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Article *in* Algological Studies · October 2009

DOI: 10.1127/1864-1318/2009/0130-0081

Algological Studies **130** 81–108 Stuttgart, October 2009

Cyanobacterial diversity and biomass in relation to nutrient regime of four freshwater reservoirs sourced for the production of drinking water in Ghana

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With 7 figures and 1 plate

Abstract: The cyanobacterial diversity, biomass and nutrients (nitrite, nitrate and phosphate) of the Weija, Kpong, Owabi and Barekese reservoirs in Accra and Kumasi Metropolitan Areas of Ghana, were monitored from January to June 2006. The results show that the reservoirs were dominated by nanocyanobacteria not recorded in earlier studies. The Weija reservoir was the most diversified in terms of cyanobacterial species, which was dominated by the nanocyanobacterium *Aphanocapsa nubilum* accompanied by *Merismopedia tenuissima*, *Planktolyngbya minor* and *Pseudanabaena recta*. The Kpong reservoir was dominated by *Geitlerinema unigranulatum*, whilst the Owabi and Barekese reservoirs, both situated in the closed-forest region of Ghana with high rainfall and human activity, were dominated by the nanocyanobacterium *Cyanogranis ferruginea*, new for Ghana and for the whole of tropical Africa. A high and significant correlation was obtained between cyanobacterial abundance and nitrite in the Weija reservoir ($r = 0.99$) as well as phosphate ($r = 0.58$), whilst a negative correlation was obtained between cyanobacterial abundance and nitrate. In the Owabi reservoir, positive correlations were obtained between cyanobacterial abundance and the three nutrients ($r = 0.85, 0.93$ and 0.84, respectively). In the Kpong and Barekese reservoirs, low correlations were obtained between cyanobacterial abundance and the three nutrients. In the Kpong reservoir a high positive correlation was obtained between monthly rainfall and cyanobacterial abundance ($r = 0.83$). Intracellular microcystins have been identified in all four reservoirs.

Key words: biomass, cyanobacteria, diversity, microcystins, nutrients, reservoirs

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DOI: 10.1127/1864-1318/2009/0130-0081 1864-1318/09/0130-081 $ 7.00

Introduction

The occurrence of cyanobacterial blooms in eutrophic lakes, reservoirs and recreational waters has become a worldwide problem. Cyanobacterial blooms often create unsightly surface scums, decrease water column transparency, and lead to unpalatable drinking water and noxious odours (BERNADETTE & JEAN 2003). Cyanobacteria produce potent toxins, which have been implicated in livestock, wildlife as well as human poisoning throughout the world (CODD et al. 1999, CHORUS 2001). These toxins defined by their chemical structure fall into three main groups: cyclic peptides, alkaloids and lipopolysaccharides (SIVONEN & JONES 1999, FALCONER 2004, MCELHINEY & LAWTON 2005, MOLICA et al. 2005, DIETRICH & HOEGER 2005). The reasons for synthesis of toxins by cyanobacteria are not well understood, but it is believed that they represent an adaptation that allows cyanobacteria to diminish the effects of herbivory and of competition with other phototrophs in resource-limited environments (ARNOLD 1971, RICHMAN & DODSON 1983, DEMOTT et al. 1991), bacteria (CHROST 1975, FLORES & WOLK 1986), and fungi (PATTERSON & BOLIS 1997). The toxins produced by cyanobacteria are resistant to boiling and can also pass through conventional water treatments. Due to these reasons, cyanobacteria have been described as the most important freshwater phytoplanktonic organisms from the view point of human health hazards (SIVONEN & JONES 1999). Water quality problems caused by dense populations of cyanobacteria are intricate, many and varied (SKULBERG 1996, FALCONER 2004) and can have great health and socio-economic impacts. The negative impacts of cyanobacteria have gained research attention and public concern. Human health effects caused by cyanobacteria and associated toxins include among others: gastroenteritis, nausea, vomiting, fevers, flu-like symptoms, sore throat, ear and eye irritations, abdominal pains including painful hepatomegaly, visual disturbances, kidney and liver damage (HITZFELD et al. 2000, OBERHOLSTER et al. 2004, CODD et al. 2005) and in some cases they are fatal as reported in Brazil where over 50 dialysis patients died due to exposure to microcystin via haemodialysis (CARMICHAEL 2001, AZEVEDO et al. 2002). Again in Brazil, phytoplankton blooms consisting of 20 % *Microcystis* were reported to be the cause of mass mortality of the fish *Parapimelodus nigribarbis* in the Northern parts of the Patos lagoon in Brazil (JOAO et al. 1998). As a result, the presence of toxic cyanobacterial blooms in water used for the production of drinking water, fisheries and recreational purposes may present a serious health risk for both the human population and wildlife resources (HITZFELD et al. 2000, HOEGER et al. 2004, FALCONER 2004).

ADDICO et al. (2006) reported the dominance of cyanobacteria over green algae and diatoms in two of the four reservoirs studied in Ghana. Blooms of cyanobacteria in Ghana have been associated with influxes of soluble phosphate from irrigation, storm water, industrial discharges, fertilizer application and sewage effluents and natural phosphate sources from catchments of water bodies (BINEY 1990, FREMPONG & ADDICO 2004). The dominance of cyanobacteria in freshwater bodies is a common phenomenon due to increasing eutrophication and warming of surface waters (HOEGER et al. 2004, BOUVY et al. 2006). According to SOMMER (1989), the annual variation of predominant species can be predicted, even though the taxa that dominate the communities will depend upon complex factors such as retention time, nutrient load and grazing pressure. CRONBERG & ANNADOTTER (2006) provided eight different hypotheses for the dominance of cyanobacteria. These are total nitrogen/total phosphorus ratio, low light hypothesis, buoyancy hypothesis, elevated temperature hypothesis, zooplankton grazing hypothesis, trace element hypothesis, storage strategy hypothesis and inorganic nitrogen hypothesis. CODD et al. (2005) recommended a hazard characterization of cyanobacterial cells (biomass) to contribute to the monitoring and control of drinking water reservoirs, which is necessary for the risk management of recreational waters that support cyanobacterial growth.

In this study we monitored the changes in cyanobacterial cells (biomass), diversity and relationship to nutrient concentrations in four freshwater reservoirs sourced for the production of drinking water in Ghana, which are also important as a fishery resource and for recreational activities.

Study Area

The study areas of Weija and Kpong reservoirs have been described in ADDICO et al. (2006). The Barekese and Owabi reservoirs, both situated in the Ashanti Region of Ghana are described below.

Owabi Reservoir

The Owabi reservoir (6° 52' N, 1° 43' W) (Fig. 1) is situated in the Ashanti Region of Ghana. It was constructed in 1928 and resulted in the formation of the reservoir with a surface area of about 7 km^2 (AMAKYE 2002). The reservoir was upgraded in 1954. At present it has the capacity to produce 13.6 x 10^6 gallons of water per day. It lies in the closed forest ecological zone of Ghana (HALL & SWAINE 1981). The Owabi reservoir is fed by seven rivers (Sukobri-Owabi-Pumpuna, Ntikyei, Anyinasu, Nwabi, Bunkunfuo, Lakyeanpon and Asuokuu) all of which flow through the Kumasi Metropolitan area, a very densely populated residential and industrial area.

Barekese Reservoir

The Barekese reservoir (6° 52' N, 1° 42' W) (Fig. 1) is located in the Ashanti Region of Ghana. It was formed in 1970 and covers an area of 16 km^2. Like the Owabi reservoir, the Barekese reservoir also lies in the closed forest

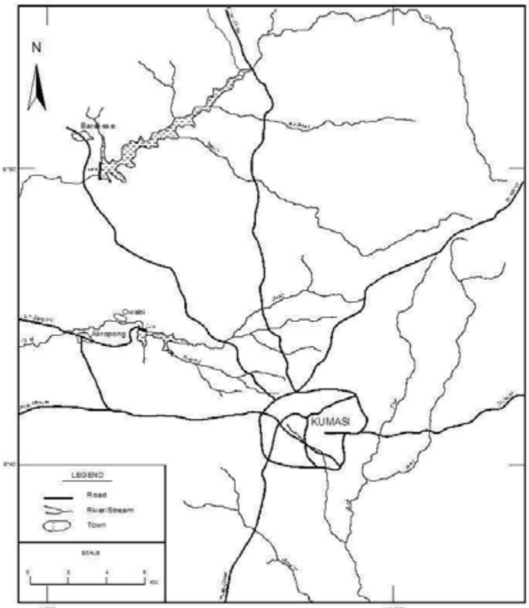

Fig. 1. Map of Owabi and Barekese reservoirs in the Ashanti Region of Ghana and its catchment area.

ecological zone of Ghana and its major tributary is the Offin river system. The basin is mostly occupied by arable lands.

Rainfall within the catchments of the Owabi and Barekese reservoirs is high and ranges between 1,500 and 1,750 mm per annum (HALL & SWAINE 1981). The soils are therefore deeply weathered with very high erosion and soil nutrients mainly derived from decomposition of leaf litter that accumulates on the forest floor. Both reservoirs lie in areas with high intensity of human activities and poultry farms with large industrial estates. Wastewaters from these activities with high nutrient loadings find their way directly into these reservoirs. The water chemistry of the two reservoirs is therefore heavily influenced by these land use activities.

Material and methods

Identification of cyanobacteria

Samples for cyanobacterial species identification and biomass determination were collected from all the four study sites from January to June 2006. Samples were collected with plankton net or by simply filling a bucket directly from the reservoir. Net samples were preserved to a final concentration of 2 % formalin, whilst water samples for quantitative analysis were preserved in Lugol's solution (GUILLARD & SIERACKI 2005). Identification of cyanobacteria was carried out at the Institute of Botany of the Czech Academy of Sciences, Trebon, Czech Republic. Identification of species was done using an Olympus light microscope BX 51. Pictures were taken using an Olympus camera C-5050.

Cyanobacterial biomass determination

Cyanobacterial biomass determination was done by direct counting of cells using an inverted microscope as described by LUND et al. (1958) and LAWTON et al. (1999). Sedimentation of cells was carried out directly in counting chambers with a settling time of 4 hours for every 1 cm of water column of the sample (WETZEL & LIKENS 1990). This method had been described as the most effective way of handling water samples with a mixture of green algae, diatoms and cyanobacteria (FALCONER 2004). All colonies and filaments were counted as individuals, and the average number of cells determined for 20 individuals and cell concentrations was calculated as described by ADDICO et al. (2006).

Picocyanobacteria

Sub-samples for counting picocyanobacteria were preserved in formalin to a final concentration 2 %. A volume of 1 to 2 mL depending on the concentration of the sample was filtered through a 0.2 μm Nucleopore filter prestained with Irgalan black. Dapi (4-diamidino-2-phenylindole dihydrochloride) was used to stain the cells for fluorescence of DNA, as described by PORTER & FEIG (1980) and STOCKNER et al. (2000). The cells were counted in red fluorescence using an Olympus BX60 microscope in the epifluorescence modification under green excitation (510–560 nm) and checked under UV excitation (330-385 nm) for the DNA distribution in the cells. About 300–400 cells were counted for each sample and the counts were converted to picocyanobacterial cells per mL. All data on abundance were expressed in numbers of cells, including the cells inside colonies.

Nutrient analysis

Water samples for nitrite and nitrate analysis were collected into cleaned 1 litre polyethylene bottles and filtered to remove any cellular debris present in the water. Samples were preserved by at –20 °C for nitrite and at 4 °C for nitrate analysis to prevent bacterial conversion of nitrite to nitrate or ammonium.

Nitrite

Nitrite-Nitrogen was determined by the diazotization method (SREEKUMAR et al. 2003) using an Ultraspec 11 Model 80-2091-73 spectrophotometer. The principle behind this method is that nitrite reacts in strongly acid medium with sulphanilamide to form a diazo compound which is coupled with N-(1-naphthyl)-ethylenediamine dihydrochloride to form an intensely red coloured azo compound. The absorbance of the dye is proportional to the concentration (mg L^{-1}) of nitrite present. The spectrophotometer was calibrated prior to analysis (n =6), ($r^2 = 0.99$). Absorbance was measured at 507 and 356 nm, respectively.

Nitrate

Nitrate-Nitrogen was determined by the hydrazine reduction method (APHA 1992). The principle of this method involves the reduction of nitrate to nitrite with hydrazine sulphate. The nitrite ion originally present plus the reduced nitrate ion are determined by diazotization with sulphanilamide coupling with N-(1-naphthyl)-ethylenediamine dihydrochloride to form a highly coloured azo dye which is measured spectrophotometrically. Calibration of the spectrophotometer was done at 6 different concentrations (n =6), ($r^2 = 0.99$).

Phosphate

Phosphate was determined by the stannous chloride method (APHA 1992). Samples for phosphate determination were collected into acid-washed 1 litre polyethylene bottles and preserved at 4 °C. Molybdophosphoric acid is formed and reduced by stannous chloride to intensely coloured molybdenum blue. The absorbance of the molybdenum blue at a wavelength of 690 nm is proportional to the concentrations of the phosphate in the samples. Standard phosphate solutions of known concentrations ranging from 0.1 to 1.0 mg L^{-1} were used to calibrate the spectrophotometer prior to analysis of samples (n =6), ($r^2 = 0.99$).

Rainfall

All rainfall data recorded at 09 GMT (9 am in Ghana) were obtained through the Ghana Meteorological Service for the respective catchments of the four reservoirs.

Results

Weija reservoir

Cyanobacteria in the Weija reservoir showed a high species diversity. A total of twenty-six species were identified belonging to sixteen genera: *Anabaena*, *Anabaenopsis*, *Aphanocapsa*, *Chroococcus*, *Coelomoron*, *Cyanogranis*, *Cylindrospermopsis*, *Geitlerinema*, *Lyngbya*, *Merismopedia*, *Mi-*

crocystis, *Planktolyngbya*, *Planktothrix*, *Pseudanabaena*, *Radiocystis* and *Romeria* (Fig. 2). Two species of *Anabaena* were identified, the straight *A. austro-africana* and the coiled *A. nygaardii,* both new species for Ghana. Two species of *Anabaenopsis, A. tanganyikae* and *A. ambigua*, were identified for the first time in this reservoir. *Aphanocapsa holsatica* and *Aph. nubilum* have been recently identified in the Weija reservoir, but the dominance of *Aph. nubilum* comprising 21.4 % of the total biomass in this study has not been observed before probably due to an improvement of the counting technique. The genus *Chroococcus* is known to be very common in Ghanaian freshwater bodies, but the species *C. cronbergae* is new. *Coelomoron tropicalis* and *Cyanogranis ferruginea* are new species for the Weija reservoir. *Cylindrospermopsis raciborskii* is a very common cyanobacterium species in Ghana as in many African countries. However, the second species of *Cylindrospermopsis* described from large East African lakes, *Cylindrospermopsis cuspis,* is new. *Geitlerinema unigranulatum* is also a new species for this reservoir even though it occurred in negligible amounts. Three species of *Microcystis* were identified: *M. aeruginosa*, *M. wesenbergii* and *M. viridis* (Fig. 2). Out of these three *Microcystis* species, *Microcystis aeruginosa* is commonly occurring in the reservoir. Two species of *Planktothrix* were identified, *P. agardhii* and *P. lacustris* var. *solitaria*, of which the latter is a new species in Ghana and so is *Romeria elegans*. Generally, there were no marked differences in species diversity throughout the study.

Aphanocapsa nubilum was the dominant species occurring together with *Merismopedia tenuissima*, *Planktolyngbya minor* and *Pseudanabaena recta* (Fig. 2). *Aph. nubilum* dominated the cyanobacterial population throughout the sampling period with a highest abundance of 26,882 cells mL^{-1} in April after the highest rainfall recorded in March (Fig. 3). *Cylindrospermopsis raciborskii,* though low in biomass as compared to *Aph. nubilum,* was consistently present with the highest abundance of 5,050 cells mL^{-1} also obtained in April (Fig. 2). *Planktothrix agardhii*, a well-known toxin producing cyanobacterium, was also present throughout the sampling period as well as *Planktothrix lacustris* var. *solitaria*. Positive and significant correlations were obtained between nitrite, phosphate and total monthly cyanobacterial abundance ($r = 0.99, 0.58$, respectively), but this correlation was negative for nitrate ($r = -0.43$). Similarly, positive correlations were obtained between total monthly rainfall and nitrite and phosphate concentrations ($r = 0.13, 0.72$, respectively) but they were negative with nitrate ($r = -0.54$). Out of the twenty-six species of cyanobacteria identified in the Weija reservoir during the study, twenty (76.9 %) are non-nitrogen fixing cyanobacteria. Figure 2 shows that for most part of the study period nitrate and phosphate concentrations were high. Figure 4 is a summary of the mean nutrient concentrations in the four reservoirs with the Weija reservoir having an average nitrate and phosphate concentration of about 0.05 and 0.04 mg L^{-1}, respectively. Out of the sixteen cyanobacterial genera

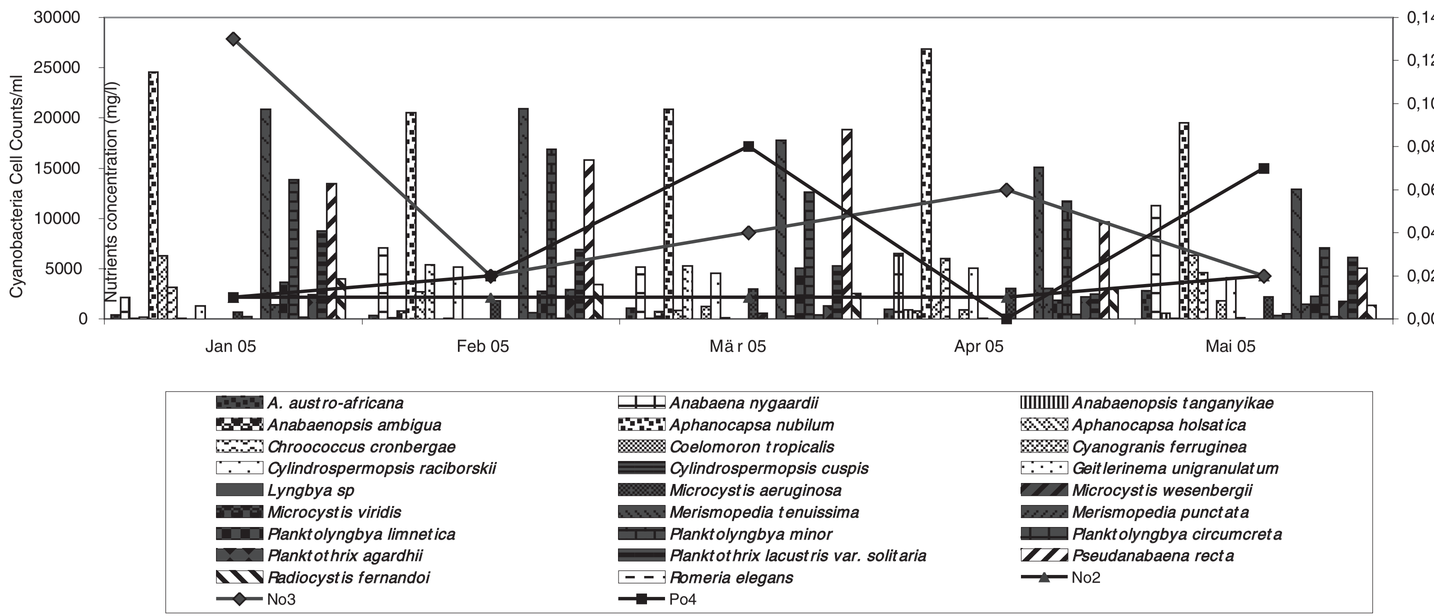

Fig. 2. Changes in cyanobacteria composition, density and nutrient concentrations in the Weija reservoir, Accra, Ghana from January to May 2005.

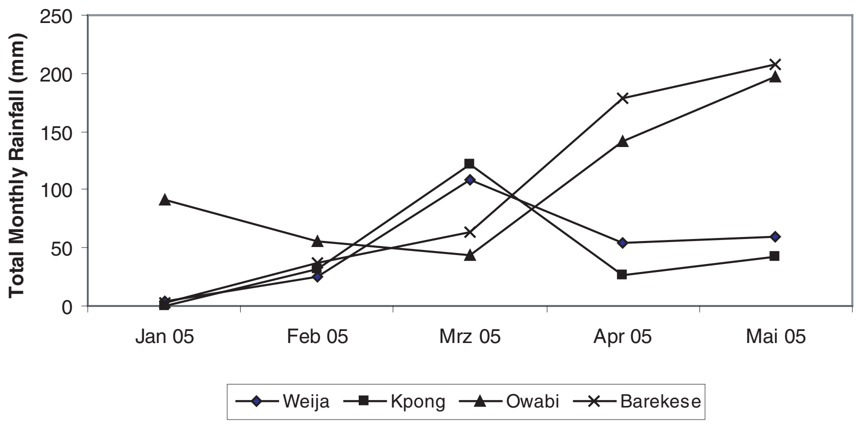

Fig. 3. Changes in total monthly rainfall (mm) in all the four catchments of the reservoir studied measured at 9 am GMT from January to June 2005.

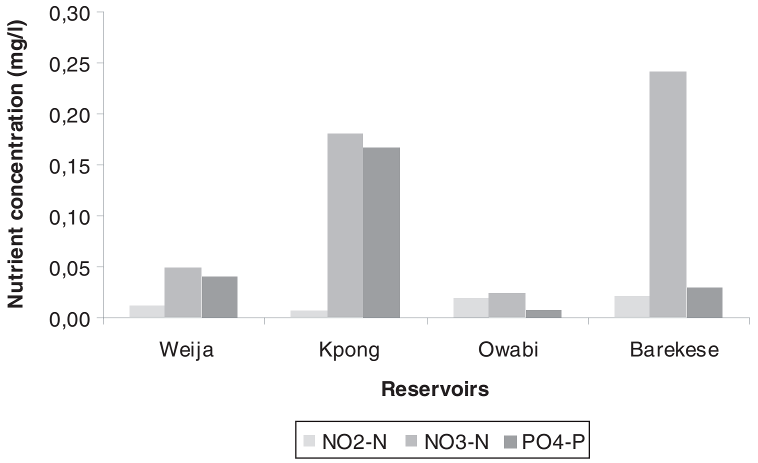

Fig. 4. Changes in nitrite, nitrate and phosphate concentrations in the Weija reservoir in Accra, Ghana.

identified in the Weija reservoir, eleven are confirmed toxin producers, producing microcystins and neurotoxins. These are *Anabaena*, *Anabaenopsis*, *Aphanocapsa*, *Cyanogranis*, *Cylindrospermopsis*, *Geitlerinema*, *Lyngbya*, *Microcystis*, *Planktothrix*, *Pseudanabaena* and *Radiocystis*.

Kpong reservoir

The Kpong reservoir, even though higher in nitrate and phosphate concentrations (Fig. 5) as compared to the Weija reservoir, does not support

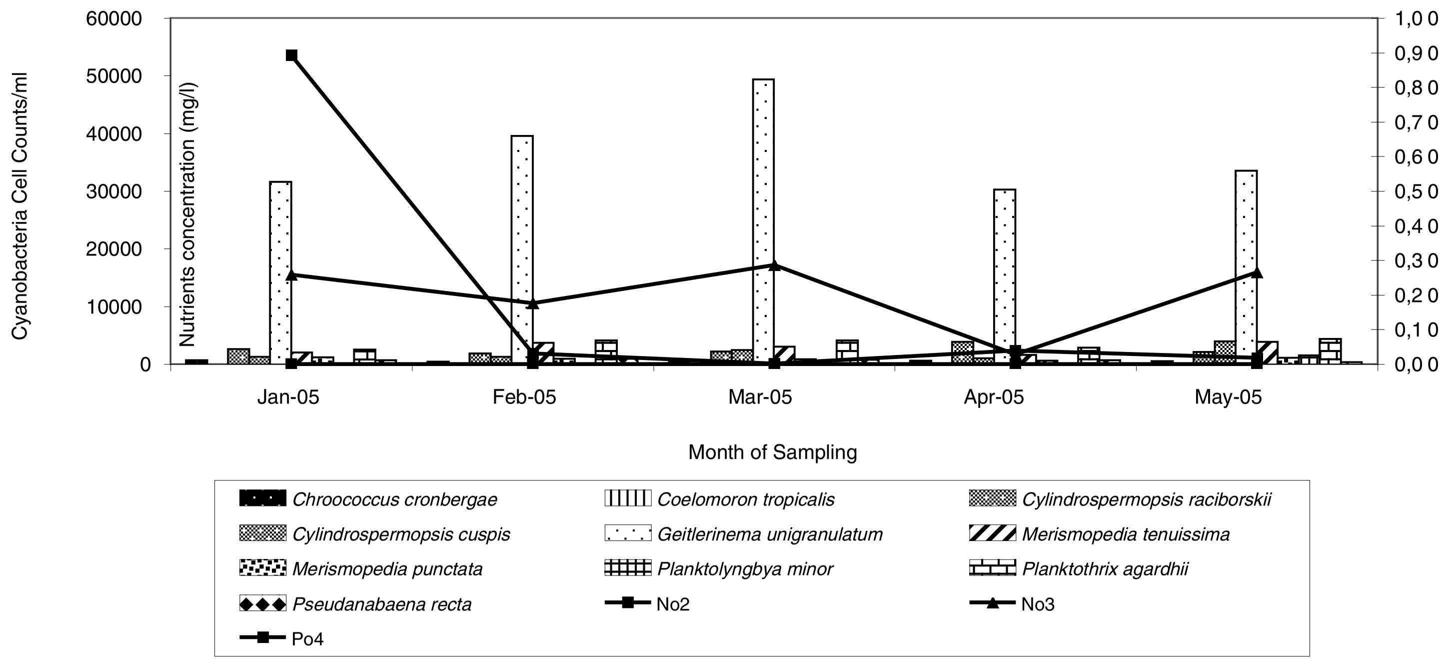

Fig. 5. Changes in cyanobacteria composition, density and nutrient concentrations in the Kpong Reservoir, Accra, Ghana from January to May 2005

a high phytoplankton diversity. The Kpong reservoir has mean nitrate and nitrate concentrations of 0.18 and 0.17 mg L^{-1}, respectively as compared to the Weija reservoir, which had mean concentrations of 0.05 and 0.04 mg L^{-1} for nitrate and nitrate, respectively. Eight genera of cyanobacteria were identified in this reservoir during the current study. A total of ten species were identified of which *Geitlerinema unigranulatum* had an overwhelming dominance, making over 68 % of the total biomass (Fig. 5) with a maximum cell concentration of over 49,000 in March when the highest nitrate concentration of 0.29 mg L^{-1} was obtained (Fig. 5), which also coincided with the lowest phosphate concentration of 0.001 mg L^{-1} (Fig. 5). The highest rainfall within this catchment was also obtained in March (Fig. 3). As a reservoir sourced for the production of drinking water, the cyanobacteria of highest concern are *Cylindrospermopsis* as well as *Planktothrix agardhii,* both known producers of cyanotoxins. Two species of *Cylindrospermopsis* were identified in the Kpong reservoir. *Cylindrospermopsis raciborskii* and *C. cuspis* were both present in appreciable numbers and so was *Planktothrix agardhii* (Fig. 5). The dominant cyanobacterium, *Geitlerinema unigranulatum,* has recently been identified to produce toxins. Positive correlations were obtained between total monthly cyanobacterial abundance and nitrite and nitrate ($r = 0.37, 0.63$, respectively), but this correlation was negative for phosphate ($r = –0.48$). The same trends were obtained between total monthly rainfall and nitrite and nitrate ($r = 0.06, 0.38$, respectively) as well as phosphate ($r = -0.57$). However, a high positive correlation was obtained between total monthly rainfall and total monthly cyanobacterial abundance ($r = 0.83$).

Barekese and Owabi reservoirs

The Barekese and Owabi reservoirs both situated in the Ashanti region, ecologically described as the closed-forest zone of Ghana, were both dominated by the cyanobacterium *Cyanogranis ferruginea*, identified for the first time in Ghana. The Owabi reservoir could be described as a monospecific population of *C. ferruginea* (Fig. 6). *C. ferruginea* comprised indeed over 96 % of the total biomass. Nutrient concentrations were very low in this reservoir (Fig. 4). Average nutrient concentrations obtained in this reservoir during the study period were 0.02 mg L^{-1} for nitrite and nitrate and 0.01 mg L^{-1} for phosphate (Fig. 4). The highes nutrient concentrations of all the three nutrients were obtained during May (Fig. 6) when the highest rainfall of 197.6 mm was recorded (Fig. 3). This resulted in a positive correlation between total monthly rainfall and nitrite, nitrate and phosphate in the Owabi reservoir ($r = 0.79, 0.65, 0.66$, respectively). Also very high positive correlations were obtained between total cyanobacteria abundance and nutrients ($r = 0.85, 0.93, 0.84$) for nitrite, nitrate and phosphate, respectively. In addition, a positive correlation was obtained between total monthly rainfall and total monthly cyanobacterial abundance ($r = 0.47$).

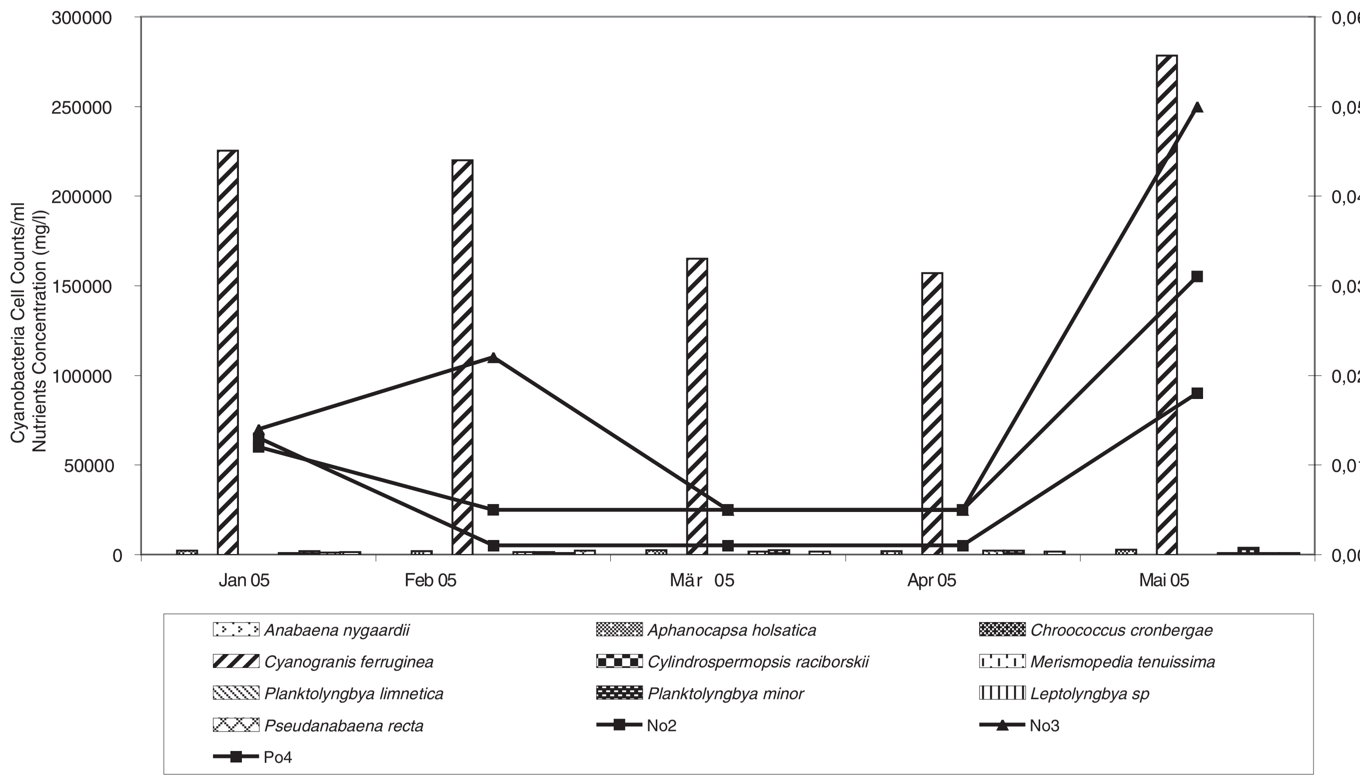

Fig. 6. Changes in cyanobacteria composition, density and nutrient concentrations in the Owabi reservoir, Accra, Ghana from January to May 2005.

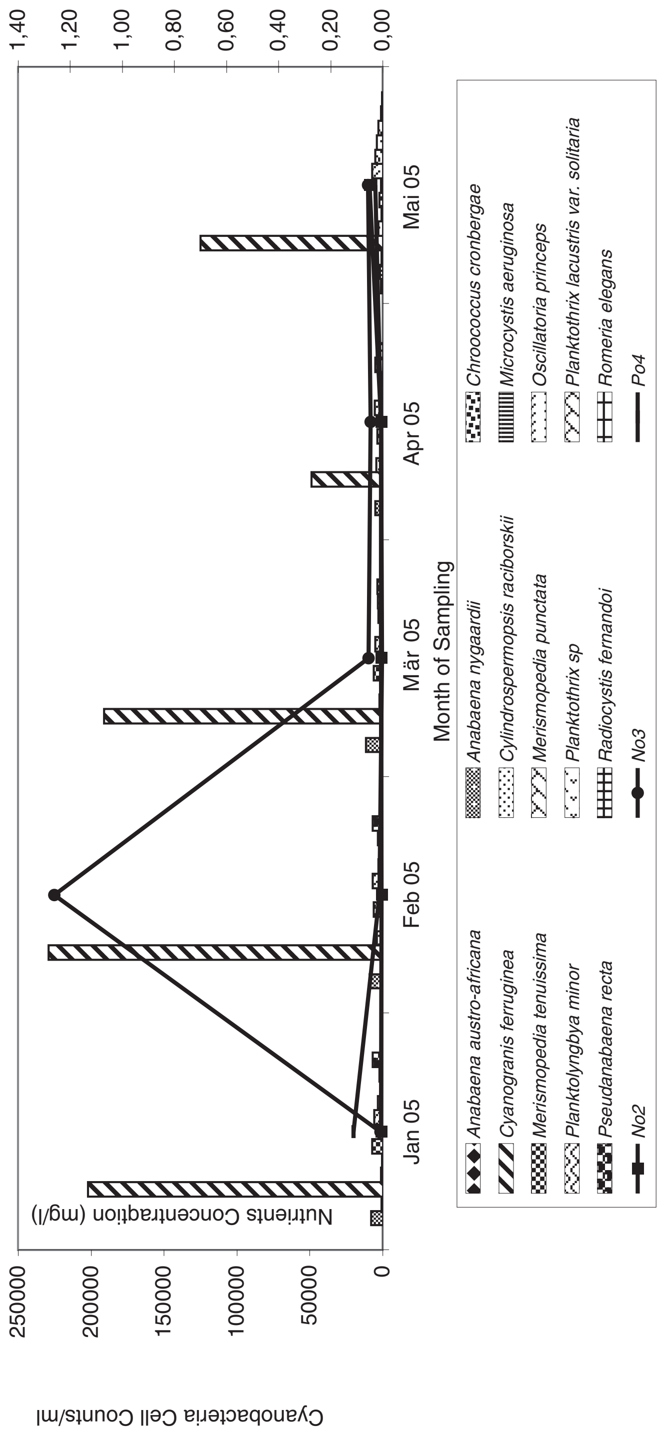

Fig. 7. Changes in cyanobacteria composition, density and nutrient concentrations in the Barekese Reservoir, Accra, Ghana from January to May 2005.

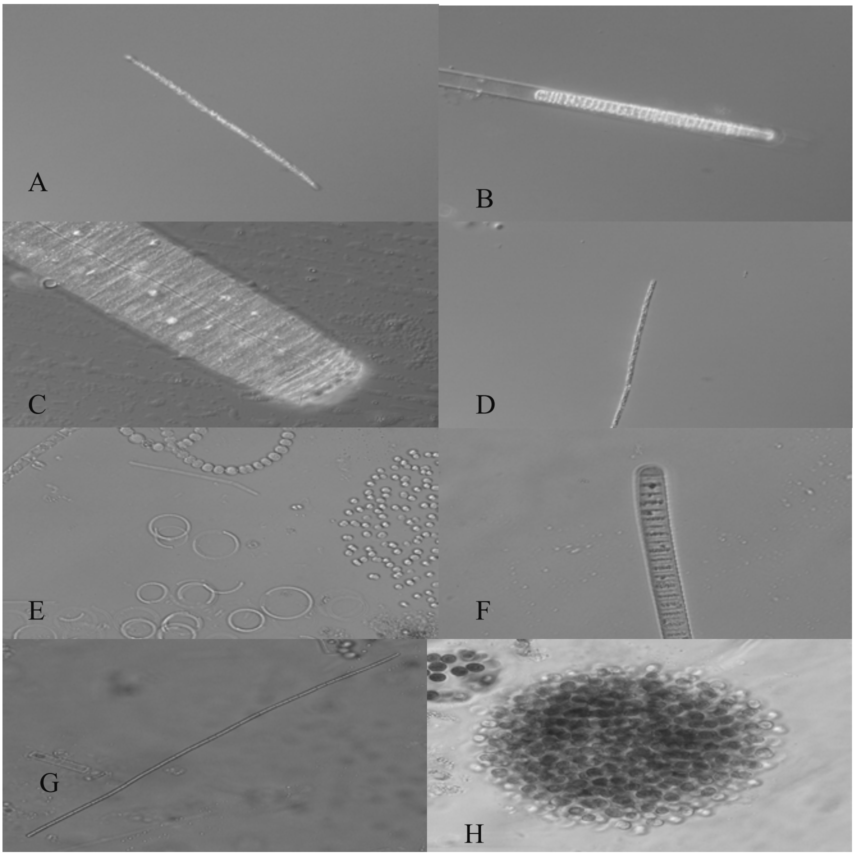

Plate 1. Light micrographs of representative cyanobacteria. **A** – *Cylindrospermopsis raciborskii*, **B** – *Lyngbya* sp., **C** – *Oscillatoria princeps*, **D** – *Planktothrix* cf. *suspensa*, **E** – Mixture of cyanobacteria (*Planktolyngbya circumcreta*, *Anabaena* sp. and *Microcystis* sp.), **F** – *Oscillatoria miniata*, **G** – *Planktolyngbya limnetica,* **H** – *Radiocystis fernandoi.*

The Barekese reservoir was also dominated by *Cyanogranis ferruginea* (Fig. 7). Even though both reservoirs lie in the same ecological zone, their nutrient concentrations varied greatly, in terms of nitrate and phosphates (Fig. 4). The only similarity between the two reservoirs was that of nitrite, with both reservoirs having an average nitrite concentration of 0.02 mg L^{-1} (Fig. 4). The differences in phosphate and nitrate concentrations in the Owabi and Barekese reservoirs may be due to differences in land use practices within their catchments. While total cyanobacteria cell abundance was positively correlated to nitrite in the Owabi reservoir it was negatively correlated in the Barekese reservoir (r = – 0.30). However, both nitrate and phosphate concentrations were positively correlated with total cyanobacterial abundance (r = 0.54, 0.29) in the Barekese reservoir as in the Owabi reservoir. This may have accounted for the dominance of *Cyanogranis ferruginea* in both reservoirs. The highest nitrate concentration recorded in the Barekese reservoir (over 1.2 mg L^{-1}) in February (Fig. 11) coincided with the beginning of the rainy season, which also coincided with the highest biomass of *C. ferruginea*. The Barekese reservoir was also more diversified than the Owabi reservoir, but the Owabi reservoir had a higher biomass of the dominant cyanobacterium *C. ferruginea*. The toxicity of *Cyanogranis ferruginea* has not been established, but microcystins have been recently identified in both the Owabi and Barekese reservoirs. Microscopic pictures of most of the cyanobacterial species discussed in the results section can be seen in Plate 1.

Discussion

The Weija and Kpong reservoirs have been well studied since their construction in 1977 and 1981, respectively with regard to their physical and chemical properties, due to their importance in the socio-economic well-being of the people of Accra, the capital city of Ghana (Amuzu 1970, Dassah & Abban 1979, Kpekata & Biney 1979, Vanderpuye 1982, Biney 1985, 1987, 1990, Gyimah-Amoako 1989, Antwi & Ofori-Danson 1993, Ameka et al. 2000, Ansa-Asare & Asante 2005). Most of these studies focused on the physico-chemical properties, fish fauna and the macrophytes of these two reservoirs, with some of the authors looking at chlorophyll-*a* as an estimate of phytoplankton biomass and the primary productivity. Addico et al. (2006) studied the phytoplankton composition in the Weija and Kpong reservoirs, focusing on the cyanobacteria and their effects on drinking water quality. The Weija and Kpong reservoirs are the only sources of potable piped drinking water supply in the capital city of Accra. The rapid increase in the population of Accra due to urbanization and industrialization has led to an increased demand for water for domestic, agricultural and commercial uses. This situation has led to an increased pressure on the already over-exploited resources of the Weija reservoir. The south-western parts of Accra, which depends on the Weija reservoir for its drinking water supply, are constantly in short of drinking water as a result of algal developments which results in delays in water treatment as the filters are constantly been clogged. The cost of drinking water production in the Weija reservoir has significantly increased as compared to that of the Kpong reservoir. Addico et al. (2006) showed that cyanobacteria represent 70 to 90 % of the total phytoplankton biomass in both reservoirs. The present study is focusing on the diversity and biomass of the cyanobacteria in the four reservoirs sourced for the production of drinking water. The Weija and Kpong reservoirs are typical tropical waters with a mean temperature range of 29.3–31.0 °C and 28.9–30.8 °C, respectively (Ameka et al. 2000)

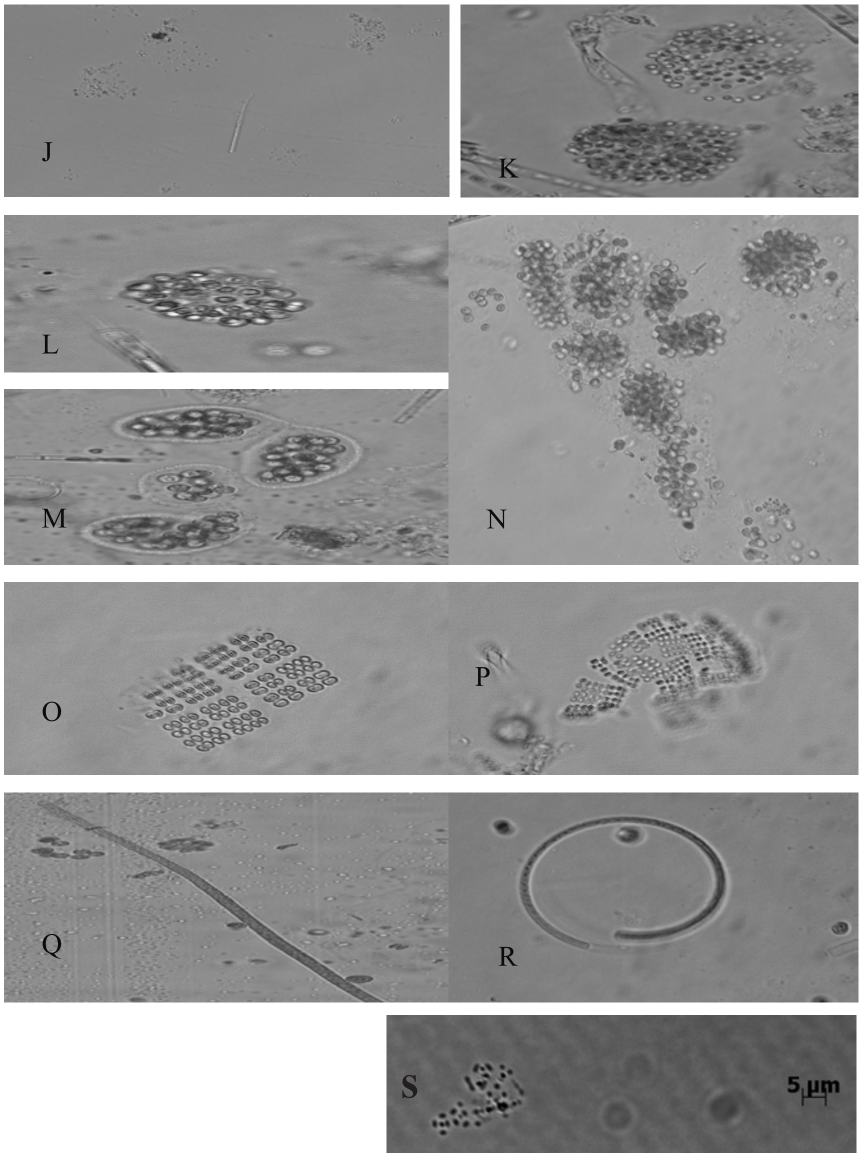

Plate 1 continued. **J** – *Pseudanabaena recta*, **K** – *Aphanothece nubilum*, **L –** *Coelomoron* sp., **M** – *Microcystis wesenbergii*, **N** – *Microsystis* sp., **O –** *Merismopedia punctata*, **P** – *Merismopedia tenuissima*, **Q** – *Planktothrix* sp., **R** – *Planktolyngbya circumcreta,* **S** – *Cyanogranis ferruginea.*

and with a near-neutral to neutral pH, ranging from 7.0 to 7.6. The Weija reservoir has been reported to be saturated with oxygen with mean oxygen saturation ranging from 85 to 90 %, which was attributed to high phytoplankton photosynthesis. The Weija reservoir is mostly turbid with a mean transparency of 59.1 cm (AMEKA et al. 2000), attributed to a high amount of suspended matter including phytoplankton (AMEKA et al. 2000) and silt contained in discharges of domestic effluents and run-off from agricultural lands within the catchment. On the contrary, the Kpong reservoir is clear with a Secchi disc reading of 180 cm (BINEY 1985). The Weija reservoir had been described as eutrophic (ANSA-ASARE & ASANTE 2005). Most of the cyanobacteria identified in this reservoir are known to thrive in eutrophic waters (KOMÁREK 2003, CRONBERG & KOMÁREK 2004, SANT'ANNA et al. 2004, KOMÁREK 2005, BOUVY et al. 2000, 2006). *Aphanocapsa* cf. *nubilum*, the dominant species in the Weija reservoir commonly occurs in the plankton of lakes, ponds and artificial reservoirs, with a cosmopolitan distribution (SANT'ANNA et al. 2004). There is no literature regarding the toxicity of this particular species but another species of *Aphanocapsa*, *Aphanocapsa incerta* described in subtropical Brazil has been described as potentially toxic (SANT'ANNA et al. 2004). *Aphanocapsa nubilum* with a cell diameter of 1.2-2 µm can be described as nanocyanobacterium. Small-coiled, colonial nanoplankton is typically not scum forming. They have been described as small unicellular simple cyanobacteria of cell size between 0.2 and 2 µm (BLAHA & MARŠÁLEK 1999, LUUC et al. 1999) and by CRONBERG & ANNADOTTER (2006) as ranging from 1–4 µm.

As a reservoir sourced for the production of drinking water the presence of potentially toxic nanocyanobacteria in such high biomass is a health risk. BLAHA & MARŠÁLEK (1999) remarked that the presence of small sized cyanobacteria producing microcystin is an important information for drinking water treatment, since they can leak through filter systems more easily than scum-forming genera like *Anabaena*, *Microcystis* and *Aphanizomenon*. Their results of *in vitro* toxicity testing based on the picocyanobacteria *Cyanobium rubescens* and *Synechococcus nidulans* showed that low molecular weight picocyanobacterial products can cause several adverse effects on mammal cell models. They also found *in vitro* cytotoxic, hepatotoxic and immunotoxic activities. BLAHA & MARŠÁLEK (1999) observed slight immunotoxic effects targeted especially on T-lymphocytes, proving the production of antimitogenic compounds in picocyanobacterial strains. ADDICO et al. (2006) measured six different microcystin peaks at the intake of this reservoir, with a total toxin concentration of 3.21 µg L^{-1}, as well as microcystin-RR in the Kpong reservoir. The dominant cyanobacterium in the Kpong reservoir, *Geitlerinema unigranulatum* with thin trichomes of about 0.8–2 µm in diameter, has been recently identified as a toxin producer (AZEVEDO pers. comm.); this taxon is commonly found in eutrophic freshwater reservoirs in tropical regions (KOMÁREK & AZEVEDO 2000). Other toxin-producing cyanobacteria found in the Kpong reservoir are *Planktothrix agardhii,* producing both hepatotoxins and neurotoxin (KRISHNAMURTHY et al. 1986, MERILUOTO et al. 1989, SIVONEN & JONES

1999, Chorus 2001, Laub et al. 2002, Falconer 2004) and *Cylindrospermopsis raciborskii*, which produces the toxin cylindrospermopsin (Sivonen & Jones 1999, Falconer 2004). This cyanobacterium was present in all the four reservoirs studied and was present through out the sampling period. In Australia, this cyanobacterium was first recognized as a result of substantial human poisoning episode through a bloom in a drinking water supply reservoir (Byth 1980, Bourke et al. 1983, Hawkins & Runneger 1985). *C. raciborskii* is a pervasive and a cosmopolitan species which is commonly found in Ghana as well as in other African countries (Ganf 1974, Komárek & Kling 1991, Cogels et al. 2001, Cronberg & Komárek 2004, Addico et al. 2006, Dufour et al. 2006, Bouvy et al. 2000, 2006). *C. raciborskii* is very toxic with a wide range of toxins (Humpage et al. 1994, Sivonen & Jones 1999, Falconer 2004, Cronberg & Komárek 2004) and can cause significant changes in the phytoplankton composition (Bouvy et al. 2001, Leonard & Paerl 2005). In addition, the ability of *C. raciborskii* to grow well below the water surface close to water intake points makes it a high-risk cyanobacterium to public health through drinking water (Fabbro 1999, Falconer 2004). Falconer (2004) reported three phylogeographical groups of *Cylindrospermopsis raciborskii*, with strains isolated from the USA and Australia producing only cylindrospermopsin, those from Brazil producing either saxitoxins and/or cylindrospermopsin, and the third group from Europe producing an unknown neurotoxin. One of the reasons attributed for the proliferation of *C. raciborskii* is its ability to compete well for nutrients. Even though the Weija reservoir had much lower nutrient concentrations than the Kpong reservoir, the Weija reservoir had higher cyanobacterial densities in general and of *C. raciborskii* than the Kpong reservoir. *C. raciborskii* takes advantage of its ability to assimilate ammonium and phosphate at low nutrient concentrations (Presing et al. 1996, Istvanovics et al. 2002, Briand et al. 2002) and also has the ability to fix atmospheric nitrogen using its terminal heterocytes (Padisak 1997). In addition it can migrate to deeper and more nutrient-rich layers through buoyancy changes (Branco & Senna 1994). These same reasons can be attributed to the high cyanobacteria diversity of the Weija reservoir as compared to the Kpong reservoir. Both the Kpong and the Weija reservoirs had low ratios of nitrogen to phosphorus (1.32 and 1.10, respectively), implying nitrogen limitation in these reservoirs. Also Meybeck et al. (1989) reported that in waters with a N/P ratio lower than 7, nitrogen will be limiting. Falconer (2004) also reported in general, the higher the ratio towards nitrogen excess, the more likely diatoms or green algae will dominate, while the lower the ratio the more likely that cyanobacteria will dominate. Bouvy et al. (2006) reported that in Lake Guiers, in spite of low nutrient concentrations during their study, the cyanobacterial community, especially *Cylindrospermopsis raciborskii*, exhibited high abundances and biovolumes similar to our results and also to those observed in other tropical ecosystems (Bouvy et al. 1999, Lung'ayia et al. 2000). Flushing and dilution of the reservoir waters by the Volta Lake which discharges into the Kpong reservoir as well as the resident time of the Kpong water reservoir may also be the cause of low cyanobacterial diversity in this reservoir. The mean annual water flow through the Kpong reservoir is 1,183 m^3 s^{-1} as compared to 54.2 m^3 s^{-1} for the Weija reservoir (Antwi & Ofori-Danson 1993). In addition, the high macrophyte cover of the Kpong reservoir, which may be in competition for nutrients and light input with phytoplankton, could also be responsible for the low diversity and biomass of cyanobacteria in the Kpong reservoir. It has been reported that about 20–25 % of the reservoir surface is covered by aquatic macrophytes (Gyimah-Amoako 1989, Antwi & Ofori-Danson 1993). Falconer (2004) reported *C. raciborskii* occurring in a mixed population with *Aphanizomenon*, *Aphanocapsa*, *Limnothrix* and *Planktolyngbya* in the Fitzroy River in Australia as in Ghana. *C. raciborskii* grows to bloom proportions only in water with temperature above 25 °C (Padisak 1997), most water bodies in Ghana have mean water temperatures higher than this and this makes our reservoirs ecologically favourable for this cyanobacterium. The second species of *Cylindrospermopsis*, *C. cuspis,* identified in these reservoirs is hardly mentioned in literature probably because it is not a commonly occurring species. The positive correlation obtained between nitrite and phosphate and rainfall and also with total monthly cyanobacteria abundance may imply that whilst nitrite and phosphate were largely controlled by land based sources via runoff from the catchment during rainfall, nitrate on the other hand may originate from other sources (probably through nutrient cycling from the sediment and decomposition of organic matter). The catchment of the Weija reservoir is a densely populated area with high human activities, both domestic and commercial horticulture and crop farming. The highest biomass of *Aphanocapsa nubilum* obtained in April may be induced to high nutrients as this period coincides with the main ploughing season in the Weija catchment when most fertilizer is applied to the land. Biney (1983) reported that ammonia in the presence of high oxygen is readily oxidized through nitrite to nitrate. The Weija reservoir as mentioned earlier is very saturated with oxygen. Again Biney (1990) reported that, while phosphorus may be introduced as a result of domestic and industrial activities, high levels of ammonium-nitrogen in these waters may be a result of nitrogen fixation by cyanobacteria.

69 % of the cyanobacterial genera in the Weija reservoir are potentially toxic as compared to 25 % for the Kpong reservoir. These are *Anabaena* (Krishnamurthy et al. 1986, Watanabe et al. 1989, Sivonen & Jones 1999), *Anabaenopsis* (Sivonen & Jones 1999), *Aphanocapsa* (Domingos et al. 1999, Oudra et al. 2002, Sant'Anna et al. 2004, Pavlova et al. 2006), *Cyanogranis* (Komárek pers. comm.), *Cylindrospermopsis* (Sivonen & Jones 1999, Senogles-Derham et al. 2003, Viera et al. 2003, Falconer 2004), *Geitlerinema* (Azevedo pers. comm.), *Lyngbya* (Sivonen & Jones

1999), *Microcystis* (BOTES et al. 1984, SIVONEN & JONES 1999, SANT'ANNA et al. 2004), *Planktothrix* (MERILUOTO et al. 1989, SIVONEN & JONES 1999, LUUKKAINEN et al. 1993), *Pseudanabaena* (OUDRA et al. 2002) and *Radiocystis* (VIERA et al. 2003, LOMBARDO et al. 2006). This situation presents a high risk to human health through exposure to microcystins and cylindrospermopsin through drinking water. Drinking water treatment facilities in Ghana are very basic (ADDICO et al. 2006) and incapable of completely removing cells from the water.

Eutrophication has been reported as the most important factor accounting for the growing incidence of cyanobacterial blooms of which approximately 50 % are known to be toxic in rivers, lakes and reservoirs (NATIONAL RIVERS AUTHORITY 1990). Nitrate and phosphate concentrations were very high in the Kpong reservoir. Mean nutrient concentrations obtained for the reservoir in this study were 0.17, 0.18 and 0.01 mg L^{-1} for phosphate, nitrate and nitrite, respectively. Previous studies on this reservoir obtained similar results for phosphate and nitrite (0.15 and 0.01 mg L^{-1}, respectively) (ANTWI & OFORI-DANSON 1993). It is obvious that over the past decade nitrate concentration have increased drastically in the Kpong reservoir. The construction of the Kpong reservoir opened opportunities for large-scale irrigation in the Kpong catchment, with increased use of nitrate fertilizer and this may have resulted in the current high nitrate concentration in the reservoir. WHITEHEAD & LACK (1982) reported that the increasing use of artificial fertilizers on farmLands, especially in developing countries, has resulted in increasing concentrations of nitrates in aquatic systems.

The Owabi and Barekese reservoirs both situated in the Ashanti region, ecologically described as the closed-forest zone of Ghana, were both dominated by the cyanobacterium *Cyanogranis ferruginea,* a species identified for the first time in Ghana. *C. ferruginea* has up to now only been identified in European temperate waters. It is the first case of development of this species in a tropical country. The phytoplankton of the Owabi reservoir can be described as a monospecific assemblage of *C. ferruginea*, the dominant cyanobacterium comprising over 96 % of the total biomass. Even though both the Owabi and Barekese reservoirs lie in the same ecological zone, the nutrient concentrations varied greatly, in terms of nitrate. Both reservoirs had the same mean nitrite concentration of 0.02 mg L^{-1}. The differences in the mean nitrate concentration in the Owabi (0.02 mg L^{-1}) and Barekese (0.24 mg L^{-1}) reservoirs may be attributed to differences in land use practices within their immediate catchments. The Barekese reservoir is located in a heavy agricultural (crop farming) area of the Ashanti region and could be receiving nutrients inputs from these activities while the Owabi reservoir is in the part of the Kumasi metropolis which is mainly built up with residential facilities and well protected by a heavily forested Ramsar site, which could have silted off some of the nitrates in runoff before reaching the reservoir. There appears to be very little information on the ecology or toxicity of *C. ferruginea*, the dominant cyanobacterium in both the Owabi and Barekese reservoirs. However, according to KOMÁREK (pers. comm.) this cyanobacterium is potentially toxic. PELECHATA et al. (2006) reported the dominance of *C. ferruginea* in the Oczko Lake with a N/P ratio of 3 close to the N/P ratio of 4 obtained for the Owabi reservoir where it composed over 96 % of the cyanobacterial biomass. SZELAG-WASIELEWSKA (2004) also observed *C. ferruginea* and *Aphanocapsa nubilum* dominating the cyanobacterial population in the polluted eutrophic Warta River in Western Poland exposed to human activities such as agriculture and urban and industrial activities, a similar situation to that of the Owabi and Barekese reservoirs. Intracellular and dissolved toxins have been recently identified in both the Owabi and Barekese reservoirs (ADDICO et al., unpublished data). Even though the Barekese reservoir has some known toxin-producing cyanobacteria, the overwhelming dominance of *C. ferruginea* (over 96 %) points to the fact that *C. ferruginea* may be producing microcystins.

Conclusion

This paper discusses fifteen cyanobacterial species identified for the first time in drinking water reservoirs in Ghana: *Anabaena austro-africana*, *Anabaena nygaardii*, *Aphanocapsa nubilum*, *Aphanocapsa holsatica*, *Chroococcus cronbergae*, *Coelomoron tropicalis*, *Cyanogranis ferruginea*, *Cylindrospermopsis cuspis*, *Geitlerinema unigranulatum*, *Microcystis wesenbergii*, *Microcystis viridis*, *Planktothrix lacustris* var. *solitaria*, *Romeria elgans*, *Leptolyngbya* sp. and *Oscillatoria princeps* (hormogonia and solitary filaments). *Cyanogranis ferruginea* is reported for the first time in tropical waters. Many of these species were recently described from tropical freshwater plankton (African large lakes and reservoirs in Brazil). Their occurrence in Ghana proves their common and wider distribution in eutrophized tropical reservoirs. In conclusion, the presence and dominance of small-sized nanocyanobacteria in the Weija, Barekese and the Owabi reservoirs, all with basic conventional water treatment facilities known to be ineffective in removing neither cyanobacteria nor their toxins, present a high risk to human health through exposure to cyanotoxins such as microcystins and cylindrospermopsin. The situation of the Owabi reservoir with low nutrient levels as compared to the Barekese reservoir, both situated in the same region, emphasizes the importance of protecting water catchments.

Acknowledgements

The authors acknowledge the Government of Ghana for providing funds for this study. We also like to thank Dr. JAROSLAVA KOMÁRKOVÁ of the Hydrobiological Institute, České Budějovice, Czech Republic, for allowing the first author to use facilities of the Institute for cyanobacteria analysis. The same appreciations are extended to staff of the Institute, especially ELISKA, PETER and JITKA for their help and hospitality while the first author was in the Czech Republic. The first author (GA) also acknowledges the support of the Council for Scientific and Industrial Research (CSIR) and the CSIR-Water Research Institute, Accra, Ghana. GA's gratitude goes to Mr FELIX AKPABEY, DOREEN OFOSU and staff of the chemistry division of the CSIR Water Research Institute for help with sample collection and analysis. RALF BUBLIZ and KERSTIN HANISCH, all of the Chemical ecology and sensory laboratory of the Biological Science Department of the University of Hull, Hull, United Kingdom are also mentioned here with gratitude. GA also wants to mention Professor EMMANUEL FREMPONG of the Kwame Nkrumah University of Science and Technology, Kumasi, Ghana for his constant encouragement. Finally, GA wants to thank the members of the Ghana Government scholarship committee for their support and encouragement. We also gratefully acknowledge Prof. PAVEL BABICA of Masaryk University, Brno, Czech Republic for assistance with toxicological analysis.

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Manuscript received September 10, 2007, accepted December 11, 2008.

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