The efficacy of a recovered wash water plant in removing cyanobacteria cells and associated organic compounds

S. Mkhonto, H. Ewerts, A. Swanepoel and G. C. Snow

ABSTRACT

The treatment works under investigation uses a recovered wash water plant (RWWP) to remove impurities prior to recycling filter backwash water. Filter backwash water (raw water) is characterized by high quantities of cyanobacteria cells and associated organic compounds; a potential threat when recovered water is recycled. The aim of this study is to identify the cyanobacteria cells and associated organic compounds in the filter backwash water and to subsequently evaluate the effectiveness of the RWWP in removing these organic impurities during the following periods; autumn-winter and spring-summer. Results showed that at least six major phytoplankton groups were present in the filter backwash water with turbidity levels (59 and 46 NTU; autumn-winter and spring-summer, respectively) being much higher than the drinking water productions standard of $\leq$5 NTU. Cyanobacteria were a dominant group (mean of 80% and above) in the total phytoplankton composition of the raw water and consisted of three genera (*Anabaena* sp., *Microcystis* sp. and *Oscillatoria* sp.), which were effectively removed by the RWWP (up to 99%). However, associated organic compounds such as geosmin, total organic carbon (TOC), dissolved organic carbon (DOC) and microcystin were not effectively removed during the different seasonal periods but were of such low concentrations that they posed no major risk to the drinking water quality, meeting the RWWP water quality standard.

Key words | geosmin, microcystin, phytoplankton, water quality, water treatment

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HIGHLIGHTS

- The seasonal occurrence of algae and cyanobacteria in recycled backwash water and the effective removal thereof.
- The correlation between microcystin and *Microcystis* sp. in recycled filter backwash water with chlorophyll pigments removal confirming the removal efficiencies of algae and cyanobacteria.
- Poor removal efficiencies of organic compounds by a recycled water treatment plant require optimization practices.
- Implement phytoplankton water quality monitoring for RWWP and the implementation of a routine sampling plan to determine water quality at different stages of the RWWP.
- Stringent water quality monitoring plans to be implemented during all seasonal periods in the RWWP, especially where organic compounds associated with cyanobacteria are a concern.

INTRODUCTION

Water is a limited and critical resource to achieve sustainable goals that include economic, environmental and social development (DWAF 2002). Access to safe drinking water is an essential component of effective policy for health protection and sanitation, as well as for quality of life (Matthews & Bernard 2015). It is evident from

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international literature that many countries are facing challenges in securing water for basic human needs and development (WEF 2017). According to Grey & Sadoff (2007), achieving water security by reducing its destructive potential and increasing the productive potential will remain a central challenge for poor countries of the world today; however, it has always been a goal of human society to be achieved. Furthermore, the degradation of water quality is putting more pressure on water security, especially in water-scarce countries such as South Africa. Good health and well-being may not be possible without access to adequate safe drinking water that meets the needs of an entire population (Govender 2016).

Population growth and several other factors such as mining, urbanization, industrialization, agriculture and power generation negatively impact on water quality. This leads to cultural eutrophication where source water becomes high in nutrient concentrations, such as nitrogen and phosphorus, supporting high phytoplankton growth rates and biomass (Oberholster 2010; Swanepoel *et al.* 2017). Cyanobacterial blooms are a threat to the supply of drinking water in South Africa, especially in areas that have shortages of water treatment facilities or where infrastructure is not functioning properly (Van Ginkel 2011). Cyanobacteria, also known as blue-green algae, produce a range of cyanotoxins (Van Ginkel 2011) such as hepatic-, neuro-, and cytotoxins, which are mostly known from the cyanobacteria genera *Microcystis* sp., *Oscillatoria* sp., *Aphanizomenon* sp., *Anabaena* sp., *Nodularia* sp., *Nostoc* sp. (Harding & Paxton 2001) and *Cylindrospemopsis* sp. (Van Ginkel 2011). The cyanotoxins produced by cyanobacteria have an effect on human health, such as poisoning incidents that might be acute or sub-acute liver damage caused by the largest group of toxins known as the microcystins (Harding & Paxton 2001). Cyanobacteria produce taste and odour compounds, the most common of which are geosmin and 2-methyl-isoborneol (2–MIB). These organic compounds may cause degradation of aesthetic quality of water yet, even though it is unpleasant, they are not harmful but can lead to consumer complaints (Swanepoel *et al.* 2008).

The rapid growth of algae in response to elevated concentrations of nutrients in water bodies may clog filters and block screens (Ewerts *et al.* 2013). Some cyanobacteria, such as *Microcystis* sp. can produce coagulant inhibitor proteins that may disturb the coagulation process (Chorus & Bartram 1999). Increasing the cost of treating water (Sibande 2013; Chinyama *et al.* 2016) and potentially penetrating the final treated water (Swanepoel 2015), giving water a greenish colour due to regrowth in the distribution system (DWAF 1996). According to Hitzfeld *et al.* (2000), coagulation can be an efficient method for eliminating cyanobacterial cells from water, whereas soluble cyanotoxins are not very efficiently removed by this method. Conventional water treatment plant processes (flocculation, sedimentation, filtration and chlorination) might not be effective in removing dissolved substances such as microcystins derived from *Microcystis* sp. (Oberholster *et al.* 2004; Ewerts *et al.* 2013; Swanepoel *et al.* 2017). In addition, when cells are present in treated water during disinfection, they may serve as precursors for the formation of harmful trihalomethanes. Trihalomethanes form when organic material reacts with chlorine during pre-oxidation (DWAF 1996).

It is important for water treatment facilities to be able to manage and monitor cyanobacteria and related organic compounds in the drinking water treatment processes. The presence of cyanobacteria affects the water treatment and the quality of water in general. South Africa is a country with water shortages (DWAF 2002), making it important to recover filter backwash water, since filter backwashing uses large volumes of treated water. Filter backwashing is an integral part of the treatment process and plant operation to clean filters periodically using treated water combined with air in a reverse direction to the normal flow. This produces a significant amount of contaminated backwash water containing high concentrations of total suspended solids (TSS), total organic carbon (TOC), inorganic precipitates as well as microorganisms such as phytoplankton cells (Li *et al.* 2017). It is therefore important to treat the recovered water to a good quality to allow for distribution to consumers for drinking. Poorly treated or untreated recovered water may have a negative impact on the final treated water; therefore, the following considerations should be given: (1) contaminants in recovered water could be more efficiently removed than those in raw water because the particles in recovered water have already been destabilized; and (2) recovered water increases the collision and adhesion probabilities for the suspended particles in the coagulation process thus further enhancing the subsequent treatment processes.

This study is aimed at understanding and gathering information regarding the efficacy of a recovered wash water plant (RWWP) associated with the main water treatment plant (main WTP) in removing cyanobacteria and associated organic compounds from the recovered water. The objectives of the study were to (1) identify the phytoplankton groups in the recovered filter water supplied to the RWWP, (2) identify cyanobacteria genera present in the recovered filter water, and (3) investigate the effectiveness of the RWWP in removing cyanobacteria and associated organic compounds during autumn-winter and spring-summer sampling occasions.

METHODS

Study area

The study was conducted at the 35 ML/D RWWP outside of Vereeniging (Gauteng Province, South Africa). The plant applies conventional water treatment processes that include coagulation, flocculation, sedimentation and sand filtration to treat recovered filter backwash water. After treatment, recycled water is mixed with water in the main water treatment plant for disinfection and distribution.

Coagulant chemicals used at RWWP

The following coagulant chemicals and dosages were dosed in the RWWP during the study period: polyelectrolyte 3,835 was dosed as the primary coagulant and 45% $FeCl_3$ as a secondary coagulant. The optimum dosages, as determined by jar test experiments, were 5 mg/L polyelectrolyte and 4 mg/L $FeCl_3$.

Sampling and water quality analysis

Raw water samples: for the purpose of this study, raw water refers to recovered filter backwash water destined for treatment by the RWWP. Raw water samples were collected as the first samples prior to entering the RWWP. Subsequent process samples were collected after sedimentation and then after filtration. All raw water and subsequent process samples were collected during March 2017–February 2018, referring to the sampling occasions as autumn-winter and spring-summer. The analysis of water samples was performed at an accredited analytical laboratory situated in Vereeniging, Gauteng, South Africa. The laboratory is accredited by SANAS (South African National Accreditation System).

Phytoplankton analyses (identification and enumeration) was determined by sedimentation/centrifugation technique that was originally described by Lund *et al.* (1958) and adapted by Swanepoel *et al.* (2008). Chlorophyll (Chl-665) was determined by spectrophotometry according to the Swanepoel *et al.* (2008) method. The taste and odour compound geosmin was extracted using solid phase extraction and quantified by means of the gas chromatography-mass spectrometry (GCMS) method (APHA 2013) and adapted for the laboratory according to Swanepoel *et al.* (2008). The concentration of the microcystin (total microcystin) was determined by means of the enzyme linked immune sorbent assay (ELISA) technique, also described by Swanepoel *et al.* (2008), using Envirologix ELISA kits (Envirologix 2013). The content of organic matter was determined as TOC and dissolved organic carbon (DOC) using standard methods for examination of water and wastewater samples (APHA 2013). TOC samples were collected headspace-free in 40 mL glass vials and preserved with 21% phosphoric acid and measurements performed (Phoenix and Fusion). The physical parameters turbidity, pH and electrical conductivity were measured using a HACH-2100AN turbidimeter, Metrohm 691 pH meter and LF 538 conductivity meter, respectively.

Percentage removal during raw water (RWWP) and after filtration for the study period was determined by the following formula:

$$\text{Removal (\%)} = \frac{\begin{array}{c}\text{Average cyanobacteria cells (raw water RWWP)}\\ - \text{Average cyanobacteria cells (After filtration)}\end{array}}{\text{Average cyanobacteria cells (raw water RWWP)}}$$

Flow of recovered filter water to RWWP treatment processes and to main treatment works

The main WTP treat water from Vaal Dam, using conventional treatment processes (coagulation, flocculation, sedimentation, carbonation, sand filtration, chlorination and distribution) to treat approximately 1,800 ML/D. The plant uses chemicals such as hydrated lime, polyelectrolytes as coagulants and carbon dioxide (to adjust pH). After the process of coagulation, flocculation and sedimentation, the water is channelled to 3 filter houses with a total of 96 rapid gravity sand filters, which run on 36-hour backwash cycles during normal operations. Recovered filter backwash water (raw water) is pumped to the RWWP as filter backwash effluent from the main water treatment plant. After conventional treatment in the RWWP (coagulation, flocculation and sedimentation), recycled or treated water is channelled to the main WTP treated sump (Figure 1). The RWWP contains a filter house with three rapid gravity sand filters set on an automatic backwash mode. An illustration of the treatment process is provided in the diagram below (Figure 1).

Statistical analysis

Three sets of data were used for the analyses, namely raw water, after sedimentation and after filtration, and they were clustered as autumn-winter and spring-summer. Different variables were examined such as cyanobacteria types and concentration present, organic compounds such as geosmin and microcystin. The datasets were used to determine the efficiency of the RWWP in removing cyanobacteria and associated organic compounds. A single factor analysis of variance (ANOVA) was used to determine removal efficiencies at different stages of water treatment by examining for statistically significant differences. The level of significance for all statistical analysis was set at a p value ≤ 0.05 and the hypothesis was that there is a significant improvement in water quality.

Datasets obtained from 47 sampling occasions were used to perform a Canonical Correspondence Analysis (CCA) using the computer software package CANOCO version 4.5. The CCA was carried out to determine the relationship between parameters such as cyanobacteria (*Microcystis* sp., *Oscillatoria* sp. and *Anabaena* sp.) with Chlorophyll-665, microcystin, geosmin, TOC and DOC. Ordinations were interpreted using the following rationale: parameters are positively correlated with each other if their arrows subtend a small angle. Negatively correlated if their arrows are in the opposite directions (180°) and correlated when their arrows are at 90° angle.

RESULTS AND DISCUSSION

Assessment of raw water entering the RWWP

Six major phytoplankton groups were detected in the raw water samples during all months of the study period. The

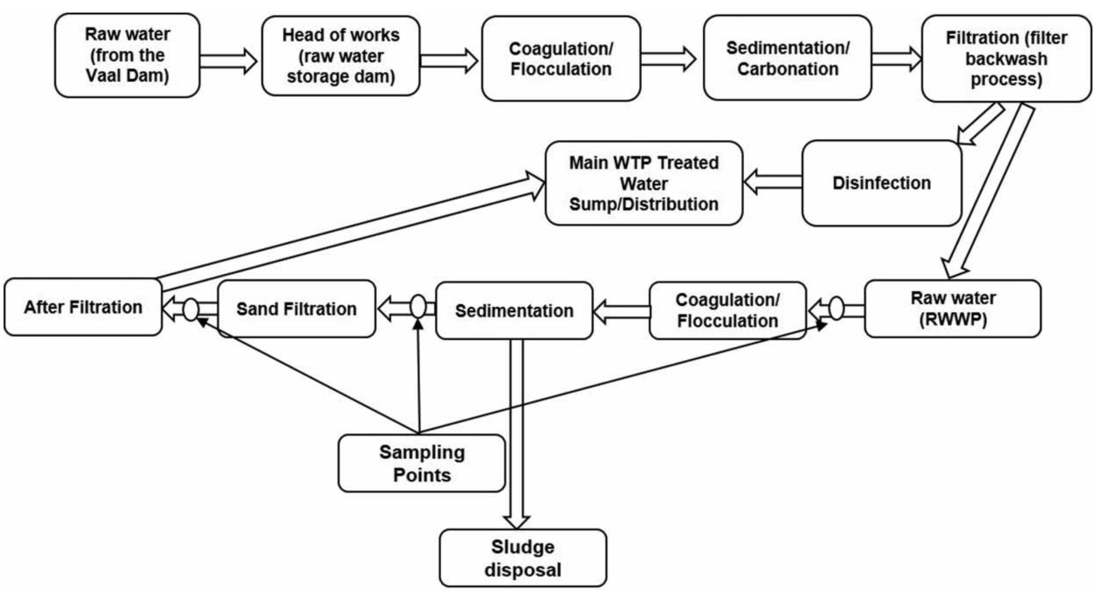

Figure 1 | Schematic of the RWWP showing the sequence of purification processes (coagulation, flocculation, sedimentation and sand filtration) and included sampling points, linked to the main water treatment plant.

phytoplankton composition consisted of the following major groups; namely, Bacillariophyceae (diatoms), Chlorophyceae (green algae), Cyanophyceae (cyanobacteria or blue-green algae), Dinophyceae (dinoflagellates), Chrysophyceae (golden-brown algae) and Euglenophyceae (euglenoids). The total phytoplankton composition in raw water was dominated (mean of 80% and above) by cyanobacteria, consisting of the following species: *Anabaena* sp., *Microcystis* sp. and *Oscillatoria* sp. *Microcystis* sp. occurred more frequently and it was the most dominant (more than 80% of the dataset) than other species of the same group in the raw water during both autumn-winter and spring-summer months. According to Van Vuuren *et al.* (2006), *Microcystis* sp. usually dominates a habitat and excludes almost all other species of cyanobacteria, which appeared to be the case in this study. Table 1 below shows the cell concentrations of phytoplankton groups, cyanobacteria species and organic compounds as well as the concentrations of three important physical parameters measured in raw water samples during the study period.

Table 1 | Average concentrations and standard deviation (±SD) for phytoplankton groups, cyanobacteria genera, organic compounds and physical parameters measured in raw water entering the RWWP during the study period

		Autumn-winter		Spring-summer	
Phytoplankton groups	**Units**	**Mean**	**± SD**	**Mean**	**± SD**
Bacillariophyceae	cells/mL	769	548	909	890
Chlorophyceae	cells/mL	200	361	315	611
Cryptophyceae	cells/mL	291	241	227	130
Dinophyceae	cells/mL	52	33	40	0
Euglenophyceae	cells/mL	45	13	40	0
Cyanophyceae	cells/mL	6,593	7,602	22,653	26,244
Cyanophyceae genera					
Anabaena sp.	cells/mL	199	224	4,358	4,677
Microcystis sp.	cells/mL	6,103	7,595	18,310	24,677
Oscillatoria sp.	cells/mL	291	710	40	0
Organic compounds					
Geosmin	ng/L	7	4.0	59	66
Microcystin	μg/L	0.85	0.7	1	0.8
Chlorophyll – 655	μg/L	18	17	34	20
TOC	mg/L	4	0.7	3	1.4
DOC	mg/L	3	1.1	3	0.9
Physical parameters					
Turbidity	NTU	59	20	46	13.0
pH	pH units	8.7	0.11	8.7	0.2
Electrical conductivity	mS/m	18	1.0	17.3	1.0

The average (Tables 1 and 3) diatom concentrations recorded during autumn-winter and spring-summer months showed important contributions to the total phytoplankton composition (>500 cells/mL), while other phytoplankton groups (green algae, golden-brown algae, dinoflagellates and euglenoids) were detected in relatively low concentrations (<500 cells/mL). Groups occurring in concentrations below 500 cells/mL may not pose a risk to the water quality and treatment processes. However, it remains a priority for treatment facilities, especially for drinking water treatment plants, to remove algae that may introduce any quality or treatment problems to acceptable levels at each stage of treatment. Although diatoms were present in lower quantities compared to the cyanobacteria, their removal efficacy should be monitored simultaneously with the dominant cyanobacteria group.

The average (Tables 1 and 3) cyanobacteria concentration in the raw water was recorded at 6,593 cells/mL during the autumn-winter, while an average (Tables 1 and 3) concentration of 22,653 cells/mL was recorded for spring-summer months. During spring-summer, SD values for Dinophyceae, Euglenophyceae and *Oscillatoria* sp. were recorded as zero, indicating that all the samples had the same values, while exceeding mean SD values were recorded for Chlorophyceae, Cyanobacteria and geosmin, indicating that the data was more spread out (Table 1). High cell concentrations are likely to affect the drinking water process when cyanobacteria enter the water treatment plant (Swanepoel *et al.* 2008). Thus, coagulant optimization strategies should form an integral part of the water treatment when raw water is characterized by relatively high cyanobacteria concentrations (>2,000 cells/mL).

The average turbidity levels determined during both occasions were recorded as 59 NTU and 46 NTU for autumn-winter and spring-summer months, respectively. Turbidity is an important parameter measured during water treatment (≤5 NTU after sedimentation) and an aesthetic criterion set by the South African National Standard (SANS 241 2011). Ewerts *et al.* (2015) found that phytoplankton content in water may have an impact on the turbidity; however, the removal of turbidity cannot necessarily be used as an effective indicator of phytoplankton removal. Other important physical parameters, such as pH and conductivity, were measured and yielded the same results for both autumn-winter and spring-summer periods and posed no treatment challenges for the RWWP unit processes (Table 1).

Multivariate data analysis

The final CCA results are displayed in Figure 2, indicating the relationship between cyanobacteria and associated organic compounds. Samples ($n = 47$) were analysed for efficacy of the RWWP (based on the removal of cyanobacteria and associated organic compounds). The cumulative percentage variance of species-environmental composition is explained by correspondence axes 1 and 2, explaining 77.8% and 100% respectively. Microcystin, geosmin and Chl-665 revealed the biggest influence on the data during the spring-summer months. Samples collected during autumn-winter months were closely associated with TOC, while cyanobacteria genera were relatively consistently associated with both seasonal periods (Figure 2).

A positive correlation was also observed between *Anabaena* sp., Chl-665 and geosmin. The positive correlation between Chl-665 and *Anabaena* sp. indicates that most of the photosynthetic pigments originate from *Anabaena* sp. TOC was negatively correlated with *Anabaena* sp., Chl-665 and geosmin. The taste and odour present in the water from the backwash cycle can thus be ascribed to the presence of geosmin produced by *Microcystis* sp. and *Anabaena* sp., which is also confirmed by Ewerts *et al.* (2013), who found a positive correlation between *Anabaena* sp. and geosmin. Shang *et al.* (2018) also investigated the co-occurrence of microcystins and taste and odour compounds in drinking water source and their removal in a full-scale drinking water treatment plant. This study confirmed the production of geosmin with 2–methylisoborneol (2-MIB) and other organic compounds such as β-cyclocitral and β-ionone.

Cyanobacteria and associated organic compound assessment: after sedimentation

The number of cyanobacteria cells after sedimentation in the RWWP was reduced to an average concentration of 68 cells/mL (Table 3) during the autumn-winter months and an average of 259 cells/mL (Table 3) during spring-summer months. All phytoplankton concentrations were reduced to acceptable levels during the study period; however, the concentrations of organic compounds (TOC and DOC) remained relatively stable throughout the study period. The conventional processes require optimization strategies to remove these compounds, especially since the raw water from filter backwash is enriched with organic

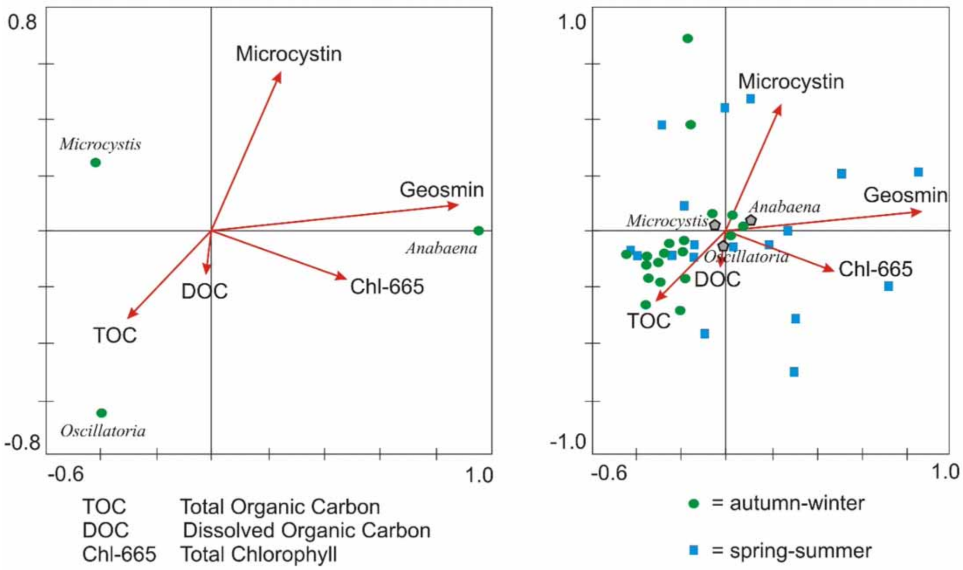

Figure 2 | CCA multivariate statistical results for cyanobacteria genera and associated organic compounds.

compounds. At this stage of the treatment process, the total phytoplankton composition remained dominated (mean of 50% and above) by cyanobacteria during the study period and showed effective removal for taste and odour compounds, in particular for geosmin concentrations during the spring-winter months. Ewerts *et al.* (2013) found that the optimization of coagulation, flocculation and sedimentation can remove a large portion of phytoplankton (which include cyanobacteria) and subsequently avoid the lysis of cells that may increase the content of organic compounds in water.

Cyanobacteria and associated organic compound assessment: after filtration

The number of cyanobacteria cells present after filtration were recorded at <60 cells/mL for the study period. The South African water quality guideline for domestic use (DWAF 1996) prescribes a threshold of 500 cells/mL present at this stage of treatment or in drinking water to limit the risk from exposure to toxins. However, no potential incidents could be expected, since cell concentrations and associated organic compounds were effectively removed to relatively low levels (Table 3). This effective removal of cell quantities subsequently promotes the removal of associated organic compounds such as cyanotoxins. Microcystin concentrations were below the guideline levels of 1 μg/L after filtration, which is also acceptable for drinking water. However, such low concentrations of microcystin can also be ascribed to frequency of occurrence of cyanobacteria cells (generally known for producing microcystin); therefore, continuous sampling and water quality monitoring in order to optimize unit processes should be implemented (Du Preez & Avenant-Oldewage 2007).

ANOVA analyses, percentage removal and average concentrations for sampling points

The presence of cyanobacteria in raw water abstracted for water treatment might affect the quality of water produced and has been found to be potentially toxic to animals and humans (Chinyama *et al.* 2016). An ANOVA of the percentage removal for the study period was performed to indicate statistically significant differences between the sampling points for cyanobacteria (*Microcystis* sp., *Anabaena* sp. and *Oscillatoria* sp.) and organic compounds. Results (Table 3) gives the average concentrations at each stage of treatment to support statistical outputs (Table 2).

Table 2 displays the ANOVA results comparing the overall water treatment processes (coagulation, flocculation, sedimentation and filtration). This was performed for cyanobacteria as well as for the organic compounds geosmin,

Table 2 | Statistical results showing the removal efficiencies for cyanobacteria genera and associated organic compounds from different stages of the RWWP, which include raw water (RW), after sedimentation (AS) and after filtration (AF)

Cyanobacteria genera and associated organic compounds	Units	Statistically Significant Differences (p-values)		Percentage removal (%)	
Cyanobacteria genera					
		autumn-winter	spring-summer	autumn-winter	spring-summer
Microcystis sp.	cells/mL	0.02 ✓	0.03 ✓	99.60	99.90
Anabaena sp.	cells/mL	0.11 ✗	0.01 ✓	99.60	99.20
Oscillatoria sp.	cells/mL	0.30 ✗	0.36 ✗	99.18	99.66
Organic compounds					
Geosmin	ng/L	0.03 ✓	0.07 ✗	63.00	85.70
Chl-665	μg/L	0.00 ✓	0.00 ✓	99.26	99.25
Microcystin	μg/L	0.20 ✗	0.01 ✓	58.57	73.45
TOC	mg/L as C	0.44 ✗	0.95 ✗	4.62	2.20
DOC	mg/L as C	0.81 ✗	0.14 ✗	11.33	29.28

The tick symbol '✓' indicates significant difference where $p<0.05$, while a cross symbol '✗' indicates no significant difference where $p>0.05$ and cyanobacteria and organic compounds removal efficiencies in percentage (%).

Table 3 | The phytoplankton and associated organic compound average concentrations measured in the raw water (RW) and at different stages (AS-AF) during seasonal periods of the study

		Autumn-winter months			Spring-summer months		
		RW	AS	AF	RW	AS	AF
Parameters	Measuring units	Average concentrations			Average concentrations		
Bacillariophyceae	cells/mL	769	37	5	909	23	8
Chlorophyceae	cells/mL	200	22	2	315	3	2
Cryptophyceae	cells/mL	291	16	6	227	8	3
Dinophyceae	cells/mL	52	1	1	40	1	1
Euglenophyceae	cells/mL	45	2	1	40	1	1
Cyanophyceae	cells/mL	6,593	68	26	22,653	259	58
Microcystis sp.	cells/mL	6,103	15	2	18,310	83	33
Anabaena sp.	cells/mL	199	46	23	4,358	171	24
Oscillatoria sp.	cells/mL	291	9	2	40	7	1
TOC	mg/l as C	4	3	4	3	3	3
DOC	mg/l as C	3	3	2	3	3	2
Geosmin	ng/l	7	5	3	59	32	8
Chlorophyll – 665	µg/l	18	2	0	34	4	0
Microcystin	µg/l	1	1	0	1	1	0

Chl-665, TOC and DOC. The statistical results obtained for cyanobacteria and microcystin displayed statistically significance differences for the study period and there was not enough evidence to suggest any statistical differences for geosmin, Chl-665, TOC and DOC (Tables 2 and 3). To evaluate the individual processes and their capabilities to remove cyanobacteria and associated organic compounds, statistical tests were performed between data collected from each unit process to determine if a statistically significant difference existed between the water quality before and after each unit process. The statistical results show that cyanobacteria and microcystin were removed effectively during coagulation, flocculation and sedimentation as well as during sand filtration. Geosmin was effectively removed by sand filtration and no statistically significant difference was found during the sedimentation process.

The percentage removal by the RWWP for the removal of cyanobacteria (*Microcystis* sp., *Anabaena* sp. and *Oscillatoria* sp.) were up to 99% efficiency. The results show that the presence of cyanobacteria did not have a major impact on the water treatment processes although initial concentrations were recorded in relatively abundant quantities (78,192 cells/mL maximum). Removal of these cells is a priority before recovered water is recycled back to the final treated water of the main treatment works, especially since the concentrations in the recovered water still exceed the acceptable concentration of 2,000 cells/mL recommended by the World Health Organization (WHO) guidelines (WHO 1998). The highest concentrations (average concentrations of 6,103 cells/mL and 18,310 cells/mL for autumn-winter and spring-summer months respectively) was due to *Microcystis* sp., a genus known to produce microcystin (Tanabe *et al.* 2018). *Anabaena* sp. was detected only once in the raw water during the autumn-winter months. The filamentous *Oscillatoria* genus occurred on only a few occasions and was not present at all sampling localities; the low frequency of occurrence of this filamentous genus in raw and after filtration of this treatment works is supported by Ewerts *et al.* (2013).

The removal efficiencies recorded for the autumn-winter and spring-winter months were 63% and 85.7% respectively and overall removal efficiency was 83.3%. The odour causing compound geosmin was reduced to acceptable levels after filtration prior to recycling water to the main treatment works. Geosmin was sporadically detected in filter backwash water treated by the RWWP, mostly during spring-summer months with occasional concentrations exceeding the production guideline of 30 ng/L of the main treatment works. This was most probably due to the succession of cyanobacteria species producing the different organic compounds. Geosmin can be expected in the water when *Anabaena* sp. cells are present either in moderate or abundant quantities. Geosmin is usually only removed by advanced treatments like adsorption to powdered activated carbon, granular activated carbon, or oxidation by ozone when released into the water (Westerhoff *et al.* 2005). Therefore, although taste and odour compounds or other organic compounds may enter the final stage or water treatment, chlorination or disinfection will reduce compounds to acceptable levels. Chlorination is one of the methods, widely applied for various water treatment purposes, especially to control algal growth and oxidize organic material (Van der Walt *et al.* 2009).

The Chl-665 in the RWWP raw water samples during spring-summer months exceeded the maximum recommended limit of (0–15 μg/L), but the plant managed to remove Chl-665 effectively. The Chl-665 contents in recovered water were effectively removed during the study period. The percentage removal of Chl-665 was recorded up to 99%. High levels of chlorophyll indicate high levels of phytoplankton cells in water (Ewerts *et al.* 2015), which may occur as result of algal growth and blooms when nutrients such as nitrogen and phosphorus are entering surface water destined for drinking water production. According to Ewerts *et al.* (2015), Chl-665 analysis can be useful in selecting coagulant treatment that will improve the removal efficiencies of phytoplankton and reduce treatment costs.

The percentage removal of microcystin ranged from 58.6% during autumn-winter and 73.5% during spring-summer months, and overall 67% removal during the study period. Microcystin concentrations on average during spring-summer months were higher than the recommended level of 1 μg/L for raw water. TOC removal percentage was low at 4.6% during autumn-winter months and 2.2% during spring-summer months, and 3.5% removal efficiency over the study period. The most effective removal occurred during spring-summer months for DOC, also showing a removal percentage of up to 29.3% (overall study period 21.0% removal). When organic compounds (TOC and DOC) react with chlorine during the disinfection process, the formation of harmful by-products may pose a risk to drinking water consumers. It is thus important for organic compounds to meet the required standards for drinking water. South African National Standards 241 (SANS 2011) prescribe a chronic health limit ($\leq$10 mg/l) for TOC, which include phytoplankton and chlorophyll. In the distribution network, increased organic compounds may lead to the potential growth of microorganisms (Ozdermir 2014).

Table 3 below indicate the average concentration of phytoplankton and associated organic compounds measured at different sampling points during seasonal study periods (autumn-winter and spring-summer months). The average values were used to calculate percentage removal according to the formula described in the methodology. Most of the parameters decreased with the flow of water treatment, indicating efficacy of the RWWP, except for TOC during autumn-winter months and measurements remained constant during spring-summer months. Table 2 above also confirms the removal efficacy of parameters.

CONCLUSIONS

The study investigated the efficacy of RWWP in removing phytoplankton and associated organic compounds. The results show that the recycled raw water supplied to RWWP contained a phytoplankton composition consisting of six major groups (diatoms, green algae, cyanobacteria, dinoflagellates, golden-brown algae and euglenoids). Among others, the cyanobacteria group (consisting of *Anabaena* sp., *Microcystis* sp., and *Oscillatoria* sp.) was the most dominant group (mean of 80% and above). Although the RWWP uses conventional unit processes, it was able to reduce the dominant cyanobacteria group effectively (up to 99% removal) during different seasonal occasions. Chlorophyll (Chl-665) removal percentages were relatively similar to percentages recorded for cyanobacteria, which was expected since this organic compound can be measured as a direct indication of phytoplankton content in water. Other organic compounds, which include geosmin, microcystin, TOC and DOC, overall removal percentages removal were lower (varying from 2.20% to

85.70%). The water treatment processes implemented in the RWWP require optimization strategies to improve the removal of organic compounds, especially for TOC and DOC. Cyanobacteria present in recycled water destined for treatment by the RWWP don't pose a risk to drinking water quality; however, chemical and operational optimization practices could improve the removal efficiencies of all organic compounds prior to mixing treated recycled water with treated water in the main treatment plant.

RECOMMENDATIONS

- Implement phytoplankton water quality monitoring for RWWP. Phytoplankton species, especially those belonging to the cyanobacteria group, are known to be complex microorganisms due to cell morphology, size and organelles such as gas vacuoles. The characteristics of cell, colonies or filaments give organisms the ability to maintain their position in the water column; thus, the effective removal of various phytoplanktons should for an integral part of water quality monitoring practices where the treatment of recycled wash water is applied.
- Implement a routine sampling plan to determine water quality at different stages of the RWWP. Routine sampling practices are often scheduled for the main treatment plant; however, different stages of water treatment in recycled water plants should be incorporated in routine sampling plans where the capacity exist. The treatment and monitoring costs associated with recycled water treatment plants may be significantly higher due to accumulation of impurities in sand filters. Occasionally, the operations of recycling water treatment may also be discontinued, depending on seasonal changes or main treatment plant operations. Therefore, effective management (budgeting and planning) may add significant value to treatment facilities where water shortages or water balance issues are posing risks to meet the demand for drinking water by consumers.
- Consider stringent water quality monitoring plans to be implemented during all seasonal periods in the RWWP. The presence of high concentrations of potentially harmful organic compounds (e.g. cyanotoxins) as well as other organic compounds (e.g. organic carbon) known as precursors for the formation of disinfection by-products were detected in the RWWP. Each step of treatment should be carefully monitored and guided by stringent measures to avoid contamination of water in the main treatment works.

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