water treatment over ordinary fabrics as it is stronger and can be reused more often with less cleaning needs. It is cost-effective and can be readily sold and easily transported in bulk to many parts of Southern Africa. Furthermore, bidim fabric is easy to wash without significant fabric loosening by normal hand wash as opposed to cloth fabrics which loosen significantly over time further reducing their contaminant removal. The fabric can also be disinfected in ordinary utility ovens at around 100 to 200^{o}C and is structurally stable up to 200^{o}C (Kaytech Engineering 2018).

4. The work in Chapter 3 and Appendix A resulted in a simple, yet innovative low-cost PoU water treatment system namely the "modified intermittently operated slow sand filtration system incorporating geotextile and GAC (ISSFGeoGAC)" which has possible application in many rural and suburban areas of Southern Africa. Different studies have explored the application of ISSF systems for low-cost drinking water treatment. However, the incorporation of filter mats made of geotextile fabric serving as a pretreatment step (to significantly reduce the particulate loads in the water before it passes through the sand body) and GAC beneath the sand layer as an adsorption media for improving aesthetic aspects (color, taste, odor) and enhanced removal of selected heavy metals has not been presented in any published literature before to the author's knowledge. In addition, the filter mats extended filter run times and offered easy filter cleaning by removal and washing of the fabric alone as opposed to the laborious "scraping" or "swirl and dump" cleaning methods in traditional ISSF systems. The durable low-cost filter mats also enabled the ISSFGeoGAC to treat a broader variety of raw water. Sand is a robust natural material which is readily available in many parts of Southern Africa. Therefore, enhancing ISSF system's contaminant removal and consistency in aesthetic improvements of the treated water while extending filter runs in a relatively affordable way is a novel initiative and a new contribution to knowledge on ISSF applications and can promote user acceptability of the investigated technology.

5. The assessment of whether the quality of the commercially available PoU system's treated water was sufficiently comparable to good quality tap water municipal supply at Stellenbosch University over the study period is important and new. This kind of work has not been presented before and can build user confidence for such systems thereby promoting their adoptability and acceptance. Furthermore, comparative analysis of commercially available low-cost PoU systems with similar process and material combination such as done in Chapter 2 can assist researchers to improve/modify or innovate even more on low-cost PoU drinking water treatment systems. The studied commercial systems significantly improved the bacteriological and aesthetic quality of the polluted surface water used and are relatively affordable. However, these may not be sustainable for application by the poorest groups in Southern Africa. The GWS requires continuous supply of NaDCC tablets while the ceramic candle filter of the DFS clogs quickly and is easily breakable and therefore requires frequent cleaning and frequent replacement. On the other hand, the novel systems mentioned above, principally constructed from local materials, were more robust and affordable, can supply relatively safe water and can be constructed by users with minimal training.

6. A novel specialized comparison framework was developed and demonstrated in this study for evaluating the low-cost PoU technologies included in this research. Although it is difficult to choose which type of PoU technology is best for all applications due to many factors required for different situations and resource availability, the comparative evaluation showed that it is possible to qualitatively and quantitatively compare low-cost PoU technologies, thereby helping decision making. A recent study by Stubbe *et al.* (2016) concluded that insufficient reliable information is available for a straightforward recommendation for the most effective and affordable PoU system/device. Therefore, the novel comparison framework finds possible application by engineers and implementers for comparatively assessing low-cost PoU systems. This can also assist engineers to improve and modify or innovate even further on low-cost PoU systems.

7. Although there is still room for improvement, the final developed and optimized multi-barrier low-cost combined system incorporating geotextile fabric for pre-filtration, SCCGM for filtration and disinfection, and GAC as an adsorption media, offers a novel concept of a drinking water treatment system that can be applied in rural and suburban settings with higher acceptability and adoptability potential. The combined three-step gravity driven system showed potential to substantially remove particles and bacteria, improve

aesthetic aspects and significantly remove iron and manganese due to its material and process combination. Moreover, as mentioned earlier, the proposed system can be easily scaled up to cater for more users. It also contains a built-in safe storage compartment for treated water to minimize recontamination which usually occurs when PoU methods are used as stand-alone items. Additionally, no chemical addition is needed due to the presence of an inbuilt disinfection step provided by the silver coating, thereby reducing running costs. Many available low-cost PoU systems chiefly depend on separate steps such as filtration followed by chlorination, solar disinfection, boiling, etc. to provide bacteriologically safe water. The proposed combined novel system has demonstrated potential to consistently supply bacteriologically safe and aesthetically acceptable water at an optimal flow rate of 2 L/h. Furthermore, production of the clay based SCCGM which is responsible for disinfection is replicable almost anywhere in Southern Africa because the ‘red firing clays’ used to produce the filter media can be found in abundance nearly anywhere in the region and according to TAM ceramics (2019) only small amounts of silver are needed. Furthermore, the pre-filtration material (geotextile), adsorption media (GAC) and containment PVC pipes are already locally produced in the Southern African region.

8. The mathematical modelling in Chapter 8 which was done using *E.coli* as an indicator organism to aid in optimization of the final system (discussed in Chapter 7 above) may support future research in terms of configuration, process combination, flow rate, material combination, etc. The theoretically combined models used demonstrated that suitable removal mechanisms can be applied integrally to model a combined PoU system to predict overall effluent bacterial quality. This kind of mathematical modelling can be used to optimize the developed system and to design and optimize similarly combined PoU systems by allowing engineers to systematically vary design parameters until desired system effectiveness is attained. In addition, modelling of PoU systems has mainly been done on uncombined systems and has generally received less attention compared to modelling of centralized water treatment systems. Therefore, the bacterial removal modelling on the developed low-cost combined PoU system done in this thesis is a new contribution to knowledge and will be useful to many combined PoU system developers and implementers.

9.4 Proposed future research

Proposed future research includes:

1. Since only fecal indicator bacteria (*E.coli* and fecal coliforms) were used in this study as indicated under delineations and limitations, making use of surrogates (bacteriophages for viruses, cryptosporidium or giardia species for protozoan parasites and *E.coli* or enterococcus for bacteria) is recommended for future tests on the developed and all other investigated systems. This is because other organisms may respond differently to particular water treatment systems as well as to fully comply with the WHO recommendations.

2. The use of microscopy and image analysis equipment such as the scanning electron microscope (SEM) before and after filtration (to: (i) visualize the longitudinal and cross-sectional characteristics (such as tracheids and vessels and pits and pit membranes) of the indigenous wood filters, (ii) approximate the pore diameter and densities of the investigated indigenous wood filters, and (iii) identify the actual filter features responsible for bacterial and particle removal) is proposed. This was not done due to budget constraints. Identification of the main features responsible for contaminant removal and estimation of characteristics such as the pore diameter and pore densities for each species may help in comparative assessment of various indigenous wood species and in further optimization of the wood filters.

3. Raw water samples for the evaluation tests were collected from the Kromrivier, a polluted urban river in Stellenbosch which was considered representative of surface waters found in rural and suburban areas. However, in some parts of Southern Africa, water resource availability is limited, and water resources are unevenly distributed necessitating development of other water sources. Therefore, feasibility of using the technologies investigated in this study for treating water from other sources (e.g. groundwater, harvested rainwater, seawater, etc.) is proposed to conceivably cater for water scarce areas and a large clientele.

4. Although the developed system is primarily intended for about 5 to 10 users and was evaluated as such in Chapter 7, it can be easily scaled up to serve e.g. 100, 1000, 2000 etc. persons or for institutional use e.g. in rural schools, rural clinics, refugee camps, etc., as elaborated in Chapter 1. According to Luh and Bartram (2017), the SDG target on clean water and sanitation for all is not only confined to household sized water treatment systems, but also extends to institutional settings, such as rural health centers, rural schools, refugee camps, etc. The scalability of the developed system can therefore enhance its adoption and implementation potential by NGOs and engineers. Hence, future research could include evaluation, modelling and optimization of scaled up systems able to serve more users e.g. 100, 1000, 2000, etc. In addition, since one limitation of the designed multibarrier system is the height, which is relatively high, future investigation into reasonably reducing the system height by e.g. use of larger diameter PVC pipes could mitigate this limitation. Also, in places where the water is generally aesthetically appealing, investigation into the possibility of leaving out the GAC column from the system could reduce system costs and avoid GAC replacement costs further minimizing potential for bacterial regrowth in the system.

5. The technical and performance evaluation studies were principally done under laboratory conditions over specific time periods. A combination of lab and field testing to ascertain removal performance sustainability and other criteria e.g. flow rates, user acceptability and maintenance requirements is recommended for future research. Although research outcomes for improving safe water needs in poor communities are primarily met by development of novel low-cost drinking water systems, field testing helps to establish suitability, field performance, effects of various user practices and operating scenarios, technology application problems and how they can be alleviated, and sustainability of novel technologies towards satisfying the needs of intended users.

6. Investigation of gravity driven wood filtration as a novel low-cost drinking water technology was done using Southern African indigenous tree species namely: *Combretum erythrophyllum*, *Tarchonanthus camphoratus*, *Leonotis leonurus* and *Salix mucronata.* Since not all indigenous species were investigated due to time and resource constraints, investigation into more indigenous tree species is proposed for future research. There is a lot of potential for further work on characterization of indigenous wood types according to various zones and development of tools toward selection of tree species for PoU water treatment systems. Thus, future work on application of Southern Africa indigenous wood filters for PoU water treatment is warranted. In addition, possible use of a single large enough raw water tank feeding multiple flexible pipes running in parallel connected to multiple wood filter elements at the desired hydraulic head could help deliver enough drinking water for a small household. Future, investigation into this application is warranted.

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Appendix A: Conference paper: Point of Use water treatment through use of activated carbon and geotextile layered within an intermittently operated slow sand filter

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ABSTRACT

Performance of an intermittently operated slow sand filter incorporating non-woven geotextile and granular activated carbon (GAC) as alternate layers for Point-of-Use water treatment was investigated. Laboratory scale systems were evaluated when exposed to polluted stream water for 4 months. Filter system 1 (FS1) incorporated GAC and filter system 2 (FS2) incorporated non-woven geotextile layers. Filter system 3 (FS3) incorporated both. Treatment effectiveness was estimated using *E.coli*, fecal coliforms, turbidity and total suspended solids (TSS). Average removals by FS1, FS2 and FS3 were 95%, 93% and 91% for *E.coli* and 96%, 94% and 90% for fecal coliforms respectively. Average reductions by FS1, FS2 and FS3 were 98%, 91% and 92% for TSS and 98%, 89% and 90% respectively for turbidity. The results suggest that FS1's layer combination made it the best performing system. SANS241 standards and WHO drinking water guidelines were only met by FS1 after chlorination, though chlorine demand was minimal due to low bacterial and turbidity levels in the treated water. Each system's effluent consistently met potable water guidelines in terms of pH, Conductivity and TDS. Each model's bacterial removal efficiency was substantial, and it may be possible to reduce pathogenic loads to below infectious dose.

Key words: design and technical aspects, filter system optimization, GAC, ISSF, point-of-use, water treatment

INTRODUCTION

Only one out of three people in rural areas use safely managed drinking water services and about 159 million people worldwide still collect drinking water directly from surface water sources, of which 58% live in sub-Saharan Africa (JMP 2017). The surface water sources are often contaminated and unsafe. Most consume the water untreated because it is the only available option. Some boil their water, but boiling requires much fuel, making it expensive and unsustainable, consequently posing a threat to natural resource sustainability (Elliott *et al.* 2006). Provision of affordable point of use (PoU) water treatment systems for rural and remote areas can greatly contribute to safe drinking water provision and reduce the risk of waterborne diseases thereby saving lives. According to JMP (2017), safe drinking water is water used for drinking, cooking, food preparation and personal hygiene; free from pathogens and elevated levels of toxic substances**.** Three lab scale PoU systems with use of GAC and geotextile within an intermittently operated slow sand filter (ISSF) were designed, constructed and evaluated.

There is increasing acceptance that small-scale PoU water treatment to ensure drinking water safety, particularly in poorly serviced communities, should be incorporated into national strategies to reduce waterborne diseases (WHO 2007). Conventional and high-tech water treatment systems (Baruth 2005; de Moel *et al.* 2007) are often unaffordable to poor communities (McAllister 2005). These are usually expensive and difficult to construct and require expensive equipment and chemicals. A growing body of research suggests that the use of PoU water treatment using technologies such as ISSFs (Mihelcic *et al.* 2009; WHO 2007): (i) dramatically improves bacteriological water quality, (ii) significantly reduces diarrhoeal disease morbidity, (ii) is among the most effective of water, sanitation and hygiene interventions, (iv) is highly cost-effective, and (v) can be rapidly deployed and taken up by vulnerable populations.

Low-cost water treatment systems, which minimize chemical usage and are easy to use, are likely to be more acceptable and can save lives in many communities. This study designed and optimized a modified ISSF system as a contribution to research and development on affordable low-cost PoU water treatment. The study findings will be applicable to both the institutional scale ISSF system (CAWST and SPC 2017)-a recently developed concept that needs further research-and to the ordinary household scale ISSF system (CAWST 2010; Manz 2004). Under suitable circumstances, ISSF systems may often be among the cheapest, simplest and most efficient methods of PoU water treatment (CAWST 2010; Manz 2004). Due to extended empty-bed contact time, slow sand filters modified to include a GAC layer can achieve dissolved organic carbon (DOC) removals of >35-40 percent, which is significantly greater than those typically achieved by ordinary slow sand filters (10-25 percent) (Baruth 2005). This may often reduce chlorine demand and the potential for disinfection byproducts which are usually associated with DOC (Kotlarz *et al.* 2009).

An attempt was also made to assess whether including GAC and geotextile layers in ISSFs could reduce bacterial loads to below infectious levels so that human health is no longer endangered before or without filter ripening. According to CAWST (2010), filter ripening (the development of the biolayer which improves removal of bacteria) takes about 1 month. It is a key feature of ISSF systems for removal of pathogens. If absent, only about 30-70% of pathogens are removed through adsorption and mechanical trapping. Although biological action is a very important part of filtration in ISSF systems, often the water passes through too quickly for much biological action to occur, particularly under short residence time of operation (Muhammad *et al.* 1996). Hence, enhancing removal of impurities by adding GAC and geotextile layers is appropriate to improving treatment effectiveness of ISSF systems.

ISSF filters remove pathogens and particles through a combination of physical and biological processes which take place in the biolayer and within the sand body. The main processes include (CAWST 2010): (i) mechanical trapping where large pathogens (e.g. helminths and protozoa) and particles (e.g. silt, algae and organic matter) become physically trapped in the spaces between the sand grains, (ii) predation whereby microorganisms living in the biologically active zone (biolayer) at the top of the filter feed on the pathogens contained in the raw water (CAWST and SPC 2017), (iii) adsorption whereby pathogens and some organic compounds get adsorbed or attached to sand grains, each other and particles in the water, and (iv) natural death whereby pathogens finish their life cycle or die naturally deeper within the filter depth as oxygen, light and food become too scarce to sustain microbial life (CAWST 2010).

Since adsorption can remove very small particles from water and is recommended to enhance performance of slow sand filters (Baruth 2005; Binnie and Kimber 2013), GAC was included in FS1 and FS3, to augment adsorption capacity. GAC can also serve as a filter media substitute or additional treatment process for removal of taste, odor, color, some organic compounds, certain pesticides and other micro-pollutants (McAllister 2005; Siwila and Brink 2018). Additionally, geotextile layers (each 0.60 cm thick) where placed on each filter surface as filter mats to enhance solids removal (Binnie and Kimber 2013) offering a form of pretreatment. The geotextile layers also concentrate the major part of water purification within the fabric and less so within the sand (Graham and Mbwette 1987). The fabric layers are also expected to extend filter run times and offer simple filter cleaning by removal and washing of the fabric alone as opposed to scraping in ordinary ISSF systems (Graham and Mbwette 1987).

The focus of this research was to (i) evaluate bacterial and particulate removal performance of each system- i.e. their treatment effectiveness (to what extent the systems can purify water when needed), (ii) assess potential for improvement, and (iii) suitably optimize the systems. FS1 incorporated GAC, FS2 incorporated non-woven geotextile layers and FS3 incorporated both filter materials.

METHODS

Study setting

This research was conducted in the Water Quality Laboratory of the Civil Engineering Department at Stellenbosch University in Cape Town, South Africa. Raw water samples for testing the systems were obtained from the Kromrivier stream, at 33°55'34.68"S and 18°51'40.56"E in Stellenbosch.

Laboratory setup

Three laboratory scale filter systems were designed and constructed using columns made from transparent Plexiglass of 60 cm height and internal diameter of 10.5 cm. The three models were constructed of alternating layers of filter media consisting of sand, GAC, geotextile and gravel. FS1 incorporated GAC, FS2 incorporated non-woven geotextile layered within the filter media and FS3 incorporated both GAC and geotextile. Sand and gravel were polished and graded at University of Stellenbosch's Civil Engineering Geotechnics Laboratory. Fabrication was done in the Hydraulics Laboratory and the systems were assembled and tested in the Water Quality Laboratory. GAC was bought from a local shop in Stellenbosch and geotextile was obtained within Cape Town making the materials relatively easy to obtain locally and affordable.

Table A-1 shows the key filter materials for each filter system from top to bottom respectively, while schematic diagrams for each system are shown in **Figure A-1**. Each filter system was provided with a tap for collecting treated water. An integrated storage for treated water was added to FS3 to minimize risk factors contributing to recontamination which include water being touched by hand. Traditional ISSFs do not normally contain a treated water storage compartment. Additionally, FS3 was mounted on the wall to demonstrate how space can be saved by users. This was done with an initial assumption that FS3 will give the best treatment effectiveness.

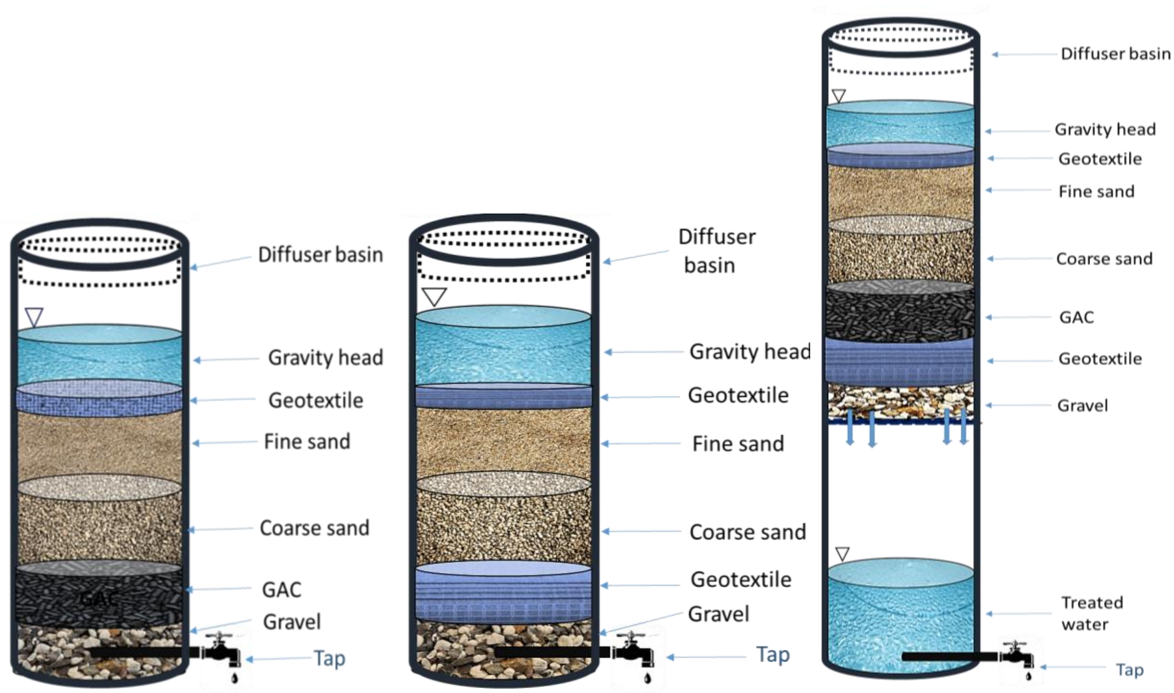

Figure A-1: Schematic diagrams of the filter systems: FS1 (left), FS2 (middle) and FS3 (right)

Table A-1: Filter material depths highlighted from top to bottom layers for each system respectively

Filter Material	*FS1*	*FS2*	*FS3*
Non-woven geotextile layers (≈75 µm pore size)	*1.80 cm*	*1.80 cm*	*1.80 cm*
Fine sand: effective size (ES): 0.16 mm, uniformity coefficient (UC) = 2.04)	*14.5 cm*	*14.5 cm*	*14.5 cm*
Coarse sand (ES: 0.30 mm, UC = 2.42)	*14.5 cm*	*14.5 cm*	*14.5 cm*
Granular activated carbon (GAC)	*10 cm*	-	*10 cm*
Non-woven geotextile layers (≈75 µm pore size)	-	*7 cm*	*7 cm*
Gravel	*9 cm*	*9 cm*	*9 cm*

It is noted here, that this paper presents study results from laboratory trials of an ongoing research and only investigated the extent to which the designed filter systems could improve the quality of the raw water used in terms of bacteria and particles and assessed potential aspects for improving water treatment effectiveness. Thus, the evaluation tests on the filter models somewhat served as pilot tests to determine feasibility (i.e. to what extent the systems can work when needed) and to uncover and resolve unanticipated operation and management issues. Other data assessed included: the expected flow, cleaning frequency, expected ripening period and effects of algae growth. It was anticipated that based on the preliminary findings, improved systems would be constructed and evaluated, and their treatment effectiveness compared with an ordinary ISSF filter with no GAC and geotextile.

Design aspects and technical considerations

When designing a slow sand filter system four dimensions have to be chosen in advance (Hofkes and Huisman 1983). These are (i) the grain size distribution of the filter material (desired effective size (ES) and uniformity coefficient (UC), (ii) the superficial velocity (filtration rate), (iii) the depth of supernatant water (hydraulic head), and (iv) the depth of the filter bed. If data from existing plants, using similar or comparable water sources, doesn't exist, the design should be based on results obtained with pilot tests carried out using experimental filters (Hofkes and Huisman 1983). The key design aspects and technical considerations for this study are highlighted below.

A 10 cm gravity water head was provided above the filter surface to drive water slowly through the filter media. This relatively low water head was chosen to produce less pressure and slower flow rate in order to achieve higher contaminant removal. This was done based on a study in the USA by Jenkins *et al.* (2009) in which two different sand sizes, 0.17 and 0.52 mm, and three maximum gravity heads (10, 20 and 30 cm), were tested under both long (mean: 16 hours) and short (mean: five hours) pause period. They observed that the best configuration of the ISSF system was the use of fine sand and a 10 cm head under long pause periods and further confirmed their study in Kenya where new sand sizes were used (0.15 and 0.30 mm). To further aid with the design, data from an institutional scale ISSF manual giving appropriate gravity heads for different sand depths by (CAWST and SPC 2017) was plotted and used to derive an empirical model for estimating gravity head for various ISSF sand depths. The empirical model (**Equation A-1**) gave a 6 cm gravity head for the sand depth used in this study, though, 10 cm was selected to cater for the other materials included.

$$\boldsymbol{H = k \times D} \qquad \textbf{(A-1)}$$

Where: H = Maximum Gravity Head (m); D = Sand Layer Depth (m); k = is a constant, estimated as 0.20 m/m

A standard 5 cm standing water level was maintained manually after each filtration run to keep the biolayer submerged in water during the pause period. Pause period, the time when the filter is not actively filtering water, is important because it allows time for the microorganisms in the biolayer to consume the pathogens in the water. A minimum pause period of 1 hour was maintained during each filter run. CAWST (2010) recommends a minimum of 1 hour of pause period after the water has stopped flowing up to a maximum of 48 hours. According to (CAWST 2010; Manz 2004), a very long pause period is not desired, because the microbes in the biolayer will consume all the pathogens and nutrients then eventually die off. This reduces removal efficiency of the system in the next filter runs.

1 mm perforated diffusers were fabricated for uniform and gentle water distribution onto the surface of each system to prevent disturbance of the biolayer. Clean quarry sand was used in the filters to ensure purity, with no fines, organics or pathogens, as recommended by CAWST (2010). Each system had three layers of geotextile (each 0.60 cm thick) placed on the filter surface to enhance mechanical trapping, support bio-layer growth, offer some pretreatment and easy filter cleaning. This was complemented by sizing the fine sand according to recommendations by CAWST (2010) and Parsons and Jefferson (2006), with ES of 0.10 to 0.20 mm and UC of 1.5 to 2.5, giving a more tightly packed sand layer and, subsequently a lower flow rate to yield better microbial and particle removal. This is expected to enhance trapping and biological removal of pollutants, in addition to adsorption and natural bacterial death, which occur within the sand body. Flowrate was maintained between 8 to 15 L/h to ensure adequate empty-bed contact time (EBCT)

for the GAC and sufficient contact time between contaminated water and the bio-layer during filtration runs.

The total filter material depths were kept between 30 and 60 cm keeping in mind that affordable systems of this type are normally housed in the most popular low cost 20 litre buckets which are mostly between 30 to 60 cm in height as opposed to traditional ISSF systems of about 55 cm sand depth and total height of 90 cm (CAWST 2010; Manz 2004). Also keeping the filter materials depth to between 30 and 60 cm was sufficiently within findings by Muhammad *et al.* (1996) showing that bacteriological purification of slow sand filters largely occurs within the top 40 cm of the filter bed. The GAC was placed just beneath the coarse sand to prevent particles from rapidly clogging the layer, and also as recommended that GAC not be used as a primary layer or filter (Binnie and Kimber 2013; McAllister 2005). This arrangement allows water with fewer particles and bacteria to pass through the GAC enabling additional removal of color, taste and organic pollutants with little interference from suspended matter (Binnie and Kimber 2013; McAllister 2005; Siwila and Brink 2018).

Volume of water collected in a given time at maximum head was recorded and flow rate calculated as:

$$Flow\ rate,\ Q\left(\frac{L}{h}\right) = \frac{Volume\ (L)}{Time(h)} \quad \textbf{(A-2)}$$

The recommended range of filtration rate (v) for ISSFs is: ≤ 1.2 (Elliott *et al.* 2006), estimated as:

$$Filtration\ velocity, v\left(\frac{m}{h}\right) = \frac{Q\ (m^3/h)}{A\ (m^2)} \quad \textbf{(A-3)}$$

Empty bed contact time (EBCT): The initial flow rates and selected GAC layer depth were used to assess if the EBCT was within typical water treatment process conditions for GAC (Schippers 2010):

$$EBCT = \frac{V_{GAC}}{Q_v} = \frac{V_{GAC}}{v.A} = \frac{h.A}{v.A} = \frac{h}{v} \quad \textbf{(A-4)}$$

Where; Q_v = flow rate (m^3/h); A = cross sectional area of the filter bed (m^2) of diameter d (m) $\left(A = \frac{\pi d^2}{4}\right)$

V_{GAC} = volume of granular activate carbon (m^3); v = filtration velocity (m/h); h = GAC bed height (m)

For instance, EBCT for FS1 at the fastest flow was estimated to be about 5.2 minutes being within 5-40 minutes recommendation by Schippers (2010) and Binnie & Kimber (2013) and is acceptable due to pause period considerations. Also, as a given dose of water runs through, the gravity head declines, and the filtration rate decreases approaching zero until more water is added. Furthermore, filtration rate naturally reduces with time in ISSF systems due to entrapment of particles and pathogens on the filter surface and between the pore spaces within the filter. Some, often most, of the flow rate reduction can be "overcome" by cleaning but it is rare to recover the initial flow rate completely without removing and "cleaning" all the filter media.

Faulty Design and Construction of filter system 3

The performance of the initial version of FS3 which had both GAC and geotextile was poorer than FS1 and FS2 due to the following flaws in the design: (i) lack of a mechanism to prevent the drying out of filter bed. The initial FS3 design was poor because the column bottom was porous thereby allowing water to flow straight through the system with no allowance for the recommended 5 cm standing water level (CAWST 2010; Manz 2004) that preserves the microbial community by preventing the *schmutzdecke* from drying out. (ii) the joint/union between the treatment and treated water storage compartments was not completely sealed, hence, allowed short-circuiting of raw water during charging. (iii) sagging of the geotextile layers was observed probably due to the weight of the materials above and being supported by gravel which partially allowed protrusion into it. This could have led to the minor observed cavities in the sand body due to the sand settling in the first few weeks of use. (iv) poor or incomplete draining of the treated water storage compartment which led to the remnants of previously filtered water mixing with the freshly treated water.

Optimization of filter system 3

Based on the above observed faulty design and construction flaws an optimised version of FS3 was constructed with the following key improvements made: (i) The treatment and storage compartments were now separated by a non-porous treatment column bottom. This prevented water from flowing straight through the systems and allowed maintenance of the standing water level thereby preserving the *schmutzdecke*. (ii) The tap for the treated water storage compartment was now carefully placed at the bottom for better draining to minimize/ prevent mixing between previously and freshly treated water. (iii) reducing of geotextile sagging and increasing of contact between water and GAC by placing a 3 cm layer of fine sand below the geotextile. (iv) The union was no longer used between the compartments as the fabricated column now had two taps one to deliver water from the filtration compartment via a glass tubing into the storage compartment and another tap at the bottom of the treated water compartment. (v) Additionally, a means for chlorination was provided on the glass tubing.

Filter charging and operation

Each system was charged with at least 7.5 liters of water per day. They were operated by pouring water onto the filter surface to provide a maximum water head of 10 cm. Since the column reservoirs could not accommodate the full charge volume, additional raw water was only added when the water head was low enough to handle more. Flow rate was measured using a 2 Litre jar and a stopwatch.

The flow rate was measured at the fastest flow point in the filter, as this determines possible detachment of particles and microbes attached to the filter media, and their subsequent flushing into the treated water (NE-WTTAC 2014). With time, as flowrate gradually decreased, effluent quality improved, especially after filter ripening for FS1 and FS2. Effluent quality for FS3 decreased with time due to absence of a biolayer as previously explained. A better version of FS3 was installed between 21st and 26th September 2017. Observed initial flow rates were 10.08, 9.97 and 9.94 L/h for FS1, FS2 and FS3 respectively, and 7.05, 6.89 L/h and 8.82 at the end of the testing period. Since FS3 was refabricated, the flow rate was still high since the biolayer was still developing in the new system and clogging was still minimal.

Water quality tests and system evaluation

To be sure of a continued presence of particles and bacteria in the source water, raw water samples were collected and tested for two consecutive weeks before the evaluation tests. Both weeks reported more than 500 CFU/100ml and 400 CFU/100ml of fecal coliforms and *E.coli* respectively. Turbidity and TSS values were consistently above 10 NTU and 14 mg/l respectively. During source water assessment, raw water samples were collected from three points along the stream to inform the selection of the study sampling point.

Indicator bacteria *(E.coli and* fecal coliforms) and particles (TSS and turbidity) were quantified before and after treatment. Electrical conductivity (EC), total dissolved solids (TDS), pH, and dissolved oxygen (DO) were additionally tested. The period of the experiments was about 4 months and 2 weeks. Treated water was collected fortnightly for bacteriological tests and daily for physico-chemical tests. Tests for the indicator bacteria were done by the Water Analytical Laboratory (WALAB) accredited to the South African National Accreditation System (SANAS), No: T0375 for microbiological analysis. Physico-chemical tests were done in the Water Quality Laboratory at Stellenbosch University. All tests were performed in accordance with the Standard Methods for the Examination of Water and Wastewater (APHA/AWWA/WEF 2012).

Treatment effectiveness calculations

Treatment (removal) effectiveness achieved by each system was calculated using **Equation A-5**:

$$\%\ Removal = \frac{\textbf{Parameter conc in Source water} - \textbf{Parameter conc in treated water}}{\textbf{Parameter conc in Source water}} X\ 100 \qquad \textbf{(A-5)}$$

RESULTS AND DISCUSSION

Raw water versus treated water quality

The raw water was characterized initially and on every sampling day over the study period for each parameter then compared to South African National Standards (SANS) 241 and World Health Organization (WHO) guidelines for drinking water – see **Table A-2**. In addition to a high content of particles, the untreated stream water was highly contaminated with bacteria (fecal coliforms and *E.coli*). The raw water was found to be unsuitable for drinking and domestic utilization. On average the pH, EC and TDS were within limits for drinking water. **Table A-2** shows the average raw water quality measurements and each system's effluent quality measurements indicating substantive removals.

Table A-2: Raw water and treated water quality compared to WHO guidelines and SANS 241 Standards

Parameter	Raw water			FS1 treated water			FS2 treated water			FS3 treated water			Potable Water Standards	
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	WHO	SANS 241
pH	7.9	7.5	8.8	9.4	8.9	10.2	9.1	7.8	10.1	8.0	7.4	8.5	6.5-9.0	≥ 5 to ≤ 9.7
TSS (mg/L)	38.4	10	150	0.4	0	4	2.5	0	8	2.1	0	5	0.1	-
Turbidity (NTU),	24	6.3	94	0.3	0	2.9	1.9	0	5.7	1.6	0	4.2	5	≤ 5
Fecal coliforms (CFU/100ml)	2043	620	3800	66	5	150	95	2	202	243	15	720	0	0
E.coli (CFU/100ml)	1398	460	3100	54	3	145	82	2	181	146	14	510	0	0
DO (mg/L)	10	8.5	11.7	4.2	2.3	9.6	10.3	7.8	14.0	8.2	6.5	9.8	-	-
Conductivity (µS/cm)	418	141	650	393	154	580	394	159	581	432	171	650	2500	≤ 1700
TDS (mg/L)	215	72	333	202	78	296	202	81	300	222	87	332	1000	≤ 1200

Removal of TSS and Turbidity

Figures A-2 to A-3 indicate that each filter system removed substantive amounts of particles and may enhance acceptability of the treated water (WHO 2017). The average particle removal efficiencies by FS1, FS2 and FS3 were 98%, 91% and 92% in terms of TSS and 98%, 89% and 90% respectively in terms of turbidity. In the first three weeks (19 June to 11 July) none of the systems showed clear superiority with respect to particle removal. From 17 July to 13 October FS1 recorded best removal efficiencies in terms of turbidity and TSS consistently meeting WHO and SANS 241 potable water standards with respect to both parameters. One possibility is that the GAC effectively augmented adsorption capacity in FS1 until its adsorption sites became saturated reducing its effectiveness and required replacement (Schippers 2010). The other possibility is that some particles were organic and served as food for microbes in the '*schmutzdecke*', which was apparently more established and healthier in FS1 than the other filter models. *Schmutzdecke* is a biologically active layer formed on the surface of an ISSF system comprising particles, algae, protozoa, bacteria, rotifers, aquatic worms and other organisms (CAWST 2010; CAWST and SPC 2017; Parsons and Jefferson 2006) from the raw water. According to CAWST (2010) and Parsons and Jefferson (2006), it is within the *schmutzdecke* that much of the water purification takes place, with impurities being removed by both physical and biological action. It is also likely that biological growth may have occurred within FS1's GAC layer thereby enhancing particle removal.

FS2 exhibited occasional breakthrough of particles and could probably not sustain sediments for long in its geotextile layers, therefore, its particle removal pattern was inconsistent and generally lower than FS1. FS3 was expected to give the best removals but had faulty design and construction problems explained under methodology. It performed far much below expectation until an optimized version of FS3 was constructed and installed between 21st September and 26th September (**depicted by the line breaks for FS3 in Figures A-2, A-3, A-6** and **A-7**). *Thus, the **FS3 line breaks** in Figures A-2, A-3, A-6 and A-7 represent the period in which FS3 was put out of operation to allow for installation of its optimized version*. It since then recorded excellent particle removal from 26th September to 12 October after which minor cavities where observed in the sand body leading to poor particle removals. The cavities in the sand body could be attributed to sand settlement in some portions, this being a new setback of FS3.

Generally, TSS and turbidity removal performance by each system was almost identical. Though turbidity is not a direct quantitative measurement of suspended solids (Ritter 2010; Siwila and Brink 2018), TSS and turbidity both measure water clarity, and overlap in measurement of particles like algae, bacteria, clay, silt and non-settleable solids (Ritter 2010; Siwila and Brink 2018) although they reflect different aspects (APHA/AWWA/WEF 2012).

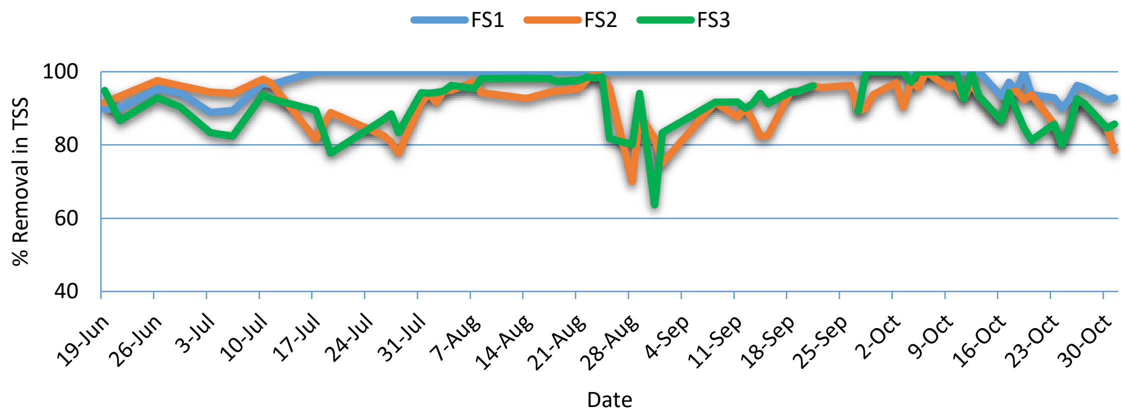

Figure A-2:TSS removal Trend of each filter system over the study period

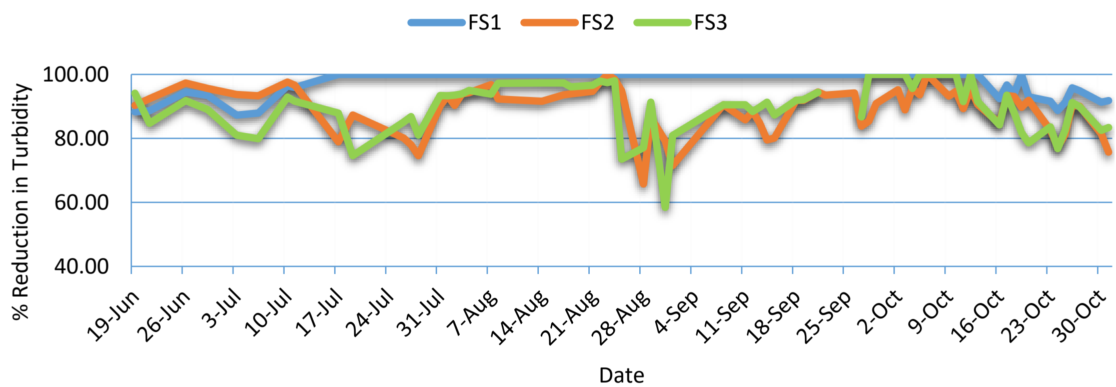

Figure A-3: Turbidity removal Trend of each filter system over the study period

Bacterial removals

All the systems recorded significant bacterial removal (**Figures A-4** to **A-5).** Higher bacterial removals by FS1 and FS2 from the raw water were observed after the filter ripening period of 4 weeks (CAWST 2010). On average, bacterial removals by FS1, FS2 and FS3 were 95%, 93% and 91% for *E.coli* and 96%, 94% and 90% for fecal coliforms respectively. After 4 to 5 weeks there was consistency in the bacterial removal percentages of above 90% for FS1 and FS2 indicating both filter systems had ripened. This shows the importance of *schmutzdecke* growth in ISSF systems. This was not so with FS3 whose initial design was faulty with no means of preserving the microbial community by preventing the *schmutzdecke* from drying out. To avoid problems of this nature, an automatic mechanism for maintaining a 5 cm standing water level as recommended by CAWST (2010), CAWST and SPC (2017) and Manz (2004) should be provided in systems of this kind.

According to CAWST (2010) and Parsons and Jefferson (2006), the *schmutzdecke* is the key element of the ISSF systems that removes pathogens and effective treatment does not occur until it has formed. However, even before filter ripening, bacterial removal by each filter was high, reporting fecal coliform removal of up to 94, 89 and 96%, and *E.coli* removal of up to 89, 84 and 93% for FS1, FS2 and FS3 respectively. This could be attributed to presence of geotextile layers on filter surfaces, GAC in FS1 and FS3, and geotextile layers in FS2. This may considerably offer advantages over ordinary ISSF systems which before filter ripening only remove about 30-70% of the pathogens through adsorption and mechanical trapping (CAWST 2010). It should be noted, however, that with lessons from FS3 which had no biolayer before optimization, physical removal alone may not be adequate in the systems.

Since none of the systems provided 100 % bacterial removal efficiency, FS1's effluent was chlorinated to meet WHO and SANS 241 limits of 0 CFU/100 ml for *E.coli* and fecal coliforms. A low chlorine dose (1.875 mg/L) was used due to low bacterial counts, turbidity levels and organic content, as recommended by Kotlarz *et al.* (2009). Reduced chlorine dosage allows lower chlorine use (Kotlarz *et al.* 2009), which could increase taste acceptability and reduce water purification costs. The design of FS1 gave the best results and may often produce clear water in poor communities significantly increasing acceptability (WHO 2017). It can improve water security for the less privileged, especially if combined with chlorination to warranty continued supply of safe water. FS1 and FS2 substantially removed bacteria and could be refined to reduce pathogenic loads to below infectious doses with consistent care.

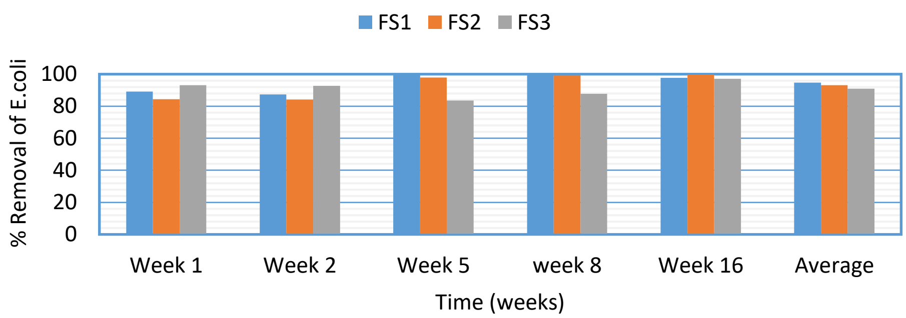

Figure A-4: E.coli removal by each filter system over the study period

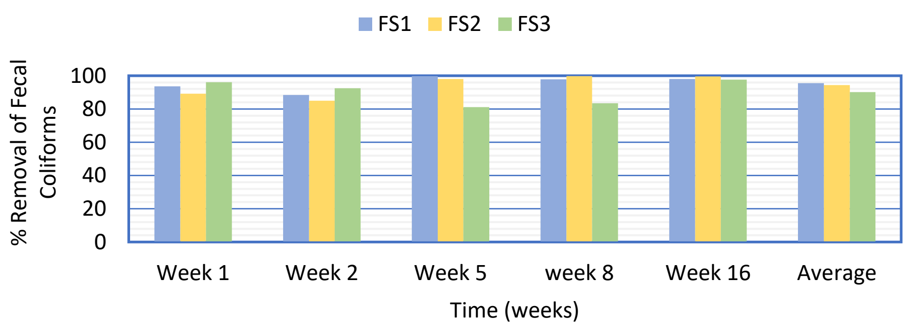

Figure A-5: Fecal coliform removal by each filter system over the study period

pH, Total Dissolved solids, Conductivity and Dissolved oxygen

Although FS1 generally recorded pH values above 9.0 and low DO levels in its effluent-see **Figures A-6** to **A-7** and **Table A-2**, all filter models met SANS 241 guidelines in terms of pH, Conductivity and TDS. The high pH levels in FS1's effluent could be attributed to presence of GAC. Typical activated carbon has a pH of 8.5-10 (Fanner *et al.* 1996). Fanner *et al.* (1996) showed that GAC can act as an ion exchange type media and contribute to pH rise. However, results for FS3 confound this explanation as it also contained GAC but had minimal effect on raw water's pH. A possible explanation is that the presence of geotextile layers in FS3 provided pH buffering and reduced change in pH. Another possible explanation may be changes in pH due to GAC adsorbing antiviral chemicals secreted by the biologically active layer (WASRAG 2012) in FS1, which was mainly absent in FS3.

The higher pH values in FS2's effluent (**Figure A-6**), from around 24 August thereabouts, may have been caused by algal growth – algal blooms were observed then in Kromrivier stream and subsequently in FS2. During photosynthesis, algae remove carbon dioxide from the water, causing an increase in pH (de Moel *et al.* 2007). FS1 had marginal algal growth as it was more "inside" the laboratory, while FS2 was much closer to the window and generally recorded higher temperatures. Each system consistently met SANS 241 and WHO guidelines in terms of TDS and conductivity – see **Table A-2**. However, their effect on source water quality was marginal in terms of these parameters (**Figure A-7**).

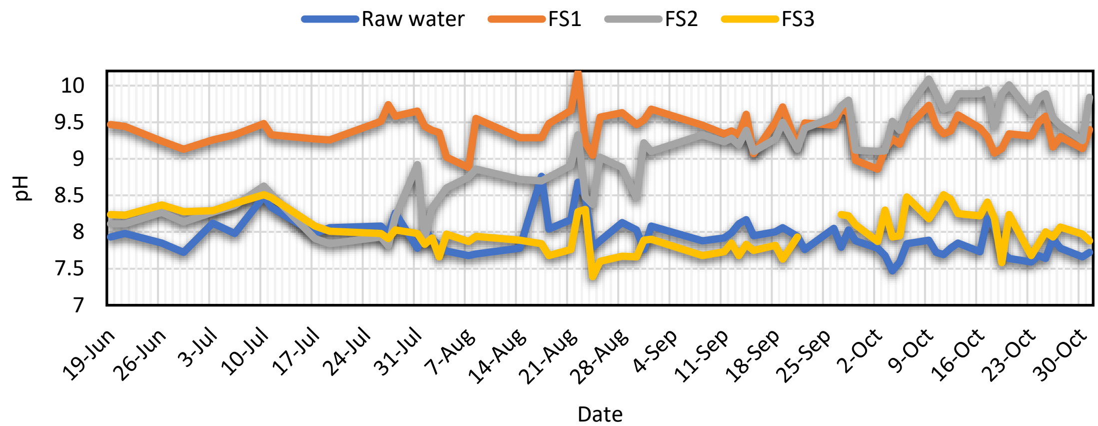

Figure A-6: pH Trend for each filter effluent and raw water over the study period

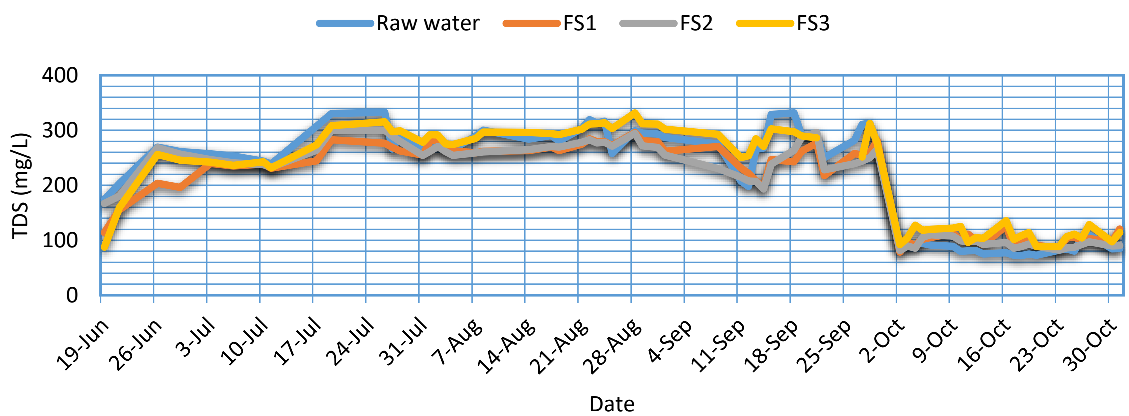

Figure A-7: TDS Trend for each filter effluent and raw water over the study period

CONCLUSIONS

Although FS3 performed below expectation due to explained factors, each system showed the ability to treat the poor-quality water used to provide relatively safe water (Harvey 2007). However, all systems tested have potential for further improvement. Each system's efficiency was substantial, and it may be possible to reduce microbial concentrations to below infectious dose reducing the risk of waterborne diseases and thereby saving lives. To warrant continued supply of safe drinking water, additional treatment by chlorination is still recommended. Investigation into possible multiplication of pathogens in systems like these, if present in the source water, was not investigated. It is recommended that future development of such systems take this possibility into account.

Each system can meet basic water needs of 7.5 to 15 litres/capita/day (The Sphere Project 2011) especially for poor communities or during emergencies. A properly designed, constructed, operated and maintained ISSF including GAC and/or geotextile could be a viable low-cost option for high quality water filtration. Filter mats may also enhance treatment efficiency and minimize cleaning problems. To avoid complete deviation from the traditional ISSF design guidelines which may in many cases cause reduction in removal efficiency and render any appropriate modification inept, the authors recommend the use of minimum 40 cm (Muhammad *et al.* 1996) sand depth before any modification. Additionally, the sand sizes, gravity head and filtration rate should be selected in accordance to recommendations by CAWST and SPC (2017) and CAWST (2010). A mechanism to maintain the standard 5 cm standing water level should also be included as maintaining it manually was observed to be rather laborious.

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>
> Stephen Siwila and Isobel C. Brink 2019 Comparison of five point-of-use drinking water technologies using a specialized comparison framework *J. Water Heath* **(in press)**, DOI: 10.2166/wh.2019.041

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Stephen Siwila
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Water and Environmental Division
Private Bag X1
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South Africa

Tuesday, May 07, 2019

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Yours sincerely

Michelle Herbert
Managing Editor
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Appendix C: Declaration by the candidate and co-authors

Declaration by the candidate (Chapter 2)

With regard to Chapter 2 of this dissertation entitled "Comparative analysis of two low cost point-of-use water treatment systems", the nature and scope of my contribution were as follows:

Nature of contribution	Extent of contribution
i. Designed the lab set ups ii. carried out the experiments iii. carried out data analysis **iv.** conceptualized and prepared the paper	95%

The following co-authors contributed to Chapter 2 of this dissertation entitled "Comparative analysis of two low cost point-of-use water treatment systems":

Name	e-mail address	Nature of contribution	Extent of contribution
I.C. Brink	icbrink@sun.ac.za	i. contributed to manuscript writing, and edited and reviewed the paper ii. provided guidance on the experiments and data analysis	5%

Signature of candidate: ……

Date: …………10 June, 2019…………………

Declaration by co-authors:

The undersigned hereby confirm that

1. The declaration above accurately reflects the nature and extent of the contribution of the candidate and the co-authors to Chapter 2 of this dissertation entitled "Comparative analysis of two low cost point-of-use water treatment systems",

2. No other authors contributed to Chapter 2 of this dissertation entitled "Comparative analysis of two low cost point-of-use water treatment systems" besides those specified above, and

3. Potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 2 of this dissertation entitled "Comparative analysis of two low cost point-of-use water treatment systems".

Signature	**Institutional affiliation**	**Date**
…… ……	Stellenbosch university	…12 August 2019……………

Declaration by the candidate (Chapter 3)

With regard to Chapter 3 of this dissertation entitled "A small-scale low-cost water treatment system for removal of selected heavy metals, bacteria and particles", the nature and scope of my contribution were as follows:

Nature of contribution	Extent of contribution
i. Designed the lab set ups ii. carried out the experiments iii. carried out data analysis **iv.** conceptualized and prepared the paper	95%

The following co-authors contributed to Chapter 3 of this dissertation entitled "A small-scale low-cost water treatment system for removal of selected heavy metals, bacteria and particles":

Name	e-mail address	Nature of contribution	Extent of contribution
I.C. Brink	icbrink@sun.ac.za	i. contributed to manuscript writing, and edited and reviewed the paper ii. provided guidance on the experiments and data analysis	5%

Signature of candidate: …..

Date: …………10 June, 2019…………………

Declaration by co-authors:

The undersigned hereby confirm that

1. The declaration above accurately reflects the nature and extent of the contribution of the candidate and the co-authors to Chapter 3 of this dissertation entitled "A small-scale low-cost water treatment system for removal of selected heavy metals, bacteria and particles",

2. No other authors contributed to Chapter 3 of this dissertation entitled "A small-scale low-cost water treatment system for removal of selected heavy metals, bacteria and particles" besides those specified above, and

3. Potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 3 of this dissertation entitled "A small-scale low-cost water treatment system for removal of selected heavy metals, bacteria and particles".

Signature	**Institutional affiliation**	**Date**
	Stellenbosch university	……12 August 2019…………

Declaration by the candidate (Chapter 4)

With regard to Chapter 4 of this dissertation entitled "Low cost drinking water treatment using nonwoven engineered and woven cloth fabrics", the nature and scope of my contribution were as follows:

Nature of contribution	Extent of contribution
i. Designed the lab set ups ii. carried out the experiments iii. carried out data analysis **iv.** conceptualized and prepared the paper	95%

The following co-authors contributed to Chapter 4 of this dissertation entitled "Low cost drinking water treatment using nonwoven engineered and woven cloth fabrics":

Name	e-mail address	Nature of contribution	Extent of contribution
I.C. Brink	icbrink@sun.ac.za	i. contributed to manuscript writing, and edited and reviewed the paper ii. provided guidance on the experiments and data analysis	5%

Signature of candidate: …… ……

Date: …………10 June, 2019…………………

Declaration by co-authors:

The undersigned hereby confirm that

1. The declaration above accurately reflects the nature and extent of the contribution of the candidate and the co-authors to Chapter 4 of this dissertation entitled "Low cost drinking water treatment using nonwoven engineered and woven cloth fabrics",

2. No other authors contributed to Chapter 4 of this dissertation entitled "Low cost drinking water treatment using nonwoven engineered and woven cloth fabrics" besides those specified above, and

3. Potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 4 of this dissertation entitled "Low cost drinking water treatment using nonwoven engineered and woven cloth fabrics".

Signature	Institutional affiliation	Date
	Stellenbosch university	………12 August 2019………

Declaration by the candidate (Chapter 5)

With regard to Chapter 5 of this dissertation entitled "Drinking water treatment using indigenous wood filters combined with granular activated carbon", the nature and scope of my contribution were as follows:

Nature of contribution	Extent of contribution
i. Designed the lab set ups ii. carried out the experiments iii. carried out data analysis **iv.** conceptualized and prepared the paper	95%

The following co-authors contributed to Chapter 5 of this dissertation entitled "Drinking water treatment using indigenous wood filters combined with granular activated carbon":

Name	e-mail address	Nature of contribution	Extent of contribution
I.C. Brink	icbrink@sun.ac.za	i. contributed to manuscript writing, and edited and reviewed the paper ii. provided guidance on the experiments and data analysis	5%

Signature of candidate: …… ……

Date: …………10 June, 2019…………………

Declaration by co-authors:

The undersigned hereby confirm that

1. The declaration above accurately reflects the nature and extent of the contribution of the candidate and the co-authors to Chapter 5 of this dissertation entitled "Drinking water treatment using indigenous wood filters combined with granular activated carbon",

2. No other authors contributed to Chapter 5 of this dissertation entitled "Drinking water treatment using indigenous wood filters combined with granular activated carbon" besides those specified above, and

3. Potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 5 of this dissertation entitled "Drinking water treatment using indigenous wood filters combined with granular activated carbon".

Signature	Institutional affiliation	Date
	Stellenbosch university	…12 August 2019……………

Declaration by the candidate (Chapter 6)

With regard to Chapter 6 of this dissertation entitled "Comparison of five Point of Use drinking water technologies using a specialized comparison framework", the nature and scope of my contribution were as follows:

Nature of contribution	Extent of contribution
i. Designed the lab set ups ii. carried out the experiments iii. carried out data analysis **iv.** conceptualized and prepared the paper	95%

The following co-authors contributed to Chapter 6 of this dissertation entitled "Comparison of five Point of Use drinking water technologies using a specialized comparison framework":

Name	e-mail address	Nature of contribution	Extent of contribution
I.C. Brink	icbrink@sun.ac.za	i. contributed to manuscript writing, and edited and reviewed the paper ii. provided guidance on the experiments and data analysis	5%

Signature of candidate: …… ……

Date: …………10 June, 2019…………………

Declaration by co-authors:

The undersigned hereby confirm that

1. The declaration above accurately reflects the nature and extent of the contribution of the candidate and the co-authors to Chapter 6 of this dissertation entitled "Comparison of five Point of Use drinking water technologies using a specialized comparison framework",

2. No other authors contributed to Chapter 6 of this dissertation entitled "Comparison of five Point of Use drinking water technologies using a specialized comparison framework" besides those specified above, and

3. Potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 6 of this dissertation entitled "Comparison of five Point of Use drinking water technologies using a specialized comparison framework".

Signature	**Institutional affiliation**	**Date**
	Stellenbosch university	…12 August 2019……………

Declaration by the candidate (Chapter 7)

With regard to Chapter 7 of this dissertation entitled "A novel low-cost multi-barrier system for drinking water treatment in rural and suburban areas", the nature and scope of my contribution were as follows:

Nature of contribution	Extent of contribution
i. Designed the lab set ups ii. carried out the experiments iii. carried out data analysis **iv.** conceptualized and prepared the paper	95%

The following co-authors contributed to Chapter 7 of this dissertation entitled "A novel low-cost multi-barrier system for drinking water treatment in rural and suburban areas":

Name	e-mail address	Nature of contribution	Extent of contribution
I.C. Brink	icbrink@sun.ac.za	i. contributed to manuscript writing, and edited and reviewed the paper ii. provided guidance on the experiments and data analysis	5%

Signature of candidate: ….

Date: …………10 June, 2019…………………

Declaration by co-authors:

The undersigned hereby confirm that

1. The declaration above accurately reflects the nature and extent of the contribution of the candidate and the co-authors to Chapter 7 of this dissertation entitled "A novel low-cost multi-barrier system for drinking water treatment in rural and suburban areas",

2. No other authors contributed to Chapter 7 of this dissertation entitled "A novel low-cost multi-barrier system for drinking water treatment in rural and suburban areas" besides those specified above, and

3. Potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 7 of this dissertation entitled "A novel low-cost multi-barrier system for drinking water treatment in rural and suburban areas".

Signature	Institutional affiliation	Date
	Stellenbosch university	……12 August 2019…………

Declaration by the candidate (Chapter 8)

With regard to Chapter 8 of this dissertation entitled "Modelling of *Escherichia coli* removal by a low-cost combined drinking water treatment system", the nature and scope of my contribution were as follows:

Nature of contribution	Extent of contribution
i. Designed the lab set ups ii. carried out the experiments iii. carried out data analysis **iv.** conceptualized and prepared the paper	95%

The following co-authors contributed to Chapter 8 of this dissertation entitled "Modelling of *Escherichia coli* removal by a low-cost combined drinking water treatment system":

Name	e-mail address	Nature of contribution	Extent of contribution
I.C. Brink	icbrink@sun.ac.za	iii. contributed to manuscript writing, and edited and reviewed the paper iv. provided guidance on the experiments and data analysis	5%

Signature of candidate: …… ……

Date: …………10 June, 2019…………………

Declaration by co-authors:

The undersigned hereby confirm that

1. The declaration above accurately reflects the nature and extent of the contribution of the candidate and the co-authors to Chapter 8 of this dissertation entitled "Modelling of *Escherichia coli* removal by a low-cost combined drinking water treatment system",

2. No other authors contributed to Chapter 8 of this dissertation entitled "Modelling of *Escherichia coli* removal by a low-cost combined drinking water treatment system" besides those specified above, and

3. Potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 8 of this dissertation entitled "Modelling of *Escherichia coli* removal by a low-cost combined drinking water treatment system".

Signature	Institutional affiliation	Date
	Stellenbosch university	……12 August 2019…………

Declaration by the candidate (Appendix A)

With regard to Appendix A of this dissertation entitled "Point of Use water treatment through use of activated carbon and geotextile layered within an intermittently operated slow sand filter", the nature and scope of my contribution were as follows:

Nature of contribution	Extent of contribution
i. Designed the lab set ups ii. carried out the experiments iii. carried out data analysis **iv.** conceptualized and prepared the paper	95%

The following co-authors contributed to Appendix A of this dissertation entitled "Point of Use water treatment through use of activated carbon and geotextile layered within an intermittently operated slow sand filter":

Name	e-mail address	Nature of contribution	Extent of contribution
I.C. Brink	icbrink@sun.ac.za	i. contributed to manuscript writing, and edited and reviewed the paper ii. provided guidance on the experiments and data analysis	5%

Signature of candidate: …… ……

Date: …………10 June, 2019…………………

Declaration by co-authors:

The undersigned hereby confirm that

1. The declaration above accurately reflects the nature and extent of the contribution of the candidate and the co-authors to Appendix A of this dissertation entitled "Point of Use water treatment through use of activated carbon and geotextile layered within an intermittently operated slow sand filter",

2. No other authors contributed to Appendix A of this dissertation entitled "Point of Use water treatment through use of activated carbon and geotextile layered within an intermittently operated slow sand filter" besides those specified above, and

3. Potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Appendix A of this dissertation entitled "Point of Use water treatment through use of activated carbon and geotextile layered within an intermittently operated slow sand filter".

Signature	Institutional affiliation	Date
	Stellenbosch university	…12 August 2019……………