A *Ceratium hirundinella* (O.F. Müller) bloom in Hartbeespoort Dam, South Africa

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Abstract

During the late winter to early spring of 1999 *Ceratium hirundinella* was recorded for the first time in the Hartbeespoort Dam, South Africa, and in bloom forming conditions. The *C. hirundinella* bloom started in July 1999 after complete mixing occurred and a *Microcystis aeruginosa* bloom disappeared. *C. hirundinella* occurred in chlorophyll *a* concentrations up to 4243 mg/ℓ. The clogging of filters at water care works and a fish kill were encountered during the same period, in the area. This paper discusses the extent of the bloom, the possible causes and the water characteristics found in the Hartbeespoort Dam during the development of the bloom.

Introduction

Ceratium hirundinella (O.F. Müller) (Figs.1a & b) is a common and widespread freshwater dinoflagellate. *C. hirundinella* has been found in numerous man-made impoundments in South Africa (Shillinglaw, 1981: Truter, 1987 & Van Ginkel, 1999), but the species has not been found in previous studies in the Hartbeespoort Dam (NIWR, 1985 & Van Ginkel, 1999). Although *C. hirundinella* has been found to be periodically dominant in many South African impoundments of different trophic status (e.g. Klipvoor Dam, Kosterrivier Dam, Boskop Dam and Bronkhorstspruit Dam) (Van Ginkel, 1999), it has not previously been associated with extreme bloom conditions.

The Hartbeespoort Dam is situated on the confluence of the Crocodile and the Magalies Rivers (Fig. 2), that drain highly populated urban areas, namely Pretoria, Johannesburg and Krugersdorp. The catchment lies in the highveld region of Southern Africa. At full supply level the impoundment lies at 1 162 m a.m.s.l. and covers an area of 20.3 km² and has a volume of 194.8 x 10^6 m^3. This gives an un-weighted mean depth of 9.5 m. Maximum depth at the dam wall is 31.3 m. Residence time in the Hartbeespoort Dam is approximately one year (Hely-Hutchinson and Schuman, 1997). The Hartbeespoort Dam is a recreational Mecca for the Gauteng and North-West regions.

The impoundment has been subject to algal blooms (*M. aeruginosa aeruginosa*) (NIWR, 1985) and massive aquatic weed *(Eichhornia crassipes*) development for over 15 years. The impoundment was classified as a hyper-eutrophic system (NIWR, 1985) and the promulgation of the former 1 mg/ℓ P effluent standard was to be applied in the catchment (DWA, 1988; Anon, 1988a; Anon, 1988b). Because of financial and capacity constraints in the metropolitan areas, sewage treatments works do not always comply with the 1 mg/ℓ P effluent standard. There are also numerous informal settlements in the catchment, as well as intensive farming activities, all of which contribute to the extent of eutrophication of the aquatic system.

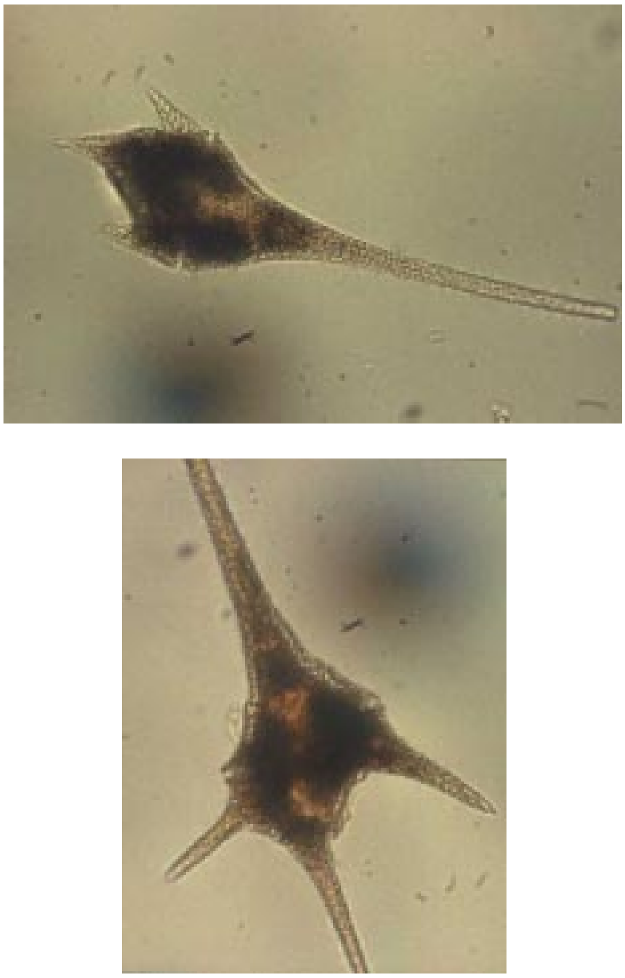

Figure 1
Photographs of Ceratium hirundinella *found in the Hartbeespoort Dam in October 1999 indicating cyclomorphosis*
a) Short horns on the hypotheca, and
b) Long horns on the hypotheca (Photographs by E. Truter)

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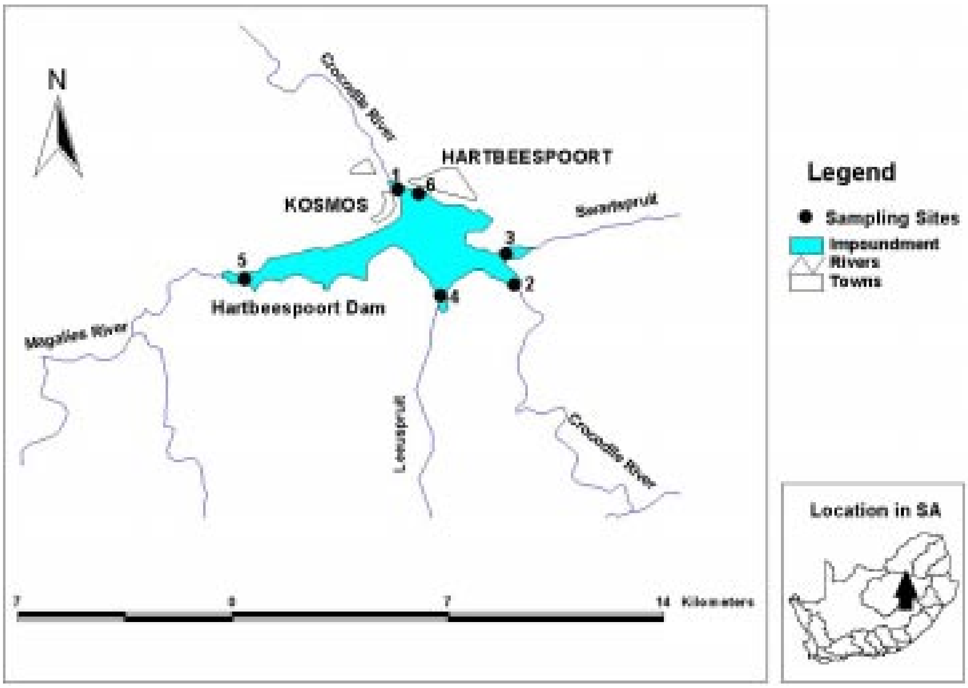

Figure 2
Sampling sites in the Hartbeespoort Dam and in the inflowing rivers during the Ceratium hirundinella *bloom in 1999.*

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Background

Ceratium spp. are unicellular dinoflagellated motile algae. The cells have a conspicuous cell wall that bears large spines (Fig. 1b) and elaborate cell-wall processes (Wetzel, 1983). The species is capable of sexual reproduction, but asexual reproduction occurs by the formation of aplanospores.

C. hirundinella has been studied extensively in different countries but mainly in northern hemisphere lakes (Cranwell, 1976; Heaney, 1976; Harris et al., 1979; Heaney and Furness, 1980; Moore, 1981; Frempong, 1984; Sommer et al., 1984; Muellerelser and Smith, 1985; Padisak, 1985; Rybak, 1985; Heaney et al., 1986; Buck, 1989; James et al., 1992; Buck and Zurek, 1994). The main characteristics of *C. hirundinella* have been identified as:

- The large size (mean length of the cell 180 μm) (Buck and Zurek, 1994).
- One large horn on the epitheca and two to three horns on the hypotheca (Figs. 1a & b) (Hutchinson, 1957; Wetzel, 1983).
- The ability to migrate from one water-column layer to another with the flagellum (Buck and Zurek, 1994; Buck, 1989; Moore 1981; Heaney et al., 1986; Harris et al., 1979). Vertical migration over a 24 h period has also been found. The species move towards the surface during the morning and early afternoon period. The organisms then redistribute to form deep water maxima above the thermocline, during the late afternoon and night (Heaney, 1976).
- The ability of *C. hirundinella* to assimilate both organic and inorganic phosphorus gives the species an advantage over other algal species that can only utilise inorganic phosphorus (Buck, 1989; James et al., 1992).
- The ability of *C. hirundinella* to undergo seasonal polymorphism or cyclomorphosis (Wetzel, 1983).

C. hirundinella has asexual resting stages or over-wintering cysts as found with periods of diapause. It was found to undergo seasonal polymorphism or cyclomorphosis by the lengthening of the cellular extensions as the temperature increases from spring into midsummer (Hutchinson, 1957; Wetzel, 1983). According to Hutchinson (1957) and Wetzel (1983) changes in horn lengths are primarily induced by increased temperatures throughout spring to midsummer. The increased horn lengths (Fig. 1b) might minimise the rate of sinking out of the photic zone and Starmach (1974). Buck (1989) and Buck and Zurek, (1994) mention that the large size of the organism favours the survival of the species, as it is too large to serve as food for zooplankton species.

The main external growth-controlling factors were identified as follows:

- Light intensity was identified as the major bloom controlling factor (Buck, 1989; Muellerelser and Smith, 1985)
- Optimum growth temperature ranges from 5°C to 30°C (Buck, 1989)
- Sufficient nutrients within the water body (Reynolds, 1978; Buck, 1989).

According to Moore (1981) *C. hirundinella* is primarily a mid-summer species and is scarce or absent in winter, thus it is meroplanktonic.

C. hirundinella is known to cause problems in raw water treatment process as filters clog due to the large size of the dinoflaggelate. The species also produce by-products that cause taste and odour problems in the final water supply (Bouwer, 1999).

Experimental procedures and methods

The Hartbeespoort Dam is monitored bi-weekly at Site 1 (Fig. 2) by the Institute for Water Quality Studies, Department of Water Affairs and Forestry (DWAF). Samples are analysed for major inorganic chemical variables, total nutrients (total phosphorus and total nitrogen), biological variables (namely, chlorophyll a, algal species, suspended solids and phaeophytin a). Physical variables (temperature and oxygen profiles, Secchi disc depth and pH) are measured *in situ*. The event of a fish kill during early October 1999 in the Hartbeespoort Dam initiated a once-off sampling survey in

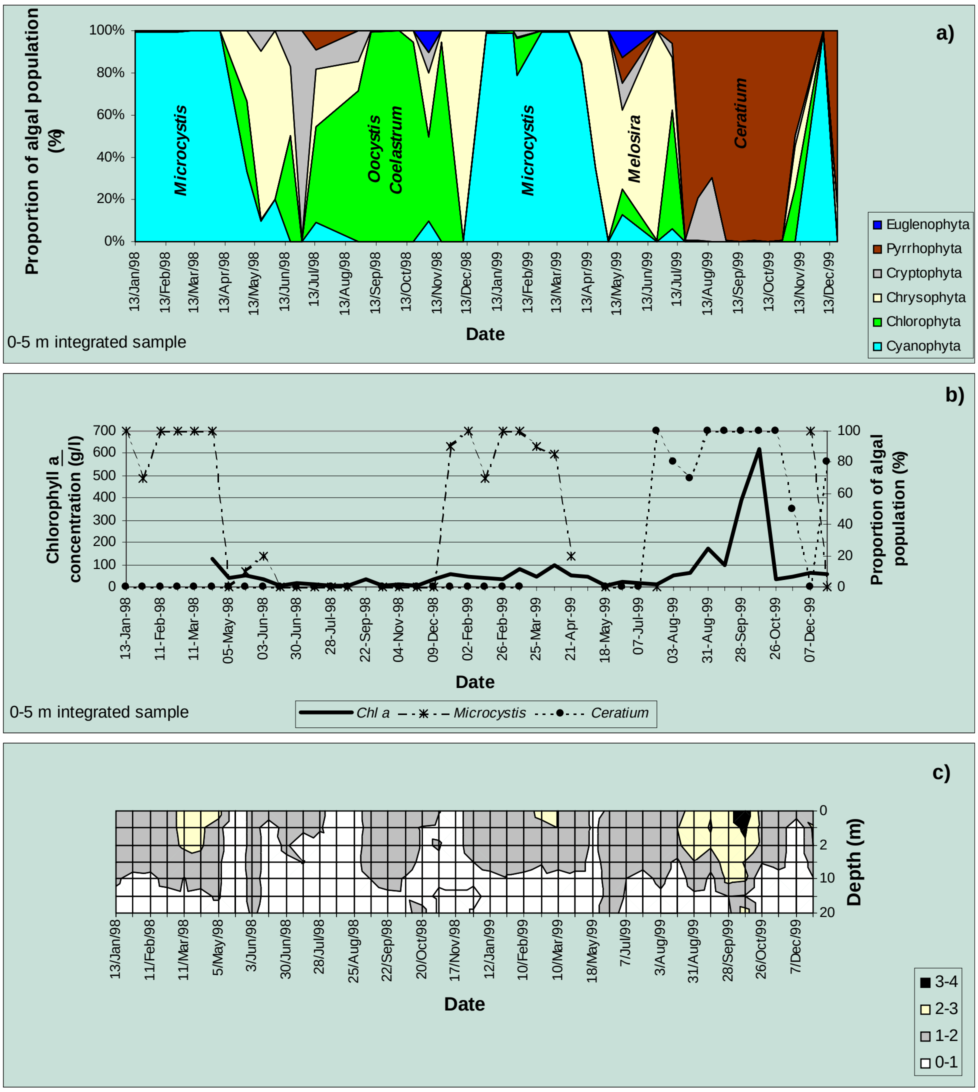

Figure 3
a) Composition of the algal population during 1998 to 1999 in the 0-5 m integrated samples, indicating the dominant species

b) Chlorophyll a concentrations in the Hartbeespoort Dam during 1998 to 1999, indicating when Microcystis *and* Ceratium *was dominant*

c) Depth distribution of chlorophyll a in the Hartbeespoort Dam, during 1998 to 1999. The concentrations are indicated on a logarithmic scale. 0-1 = 0-10 mg/ℓ; 1-2 = 10-100 mg/ℓ, 2-3 = 100-1000 mg/ℓ, and 3-4 = >1000 mg/ℓ

the inflowing rivers (Sites 2, 3, 4, 5) and at the main water extraction point for the local village (Site 6 in Fig. 2). This survey was conducted on 14 October 1999, to determine the water quality situation and phytoplankton composition in the inflowing rivers and at the extraction point to the Hartbeespoort Water Care Works.

The regular sampling site is close to the dam wall (Site 1 in Fig. 2). Depth profiles were done at the surface, 1 m, 2 m, 5 m, 10 m, 15 m, and 20 m with a Van Dorn sampler. These water samples were analysed for chlorophyll *a*, major inorganic chemical constituents and total nutrient concentrations.

The analysis methods are discussed in detail in the test methods manual of the Institute for Water Quality Studies (IWQS, 1998). Algal quantification is done as an estimated percentage of total algal population and not as cell counts. Therefore, it might be prone to the subjectivity of the analyser. In the case of the *C. hirundinella* bloom in the Hartbeespoort Dam this did not pose a significant problem, as the species dominated to such an extent at the dam wall, that the presence of other algal species seemed to be negligible.

Field measurement includes fortnightly *in situ* temperature and oxygen profiles. These measurements were done with an automatic temperature and oxygen meter. Light penetration into the water column was determined by using a Secchi disc.

Results and discussion

The phytoplankton population composition of the water in the Hartbeespoort Dam is discussed in relation to the variables that contribute to phytoplankton growth.

M. aeruginosa dominated the phytoplankton assemblage during the summer to autumn periods (January to April 1998 & 1999) in the Hartbeespoort Dam (Figs. 3a & b). Overturn that took place during April to May (Figs. 6a & b) led to the decrease and disappearance of the *M. aeruginosa* population from the phytoplankton during the winter periods in 1998 and 1999. The chlorophyll *a* concentration during late autumn (May 1999) was below 10 mg/ℓ chlorophyll *a* throughout the water column (Fig. 3c) during both years. However, during 1998 the low concentrations prevailed for much longer periods when compared to 1999. Dense chlorophyll *a* patches were found only to a depth of over 1 m with the *M. aeruginosa* bloom at the beginning of 1999.

During 1998 the July to November algal population was dominated by green algae (*Oocystis and Coelastrum*) (Fig. 3a), while during 1999 the same period was dominated by *C. hirundinella*. The chlorophyll *a* concentrations in the Hartbeespoort Dam (Fig. 3b) show clearly the gradual build-up and eventual extreme bloom conditions of *C. hirundinella* that started in June 1999. A peak of 4243 mg/ℓ chlorophyll *a* on 12 October 1999 was found at a depth

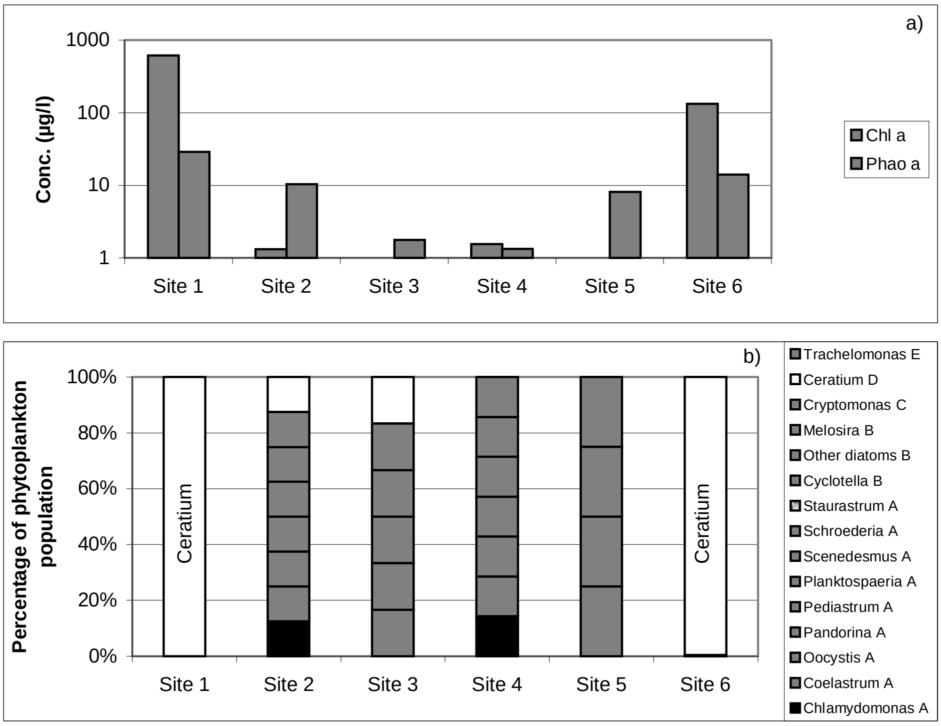

Figure 4
a) The spatial distribution of chlorophyll a and phaophytin a in the Hartbeespoort Dam and the inflowing tributaries on a logarithmic scale. b) The composition of the phytoplankton population at Site 1 (12/10/99) and Sites 2, 3, 4, 5, & 6 (14/10/99) in the Hartbeespoort Dam during the once off sampling survey in October 1999.
A = Chlorophyta;
B = Chrysophyta;
C = Cryptophyta;
D = Phyrrophyta and
E = Euglenophyta.

TABLE 1
The temperature (°C) and dissolved oxygen concentrations (mg/ℓ) at 0 m, 1 m and 2 m depths at the six sampling sites in the Hartbeespoort Dam during the once off sampling survey on 14 October 1999

Site	Temperature (° C)			Dissolved oxygen (mg/ℓ)		
	0 m	1 m	2 m	0 m	1 m	2 m
1	23	21.1	20.6	18.2	8.7	8.1
2	23.3	22.9	21.8	6.2	6.1	5.72
3	21.6	21.3	-	5.95	6.04	-
4	23.9	23.5	22.5	8.27	8.5	7.98
5	24.3	22.1	-	0.47	0.42	-
6	23.6	20.7	19.9	10.65	9.3	5.47

of 0 m (Fig. 3c). This development of the *C. hirundinella* dominance after lake overturn is in contrast with the findings of Heaney (1976), where a decline in *C. hirundinella* population was found after lake overturn, in a northern hemisphere lake.

In the Hartbeespoort Dam the *C. hirundinella* population decreased at the beginning of stratification formation in the impoundment during August. Chlorophyll *a* concentrations of over 100 mg/ℓ were found down to a depth of 10 m with the *C. hirundinella* bloom. This phenomenon confirms the fact that *C. hirundinella* migrates through the water column to utilise nutrients. This characteristic gives this species an advantage over other phytoplankton species.

According to Starmach (1974), the size of the species makes it unacceptable as a food source for most zooplankton species and the indigestibility of *C. hirundinella* even caused major decreases in zooplankton numbers (Buck and Zurek, 1994). No information on the present zooplankton status in the Hartbeespoort Dam is available, and the effect of the zooplankton is not included in this assessment. It is, however, possible that the lack of *C. hirundinella* predators contributed to the bloom conditions in the impoundment.

The algal bloom also seems to have been confined to the main basin of the impoundment. The once-off sampling survey (initiated by a fish kill at Site 5) on 14 October 1999 (Figs. 4a & b) shows clearly that very low chlorophyll *a* concentrations and low numbers of *C. hirundinella* were found in the inflowing streams (Sites 2, 3, 4 & 5). This phenomenon might be explained by the findings of Padisak (1985) who noted low abundance of *C. hirundinella* at sites where the strongest currents are present. The variability of the distribution of phytoplankton (Heaney, 1976; Padisak, 1985) and other water quality determinants in a large impoundment is a phenomenon that poses a problem to researchers. This also highlights the fact that only one sampling site does not represent the overall conditions of what is happening in an impoundment. It does, however, assist in determining variable trends for management purposes close to the water abstraction point.

It is interesting to note that there is quite a variety in the number of species and the species composition within the phytoplankton population at the different sites on the Hartbeespoort Dam (Fig. 4b). No cyanobacteria were present during the bloom of *C. hirundinella*. The phytoplankton in the basin consisted mainly of *C. hirundinella*. At the inflowing sites, Site 5 had the lowest number of species. This phenomenon can be explained by the extent of eutrophic conditions that prevailed at this site during sampling. Major bacteriological activity at Site 5 was identified visually in the algal identification of the once-off samples. This is an indication of the extent of organic decomposition that was taking place at this site. This phenomenon is supported by the extent of oxygen depletion (less than 1 mg/ℓ) at Site 5 (Table 1).

Figure 5a shows clearly that nitrates and nitrites were pesent in higher concentrations throughout the water column during the bloom of *C. hirundinella*, than during the *M. aeruginosa* bloom. However, during June 1998 to January 1999 higher concentrations of nitrates ad nitrites were found throughout the water column, when compared to the same period in 1999. All the other nitrogen species (Figs. 5b & c) were present in relatively low concentrations during the *C. hirundinella* bloom period. The phosphorus concentrations (ortho-phosphorus (PO_4-P) and total phosphorus (TP) were only low during the mixed winter period during 1998 to 1999. The high phosphorus concentrations and the release of phosphorus (up to 339 mg/ℓ PO_4-P and 702 mg/ℓ TP) from the hypolimnetic sediment-water phase during January to April 1999 is evident in Figs. 5d-e. When 1999 is compared to 1998 it is evident that higher concentrations of phosphorus were released from the sediments during 1999 and thus the *C. hirundinella* bloom year (Figs. 5d & e). From the nutrient profiles, it seems to be the availability of dissolved inorganic nitrogen that favours the development of *C. hirundinella*, although the total nitrogen showed the highest correlation with the chlorophyll a concentrations (Table 1). The phosphorus concentrations were lowest during the initial start of the *C. hirundinella* bloom (Fig. 3b and Figs. 5d & e), but cannot be ignored as a contributing factor to the *C. hirundinella* bloom, as much higher concentrations were found in the sediment-water interface during 1999 when compared to 1998.

According to Starmach (1974), Padisak (1985) and Buck and Zurek (1994) *C. hirundinella* is an indicator of clean waters, as it avoids water that is rich in organic compounds. However, according to Rosen (1981), *C. hirundinella* is found in mesotrophic to eutrophic systems and appears in great quantities when water blooms occur. The situation in the Hartbeespoort Dam is hyper-eutrophic with mean TP concentrations higher than 50 mg/ℓ. Phosphorus does seem to be one of the driving forces of the bloom. The ability of *C. hirundinella* to assimilate both organic and inorganic phosphorus might have started the bloom during the period of low PO_4-P concentration. This study supports the findings of Rosen (1981). The correlation coefficients show that during the period of the *C. hirundinella* bloom, the chlorophyll a concentrations correlate positively (Table 2) with total nitrogen (TN) (r^2 = 0.82), dissolved

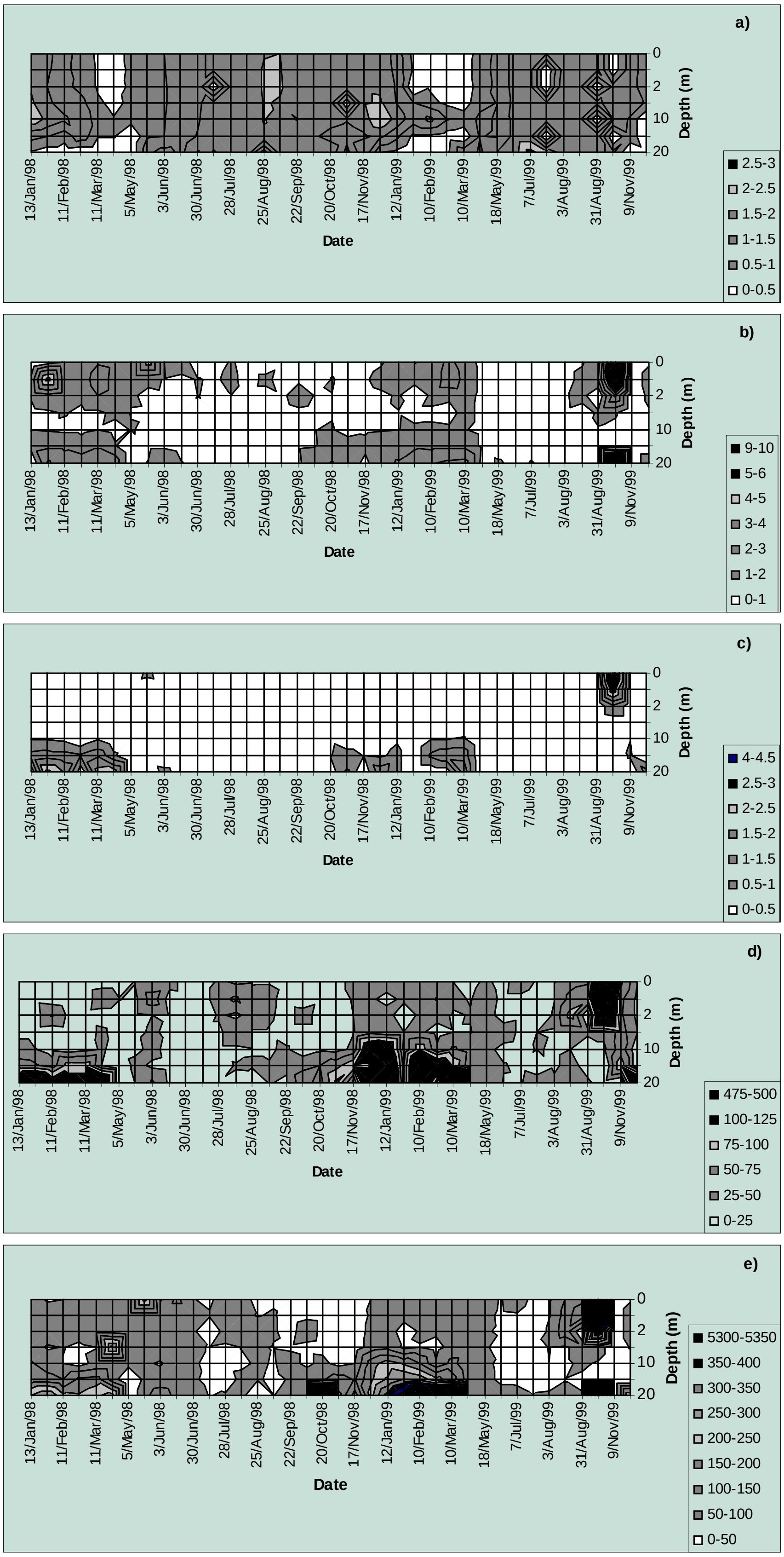

Figure 5

The depth distributrion of nutrient species in the Hartbeespoort Dam. a) The NO_3+NO_2 concentrations (mg/ℓ). b) The KN (Kjeldahl nitrogen) concentrations (mg/ℓ). c) The NH_4-N concentrations (mg/ℓ). d) The PO_4-P concentrations (mg/ℓ) and e) The TP concentrations (mg/ℓ).

TABLE 2
The correlation coefficients of the chlorophyll *a* concentrations and the major nutrient variables (Total nitrogen (TN), dissolved nitrogen (DIN), total phosphorus (TP) and ortho-phosphorus (PO_4-P)) during 1998 (n = 163) and during the *Ceratium hirundinella* bloom (n = 66)

	1998						June 1999 to Dec 1999					
	TN	DIN	TP	PO4	EC	pH	TN	DIN	TP	PO4	EC	pH
Chl a	-0.15	-0.55	-0.02	-0.22	-0.40	0.36	0.82	0.60	0.44	0.76	0.31	-0.39
TN		0.60	0.13	0.09	0.23	0.04		0.45	0.86	0.54	0.73	-0.41
DIN			0.06	0.26	0.49	-0.18			0.12	0.44	0.15	-0.42
TP				0.62	0.21	-0.17				0.29	0.88	-0.33
EC					0.29	-0.19					0.33	-0.38
pH						-0.28						-0.17

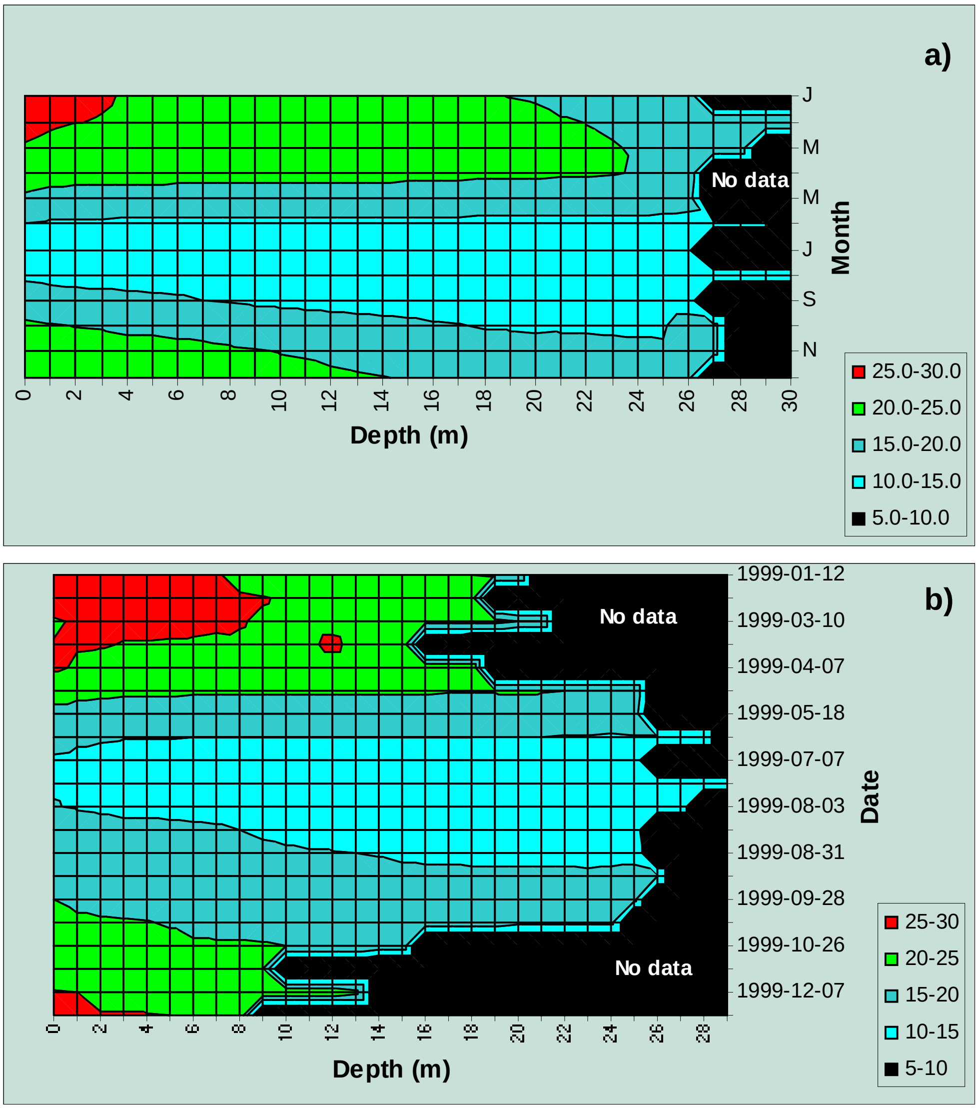

Figure 6
a) The mean monthly thermal gradient (°C) in the water column of the Hartbeespoort Dam at Site 1 (1980 to 1996) and b) the thermal gradient (°C) in the water column of the Hartbeespoort Dam during 1999 at Site 1 near the dam wall.

inorganic nitrogen (NO_3-N + NO_2-N & NH_4-N) (r^2 = 0.60), and ortho-phosphorus (PO_4-P) (r^2 = 0.76). The mean TN:TP concentrations from January to May was 21.8 during the *Microcystis* bloom. During the *C. hirundinella* bloom from July to December the mean TN:TP concentration was 42.7. This shows that during both blooms, phosphorus was the limiting factor, even though higher concentrations were released from the sediments. During 1998 chlorophyll *a* showed a meaningful negative correlation with DIN.

No correlation could be found between the chlorophyll *a* concentration and both electrical conductivity and pH (Table 2) during the previous study year (1998) as well as during the *C. hirundinella* bloom. However, EC showed positive correlations with TN and TP during the bloom period.

During the once-off sampling survey the nutrient concentrations (Table 3) in the inflowing rivers seem to be unacceptably high in the Crocodile River (Site 2) and the Magalies River (Site 5), although it was much less than measured at Site 1 two days previously. Site 5 had less than 36 mg/ℓ PO_4-P compared to the 238 mg/ℓ PO_4-P at Site 2. Yet, Site 5 had all the indications of decomposition of high organic load because NH_4-N concentrations (Table 3) accumulate from the decomposition of organic matter and release NH4-N from sediments under anaerobic conditions (Wetzel, 1983). The oxygen depletion found at Site 5 also indicates the presence of a high organic load and the bacterial activity that was visually detected in the Magalies River inflow (Table 1). The fish kill that was experienced during October in the Hartbeespoort Dam was also confined to this section of the impoundment. This fish kill can be explained by the fact that at high temperatures (Table 1) and at an alkaline pH, most ammonium N is available in the highly toxic form of ammonia.

The thermal gradient in the Hartbeespoort Dam can have temperatures of between 20ºC and 25ºC (Fig. 6a). The thermal gradient in the water of the Hartbeespoort Dam (Fig. 6b) clearly shows the increase in water temperatures from below 15ºC during August to maximum temperatures of higher than 25ºC in February. These high temperatures were present in the system down to a depth of 9 m during February 1999. Compared to previous years (Fig. 6a), the temperatures higher than 25ºC were only found to occur down to 3 m and 4 m. The higher temperatures seem to be an advantage to *Microcystis* for bloom development. The origin of the *C. hirundinella* bloom was found to have started during the cooler to temperate period. The temperatures that were found during the extreme bloom of the *C. hirundinella* were between 15ºC and 25ºC.

The mean monthly dissolved oxygen (DO) concentration profiles (1989 to 1996) in the Hartbeespoort Dam near the dam wall indicate the large anoxic hypolimnia that occurred from a depth of 8 m during January (Fig. 7a). The DO concentration profile that persisted during 1999, showed high concentrations between 10 mg/ℓ and 20 mg/ℓ down to a depth of 4 m. The DO concentration of the water column during the start of the *C. hirundinella* bloom varied from total mixed conditions with high oxygen concentrations (when the species was first found in the impoundment) to extreme hypolimnion formations from a depth of 8 m during December (Fig. 7b). The high chlorophyll *a* concentrations

TABLE 3
The nutrient concentrations [total nitrogen (TN), dissolved inorganic nitrogen (DIN), ammonium (NH_4-N), total phorphorus (TP) and ortho-phosphorus (PO_4-P)], electrical conductivity (EC) and pH values at Sites 2,3,4,5,6 in the Hartbeespoort Dam during the once-off sampling survey on 14 October 1999 and at Site 1 on 12 October 1999

Site	Nitrogen			Phosphorus		EC (mS/m)	pH
	TN (mg/ℓ)	DIN (mg/ℓ)	NH_4-N (mg/ℓ)	TP (mg/ℓ)	PO_4-P (mg/ℓ)		
1	29.05	4.28	<u>4.16</u>	2217	294	58.3	7.8
2	4.72	3.6	0.24	349	238	62.4	8.3
3	2.88	2.15	0.17	98	54	56.0	8.5
4	2.37	1.64	0.12	51	17	53.8	9.2
5	3.26	1.61	<u>1.31</u>	328	38	55.8	8.1
6	2.87	1.51	0.19	123	36	53.0	9.3

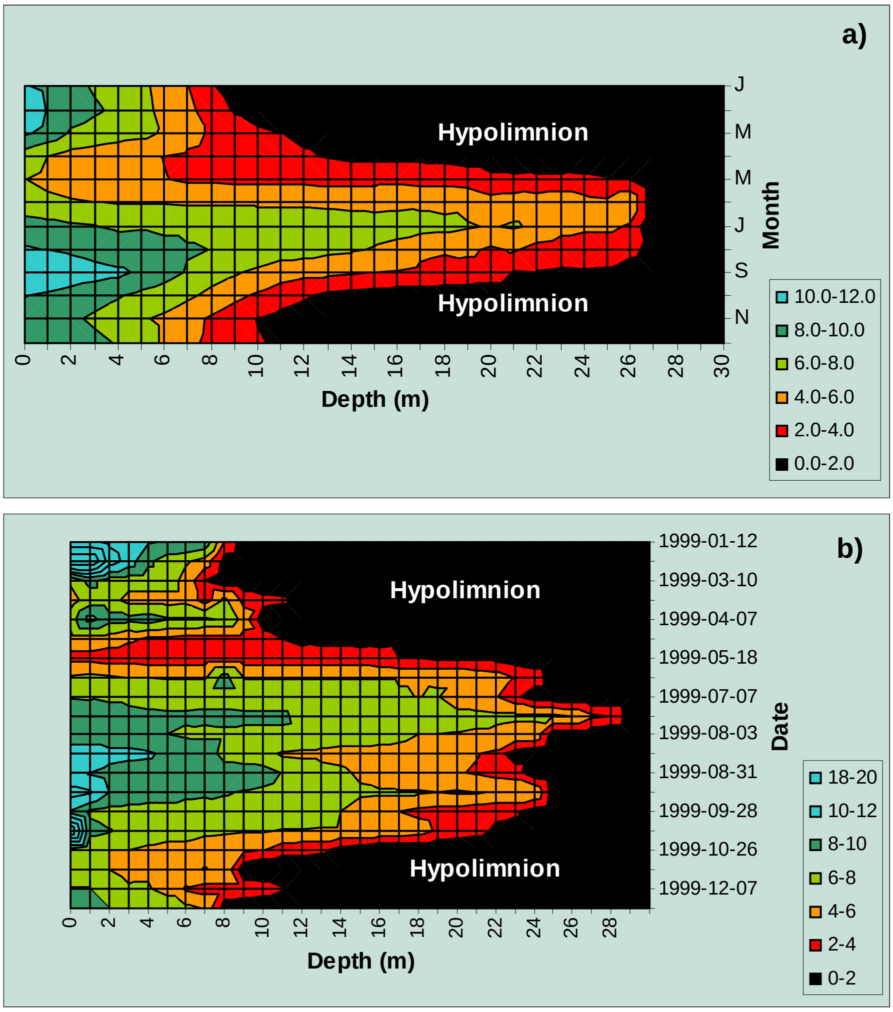

Figure 7
a) The mean monthly oxygen concentration (mg/ℓ) distribution in the water column of the Hartbeespoort Dam (1980 to 1996) and b) the oxygen concentration (mg/ℓ) distribution in the water column of the Hartbeespoort Dam during 1999

were found to a depth of 10 m (Fig. 3), although concentrations of between 10 and 100 mg/ℓ were found at a depth of 20 m. The *C. hirundinella* species, therefore, do occur in the hypolimnetic area in high concentrations. The DO concentrations were much higher in the upper layers of the water column during 1999 when compared to the mean monthly DO concentrations during previous years (Figs. 7a & b).

Conclusions

Impoundments such as the Hartbeespoort Dam are over-enriched and reduces the ecological stability and ecosystem integrity, and contain more than enough nutrients to give rise to massive algal blooms. Penetration of light uniquely determines the depth to which photosynthesis is practical and algae can flourish (Hely-Hutchinson and Schuman, 1997). This is also the case in the Hartbeespoort Dam.

The main conclusions of the study were:

- *C. hirundinella* was found for the first time in the Hartbeespoort Dam and in bloom-forming conditions. This might suggest a significant change in chemical conditions in the impoundment as algae respond rapidly to changes in the ecosystem condition.
- *C. hirundinella* does occur in hyper-eutrophic conditions.
- The chlorophyll *a* concentrations correlate well with the total nitrogen, dissolved inorganic nitrogen and the orthophosphorus concentrations in the impoundment. Thus, the bloom is probably linked to a change in nutrient composition.
- The bloom started in the winter period, peaked during October and persisted until December 1999.
- The *C. hirundinella* bloom started in temperatures of 15°C and peaked at temperatures of between 20°C and 30°C.
- The dissolved oxygen concentration in the upper layers of the impoundment was periodically higher during the year of the *C. hirundinella* bloom than previous years.
- The changes in algal composition need further investigation to determine the effect on the ecology of the system.

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References

ANON (1988a) Phosphate standard now strictly enforced. *SA Waterbulletin* **14** (5) 22. Pretoria.

ANON (1988b) Special phosphate standard for sensitive catchments. *Water Sewage and Effl.* **8** (4) 10-11. Pretoria.

BOUWER D (1999) Personal communication. Hartbeespoort Forum.

BUCK H (1989) Ecology of selected planktonic algae causing water blooms. *Acta Hydrobiol.* **31** 207-258.

BUCK H and ZUREK R (1994) Trophic relations between phyto- and zooplankton in a field experiment in the aspect of the formation and decline of water blooms. *Acta Hydrobiol.* **34** 139-155.

CRANWELL PA (1976) Decomposition of aquatic biota and sediment formation: Organic compounds in detritus resulting from microbial attack on the alga *Ceratium hirundinella*. *Freshwater Biol.* (Oxford England) **6** (1) 41-48.

DWA (1988) Important announcement on implementation of the Special Phosphate standard in sensitive catchments. *IMIESA* (Johannesburg), **13** (9) 35.

FREMPONG E (1984) A seasonal sequence of diel distribution patterns for the planktonic dinoflagellate *Ceratium hirundinella* in a eutrophic lake. *Freshwater Biol.* (Oxford England) **14**(4) 401-421.

HARRIS GP, HEANEY SI and Talling JF (1979) Physiological and environmental constraints in the ecology of the planktonic dinoflagellate *Ceratium hirundinella*. *Freshwater Biol.* (Oxford England) **9** (5) 413-428.

HEANEY SI (1976) Temporal and spatial distribution of the dinoflagellate *Ceratium hirundinella* O.F. Muller within a small productive lake. *Freshwater Biol.* (Oxford England) **6** (6) 531-542.

HEANEY SI and FURNASS TI (1980) Laboratory models of diel vertical migration in the dinoflagellate *Ceratium hirundinella*. *Freshwater Biol.* (Oxford England) **10** (2) 163-170.

HEANEY SI, SMYLY WJ and TALLING JF (1986) Interactions of physical, chemical and biological processes in depth and time within a productive English Lake during summer stratification. *Int. Revue der gesamten Hydrobiol.* (Berlin) **71** (4) 441-494.

HELY-HUTCHINSON JR and SCHUMAN EH (1997) Seasonal and inter-annual variability in the physical properties of Hartbeespoort Dam. *S. Afr. J. Sci.* **93** 283-289.

HUTCHINSON (1957) *A Treatise on Limnology* 3. John Wiley, New York.

IWQS (1998) *Institute for Water Quality Studies: Biological Laboratory Test Methods and SOP Manual.* Revision 1. Institute for Water Quality Studies. Dept. of Water Affairs and Forestry, South Africa.

JAMES WF, TAYLOR WD and BARKO JW (1992) Production and vertical migration of *Ceratium hirundinella* in relation to phosphorus availability in Eau Galle Reservoir, Wisconsin. *Can. J. Fish. Aquat. Sci.* **49**(4) 694-700.

MOORE JW (1981) Seasonal abundance of *Ceratium hirundinella* (O.F. Muller) Schrank in lakes of different trophy. *Arch. Hydrobiol.* (Stuttgart) **92** (4) 535-548.

MUELLERELSER M and SMITH WO (1985) Phased cell division and growth rate of planktonic dinoflagellate, *Ceratium hirundinella,* in relation to environmental variables. *Arch. Hydrobiol.* (Stuttgart) **104** (4) 447-491.

NIWR (1985) *The Limnology of Hartbeespoort Dam*. South African National Scientific Programmes Report No. 110. Pretoria, South Africa.

PADISAK J (1985) Population dynamics of the freshwater dinoflagellate *Ceratium hirundinella* in the largest shallow lake of Central Europe, Lake Balaton, Hungary. *Freshwater Biol.* (Oxford England) **15** (1) 43-52.

REYNOLDS CS (1978) The plankton of the north-west Midland meres. Caradoc and Secern Valley. *Field Club. Occasional Paper* **2** 1-36.

ROSEN G (1981) Phytoplankton indicators and their relations to certain chemical and physical factors. *Limnologica* (Berlin) **13** (2) 263-290.

RYBAK M (1985) Some ecological effects of artificial circulation on the phytoplankton. *Hydrobiol.* (The Hague) **122**(1) 89-96.

SHILLINGLAW SN (1981) *Common Algae Found in South African Impoundments* (revised edn.) RSA Department of Environment Affairs. Technical Report No. TR 106. I 33 pp.

SOMMER U, WEDEMEYER C and LOWSKY B (1984) Comparison of potential growth rates of *Ceratium hirundinella* with observed density changes. *Hydrobiol.* (The Hague) **109** (2) 159-164.

STARMACH K (1974) Cryptophyceae – Kriptofity, Dinophyceae – Dinofity, Raphidophyceae – Rafidofity. *Flora Slodkowodna Poliski. [Freshwater Flora of Poland]* **4**. Warszaa. PWN. 520 pp.

TRUTER E (1987) *An Aid to the Identification of the Dominant and Commonly Occurring Genera of Algae Observed in some South African Impoundments.* RSA Department Of Water Affairs, Technical Report No. TR 135, 1-106

VAN GINKEL CE (1999) Unpublished data. Institute for Water Quality Studies, Department of Water Affairs and Forestry. Pretoria.

WETZEL RG (1983) *Limnology* (2nd edn.). Saunders College Publishing, Philadelphia. USA.