Research Paper

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

Stephen Siwila and Isobel C. Brink

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% *Escherichia 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

Stephen Siwila (corresponding author)
Isobel C. Brink
Department of Civil Engineering, Water Engineering Division,
Stellenbosch University,
Private Bag X1, Matieland 7602, Cape Town,
South Africa
E-mail: *ssiwilatabbie@yahoo.co.uk*

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 waterborne diseases in developing communities (McAllister 2005; Supong *et al.* 2017; Kausley *et al.* 2018). Many technologically advanced water treatment technologies, for example, pasteurization, ultrafiltration, nanofiltration, reverse osmosis, ion exchange, ozonation, water softening and ultraviolet disinfection exist (Binnie & 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 (McAllister 2005; Binnie & Kimber 2013; Kim *et al.* 2016). The advanced technologies are costly and suffer from high power usage, expensive running costs and complexity (McAllister 2005; Kim *et al.* 2016; Supong *et al.* 2017; Kausley *et al.* 2018).

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

doi: 10.2166/washdev.2019.187

indigenous tree species native to Southern Africa; incorporating GAC (granular activated carbon) 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 of this application is warranted. Gravity-driven wood filtration is used as an alternative to pressure-driven wood filtration and the resulting flow rates were 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, and appropriate and affordable to the rural poor (McAllister 2005; Kim *et al.* 2016; Kausley *et al.* 2018). 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 nm in size). However, viruses cause fewer health problems as a result of drinking contaminated water compared to bacterial diseases (WHO/UNICEF 2004; McAllister 2005).

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, *L. 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, hemorrhoids and dysentery (SANBI 2018; SUBGSA 2018).

Although the main objective of PoU drinking water treatment is to produce microbiologically safe water (McAllister 2005; CAWST 2017; WHO 2017a), the water must be aesthetically acceptable and therefore free from apparent turbidity, color, odor and objectionable taste (Hammer & Hammer 2012; Nathanson & Schneider 2015). Particles that cause turbidity shield disease-causing microbes against disinfection (Nathanson & 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 discoloration (Nathanson & Schneider 2015; CAWST 2017; 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 among the most common environmental pollutants (Turkez *et al.* 2012). According to Llobet *et al.* (2003), these elements are not beneficial to humans and there are no known means of removing them from the human body. They are toxic and when present in water supplies require removal (Okun & Ernst 1987). Other heavy metals evaluated were Al, Cr, Cu, Fe, Mn, Ni and Zn. According to the literature (see Siabi 2003; Kearns 2007; Mihelcic *et al.* 2009; Binnie & Kimber 2013), 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 of 60 cm length and 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 1). A leak-tight seal was provided between the flexible pipe and the 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 to see 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 6,894.8–34,473.8 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 (1). The Darcy–Weisbach head loss formula (Equation (2)) and Hagen–Poiseuille formula (Equation (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/day (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.

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

where h = gravitational pressure head in m; P = applied pressure in Pa; ρ = density of water ≈ 1,000 kg/m^3; g = gravitational acceleration ≈ 9.81 m/s^2.

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

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; $H_{\text{minor losses}} = 0.026$ m (i.e. assumed to be 1% of the static head).

$$f = \frac{64}{\text{Re}} \tag{3}$$

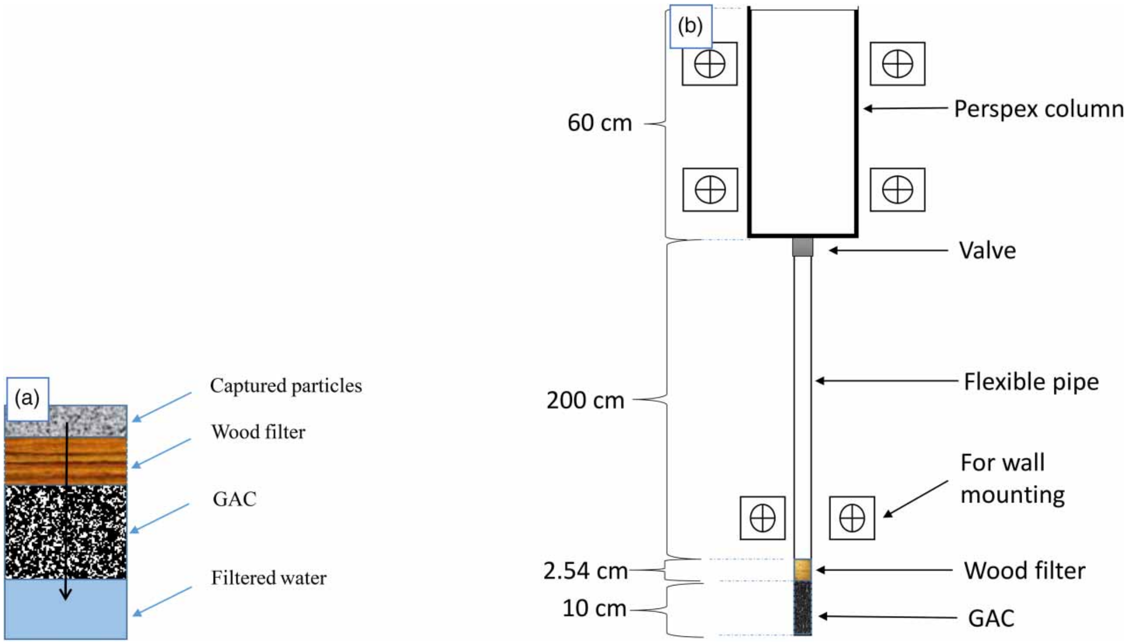

Figure 1 | Combined wood and GAC filtration: (a) process schematic diagram and (b) designed filter system.

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

Baseline study

Parallel experiments were performed on fresh, wet preserved and dry preserved wood filters. The four indigenous wood species used (Table 1) were obtained from the Stellenbosch University Botanical Garden. Although the final design included GAC (Figure 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 were 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 were 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 highlighted in Table 1.

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 of operational time to ensure adequate representation of the water treatment process. Figure 2 depicts the wood species *Combretum erythrophyllum*, *T. camphoratus*, *L. leonurus* and *S. mucronata* shown from left to right on top right and bottom images of Figure 2. The respective effluents are depicted in Figure 3.

Fresh wood filter testing: Testing on fresh wood filters was done as replicates over two testing periods (Figures 5 and 6). The testing period on the first set of fresh filters was 2 days (15th August 2018 and 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 7 days (from 21st August 2018 to 27th August 2018). Sampling for physical–chemical tests was done only for 4 days (see Figures 5 and 6), while sampling for *Escherichia coli* and fecal coliform 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 7 days under room temperature and afterwards used as filters in the designed system. Similarly, testing on wet preserved filters was also done as replicates over two testing periods (Figures 5 and 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 3 days (Figures 5 and 6). Then new wet preserved filters were tested for 1 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 and 6).

Dry preserved filter testing: Dry preservation was done by keeping unpeeled wood pieces away from direct sunlight

Table 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 elimhlophe (Zulu)	*Tarchonanthus camphoratus*
System 3 (WFS3)	Lion's ear (Eng.), imunyane (Zulu)	*Leonotis leonurus*
System 4 (WFS4)	Cape Willow (Eng.), Umzekana (Zulu)	*Salix mucronata*

Figure 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.

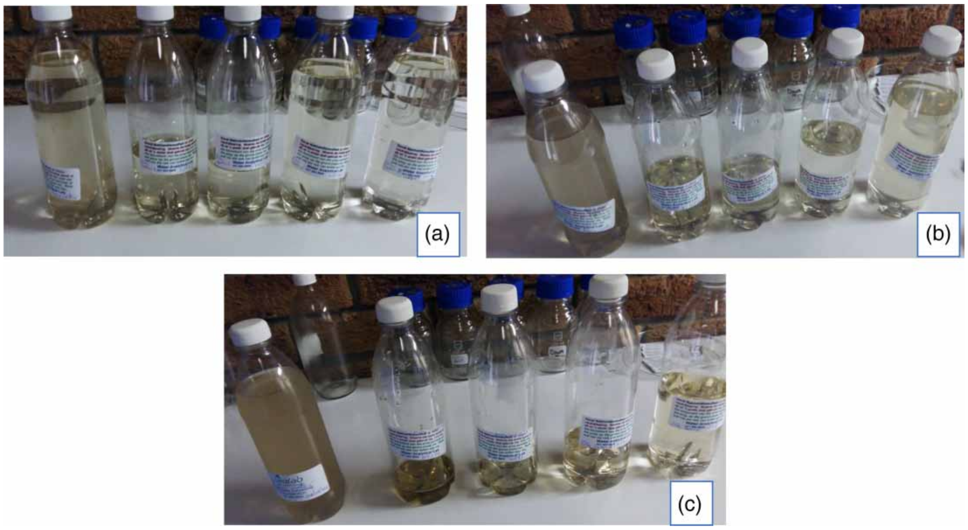

Figure 3 | Raw water and corresponding treated effluents: (a) fresh wood, (b) wet preserved wood and (c) dry preserved wood.

under room temperature which was generally between 8 and 20 °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 only for 2 days (Figures 5 and 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 flow rates.

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, *C. erythrophyllum* (WFS1) and *S. 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, *C. erythrophyllum* generally recorded the most objectionable color in the filtered water seconded by *S. mucronata*. Also, *C. erythrophyllum* yielded the lowest flow rates, while *S. mucronata* recorded the highest filter flow rates.

Testing of the combined wood and GAC systems and the respective controls was done over one testing period (Figure 7) for 8 days (from 4th September 2018 to 11th September 2018). Sampling for physical–chemical tests was done only for 5 days (see Figure 7), while sampling for *E. coli* and fecal coliform 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 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 (4) for an anticipated flow rate 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 (Pizzi 2010; Binnie & Kimber 2013).

$$\mathrm{EBCT} = \frac{V_{\mathrm{GAC}}}{Q_v} = \frac{V_{\mathrm{GAC}}}{v \cdot A} = \frac{h \cdot A}{v \cdot A} = \frac{h}{v} \tag{4}$$

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 physicochemical tests were done in the Civil Engineering Department's Water Quality Laboratory at Stellenbosch University. All tests were done in compliance with *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 1. The treatment effectiveness achieved by each filter system for *E. coli*, fecal coliforms, turbidity, TSS and metals was calculated using Equation (5):

$$\%\ \text{removal of contaminant} = \frac{C_i - C_e}{C_i} \times 100 \tag{5}$$

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 *C. erythrophyllum* (WFS1), *T. camphoratus* (WFS2), *L. leonurus* (WFS3) and *S. 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 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 4 and 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%, for fresh, wet preserved and dry preserved filter elements, respectively. *L. 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 *L. leonurus* and *T. camphoratus* may be attributed to their medicinal properties (SANBI 2018; SUBGSA 2018) and smaller xylem pore sizes were observed.

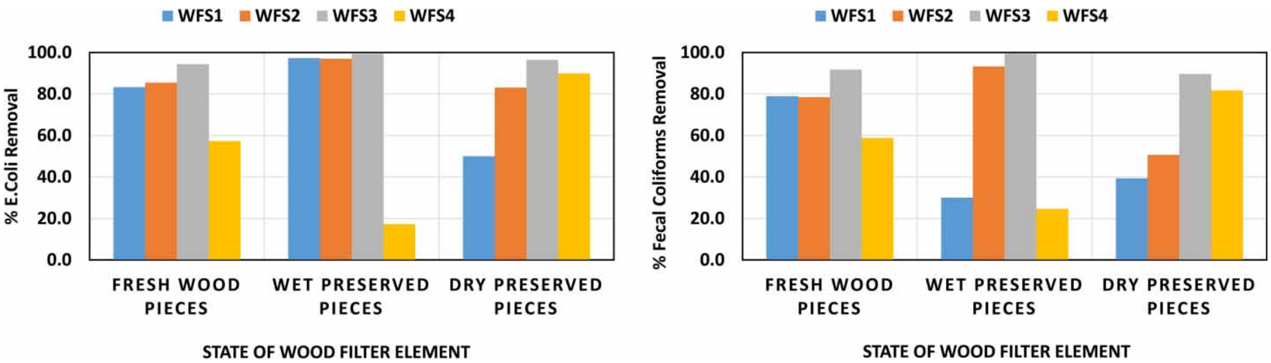

Figure 4 | Baseline study: bacterial removals by fresh and preserved wood filters.

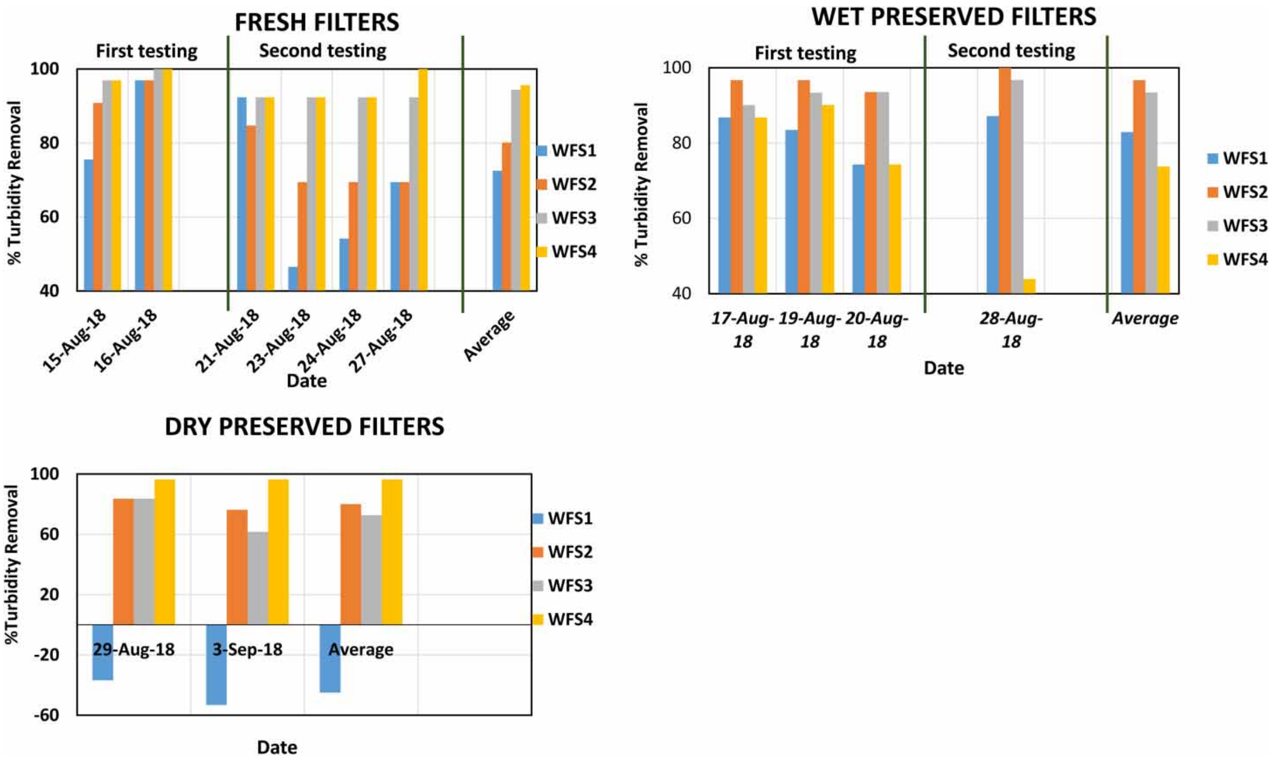

Figure 5 | Baseline study: percentage turbidity removals by fresh, wet preserved and dry preserved wood filters.

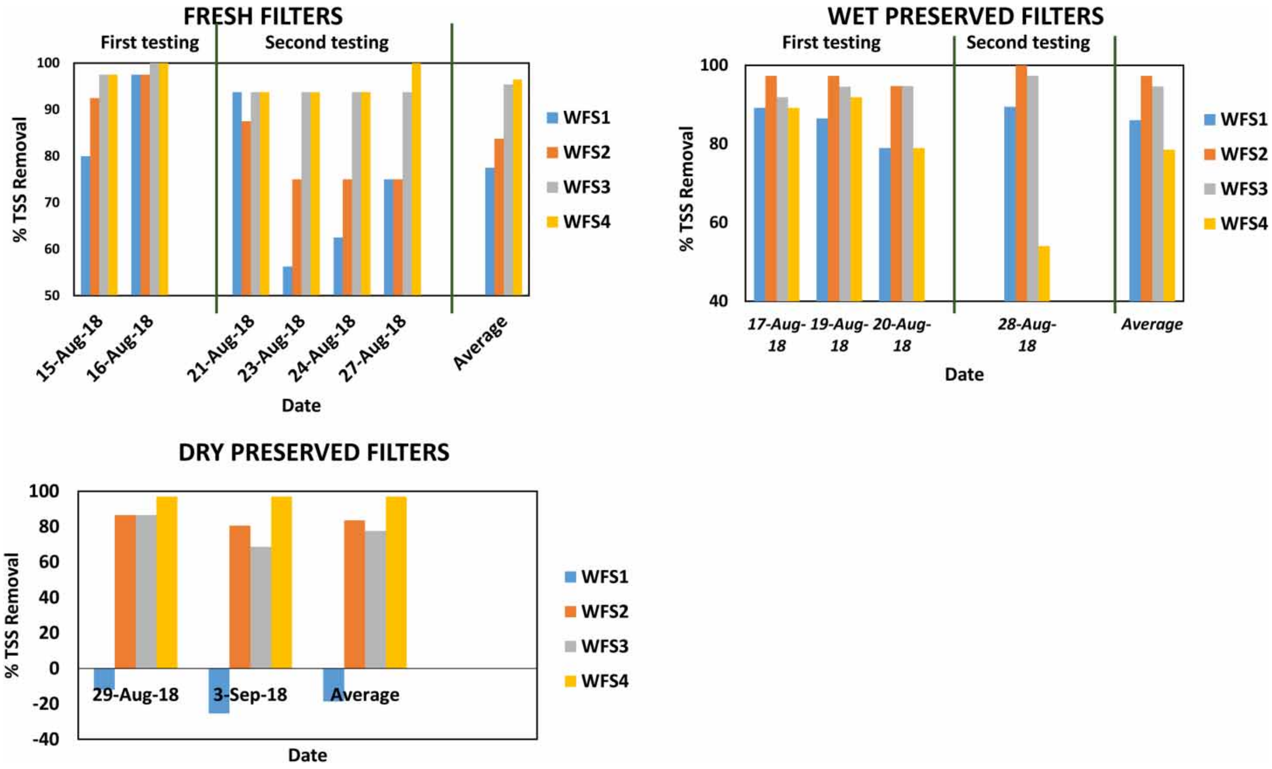

Figure 6 | Baseline study: percentage TSS removals by fresh, wet preserved and dry preserved wood filters.

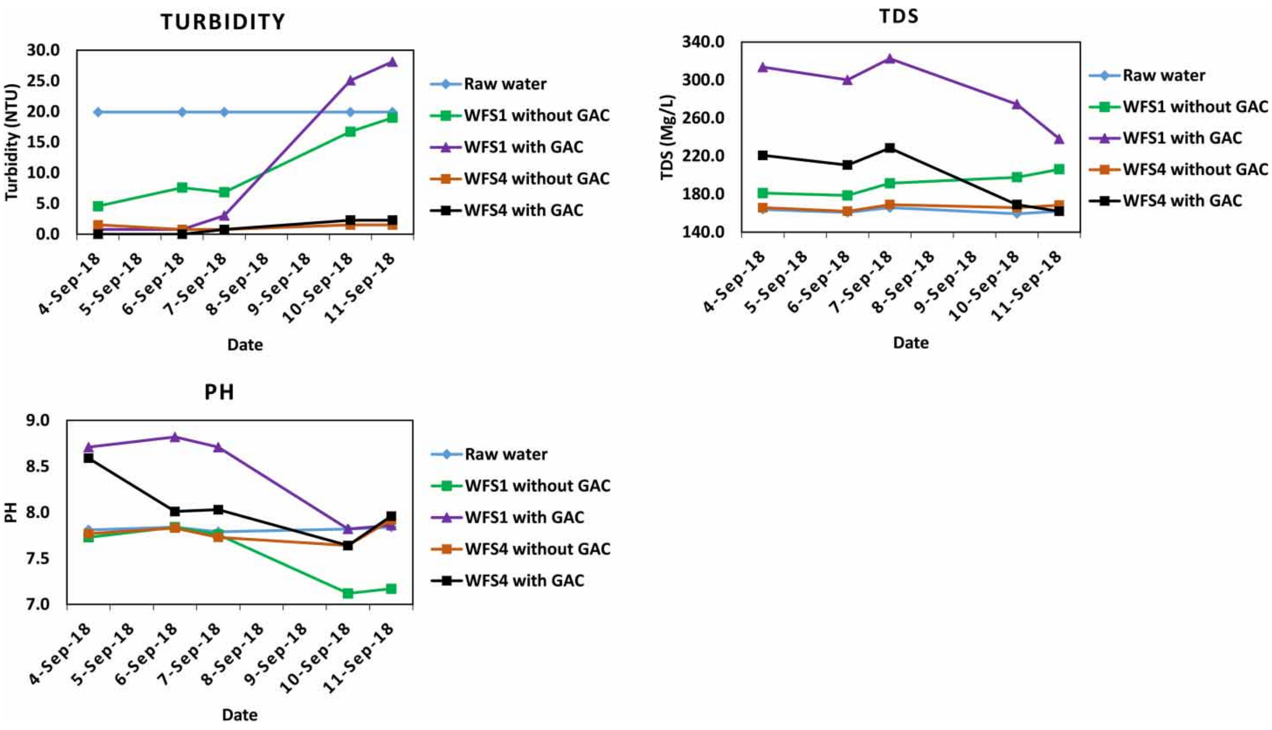

Figure 7 | GAC effect on produced water and assessment of the period after which the filter elements should be replaced.

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

Fresh wood filters average metal removals (sampling done on 16th and 21st August 2018)

				WFS1		WFS3		WFS4		WFS5	
Metal	Unit	LoD	Raw water Influent conc.	Effluent conc.	% removal	Effluent conc.	% removal	Effluent conc.	% removal	Effluent conc.	% removal
Al	μg/L	1.67	244.6	13.9	93.6	1.7	99.3	23.9	90.5	28.7	86.8
Cr	μg/L	0.18	<LoD	<LoD	<LoD	<LoD	<LoD	<LoD	<LoD	<LoD	<LoD
Cu	μg/L	1.69	15.0	25.8	**	53.1	**	22.9	**	28.1	**
Fe	μg/L	0.97	699.0	57.1	90.1	62.0	89.6	123.8	81.8	106.8	83.5
Mn	μg/L	0.29	24.0	39.4	**	33.5	**	21.8	9.2	67.0	**
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	24.6	**	19.7	**	<LoD	**	25.5	**

LoD = limit of detection; ** = increase in concentration over influent level.

The authors believe that the ‘medicinal properties’ may be anti-bacterial. *S. mucronata* was expected to perform like *L. leonurus* and *T. 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 *C. erythrophyllum* in the wet preserved state could be attributed to the absence of medicinal properties in its xylem. Signs of filter decay were observed during the preservation period for the wet preserved *C. erythrophyllum* and after 4 days of fresh filter use.

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

Although color, odor and taste were not adequately removed at this stage, particle removals were still appreciable (Figures 5 and 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 and 6) with worst removals being TSS (−18.7%) and turbidity (−45.0%) for dry preserved filters. That is, *C. 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 and 97.3% TSS removals and 82.9 and 96.7% turbidity removals, respectively. But, WFS3 and WFS4 gave their best particle removals as fresh filters recording 95.4 and 96.5% TSS removals and 94.4 and 95.7% turbidity removals, respectively (Figures 5 and 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.

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 2), while wet preserved wood filters recorded up to 99.9 and 99.8% Al and Fe removals, respectively (Table 3a). Dry preserved wood filters recorded up to 99.9 and 91.1% Al and Fe removals, respectively (Table 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 & McDonald 2015; Sumiahadi & Acar 2018). According to DalCorso *et al.* (2014), metal nutrients, such

Table 3 | Baseline heavy metal removal by wet and dry preserved wood filters

			Wet preserved wood filters (sampling done on 28th August 2018)								
				WFS1		WFS2		WFS3		WFS4	
Metal	**(a) Unit**	**LoD**	**Raw water Influent conc.**	**Effluent conc.**	**% removal**	**Effluent conc.**	**% removal**	**Effluent conc.**	**% removal**	**Effluent conc.**	**% removal**
Al	μg/L	1.67	1,275.0	<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	**	2,512.0	**	846.1	**

			Dry preserved wood filters (sampling done on 29th August 2018)								
				WFS1		WFS2		WFS3		WFS4	
Metal	**(b) Unit**	**LoD**	**Raw water Influent conc.**	**Effluent conc.**	**% removal**	**Effluent conc.**	**% removal**	**Effluent conc.**	**% removal**	**Effluent conc.**	**% removal**
Al	μg/L	1.67	1,252.0	<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	1,251.0	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	1,392.0	**	82.4	**	1,021.0	**	27.5	**

LoD = limit of detection; ** = increase in concentration over influent level.

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 were done on three separate days.

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/day 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/day for WFS1, WFS2, WFS3 and WFS4, respectively. 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 0.2, 0.2, 0.3 and 0.5 L/day for WFS1, WFS2, WFS3 and WFS4, respectively. Overall, the flow rate values were in the following order: WFS1 < WFS2 < WFS3 < WFS4. Therefore, in terms of flow rate, *L. leonurus* and *S. mucronata* are the most promising species for the designed gravity-driven filter system. Flow rates for fresh and wet preserved *L. leonurus* and *S. 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 the quality of produced water

High pollutant removals were recorded by the combined system (Tables 4 and 5). This may be attributed to the

Table 4 | Effect of GAC on heavy metal removal by the filter systems

				WFS1 with GAC		**WFS1 without GAC**		**WFS4 with GAC**		**WFS4 without GAC**	
Metal	**Unit**	**LoD**	**Raw water 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 was done on 5th September 2018.

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

			Gravity-driven filter systems with and without GAC				**Drinking water standards**	
Bacteriological and physical parameters	***N***	**Raw water**	**WFS1 with GAC**	**WFS 1 without GAC**	**WFS 4 with GAC**	**WFS 4 without GAC**	**SANS241**	**WHO (2017a)**
Color	5	Yellow to Brownish	Pleasing and clear	Objectionable	Pleasing and 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	1,420	0	2,200	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	≤1,700	2,500
TDS (mg/L)	5	163.4 ± 2.1	312.1 ± 9.2	183.7 ± 5.5	219.9 ± 7.3	165.5 ± 2.9	≤1,200	1,000
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.

low flow rates and large EBCT >20 min which was adequate for removal of most contaminants by GAC (Pizzi 2010; Binnie & Kimber 2013). 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 3 and 4) and control filters used here (Tables 4 and 5) depict some appreciable contaminant removals by wood filters alone.

Wood filters combined with GAC: removal of TSS, turbidity, color, odor and taste

Figure 7 shows that wood filters combined with GAC caused high particle removals, recording up to 97% TSS and 96% turbidity removals by WFS1, and 100% TSS and 100% turbidity removal by WFS4 in the first 4 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 particulate 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 4 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 (8th) 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 & Schneider 2015).

The combined systems removed color, odor and taste remarkably well (Table 5), further improving the acceptability of the treated water. Improving aesthetic characteristics of water (TSS, turbidity, color, odor and taste) is key to acceptability of a low-cost water treatment system (McAllister 2005; CAWST 2017; 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 & Hammer 2012; Nathanson & 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, the 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

Bacterial removal for the combined wood and GAC system was high recording >99.9% *E. coli* removals by both WFS1 and WFS4 (Table 5). Likewise, fecal coliform removal was >99.9% by WFS1 and ≥99.9% by WFS4 (Table 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 Kearns 2007; Pizzi 2010; Binnie & Kimber 2013; CAWST 2017; 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 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 and 0.0% for Fe, Pb, Ni, Al, Zn, Cu, As, Cr, Cd and Mn, respectively. But, 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 and 0.0% for Fe, Pb, Ni, Al, Zn, Cu, As, Cr, Cd and Mn, respectively. Similarly, metal removals by WFS4 combined with GAC were 99.4, 93.8, 88.6, 92.4, 93.7, 94.3, 65.1, 62.8, 73.7 and 0.0% for Fe, Pb, Ni, Al, Zn, Cu, As, Cr, Cd and Mn, respectively. 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 and 0.0% for Fe, Pb, Ni, Al, Zn, Cu, As, Cr, Cd and Mn, respectively. 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 with ** in Table 4). It is not clear whether Mn leached from the filter media or not e.g., with initial capture and subsequent release. According to the literature (see Siabi 2003; bin Jusoh *et al.* 2005; Binnie & Kimber 2013), GAC is expected to remove Mn. For instance, Siabi (2003) reported 75–92% Mn removals 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 give 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.

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 and Figure 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). 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, odor 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 so that people can build it themselves, but so that NGOs could possibly use the knowledge towards application on site. The NGOs should be able to source GAC at reasonably low cost.

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/day for fresh wood filters and 7.6 and 3.3 L/day for wet preserved wood filters, respectively. However, it is possible that each of the investigated systems could, with a higher gravity head – say 3.5–4 m – and parallel units, conceivably deliver adequate drinking water amounts. The designed gravity-driven combined wood and

GAC system was found to be of relatively low cost (<4 US$) and can be easily constructed and fabricated. This technology, therefore, 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 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. Long-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.

REFERENCES

American Public Health Association (APHA)/American Water Works Association (AWWA)/Water Environment Federation (WEF) 2012 *Standard Methods for the Examination of Water and Wastewater*, 22nd edn. American Public Health Association (APHA)/American Water Works Association (AWWA)/Water Environment Federation (WEF), Washington, DC, USA.

bin Jusoh, A., Cheng, W. H., Low, W. M., Nora'aini, A. & Megat Mohd Noor, M. J. 2005 Study on the removal of iron and manganese in groundwater by granular activated carbon. *Desalination* **182**, 347–353. doi:10.1016/j.desal.2005.03.022.

Binnie, C. & Kimber, M. 2013 *Basic Water Treatment*, 5th edn. Institution of Civil Engineers (ICE) Publishing, London.

Boutilier, M. S. H., Lee, J., Chambers, V., Venkatesh, V. & Karnik, R. 2014 Water filtration using plant xylem. *PLoS ONE* **9**, e89934. doi:10.1371/journal.pone.0089934.

Center for Affordable Water and Sanitation (CAWST) 2017 *Introduction to Drinking Water Quality for Household Water Treatment Implementers*. Technical Brief, Calgary, Alberta, Canada.

Choat, B., Ball, M., Luly, J. & Holtum, J. 2003 Pit membrane porosity and water stress-induced cavitation in four co-existing dry rainforest tree species. *Plant Physiology* **131**, 41–48.

DalCorso, G., Manara, A., Piasentin, S. & Furini, A. 2014 Nutrient metal elements in plants. *Metallomics* **6**, 1770–1788. doi:10.1039/C4MT00173G.

Ellis, K. V. 1991 Water disinfection: a review with some consideration of the requirements of the third world. *IWA Critical Reviews in Environmental Control* **20**, 341–407. doi:10.1080/10643389109388405.

Fanner, R. W., Dussert, B. W. & Kovacic, S. L. 1996 *Improved Granular Activated Carbon for the Stabilization of Wastewater pH*. Calgon Carbon Corporation, Pittsburgh, Pennsylvania, USA.

Hammer Sr, M. J. & Hammer Jr, M. J. 2012 *Water and Wastewater Technology: New International Edition*, 7th edn. Pearson, Harlow, UK.

Hijnen, W. A. M., Suylen, G. M. H., Bahlman, J. A., Brouwer-Hanzens, A. & Medema, G. J. 2010 GAC adsorption filters as barriers for viruses, bacteria and protozoan (oo)cysts in water treatment. *Water Research* **44**, 1224–1234. doi:10.1016/j.watres.2009.10.011.

Ispotnature 2018 *The Open University OpenScience Laboratory*. Available from: https://www.ispotnature.org/ (accessed 10 June 2018).

Kausley, S. B., Dastane, G. G., Kumar, J. K., Desai, K. S., Doltade, S. B. & Pandit, A. B. 2018 Clean Water for Developing Countries: Feasibility of Different Treatment Solutions. In: *Encyclopedia of Environmental Health*, 2nd edn. Elsevier. doi:10.1016/B978-0-12-409548-9.11079-6.

Kearns, J. 2007 *Charcoal Filtration Basics: Aqueous Solutions Drinking Water Systems. Advancing the Science of Self-Reliance*. Available from: aqsolutions.org.

Kim, K., Seo, E., Chang, S. K., Park, T. J. & Lee, S. J. 2016 Novel water filtration of saline water in the outermost layer of mangrove roots. *Scientific Reports* **6**, 20426. doi:10.1038/srep20426.

Llobet, J. M., Falcó, G., Casas, C., Teixidó, A. & Domingo, J. L. 2003 Concentrations of arsenic, cadmium, mercury, and lead in common foods and estimated daily intake by children, adolescents, adults, and seniors of Catalonia, Spain. *Journal of Agricultural and Food Chemistry* **51** (3), 838–842.

McAllister, S. 2005 *Analysis and Comparison of Sustainable Water Filters*. Available from: http://potterswithoutborders.com/wp-content/uploads/2011/06/analysis-and-comparison-of-sustainable-water-filters.pdf (accessed 4 October 2017)

Mihelcic, J., Fry, L., Myre, E., Phillips, L. & Barkdoll, B. 2009 *Field Guide to Environmental Engineering for Development Workers*. American Society of Civil Engineers, Reston, Virginia, USA.

Nathanson, J. A. & Schneider, R. A. 2015 *Basic Environmental Technology: Water Supply, Waste Management, and Pollution Control*, 6th edn. Pearson, Upper Saddle River, New Jersey, USA.

Okun, D. A. & Ernst, W. R. 1987 *Community Piped Water Supply Systems in Developing Countries: A Planning Manual, World Bank Technical Paper*. World Bank, Washington, DC, USA.

Pizzi, N. G. 2010 *Water Treatment: Principles and Practices of Water Supply Operations*. American Water Works Association, Denver, Colorado, USA.

Rotocarb 2018 Rotocarb South Africa. Activated carbon producers. Available from: http://www.rotocarb.co.za/ (accessed 27 June 2018).

Roy, M. & McDonald, L. M. 2015 Metal uptake in plants and health risk assessments in metal-contaminated smelter soils: remediation of metal-contaminated soils. *Land Degradation & Development* **26**, 785–792. doi:10.1002/ldr.2237.

SANBI 2018 *Plantz Africa*. South African National Biodiversity Institute (SANBI). Available from: http://pza.sanbi.org/ (accessed 10 June 2018).

Sens, M. L., Emmendoerfer, M. L. & Muller, L. C. 2013 Water filtration through wood with helical cross-flow. *Desalination and Water Treatment* **53**, 15–26. doi:10.1080/19443994.2013.837010.

Siabi, K. W. 2003 Potential of activated carbon for manganese and iron removal. In: *29th Water, Engineering and Development Centre (WEDC) International Conference*, Abuja, Nigeria, pp. 152–155.

SUBGSA 2018 *Garden Explorer: Stellenbosch University Botanical Garden, South Africa (SUBGSA)*. Available from: https://sun.gardenexplorer.org/ (accessed 10 June 2018).

Sullivan, P. J., Agardy, F. J. & Clark, J. J. J. 2005 *The Environmental Science of Drinking Water*, 1st edn. Elsevier Butterworth-Heinemann, Burlington.

Sumiahadi, A. & Acar, R. 2018 A review of phytoremediation technology: heavy metals uptake by plants. *IOP Conference Series: Earth and Environmental Science* **142**, 012023. doi:10.1088/1755-1315/142/1/012023.

Supong, A., Bhomick, P. C. & Sinha, D. 2017 Waterborne pathogens in drinking water-existing removal techniques and methods. *MOJ Toxicology* **3**, 146–147. doi:10.15406/mojt.2017.03.00072.

Turkez, H., Geyikoglu, F., Tatar, A., Keles, M. S. & Kaplan, İ. 2012 The effects of some boron compounds against heavy metal toxicity in human blood. *Experimental and Toxicologic Pathology* **64** (1–2), 93–101. doi:10.1016/j.etp.2010.06.011.

WHO 2017a *Guidelines for Drinking-Water Quality: 4th edn. Incorporating the First Addendum*. World Health Organization (WHO), Geneva. Available from: http://apps.who.int/iris/bitstream/10665/254637/1/9789241549950-eng.pdf (accessed 4 December 2017).

WHO 2017b *Water Quality and Health-Review of Turbidity: Information for Regulators and Water Suppliers*. Available from: http://apps.who.int/iris/bitstream/10665/254631/1/WHO-FWC-WSH-17.01-eng.pdf (accessed 4 December 2017).

WHO/UNICEF 2004 World Health Organization and United Nations Children's Fund. In: *Meeting the MDG Drinking Water and Sanitation Target: A Mid-Term Assessment of Progress*. UNICEF and WHO, Geneva.

First received 23 November 2018; accepted in revised form 23 April 2019. Available online 9 May 2019