

# On the limnology of Spioenkop, a turbid reservoir on the upper Thukela River, with particular reference to the structure and dynamics of its plankton community

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## Abstract

Basic features of the physical and biological limnology of Spioenkop, a large turbid impoundment on the Thukela River, were studied between July 1989 and May 1990, following surveys in spring 1987 and 1988. The lake showed a typical monomictic pattern of summer stratification (November through April) and holomictic winter circulation (May to October). Water quality was chemically good, with little evidence of nutrient enrichment (South African DWAF records). Biological production was confined by high turbidity (SD around 25 cm, NTU values of ca 90) imposed by suspended sediments, limiting annual maximum surface chlorophyll content to below  $5 \mu\text{g}\cdot\text{L}^{-1}$ , and spring primary production to  $< 500 \text{ mg C}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ .

Zooplankton was dominated (numerically and/or gravimetrically) by typical turbid-water fauna; the copepods *Metadiaptomus colonialis* and *Lovenula falcifera*, and cladocerans *Daphnia barbata* and *Moina micrura*. These species and other taxa present showed considerable seasonal periodicity, but maximal total abundance of the entire community ( $680 \text{ mg}\cdot\text{m}^{-2}$  DW) was attained in mid-summer. Limited information regarding littoral zoobenthos and fish is provided.

Considerations of Spioenkop as a mirror of its catchment, and in relation to the major Thukela-Vaal inter-basin transfer scheme invite critical appraisal of the level of scientific knowledge and understanding. The plea and challenge is made for more holistic and integrated approaches to ensure sustainable environmental management.

## Nomenclature

CPUE	catch per unit effort
DW	dry weight
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
$K_d$	downwelling extinction coefficient
MAR	mean annual runoff
NTU	nephelometric turbidity unit
PAR	photosynthetically active radiation (400 - 700 nm)
P/B	production to biomass ratio
$P_{\text{max}}$	maximum volumetric primary production
SD	Secchi depth transparency

## Introduction

Man-made lakes dominate the limnetic landscape of South Africa (Allanson et al., 1990), with some 520 major state dams capturing 50% of the nation's MAR (Uys, 1996). As dams are logically sited to maximise capture of river flow, the resulting impoundments are rendered especially vulnerable to all land uses and developments in their respective catchments; water quality is almost inevitably impaired (Marzolf, 1984). In South Africa, as elsewhere globally, eutrophication and chemical pollution represent major water-quality threats to river impoundments. But in contrast to relatively mesic conditions experienced in many nations, the aridity or semi-aridity of South Africa renders its impoundments especially susceptible to two additional water quality problems. Firstly, elevated mineral turbidity - a consequence of erosion of land surfaces with limited vegetal cover, high intensity rainfall, etc. Secondly,

salinisation arising through evaporative concentration (DWA, 1986a).

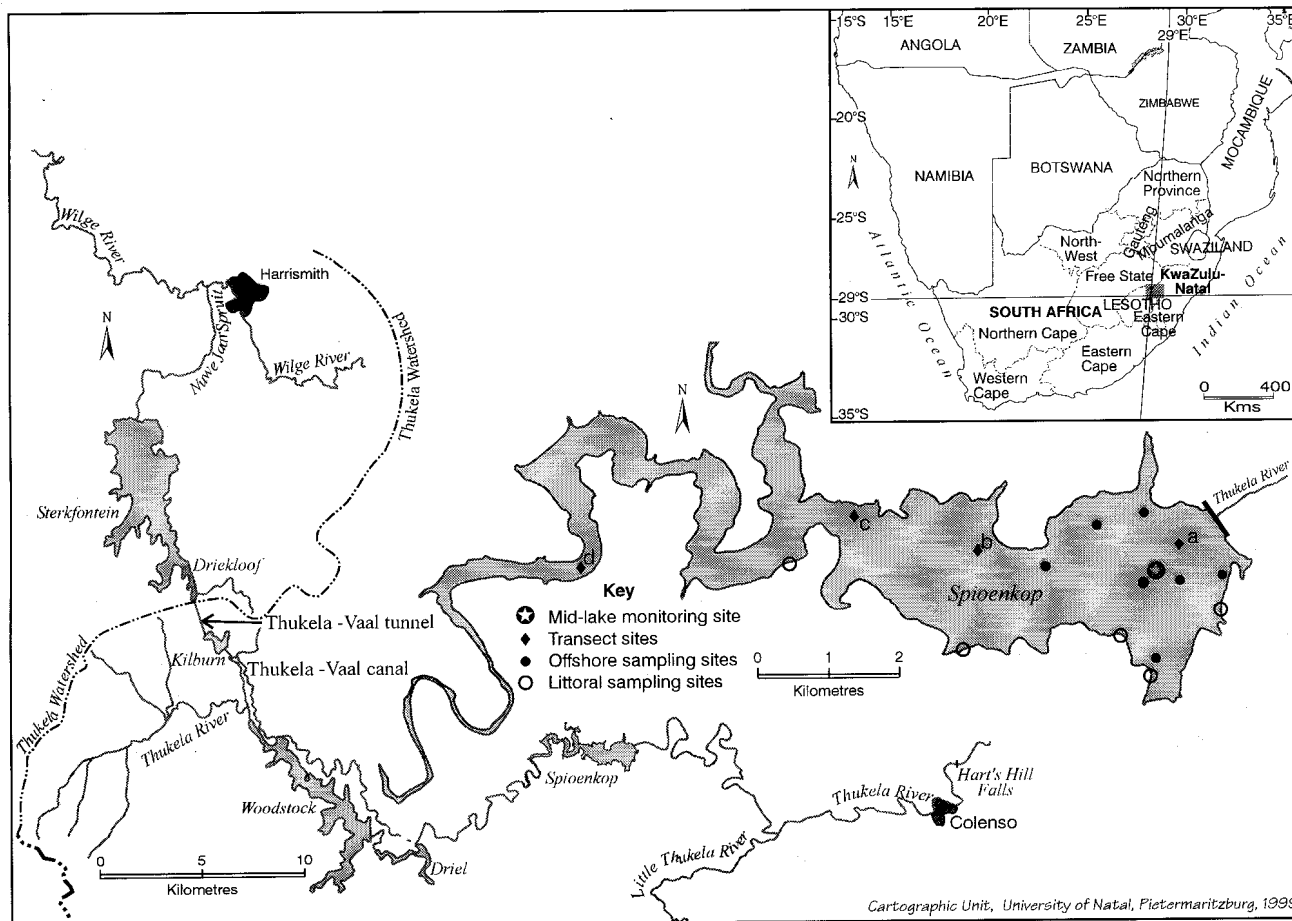
Despite the large number of storage reservoirs (DWA, 1986a), baseline limnological information is available for relatively few. What does exist is often meagre, and based on once-off or short-term studies. Seasonally comprehensive data are seldom available for a complete year, let alone spanning sufficient time to encompass the inherent hydrological variability of the region (Schulze, 1997). Ironically, such deficiencies exist even in respect of significant major impoundments in this water-limited nation. The present study was undertaken as a preliminary attempt to improve this deficiency in respect of selected reservoirs in the midlands of KwaZulu-Natal. This paper considers Spioenkop, a system highly impacted by mineral turbidity. A parallel comparative study on Wagendrift, a neighbouring and relatively clear-water impoundment on the Bushmans River, will be reported separately.

The primary objective of this study was to provide a baseline limnological study of Spioenkop, with particular reference to the seasonal abundance and community composition of its plankton in relation to annual changes in thermal stratification and turbidity. As such, it merely provides introductory documentation of the limnology of this reservoir, augmenting similarly descriptive studies undertaken elsewhere e.g. Sterkfontein (Dörgeloh et al., 1993).

## Study site

Spioenkop is a large reservoir sited on the Thukela (formerly Tugela) River near Bergville (KwaZulu-Natal), some 65 km downstream from this river's headwater sources in the Drakensberg mountains (Fig. 1). It was impounded in 1972 by Spioenkop Dam ( $28^{\circ}38'S$ ,  $29^{\circ}28'E$ ), to regulate river flow for downstream users following development of the Thukela-Vaal inter-basin transfer and pumped storage scheme, but is operationally divorced from the

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**Figure 1**  
 General geographic position (inset), and location of Spioenkop in relation to other Thukela-Vaal transfer scheme water-bodies named in the text. Main outline map shows approximate positions of the routine mid-lake monitoring site (⊕), transect sites (◆), and other offshore (●) and littoral (○) sampling sites.

TABLE 1 MORPHOMETRIC FEATURES OF SPIOENKOP AT FULL SUPPLY LEVEL. DATA FROM NOBLE AND HEMENS (1978), DWA (1986A), AND MIDGLEY ET AL. (1994)	
<b>Catchment attributes</b>	
Quaternary catchment number	V 11L
Catchment area (km <sup>2</sup> )	2 452
MAR from catchment (10 <sup>6</sup> m <sup>3</sup> )	1 800
<b>Reservoir attributes</b>	
Surface area (ha)	1 538
Maximum depth (m)	46.8
Mean depth (m)	18.2
Volume (10 <sup>6</sup> m <sup>3</sup> )	280
Elevation (m a.s.l.)	1 071
Mean hydrological retention time (d)	57

transfer scheme itself (DWA, 1986b). Relevant morphometric and related attributes of the reservoir are summarised in Table 1.

### Methods

Spioenkop was sampled approximately monthly between July 1989 and May 1990, following reconnaissance studies during early spring (September) in 1987 and 1988. Routine monitoring in 1989/90 was undertaken around midday at a deep offshore station in the main basin of the lake (see Fig. 1), while sampling was done at various times at several sites (Fig. 1) within the main basin during the preceding spring surveys.

Vertical profiles of temperature (with dissolved oxygen in the 1987 survey), and underwater light intensity were measured using appropriate electronic meters (YSI thermistor thermometer, Lambda PAR radiometer).  $K_d$  PAR (m<sup>-1</sup>) was estimated conventionally as:

$$K_d = \frac{\ln I_0 - \ln I_z}{z}$$

Water transparency was determined with a white Secchi disc (20 cm diameter), while direct turbidity measurements of near-surface (0 to 2 m hose-pipe sampler) and deeper water (Van Dorn sampler) were made using a Hach turbidimeter.

Chlorophyll concentration was determined from integrated hose-pipe samples of water encompassing the upper 2 m of the water column. Samples were filtered on site (Whatmans GF/F filters); filters were briefly air-dried and stored in the dark during transportation to the laboratory, where boiling 95% methanol extraction was undertaken within 6 h of sample collection. Chlorophyll content ( $\mu\text{g}\cdot\text{L}^{-1}$ ) was determined from spectrophotometric absorbances (E) read at 665 and 750  $\mu\text{m}$ , using the conventional formulation:

$$\text{Chlorophyll } a = \frac{13.9 \times 0.89 \times (E_{665} - E_{750}) \times v}{V \times l}$$

where:

- v = volume of solvent (mL)
- V = volume of sample filtered (L)
- l = photometric light- path length (cm)

Values were not corrected for phaeo-pigments.

Attempts were made to determine phytoplankton abundance and composition using hose-pipe samples preserved in the field with Lugol's iodine, and subsequent conventional (Ütermohl) inverted microscopy analysis (Lund et al., 1958). However, this was unsuccessful in view of obscuring silt particles, and was accordingly discontinued after two months.

Primary production was estimated during the 1987 and 1988 surveys. Changes in dissolved oxygen concentration over an incubation period of around 6 h were measured by Winkler titration (Mackereth et al., 1978), in light and dark bottles suspended *in situ* at 10 cm intervals through the upper 1 m of the water column.

Zooplankton was collected in a conical tow-net, with mouth and reducing cone diameters of 25 and 50 cm respectively, and mesh aperture of 53  $\mu\text{m}$  (see legend to Fig. 6 for exception), hauled vertically from just above the lake bottom to the surface. Samples were briefly ( $\leq 30$  s) fixed by flooding with 95% ethanol, and then preserved with formalin (final concentration of  $\pm 5\%$ ) for subsequent laboratory analysis of the entire sample (for adult calanoid copepods, cladocerans, and *Chaoborus*) or variable subsample fractions (1/5 to 1/50) for cyclopoids and juvenile calanoid copepods, and rotifers. Biomass was estimated from numerical counts using pre-determined values of individual species and stage-specific dry mass.

Littoral benthic macro-invertebrates were collected during 1987 from representative marginal habitats (rocky, sandy and muddy substrata), in water depths ranging from 0 to approximately 1 m, using a sweep net with 0.5 mm mesh aperture. These qualitative samples were analysed in entirety, to provide a measure of relative abundance of the taxa collected. Semi-quantitative sampling (25 cm x 25 cm quadrats) was used to examine the distribution of this fauna in relation to distance from shore (and water depth).

## Results

### Thermal characteristics

Spioenkop showed a typical warm monomictic pattern of thermal stratification, with holomictic cool season circulation (Fig. 2a). While surface warming was evident by September, thermal stratification was not developed until December. Vertical penetration of surface-heated waters was pronounced, and seasonally continuous, as reflected particularly in the plunging 18°C isotherm (Fig. 2a). Sustained summer surface water temperatures were 24°C and above, with extreme surface heating evident in the mid-December

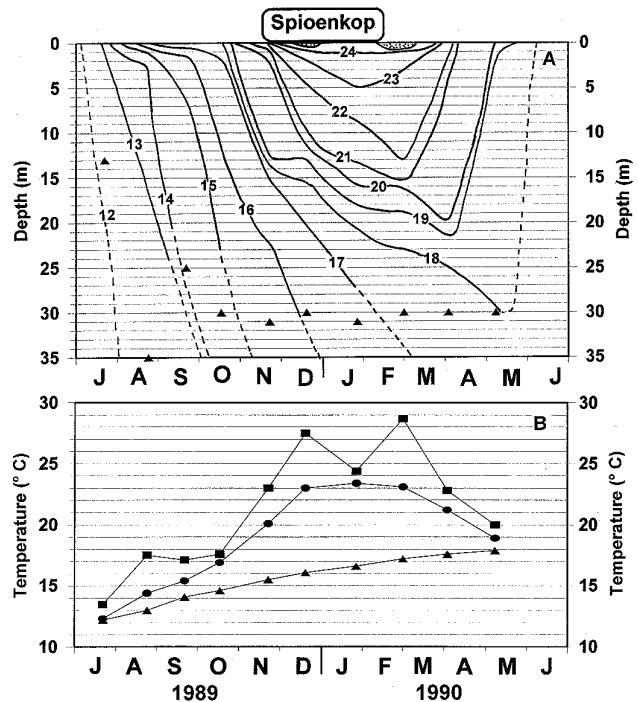


Figure 2

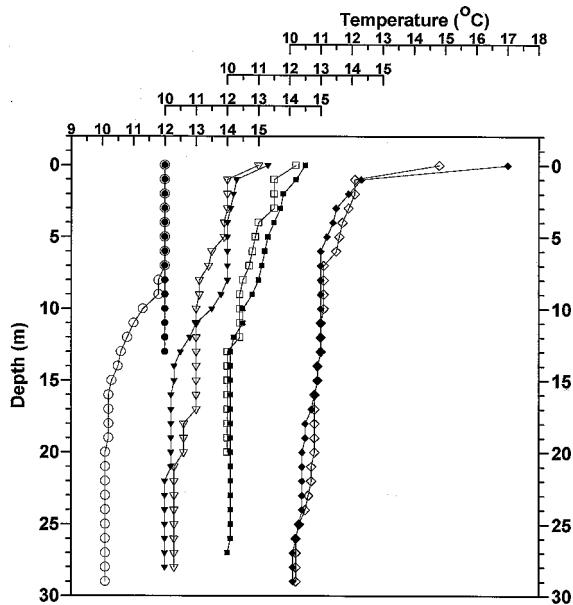
- A) Time-depth isopleth diagram (isotherms at 1°C intervals) for Spioenkop during 1989/90. Broken lines reflect isotherm extrapolations below a profile's deepest point ( $\blacktriangle$ ), and/or outside the period studied.
- B) Seasonal variation in temperature in surface ( $\blacksquare$ —) = 0 m,  $\bullet$ — = 2 m) and deep waters ( $\blacktriangle$ —), showing extent of vertical heat transfer during an annual cycle (1989/90).

and early March profiles (see Fig. 2b). Turnover occurred during April. Subsequent cooling to winter isothermy was not monitored, but was presumably very rapid, requiring cooling of the entire water column by some 6°C in little more than one month to return to the isothermal temperature (ca. 12°C) observed at the onset of the study. Such rapid heat loss is not incompatible with the severity of the local and neighbouring Drakensberg mountain climate (Schulze, 1997).

Figure 2b compares temperatures in surface (0 and 2 m) and deep waters (generally around 30 m). It illustrates both the localisation of surface heating (thermal gradients of up to 5°C over 2 m) and progressive vertical transfer of heat (hypolimnetic warming of some 6°C) in this turbid reservoir. Vertical profiles on several consecutive days during the spring 1987 and 1988 surveys indicated the rapidity of surface heating over several hours (Fig. 3), as well as considerable differences in isothermal temperatures between the two years (also see Table 2). Strong thermal differentiation (up to 4.5°C) between the relatively sheltered inflow region and open waters of the lake was evident during spring 1988, when respective temperatures of 19.5, 14.9, 16.5 and 15.0°C were recorded at Stations d, c, b and a (Fig. 1).

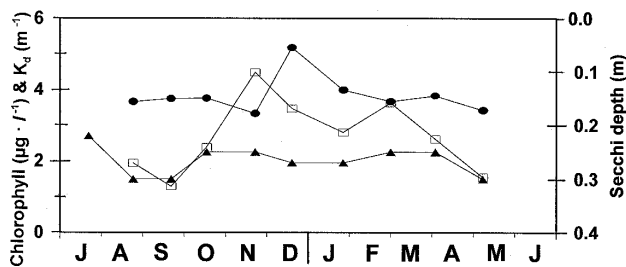
### Underwater light climate and turbidity

Spioenkop was consistently very turbid throughout this study period. Secchi depth transparency in the main basin was seldom greater than 0.3 m, and  $K_d$  PAR averaged 3.86  $\text{m}^{-1}$  (Fig. 4). The turbidity was predominantly of a mineral character, attributable to fine suspended clay particles obviously eroded from the upper catchment of the Thukela River.



**Figure 3**

Vertical thermal profiles measured on consecutive days at a range of stations illustrated in Fig. 1 during spring surveys in 1987. Open and shaded symbols distinguish "early" (ca. 09:00) and "late" (ca. 11:00) morning profiles on successive days (viz: ○ and ●; ▽ and ▼; □ and ■; ◇ and ◆) for illustrative purposes.



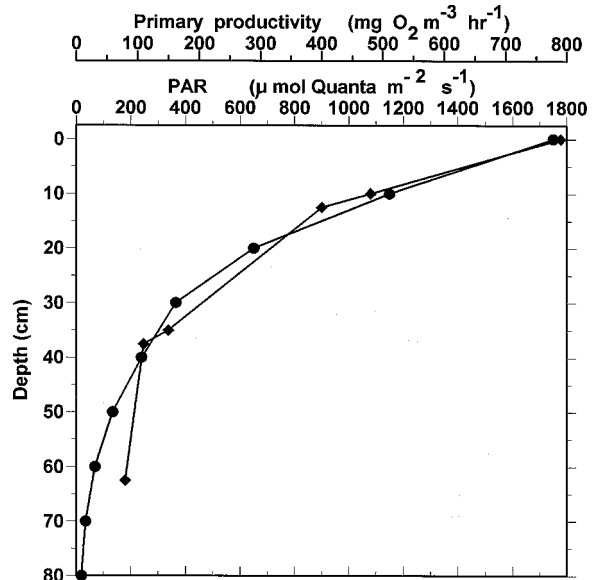
**Figure 4**

Seasonal changes in water transparency (—●— =  $K_d$  PAR, —▲— = Secchi depth) and chlorophyll content (—□—) of near surface river waters through one hydrographic year (1989/90).

No turbidity gradation between inflow reaches and the open waters of the lake was evident in early spring, when SD was uniformly around 15 cm at Stations a to d (Fig. 1). However, gradients would be expected to develop with the onset of stronger river inflows following summer rains. While the high mean flushing rate of Spioenkop (Table 1) undoubtedly reduces prospective sedimentation of fine colloidal particles with inherently low settling rates, some vertical turbidity differentiation was evident in spring 1988 (see Table 2), prior to the onset of the rainy season, perhaps reflecting sedimentation through the winter.

### Water chemistry

Discounting high turbidity, the water quality of Spioenkop was good (Table 2), with no remarkable or unusual chemical attributes, apart from the switch in anionic dominance of  $\text{SO}_4^{2-}$  and  $\text{Cl}^-$  relative to average river water ( $\text{Ca}^{2+} > \text{Mg}^{2+} > \text{Na}^+ > \text{K}^+$ ; and  $\text{CO}_3^{2-} > \text{SO}_4^{2-} > \text{Cl}^-$ ) (Wetzel, 1983). Waters were soft and circum-neutral, with little evidence of either phosphorus or nitrogen enrichment, al-



**Figure 5**

A typical primary production profile (—◆—) in relation to underwater light intensity (—●—)

though in terms of the Redfield ratio (Redfield, 1958), the average N:P ratio of 11.2 reflects marginal relative enrichment of P to N. While no measurements of dissolved oxygen were made during thermal stratification, serious hypolimnetic de-oxygenation is considered unlikely, in view of the oligotrophic nature of the reservoir.

Not surprisingly, seasonal and inter-annual variability was evident in several water quality variables measured by DWAF, but these are not examined here. A crude indication of some of the inter-annual variability observed between the three successive spring periods spanned by the present study is evident in Table 2, which reflects particular disparities in water clarity. This incomplete data set is included merely to emphasise the realities of such variability.

### Phytoplankton and primary production

Owing to sediment screening, only the relatively large diatom *Melosira* sp. (= *Aulacoseira* sp.) was evident in samples examined, and inverted microscopy was abandoned. However, measured as chlorophyll concentration, total phytoplankton abundance during the study period was reasonably high, particularly in regard to high prevailing levels of mineral turbidity. Seasonally, chlorophyll content varied nearly 3-fold, from winter lows barely greater than  $1 \mu\text{g}\cdot\text{l}^{-1}$  to summer highs above 3 to  $4 \mu\text{g}\cdot\text{l}^{-1}$  (Fig. 4). The concurrence of chlorophyll minima with transparency maxima is considered to be coincidental, reflecting reductions in transparency attributable to inputs of suspended sediment during summer rains rather than as biogenic turbidity associated with phytoplankton development.

Six primary production profiles determined in spring closely mirrored changes in underwater light intensity, with photosynthetic compensation points closely matching the depth reached by 1% of surface radiation. Figure 5 illustrates the most productive profile obtained (with a  $P_{\text{max}}$  value of  $750 \text{ mg O}_2\cdot\text{m}^{-3}\cdot\text{h}^{-1}$ ) from which integral daily production was estimated as  $500 \text{ mg C}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ . Values estimated for the other profiles were between 30% and 50% lower. No concurrent chlorophyll estimates are available.

**TABLE 2**  
**MAJOR WATER QUALITY VARIABLES AND DISSOLVED CONSTITUENTS DETERMINED ON > 200 SAMPLING DATES BETWEEN MARCH 1975 AND JUNE 1988. MEDIAN VALUES  $\pm$  95 % CL (IN  $\text{mg}\cdot\text{l}^{-1}$ , EXCEPT WHERE OTHERWISE INDICATED). DATA KINDLY SUPPLIED BY DWAF (GELDENHUYS ET AL., 1991). COMPARATIVE VALUES OF SELECTED WATER QUALITY ATTRIBUTES DURING SPRING IN THREE CONSECUTIVE YEARS (1987 TO 1989) ARE LISTED IN THE LOWER SECTION.**

Electrical conductivity ( $\text{mS}\cdot\text{m}^{-1}$ )	8.3	0.1
pH (pH units)	6.9	0.1
Total dissolved solids	61.0	1.0
$\text{Na}^+$	3.0	< 0.1
$\text{Mg}^{2+}$	3.0	< 0.1
$\text{Ca}^{2+}$	7.0	< 0.1
$\text{K}^+$	1.4	0.1
$\text{Si}^+$	6.0	< 0.1
Total ( $\text{CaCO}_3$ ) alkalinity	28.0	1.0
$\text{SO}_4^{2-}$	5.0	< 0.1
$\text{Cl}^-$	4.0	< 0.1
$\text{F}^-$	0.12	0.01
$\text{PO}_4 - \text{P}$	0.026	0.002
$\text{NH}_4 - \text{N}$	0.05	< 0.1
$\text{NO}_3 + \text{NO}_2 - \text{N}$	0.29	0.1

	7-10 Sep 1987	5-8 Sep 1988	20 Sep 1989
Chlorophyll ( $\mu\text{g}\cdot\text{l}^{-1}$ )	-	-	1.3
Primary production			
$\text{P}_{\text{max}}$ ( $\text{mgC}\cdot\text{m}^{-3}\cdot\text{h}^{-1}$ )	-	280	-
$\Sigma\text{P}$ ( $\text{mgC}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ )	-	60	-
$\Sigma\Sigma\text{P}$ ( $\text{mgC}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ )	-	500	-
Conductivity ( $\text{mS}\cdot\text{m}^{-1}$ )	-	5.4 - 6.8	-
Turbidity (NTU)			
< 20 m	60	92 - 112	-
> 20 m	-	122 - 145	-
Secchi transparency (cm)	17 - 22	15 - 18	30
$\text{K}_d\text{PAR}$ ( $\text{m}^{-1}$ )	5.3 - 6.1	4.9 - 6.5	4.1
Temperature ( $^{\circ}\text{C}$ )			
1 m	11.5 - 12.3	15.5 - 17.6	15.8
> 20 m	10.0 - 10.3	12.2 - 12.5	14.1
Dissolved oxygen (% saturation)			
1 m	95 - 100	-	-
> 20 m	90 - 95	-	-

**TABLE 3**  
**SYSTEMATIC LIST OF PLANKTONIC CRUSTACEA AND INSECTA COLLECTED FROM SPIOENKOP**

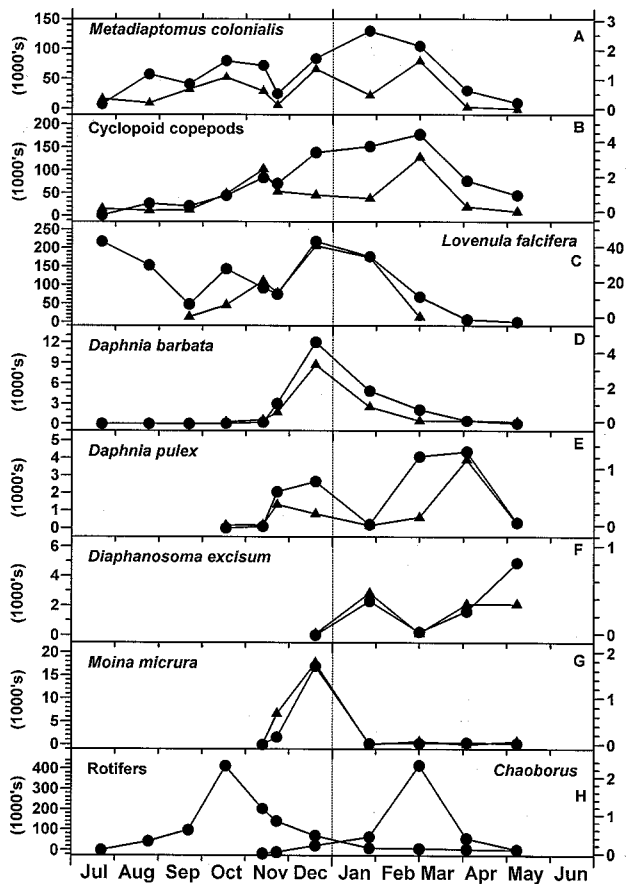
<b>Crustacea</b>
Cladocera
<i>Daphnia barbata</i> Weltner
<i>Daphnia pulex</i> Leydig
<i>Diaphanosoma excisum</i> Sars
<i>Moina micrura</i> Kurz
Copepoda
<i>Lovenula falcifera</i> (Lovén)
<i>Metadiaptomus colonialis</i> (Van Douwe)
Unidentified cyclopoid copepods
<b>Insecta</b>
<i>Chaoborus ? flavicans</i>

### Zooplankton

Zooplankton species collected during the study are listed in Table 3, while seasonal changes in their composition and abundance are shown in Fig. 6. All taxa apart from the predatory *Lovenula falcifera* (Fig. 6c) were very sparse at the start of the study, reflecting the strongly depressed winter zooplankton populations. Subsequent seasonal increases of all zooplankton taxa varied in magnitude and timing, although copepods (Figs. 6a to c) in general showed less seasonality than cladocerans (Figs. 6d to g) and other taxa (Fig. 6h).

The first major increase during the study was shown in spring by the rotifers (Fig. 6h), with subsequent strong increases shown by cladoceran taxa in summer. A minor peak of *Daphnia pulex* (Fig. 6e), and strong coincident peaks of *D. barbata* (Fig. 6d) and *Moina micrura* (Fig. 6g) developed in early summer, followed by a second peak of *D. pulex*. *Diaphanosoma excisum* showed the latest annual increase, only reaching its annual maximum on the final sampling date in late autumn (Fig. 6f), by which time all other zooplankton had virtually disappeared ahead of winter.

Unlike the generally sharp and relatively confined increases apparent in the cladocerans, copepod populations showed slower but sustained development. The cyclopoid copepod assemblage increased until early March (Fig. 6b), peaking concurrently with *Chaoborus* sp. (Fig. 6h), and the second peak of *D. pulex*. *Metadiaptomus colonialis*, a relatively small 'herbivorous' calanoid, gradually increased through the study (Fig. 6a), reaching its annual peak after the joint *D. barbata* and *M. micrura* maximum. The very large and relatively scarce predatory calanoid, *Lovenula falcifera*, was commonest at the start of the study, but declined thereafter until breeding females appeared in spring. Its population subsequently increased to a mid-summer peak coinci-



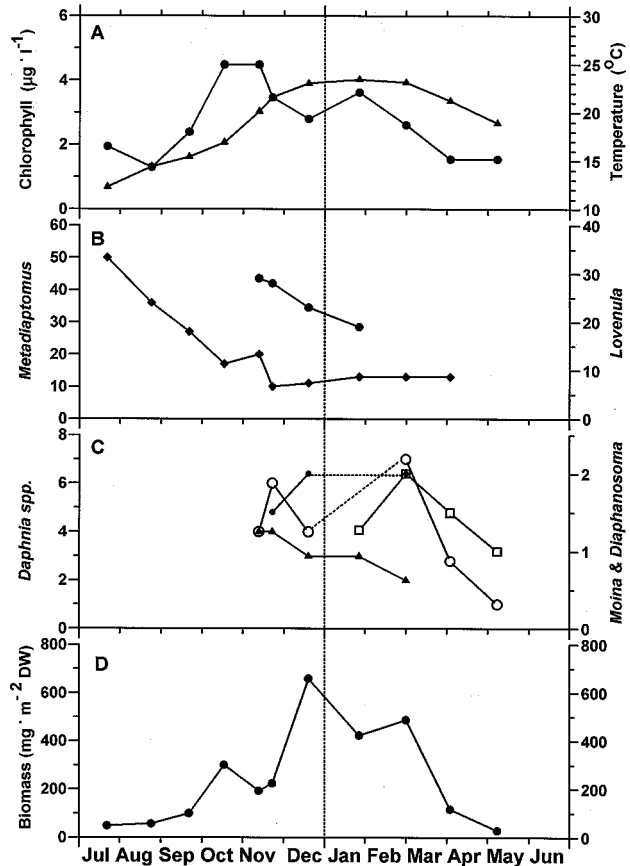
**Figure 6**

Seasonal occurrence and abundance (individuals  $m^{-2}$ ) of the named zooplankton taxa during 1989/90. Abundance values of breeding ( $\triangle$ ) right hand ordinates) and total ( $\bullet$ — left hand ordinates) populations of the crustacean taxa listed are plotted separately. Note that July 1989 estimates for small taxa (rotifers, copepod nauplii) are conservative, owing to use of a coarse net ( $158 \mu m$  mesh, cf  $53 \mu m$  in all subsequent samples).

dent with peaks of *D. barbata* and *M. micrura*.

*L. falcifera* showed a pattern substantially different from that evident in all other zooplankton taxa, in that the final autumnal population was substantially lower than that apparent at the onset of the study in late winter. If this is a consistent annual pattern, it suggests that the early spring peak may be attributable to a very early hatch of resting eggs, or emergence from a subsequent diapausing stage. Demographic analyses showing that breeding females were consistently present (except when densities were very low) in populations of all planktonic crustacean species apart from *L. falcifera* (Figs. 6a to g), is consistent with this. Although small sample size compromises this analysis, early populations of *L. falcifera* predominantly comprised juvenile instars, with adult stages only appearing subsequently.

Variation in fecundity was evident in all zooplankton species (Fig. 7), during their temporal occurrence in the system. In the apparently herbivorous *M. colonialis*, clutch size declined progressively and severely through the first half of the (hydrographic) year, and remained stable for the balance of the year (Fig. 7b), showing no obvious correlation with chlorophyll content (Fig. 7a). For most of the cladocerans (Fig. 7c), however, clutch size varied with chlorophyll content, seemingly reflecting changes in food availability. In predatory *Lovenula* (Fig. 7b), clutch size weakly



**Figure 7**

Seasonal changes in mean clutch size of (B) planktonic copepods (*Metadiaptomus colonialis* (left ordinate;  $\blacklozenge$ ) and *Lovenula falcifera* (right;  $\bullet$ —)) and (C) cladocerans (left: - *Daphnia* spp. ( $\blacktriangle$ ); *D. pulex* ( $\circ$ —); right: - *Moina micrura* ( $\bullet$ —) and *Diaphanosoma excisum* ( $\square$ —)), in relation to (A) chlorophyll content ( $\bullet$ —) and water temperature ( $\blacktriangle$ —) and (D) total zooplankton biomass during 1989/90.

paralleled changes in total zooplankton biomass (Fig. 7d), perhaps reflecting changes in its food supply.

### Littoral zoobenthos

Limited sampling of the littoral benthic fauna revealed the existence of profound differences between rocky and muddy shorelines (Table 4). The littoral zoobenthos was dominated by insect larvae - notably Ephemeroptera and Chironomidae - both in rocky and muddy shorelines, although species diversity and abundance of macro-invertebrates was notably greater on rocky than on gently-sloping muddy shorelines. Ephemeropteran larvae increased in abundance offshore quite consistently (Table 4 - lower), with chironomids showing a parallel trend on rocky shores, but no clear pattern on muddy shorelines.

Although numerically sparse, bivalve molluscs (*Unio caffer*) were conspicuous in some shallow margins of the reservoir.

### Fish

No fish sampling was undertaken, but some appraisal of the fish community is possible from angling catch returns, provided that the inevitably strong sampling bias which exists therein is borne in

mind. Table 5 show the existence of five indigenous and three exotic species. While catches appear overwhelmingly dominated both numerically and by mass by the exotic *Cyprinus carpio*, indigenous species held the subsequent five ranking catches (by mass). No information exists on the population structure of the angling species/catches.

## Discussion

### Seasonality

In keeping with the considerable annual climatic variability in the reservoir basin and its surrounds, seasonal variability was quite pronounced in Spioenkop. The annual thermal range of more than 10°C for the upper 5 m water column in Spioenkop broadly corresponds in magnitude with changes observed in Vanderkloof (Allanson et al., 1983), a comparably turbid but cooler reservoir. Vertical heat transfer was substantially greater in Spioenkop than in Vanderkloof, leading to more pronounced seasonal changes for the entire water column (Fig. 2b). This difference is unlikely to have influenced biological productivity, however, given the turbidity-generated light limitation in both lakes.

Zooplankton abundance (as biomass) varied more than 20-fold through the year, while by contrast, annual variations in chlorophyll, water transparency and water temperature were much lower, with respective ranges of approximately 5-fold, 2-fold, and barely 1½-fold (Fig. 7). Correlation analysis indicates that seasonal changes in zooplankton biomass were most strongly related to annual changes in water temperature ( $r^2 = 0.509$ ). In contrast, the

Taxon	Rocky %	Muddy %
Diptera: Chironomid larvae	23.8	33.3
Mosquito larvae	4.2	23.8
Ephemeroptera: larvae	48.3	28.6
Annelida: Hirudinea	9.4	7.1
Mollusca: Gastropoda	3.8	4.8
Miscellaneous taxa: (A)	1.0	0.0
(B)	2.4	0.0
(C)	5.2	0.0
(D)	1.7	0.0
Total sample size (n)	286	42

Distance offshore (m)		0 - 1	1 - 2	2 - 3	3 - 4
	Sub-stratum				
Chironomidae	Rocky	50	210	510	1000
	Muddy	2	13	12	4
Ephemeroptera	Rocky	20	80	70	105
	Muddy	0	1	7	16
Total	Rocky	70	290	580	1105
	Muddy	2	14	19	20

	Mean	Range
Fishing effort		
No. of anglers	1 407	737 - 2 124
No. of competitions	36	21 - 51
Man-hours fished	13 489	7 710 - 20 565
Total catch		
Number	1 074	579 - 1 729
Biomass (kg)	1 071	632 - 1 634
Carp ( <i>Cyprinus carpio</i> )		
No	833	464 - 1 388
kg	932	532 - 1 456
Eel ( <i>Anguilla mossambica</i> )		
No	60	14 - 117
kg	51	7 - 85
Scaly ( <i>Barbus natalensis</i> )		
No	103	7 - 240
kg	42	1 - 97
Catfish ( <i>Clarias gariepinus</i> )		
No	53	14 - 84
kg	39	9 - 73
Mudfish ( <i>Labeo rubromaculatus</i> )		
No	7	0 - 20
kg	3	0 - 6
Tilapia ( <i>Oreochromis mossambicus</i> )		
No	6	0 - 13
kg	2	0 - 6
Bass ( <i>Micropterus salmoides</i> )		
No	2	0 - 8
kg	< 1	0 - 4
Bluegill ( <i>Lepomis machrochirus</i> )		
No	11	0 - 61
kg	< 1	0 - 2

relationship with chlorophyll content was marginal ( $r^2 = 0.332$ ), while that with water transparency was barely apparent ( $r^2 = 0.029$ ).

In Spioenkop as in Vanderkloof (relevant papers in Hart, 1994), zooplankton abundance peaked between mid and late summer, in contrast to the spring peak commonly observed in clear-water monomictic lakes (Sommer et al., 1986). The annual development of zooplankton was furthermore unimodal, in contrast to the bimodal pattern common in temperate lakes. Winter depression of zooplankton was strong in Spioenkop, but less pronounced than in Vanderkloof, broadly in keeping with the slightly warmer conditions in Spioenkop during winter.

### Influences (and implications) of mineral turbidity

Many if not most limnological features of Spioenkop are attributable to the prevailing high levels of mineral

<p style="text-align: center;"><b>TABLE 6</b>  <b>COMPARATIVE PHYTOPLANKTON STANDING STOCKS AND PRIMARY PRODUCTION VALUES IN SOME TURBID SOUTH AFRICAN IMPOUNDMENTS. THE SECOND ROW FOR EACH NAMED LAKE SHOWS AVERAGE VALUES WHERE STATISTICALLY RELIABLE ESTIMATES ARE AVAILABLE.</b></p>					
Reservoir	Year	Secchi depth (cm)	Turbidity (NTU)	Chlorophyll $\mu\text{g}\cdot\text{L}^{-1}$	Primary production* (mg C·m <sup>-2</sup> ·d <sup>-1</sup> )
Gariiep (Hendrik Verwoerd) <sup>1</sup>	1971-73	-	-	-	0.5 - 623
Wuras <sup>1</sup>	1977-80	- -	- -	12 - 23 <sup>†</sup> -	190 - 2011 725
Vanderkloof (Le Roux) <sup>2,3</sup>	1977-84	23-75 -	- -	1.0 - 4.2 -	6 - 890 -
Spioenkop <sup>4</sup>	1988/89	22-30 27	90-145 -	1.3 - 4.5 2.7	240 - 500 -
<p>* Hourly rate measurements converted to daily estimates assuming a constant factor of 10, and oxygen values converted to carbon using 1 mg C = 0.375 mg O<sub>2</sub>.</p> <p>† Most frequent range - extremes excluded.</p>					
<p><b>Sources</b></p> <p><sup>1</sup> Stegmann (in Allanson et al., 1990)  <sup>2</sup> Allanson et al. (1983)  <sup>3</sup> Hart (1986)  <sup>4</sup> This study</p>					

turbidity, the strong or controlling influences of which on thermal behaviour, water chemistry, biological productivity and community structure are widely recognised (e.g. Marzolf, 1984; Allanson and Jackson, 1983; Allanson et al., 1990; Hart, 1994). As the general principals underlying these influences are familiar, only selected points of contextual relevance, regional topicality, or comparative value are discussed below.

A common interest and central concern with mineral turbidity relates to its overriding direct and indirect controls and influences on primary and secondary producers and their productivity. In this context, however, quantitative data are remarkably limited, both at regional and global scales (Allanson et al., 1990). Table 6 lists the comparative chlorophyll ranges and primary production estimates available for minerally turbid waters in South Africa. Ideally, the few oxygen-based primary production estimates for Spioenkop require corroboration with more sensitive and accurate radio-carbon assays. Despite the limited reliance which can be placed on them however, these values compare broadly with data recorded in other lakes, and generally, the variables in this limited data set (Table 6) exhibit a surprising level of internal consistency. Quantitatively, Spioenkop shows similarities with Vanderkloof, whereas the Wuras data reflect the much shallower depth and commensurately more favourable underwater light climate of that small reservoir.

Consequent on the light-limited primary productivity of Spioenkop, the abundance of secondary producer components is limited. At an annual average level of 240 mg·m<sup>-2</sup> DW (around 13 mg·m<sup>-3</sup>), total zooplankton standing stocks (Fig. 7) were low, and remarkably similar to those recorded in Vanderkloof during years of comparable turbidity (Hart, 1986).

Zooplankton clearly provides a rather limited resource base for higher trophic levels, especially zooplanktivores. Based on

a likely annual production to biomass (P/B) ratio of 50 (Hart 1987), zooplankton production in Spioenkop amounts to barely 12 g·m<sup>-2</sup>·a<sup>-1</sup>. At a transfer efficiency of 10%, this would support annual productivity in a subsequent trophic level of a mere 1.2 g·m<sup>-2</sup> (12 kg·ha<sup>-1</sup>), some 7-fold less than the weighted mean estimate of fish production/yield in South African reservoirs (Allanson et al., 1990). A corresponding depression of secondary production is implicit in the angling data, which reflects a low average CPUE of around 0.64 kg per angler-day (Table 5).

Several of the zooplankton collected in Spioenkop are characteristic of minerally turbid waters. Among the Cladocera, *Daphnia barbata* is exemplary in this regard, although the large-bodied *D. gibba*, another species characteristic of many turbid waters, was surprisingly absent. Large individuals of the more typically clear-water *D. pulex* were present, perhaps functioning as an ecological equivalent. The presence of this large cladoceran, along with *L. falcifera*, reflects the paucity of visual planktivory in turbid waters (Hart, 1994).

#### **Spioenkop as a mirror of the catchment, and comments on inter-basin transfer**

Transparency levels of Spioenkop were comparable to the characteristic modal range of 0 to 50 cm encountered in South African impoundments (Walmsley and Bruwer, 1980). However, the existence of such high turbidity in a lake so close to the headwaters of the Thukela River is very disturbing, particularly as these headwaters lie in the Royal Natal National Park nature conservancy area, and the presence of Woodstock, effectively a large upstream 'pre-impoundment' (Fig. 1). While sediment accumulation statistics for Woodstock (DWA, 1986a) imply little infilling, the boating experiences of long-standing residents (e.g. Dowling, 1998) are



directly contradictory, and indicate radical sediment infilling of Woodstock.

Local geology, topography, and meteorology (Midgley et al., 1994; Schulze, 1997) are natural factors pre-disposing the general catchment to high erosion rates. But Spioenkop also appears to be reflecting (*sensu* Hynes, 1975) undesirable anthropogenic developments. While overpopulation, with concomitant utilisation and overgrazing of steep and vulnerable upper catchment regions of the Thukela River is a legacy of the former socio-political climate and "Tribal Land" policy, sustainability of this river's water resources requires prudent and judicious management. Limitations on further or future developments, and the implementation of restoration measures, are environmentally warranted. Reduction of the agricultural livestock, especially in the sensitive upper catchment, is one obvious possibility to facilitate regeneration of the vegetal cover, thereby reducing sediment erosion. An improved holistic appraisal of the circumstances and issues facing these reservoirs is a clear necessity, requiring the incorporation of comparative data on Woodstock.

Inter-basin transfers, with their associated environmental impacts and costs, have become a significant management option to cater for burgeoning water demands in South Africa (Petitjean and Davies, 1988). Although only a peripheral component of the Thukela-Vaal inter-basin transfer scheme, Spioenkop merits passing consideration in this regard.

The only other reservoir in the scheme for which limnological studies exist is Sterkfontein. Lying at 1 620 m a.s.l. on the edge of the Drakensberg escarpment (Fig. 1), this very deep, high-capacity impoundment in a very small natural catchment, stores water pumped from the Thukela River into Driekloof, a small reservoir which abuts and overflows directly into Sterkfontein. Despite their common water source, Sterkfontein is much clearer than Spioenkop, with Secchi depths averaging more than 2 m at a deep open-water site (Dörgeloh et al., 1993). This difference in water clarity is remarkable, and remains largely inexplicable on available evidence. Sediment settling in either Driekloof and/or Driel Barrage can contribute only marginally to the difference in view of short hydrological residence times in these small reservoirs. Furthermore, given the severe sedimentation observed in Woodstock (Dowling, 1998), consequent both on natural effects and land-use malpractices in the upper catchment, it appears highly unlikely that turbidity of the Thukela River at the Driel Barrage pump off-take site (Fig. 1) can be radically lower than that downstream at Spioenkop. (If it is indeed lower, it would severely indict the land-use practices and activities in the intervening catchment area.)

Species (or genetic) transfers or introductions represent a pressing environmental concern associated with water transfer schemes. On the basis of the limited biotic surveys presently available, Sterkfontein and Spioenkop appear to support somewhat distinctive faunas, although prospects of species introductions remain. For instance, the low diversity of fishes collected in Sterkfontein during 1984/85 was attributed by Dörgeloh (1987) to the newness and artificiality of this reservoir, but he listed 13 additional species (including 5 exotics) known from the upper Thukela River, which could possibly reach Sterkfontein. Despite their illegality, purposeful transfers remain an unfortunate reality. For instance, the occurrence of *Clarias gariepinus* in the Spioenkop catches was attributed to an illegal introduction (Coke, 1985), in view of this indigenous species' natural restriction to the Thukela River below Colenso by the Thukela Falls at Hart's Hill (Fig. 1).

While no comprehensive listing of invertebrates has been published for Sterkfontein, mention of the presence therein of the copepod *Metadiaptomus meridianus* (Dörgeloh et al., 1993) indi-

cates the existence of distinct species within this calanoid genus between the two reservoirs. By contrast, a common species of the massive predatory copepod *Lovenula falcifera* occurs in both reservoirs (Rayner, 1992). Among the cladoceran zooplankton, only *D. pulex* is noted for Sterkfontein (Dörgeloh et al., 1993). The apparent absence of *D. barbata* is not surprising, given this species' typical occupancy of turbid waters, related to its feeding adaptations thereto (Hart, 1988).

## Conclusions

Spioenkop exemplifies many of the common features and attributes of turbid inland water ecosystems in Southern Africa. However, the information "transparency" implicit in this statement obscures a major deficiency of knowledge and understanding. Perhaps the most important message to emanate from the foregoing discussion concerns the sparsity of information and holistic integrated understanding about the reservoirs which collectively comprise the Thukela-Vaal scheme, despite its recognition as "undoubtedly the most important water transfer scheme in South Africa" (DWA, 1986b). Particularly needed in the limnological arena are investigations extensive enough to incorporate and address intrinsic seasonal variability, the general predictability of which is seriously limited under the inherently variable conditions which constitute the Southern African environment. While hard evidence may be limited, clear indications of unsustainable land management practices are evident in the foregoing account. Holistically integrated catchment management is an obvious prerequisite for sustainability not only of pricelessly precious water resources, but of the terrestrial ecosystem(s) from which these waters drain. This is an inescapable challenge for the New South Africa.

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## Note added in proof

In view of the long delay in publication of these data, some update on Spioenkop's status was called for by one reviewer, and the lake was accordingly visited and inspected on 23 May 1999. This single spot sample provided no basis to revise opinions expressed in the foregoing discussion. With SD readings of 25 cm, no improvement in mineral turbidity was evident; and conversely, prolific growths of filamentous algae on rocks in the wave-wash zone suggested that significant nutrient enrichment may have occurred in the interim. These observations collectively indicate that inferences regarding catchment conditions made above still prevail, and may indeed have deteriorated further. The collection of a freshwater shrimp

(*Caridina nilotica*) in vertical plankton trawls during this visit also provided a new species record for the lake.

## References

- ALLANSON BR, HART RC, O'KEEFFE JH and ROBARTS RD (1990) *Inland Waters of Southern Africa. An Ecological Perspective*. Kluwer Academic Press Dordrecht. 458pp.
- ALLANSON BR and JACKSON PBN (eds.) (1983) *The Limnology and Fisheries Potential of Lake Le Roux*. South African National Scientific Programmes Report No. 77. CSIR, Pretoria. 182 pp.
- COKE M (1985) Angling quality at Spienkop from 1976 to 1985. Unpublished report. Natal Parks Board, Pietermaritzburg. Unpaginated.
- DÖRGELOH WG (1987) Fish species in Sterkfontein Dam, Tugela-Vaal System, South Africa. *J. Limnol. Soc. South. Afr.* **13** 48-49.
- DÖRGELOH WG, SEAMAN MT and GAIGHER IG (1993) The physical and chemical limnology of Sterkfontein Dam, eastern Orange Free State, South Africa. *Water SA* **19** 177-184.
- DOWLING DA (1988) Personal communication. Private individual.
- DWA (1986a) *Management of the Water Resources of the Republic of South Africa*. Department of Water Affairs, Pretoria.
- DWA (1986b) *Water Transfer Schemes in RSA*. Information Brochure, Department of Water Affairs, Pretoria. 19 pp.
- GELDENHUYS W, NELL U and VAN VEELLEN M (1991) Surface Water Quality of South Africa; 1979 - 1988. Technical Report Number 145. Department of Water Affairs and Forestry, Pretoria. 27 pp + appendices.
- HART RC (1986) Zooplankton abundance, community structure and dynamics in relation to inorganic turbidity, and their implications for a potential fishery in subtropical Lake le Roux, South Africa. *Freshwater Biol.* **16** 351-371.
- HART RC (1987) Population dynamics and production of five crustacean zooplankters in a subtropical reservoir during years of contrasting turbidity. *Freshwater Biol.* **18** 287-318.
- HART RC (1988) Zooplankton feeding rates in relation to suspended sediment content: Potential influences on community structure in a turbid reservoir. *Freshwater Biol.* **19** 123-139.
- HART RC (1994) Quantitative and Experimental Studies on the Ecology, Dynamics, and Productivity of Plankton and Benthos: Contributions to the Biological Limnology of Warm and Turbid Lakes in Particular. D.Sc. Dissertation, Univ. of Natal, Pietermaritzburg.
- HYNES HBN (1975) The stream and its valley. *Verh. Int. Verein. Limnol.* **19** 1-15.
- LUND JWG, KIPLING C and LeCREN ED (1958) The inverted microscope method of estimating algal numbers and the statistical basis of estimations by counting. *Hydrobiol.* **11** 143-170.
- MACKERETH FJH, HERON J and TALLING JF (1978) *Water Analysis: Some Revised Methods for Limnologists*. Scientific Publication No 36 Freshwater Biological Association, Ambleside. 120 pp.
- MARZOLF GR (1984) Reservoirs in the Great Plains of North America. In: Taub FB (ed.) *Ecosystems of the World 23. Lakes and Reservoirs*. Elsevier. 291-302.
- MIDGLEY DC, PITMAN W V and MIDDLETON BJ (1994) Surface Water Resources of South Africa 1990: Volume VI. Report Number 298/6.1/94. Water Research Commission, Pretoria.
- NOBLE RG and HEMENS J (1978) Inland Water Ecosystems in South Africa - A Review of Research Needs. South African National Scientific Programmes Report Number 34. CSIR, Pretoria. 150 pp.
- PETITJEAN MOG and DAVIES BR (1988) Ecological impacts of inter-basin transfers - Some case studies, research requirements and assessment procedures. *S. Afr. J. Sci.* **84** 819-824.
- RAYNER NA (1992) Revision of the freshwater diaptomid genus *Lovenula* (Crustacea, Copepoda) in Africa. *Ann. S. Afr. Mus.* **101** 297-332.
- REDFIELD AC (1958) The biological control of chemical factors in the environment. *Am. Sci.* **46** 205-221.
- SHULZE RE (1997) South African Atlas of Agrohydrology and -Climatology. Report Number TT82/96. Water Research Commission, Pretoria. 276 pp.
- SOMMER U, GLIWICZ ZM, LAMPERT W and DUNCAN A (1986) The PEG-Model of seasonal successional events in fresh waters. *Arch. Hydrobiol.* **106** 433-471.
- UYS M (1996) A Structural Analysis of the Water Allocation Mechanism of the Water Act 54 of 1956 in the Light of the Requirements of Competing Water User Sectors. Report Number 406/1/96. Water Research Commission, Pretoria. 793 pp.
- WALMSLEY RD and BRUWER CA (1980) Water transparency characteristics of South African impoundments. *J. Limnol. Soc. South. Afr.* **6** 69-76.
- WETZEL RG (1983) *Limnology* (2nd edn). WB Saunders, Philadelphia. 767 + 81 + 10 pp.