Planktonic algae and cyanoprokaryotes as indicators of ecosystem quality in the Mooi River system in the North-West Province, South Africa

A Venter[1]*, S Barnard[1], MA Dickinson[1], S Janse van Vuuren[1], A Levanets[1] and JC Taylor[1,2]
[1]*Unit for Environmental Science and Management, North-West University, Potchefstroom 2520, South Africa*
[2]*South African Institute for Aquatic Biodiversity, Grahamstown 6140, South Africa*

ABSTRACT

An ecologically healthy Mooi River system is important for maintaining the quality of potable water of Potchefstroom and surrounding areas. However, this system is under constant threat from anthropogenic pollution arising from both agricultural and mining activities in its catchment. A survey of planktonic algal and cyanoprokaryote assemblages in Klerkskraal, Boskop and Potchefstroom reservoirs was undertaken during 1999–2000 and 2010–2011. In all three dams, total algal and cyanoprokaryote concentrations were lower during the second survey (2010–2011), suggesting an improvement in ecosystem health. However, results also show a change from a Chrysophyceae-dominated community to one dominated by Bacillariophyceae. Increased numbers of diatom species that usually occur in eutrophic impoundments (*Melosira varians*, *Cyclotella meneghiniana* and *Aulacoseira granulata*) indicate an increase in the trophic status of the reservoirs, especially that of Boskop Dam, a trend mirrored by increases in conductivity as well as phosphorus and ammonium concentrations in all three reservoirs. It can therefore be concluded that although the ecosystem health of the Mooi River system is currently still good, further increases in nutrients such as phosphorus can cause proliferation of problem species (detected in enrichment cultures) and a deterioration of its water quality.

Keywords: Mooi River reservoirs, algal communities, cyanoprokaryotes, water quality

INTRODUCTION

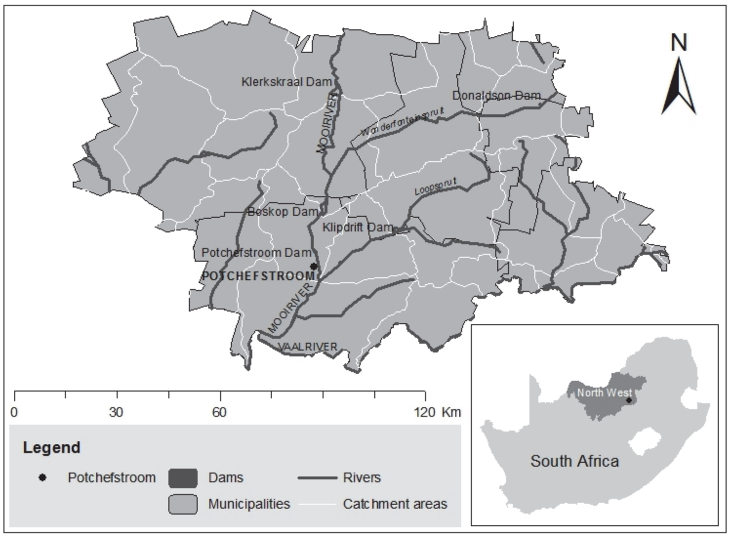

Figure 1
A map of the Mooi River System

The Mooi River originates in the Boons area and flows southwards through agricultural land into the Klerkskraal Dam, Boskop Dam and Potchefstroom Dam from where it meanders until it joins the Vaal River (Fig. 1). Other dams in the catchment of the Mooi River include Klipdrift Dam in the Loopspruit and Donaldson Dam in the Wonderfonteinspruit (Currie, 2001). The city of Potchefstroom gathers its potable water from surface- and groundwater in the Mooi River catchment. The water is collected and stored in the Boskop Dam from where it is transported in a 12-km long uncovered cement canal to the water purification plant of the city (Annandale and Nealer, 2011).

Surface water quality in a region is largely determined both by natural processes and anthropogenic inputs (Kazi et al., 2009) and, in the case of the Mooi River system, anthropogenic inputs include agricultural as well as mining pollutants. The Mooi River is situated downstream of the current environmental crises on the West Rand and far West Rand regarding aspects such as acid mine drainage, closure of mines, and naturally rewatered gold mines which have negative effects on the Wonderfonteinspruit, as well as the underground located groundwater aquifers and springs in the karst landscape (Annandale and Nealer, 2011). During high rainfall conditions, Boskop and Potchefstroom dams receive water from the Mooirivierloop that is fed by water from the highly-polluted Wonderfonteinspruit. Although Klerkskraal Dam has no direct waterborne impacts from mining activity, windblown contamination from tailing storage facilities in the catchment is possible (Coetzee et al., 2006). The area surrounding the Mooi River, especially in the Boskop Dam area, has also been extensively surveyed for minerals, metals

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* To whom all correspondence should be addressed.
☎ +27 18 299-2517; fax: +27 18 299-2370;
e-mail: 10066551@nwu.ac.za

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and other deposits and is therefore under constant threat from potential mining activity. Diamondiferous gravel diggings are already a common sight along the Mooi River between Klerkskraal Dam and the confluence with the Vaal River (Currie, 2001). As the Mooi River system is the main source of potable water for the University town of Potchefstroom and surrounding areas, deterioration in its water quality will impact a large number of people.

Biological communities reflect the overall ecological integrity by integrating various stressors, thus providing a broad measure of their synergistic impacts (De la Rey et al., 2004). Eutrophication is well known to affect planktonic autotroph abundance and composition. Phosphorus enrichment, in particular, often favours cyanophytes, including harmful toxin-producing taxa (Steinberg and Hartmann, 1988; O'Niel et al., 2012). These organisms have the potential to produce a variety of toxins that can be a health risk to humans and animals alike.

In 2004 the Department of Water Affairs and Forestry classified Boskop Dam as oligotrophic with very low algal productivity (Mogakabe, 2004); the aim of this study was to explore whether (and how) the phytoplankton communities and trophic status have changed in the past decade. During this study a survey of planktonic autotrophs of the dams in the Mooi River tributary was made, not only to determine if the health of the ecosystem has deteriorated over time, but also to serve as a baseline for future studies and environmental planning for the region.

MATERIALS AND METHODS

Water samples were collected on a monthly basis from May 1999 to July 2000 as well as from March 2010 until March 2011 at the wall of Klerkskraal Dam (S 26° 15' 09.3'' E 27° 09' 34.1''), close to the main inflow of Boskop Dam (S 26° 32' 43.6''; E 27° 06' 51.9'') and near the centre of Potchefstroom Dam (S 26° 40' 15.5''; E 27° 05' 38.7''). Samples were taken in the mornings, starting with Klerkskraal Dam and ending with Potchefstroom Dam. Water was sampled by lowering a bucket into the water, sampling water at about 20–30 cm and pouring it into 2-ℓ plastic bottles. Samples were processed on the day of collection. On each sampling occasion physical parameters such as pH, temperature (temp), conductivity (cond), turbidity (turb) and dissolved oxygen (LDO) were measured in situ at about 20 cm below the surface *w*ith an YSI 556 MPS Multimeter.

The 2-ℓ water samples collected from each reservoir were subdivided into samples for chemical analysis, chlorophyll-*a* (Chl *a*) determination and algal identification. Chemical variables such as ammonium (NH_4), nitrate (NO_3), nitrite (NO_2) and orthophosphate (PO_4) were measured with a Palintest 8000 photometer.

Chlorophyll-*a* concentration was determined with the method described by Sartory (1982) and Swanepoel et al. (2008). Two hundred (200) mℓ water was filtered through a Whatman GF/C filter. The chlorophyll gathered on the filter was extracted with 10 mℓ 95% ethanol in a water bath at 78°C for 5 min. The samples were removed and left in the dark to cool down. The difference in absorbance of the extract was determined at 665 and 750 nm respectively, using 95% ethanol as the blank. The difference in absorbance of the same sample was again determined 2 min after acidification with 0.1 mℓ 1 N HCl. The chlorophyll-*a* concentration was calculated with the following equation: chlorophyll-*a* ($\mu g \cdot \ell^{-1}$) = [(A665–A750) – ($A665_a$–$A750_a$) x 28.66 x extract volume]/volume of sample, where A665 and $A665_a$ (and A750, $A750_a$) represent absorbance measured at 665 (and 750) nm before and after acidification.

Phytoplankton samples were preserved in 2% formaldehyde (final concentration) immediately after collection. Despite the fact that formalin poses a health hazard, as well as sometimes causing changes in cell dimensions, damage and distortion of chloroplasts, it remains the most commonly used liquid preservative (John et al., 2002). Concentrations of 2.5% are less damaging than higher concentration ranges in the order of 4% (John et al., 2002). Formaldehyde was preferred to Lugol's solution because the latter often discolours the cell contents, which must be clearly visible for correct identification. Phytoplankton identification and enumeration were done according to the sedimentation technique using gravity as described in Utermöhl (1958) and Swanepoel et al. (2008). Gas vacuoles of cyanoprokaryotes were pressure-deflated in a special container using a mechanical hammer. Up to 5 mℓ (depending on the density of the algae) was then pipetted into sedimentation tubes. The sedimentation tubes were filled with distilled water and covered with circular glass coverslips. The sedimentation tubes were left for a period of at least 2 days in a desiccator in order to allow the cells to settle. Algae and cyanoprokaryotes were identified and counted using an inverted microscope. Identification and enumeration was done by the same analyst to ensure comparability between the two periods. Literature used for identification were Croasdale et al. (1994); Ettl et al. (1999); Hindak (2008); Huber-Pestalozzi (1961); John et al. (2002); Komárek and Anagnostidis (2005); Taylor et al. (2007a); Wehr and Sheath (2003) and Oyadomari (2001).

An aliquot of 50 mℓ from each sampling site was enriched with 100 mℓ GBG11 growth medium (Krüger, 1978) and incubated at a temperature of 20°C and a continuous light intensity of 15 $\mu mol\ m^{-2} s^{-1}$ to stimulate the growth of algae and cyanoprokaryotes present in low concentrations. Enrichment studies were not done during the first survey.

The survey done from March 2010 to March 2011 (hereafter referred to as current survey) and the survey from May 1999 to July 2000 (hereafter referred to as previous survey) were done at the same localities using the same methods and supervised by the same person. Differences in algal and cyanoprokaryote composition, as well as in physical and chemical variables between samples collected during the current and previous surveys were explored and tested using Statistica version 10 software (StatSoft Inc.). The Kolmogorov-Smirnov and Lilliefors test for normality was used to determine if the variables were distributed parametrically. The data did not meet the assumptions of normality in the distribution of all variables. The Kruskal-Wallis ANOVA for non-parametric data was used for comparing multiple independent samples to determine differences between the variables in each reservoir, as well as between variables from the two time periods. CANOCO version 4.5 software was used to perform multivariate and ordination analyses (Ter Braak and Smilauer, 1998). Only the datasets that contained all the variables were used for multivariate analysis.

RESULTS

Community composition

A species list of cyanoprokaryotes and algal taxa was compiled for each impoundment to examine any changes in the 10-year interval between the previous and current surveys (Table 1).

In Klerkskraal Dam, 4 Cyanophyceae species occurred during both periods. Diatoms increased from 10 to 15 species,

TABLE 1
Comparison of the species composition between the two sampling periods (1999–2000 and 2010–2011) in the three dams located on the Mooi River

	Klerkskraal Dam		Boskop Dam		Potchefstroom Dam	
	1999–2000	2010–2011	1999–2000	2010–2011	1999–2000	2010–2011
CYANOPHYCEAE						
Arthrospira sp.					✓	✓
Cyanobacterium sp.				✓		
Cylindrospermopsis raciborskii (Woloszynska) Seenayya et Subba Raju				✓		
Merismopedia minima Beck		✓	✓	✓	✓	
Microcystis aeruginosa (Kützing) Kützing	✓	✓	✓	✓	✓	✓
Microcystis flos-aquae (Wittrock) Kirchner						✓
Microcystis wesenbergii (Komárek) Komárek	✓			✓	✓	
Oscillatoria sp.	✓			✓	✓	✓
Oscillatoria simplicissima Gomont					✓	
Pseudanabaena sp.	✓	✓	✓	✓	✓	✓
Snowella sp.		✓		✓		✓
Total number of Cyanophyceae species	**4**	**4**	**3**	**8**	**7**	**6**
Total number of Cyanophyceae species shared between surveys	**2**		**3**		**4**	
BACILLARIOPHYCEAE						
Achnanthidium minutissimum (Kützing) Czarnecki		✓	✓	✓		
Amphipleura sp.						✓
Aulacoseira granulata (Ehrenberg) Simonsen	✓	✓	✓	✓	✓	✓
Aulacoseira muzanensis (Meister) Krammer	✓	✓				
Asterionella formosa Hassall		✓	✓		✓	
Cocconeis pediculus Ehrenberg	✓	✓	✓	✓	✓	✓
Cyclotella meneghiniana Kützing	✓	✓	✓	✓	✓	✓
Cymatopleura sp.						✓
Cymbella spp.				✓	✓	✓
Diadesmus confervacea Kützing (syn. *Navicula confervacea* (Kützing) Grunow in Van Heurck*)*	✓	✓	✓	✓	✓	✓
Diatoma vulgaris Bory		✓		✓		✓
Epithemia sp.						✓
Fragilaria ulna (Nitzsch) Lange-Bertalot	✓	✓	✓	✓		
Gomphonema spp.		✓		✓		✓
Gyrosigma sp.						✓
Melosira varians C.Agardh	✓	✓	✓	✓	✓	✓
Navicula spp.	✓	✓	✓	✓	✓	✓
Nitzschia palea (Kützing) W.Smith		✓	✓	✓	✓	✓
Nitzschia spp.	✓	✓	✓	✓	✓	✓
Pinnularia sp.				✓		✓
Pleurosigma sp.						✓
Rhopaloidia sp.		✓		✓		✓
Stephanodiscus spp.						✓
Surirella sp.	✓		✓	✓	✓	✓
Total number of Bacillariophyceae species	**10**	**15**	**12**	**16**	**11**	**20**
Total number of Bacillariophyceae species shared between surveys	**9**		**11**		**10**	
CHLOROPHYCEAE						
Actinotaenium sp.				✓		
Ankistrodesmus sp.			✓			
Carteria sp.	✓		✓		✓	✓
Carteria simplicissima Pascher			✓		✓	
Characium limneticum Lemmermann			✓		✓	
Chlamydomonas incerta Pascher	✓	✓			✓	✓

Chlamydomonas bicocca Pascher	✓	✓			✓	
Chlamydomonas conferta Korshikov						✓
Chlamydomonas sp.	✓	✓	✓	✓	✓	✓
Chlorella sp.	✓	✓	✓	✓	✓	
Chlorococcum infusionum (Schrank) Meneghini	✓		✓		✓	
Chlorogonium sp.	✓	✓				
Closterium cornu Ehrenberg ex Ralfs	✓	✓	✓		✓	✓
Coelastrum pseudomicroporum Korshikov	✓		✓	✓	✓	
Coelastrum reticulatum (P.A.Dangeard) Senn	✓				✓	
Conococcus elongates H.J.Carter	✓					
Cosmarium sp.	✓		✓	✓	✓	✓
Crucigenia fenestrate (Schmidle) Schmidle					✓	
Crucigenia lauterbornii (Schmidle) Schmidle	✓		✓		✓	
Crucigenia tetrapedia (Kirchner) Kuntze	✓		✓	✓	✓	✓
Crucigeniella rectangularis (Nägeli) Komárek	✓		✓		✓	
Dictyosphaerium elegans Bachmann					✓	
Golenkinia radiata Chodat	✓	✓	✓	✓	✓	✓
Gonatozygon sp.		✓		✓		✓
Kirchneriella sp.	✓	✓	✓	✓	✓	
Lagerheimia balatonica (Scherffel) Hindák			✓			
Lagerheimia chodatii C.Bernard	✓		✓		✓	
Lagerheimia longiseta (Lemmermann) Printz			✓			
Micractinium sp.					✓	
Monoraphidium arcuatum (Korshikov) Hindák		✓			✓	
Monoraphidium circinale (Nygaard) Nygaard	✓			✓	✓	✓
Monoraphidium contortum (Thuret) Komàrková-Legnerová	✓					
Monoraphidium minutum (Nägeli) Komárková-Legnerová	✓		✓	✓	✓	✓
Monoraphidium pseudobraunii (Belcher et Swale) Heynig						✓
Monoraphidium sp.	✓	✓	✓	✓	✓	✓
Oocystis lacustris Chodat	✓	✓	✓	✓	✓	✓
Oocystis marsonii Lemmermann					✓	
Oocystis pusilla Hansgirg					✓	✓
Oocystis sp.	✓	✓	✓	✓		
Pandorina morum (O.F.Müller) Bory de Saint-Vincent		✓	✓	✓	✓	✓
Pediastrum duplex Meyen	✓		✓		✓	✓
Pediastrum simplex Meyen	✓	✓	✓	✓	✓	
Pediastrum tetras (Ehrenberg) Ralfs	✓	✓	✓	✓	✓	✓
Phacotus lenticularis (Ehrenberg) Stein	✓		✓		✓	
Pteromonas angulosa Lemmermann	✓					
Scenedesmus abundans (O. Kirchner) Chodat				✓		✓
Scenedesmus acuminatus (Lagerheim) Chodat		✓				
Scenedesmus disciformis (Chodat) Fott et Komárek		✓	✓	✓	✓	✓
Scenedesmus lefevrii Komárek		✓	✓	✓	✓	✓
Scenedesmus quadricauda Chodat	✓	✓	✓	✓	✓	✓
Scenedesmus sp.	✓	✓	✓	✓	✓	✓
Sphaerocystis planctonica R. Chodat					✓	
Sphaerocystis schroeteri Chodat	✓	✓			✓	✓
Staurastrum sp.	✓	✓	✓	✓	✓	
Tetraedron caudatum (Corda) Hansgirg				✓		✓
Tetraedron mediocris Hindák						✓
Tetraedron minimum (A.Braun) Hansgirg	✓		✓	✓	✓	✓
Tetraedron sp.	✓			✓		✓
Tetrastrum komarekii Hindák		✓	✓	✓	✓	✓
Tetrastrum staurogeniaeforme (Schröder) Lemmermann				✓	✓	

Volvox sp.	✓				✓	
Total number of Chlorophyceae species	**36**	**24**	**34**	**28**	**44**	**29**
Total number of Chlorophyceae species shared between surveys	**17**		**21**		**22**	
CRYPTOPHYCEAE						
Cryptomonas major Butcher	✓	✓	✓	✓	✓	✓
Cryptomonas minor J.Schiller	✓	✓	✓	✓	✓	✓
Rhodomonas lacustris Pascher et Ruttner var. *nannoplanctica* (Skuja) Javornicky	✓	✓	✓		✓	
Total number of Cryptophyceae species	**3**	**3**	**3**	**2**	**3**	**2**
Total number of Cryptophyceae shared between surveys	**3**		**2**		**2**	
CHRYSOPHYCEAE						
Dinobryon sp. (shared between surveys)	✓	✓	✓	✓	✓	✓
Total number of Chrysophyceae species	**1**	**1**	**1**	**1**	**1**	**1**
DINOPHYCEAE						
Ceratium hirundinella (O.F.Müller) Dujardin			✓	✓	✓	✓
Peridinium sp.	✓		✓	✓	✓	✓
Peridinium gatunense Nygaard		✓				
Sphaerodinium sp.	✓	✓	✓	✓	✓	✓
Total number of Dinophyceae species	**2**	**2**	**3**	**3**	**3**	**3**
Total number of Dinophyceae species shared between surveys	**1**		**3**		**3**	
EUGLENOPHYCEAE						
Euglena hemichromata Skuja					✓	
Euglena pusilla Playfair			✓			
Euglena sp.	✓	✓		✓	✓	✓
Phacus acuminatus Stokes			✓		✓	
Phacus meson Pochmann	✓	✓	✓		✓	✓
Strombomonas fluviatilis (Lemmermann) Deflandre					✓	
Strombomonas jaculata (Palmer) Deflandre	✓	✓		✓		✓
Strombomonas ovalis (Playfair) Deflandre		✓	✓	✓		✓
Trachelomonas hispida (Perty) F. Stein		✓		✓		
Trachelomonas intermedia P.A. Dangeard	✓	✓	✓	✓	✓	✓
Trachelomonas volvocina (Ehrenberg) Ehrenberg	✓	✓	✓	✓	✓	✓
Total number of Euglenophyceae species	**5**	**7**	**6**	**6**	**7**	**6**
Total number of Euglenophyceae species shared between surveys	**5**		**3**		**4**	
TOTAL PHYTOPLANKTON SPECIES RICHNESS	**61**	**56**	**62**	**64**	**76**	**67**

whereas Chlorophycean species declined from 36 to 24. The number of species of Cryptophyceae (3), Chrysophyceae (1) and Dinophyceae (2) did not change, but Euglenophyceae increased slightly from 5 to 7. Total phytoplankton species richness in Klerkskraal Dam decreased from 61 to 56 during the decade.

In Boskop Dam, increases in species number of Cyanophyceae and Bacillariophyceae were observed (3 to 8 and 12 to 16, respectively), while species richness of Chlorophyceae and Cryptophyceae decreased (34 to 28, and 3 to 2, respectively). The number of Chrysophyceae (1), Dinophyceae (3) and Euglenophyceae (6) species remained constant. Overall phytoplankton species richness in Boskop Dam increased from 62 to 64 species.

In Potchefstroom Dam, Cyanophyceae species decreased from 7 to 6, but as with the other 2 dams, species numbers of Bacillariophyceae increased from 11 to 20 and Chlorophyceae species decreased from 44 to 29. Numbers of Cryptophyceae and Euglenophyceae species decreased slightly from 3 to 2 and 7 to 6, respectively, while numbers of the Dinophyceae (3) and Chrysophyceae (1) remained constant (Table 1). Total phytoplankton species richness decreased from the previous (76 species) to the current survey (67 species) by 9 species.

During the previous survey, species richness differed slightly in Klerkskraal (61 species) and Boskop Dams (62 species) but increased to 76 species in the downstream Potchefstroom Dam. During the present survey, downstream increases in species richness were evident down the entire reservoir cascade (Klerkskraal Dam – 56, Boskop Dam – 64 and Potchefstroom Dam – 67 species).

The current survey shows that several species, absent during the previous survey, now occur in all three impoundments. Examples are the cyanobacterium *Snowella*; the green alga *Gonatozygon* as well as genera from the Bacillariophyceae, namely *Diatoma vulgaris* Bory (typical of eutrophic waters) and *Gomphonema* species. Conversely, several species of Chlorophyceae (*Crucigenia lauterbornii, Crucigeniella rectangularis, Lagerheimia codatii* and *Phacotus lenticularis*) disappeared. Enrichment experiments (Table 2) also demonstrated

TABLE 2
Species list obtained from enriched samples from March 2010 – March 2011

	Klerkskraal Dam	Boskop Dam	Potchefstroom Dam
CYANOPHYCEAE			
Anabaena sp.		✓	✓
Aphanocapsa sp.	✓	✓	✓
Aphanothece flocossa (Zalessky) G. Cronberg et Komárek	✓	✓	
Calothrix sp.			✓
Cyanosarcina sp.		✓	
Geitlerinema amphibium (C. Agardh ex Gomont) Anagnostidis	✓	✓	✓
Leptolyngbya sp.	✓	✓	✓
Lyngbya martensiana Meneghini ex Gomont			✓
Merismopedia sp.	✓	✓	✓
Microcystis sp.		✓	✓
Oscillatoria tenuis	✓	✓	
Planktothrix sp.			✓
Phormidium aerugineo-caeruleum (Gomont) Anagnostidis			✓
Phormidium sp.	✓	✓	✓
Pseudanabaena biceps Böcher	✓		✓
Pseudanabaena rosea (Skuja) Anagnostidis	✓	✓	✓
Pseudophormidium sp.			✓
Spirulina sp.	✓		✓
Synechococcus sp.	✓	✓	✓
Synechocystis sp.	✓	✓	✓
Tychonema sp.		✓	✓
Total number of Cyanophyceae species	**12**	**14**	**18**
BACILLARIOPHYCEAE			
Achnanthidium sp.	✓	✓	✓
Aulacoseira ambigua (Grunow) Simonsen	✓	✓	✓
Cyclotella meneghiniana Kützing	✓		✓
Cyclotella ocellata Pantocsek		✓	
Cymbella cymbiformis Agardh	✓	✓	✓
Diploneis sp.		✓	
Encyonopsis microcephala (Grunow) Krammer	✓	✓	
Eunotia sp.	✓		
Fallacia sp.			✓
Fragilaria sp.	✓		
Fragilaria crotonensis Kitton		✓	✓
Gomphonema sp.		✓	
Hantzschia amphioxys (Ehrenberg) Grunow		✓	
Melosira varians C. Agardh	✓		✓
Navicula veneta Kützing		✓	✓
Nitzschia sp.		✓	
Nitzschia amphibia Grunow			✓
Nitzschia dissipata (Kützing) Grunow		✓	
Nitzschia draveillensis Coste et Ricard	✓	✓	
Nitschia palea (Kützing) W.Smith	✓	✓	✓
Pinnularia subbrevistriata Krammer	✓		✓
Pseudostaurosira brevistriata (Grunow) D.M.Williams et Round		✓	
Rhopalodia sp.			✓
Sellaphora seminulum (Grunow) D.G.Mann	✓	✓	
Staurosira construens Ehrenberg	✓	✓	
Staurosira elliptica (Schumann) D.M. Williams et Round		✓	

Staurosira sp.	✓	✓	✓
Staurosirella sp.	✓	✓	✓
Suriella angusta Kützing		✓	
Synedra tenera W. Smith	✓	✓	✓
Tabellaria flocculosa (Roth) Kützing	✓		
Tryblionella apiculata Gregory		✓	✓
Total number of Bacillariophyceae species	**17**	**23**	**16**
CHLOROPHYCEAE			
Ankistrodesmus densus Korshikov		✓	
Ankistrodesmus fusiformis Corda ex Korshikov			✓
Ankistrodesmus gracilis (Reinsch) Korshikov	✓	✓	
Ankistrodesmus spiralis (W.B.Turner) Lemmermann	✓	✓	
Bracteacoccus sp.	✓	✓	✓
Chaetophora sp.			✓
Chlorella sp.	✓	✓	✓
Chlamydomonas sp.	✓	✓	✓
Chlorococcum sp.	✓	✓	✓
Chroococcus sp.	✓	✓	
Chroomonas sp.	✓	✓	✓
Coelastrum sp.	✓	✓	✓
Coelospaerium sp.	✓		
Crucigeniella sp.		✓	✓
Dictyosphaerium sp.		✓	
Geminella sp.		✓	
Kirchneriella sp.	✓		
Monoraphidium contortum (Thuret) Komárková-Legnerová	✓	✓	✓
Monoraphidium minitum (Nägeli) Komárková-Legnerová		✓	
Monoraphidium pusillum (Printz) Komárková-Legnerová		✓	
Monoraphidium tortile (West et G.S.West) Komárková-Legnerová	✓		
Oocystis sp.	✓	✓	✓
Pandorina sp.			✓
Pediastrum duplex Meyen	✓	✓	✓
Pediatrum tetras (Ehrenberg) Ralfs	✓	✓	✓
Scenedesmus acutus Meyen	✓	✓	
Scenedesmus dimorphus (Turpin) Kützing		✓	✓
Scenedesmus dispar Brébisson		✓	
Scenedesmus linearis Komárek	✓	✓	✓
Scenedesmus longispina R. Chodat		✓	
Scenedesmus opoliensis P.G. Richter		✓	
Scenedesmus quadricauda Chodat		✓	
Scenedesmus spinosus Chodat		✓	
Scenedesmus tenuispina Chodat	✓	✓	✓
Selenastrum sp.		✓	
Sphaerocystis sp.		✓	
Staurastrum sp.		✓	
Tetraedron caudatum (Corda) Hansgirg			✓
Tetraedron minimum (A. Braun) Hansgirg	✓		
Tetraedron sp.		✓	
Total number of Chlorophyceae species	**20**	**32**	**18**
CRYPTOPHYCEAE			
Cryptomonas sp.	✓		✓
Total number of Cryptophyceae species	**1**	**0**	**1**

CHRYSOPHYCEAE			
Paraphysomonas sp.	✓		
Total number of Chrysophyceae species	**1**	**0**	**0**
EUGLENOPHYCEAE			
Euglena sp.	✓		
Total number of Euglenophyceae species	**1**	**0**	**0**
PRYMNESIOPHYCEAE			
Hymenomonas roseola Stein	✓	✓	✓
Total number of Prymnesiophyceae species	**1**	**1**	**1**
XANTHOPHYCEAE			
Goniochloris sp.		✓	
Total number of Xanthophyceae species	**0**	**1**	**0**
TOTAL PHYTOPLANKTON SPECIES RICHNESS	**53**	**71**	**54**

the presence of potentially problematic species scarce in ambient dam waters. These include several cyanoprokaryote genera that can lead to potential water quality problems, namely *Anabaena, Leptolyngbya, Phormidium, Synechococcus, Lyngbya, Microcystis, Oscillatoria* and *Synechocystis*.

Figures 2–4 compare the algal classes and Cyanophyceae (cells·mℓ$^{-1}$) in Klerkskraal, Boskop and Potchefstroom dams during the previous survey with that of the current survey. During both surveys the Chrysophyceae was more prominent during the cooler months in all three dams. During the previous survey the Chlorophyceae usually dominated during the warmer months, but during the current survey the Bacillariophyceae were more abundant during summer in all three dams. This tendency is also reflected in the richness of Chlorophyceae, where species numbers generally decreased from the previous to current survey, and in the richness of the Bacillariophyceae, which showed a general increase in species number from the previous to current study (Table 1).

Figure 2 clearly shows that the Chrysophyceae was the dominant algal group in Klerkskraal Dam during the previous survey, but their cell numbers were significantly ($p = 0.02$) lower during the current survey. Cryptophyceae (Table 3) were also less abundant ($p = 0.03$) during the current survey than during the previous survey. The decline in concentration of both these groups probably accounts for the significant decrease in the total number of cells observed during the current sampling period. No significant difference was observed between the abundance of any of the other algal classes, including the Cyanophyceae ($p > 0.05$), during the two surveys. During the current period the Bacillariophyceae dominated with an average of 203 cells·mℓ$^{-1}$. The abundance of Cyanophyceae, often indicative of nutrient pollution levels, remained low during both study periods.

There were no significant changes in the algal and cyanoprokaryote concentrations of Boskop Dam (Fig. 3), except for a significant increase in the Bacillariophyceae cells ($p = 0.01$) which dominated during the current period. Although there was a drastic decline in the numbers of the Chrysophyceae this was not statistically significant ($p = 0.6$). However, species number of Cyanophyceae increased from 3 to 8, with new genera, including bloom-forming *Cylindrospermopsis* and *Microcystis,* appearing during the current survey.

No significant change ($p > 0.05$) was evident in the concentration of the algal or cyanoprokaryote groups found in Potchefstroom Dam (Fig. 4), where the Bacillariophyceae was also the dominant algal group during the current survey with an average of 316 cells·mℓ$^{-1}$.

Overall, in the three dams, both total algal and cyanoprokaryote concentrations (cells·mℓ$^{-1}$) were much lower during the second study period (2010–2011) than during the previous survey.

Environmental factors and multivariate analysis

The data used in statistical models for multivariate analyses from the Klerkskraal, Boskop and Potchefstroom dams are shown in Figs. 5 to 7. An indirect linear gradient analysis, the principal component analysis (PCA), was used as an investigative tool to determine relationships between the different water quality variables (with the ranges for these variables summarised in Table 3).

The results of the PCA ordination plot for Klerkskraal Dam (Fig. 5) indicate that the first axis explains 99% of the variance in the data. This is probably due to the significant increase ($p < 0.05$) in conductivity, from an average value of 236 µS·cm^{-1} during the previous survey to 365 µS·cm^{-1} during the current survey. Conductivity was a major driver in the system which can also be inferred from the length of the vector. The average orthophosphate and ammonium concentrations increased from 10 µg·ℓ$^{-1}$ to 110 µg·ℓ$^{-1}$ and 30 µg·ℓ$^{-1}$ to 110 µg·ℓ$^{-1}$, respectively, while the dissolved oxygen decreased significantly ($p < 0.05$) from the previous survey (8.45 mg·ℓ$^{-1}$) to the current survey (5.06 mg·ℓ$^{-1}$).

The same tendency seen in Klerkskraal Dam was also observed in Boskop Dam (Fig. 6). Conductivity, ammonium and orthophosphate concentrations increased significantly in Boskop Dam, while dissolved oxygen decreased significantly from 9.01 mg·ℓ$^{-1}$ during the previous survey to 7.35 mg·ℓ$^{-1}$ during the current survey. The pH of Boskop decreased significantly ($p < 0.05$) from 8.4 during the previous survey to 8.12 during the current survey. In Fig. 5 the PCA ordination plot for Boskop Dam indicates that the first axis explains 99.98% of the variance in the data. This is most probably due to the 42% increase in the average conductivity from 347 µS·cm^{-1} to 595 µS·cm^{-1} and 97% increase in the average concentration of orthophosphate from 10 µg·ℓ$^{-1}$ to 200 µg·ℓ$^{-1}$ from the previous to the current survey. The pH and oxygen of all the dams were measured during the morning but diurnal fluctuations could influence the data.

The PCA ordination plot for Potchefstroom Dam (Fig. 7) shows that the first axis explains 99.7% of the variance

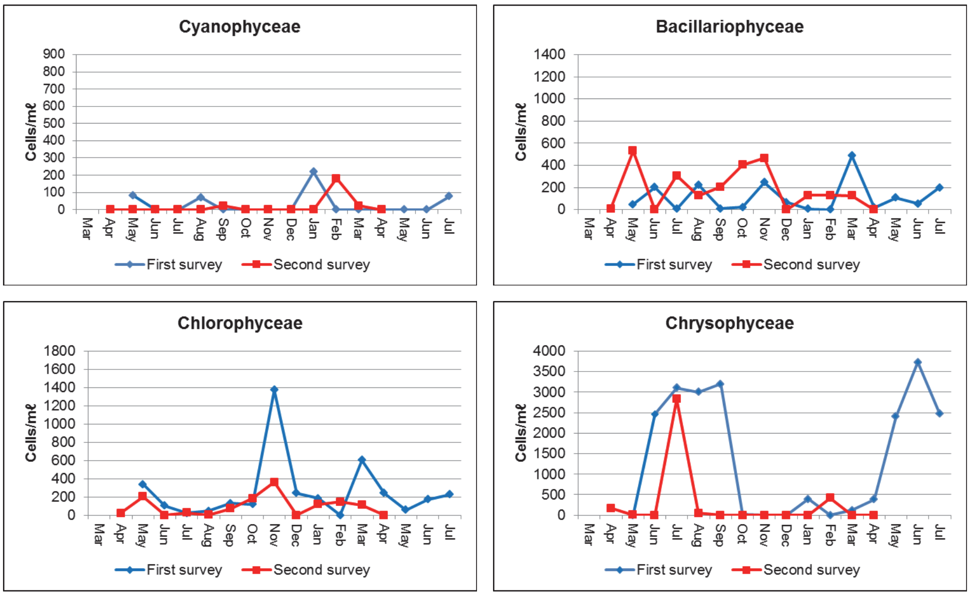


Figure 2
A comparison of the occurrence of specific algal classes and Cyanophyceae in Klerkskraal Dam during 1999–2000 (first survey) and 2010–2011 (second survey)

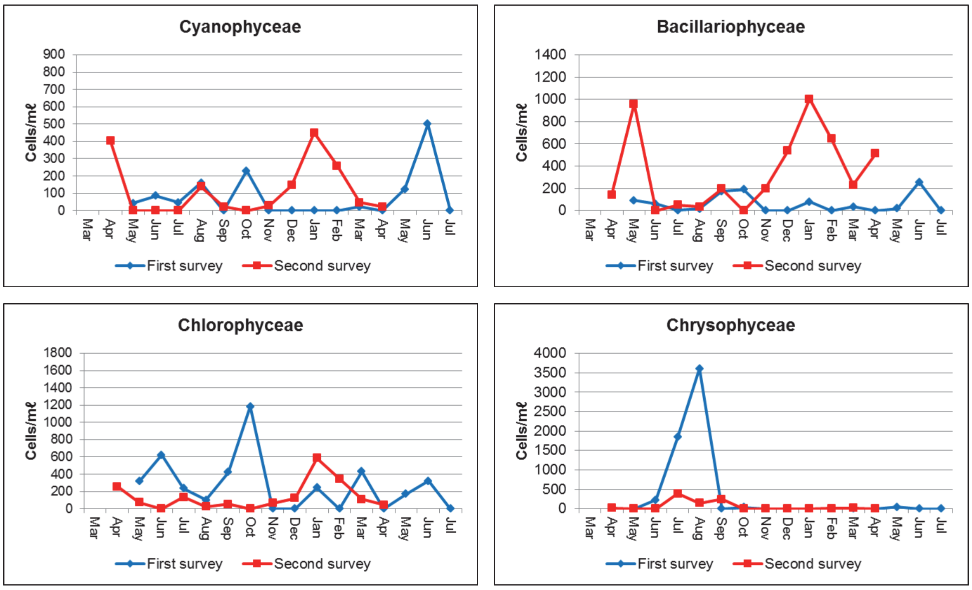


Figure 3
A comparison of the occurrence of specific algal classes and Cyanophyceae in Boskop Dam during 1999–2000 (first survey) and 2010–2011 (second survey)

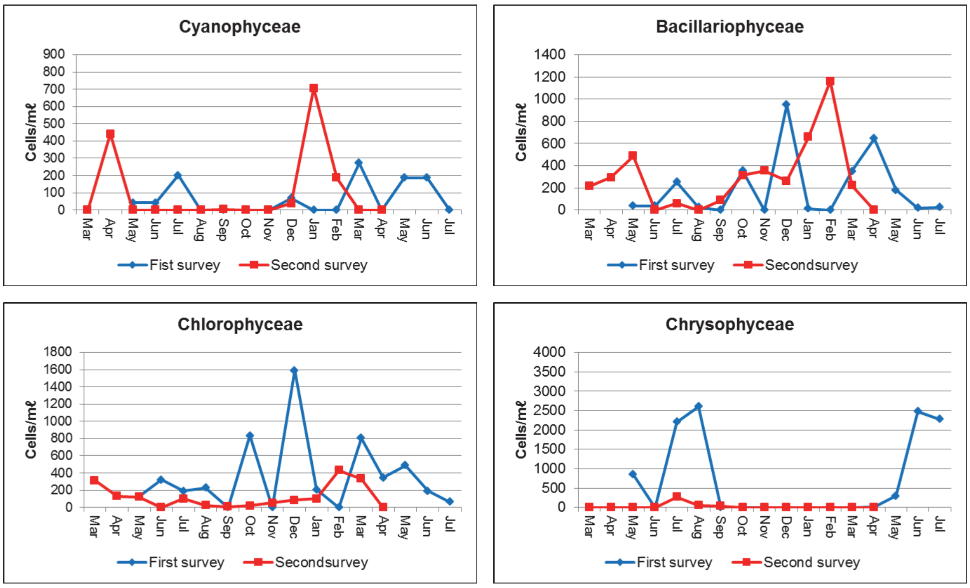
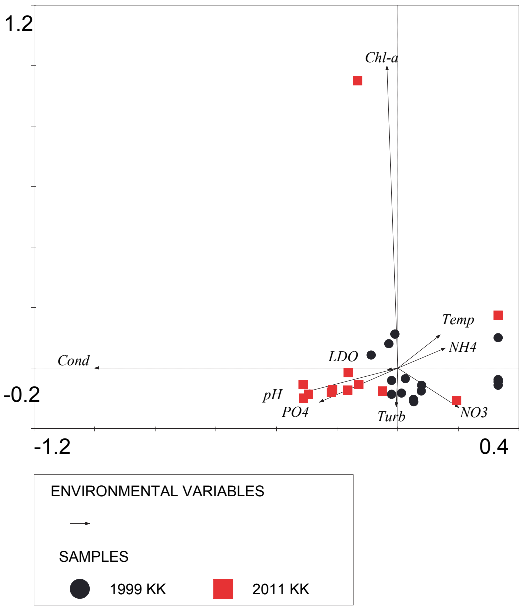
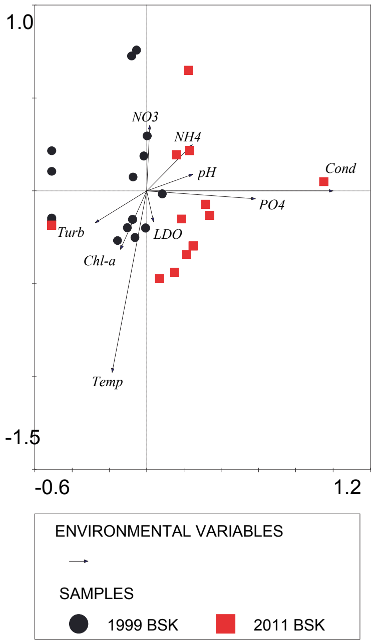


Figure 4
A comparison of the occurrence of specific algal classes and Cyanophyceae in Potchefstroom Dam during 1999–2000 (first survey) and 2010–2011 (second survey)



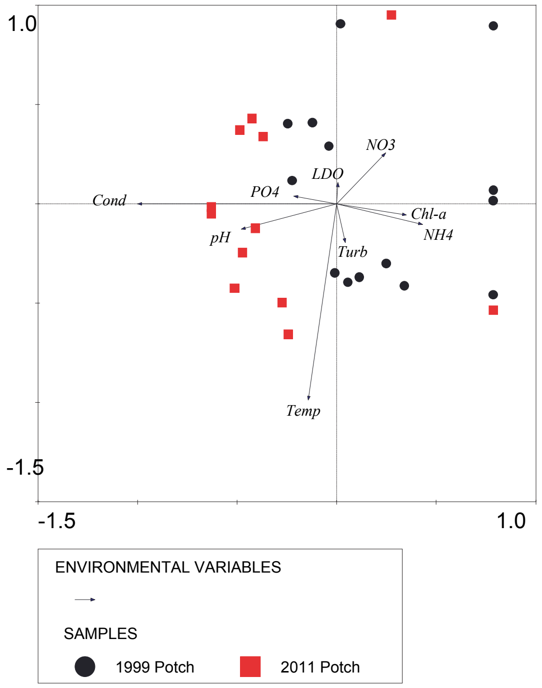
Axes		1	2	3	4	Total variance
Eigenvalues	:	0.990	0.007	0.002	0.000	1.000
Cumulative percentage variance						
of species data	:	99.0	99.7	99.9	100.0	
Sum of all eigenvalues						1.000

Figure 5
A PCA of the environmental variables of Klerkskraal Dam (KK) measured during the 1999–2000 study period as well as those measured during the 2010–2011 study period



Axes		1	2	3	4	Total variance
Eigenvalues	:	0.998	0.001	0.000	0.000	1.000
Cumulative percentage variance						
of species data	:	99.8	99.9	100.0	100.0	
Sum of all eigenvalues						1.000

Figure 6
A PCA of the environmental variables of Boskop Dam (BSK) measured during the 1999–2000 study period as well as those measured during the 2010–2011 study period



Axes		1	2	3	4	Total variance
Eigenvalues	:	0.997	0.001	0.001	0.000	1.000
Cumulative percentage variance						
of species data	:	99.7	99.8	100.0	100.0	
Sum of all eigenvalues						1.000

Figure 7
A PCA of the environmental variables of Potchefstroom Dam (Potch) measured during the 1999–2000 study period as well as those measured during the 2010–2011 study period.

in the data. Once again the differences in conductivity and orthophosphate were the most important, with average values that increased from 348 µS·cm^{-1} and 10 µg·ℓ$^{-1}$ during the previous survey to 573 µS·cm^{-1} and 200 µg·ℓ$^{-1}$ during the current survey respectively.

It is puzzling that the chlorophyll-*a* concentrations of the three dams did not change significantly during the decade despite significant increases in orthophosphate concentrations, alongside paradoxical reductions in average cell concentrations. The average concentration of all algae and cyanoprokaryota decreased from 2 447 to 629 cells·mℓ$^{-1}$ for Klerkskraal Dam; from 828 to 680 cells·mℓ$^{-1}$ for Boskop Dam and from 1 462 to 544 cells·mℓ$^{-1}$ for Potchefstroom Dam. This decrease is largely due to the decrease in the number of *Dinobryon* cells. Chrysophyceae such as *Dinobryon* species are widely recognised as mixotrophs (Bellinger and Sigee, 2010) that can supplement nutrients in an oligotrophic environment by consuming bacteria (Holen and Boraas, 1995). Lewitus and Caron (1991) suggested that heterotrophic nutrition ensues at the expense of photosynthetic capabilities and a high probability of the loss of chloroplast function (Holen and Boraas, 1995). Therefore, it is possible that the chlorophyll-*a* content per cell of *Dinobryon* is lower than the chlorophyll-*a* content per Bacillariophyceae cell (dominating during the current survey) accounting for the stable chlorophyll-*a* concentration. Myers and Graham (1956) found that *Poterioochromonas malhamensis* (Chrysophyceae) has a lower concentration of cellular chlorophyll in comparison with similar-sized algae.

TABLE 3
Descriptive statistics for variables measured in the three dams for the surveys in 1999–2000 and 2010–2011

Variable	Survey	Unit	Descriptive statistics											
			Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD
			Boskop Dam				Potchefstroom Dam				Klerkskraal Dam			
Chl *a*	1999–00	μg·ℓ$^{-1}$	5.4	0.57	11.5	3.91	10.9	1.59	22.9	7.21	5.52	0.29	14.14	4.79
	2010–11		7.2	0.10	18	5.89	6.72	0.10	25	7.83	9.36	0.1	67	18.7
DO	1999–00	mg·ℓ$^{-1}$	9	7	12.8	1.44	9.1	7.42	11.61	1.29	8.45	6.82	13.58	1.73
	2010–11		7.4	3.66	10.6	2.30	70.2	52	96	15.42	5.06	0	10	3.47
Temp	1999–00	°C	18.9	10.6	25.5	5.13	19.9	10.9	23.6	4.75	18.2	9.8	23.9	4.72
	2010–11		19.3	10.9	27.8	5.72	19.87	11.05	29.5	5.95	18.8	10.4	25.4	5.12
Turb	1999–00	NTU	2.2	1.30	3.46	0.65	3.87	1.3	8	2.08	2.22	0.8	4.1	0.94
	2010–11		2.5	0	4.80	2.32	3.25	0	6.9	3.03	2.17	0	5.1	2.42
Cond	1999–00	μS·cm^{-1}	347	266	447	47.9	348.6	206	476	86.9	236	187	310	37.9
	2010–11		595.7	436	1101	176.9	537.8	236	653	115	364.8	101	476	108
pH	1999–00		8.4	7.98	8.81	0.27	8.46	7.78	8.90	0.33	8.25	7.50	8.79	0.41
	2010–11		8.12	7.65	8.67	0.35	8.30	7.7	8.83	0.37	8.2	7.4	8.9	0.42
PO_4	1999–00	mg·ℓ$^{-1}$	0.01	0	0.03	0.01	0.01	0	0.03	0.01	0.01	0.0001	0.03	0.01
	2010–11		0.20	0.05	0.99	0.28	0.20	0.03	0.95	0.28	0.11	0	0.3	0.09
NO_3	1999–00	mg·ℓ$^{-1}$	0.38	0	1.9	0.58	0.15	0	1.29	0.33	0.13	0	0.72	0.19
	2010–11		0.32	0	1.30	0.39	0.14	0	0.40	0.15	0.12	0	0.4	0.14
NH_4	1999–00	mg·ℓ$^{-1}$	0.03	0	0.09	0.03	0.06	0	0.41	0.11	0.03	0	0.1	0.03
	2010–11		0.06	0.02	0.10	0.03	0.09	0	0.28	0.08	0.11	0	0.5	0.13
Cyano	1999–00	cells· mℓ$^{-1}$	81	0	501	136	68	0	272	98	30	0	220	61
	2010–11		92	0	449	138	788	0	706	205	19	0	180	52
Bacil	1999–00	cells·mℓ$^{-1}$	61	0	255	82	204	0	950	289	113	0	486	136
	2010–11		364	0	1 001	361	300	0	116	342	202	0	532	185
Chloro	1999–00	cells·mℓ$^{-1}$	270	0	1 181	317	376	0	1 590	441	259	0	1 373	343
	2010–11		129	0	583	170	106	0	429	136	108	0	360	110
Crypto	1999–00	cells·mℓ$^{-1}$	21	0	126	37	11	0	103	28	23	0	149	38
	2010–11		3	0	14	6	8	0	3	11	6	0	23	9
Chryso	1999–00	cells·mℓ$^{-1}$	383	0	3 604	1 008	704	0	2 603	1 111	1 419	0	3 730	1 485
	2010–11		67	0	386	127	30	0	266	76	276	0	2 831	814
Dino	1999–00	cells·mℓ$^{-1}$	7	0	34	10	4	0	26	7	3	0	17	6
	2010–11		13	0	109	31	9	0	61	19	2	0	20	6
Eugleno	1999–00	cells·mℓ$^{-1}$	5	0	51	14	34	0	389	103	13	0	69	18
	2010–11		11	0	46	15	14	0	74	26	6	0	32	11
Tcells	1999–00	cells·mℓ$^{-1}$	828	0	3 907	1 070	1 462	0	2 891	1 123	2 447	0	11 357	2 773
	2010–11		680	0	2 065	589	544	0	1 785	550	629	0	3 180	868

According to Oliver et al. (1999) the correlation between chlorophyll and total phosphorus concentrations has been described for a broad range of lakes and is surprisingly congruent for one-factor dependency, but is not suitable in environments where the biomass yield is limited by light or by nutrients other than phosphorus. Environmental factors of importance in modifying the total phosphorus-chlorophyll models are light availability and the supply of nutrients from sources such as bottom sediments (Oliver et al. 1999; Nicholls and Dillon, 1978; Walker, 1995). We did not measure the total phosphate or the total nitrogen but nitrogen limitation could have played a role. The supply of nutrient from sediments is also an issue that is being addressed in ongoing studies in the Mooi River System.

DISCUSSION

By virtue of their high reproductive rates, algae can respond rapidly to natural and/or anthropogenic changes in environmental conditions (Sharov, 2008). Accordingly, they can serve as valuable bio-indicators of water body health. Dominant genera in algal groupings change not only spatially but also seasonally, as physical, chemical and biological conditions in a water body change (Wetzel, 2001). In addition to seasonal changes in the three reservoirs there was also a change in the algal community from Chrysophyceae dominance during the previous study period to Bacillariophyceae dominance during the current study period. According to Bellinger and Sigee (2010), Chrysophyceae occur in low-nutrient lakes and are considered by some authors as an indicator of oligotrophy (Rawson, 2012). The replacement of Chrysophyceae species by Bacillariophyceae species, such as *Melosira varians*, *Cyclotella meneghiniana* and *Aulacoseira granulata,* that are typical of eutrophic impoundments, was more pronounced in Boskop Dam than in any of the other dams. High numbers of *Fragilaria ulna* present in mesotrophic to eutrophic, alkaline water (Taylor et al., 2007a) were also observed in Boskop Dam, indicating a decrease in the water quality of this dam over time. The diatom *Asterionella formosa* was not found during the current survey in the Boskop or Potchefstroom dams. This species is generally found in the plankton of mesotrophic dams (Taylor et al., 2007a) and appears to have been replaced by the nutrient-tolerant taxa mentioned above.

Diatoma vulgaris, a diatom species indicative of hard water, with elevated nutrient levels (Janse van Vuuren et al., 2006), was absent in all three dams during the previous survey. Its presence in all of the dams during the current survey (Table 1) is indicative of enrichment over the past decade. Walsh and Wepener (2009) showed that agricultural enrichment favours the presence of this species, as illustrated by its high abundance in Bloemhof Dam, an irrigated agricultural region. According to Taylor et al. (2005) and Hill et al. (2001), environmental preferences for *D. vulgaris* include conductivity levels of 100 to 500 $\mu S \cdot cm^{-1}$ and mesotrophic to eutrophic conditions. Results from this study indicated that conductivity was one environmental variable that increased most markedly (by 42%) from the previous to current survey. South African studies by Taylor et al. (2007b) linked *D. vulgaris* specifically to freshwaters with elevated levels of phosphate-phosphorus. Our results showed that nutrient concentrations (phosphorus and ammonium) increased over the decade. In Boskop Dam the phosphorus concentration increased by 97%. Increasing nutrient concentrations, together with high conductivity values, probably triggered the occurrence of this species.

The number of Cyanophyceae species identified during the previous and current surveys stayed the same in Klerkskraal Dam and more or less the same in Potchefstroom Dam (Table 1). However, in Boskop Dam, Cyanophyceae increased both in species richness (3 to 8) and average numerical abundance (81 to 93 $cells \cdot m\ell^{-1}$). The numerical increase resulted from an increase in the abundance of potentially harmful species, such as *Microcystis* sp., *Oscillatoria* sp. and *Cylindrospermopsis raciborskii*. The potential for these organisms to become problematic under changing conditions is high, as even more Cyanophyceae species were observed in the enriched medium than during the enumeration of the samples (Table 2). Although the Chlorophyceae was the most species-rich algal class (Tables 1 and 2), there was a decline in the species richness of the Chlorophyceae in all three dams (Table 1) from the previous to the current survey.

While only one species of Chrysophyceae (*Dinobryon*) was recorded in lake water samples (Table 1), additional chrysophytes appeared in enriched samples (Table 2), namely, *Paraphysomonas* sp. in Klerkskraal Dam, and an unidentified naked colonial species that occurred in all three dams (not listed).

Some of the algae that are scarce (or absent) in dam water samples were found in enriched samples. These algae include *Geminella* sp., *Paraphysomonas* sp. as well as *Hymenomonas roseola*. *Geminella* sp. is classified under the Chlorophyceae and has turpin filaments that consist of cells in a separate, but loose, linear arrangement. Cells are longer than broad, cylindrical with round apices, with a parietal chloroplast and usually one pyrenoid. This alga was only found in the enriched sample from Boskop Dam. *Hymenomonas roseola* Stein 1878 is a freshwater coccolithophorid classified under the Class Prymnesiophyceae (Stang, 2004). According to John et al. (2002), the motile cells are ellipsoidal to subspherical and 13–50 x 10^{-24} μm with a long flagellum and a short haptoneme. Coccoliths (scales) are circular to elliptical. This species was found at all the sampling localities. *Paraphysomonas* sp. De Saedeler belongs to the Chrysophyceae and has a long flimmer flagellum and one short smooth flagellum. Cells are solitary, covered in siliceous scales and lack any chloroplast (Wehr and Sheath, 2003). This alga was only found in the enriched samples from Klerkskraal Dam.

Conductivity, as well as orthophosphate and ammonium levels of all three dams increased between the previous and current survey, while the dissolved oxygen concentration decreased (in line with the lower algal concentration). The pH decreased significantly in Boskop and Potchefstroom dams and has the potential to increase the bioavailability and toxicity of metals (Wetzel, 2001) in the water bodies. Metals most likely to have increased detrimental environmental effects, as a result of lowered pH, are silver, aluminium, cadmium, cobalt, copper, mercury, manganese, nickel, lead and zinc (DWAF, 1996). However, as these problems only emerge below pH 7, there would have to be a significant and constant source of acid pollution sufficient to exceed the Mooi River system's naturally high buffering capacity, related to its hard dolomite catchment. The average pH for all three dams was higher than 8 for both study periods and can cause the conversion of ammonium ions to the highly toxic un-ionized ammonia (DWAF, 1996). The ammonium ion is not toxic to aquatic biota, but contributes to eutrophication (DWAF, 1996).

CONCLUSIONS

An overview of Klerkskraal, Boskop and Potchefstroom dams showed that both total algal and cyanoprokaryote concentrations were lower during the current survey (2010–2011), suggesting improved ecosystem health. Therefore, these dams can still be classified as oligo- to mesotrophic (using criteria of Van Ginkel, 2002). However, there are indications, such as increasing conductivity and nutrient concentrations (particularly phosphate), that the trophic status, especially for Boskop Dam, is changing. A shift in the main drivers of these ecosystems is reflected in the change from a Chrysophyte-dominated community to a community where the Bacillariophyceae, particularly those species common in eutrophic impoundments, are dominant. Enrichment of samples under culture conditions also revealed the presence of problem species such as *Cylindrospermopsis* and *Microcystis*, that are likely to proliferate if these reservoirs experience further increases in nutrient concentrations, thereby decreasing the water quality of the Mooi River system.

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