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

Stephen Siwila* and Isobel C. Brink

Department of Civil Engineering, Water Engineering Division, Stellenbosch University, Private Bag X1, Matieland 7602,
Cape Town, South Africa

*Corresponding author. E-mail: ssiwilatabbie@yahoo.co.uk

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 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 SCCGM-only 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 SCCGM-only systems respectively.

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

INTRODUCTION

Access to safe drinking water is often limited in rural and suburban areas of developing countries (Chaudhuri & Sattar 1990; Supong *et al.* 2017; Savage 2018). Safe piped water is sometimes unavailable in such settings and many water sources contain pathogens (Chaudhuri & Sattar 1990). Mortality rates from contaminated water are correspondingly high, with communicable diseases a threat (Demena *et al.* 2003; Eitner & 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 & Sattar 1990; McAllister 2005; Kausley *et al.* 2015). This is particularly true for systems based on advanced technologies like ozonation, ion exchange, reverse osmosis, ultrafiltration membranes, and so on (Lykins & Clark 1992; Gadgil 1998; de Moel *et al.* 2007; Pizzi 2010; Ritter 2010; WHO 2016, 2017a). 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).

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. This is expected to enable the system to cope with the varying turbidity loads which are found in many rural and suburban areas of developing countries, necessitating a pre-processing step for the raw water. This claim is supported by literature (e.g. Binnie & Kimber 2013) where they indicated that fabric-protected slow sand filters have longer filtration runs. Furthermore, 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 (Kausley *et al.* 2018) thereby necessitating adequate pre-filtration. Thus, it is important to have a pre-treatment step to remove most of the suspended particles in the raw water prior to the more advanced treatment steps, namely disinfection and filtration by SCCGM and GAC 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 that may be contaminated (Gadgil 1998; Sullivan *et al.* 2005; CAWST 2017; 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 Siabi 2003; Mihelcic *et al.* 2009; Pizzi 2010; Binnie & Kimber 2013), 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$/m^2 (Kaytech Engineering 2018). It is a nonwoven continuous filament, needle punched 'food grade' fabric manufactured by Kaytech Engineering, South Africa. The engineered fabric is normally applied in hydraulic applications such as filtration and drainage, erosion control, water and waste containment, retaining and hydraulic structures, and as a turbidity curtain during bay constructions (Kaytech Engineering 2018). The GAC used was ProCarb-900 produced by Rotocarb South Africa with an effective size of between 0.6 and 1.0 mm and costs <2.5 US$/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 (Lantagne *et al.* 2006; CAWST 2010, 2011; 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 and solar disinfection are other alternatives with various limitations.

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 (Kausley *et al.* 2015; Supong *et al.* 2017; Harvey *et al.* 2019). 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 & Sattar 1990; Gadgil 1998; McAllister 2005; Kausley *et al.* 2015). Therefore, PoU systems with an inbuilt disinfection step such as the designed multi-barrier system may be more effective and attractive.

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 system has demonstrated potential to consistently supply bacteriologically safe and aesthetically acceptable water at an optimal flow rate of 2 L/h.

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 5–10 users, it can be easily scaled up to serve, for example, 100, 1,000, 2,000 and so on persons or for institutional use, for example 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 SCCGM-only system (Figure 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 1(a)) 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

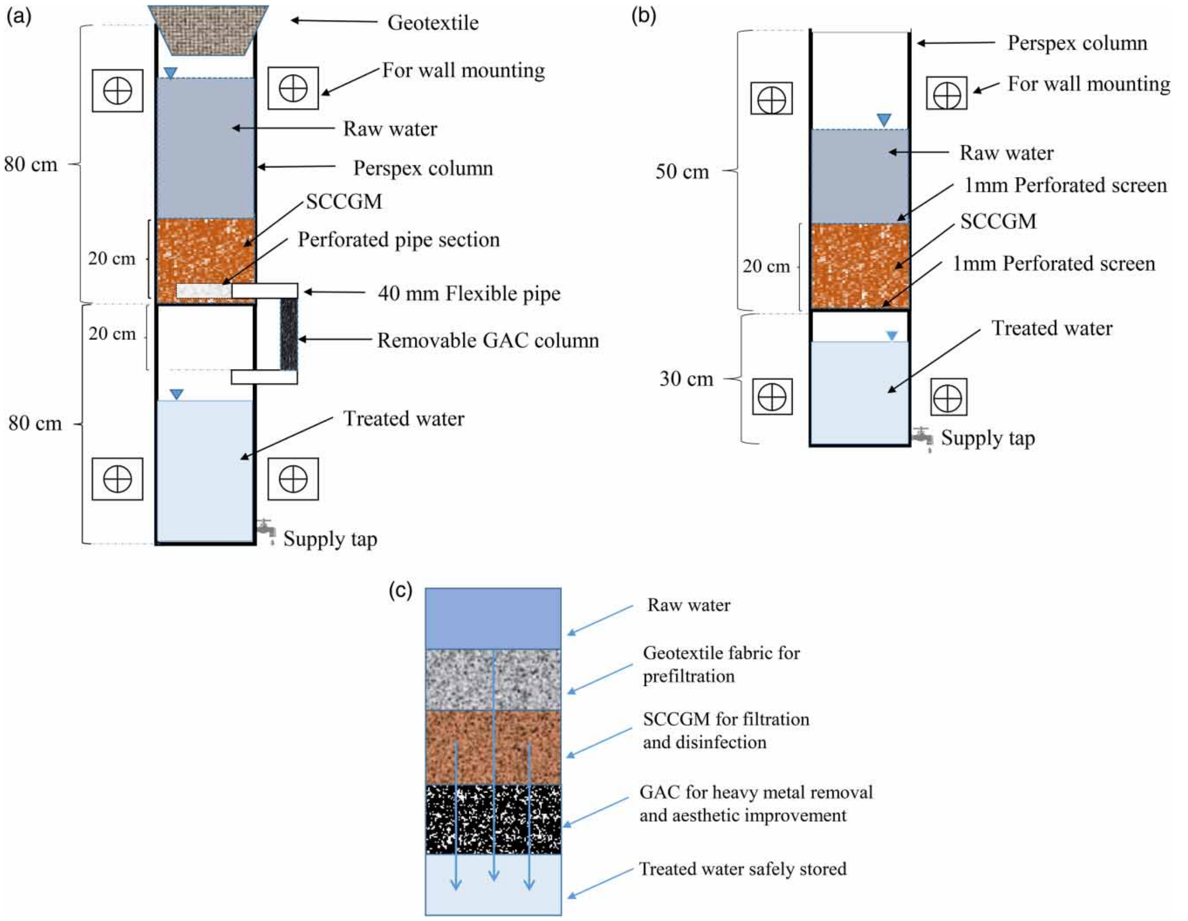

Figure 1 | Novel filter system: (a) designed multi-barrier system, (b) SCCGM-only system, and (c) process schematic diagram.

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 (Figure 1(a)). 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 such as 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 SCCGM-only system (Figure 1(b)), 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 SCCGM-only 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 SCCGM-only systems respectively.

The 20 cm depth for GAC was chosen based on Binnie & 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 SCCGM-only systems. The 25 cm water head for the SCCGM-only system 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 2(a)) 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 2(b)). Triaxial diagrams such as Figure 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 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 (2)).

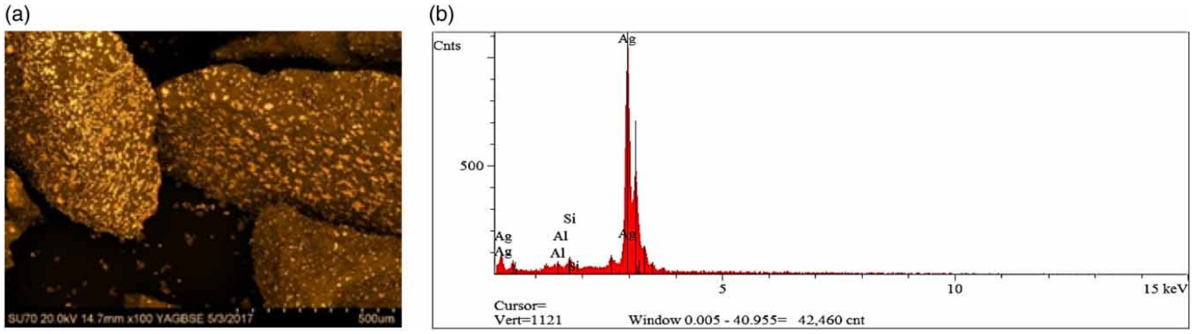

Figure 2 | (a) Scanning electron micrograph showing silver deposits on the SCCGM, (b) energy dispersive spectroscopy X-ray spectrum showing localized silver deposits on a clay particle; source TAM Ceramics 2019.

The desired working area for the designed system is represented by the shading in Figure 3, which is typical for most low-cost small scale PoU systems. The shaded area is adequate for a household system using (i) 20–50 cm media depth, (ii) 0.15–0.40% weight percent of silver, and (iii) residence time of 0.4–0.7 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.

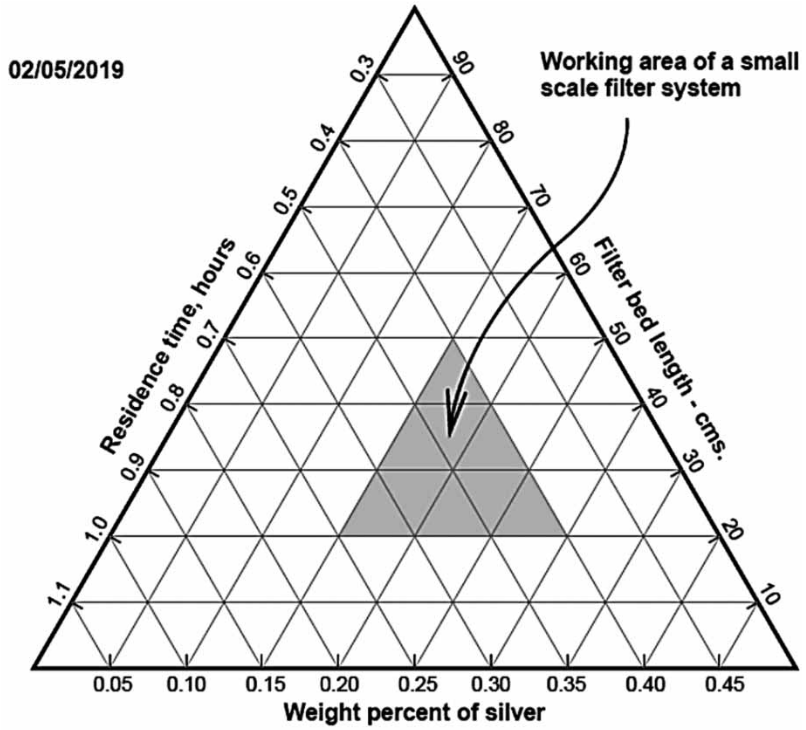

Figure 3 | Triaxial diagram working area for the designed small scale PoU system.

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 (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.

$$\text{Flow rate,}\quad Q = \frac{V}{t} \tag{1}$$

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. Input and output water samples were collected at intervals of every 7.5 liters; that is, after passing at least 7.5 liters of water through the system (Table 1) during each run. This sampling methodology was adopted from Malhotra *et al.* 2013, where they collected input and output water samples at intervals of every 2 liters before analysis. Therefore, collecting input and output water samples at intervals of every 7.5 liters for analysis was assumed adequate for assessing system performance with relation to filtered water volume for each filter run. However, future studies may consider more filtered volume in this regard. 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 1). The first four runs for the multi-barrier system were done at the maximum possible flow rate, 10 L/h (Table 1). For the SCCGM-only system, only the first two runs were done at the maximum flow rate, 20 L/h (Table 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 SCCGM-only system respectively (Table 1). Varying the flow rate was done to

Table 1 | Flow rate used, and volume of water treated for each run

Run number	Experimentation stages	Date of testing	Volume of water treated	Multi – barrier system flow rate (L/h)	SCCGM-only flow rate (L/h)
1	Preliminary runs	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	Controlled flow rate runs	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	Optimized flow rate runs	11/2/2019	7.5	2	2
11		12/2/2019	7.5	2	2
12		13/2/2019	7.5	2	2

arrive at an optimal flow rate and yield varied contact time to provide data for further modelling in future research. The optimal flow rate (which was found to be 2 L/h) was the flow rate required to produce 0 CFU/100 ml for *E. coli* and fecal coliforms in the effluent. Thus, optimal flow (2 L/h) was arrived at after varying the flow rate for each system from the highest obtainable to the least possible flow rate (2 L/h) (Table 1) that was able to consistently produce 0 CFU/100 ml for *E. coli* and fecal coliforms in the effluent. To wit, since the World Health Organization (WHO) guidelines and South African National Standards (SANS) 241 recommend 0 CFU/100 ml for both fecal coliforms and *E. coli* in drinking water (Table 3), flow rates were staggered from the highest obtainable by each system to an optimal 2 L/h where >99.99% removals of the indicator bacteria were consistently achieved. Three runs were therefore done at 2 L/h flow rate to assess removal consistency.

Experimentation stages

It is worth noting that the two investigated systems were essentially independent and were mainly meant to show the difference in pollutant removal performance with respect to their material combination, in particular with respect to the volume of water filtered. That is, the main idea of the study was to demonstrate how the pre- and post-treatment steps can help to improve the performance of 'SCCGM-only systems', especially when treating natural raw waters. Consequently, the SCCGM-only system was evaluated alongside the designed multi-barrier system. The experimental runs essentially comprised the three experimental stages given in Table 1 and further highlighted in the graphical representation of the results:

(i) **Preliminary runs** refers to the first four runs, where both systems were run at maximum flow rate as explained above.
(ii) **Controlled flowrate runs** refers to the stage at which the flow rate was varied to arrive at an optimal flow rate and yield varied contact times to provide data for further modelling in future research and for flow rate optimization. At this stage, flow rates were staggered from 8 L/h for each system to an optimal flow rate of 2 L/h until >99.99% removals of the indicator bacteria were consistently achieved as indicated in Table 1 and elaborated above.
(iii) **Optimal flow rate runs** refers to the stage at which the filter runs were done at the optimal flow rate of 2 L/h to give 0 CFU/100 ml of *E. coli* and fecal coliforms in the treated water.

Contact time estimation

Empty-bed contact time (EBCT) is a key factor in the performance of GAC and similar granular media (Pizzi 2010; Binnie & Kimber 2013). 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 (2).

$$EBCT = \frac{V_{\text{media}}}{Q_v} = \frac{V_{\text{media}}}{v.A} = \frac{h.A}{v.A} = \frac{h}{v} \tag{2}$$

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 7,900 as the analytical instrument. The Agilent 7,900 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 (3)**:**

$$\text{Contaminant removal efficiency (\%)} = \frac{C_i - C_e}{C_i} \times 100 \tag{3}$$

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 SCCGM-only 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 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 & 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 (4)) (Montgomery & Runger 2018).

$$SE = \frac{\sigma}{\sqrt{N}} \tag{4}$$

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 (3) and (4)) for all metal removals in all the experimental runs ($N = 12$) (Montgomery & 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 SCCGM-only systems particularly after the fourth run (Figure 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 SCCGM-only 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 3).

The multi-barrier system significantly improved the other aesthetic aspects (color, odor and taste) of water (Table 3) and performed much better than the SCCGM-only system in this regard. As previously mentioned, improving aesthetic characteristics of water is critical to the acceptability of a PoU drinking water system (McAllister 2005; CAWST 2017; 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 (McAllister 2005; Sullivan *et al.* 2005; CAWST 2017; 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 SCCGM-only system 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 SCCGM-only system.

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

In general, both the designed and SCCGM-only system produced water with higher pH and conductivity values in relation to the raw water (Figure 4). However, the parameters were well within SANS 241 drinking water standards (Table 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 and 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 SCCGM-only 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 such as Bell (1991), disinfection action by silver is most efficient at higher pH values (>8) and higher temperatures (>20 °C). 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 SCCGM-only systems had little if any effect on the raw water's DO levels (Figure 4). This suggests that the effluent DO levels were mainly dependent on the raw water DO values.

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

The designed multi-barrier and SCCGM-only systems both recorded significant bacterial removals (Table 2). *E. coli* removal ranged between 98.7 and >99.99% and 51.7 and >99.99%, respectively, for the designed and SCCGM-only 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 2 | Bacterial removal by the designed (multi-barrier) and SCCGM-only systems

	Raw water (Influent)		**Multi-barrier system**				**SCCGM-only system**			
Run number	***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/100 ml)**	**% removal**	**Effluent fecal coliforms (CFU/100 ml)**	**% removal**
1	2,600	2,600	7	99.73	7	99.73	70	97.31	108	95.85
2	2,600	2,600	33	98.73	35	98.65	77	97.04	131	94.96
3	2,600	2,600	29	98.88	34	98.69	103	96.04	122	95.31
4	2,600	2,600	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	1,240	1,480	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 ($\leq$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, for example (de Moel *et al.* 2007; Pizzi 2010; Binnie & Kimber 2013, contact time is a key factor for significant contaminant removal by granular media. It is still possible that with further optimization; for example, 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 3–7 L/h. Early bacterial breakthrough was exhibited by the SCCGM-only system (Table 2) due to high turbidity levels in the influent (Table 3) combined with higher initial flow rates (Table 1).

As can be seen in Table 1, the flux during the preliminary runs was up to two times higher in the SCCGM-only system, hence the treatment capacity was apparently exceeded; as a result, bacterial breakthrough was observed in the system. Additionally, in the controlled flow runs bacterial breakthrough was experienced in the SCCGM-only system. Therefore, the top 10 cm of the SCCGM in both systems was cleaned then replaced and the systems were thereafter flushed with distilled water before the 2 L/h runs. This was done to remove most of the entrapped particles observed in the filter systems (particularly in the SCCGM-only system) in roughly the top 5–10 cm of the filter body, and thereby ensure uniform conditions for both systems. Thus, the cleaning was mainly done to remove the previously captured debris and most suspended particles and thereby ensure that silver disinfection by the SCCGM was uniformly and consistently effective in both systems. Some, often most, entrapped particles can be removed by cleaning, but it is rare to completely remove all the captured particles without removing and cleaning all the filter media. Cleaning all the media is recommended for future studies in this context on the investigated and similar systems.

Problems in complete removal of bacteria can arise from an overload of particles and suspended bacteria in the raw water and their subsequent capture and release into the treated 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 that proposed would be used, assessing the removal efficiency of other waterborne pathogens (e.g. viruses and protozoa) not tested in this study is recommended.

Table 3 | Bacteriological and physical parameters: raw water vs multi-barrier (designed) and SCCGM-only system effluents

			Raw water (influent)			Multi-barrier system effluent			SCCGM-only system effluent			Drinking Water Standards	
Parameter	**Risk (SANS241)**	**N**	**Range**	**Mean**	**SE**	**Range**	**Mean**	**SE**	**Range**	**Mean**	**SE**	**SANS241**	**WHO (2017a)**
Color	Aesthetic	12	Yellow to Brownish			Pleasing and 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	≤1,700	2,500
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	400–2,600	1,274.2	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	430–2,600	1,345.8	278.7	0.0–35	9.1	3.7	0.0–252	119.0	23.5	0	0
Al (μg/l)	Operational	12	620.7–8,813.3	3,498.0	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	≤2,000	2,000
Fe (μg/l)	Aesthetic	12	722.5–6,891.7	2,766.6	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	≤5,000	5,000

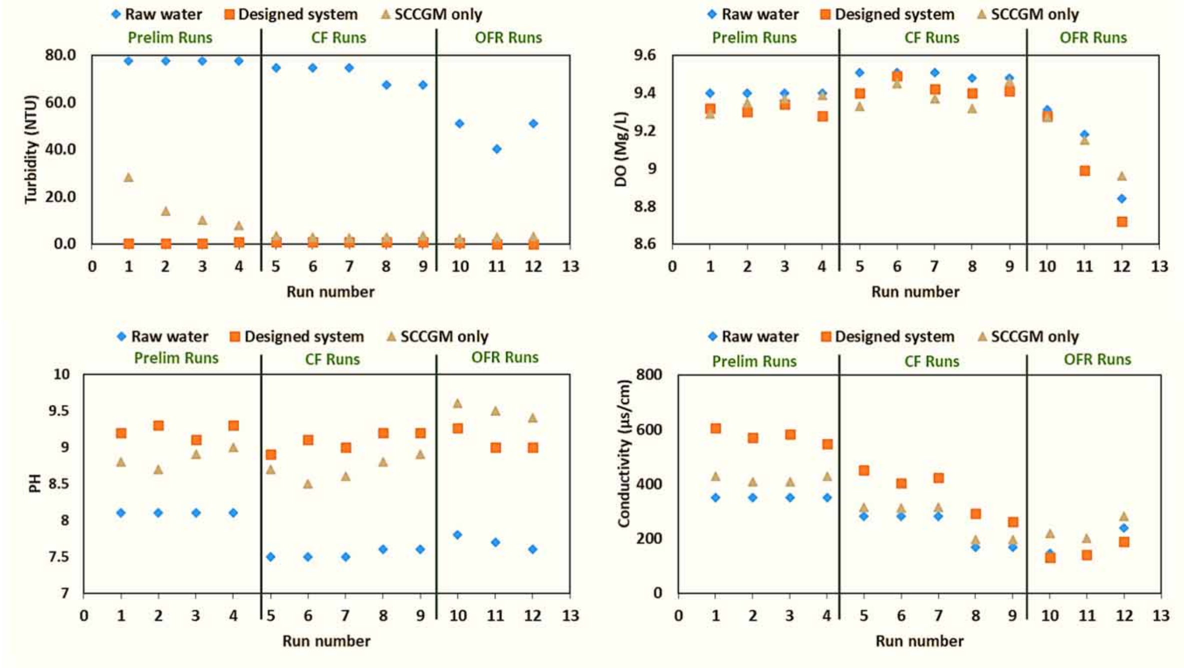

Figure 4 | Raw water versus treated water quality: Turbidity, pH, DO and conductivity for the multi-barrier (designed) and SCCGM-only systems (Prelim = Preliminary; CF = controlled flowrate; OFR = optimal flow rate).

Possible heavy metal removals

Although the designed multi-barrier system generally showed higher heavy metal removal potential than the SCCGM-only system (Figure 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 SCCGM-only 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 SCCGM-only 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 5) and were essentially not able to remove Hg (Figure 5). Overall, the SCCGM-only system 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 (Sullivan *et al.* 2005; Nathanson & Schneider 2015; CAWST 2017; WHO 2017a).

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,

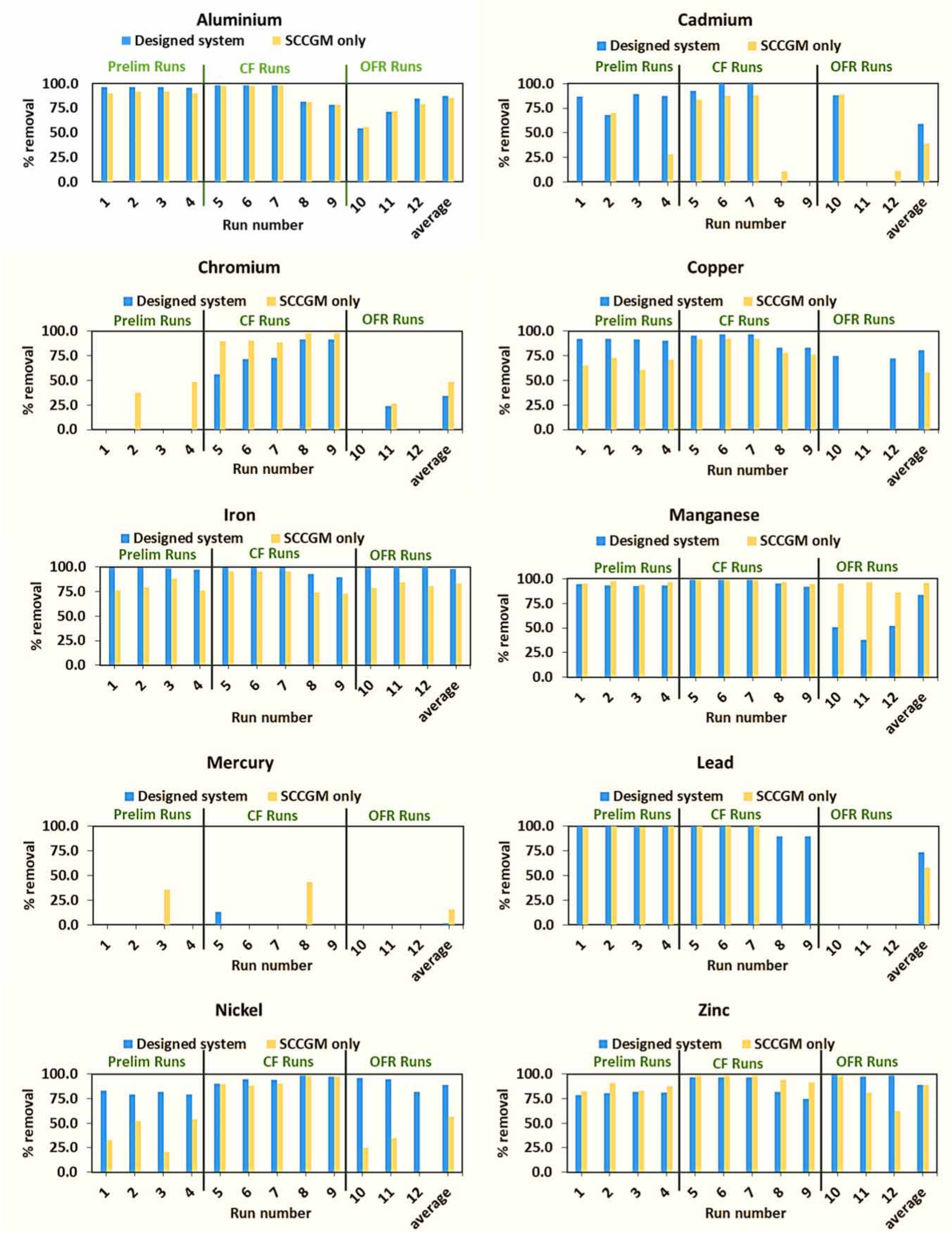

Figure 5 | Heavy metal percentage removals by the multi-barrier (designed) and SCCGM only systems for each run number (Prelim = Preliminary; CF = Controlled flowrate; OFR = Optimal flow rate).

(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 SCCGM-only systems

The geotextile used in the study costs around 1.76 US$/sqm (Kaytech Engineering 2018), while the GAC (ProCarb-900) costs $\leq$2.5 US$/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 100–200 °C and is structurally stable up to 200 °C (Kaytech Engineering 2018). The main limitation of the SCCGM-only 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 and is subsequently expected to have a substantial life span (TAM Ceramics 2019). The life span of the two systems is therefore mainly dependent on the SCCGM, which is estimated to be sufficiently long according to initial studies carried out on the filter media by TAM Ceramics (2019). As mentioned earlier, 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 of the filter media (TAM Ceramics 2019). Furthermore, it is perceived that with proper maintenance and cleaning, the pre-treatment step will contribute to a more consistent performance and potentially allow the multi-barrier system to have longer filtration runs.

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 & 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 6–8 times can be used in place of geotextile. Both systems can meet basic water needs of about 7.5–15 liters/capita/day (The Sphere Project 2011), particularly for rural and suburban areas. If source water primarily requires bacterial inactivation, the SCCGM-only system configuration will be preferable, probably with fabric pre-filtration (as a pre-processing step for the raw water), and costs around US$10.

If resources allow, running 4–5 systems concurrently for the designed and SCCGM-only 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 being relatively high, future investigation into reducing the system height by for example use of larger diameter PVC pipes could mitigate this limitation. In addition, in places where the water is generally aesthetically appealing, investigating the possibility of removing the GAC column from the system could reduce system costs and avoid GAC replacement costs, further minimizing the 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 (multi-year) 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 while ensuring that samples of the treated water are taken from the batch of the entire filtered volume for each respective run. This can also help to ascertain performance consistency of each system as well as ascertain performance of each system component such as how sustainably the pre- and/or post-treatment steps will contribute to a more consistent performance.

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