Preliminary observations on cross-channel and vertical heterogeneity in environmental and algological parameters in the Vaal River at Balkfontein, South Africa

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Abstract

Cross-channel and vertical variations in environmental and algological parameters in the Vaal River at Balkfontein were studied. PO_4-P, SiO_2, K, Na, Fe, Zn and temperature did not show much variation at 5 cross-channel and 4 mid-channel depth positions. Turbidity (as NTU), Total suspended material (TSM) and Total dissolved substances (TDS) varied across the river channel and with depth, the first two being closely related to the phytoplankton. All other parameters ($NO_3 + NO_2$-N, NH_4-N, total P, Ca, Mg, Mn) were also heterogeneously distributed indicating the absence of intensive mixing patterns generated by channel flow and wind action. NTU, pH, TSM, chlorophyll *a*, phytoplankton concentration and species richness reached highest values in the middle of the river.

The phytoplankton consisted of six algal groups with the Chlorophyceae (46,9% of the total concentration) as the dominant group. On a quantitative basis *Chlamydomonas ulla* and *Carteria globosa* were the dominant algae. Flagellated algal species constituted 70% of the algal association indicating the absence of mixing conditions that would have prevented the non-flagellated algae from settling out. Bacillariophyceae, Dinophyceae and Chlorophyceae displayed preference for pelagic areas up to 19 m from either river bank. Euglenophytes and Cryptophytes were the more important components of the mid-channel phytoplankton.

Different diversity indices, i.e. Margalef D, Simpson D, Shannon-Weiner H', Hurlbert PIE, and phytoplankton indices devised for the Vaal River, illustrated cross-channel and vertical variation and were found suitable to compare the phytoplankton associations at different positions.

Introduction

The Vaal River can be regarded as the most important river in South Africa. Large population centres occur in the catchment area of this river containing industrial, gold mining and agricultural activities.

Urbanization, industrialization and mining activities cause an increase of nutrients in the water resulting in increased productivity and increases in the concentration of dissolved substances to such an extent that the water becomes brackish at times (Bruwer *et al.*, 1985; Grobler *et al.*, 1983). As a consequence of eutrophication massive development of planktonic algae is sometimes observed, especially in sections of low flow, resulting in interferences with treatment processes and problems in distribution systems (Bruwer *et al.*, 1985).

The catchment of the Vaal River covers approximately 194 000 km² and is situated in the geographical centre of South Africa (Bruwer *et al.*, 1985). The Vaal River contributes approximately 8,6% of the total mean annual runoff of South Africa, making it the river with the third largest annual runoff after the Tugela and Orange Rivers (Noble and Hemens, 1978). The Lower Vaal River region on which the present study is undertaken (Figure 1), includes the region from the Barrage to the Douglas weir, comprising a catchment area of 155 000 km² in which some 1,3 million people reside in magisterial districts bordering the river (Bruwer *et al.*, 1985). Water demand in the Lower Vaal River region exceeds the local water resources, making all aspects of water quality extremely important.

As very little environmental, and particularly biological information pertaining to water quality aspects, is available for the Vaal River, the need arose for a biologically orientated study of the river.

A site at Balkfontein (Figure 1) was chosen as the main study site in the Lower Vaal River region. At this site the river shows meso- to eutrophic characteristics and supports a diverse phytoplankton assemblage (Pieterse, unpublished information).

Rivers, being dynamic systems, are subject to physical, chemical and biological variation. In addition, cross-channel, vertical and along-channel variation in biological and environmental parameters can be expected to occur in a river system. Various samples across, at different depths and along the river channel should therefore be taken to account for this variation (Nemerow, 1974). In this study cross-channel and depth variation of environmental and algological parameters were compared in order to assess the extent of homogeneity or heterogeneity in the Vaal River at Balkfontein on 20 May 1985. The vertical and particularly cross-channel, distribution of phytoplankton has barely been studied in rivers in general and has not been undertaken in the Vaal River before. The present study, although based on a single data set, makes an important contribution to the knowledge of the types, diversity, abundance and distribution of phytoplankton species in the riverine ecosystem.

Experimental

Sampling site and sampling

The sampling site (at Balkfontein) is situated in the Lower Vaal River region, approximately 20 km from Bothaville at the water intake point (pumping station) of the Balkfontein purification plant (27°23'45"S, 26°30'30"E) which is managed by the Orange Free State Gold Fields Water Board (Figure 1). The width of the river at the study site was 77 m on 20 May 1985 and the maximum depth was 5,1 m. Water samples were taken with a Van Dorn sampler (0,5 m long, inside diameter 120 mm). The different cross-channel and mid-channel sampling positions are illustrated in Figure 2. Sampling commenced at 11h00 and was completed within an hour. Sub-samples for phytoplankton analysis (100 ml) were taken for each position and fixed with 2 ml

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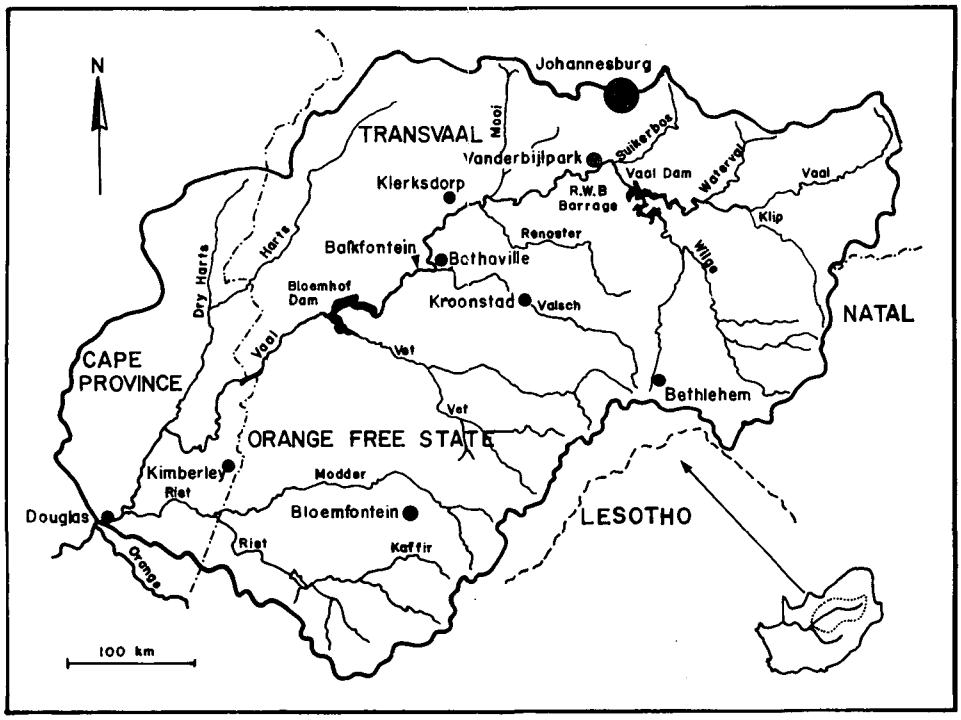

Figure 1
Catchment of the Lower Vaal River Region (adapted from Bruwer et al., 1985).

Lugol's solution (Vollenweider, 1969) or formaldehyde (5% final concentration). The remaining samples were cooled and transported to the laboratory for chlorophyll *a* and chemical analyses.

Environmental analyses

Secchi disc transparency and temperature were estimated by standard procedures. pH was measured with an Orion Research Digital pH meter (Model 231), and turbidity with a Chemtrix Type 10 Turbidimeter. For total suspended material (TSM) appropriate volumes of water were filtered through pre-cleaned and pre-dried 0,7 μm mesh sized Sartorius filters. The filtrate was evaporated in an oven at 85 °C for the estimation of total dissolved substances (TDS). Analyses for $NH_4 - N$, $NO_3 + NO_2 - N$, $PO_4 - P$, total P and SiO_2 were done according to standard procedures described in APHA (1971). Samples for $NO_3 + NO_2 - N$ analyses were filtered through 0,7 μm mesh sized Sartorius filters. For analyses of dissolved metal ions (Ca, Mg, K, Na, Mn, Fe, Zn; surface samples only), the water was filtered through pre-cleaned 0,45 μm mesh sized Sartorius filters. The concentration of these ions was determined according to procedures described by Adams *et al.* (1980) using a Perkin-Elmer 603 Atomic Absorption Spectrophotometer. As not enough water had been collected, samples for positions 1 and 2, and 3 and 4 were combined for dissolved metal ion analyses.

Phytoplankton analyses

The concentration of chlorophyll *a* (Chl *a*) was determined by the procedures described by Sartory (1982).

The 100 ml phytoplankton samples were thoroughly mixed and 2 aliquots (2 ml each) per sample were transferred to 5 ml counting chambers. The counting chambers were filled with dilute Lugol's or formaldehyde solutions, covered and allowed to settle for at least 4 days before counting. Counting of the cells was made difficult because suspended matter other than algal cells had been stained by the Lugol's solution. Counts based on the formaldehyde fixed samples were found to be more accurate and are therefore presented in this report. Counting was done with a binocular Zeiss inverted light microscope according to the method of Utermöhl (1958; see also Lund *et al.*, 1958). Counts for the two sub-samples were averaged and the % composition of the phytoplankton association of each position was calculated.

For the purpose of this report the collective term 'algal units' will be used when the concentration of organisms (populations) is considered. 'Algal units' include cells, colonies and coenobia.

In order to facilitate comparison between the phytoplankton composition of the different positions, diversity indices of Margalef (Margalef D), Simpson (Simpson D), Shannon-Weiner (Shannon-Weiner H') and Hurlbert (Hurlbert PIE) were calculated according to equations from Washington (1984). In addition, the richness in species of the major phytoplankton groups at the different positions was compared by employing the following relatively simple indices:

Relative Species Number (RSN) indices:

$$\text{Chlorophyceae RSN} = S_c/S_o \quad \ldots\ldots (1)$$
$$\text{Bacillariophyceae RSN} = S_b/S_o \quad \ldots\ldots (2)$$
$$\text{Euglenophyceae RSN} = S_e/S_o \quad \ldots\ldots (3)$$

Relative Species Percentage (RSP) indices:

$$\text{Chlorophyceae RSP} = S_c/S_o.(100N_c/N_t) \quad \ldots\ldots (4)$$
$$\text{Bacillariophyceae RSP} = S_b/S_o.(100N_b/N_t) \quad \ldots\ldots (5)$$

Euglenophyceae RSP $= S_e/S_o.(100N_e/N_t)$ ..... (6)

where

S_c, S_b, S_e = number of Chlorophyceae, Bacillariophyceae and Euglenophyceae species respectively
S_o = number of other species
N_c, N_b, N_e = number of Chlorophyceae, Bacillariophyceae and Euglenophyceae individuals respectively
N_t = total number of individuals in the association

Similarity index:

A comparison of samples was also done based on the Bray-Curtis Index of Similarity (Washington, 1984):

$C = 2W/a + b$ ..... (7)

where

W = the sum of lesser values of those species common to both samples A and B
a = the sum of the numbers of organisms of all species found in sample A
b = the sum of the numbers of organisms of all species found in sample B

The phytoplankton concentration results (Table 3) were reduced to uniform size by percentage transformation, a and b then becoming 100 (eq. 7). C consequently equals 2W/200 and 100C = W. 100C is indicated as the percentage of similarity (Southwood, 1966). Indices of similarity were computed for all sample pairs, the resulting similarity matrices were clustered by Group Average Sorting (Lance and Williams, 1967) and plotted as a dendrogram (Figure 7).

Results and discussion

Physical and chemical parameters

Temperature results are given in Table 1. Slight cross-channel and vertical variations (± 1°C) in temperature were observed in the Vaal River on 20 May 1985. Bruwer *et al.* (1985) found no depth related differences in temperature at Balkfontein in April 1983. In the White Nile Karim and Saeed (1978) observed higher or lower temperatures on a few occasions in the deep water (4,5 to 6,0 m), but the differences were also small (0,5 to 1°C). For the rest of the study period (1975 and 1976) the water column of the White Nile was homothermal.

Secchi disc depth was 340 mm at the OFS bank and mid-channel positions on 20 May 1985 (Figure 5) indicating fairly turbid conditions. Turbidity values in NTU (Table 1) of the surface water indicated highest turbidity in the mid-channel region, decreasing with depth. During April 1983 Bruwer *et al.* (1985) reported a Secchi disc depth of 430 mm for the river at Balkfontein indicating, together with the results on 20 May, relatively high turbidities which suggest that light intensity would be rapidly attenuated with depth.

The pH of the surface water was highest in mid-channel (8,9) and lower at the other positions (8,6), while the pH decreased with depth in the middle of the river to 8,0 at 3 m (Table 1). The higher surface mid-channel pH value was most probably the result of photosynthetic uptake of CO_2 by the higher concentration of phytoplankton populations in the middle of the river (Figure 4).

TSM varied in concentration across the river channel in the surface waters and with depth in the mid-channel region (Table 1). TSM and turbidity were closely related to each other ($p = 0,05$; $r^2 = 0,83$; $n = 4$). Regression analyses between chlorophyll *a* (Figure 4) and turbidity (Table 1), and between chlorophyll *a* and TSM of the surface water gave r^2 values of 0,94 ($n = 5$) and 0,95 ($n = 4$) respectively, indicating that the phytoplankton was primarily responsible for TSM and turbidity on 20 May 1985. The phytoplankton therefore determined light penetration in May. In April 1983 Bruwer *et al.* (1985) found that light penetration at a number of stations along the river was primarily determined by turbidity and secondarily by chlorophyll *a*.

TDS concentration (Table 1) showed cross-channel and vertical variation on 20 May with values within the range of 142 to 816 mg ℓ^{-1} recorded for the Vaal River during the period 1977 to 1981 (Bruwer *et al.*, 1985).

PO_4-P was relatively uniformly distributed in the surface water (Figure 3). A slight mid-channel increase in PO_4-P concentration occurred with depth on 20 May 1985 (Figure 3), with 30 $\mu g\ \ell^{-1}$ at the surface and 31,5 $\mu g\ \ell^{-1}$ at 3 m depth. In contrast, Saad and Antoine (1978a) found that phosphate varied irregularly with depth in the River Tigris while PO_4-P ranged between 32 and 459 $\mu g\ \ell^{-1}$ in the surface water during 1975 and 1976.

Total P (Figure 3) concentrations ranged between 810 and 930 $\mu g\ \ell^{-1}$ in the surface water. In the middle of the river total P

TABLE 1
VALUES FOR CERTAIN ENVIRONMENTAL PARAMETERS ON 20 MAY 1985 IN THE VAAL RIVER AT BALKFONTEIN AT DIFFERENT SAMPLING POSITIONS

	1 OFS Bank	2 OFS 1 to 3	3 Mid Om	4 Tvl 3 to 5	5 Tvl Bank	6 Mid 1 m	7 Mid 2 m	8 Mid 3m
Temperature (°C)	20,5	20	19,5	20	21	19	19	18,5
Turbidity (NTU)	8,5	7,8	8,9	8,1	8,0	8,0	7,0	7,3
TSM (mg ℓ^{-1})	30	22	42	—	—	30	—	31
TDS (mg ℓ^{-1})	445	545	373	353	440	400	375	365
$NH_4 - N$ ($\mu g\ \ell^{-1}$)	37	41	—	—	—	47	45	41
SiO_2 (mg ℓ^{-1})	6,3	6,4	5,9	6,1	5,9	6,4	6,1	6,3
pH	8,6	8,6	8,9	8,6	8,6	8,5	8,4	8,0
N/P ratio*	3,4	3,8	—	—	—	5,6	5,2	4,5

*N as $NO_3 + NO_2 + NH_4 - N$; P as $PO_4 - P$

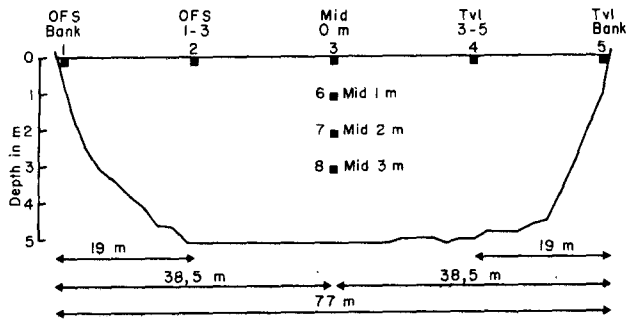

Figure 2
Cross-channel section of the Vaal River at Balkfontein illustrating the surface and mid-channel sampling positions (black squares). OFS = Orange Free State; Tvl = Transvaal; Mid = mid-channel; 1-3, 3-5 = halfway between positions 1 and 3, and 3 and 5 respectively.

increased from the surface (930 $\mu g\ \ell^{-1}$) to 2 m (950 $\mu g\ \ell^{-1}$) and then rapidly to 1 110 $\mu g\ \ell^{-1}$ at 3 m. In April 1983 the total P concentration at Balkfontein was much lower (80 $\mu g\ \ell^{-1}$; Bruwer *et al.*, 1985), indicating a large temporal variation in total P concentrations.

The cross-channel surface $NO_3 + NO_2 - N$ concentrations varied somewhat on the OFS side and increased to the Transvaal bank where a value of 96 $\mu g\ \ell^{-1}$ was recorded (Figure 3). A sharp increase in concentration was found in the first 1 m (69 to 126 $\mu g\ \ell^{-1}$) of the mid-channel water column whereafter a decrease occurred with depth to 122 $\mu g\ \ell^{-1}$ at 3 m. Saad and Antoine (1978a) found an irregular distribution of NO_3-N and NO_2-N with depth (0 to 9 m) in the River Tigris with values ranging between 2 and 249 $\mu g\ NO_3 - N\ \ell^{-1}$ and between 0,5 and 83 $\mu g\ NO_2 - N\ \ell^{-1}$ in 1975 and 1976. In the Vaal River the $NH_4 - N$ concentration ranged horizontally and vertically between 37 and 47 $\mu g\ \ell^{-1}$ on 20 May 1985 (Table 1).

The N/P ratios (where $N = NO_3 + NO_2 + NH_4$ as N and $P = PO_4$ as P; Table 1) were lower (3,4 to 3,8) in the surface waters on 20 May 1985 than in the deeper waters (4,5 to 5,6) in the middle of the river, possibly indicating potential nitrogen limitation in general which could be more prevalent in the surface water.

The SiO_2-concentration varied irregularly with depth in the middle of the river as well as across channel in the surface water (Table 1). In the River Tigris Saad and Antoine (1978a) found a similar irregular variation with depth at most of the sampling stations during 1975 and 1976 where the concentrations ranged between 6,4 and 10,3 mg $SiO_2\ \ell^{-1}$.

In the surface water Ca, Mg and Mn were heterogeneously distributed, while K, Na, Fe and Zn were more uniformly distributed (Table 2).

Algological parameters

The chlorophyll *a* (Chl *a*) concentration in surface waters (Figure 4) showed a high mid-channel value of 55 $\mu g\ \ell^{-1}$. At the other surface positions the concentration varied between 14 and 32 $\mu g\ \ell^{-1}$. Chl *a* was present in the upper 2 m of the mid-channel water column (Figure 5).

Table 3 presents the algal species found in the Vaal River at Balkfontein on 20 May 1985. Six algal groups occurred in the Vaal River. The Euglenophyceae (14 species) were the best represented group with *Strombomonas* (5 species), *Euglena* (4 species) and *Trachelomonas* (3 species) the best represented genera. *Chlamydomonas* (Chlorophyceae) was also represented by 3 species. On a quantitative basis *Chlamydomonas ulla* and *Carteria globosa* reached the highest concentrations followed by *Cryptomonas* sp. 2, *Trachelomonas intermedia*, *Cryptomonas* sp. 1, *?Gymnodinium obesum*, *Melosira granulata* var. *angustissima* and *Strombomonas fluviatilis*. Bruwer *et al.* (1985) stated that the riverine phytoplankton association in April 1983 at Balkfontein was dominated by *Platymonas* sp. (a flagellated chlorophyte) which comprised 83% of the algal community indicating, in accordance with the results on 20 May, the important role of flagellated chlorophytes in the phytoplankton flora of the Vaal

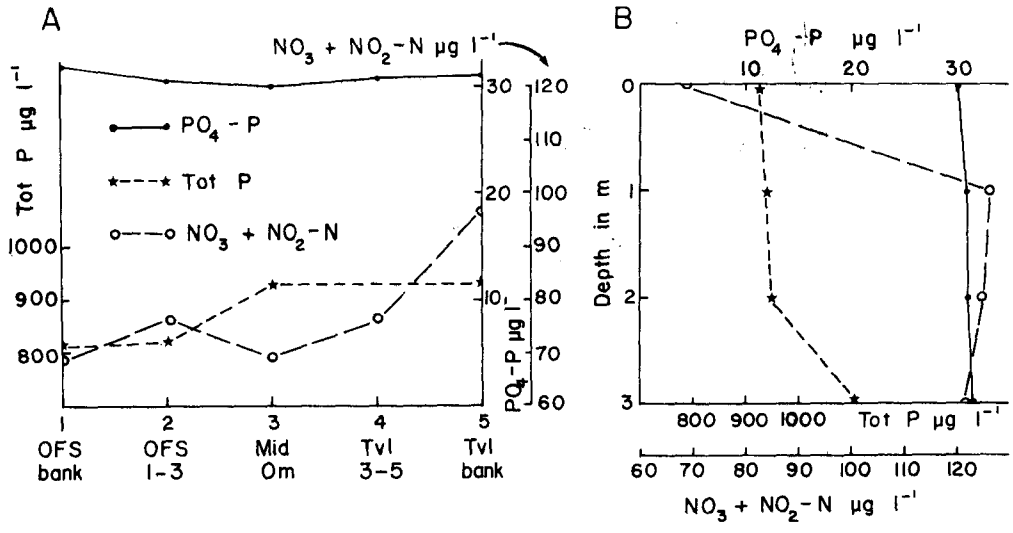

Figure 3
Horizontal (A) and depth (B) profiles of dissolved substances in Vaal River water at Balkfontein on 20 May 1985.

River at Balkfontein at this time of the year. Since Müller (1984) concluded that flagellates are more sensitive to conditions in flowing waters than diatoms, results on the abundance of flagellates (particularly *Chlamydomonas* species) presented here possibly indicate more favourable (less intensive) turbulence conditions which stimulate the growth of flagellated algae. It is not uncommon for *Chlamydomonas* species to dominate river phytoplankton assemblages because species of this genus also reached dominant proportions in the River Lee (Swale, 1964) and the River Tigris (Saad and Antoine, 1978b).

The phytoplankton composition results (Figures 4 and 5) clearly illustrate that the Chlorophyceae (46,9%, average for all positions in May) was the dominant group followed by the Euglenophyceae (22,1%), Cryptophyceae (17,9%), Bacillariophyceae (7,4%), Dinophyceae (4,8%) and Chrysophyceae (1%). Referring briefly to information from elsewhere, the following comparison between Vaal River phytoplankton at Balkfontein and other rivers can be made. Lizotte and Simmons (1985) found the same groups in the Kanawha River where individual groups

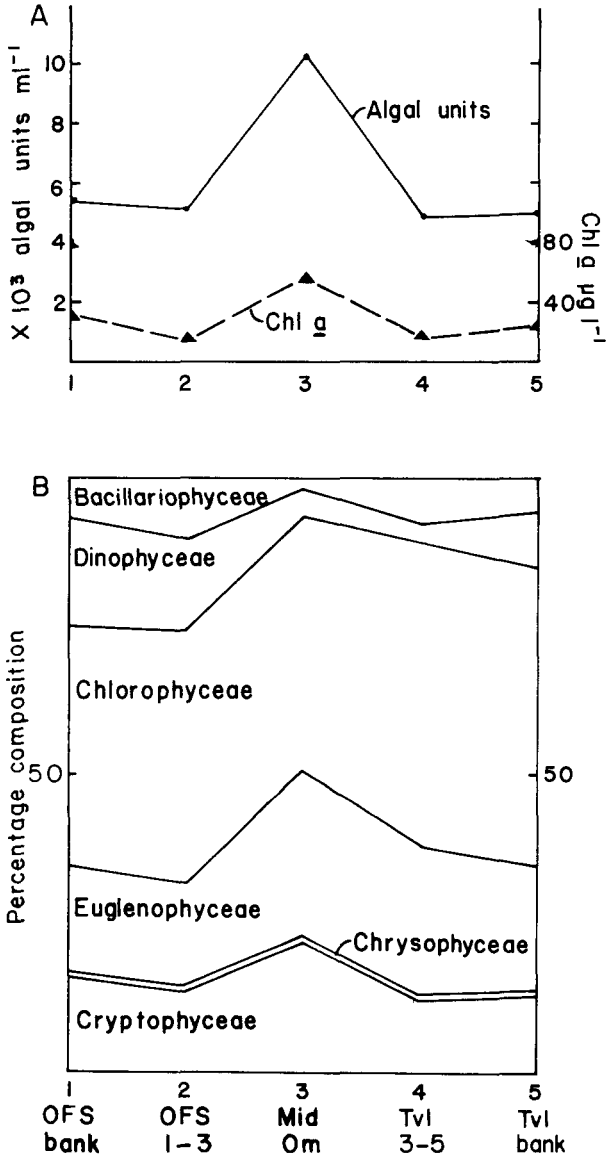

Figure 4
Cross-channel variation in total algal units and chlorophyll a (A) and % composition of the phytoplankton association (B) of surface water in the Vaal River at Balkfontein on 20 May 1985.

TABLE 2
CONCENTRATION OF DISSOLVED IONS IN mg ℓ^{-1} ON 20 MAY 1985 IN THE VAAL RIVER AT BALKFONTEIN AT DIFFERENT SAMPLING POSITIONS.

	1+2 OFS Bank +OFS 1 to 3	3+4 Mid Om +Tvl 3 to 5	5 Tvl Bank
Ca	60	53	98
Mg	10	3	4
K	6,0	5,8	5,8
Na	29	32	31
Mn	10	3	4
Fe	0,1	0,2	0,2
Zn	0	0,1	0,3

can account for 80 to 100% of the cells counted. In the River Lot the chlorophytes comprised 70 to 90% and the diatoms 5 to 20% of the phytoplankton community (Capblancq and Décamps, 1978), while in the River Shatt al-Arab (Huq *et al.*, 1978) and the River Elbe (Müller, 1984) the diatoms were dominant. In the upper 2 m of the Rio Negro cryptophytes comprised 85% of the algal assemblage in July 1984 (compared to 17,9% in the Vaal River), while diatoms and chlorophytes comprised 6% and other groups 7% (Uherkovich, 1984).

According to Round (1981) temperate rivers are generally dominated by centric diatoms and tropical rivers by pennate forms. The Vaal River therefore showed characteristics of temperate rivers due to the relative abundance of centric diatoms (Table 3).

The total phytoplankton concentration in the surface water ranged between 10 316 and 4 802 algal units mℓ^{-1} (Table 3, Figure 4), with the highest concentration occurring in the middle of the river on 20 May 1985. Curves for the algal unit and Chl *a* concentrations showed essentially the same shape in the surface water. Here algal unit concentration was significantly correlated with Chl *a* ($p = 0,01$; $r^2 = 0,93$; $n = 5$). The phytoplankton concentration (algal units) in the surface waters of the Vaal River in May was correlated with turbidity expressed as NTU ($p = 0,05$; $r^2 = 0,68$; $n = 5$), and with TSM ($r^2 = 0,86$; $n = 3$) indicating, together with the Chl *a* results presented earlier, that the phytoplankton was primarily responsible for turbidity in the river on 20 May 1985. Little information is available on the variation in cross-channel distribution of phytoplankton in river systems. Shiel *et al.* (1982) showed that the zooplankton concentration was greater in the middle of the River Murray than towards the banks. Indications of shore and surface avoidance by the zooplankton were found when the river was flowing slowly. Cross-channel variability was low when flooding occurred.

In the middle of the river the phytoplankton concentration decreased from 10 316 at the surface to 1 467 algal units mℓ^{-1} at 3 m (Table 3, Figure 5). Mixing currents in the water column were therefore not such that the phytoplankton could be evenly distributed with depth. These results compare as follows with results from other rivers. Decrease in phytoplankton concentration with an increase in depth was found in the River Shatt al-Arab (Huq *et al.*, 1978) and the River Tigris (Saad and Antoine, 1978b), but no appreciable differences in phytoplankton concentration over depth were found in the River Ottawa (Rosemarin and Hart, 1978), the River Lot (Capblancq and Décamps, 1978) and the Kanawha River (Lizotte and Simmons, 1985). In the White Nile Brook and Rzóska (1954) and Prowse and Talling (1958) found little or no indication of phytoplankton stratifica-

TABLE 3

CONCENTRATION OF DIFFERENT ALGAL SPECIES (CELLS, c; COLONIES, co; COENOBIA, ce; $m\ell^{-1}$) ON 20 MAY 1985 IN THE VAAL RIVER AT BALKFONTEIN AT DIFFERENT SAMPLING POSITIONS

	1 OFS Bank	2 OFS 1 to 3	3 Mid Om	4 Tvl 3 to 5	5 Tvl Bank	6 Mid 1 m	7 Mid 2 m	8 Mid 3 m
BACILLARIOPHYCEAE								
Cyclostephanos sp. (c)***	24	19	5	15	19	24	53	0
Cyclotella meneghiniana (c)***	35	28	7	21	28	35	78	0
Melosira cf. *varians* (c)**	25	0	30	0	0	31	15	31
Mel. granulata (c)***	15	15	30	15	15	137	15	0
Mel. granulata var. *angustissima* (c)	175	458	122	321	214	61	305	76
Stephanodiscus sp. (c)	2	2	0	1	2	2	4	0
Thalassiosira weissflogii (c)***	15	12	3	9	12	15	33	0
TOTAL	291	534	197	382	290	305	503	107
DINOPHYCEAE								
?*Gymnodinium obesum* (c)	443	290	427	137	458	107	92	61
?*Gyrodinium pascheri* (c)**	0	0	15	0	0	0	0	0
TOTAL	443	290	442	137	458	107	92	61
CHLOROPHYCEAE								
Actinastrum hantzschii (c)*	107	824	122	122	92	76	0	0
Carteria globosa (c)**	824	0	1 282	412	610	1 404	580	137
Chlamydomonas bicocca (c)*	15	107	214	534	122	244	46	0
Chl. ulla (c)**	916	839	2 198	488	900	687	443	213
Chlamydomonas sp. 1 (c)	183	244	198	122	153	122	46	31
Oocystis marssonii (c)	260	198	305	443	183	76	305	153
Pandorina morum (co)*	31	46	0	15	31	15	0	0
Pteromonas sp. 1 (c)*	299	321	0	260	144	31	15	0
Scenedesmus acuminatus (ce)**	0	0	46	0	0	0	0	0
Sc. lefevrii (ce)*	137	92	46	76	153	61	61	92
TOTAL	2 772	2 671	4 411	2 472	2 388	2 716	1 496	626
EUGLENOPHYCEAE								
Euglena allorgei (c)***	107	46	0	46	122	153	214	61
Eu. clavata (c)**	15	15	397	61	15	183	31	31
Eu. hemichromata (c)**	30	15	122	0	31	46	15	0
Eu. oblonga (c)**	31	15	122	40	46	31	0	0
Lepocinclis salina (c)**	0	15	46	0	0	15	46	0
Phacus pyrum (c)*	61	107	46	122	61	92	107	92
Strombomonas fluviatilis (c)	214	153	214	183	198	31	15	122
Str. jaculata (c)**	0	0	31	0	0	0	0	0
Str. ovalis (c)	31	31	31	61	31	61	31	0
Str. triquetra (c)**	0	0	15	0	0	0	0	0
Str. verrucosa (c)**	0	0	30	0	0	15	0	0
Trachelomonas intermedia (c)**	336	336	1 709	565	382	183	153	46
Tr. scabra (c)*	122	153	107	76	153	122	15	61
Tr. volvocina (c)**	15	15	46	31	15	31	31	61
TOTAL	962	901	2 916	1 185	1 054	963	658	474
CHRYSOPHYCEAE								
Mallomonas trummensis (c)	0	15	15	31	15	15	0	0
Mallomonas corymbosa (c)**	31	15	46	0	31	46	107	0
TOTAL	31	30	61	31	46	61	107	0
CRYPTOPHYCEAE								
Chroomonas sp. 1 (c)**	137	46	244	137	92	336	137	31
Cryptomonas sp. 1 (c)**	198	275	1 206	183	183	397	137	92
Cryptomonas sp. 2 (c)**	565	412	839	275	412	1 023	488	76
TOTAL	900	733	2 289	595	687	1 756	762	199
GRAND TOTAL	5 399	5 159	10 316	4 802	4 923	5 908	3 618	1 467

Apparent preference for:
*shore conditions;
**mid-channel surface conditions;
***mid-channel 1 to 3 m conditions.

tion, while Karim and Saeed (1978) stated that uniform distribution of *Melosira granulata* in this river occurred during periods of river flow and wind-induced mixing.

The concentration of phytoplankton units in the Vaal River in May is generally comparable with that of other rivers. Phytoplankton concentrations ranged between 16 and 11 620 cells $m\ell^{-1}$ in the Kanawha River (Lizotte and Simmons, 1985), and between 373 and 903 cells $m\ell^{-1}$ in the River Shatt al-Arab (Antoine, 1983). A maximum concentration of 15 000 cells $m\ell^{-1}$ was found in the Mwenda River (King and Thomas, 1985), 50 000 cells $m\ell^{-1}$ in the Upper Mississippi River (Baker and Baker, 1981) and 200 000 cells $m\ell^{-1}$ in the River Ruhr (Nusch, 1978).

The differences in composition of the phytoplankton association are illustrated by Figures 4 and 5 which represent % composition based on the concentration values given in Table 3. Table 4 compares the % composition of the surface phytoplankton at the OFS (Orange Free State) side (average for positions 1 and 2), in the middle of the river, and at the Tvl (Transvaal) side (average for positions 4 and 5) with the average % composition of the subsurface positions in the middle of the river (positions 6 to 8, depths 1 to 3 m). These results indicate cross-channel and depth variation in the composition of the phytoplankton assemblages (Figures 4 and 5). Of the 37 algal species found in the Vaal River in May, 33 occurred in the middle of the river at the surface and at 1 m depth (Table 3). The number of species decreased with increasing depth from 33 at 0 m and 1 m in the middle of the river to 28 at 2 m to 18 at 3 m. The number of species varied between 28 and 30 for the surface sampling positions other than the mid-channel position. The mid-channel region therefore supported the largest number of species in the upper 1 m water column.

The following species did not occur at 2 and 3 m depths: *?Gyrodinium pascheri*, *Actinastrum hantzschii*, *Pandorina morum*, *Scenedesmus acuminatus*, *Euglena oblonga*, *Strombomonas jaculata*, *Str. triquetra*, *Str. verrucosa* and *Mallomonas trummensis*. Five algal species, namely *?Gyrodinium pascheri*, *Scenedesmus acuminatus*, *Strombomonas jaculata*, *Str. triquetra* and *Str. verrucosa* were found only in the mid-channel region of the river. Their concentrations were too low to constitute a significant proportion of the phytoplankton association.

Table 4 illustrates that the Bacillariophyceae, Dinophyceae and Chlorophyceae were more important components of the phytoplankton association in the water of the Vaal River up to at least 19 m from the river banks on both sides, while the Euglenophyceae and the Cryptophyceae were more important components of the mid-channel phytoplankton. When the abundance of phytoplankton species is considered (Table 3), 7 algal species (71% flagellated, 29% non-flagellated) were more important components of the phytoplankton assemblage in the water up to at least 19 m from both river banks, 18 species (89% flagellated, 11% non-flagellated) were more important in the mid-channel surface waters, 5 species (20% flagellated, 80% non-flagellated) were more important in the mid-channel sub-surface water, while 7 algal species and 1 variety (50% flagellated, 50% non-flagellated) were not a particularly important component of the phytoplankton in any section of the river. The higher proportion of non-flagellated algae in the mid-channel sub-surface layers may indicate the avoidance of unfavourable light conditions by the flagellated algae. The largest number of species occurred in the middle of the river where flagellated species apparently concentrated to a larger degree. The highest concentration of total phytoplankton also occurred in this region (Table 3, Figure 4). Not enough information is available to explain the apparent preference of the algal species

TABLE 4
COMPARISON OF THE AVERAGE % COMPOSITION OF PHYTOPLANKTON AT THE ORANGE FREE STATE (POSITIONS 1 AND 2) AND TRANSVAAL (POSITIONS 4 AND 5) SIDES WITH THE MID-CHANNEL SURFACE % COMPOSITION AND THE AVERAGE % COMPOSITION OF THE MID-CHANNEL SUB-SURFACE PHYTOPLANKTON (POSITIONS 6, 7 AND 8)

	1+2 OFS side	3 Middle surface	4+5 Tvl side	6+7+8 Middle 1 to 3 m
Bacillariophyceae	8,8	2,0	6,9	8,7
Dinophyceae	6,9	4,3	6,0	2,8
Chlorophyceae	50,5	42,8	50,4	43,3
Euglenophyceae	17,8	28,0	23,0	22,4
Chrysophyceae	0,6	0,7	0,8	1,4
Cryptophyceae	15,3	22,2	13,6	21,4

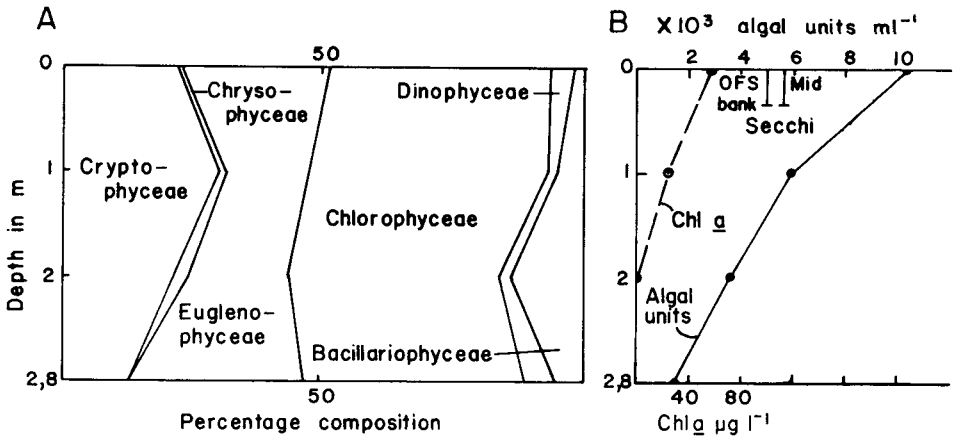

Figure 5
Depth profiles of total algal units and chlorophyll a (B) and % composition of the phytoplankton association (A) of the Vaal River mid-channel station at Balkfontein on 20 May 1985.

and groups for specific sections of the river on 20 May 1985, but it is known that a tendency exists in flowing water for surface water to be drawn towards the centre of the stream because of retardation of flow along the banks (Hynes, 1970). This tendency could at least partly explain the higher total phytoplankton concentration in the middle of the river if appreciable flow occurred, an aspect that will be referred to again in another section.

The list of algal species occurring in the Vaal River on 20 May 1985 (Table 3) shows that 70% of the phytoplankton were flagellated, indicating that conditions in May were more favourable for this group. Flagellated algae are able to remain in suspension under conditions of low turbulence, whereas non-flagellated species would tend to settle out.

The results presented in this report clearly indicate cross-channel and vertical heterogeneity in the Vaal River at Balkfontein. In order to assess the statistical significance of differences between the cross-channel and mid-channel depth positions chi-square analysis were applied to the phytoplankton results (Tables 3 and 5). Table 5 contains only instances in which the differences were too small to indicate significance at the $p = 0,01$ confidence level. The results indicate that the differences between most of the surface positions, with the exception of the mid-channel position, were generally not significant for all the phytoplankton categories. The total phytoplankton, Bacillariophyceae and Euglenophyceae appear to be more heterogeneously distributed, whereas members of the Dinophyceae, Chlorophyceae, Chrysophyceae and Cryptophyceae appear to be more homogeneously distributed. The apparent preference for specific sections in the Vaal River by different algal groups, as illustrated in Table 4, cannot be substantiated by chi-square analysis.

TABLE 5
SIMILAR PHYTOPLANKTON ASSEMBLAGES AT THE DIFFERENT SAMPLING POSITIONS IN THE VAAL RIVER AT BALKFONTEIN ON 20 MAY 1985 BASED ON CHI-SQUARE ANALYSIS OF ALGAL UNIT CONCENTRATION

Total phytoplankton:	2 and 5*; 1 and 2**; 4 and 5**
Bacillariophyceae:	1 and 4*; 2 and 7**
Dinophyceae:	1, 3 and 5*; 4 and 5*; 4 and 6*; 6 and 7*; 7 and 8**
Chlorophyceae:	1, 2 and 6*; 2 and 5*; 4 and 5*
Euglenophyceae:	1, 2 and 6*; 1 and 5**; 5 and 6**
Chrysophyceae:	1, 2, 4 and 5*; 3 and 5*; 3 and 6*; 6 and 5*
Cryptophyceae:	2 and 5*; 2 and 7; 4 and 5**; 5 and 7**

*difference too small to indicate significance at 0,05 level
**difference indicating significance at 0,05 but not at 0,01 level.
1 = OFS Bank; 2 = OFS 1 to 3; 3 = Mid Om; 4 = Tvl 3 to 5; 5 = Tvl Bank; 6 = Mid 1 m; 7 = Mid 2 m; 8 = Mid 3 m.

Diversity indices have been developed to describe community structure resulting in numerical expressions that can be used to compare different communities (Hodgkiss and Law, 1985). Several indices were applied to compare the composition of the phytoplankton at the different cross-channel and mid-channel positions, all of which involve aspects of species diversity. Species diversity, according to Washington (1984), is a function of the species present (species richness or species abundance) and the evenness with which individuals are distributed within these species (species evenness or species equitability). Diversity is therefore dependent on both the number of species present and the abundance of individuals within the species.

Benson-Evans *et al.* (1975) stated that biotic indices involving species are more effective when devised for a particular type of river. For this reason indices were devised for the Vaal River with which the phytoplankton composition at the different sampling positions could be compared. Relative Species Number (RSN) indices (eq. 1 to 3) were developed to relate the number of species in a specific group to the total number of other species in the assemblage. Relative Species Percentage (RSP) indices were developed to relate both the number of species in a group and their respective abundancies to the total number of species and the total abundance of the phytoplankton (eq. 4 to 6). The RSN indices are similar to the phytoplankton indices of Thunmark and Nygaard (in Hutchinson, 1967).

RSN and RSP indices (Table 6) showed that the mid-channel surface water was richer in euglenophytes, whereas the surface waters up to 19 m from the river banks were richer in chlorophyte and diatom species. These results are in accordance with the apparent preference of these species for specific sections in the river as illustrated in Table 4. If all the positions except the mid-channel surface water are considered, RSN values for the Bacillariophyceae and Euglenophyceae were fairly similar in the surface water, indicating that these groups were more evenly distributed in the phytoplankton assemblage. The variation in RSN values for the Chlorophyceae and the variation in RSP values for all three groups (Chlorophyceae, Bacillariophyceae, Euglenophyceae) in the surface and sub-surface positions was such that the conclusion on the heterogeneous distribution of the phytoplankton seems to be valid. Generally speaking the phytoplankton indices gave a rather clean separation between the mid-channel surface position (and to a certain extent the mid-channel 3 m position) and the other positions (see Table 6), and might prove useful if the specific algal groups can be related to specific environmental conditions. This relation is of importance and will be considered in future work.

Washington (1984) reviews a large number of diversity indices and explains his preference for two, namely Simpson's and Hurlbert's indices. Both these indices were applied as well as that of Margalef and Shannon-Weiner. This was done to compare the phytoplankton at the different cross-channel and mid-channel positions. Benson-Evans *et al.* (1975) found for rivers in South Wales that diversity indices are a satisfactory method of biological appraisal of certain environmental effects if applied to individual river systems.

Values for Margalef's index (Figure 6) ranged between 3,19 and 3,40 in the surface waters with the greatest diversity occurring in the middle of the river and the smallest in Tvl 3 to 5. Diversity increased with depth from 3,46 at 0 m to 3,69 at 1 m, followed by a marked decrease through 3,3 at 2 m to 2,33 at 3 m where the smallest diversity was found. Margalef's index showed no significant correlation with NTU, TSM, and Chl *a*. Because of the difference in diversity illustrated by Margalef's index for the phytoplankton at the various positions, this index appears to be suitable for comparative purposes in the Vaal River.

Diversity values for Simpson's index (Figure 6) ranged between 0,0703 and 0,1152 in the surface waters with the greatest diversity occurring in the middle of the river and the smallest at Tvl 3 to 5. Diversity values were similar at the surface and 1 m depths in the middle of the river and decreased with depth through 0,0855 at 2 m to 0,0730 at 3 m. Simpson's index values were significantly correlated with Chl *a* ($p = 0,05$; $r^2 = 0,78$; $n = 5$). Fairly good correlations were found between Simpson's index and NTU ($r^2 = 0,54$; $n = 5$) in the surface water, and between this index and NTU ($r^2 = 0,66$; $n = 4$) and Chl *a* ($r^2 = 0,72$; $n = 4$) in mid-channel water. Simpson's index therefore appears to be

suitable for comparing phytoplankton assemblages in the Vaal River.

Diversity values for the Shannon-Weiner index (Figure 6) ranged between 2,46 (at Tvl 3 to 5) and 2,74 (at OFS 1 to 3) in the surface waters. Pronounced difference in diversity was therefore not indicated for mid-channel surface waters as was done by the Margalef and Simpson indices. Values for the Shannon-Weiner index increased with depth in the middle of the river with the highest value of 2,78 occurring at 2 m. In the surface water this index was significantly correlated only with TSM ($p = 0,01$; $r^2 = 0,98$; $n = 5$). Significant correlations were found with NTU ($p = 0,01$; $r^2 = 0,93$; $n = 4$) and Chl *a* ($p = 0,05$; $r^2 = 0,90$; $n = 4$) at different depths in mid-channel waters. Fairly good correlations were also found in the mid-channel positions between this index and TSM ($r^2 = 0,50$). The Shannon-Weiner index therefore appears to be suitable for comparing phytoplankton at the different positions and is apparently of particular importance in the evaluation of differences with depth. In the River Taff Benson-Evans *et al.* (1975) illustrated significant correlations between the Shannon-Weiner index for benthic algae and TSM and BOD, while Baker and Baker (1981) found that this index's values for phytoplankton in the Upper Mississippi River reached maximum values in summer and decreased towards winter.

Diversity values for Hurlbert's index (Figure 6) ranged between 0,940 at Tvl 3 to 5 and 0,855 at the mid-channel surface water position. A gradual increase in index values occurred from the surface (0,858) to 3 m (0,927) in the middle of the river. Fairly good correlations existed between this index and NTU ($r^2 = 0,54$), TSM ($r^2 = 0,54$) and Chl *a* ($r^2 = 0,79$) in the surface waters and between this index and NTU ($r^2 = 0,69$) and Chl *a* ($r^2 = 0,71$) at different depths in mid-channel waters. Hurlbert's index therefore appears to be suitable for the comparison of phytoplankton associations at the different positions.

A theoretical discussion on the differences between the diversity indices employed falls outside the scope of this communication. It must be pointed out, however, that although the Shannon-Weiner index is most commonly used, Washington (1984) regards the Simpson index as being more suitable for aquatic environments. The application of the Shannon-Weiner index for comparative purposes over short-term periods is apparently justifiable (Washington, 1984). The Simpson index is one of the simpler approaches in the measurement of diversity and is determined by sample size and the more abundant species giving little weight to the rarer ones. The Shannon-Weiner index apparently is more sensitive towards rare species where sampling error may be more pronounced (Washington, 1984). The Shannon-Weiner index is relatively independent of sample size and accurately reflects the types of changes in the community caused by environmental stress (Benson-Evans *et al.*, 1975). The better correlation between the Shannon-Weiner index and certain parameters in the mid-channel sub-surface positions of the Vaal River may be a reflection of the influence of stress factors.

According to Washington (1984) Hurlbert's index measures the importance of interspecific competition if calculated for a collection of related species within the same trophic level. As Hurlbert's index was applied for comparative purposes and since the Vaal River results do not reflect all the different environmental conditions, these results cannot be interpreted on the basis of interspecific competition.

In order to determine how closely the indices were correlated with one another linear regression analyses were applied to results of the cross-channel surface water and mid-channel water column values. In the cross-channel surface waters Simpson's index (Table 7) was significantly negatively correlated (at $p = 0,01$) with Hurlbert's index. Fairly good correlation was shown between Margalef's index and the Simpson (positive), Shannon-Weiner (positive) and Hurlbert (negative) indices. In the mid-channel water column significant correlations existed between Simpson's index and the Hurlbert (negative at $p = 0,01$), Shannon-Weiner (negative at $p = 0,05$) and Margalef (positive at $p = 0,05$) indices, as well as between the Hurlbert and Shannon-Weiner indices (positive at $p = 0,01$). Margalef's index was fairly well correlated with Shannon-Weiner's (negative) and Hurlbert's (negative). The best correlation in the surface water as well as at different depths occurred between Simpson's and Hurlbert's, the two in-

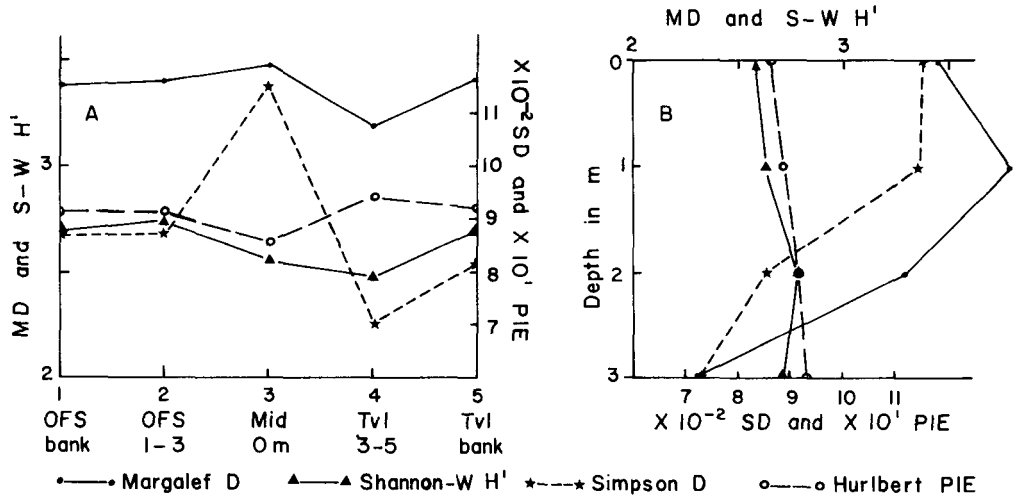

Figure 6
Graphical illustration of different indices used to compare surface water (A) and mid-channel (B) phytoplankton associations at different sampling positions along a cross-channel section in the Vaal River at Balkfontein on 20 May 1985.

dices for diversity preferred by Washington (1984) for aquatic environments. Washington's statement that these two indices are closely related is therefore supported by results on the Vaal River. Diversity indices for the mid-channel water column were generally much better correlated with one another than for the cross-channel surface waters. The reason for this phenomenon is not apparent, but should be investigated further.

In addition to diversity indices Washington (1984) also reviewed a number of similarity indices that could be applied to aquatic environments. Dyer (1978) pointed out that it might be desireable to employ diversity as well as similarity indices for the exploitation of information that is not utilized by either type of index on its own. A similarity index is basically a measure of the similarity of the structure of two communities, it takes into account both abundance and number of species. The Bray-Curtis index of similarity (eq. 7) was applied to compare the phytoplankton of the Vaal River at Balkfontein for the different cross-channel and mid-channel positions. In the Bray-Curtis index the unique species are of lesser importance, and the degree of similarity is given by the number and quantity of the more common species (Washington, 1984). Percentages of similarity appear to be useful for comparing phytoplankton of different rivers and streams as illustrated by Garcia de Emiliani (1981) for the River Parana and nearby streams.

The percentage of similarity results (Figure 7) indicates that the cross-channel surface phytoplankton at the different positions is similar to the 64% level. The highest level of similarity (92%) occurred between the river bank positions, a conclusion also borne out by the other results already discussed. The mid-channel positions are separated from the other positions, with the phytoplankton from 3 m depth relatively dissimilar to the phytoplankton from all the other positions. With the percentage of similarity values greater than 50% for all the positions it can be assumed that the algal associations at the different positions are components of the same phytoplankton community. The difference in phytoplankton composition and abundance at the different cross-channel and mid-channel positions could therefore have been brought about by the absence of horizontal and vertical mixing due to relatively low flow conditions and less intensive wind mixing.

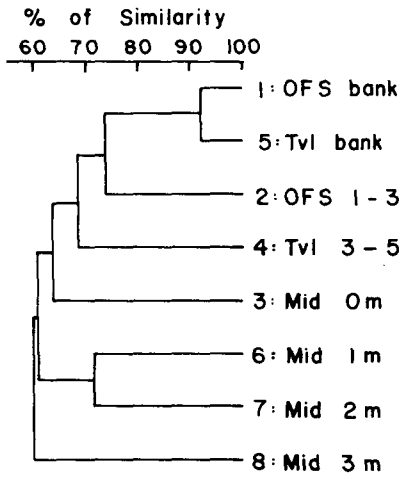

Figure 7
Dendrogram of similarity between phytoplankton of the different sampling positions in the Vaal River at Balkfontein on 20 May 1985 based on the Bray-Curtis index and Group Average sorting.

Conclusions

Not much horizontal and vertical variation in temperature, $PO_4 - P$ and SiO_2 occurred in the Vaal River on 20 May 1985. On the other hand, turbidity, TSM and TDS showed vertical and cross-channel heterogeneity, of which the first two apparently follow the heterogeneous distribution pattern of the phytoplankton. All the other substances analysed also showed heterogeneous distribution indicating a general absence of intensive mixing. The results clearly illustrate cross-channel and vertical heterogeneity in the distribution of phytoplankton species and groups (particularly within the Euglenophyceae and Bacillariophyceae); heterogeneity being most pronounced in the mid-channel region on 20 May. These results are contrary to that of Rosemarin (1975) for the River Ottawa where the distribution of the phytoplankton

TABLE 6
PHYTOPLANKTON INDICES AT DIFFERENT SAMPLING POSITIONS FOR THE VAAL RIVER AT BALKFONTEIN ON 20 MAY 1985

	1 OFS Bank	2 OFS 1 to 3	3 Mid Om	4 Tvl 3 to 5	5 Tvl Bank	6 Mid 1 m	7 Mid 2 m	8 Mid 3 m
RELATIVE SPECIES NUMBER INDEX								
Chlorophyceae RSN	0,43	0,37	0,32	0,47	0,43	0,38	0,33	0,39
Bacillariophyceae RSN	0,25	0,20	0,18	0,22	0,20	0,22	0,27	0,13
Euglenophyceae RSN	0,50	0,58	0,65	0,47	0,50	0,57	0,56	0,64
RELATIVE SPECIES PERCENTAGE INDEX								
Chlorophyceae RSP	22,00	18,83	13,69	24,38	20,79	17,24	13,78	16,41
Bacillariophyceae RSP	1,35	2,07	0,34	1,73	1,18	1,14	3,79	0,91
Euglenophyceae RSP	8,91	10,11	18,37	11,69	10,71	9,31	10,10	20,56

TABLE 7
CORRELATION BETWEEN DIVERSITY INDICES OF THE SURFACE WATER AND MID-CHANNEL WATER COLUMN OF THE VAAL RIVER AT BALKFONTEIN ON 20 MAY 1985

MID-CHANNEL WATER COLUMN (n = 4)	CROSS-CHANNEL SURFACE WATER (n = 5) Margalef D	Shannon-Weiner H'	Hurlbert PIE	Simpson D
Margalef D	—	r = 0,60 r^2 = 0,36	r = −0,79 r^2 = 0,63	r = 0,80 r^2 = 0,64
Shannon-Weiner H'	r = −0,56 r^2 = 0,31	—	r = −0,04 r^2 = 0,002	r = 0,07 r^2 = 0,01
Hurlbert PIE	r = −0,82 r^2 = 0,67	r = 0,92* r^2 = −0,85	—	r = −0,99** r^2 = 0,99
Simpson D	r = 0,87* r^2 = 0,76	r = −0,89* r^2 = 0,80	r = −0,99** r^2 = 0,99	—

*significant at p = 0,05
**significant at p = 0,01

was generally homogeneous, enabling Rosemarin to sample only at 0,5 m in the mid-channel region. Minimum heterogeneity was also observed in the main channel of the Upper Mississippi River (Baker and Baker, 1979) and the River Thames (Kowalczewski and Lack, 1971). Baker and Baker (1979) pointed out, however, that heterogeneity of phytoplankton in river systems is the major barrier in establishing clear patterns of its distribution and activity and is enhanced by minimal mixing, maximum retention time and is greatest in large, almost lacustrine rivers. In May the Vaal River therefore apparently displayed lacustrine characteristics of large rivers. Turbulent flow and intensive wind mixing resulting in more or less uniform vertical and horizontal distribution of phytoplankton were apparently of less importance in the Vaal River at Balkfontein on 20 May 1985. The apparent preference of specific algal species and groups for certain sections of the river, and the high phytoplankton concentration in the middle of the river support this conclusion, as does the fact that flagellated algae played a more important role in the composition of the phytoplankton in the surface water than at the sub-surface positions.

With uni-directional flow occurring in a river, Talling and Rzóska (1967) pointed out that plankton is continually moving past a point of observation making it necessary to establish the source of the plankton. In the case of the Vaal River at Balkfontein in May, where results indicate low flow conditions, it can be assumed that the phytoplankton association originated in the vicinity of the sampling positions. The fact that the phytoplankton association of the mid-channel surface water differs from that of the other surface positions indicates that this assemblage and concentration apparently did not come about by the phytoplankton being drawn to the middle of the river because of water flow.

All indices applied to the phytoplankton of the Vaal River at Balkfontein appear to be suitable for comparative purposes. Simpson's index seems to be particularly suitable for general comparative purposes, as it was closely related to a number of parameters measured. The Shannon-Weiner index, on the other hand, appears to be particularly suitable in the evaluation of depth related differences. The phytoplankton indices devised for the Vaal River situation gave a rather clean separation of surface mid-channel and deep water phytoplankton associations from the rest, and might prove useful if the algal groups can be related to specific environmental conditions. Since Hurlbert's index apparently measures aspects of species competition, the application of all the indices to Vaal River phytoplankton under different sets of environmental conditions (such as seasonal variation or variation along the river channel) might prove useful and should be pursued.

All the indices employed in this study emphasize the importance of common species, while sample size and accuracy of species identification are of special importance. In the case of the Vaal River, the technique used to enumerate the phytoplankton also emphasizes to a degree the common and abundant species. In this regard, Hallegraeff and Ringelberg (1978) refer to the unfortunate situation that all the diversity indices respond to changes in a few abundant species. Although this is accepted as a problem in the present study, the expressed purpose was to facilitate the comparison of the phytoplankton at the different positions in the river by employing different indices. The statement of Hallegraeff and Ringelberg (1978) that phytoplankton volume abundance units represent a more meaningful and practical way of evaluating species diversity in phytoplankton assemblages and association is accepted, but the relevant information is not presently available.

The indicated cross-channel and vertical heterogeneity of phytoplankton in the Vaal River at Balkfontein on 20 May is in itself of importance and interest, bringing to light certain aspects of the ecology of the phytoplankton if the correlations between diversity values and certain environmental conditions are considered. Heterogeneity has, however, also a direct bearing on the development and execution of a sampling programme for seasonal variation in environmental parameters in order to arrive at sound generalizations regarding seasonal patterns of algae and their causative factors.

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