Diurnal variations in the Vaal, a turbid South African river: Physical, chemical and phytoplankton biomass characteristics

AJH Pieterse* and JC Roos
Department of Botany and Genetics, University of the Orange Free State, PO Box 339, Bloemfontein 9300, South Africa

Abstract

Diurnal changes in physical, chemical and phytoplankton biomass (chlorophyll *a* concentration) characteristics, the extremes between which they fluctuate, as well as interrelationships between them, were investigated during September 1988 in the Vaal River at Venterskroon. At a discharge of about 14 $m^3 \cdot s^{-1}$ (resulting in a velocity of about 20 $cm \cdot s^{-1}$ or about 700 $m \cdot h^{-1}$) vertical mixing was not intensive enough to result in complete mixing of the water column. Diurnal cycles in underwater irradiance (light intensity, ranging between 0 and about 2 000 $\mu E \cdot m^{-2} \cdot s^{-1}$ at the surface), temperature (ranging between 18,9 and 20,2°C at the surface), concentrations of oxygen (ranging between 8 and 12 $mg \cdot \ell^{-1}$ at the surface and 12 and 6,8 $mg \cdot \ell^{-1}$ at the bottom), NH_4-N (ranging between about 5 and 45 $\mu g \cdot \ell^{-1}$), NO_3-N (ranging between about 300 and 1 300 $\mu g \cdot \ell^{-1}$), PO_4-P (ranging between about 100 and 180 $\mu g \cdot \ell^{-1}$) as well as N/P ratios (ranging between about 2 and 10) were demonstrated. The importance of these cycles was considered in relation to published information which indicated that phytoplankton species have diurnal periodicities of nutrient uptake and could therefore utilise the same nutrient flux in different ways. The pH cycle followed that of oxygen which, in turn, is primarily the result of oxygen and carbon dioxide production and consumption processes.

Introduction

Rivers and streams are characterised by a continual downstream movement of dissolved substances and suspended materials (Hynes, 1970), resulting in dynamic interactions between components of the ecosystem. Although unidirectional flow in rivers can be expected to result in vertical and horizontal mixing, Pieterse et al. (1986) and Pieterse and Roos (1987a) demonstrated cross-channel and vertical heterogeneity in environmental variables and algal biomass in the Vaal River. In other studies Pieterse (1986; 1987; 1989), Pieterse and Roos (1987b) and Pieterse and Van Zyl (1988) illustrated seasonal variation in these parameters. Short-term or diurnal changes had, therefore, not been studied in the Vaal River before.

The existence of diurnal oxygen changes in the aquatic environment has been known since the early 1900s (Hall and Moll, 1975). The phenomenon of diurnal oxygen changes has more recently been used to investigate aspects of community metabolism in streams (amongst others by Odum, 1957; Hall, 1972; and Fisher and Likens, 1973). In the present study changes in physical and chemical variables as well as in algal biomass of the Vaal River at Venterskroon were investigated over a 29-h period to determine the ranges between which these variables vary and to evaluate functional aspects of the river ecosystem. Physical, chemical and chlorophyll *a* aspects are considered here, while aspects of primary productivity and community metabolism will be considered by Roos and Pieterse (in press).

Sampling site and methods

The sampling site was situated in the Middle Vaal River Region at Venterskroon approximately 100 km SE from Johannesburg on the Rooderand small holding (Fig. 1). The width of the river at the sampling site was 62 m on 28 September 1988, and the average depth was 1,14 m (Fig. 2). The cross-sectional area was 73 m^2.

Water samples for chlorophyll *a* ($\mu g \cdot \ell^{-1}$; method described by Sartory, 1982) and chemical analyses were taken with a Van Dorn sampler at the surface and at 1,5 m at the position of maximum depth (1,75 m; Fig. 2). Environmental variables were measured at the same position. The investigation commenced at 05:00 on 29 September and lasted for 29 h.

Discharge (flow rate; $m^3 \cdot s^{-1}$) was measured every 2 to 3 h according to the method described by Wetzel and Likens (1979). Secchi disc transparency (in dm; measured approximately every hour during the daylight period), turbidity (NTU), pH and conductivity ($mS \cdot m^{-1}$) measurements (last 3 measured approximately every 2 h), were made on samples from 0,0 and 1,5 m depths using standard equipment. Standard equipment was also used to measure dissolved oxygen concentration (membrane electrode method; $mg \cdot \ell^{-1}$), temperature (°C) and above- and underwater irradiance or light intensity (total scalar; $\mu E \cdot m^{-2} \cdot s^{-1}$) approximately every 1 h at 0,1 m depth intervals for irradiance and at 0,25 m depth intervals for oxygen and temperature. In addition, at 13:00 on 29 September penetration of blue (478 nm) and red (673 nm) light was measured. Underwater irradiance values were used to calculate extinction coefficients ($\eta \cdot m^{-1}$) and the depth of the euphotic zone (Z_{eu}; m) using the equation given by Wetzel (1983).

Alkalinity (mg $CaCO_3 \cdot \ell^{-1}$), inorganic carbon (mg $C \cdot \ell^{-1}$), NO_3-N, NH_4-N and PO_4-P ($\mu g \cdot \ell^{-1}$) concentrations were determined on water, sampled approximately every 2 h at 0,0 and 1,5 m depths, by using methods described in Standard Methods (1985).

Results

A relatively slow morning increase in irradiance occurred in the surface layers (Fig. 3) between approximately 06:00 and 10:00 (on the 29th and 30th), while the afternoon decline was more rapid between 15:00 and 17:30 (on the 29th). Higher underwater light intensities were, therefore, illustrated for the midday and afternoon than for the morning period.

Secchi disc (ranging between 4,7 and 6,0 dm) and euphotic zone (Z_{eu}; 1,3 to 1,7 m) depths as well as extinction coefficients (2,4 to 3,3 $\eta \cdot m^{-1}$) were variable and changed markedly between

*To whom all correspondence should be addressed.
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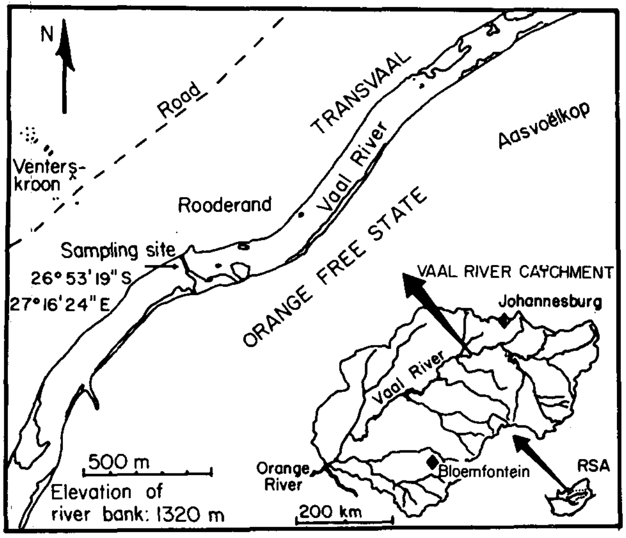

Figure 1
Location of the sample site in the middle Vaal River region at Rooderand near Venterskroon

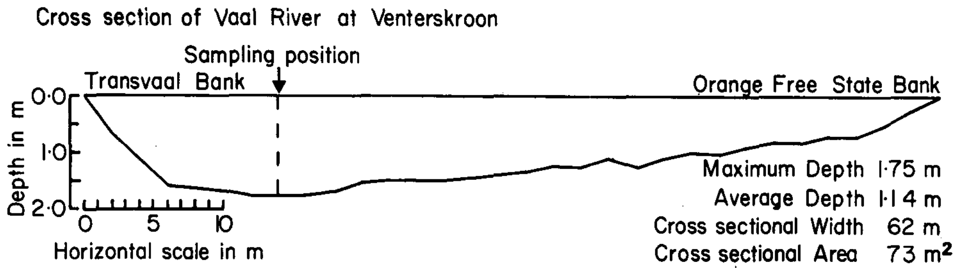

Figure 2
Cross-channel section of the Vaal River at Rooderand indicating the position where all measurements were made and where all samples were taken for analysis on 29 and 30 September 1988

06:00 and 10:00 on each day (Fig. 4A). The surface water was, as could be expected, slightly less turbid than the bottom water (Fig. 4A). Turbidity (as NTU) was lower between 14:00 and 20:00 on the 29th. Blue light was available in the upper 1,3 m of the water column (Fig. 4B), while red light penetrated to the bottom and was predominant at levels below 1,3 m. This observation is supported by others (see Wetzel, 1983) which showed that red light penetrates turbid waters to a greater degree than other components of the light spectrum.

Depth profiles of extinction coefficients (calculated for successive 0,1 m layers) for total, red and blue light at 13:00 on the 29th (Fig. 4B) showed higher values and more intensive variation with depth in the upper 0,1 to 0,8 m of the water column. This observation indicates vertical heterogeneity in suspended material in support of a similar observation made by Pieterse et al. (1986). On the basis of extinction coefficient figures given by Wetzel (1983), the Vaal River can be considered a highly turbid system.

The vertical (spatial) heterogeneity shown in Fig. 4B at 13:00 and repeated temporally as illustrated in Fig. 5, strongly indicates the occurrence of suspended material in distinct patches in the water column after approximately 10:00 on the 29th and after 06:00 on the 30th.

Discharge (Fig. 6) varied around 14,5 $m^3.s^{-1}$ (velocity about 20 $cm.s^{-1}$) between the 29th and the 30th. At a velocity of about 20 $cm.s^{-1}$ and with a depth of 1,7 m, the Vaal River at the sampling site resembled a pool situation with a sandy bottom (compare Ryke, 1978; Wetzel and Likens, 1979). At an average discharge of 14,5 $m^3.s^{-1}$, the average velocity amounted to about 710 $m.h^{-1}$, resulting in a stretch of water 20,6 km long passing through the sampling point during the 29-h period of investigation.

Atmospheric temperature (Fig. 6) varied between 14 and 30°C (at 05:00 and 13:00 respectively) and water temperature (Figs. 6 and 7) between 20,2 and 18,8°C (15:00 to 21:00 and 04:00 to 08:00 respectively). Surface water temperature was higher than that of the bottom between 11:00 and 16:00, and lower between 24:00 and 06:00 (Figs. 6 and 7), during which times the water was respectively warmed (primarily by the atmosphere and solar irradiance) and cooled (primarily by heat loss to the atmosphere). The water temperature increased at a higher rate between 08:00 and 16:00 than it decreased between 21:00 and 08:00, which indicates that processes responsible for heat gain are more prevalent than those for heat loss. This was expected for the spring/early summer season.

Conductivity, alkalinity and inorganic carbon values (Fig. 8) were relatively constant for the entire study period except for the period between approximately 14:00 and 18:00 when all three variables reached low values. Surfaces and bottom water pH values (Fig. 8A) were generally slightly lower during the dark than during the light period, more or less in accordance with the temperature (Figs. 6 and 7) and irradiance in the surface waters (Fig. 3). Values for pH were slightly higher during the daylight and early evening hours (approximately 10:00 to 19:00) in the surface than in the bottom waters (Fig. 8A), most probably

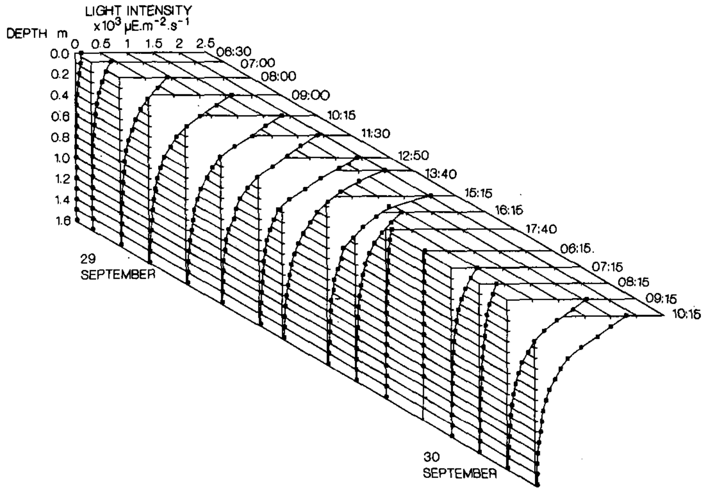

Figure 3
Depth profiles of underwater irradiance in $\mu E.m^{-1}\cdot s^{-1}$

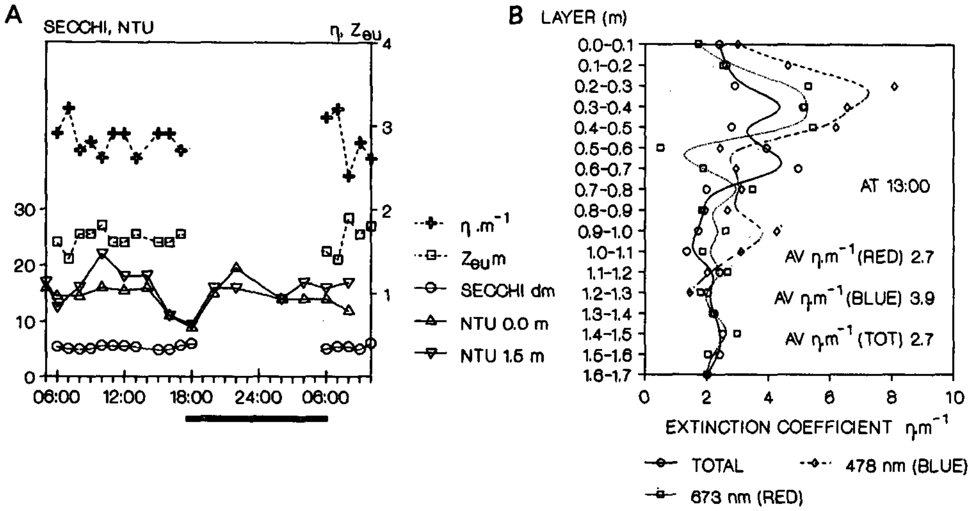

Figure 4
A: Secchi disc depth in dm, euphotic zone (Z_{eu}) depth in m, extinction coefficient in η·m⁻¹, and turbidity in NUT.
B: Extinction coefficient of red, blue and total light in η·m⁻¹ for successive 10 cm layers of the water column

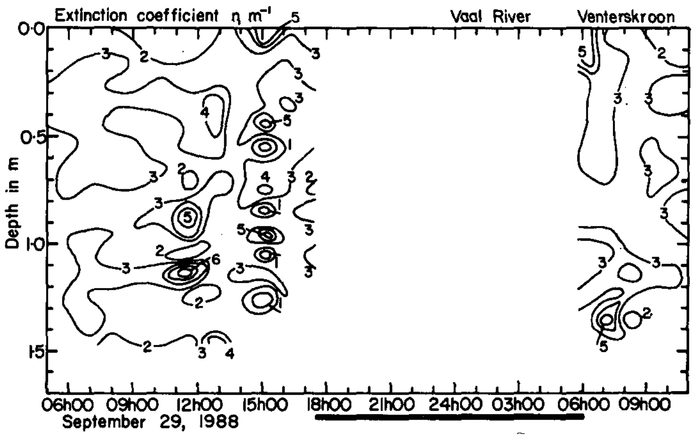

Figure 5
Isopleth diagram of extinction coefficient values in η·m⁻¹ for successive 10 cm layers

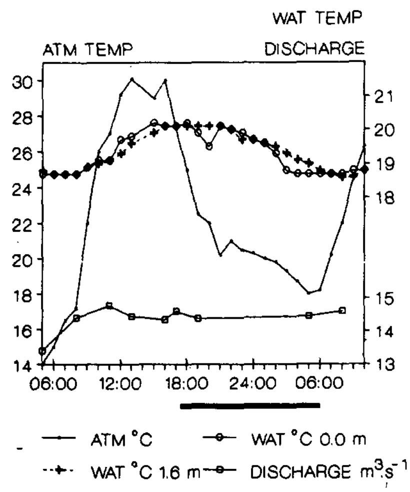

Figure 6
River discharge in $m^{2}\cdot s^{-1}$ and atmospheric, surface and bottom water temperature in °C

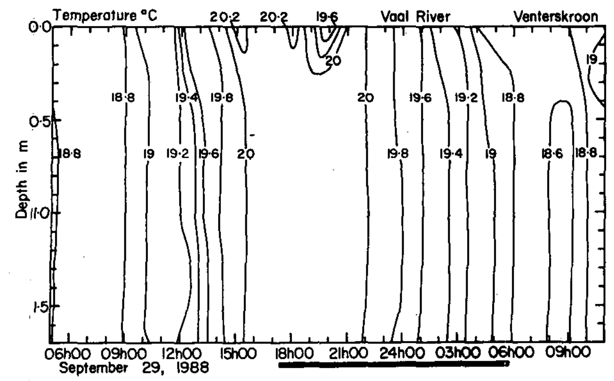

Figure 7
Isopleth diagram of temperature in °C

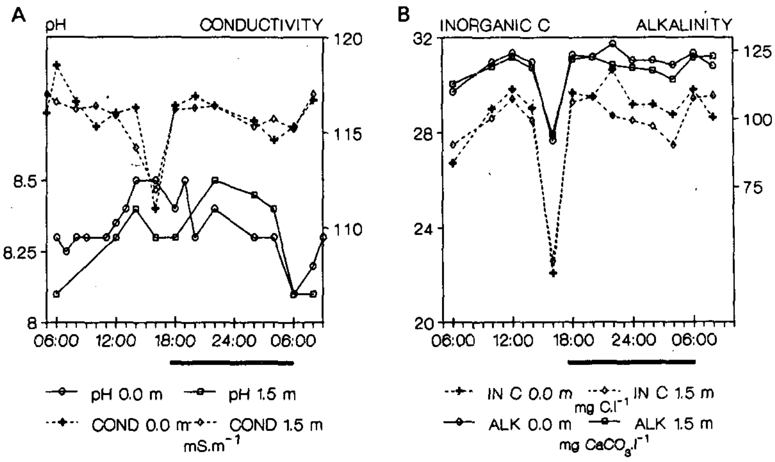

Figure 8
A: Hydrogen ion concentration (pH), and conductivity in mS·m⁻¹
B: Alkalinity in mg $CaCO_3$·ℓ^{-1} and inorganic carbon concentration in mg C·ℓ^{-1}

because of CO_2 uptake by photosynthesis (Wetzel, 1983; Golterman, 1975). This conclusion is confirmed in Fig. 11 which shows that the oxygen concentration in the surface waters is higher during this period. The lower pH values in the surface waters during the night hours (Fig. 8A; 20:00 to 06:00) probably indicate replenishment of CO_2 from the atmosphere and by respiration, resulting in the decrease in the pH of the entire water column after 05:00 on the 30th. Increase in pH between 18:00 and 22:00 in the surface water cannot be explained with the available data.

Highest oxygen concentrations (12 mg.ℓ^{-1}; 156% saturated) were reached at approximately 16:00 and lowest concentrations (7,2 mg.ℓ^{-1}; 91% saturated) between approximately 06:00 and 08:00 (Figs. 9 and 11). Figure 11 clearly shows a more rapid increase in oxygen concentration between 09:00 and 16:00 than the decrease between 16:00 and 06:00, an aspect that was also shown by atmospheric and water temperatures (Fig. 6). The decrease in oxygen concentration is primarily due to oxygen consumption by respiration in the water column (Roos and Pieterse, in press). The highest rate of oxygen increase (from 8,2 to 10,3 mg.ℓ^{-1}) occurred between 11:30 and 13:30 (Figs. 9 and 11), a period corresponding with that (14:00 to 20:00) during which conductivity, alkalinity, inorganic carbon (Fig. 8) and turbidity (Fig. 4A) values were lower.

The NH_4-N concentrations increased during the day and decreased after 16:00 on the 29th (Fig. 10A). The bottom waters had higher concentrations which possibly indicate a supply of NH_4-N as a result of decomposition of organic material carried along the bottom of the river. NO_3-N concentrations (Fig. 10A) showed peaks at approximately 8:00 and 22:00 on the 29th for the water column as a whole. Low NO_3-N concentrations were reached at midday on the 29th and at 08:00 on the 30th. PO_4-P concentrations (Fig. 10B) on the 29th generally increased between 06:00 and 12:00, after which a general decrease was demonstrated, reaching relatively low concentrations at 06:00 on the 30th.

N/P ratios (Fig. 10B) showed a similar pattern to those of NO_3-N concentrations (Fig. 10A) and varied between 2 and 10. Such ratios indicate nitrogen limitation (Dokulil, 1984; Saad and Antoine, 1978) and support a previous conclusion by Pieterse

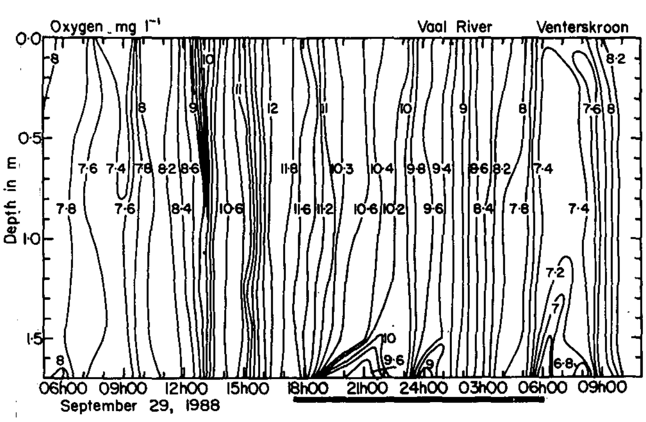

Figure 9
Isopleth diagram of dissolved oxygen in mg·ℓ^{-1}

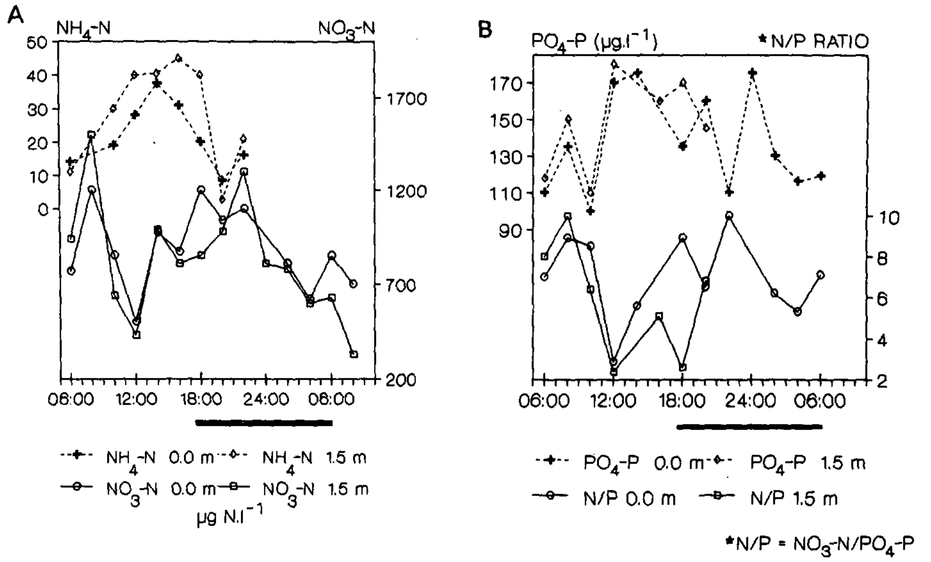

Figure 10
Ammonia (NH_4-N), nitrate (NO_3-N) (A), and phosphate (PO4-P) concentrations in μg·ℓ⁻¹ as well as N/P ratios (B)

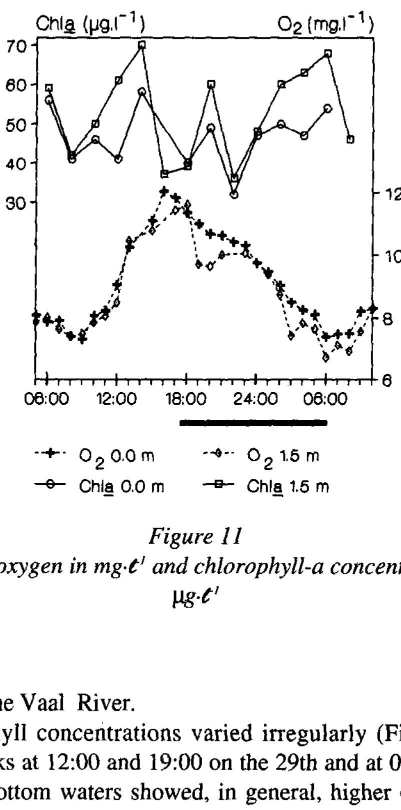

Figure 11
Dissolved oxygen in mg·ℓ⁻¹ and chlorophyll-a concentrations in μg·ℓ⁻¹

(1986) for the Vaal River.

Chlorophyll concentrations varied irregularly (Fig. 11) and showed peaks at 12:00 and 19:00 on the 29th and at 06:00 on the 30th. The bottom waters showed, in general, higher chlorophyll concentrations which indicate that phytoplankton cells settled out and may, therefore, have contributed to ammonium production in the bottom waters.

Results on conductivity, inorganic carbon, alkalinity (Fig. 8), turbidity (Fig. 4A), oxygen and chlorophyll (Fig. 11) showed that conditions in the river between 14:00 and 20:00 on the 29th were markedly different from those before and after. This clearly indicates the existence of a distinct stretch of water or plug in the river. At an average velocity of 710 m·h⁻¹, the length of the plug was approximately 4,3 km or 20% of the total length (20,6 km) of the stretch of water that was investigated in the channel.

Discussion

Although diurnal changes (events occurring in a 24-h period or recurring each day; Wetzel, 1983) were studied during the 1988 spring/early summer period (29 to 30 September) in the Vaal River, the observations made over one day only cannot strictly be taken as representative of that climatic period. The observations do, however, clearly illustrate interrelationships between variables as well as the extremes between which they can fluctuate during a diurnal cycle.

In the Vaal River, located in a subtropical/temperate region, the difference between the minimum and maximum temperatures was approximately 1°C (Fig. 6), while annual differences amounted to approximately 12°C (Pieterse, 1986). This observation is in accordance with that of Ganf and Horne (1975) who showed that seasonal changes in temperate inland waters are relatively large compared to diel changes.

Results in Fig. 10 clearly illustrate the possible occurrence of diurnal cycles in inorganic nitrogen and phosphorus in the Vaal River. Ryther et al. (1961) also detected diurnal cycles in PO_4-P concentrations in the Sargasso Sea, while similar cycles in ponds have been attributed to the periodic release of phosphate by *Scenedesmus quadricauda* (Turp.) Bréb. (Overbeck in Soeder et al., 1971). In addition, diurnal changes in nutrient concentrations may be important factors influencing phytoplankton, because Stross and Pemrick (1974) showed that species had different diurnal periodicities of nutrient uptake and could therefore utilise the same nutrient flux in different ways. When coupled to a diurnal periodicity in the regenerated nutrient flux, coexistence is theoretically possible (Harris, 1986).

Barbosa and Tundisi (1989) illustrated that diel temperature changes were restricted to the upper layers of the water column in a shallow (11 m deep) lake and affected the distribution of dissolved oxygen and nutrients. The period of maximum oxygen concentration (12:00 to 16:00) on the 29th occurred in the Vaal River in conjunction with relatively low chlorophyll concentrations (Fig. 11). The high oxygen concentration can, therefore, be attributed to higher rates of photosynthetic oxygen production because of improved light conditions due, in turn, to low turbidities (Fig. 4A). These observations were confirmed by Simonsen and Harremoës (1978) who illustrated a positive correlation between diurnal oxygen and pH fluctuations in a small Danish river. A negative correlation was illustrated in another Danish river between diurnal carbon dioxide and oxygen concentrations. Chlorophyll and oxygen concentration patterns (Fig. 11) did not resemble each other, which indicates that the diurnal oxygen pattern was most probably coupled with the underwater light pattern (Fig. 3) and possibly temperature (Fig. 6). This observation is in accordance with that of Jewson (1975) who showed that a diurnal change in the rate of photosynthesis was coupled to the diurnal change in surface irradiance which, according to Ganf and Horne (1975), may in some instances be correlated with diurnal patterns of heating and cooling. In this regard Barbosa et al. (1989) showed that diel variations in underwater temperature conditions affected deepwater phytoplankton maxima. On the other hand, Melack and Fisher (1983) clearly illustrated that conditions such as air-water exchanges and vertical mixing can strongly influence diel oxygen patterns in water bodies.

When the trophic classification of lakes given by Wetzel (1983) is considered, chlorophyll and PO_4-P concentrations given here indicate that the Vaal River is an eutrophic system. The maintenance of relatively high chlorophyll concentrations in spite of high turbidities, can most probably be ascribed to the mixing action of water in the river.

As indicated, spatial (cross-channel and vertical or with depth; Pieterse et al., 1986; Pieterse and Roos, 1987a) and long-term temporal (seasonal) heterogeneity in physical, chemical and algological variables (Pieterse, 1986; 1987; Pieterse and Van Zyl, 1988) have previously been demonstrated for the Vaal River. In the present study, short-term diurnal patterns in some of the same variables were elucidated and were shown to be interrelated with one another. In this way aspects of the dynamic nature of the Vaal River ecosystem were quantified in greater detail. Aspects of the dynamic nature of the phytoplankton assemblage will be investigated by Roos and Pieterse (in press).

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