Total photosynthetic pigments in addition to turbidity during the selection of coagulant treatments: a drinking water treatment perspective

H. Ewerts, A. Swanepoel, H. H. du Preez and N. Van der Walt

ABSTRACT

Total photosynthetic pigments (TPP) or chlorophyll-*a* analysis can be useful in selecting coagulant treatments that will improve phytoplankton removal and reduce treatment costs. The objectives of this study were to compare the efficacy of phytoplankton and turbidity removal when using TPP and turbidity as indicator parameters of appropriate coagulant treatments as well as to evaluate the cost impacts thereof. During seven different sampling occasions, source water samples with substantially different TPP and turbidity contents were collected from two South African freshwater sources (Benoni Lake and Vaal Dam) to conduct jar stirring tests. After sedimentation, TPP and turbidity analyses were performed to assess the efficacy of coagulant treatments ($Ca(OH)_2$-SiO_2, $Ca(OH)_2$-organic polymer and organic polymer). Results showed that TPP analysis is indeed a useful indicator parameter to consider purifying source water enriched with phytoplankton. $Ca(OH)_2$-organic polymer treatment was more costly than $Ca(OH)_2$-SiO_2 and organic polymer, but the only coagulant treatment that met the removal criteria after sedimentation. Benoni Lake source water (TPP: 34.29 μg/l; 4.29 NTU) was more costly to treat than Vaal Dam source water (TPP: 2.29 μg/l; 80.29 NTU). Findings made from this study confirm that high phytoplankton concentrations in source water due for treatment will increase the treatment costs.

Key words | chlorophyll, jar stirring tests, water purification

H. Ewerts (corresponding author)
A. Swanepoel
H. H. du Preez
N. Van der Walt
Rand Water Analytical Services,
PO Box 3526,
Vereeniging 1930,
South Africa
E-mail: *hendrik.ewerts50@gmail.com*;
hewerts@randwater.co.za

H. H. du Preez
Department of Zoology,
University of Johannesburg,
Auckland Park,
South Africa

INTRODUCTION

Turbidity of water is widely used to evaluate the efficacy of coagulation, flocculation and sedimentation during drinking water treatment (Ma & Liu 2002; Cheng & Chi 2003; Eikebrokk *et al.* 2006; Bekri-Abbes *et al.* 2007). However, turbidity alone is not necessarily the best parameter to use when selecting appropriate coagulant treatment options which will also be effective for algal removal. This is because not all phytoplankton species are removed under the same conditions. Removal is influenced by parameters such as algal motility and surface characteristics (e.g. frustules, loricas and thecal plates) (Henderson *et al.* 2008). In addition, algae with flagella may disrupt flocs formed during flocculation (Pieterse *et al.* 2000). Therefore it is proposed that the assessment of coagulant efficacy should consider both total photosynthetic pigment (TPP) concentrations, as well as turbidity.

For the present study TPP analysis was selected over chlorophyll-*a* analysis since TPP analysis is more sensitive at detecting low concentrations of phytoplankton (Swanepoel *et al.* 2008). In addition, TPP analysis is less complex than chlorophyll-*a* analysis and results can be available within 2 hours after receiving a sample. This may aid managers and operators of water treatment utilities to respond to phytoplankton-related problems immediately. TPP can also be used for coagulant optimization during jar stirring tests to effectively remove phytoplankton during full scale water treatment.

doi: 10.2166/aqua.2014.020

Two South African freshwater sources (Benoni Lake and Vaal Dam) were selected for the study. The sites were selected because the source waters have substantially different turbidity levels and total photosynthetic pigment (TPP) concentrations. The study involved simulations of conventional coagulation, flocculation and sedimentation processes using source waters from the two sites. The aims were to: (1) compare the efficacy of phytoplankton and turbidity removal when using TPP and turbidity as indicator parameters of appropriate coagulant treatments; and (2) evaluate the cost of using different coagulant treatments when treating source waters with different turbidity levels and TPP concentrations.

MATERIALS AND METHODS

Source waters

Source water samples were taken from the Benoni Lake (26°10′50.40″S; 28°17′50.11″E) and Vaal Dam (26°10′50.40″S; 28°17′50.11″E). The Benoni Lake is characterized by low average turbidities (4.29 NTU), while the Vaal Dam typically has high average turbidities (80.29 NTU). Source water samples were taken seven times to obtain samples with 'low turbidity levels and high TPP concentrations' and 'high turbidity levels and low TPP concentrations'. The Benoni Lake samples were collected in May and July 2010, while the Vaal Dam samples were collected from November 2011 to February 2012.

Coagulant stock solutions and dosage ranges

A hydrated lime stock solution (20,000 mg/l) was prepared by dissolving Super Separated Hydrated calcium type lime (65% purity) in Milli-Q® water. Liquid activated silica (SiO_2) was dissolved in Milli-Q® water to prepare a 2000 mg/l SiO_2 stock solution. A high molecular weight liquid organic polymer was dissolved in Milli-Q® water to prepare a 2000 mg/l stock solution. These stock solutions were used to prepare the following dosage ranges.

- **Hydrated lime in combination with activated silica ($Ca(OH)_2$-SiO_2)**: A constant SiO_2 dosage of 3 mg/l in combination with a $Ca(OH)_2$ dosage range (32.5–82.5 mg/l, with equal increments). This coagulant option increases pH to levels above 10.
- **Hydrated lime in combination with organic polymer:** A constant $Ca(OH)_2$ dosage of 7.5 mg/l in combination with a range of organic polymer dosages (5–15 mg/l, with equal increments). This constant coagulant dosage of 7.5 mg/l is sufficient to adjust the pH to levels between 9 and 10.
- **Organic polymer:** A range of organic polymer dosages (5–15 mg/l, with equal increments). This coagulant option has no effect on pH.

Jar stirring tests

The conventional water purification processes of coagulation, flocculation and sedimentation were simulated with a jar tester apparatus (Phipps and Bird, Model 7790–704). Jar stirring tests were conducted at room temperature (±22 °C), using six 2 l beakers filled with source water. The 2-l source water samples were subjected to high energy flash mixing conditions (G-value 400 s^{-1}) for 30 seconds. Different coagulant dosages were added with syringes and allowed to disperse uniformly at high energy flash mixing conditions for another 30 seconds. Jar stirring tests were subjected to three decreasing energy stages of 125, 54 and 14 s^{-1}, respectively, for a time period of 8, 1.5 and 1 min, respectively. Flocs were allowed to settle for a period of 20 min. After settling, approximately 250 ml of sample was withdrawn from the supernatant for analyses.

Analytical determinations

All water analyses were performed in the laboratories of Rand Water Analytical Services (Laboratory number: T0046), which is a SANAS (South African National Accreditation System) accredited laboratory. SANAS is affiliated with ILAC (International Laboratory Accreditation Cooperation). Phytoplankton identification and enumeration was performed with the sedimentation technique, originally described by Lund *et al.* (1958) and adapted for Rand Water according to Swanepoel *et al.* (2008). Chlorophyll-*a* (Chl-*a*) analyses are usually used to determine the concentration of phytoplankton; however, in this study, TPP analyses (being more sensitive to detect low concentrations of phytoplankton than chlorophyll–*a*) were performed by extracting pigments from phytoplankton cells using methanol and analysed with a Beckman spectrophotometer (650i) as described by Swanepoel *et al*. (2008). Swanepoel (2014) developed a model to represent the relationship between TPP and Chl-*a*, which can be determined as follows: TPP = 1.24 * Chlorophyll-*a* (with the correlation coefficient R^2-value = 0.75 and the root mean squared error = 1.57 μg/L where $n = 254$). Turbidity was analyzed with a HACH-2100*AN* turbidimeter.

Coagulant selection procedure

Turbidity levels measured in Benoni Lake and Vaal Dam varied between 2.10 and 7.00 NTU and 69.00 and 85.00 NTU, respectively, while TPP concentration varied between 6.86 and 100 μg/l and 1.7 and 4.7 μg/l, respectively. In South Africa, the requirements for drinking water indicate an operational standard limit of ≤1 NTU and aesthetic standard limit of ≤5 NTU (SANS 241, 2011). During the coagulant selection procedure (after sedimentation) the turbidity removal criterion was to comply with the SANS 241-1 (2011) aesthetic turbidity standard limit of ≤5 NTU. The SANS 241-1 (2011) standard only indicates a chronic health limit of ≤10 mg/l for total organic carbon (TOC) which also includes phytoplankton and TPP concentrations. Therefore, during the coagulant selection procedure, where TPP ranged between 1.7 and 100 μg/l, a 50% removal criterion (after sedimentation) was set for application during this study.

Determination of cost ratios (cost effectiveness)

Cost ratio values (R/mg) are an indication of actual Rand value per milligram required to achieve the target turbidity (≤5 NTU) and TPP (≥50%) removal after sedimentation.

RESULTS

Turbidity, TPP and pH in Benoni Lake and Vaal Dam

Samples from the Vaal Dam had turbidity levels approximately 20 times higher than samples from the Benoni Lake. By contrast, the TPP concentrations for samples from the Vaal Dam were approximately 15 times lower than for samples from the Benoni Lake (Table 1). The average TPP concentrations measured in the Benoni Lake give an indication of high phytoplankton concentrations when compared with the average concentrations measured in Vaal Dam.

Phytoplankton community composition

The phytoplankton communities identified in both water sources were relatively similar (Table 2). Only a few genera were identified exclusively in Benoni Lake (e.g. *Melosira*, *Rhopalodia*), while *Ankistrodesmus* and *Chlorella* were identified exclusively in the Vaal Dam. The phytoplankton groups that were recorded in the two water sources were Bacillariophyceae (diatoms), Cyanophyceae (cyanobacteria), Cryptophyceae (cryptophytes), Dinophyceae (dinoflagellates), Chlorophyceae (green algae) and Euglenophyceae (euglenoids). The dominant and important genera (highlighted with an asterisk*) in Table 2 were selected by means of the frequency of occurrence as well as the contribution of genera to the total percentage composition (TPC).

In Benoni Lake source water, nine diatom genera were identified, while eight genera were identified in the Vaal Dam source water (Table 2). The filamentous diatom genus *Aulacoseira* contributed 20% to the TPC in Benoni Lake source water and centric diatoms (mostly

Table 1 | Minimum (min), maximum (max) and mean (average) values for turbidity, TPP and pH measured in Benoni Lake (November 2011–February 2012) and Vaal Dam (May–July 2010) source waters ($n = 7$)

		Benoni Lake			Vaal Dam		
		Min	**Max**	**Mean**	**Min**	**Max**	**Mean**
Turbidity	NTU	2.10	7.00	4.29	69.00	85.00	80.29
TPP	μg/l	6.86	100.00	34.94	1.70	4.70	2.29
pH		6.24	8.79	7.21	7.38	10.18	8.48

Cyclotella) contributed to 8% of the TPC in Vaal Dam source water. The cyanobacteria genera *Anabaena* and *Microcystis* were identified in both water sources, but were recorded as important genera only in the Vaal Dam due to their contributions to the TPC of 32 and 19% respectively (Table 2). Furthermore, *Anabaena* was recorded as the dominant genus of the phytoplankton community composition in Vaal Dam source water. Two dinoflagellates, namely *Ceratium* and *Peridinium*, were identified in Benoni Lake with TPC of 62% and 4%, respectively. *Ceratium* with its significant contribution of 62% was recorded as the dominant genus in Benoni Lake (Table 2). Green algae consisting of the largest diversity (8–12 genera) were identified in the water sources. The green algae genera *Pediastrum* (TPC 8%) and *Chlamydomonas* (TPC 12%) were recorded as important in Benoni Lake and Vaal Dam, respectively. Only one cryptophyte genus was identified in Vaal Dam with a TPC of 29%. Three euglenoids were identified, but none was recorded as an important genus because of the low contributions to the TPC (Table 2).

Table 2 | The presence (✓) or the absence (✗) of phytoplankton genera, identified in Benoni Lake and Vaal Dam source waters

	Benoni Lake	% TPC	Vaal Dam	% TPC
1) Bacillariophyceae				
Ankistrodesmus	✗	–	✓	–
Aphanizomenon	✗	–	✗	–
*Aulacoseira**	✓	20	✓	–
Centric diatoms*	✓	–	✓	8
Cocconeis	✓	–	✓	–
Cymbella	✓	–	✗	–
Diatoma	✓	–	✓	–
Fragillaria	✓	–	✓	–
*Melosira**	✓	5	✗	–
Pennate diatoms	✓	–	✓	–
Rhopalodia	✓	–	✗	–
Surirella	✗	–	✓	–
2) Cyanophyceae				
*Anabaena**	✓	–	✓	32
Merismopedia	✓	–	✗	–
*Microcystis**	✓	–	✓	19
Oscillatoria	✓	–	✓	–
3) Chryptophyceae				
*Cryptomonas**	✗	–	✓	29
4) Dinophyceae				
*Ceratium**	✓	62	✓	–
Peridinium	✓	4	✗	–
5) Chlorophyceae				
*Chlamydomonas**	✓	–	✓	12
Chlorella	✗	–	✓	–
Coelastrum	✓	–	✓	–
Cosmarium	✓	–	✓	–
Crucigenia	✗	–	✓	–
Dictyosphaerium	✗	–	✓	–
Monoraphidium	✓	–	✓	–
Oocystis	✗	–	✓	–
Pandorina	✓	–	✓	–
*Pediastrum**	✓	9	✓	–
Scenedesmus	✗	–	✓	–
Sphaerocystis	✗	–	✗	–
Spyrogira	✓	–	✗	–
Staurastrum	✓	–	✗	–
Tetraedron	✗	–	✓	–
6) Euglenophyceae				
Euglena	✓	–	✓	–
Phacus	✓	–	✗	–
Strombomonas	✓	–	✓	–
Trachelomonas	✓	–	✓	–

*Phytoplankton genera contributing significantly to the TPC.

Turbidity and TPP removal by $Ca(OH)_2$-SiO_2 dosages from Benoni Lake and Vaal Dam source waters

The $Ca(OH)_2$-SiO_2 dosage range of 32.5–82.5 mg/l (SiO_2 3 mg/l) was not effective in removing turbidity to levels of $\leq$5 NTU from source waters with either low or high initial turbidity (Table 3). The lowest $Ca(OH)_2$-SiO_2 dosage of 32.5 mg/l (SiO_2 3 mg/l) increased the turbidity levels of Benoni Lake source water significantly (190% $^{\uparrow}$) after sedimentation. In the case of the Vaal Dam source water, the same dosage removed the highest turbidity (78% $^{\downarrow}$), but was not able to meet the proposed target turbidity after sedimentation. Although $Ca(OH)_2$-SiO_2 was not able to meet the target turbidity levels of $\leq$5 NTU, relatively good TPP removal was observed in the high dosage range (Table 3). The $Ca(OH)_2$-SiO_2 was more effective for the removal of phytoplankton, especially from Vaal Dam source water, since all dosages removed more than 50% of the initial TPP concentrations. The dosage from 62.5 mg/l (SiO_2 3 mg/l) upwards, met the 50% TPP removal criterion in the case of Benoni Lake source water.

Turbidity and TPP removal by $Ca(OH)_2$ in combination with organic polymer dosages from Benoni Lake and Vaal Dam source waters

The $Ca(OH)_2$-organic polymer dosage range of 5–15 mg/l ($Ca(OH)_2$ 7.5 mg/l) was more effective than $Ca(OH)_2$-SiO_2 in removing turbidity (Tables 3 and 4). The lowest $Ca(OH)_2$-organic polymer dosage of 5 mg/l ($Ca(OH)_2$ 7.5 mg/l) increased turbidity (116%$^{\uparrow}$) of Benoni Lake source water after sedimentation. However, the subsequent dosage of 7 mg/l ($Ca(OH)_2$ 7.5 mg/l) was able to remove turbidity from both Benoni Lake and Vaal Dam source waters to levels of ≤5 NTU. The percentage removal for Benoni Lake and Vaal Dam source waters was 2% (4.22 NTU) and 95% (3.97 NTU), respectively. The whole $Ca(OH)_2$-organic polymer dosage range (5–15 mg/l) effectively removed TPP from Vaal Dam source water (≥50%). In the case of Benoni Lake source water, only the highest $Ca(OH)_2$-organic polymer dosage of 15 mg/l ($Ca(OH)_2$ 7.5 mg/l) met the 50% TPP removal criterion (57% $^{\downarrow}$).

Table 3 | $Ca(OH)_2$-SiO_2: The average turbidity and TPP values ($n = 7$) after jar stirring tests conducted using Benoni Lake and Vaal Dam source waters. The percentage removal ($^{\downarrow}$) or the percentage addition ($^{\uparrow}$) after sedimentation by each dosage is also indicated. The appropriate coagulant dosages are indicated with a '✓'

$Ca(OH)_2$:SiO_2 (pH 10–12)	**Benoni Lake**	**Vaal Dam**
Turbidity removal after sedimention		
32.5:3	12.44 NTU (190% $^{\uparrow **}$)	17.44 NTU (78% $^{\downarrow}$)
42.5:3	9.79 NTU (128% $^{\uparrow **}$)	18.12 NTU (77% $^{\downarrow}$)
52.5:3	9.19 NTU (114% $^{\uparrow **}$)	22.96 NTU (71% $^{\downarrow}$)
62.5:3	8.41 NTU (96% $^{\uparrow **}$)	21.57 NTU (73% $^{\downarrow}$)
72.5:3	6.33 NTU (48% $^{\uparrow **}$)	24.03 NTU (70% $^{\downarrow}$)
82.5:3	6.43 NTU (50% $^{\uparrow **}$)	22.48 NTU (72% $^{\downarrow}$)
TPP removal after sedimention		
32.5:3	33.67 μg/l (4% $^{\downarrow}$)	✓ 0.86 μg/l (62% $^{\downarrow}$)
42.5:3	30.27 μg/l (13% $^{\downarrow}$)	0.77 μg/l (66% $^{\downarrow}$)
52.5:3	21.53 μg/l (38% $^{\downarrow}$)	0.57 μg/l (75% $^{\downarrow}$)
62.5:3	✓ 15.30 μg/l (56% $^{\downarrow}$)	0.54 μg/l (76% $^{\downarrow}$)
72.5:3	10.48 μg/l (70% $^{\downarrow}$)	0.52 μg/l (77% $^{\downarrow}$)
82.5:3	7.68 μg/l (78% $^{\downarrow}$)	0.33 μg/l (86% $^{\downarrow}$)

↑ **Increased turbidity levels are most probably the result of residual $Ca(OH)_2$ particles in the supernatant after sedimentation.

Table 4 | $Ca(OH)_2$-organic polymer: The average turbidity and TPP values ($n = 7$) after jar stirring tests conducted using Benoni Lake and Vaal Dam source waters. The percentage removal ($^{\downarrow}$) or the percentage addition ($^{\uparrow}$) after sedimentation by each dosage is also indicated. The appropriate coagulant dosages are indicated with a '✓'

$Ca(OH)_2$:Organic polymer (pH 9–10)	**Benoni Lake**	**Vaal Dam**
Turbidity removal after sedimention		
7.5:5	9.28 NTU (116% $^{\uparrow *}$)	5.08 NTU (94% $^{\downarrow}$)
7.5:7	✓ 4.22 NTU (2% $^{\downarrow}$)	✓ 3.97 NTU (95% $^{\downarrow}$)
7.5:9	3.20 NTU (25% $^{\downarrow}$)	4.01 NTU (95% $^{\downarrow}$)
7.5:11	2.61 NTU (39% $^{\downarrow}$)	3.34 NTU (96% $^{\downarrow}$)
7.5:13	2.07 NTU (52% $^{\downarrow}$)	3.15 NTU (96% $^{\downarrow}$)
7.5:15	1.87 NTU (56% $^{\downarrow}$)	2.90 NTU (96% $^{\downarrow}$)
TPP removal after sedimention		
7.5:5	45.13 μg/l (29% $^{\uparrow *}$)	✓ 0.42 μg/l (82% $^{\downarrow}$)
7.5:7	40.27 μg/l (15% $^{\uparrow *}$)	0.39 μg/l (83% $^{\downarrow}$)
7.5:9	34.79 μg/l (0.4% $^{\downarrow}$)	0.31 μg/l (86% $^{\downarrow}$)
7.5:11	25.59 μg/l (27% $^{\downarrow}$)	0.55 μg/l (76% $^{\downarrow}$)
7.5:13	18.63 μg/l (47% $^{\downarrow}$)	0.32 μg/l (86% $^{\downarrow}$)
7.5:15	✓ 15.04 μg/l (57% $^{\downarrow}$)	0.35 μg/l (85% $^{\downarrow}$)

↑ *Increased TPP concentrations are most probably due to the presence of filamentous (e.g. *Aulacoseira*, *Melosira* and *Anabaena*) and colonial (e.g. *Microcystis* and *Pediastrum*) phytoplankton genera.

Turbidity and TPP removal by organic polymer dosages from Benoni Lake and Vaal Dam source waters

Organic polymer alone (ranging between 5 and 15 mg/l) removed turbidity effectively from both water sources to levels of ≤5 NTU (Table 5). The lowest organic polymer dosage of 5 mg/l was able to remove turbidity effectively from both Benoni Lake (23% $^{\downarrow}$) and Vaal Dam (94% $^{\downarrow}$) source waters. However, these dosages completely failed to remove phytoplankton from Benoni Lake, since no dosage was able to meet the ≥50% TPP removal criterion. For Vaal Dam source water, all dosages were able to remove TPP effectively, because of the low initial TPP concentrations.

Table 6 presents the cost ratios of coagulant treatment options which effectively removed turbidity and TPP from Benoni Lake and Vaal Dam after sedimentation. The $Ca(OH)_2$-organic polymer and organic polymer treatments achieved cost ratios of 1.6:1.6 (Benoni Lake:Vaal Dam) and 1.0:1.0 (Benoni Lake:Vaal Dam) for turbidity removal. The

Table 5 | Organic polymer: The average turbidity and TPP values (*n* = 7) after jar stirring tests conducted using Benoni Lake and Vaal Dam source waters. The percentage removal (↓) or the percentage addition (↑) after sedimentation by each dosage is also indicated. The appropriate coagulant dosages are indicated with a '✓'

Organic polymer (no pH changes)		**Benoni Lake**		**Vaal Dam**
Turbidity removal after sedimention				
5	✓	3.29 NTU (23% ↓)	✓	5.02 NTU (94% ↓)
7		2.97 NTU (31% ↓)		1.00 NTU (99% ↓)
9		2.45 NTU (43% ↓)		4.07 NTU (95% ↓)
11		2.38 NTU (45% ↓)		3.30 NTU (96% ↓)
13		1.98 NTU (54% ↓)		3.28 NTU (96% ↓)
15		1.93 NTU (55% ↓)		3.12 NTU (96% ↓)
TPP removal after sedimention				
5		46.85 μg/l (34% ↑*)	✓	0.44 μg/l (81% ↓)
7		43.58 μg/l (25% ↑*)		0.49 μg/l (79% ↓)
9		38.34 μg/l (10% ↑*)		0.35 μg/l (85% ↓)
11		31.50 μg/l (10% ↓)		0.38 μg/l (83% ↓)
13		25.63 μg/l (27% ↓)		0.35 μg/l (85% ↓)
15		23.36 μg/l (33% ↓)		0.30 μg/l (87% ↓)

↑*Increased TPP concentrations are most probably due to the presence of filamentous (e.g. *Aulacoseira*, *Melosira* and *Anabaena*) and colonial (e.g. *Microcystis* and *Pediastrum*) phytoplankton genera.

Table 6 | Ratios to compare the cost effectiveness when treating Benoni Lake and Vaal Dam source water with various coagulants

	$Ca(OH)_2$-SiO_2		**$Ca(OH)_2$-organic polymer**		**Organic polymer**	
	Benoni Lake	**Vaal Dam**	**Benoni Lake**	**Vaal Dam**	**Benoni Lake**	**Vaal Dam**
Turbidity	-	-	1.6	1.6	1.0	1.0
TPP	1.8	1.0	3.9	1.2	-	-

No cost ratios are indicated for coagulant options that were not able to effectively remove TPP or turbidity.

$Ca(OH)_2$–SiO_2 and $Ca(OH)_2$-organic polymer treatments achieved cost ratios of 1.8:1.0 (Benoni Lake:Vaal Dam) and 3.9:1.2 (Benoni Lake:Vaal Dam) for TPP removal.

DISCUSSION

The source water quality of the two water bodies studied was substantially different (Table 1). Low turbidity (4.29 NTU) levels measured in Benoni Lake were associated with high TPP concentrations (34.94 μg/l), while high turbidity levels (80.29 NTU) of Vaal Dam water were associated with lower TPP concentrations (2.29 μg/l). Although there was a substantial difference in the TPP concentrations measured in the water sources, the phytoplankton communities were relatively similar (Table 2). The dominant genera identified in the water sources were also significantly different with regards to cell size, which have an influence on the TPP content in the water. Benoni Lake source water was dominated by the large *Ceratium* cells (±450 μm long and 30–100 μm wide), while smaller *Anabaena* cells (12 μm in diameter) (Janse van Vuuren *et al.* 2006) dominated Vaal Dam source water. *Ceratium* dominated the phytoplankton composition found in Benoni Lake source water with 62%, while *Anabaena* dominated the phytoplankton composition of the Vaal Dam source water with 32% (Table 2). Most of the genera indicated in Table 2 were present in both freshwater sources (e.g. *Aulacoseira*, *Chlamydomonas* and *Coelastrum*). The pH levels of the two water bodies were also significantly different (7.21 and 8.28). The pH in source water used for drinking water treatment is important since pH corrections during coagulation enhance the removal of phytoplankton genera (Knappe *et al.* 2004; Henderson *et al.* 2008).

Turbidity is widely used as an indicator of appropriate coagulant treatments after simulating conventional coagulation, flocculation and sedimentation by means of jar stirring tests (Ma & Liu 2002; Cheng & Chi 2003; Eikebrokk *et al.* 2006; Bekri-Abbes *et al.* 2007). Coagulation is often considered to be the main unit process during conventional drinking water treatment to remove phytoplankton (Henderson *et al.* 2008). Inorganic (turbidity) and organic (phytoplankton) particles are removed by similar mechanisms (Bernhardt & Clasen 1991; Bolto 1995). Removal challenges can be addressed by selecting the appropriate coagulant treatments, since both phytoplankton and turbidity can effectively be removed by cationic coagulants (Knappe *et al.* 2004). These coagulant treatments include aluminium (Al^{3+}), iron (Fe^{3+}) (Knappe *et al.* 2004), $Ca(OH)_2$-SiO_2 (Geldenhuys *et al.* 2000) and organic polymers (Bolto 1995; Knappe *et al.* 2004). These coagulants destabilize the negatively charged impurities and aid in its removal during the production of drinking water (Knappe *et al.* 2004). The use of Ca(OH)-SiO$_2$ for destabilization and flocculation of suspended material is unique for the purification of Vaal Dam water in South Africa (Geldenhuys *et al.* 2000). South Africa's largest drinking water treatment plant selects coagulants and appropriate quantities based on a settling turbidity of $\leq$5 NTU, during jar stirring tests. This study showed that TPP analysis can be effectively implemented additional to turbidity to assess coagulant treatments for the simultaneous removal of turbidity and phytoplankton after sedimentation.

The treatability of different phytoplankton genera require different treatment strategies, since motility and surface characteristics (e.g. frustules, loricas and thecal plates) have an influence on their removal efficiencies (Henderson *et al.* 2008). Visser & Pieterse (1999) investigated the occurrence of phytoplankton in the Vaal River at Balkfontein drinking water treatment plant (South Africa) as well as the penetration of genera into the different unit processes. Findings made by Visser & Pieterse (1999) indicated that penetration of phytoplankton were related to specific treatability of genera. Phytoplankton genera identified during this study were similar to those recorded by Visser & Pieterse (1999). Genera such as *Aulacoseira* and *Cyclotella* (centric diatom) are covered with silica-frustules and can be effectively removed by Ca(OH)$_2$ treatment options (Visser & Pieterse 1999). Green algae such as *Chlamydomonas* on the other hand can be effectively removed by FeCl$_3$ treatment options (Visser & Pieterse 1999). Flagellated algae such as *Chlamydomonas*, *Cryptomonas*, *Ceratium* and *Peridinium* can be rendered immobile by pH shock created when dosing coagulants such as Ca(OH)$_2$ to assist coagulation (Van der Walt 2011; Ewerts *et al.* 2014). In the light of various surface characteristics and motile adaptations of the different genera, specific coagulant requirements and coagulation conditions are needed to ensure their removal.

The Ca(OH)$_2$-SiO$_2$ dosage range 32.5–82.5 mg/l (3 mg/l) was not effective in removing turbidity to levels of $\leq$5 NTU after sedimentation from either Benoni Lake or Vaal Dam source water. The addition of Ca(OH)$_2$ increased the turbidity in both water sources and therefore poor turbidity removal was observed. However, the Ca(OH)$_2$-SiO$_2$ dosage range 32.5–82.5 mg/l (3 mg/l) achieved the best TPP removal.

Good turbidity removal by organic polymers is well-known (Bolto & Gregory 2007). This fact was confirmed during this study where the organic polymer option (ranging between 5 and 15 mg/l) removed turbidity effectively from both water sources, but failed to remove phytoplankton effectively (Table 5).

Good phytoplankton removal or the lack thereof can be ascribed to the fact that pH is an important factor affecting the efficiency of coagulation (Knappe *et al.* 2004). The pH adjustment, caused by the addition of Ca(OH)$_2$, which inactivates phytoplankton cells, is known to enhance their removal (LeChevallier & Au 2004; Eikebrokk *et al.* 2006). Therefore, the adverse impacts on turbidity removal by using Ca(OH)$_2$ as coagulant can be reduced by dosing lower Ca(OH)$_2$ concentrations for pH adjustment (e.g. pH 9–10) which is sufficient for the inactivation of phytoplankton cells (Van der Walt 2011). Once phytoplankton cells are inactivated, organic polymers can remove inactivated cells together with other suspended particulate matter (e.g. turbidity).

Organic polymer alone should not be considered as coagulant option when treating water containing relatively high phytoplankton concentrations (Table 5). Organic polymers should rather be used to treat source water (e.g. Vaal Dam) with relatively low phytoplankton concentrations or where the primary aim is to remove turbidity. The presence of phytoplankton not only interferes with the functioning of unit processes, but also impacts negatively on source water quality and subsequently increases the water treatment costs (Graham *et al.* 2012). Selecting the appropriate coagulant options with regards to the source water quality may not always be cost effective, but will ensure the production of final treated water with good quality. This statement is confirmed by the cost ratios calculated for Ca(OH)$_2$-organic polymer in comparison with other coagulant options (Table 6).

In order to meet drinking water requirements, it is important that the functioning of unit processes is evaluated by assessing parameters such as turbidity and phytoplankton levels (as indicated by TPP). Assessing these parameters during coagulant selection processes will improve suspended particle removal during coagulation, flocculation and sedimentation and subsequently reduce the load on sand filters. This in turn will eliminate unnecessary costs due to increased filter backwash frequency and will aid in the continuous supply of good quality drinking water.

CONCLUSIONS

During the selection of coagulants and appropriate dosages, turbidity measurements are used during the selection procedure. Turbidity removal, however, is not an effective indicator of phytoplankton removal. Therefore it is proposed that a phytoplankton concentration indicator like chlorophyll-*a* or TPP be used together with turbidity during the selection procedure. Although certain coagulants may not be cost effective (e.g. $Ca(OH)_2$-organic polymer), it may represent the best option to produce water that complies with drinking water standards.

Setting removal criteria such as ≤ 5 NTU or 50% TPP removal after sedimentation is essential to ensure the production of good drinking water quality at a reasonable cost. Criteria for selecting appropriate coagulant dosages should be determined and verified for individual water sources.

Treating source water enriched with phytoplankton often requires advanced water treatment processes that are more expensive than conventional processes. From this study it has also become evident that using TPP together with turbidity as indicators of appropriate coagulant treatments (especially when treating water enriched with phytoplankton) may eliminate the necessity of advanced water treatment strategies altogether.

ACKNOWLEDGEMENTS

The authors acknowledge Rand Water, South Africa for their facilities and support to the project; Professor S. Barnard from the North-West University, Potchefstroom Campus, South Africa for scientific input; and Dr R. Hendricks from Analytical Services, Rand Water, South Africa for scientific input.

REFERENCES

Bekri-Abbes, I., Bayoudh, S. & Baklouti, M. 2007 A technique for purifying wastewater with polymeric flocculant produced from waste plastic. *Desalination* **204**, 198–203.

Bernhardt, H. & Clasen, J. 1991 Flocculation of micro-organisms. *Journal of Water Supply: Research and Technology – AQUA* **40**, 76–87.

Bolto, B. A. 1995 Soluble polymers in water purification. CSIRO Chemical and Polymers. *Progress in Polymer Science* **20**, 987–1041.

Bolto, B. & Gregory, J. 2007 Review: organic polyelectrolytes in water treatment. *Water Research* **41**, 2301–2324.

Cheng, W. P. & Chi, F. 2003 Influence of eutrophication on the coagulation efficiency in reservoir water. *Chemosphere* **53**, 773–778.

Eikebrokk, B., Juhna, T. & Østerhus, S. W. 2006 Water treatment by enhanced coagulation: operational status and optimization issues. *Techneau* 1–107.

Ewerts, H., Barnard, S., Swanepoel, A., Du Preez, H. H. & Janse van Vuuren, S. 2014 Strategies of coagulant optimization to improve the removal of turbidity and *Ceratium hirundinella* cells during conventional drinking water purification. Manuscript number WS-EM1415R1. *Water Science and Technology: Water Supply* **14**, doi:10.2166/ws.2014.038.

Geldenhuys, J. C., Giard, E., Harmse, M., Neveling, K. & Potgieter, M. 2000 The Use of Ozonation in Combination with Lime and Activated Sodium Silicate in Water Treatment. Report to the Water Research Commission 446/1/00.

Graham, M., Blignaut, J., de Villiers, L., Mostert, D., Sibande, X., Gebremedhin, S., Harding, W., Rossouw, N., Freese, N. S., Ferrer, S. & Browne, M. 2012 Development of a Generic Model to Assess the Costs Associated with Eutrophication. Report to the Water Research Commission 1568/1/12.

Henderson, R., Parsons, S. A. & Jefferson, B. 2008 The impact of algal properties and pre-oxidation on solid-liquid separation of algae. *Water Research* **42** (8–9), 1827–1845.

Janse van Vuuren, S., Taylor, J., Gerber, A. & Van Ginkel, C. 2006 *Easy Identification of the Most Common Freshwater Algae: A Guide for the Identification of Microscopic Algae in South Africa*. North-West University and Department of Water Affairs and Forestry.

Knappe, D. R. U., Belk, R. C., Briley, D. S., Grandy, S. R., Rastogi, N. & Rike, A. H. 2004 *Algae Detection and Removal Strategies for Drinking Water Treatment Plants*. AWWA Research Foundation, 1–466.

LeChevallier, M. & Au, K. 2004 *Water Treatment and Pathogen Control: Process Efficiency in Achieving Safe Drinking Water*. WHO and IWA Publishing, London, UK.

Lund, J. W. G., Kipling, C. & LeCren, E. D. 1958 The inverted microscope method of estimating algal numbers and the statistical basis of estimations by counting. *Hydrobiologia* **11**, 143–170.

Ma, J. & Liu, W. 2002 Effectiveness of ferrate (VI) peroxidation in enhancing the coagulation of surface waters. *Water Research* **36**, 4959–4962.

Pieterse, A. J. H., Basson, N. D., Cloot, A., Mienie, L. J., Traut, D. F. & Visser, R. 2000 The Occurrence, Distribution and Removal of Algal Species and Related Substances in a

Full-Scale Water Purification Plant. Water Research Commission Report 567/1/00.

South African National Standards 241-1, (SANS 214-1) 2011 Drinking Water. Part 1: Microbiological, Physical, Aesthetic and Chemical Determinants. 1st edn.

Swanepoel, A. 2014 *Early Warning System for the Prediction of Algal-Related Impacts on Drinking Water Purification*. PhD thesis, North West University, Potchefstroom campus, South Africa.

Swanepoel, A., Du Preez, H., Schoeman, C., Janse van Vuuren, S. & Sundram, A. 2008 Condensed Laboratory Methods for the Monitoring of Phytoplankton, Including Cyanobacteria, in South African Freshwaters. Report to the Water Research Commission TT 323–08, 1–108.

Van der Walt, N. 2011 *Investigation into the Occurrence of the Dinoflagellate*, Ceratium hirundinella *in Source Waters and the Impact Thereof in Drinking Water Purification*. MSc dissertation, North-West University, Potchefstroom Campus, South Africa.

Visser, R. & Pieterse, A. J. H. 1999 Algal species penetrating unit processes in the Balkfontein purification plant. In (A.J.H. Pieterse ed.) *The Occurrence, Distribution and Removal of Algal Species and Related Substances in a Full-Scale Water Purification Plant*. Part 2, Detailed report. Report to the Water Research Commission, Pretoria, South Africa.

First received 20 February 2014; accepted in revised form 19 May 2014. Available online 6 June 2014