THE ECOLOGY OF SOME URBAN-IMPACTED COASTAL VLEIS ON THE CAPE FLATS NEAR CAPE TOWN, WITH SPECIAL REFERENCE TO PHYTOPLANKTON PERIODICITY.

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PREFACE

This thesis stemmed initially from the author's desire to investigate the phytoplankton assemblages of the freshwater vleis of the Cape Peninsula. This aspect of the limnology of the Cape Flats vleis has received only scant attention by other researchers (over 40 years ago), and no comprehensive studies of their seasonal phytoplankton periodicities had been attempted. The paucity of information regarding the phytoplankton of the winter-rainfall, Mediterranean-climatic systems of the Cape Peninsula was found to not only be limited to South Africa. The literature survey undertaken for this study (Chapter 1) revealed a general lack of information for shallow, nutrient-enriched, coastal systems, with virtually no data available for coastal systems in winter-rainfall regions.

The thesis includes a description not only of the phytoplankton, but also of the limnology of each vlei as they are currently understood; this information is synthesized in Chapters 2 and 3 and collates all the available information accumulated by the Cape Town City Council (CCC) since it commenced monitoring of both vleis almost a decade ago. These chapters also contain details of the available bibliography for each system and form the first compilation of the available data for these waters. The inclusion of these chapters enabled comparisons to be made between the water chemistry regimes during the current study with those prevailing during earlier years. During the course of the study the author came across other pertinent aspects of each vlei which necessitated sub-investigations. The details of these are also included in the limnological chapters.

The study of the phytoplankton assemblages and periodicity covers two full years, and the work is continuing as part of the routine monitoring programmes of the two vleis. The first year's data for each vlei are included in the limnology chapters, and the data for the full two-year study is dealt with in detail in Chapters 4 and 5.

Each chapter was written as a separate entity to facilitate their individual use either for internal (CCC) reporting or for later publication. The chapters were not written in chronological sequence, but are cross-referenced in the text, where necessary, to clarify various aspects.

The work attempts not only to provide a detailed, introductory account of the phytoplankton ecology of both Zeekoevlei and Princess Vlei, but also addresses certain crucial aspects of each waterbody pertinent to their rehabilitation and management. Both vleis, and Zeekoevlei in particular, are the focus of on-going City Council investigations which have as their goal the formulation of management strategies for their rehabilitation in an urban-impacted context. In this context, Chapter 6 addresses the options available for the rehabilitation of Zeekoevlei, a grossly nutrient-enriched waterbody which, in its class, probably has no equal elsewhere in the world.

CAPE TOWN
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WATER

Nothing is lovelier than moving water,
The diamond element, innumerable jewel,
Brittle and splintering under the sharp sun,
Yet softer than dove's feathers and more smooth
Than down of swan.

Nothing is lovelier than water lying still,
When the moon takes that stillness for her glass.

Gerald Bullett
Poems in Pencil, 1937

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SUMMARY

This study examines the phytoplankton periodicity in two shallow, freshwater lakes (vleis) situated on the Cape Peninsula near Cape Town, South Africa. Although a significant data-base of physical and chemical variables for the two lakes has previously been accumulated, no long term studies of the phytoplankton diversity and periodicity have been undertaken in either system.

The manuscript is divided into six chapters and an appendix, with each chapter written as a separate entity to facilitate its later incorporation into publications. Chapter 1 consists of a review covering the literature on phytoplankton periodicity between 1975 and 1991. The paucity of available information on shallow, winter rainfall region systems such as the two forming the focus of this work, is highlighted. The concepts of algal succession and periodicity are examined and the results of both local and overseas studies are evaluated.

Chapters 2 and 3 provide descriptions of the limnological features of, respectively, Zeekoevlei and Princess Vlei. The period covered by this authors involvement, *viz.* 1989-1991, is compared with data previously collected for each system by the City of Cape Town (CCC), and these two chapters constitute the first compilation of this [CCC] information. The two lakes contrast each other in that the larger Zeekoevlei is poorly-flushed, hyper-eutrophic and dominated year-round by the cyanobacterium *Microcystis* spp., while Princess Vlei, which is one-tenth the size of Zeekoevlei, is subject to hydraulic removal of phytoplankton biomass and shows signs of being biologically disturbed. The reasons for the latters biologically perturbed condition are not clear. Inadequate management of the Zeekoevlei catchment has resulted in very high loads of nitrogen and phosphorus being delivered to the lake via catchment runoff for many years.

Chapters 4 and 5 provide a detailed description of the phytoplankton assemblages and periodicities of the two lakes for the period April 1989 to March 1991. The features of each lakes phytoplankton periodicity are described in relation to the prevailing environmental forcing factors and discussed with a view to future management options for each system. A combination of morphological, climatic and nutrient factors have resulted in Zeekoevlei presenting as a well stirred reactor having conditions ideally conducive to sustaining large populations of *Microcystis*. Hydraulic changes in Princess Vlei have served to offset and control dominance of this smaller lake by cyanobacteria, although the system appears to be readily susceptible to colonization by genera of *Anabaena* and *Microcystis*.

Chapter 6 is a detailed study of the available management options for Zeekoevlei, with special attention being paid to the reasons why the system is dominated by the blue-green alga, *Microcystis* spp. The management options are considered in two catagories, *viz.* catchment- and lake based. It is quite clear from this that any attempts undertaken to improve the conditions in the vlei would prove useless without prior control of the high nutrient loadings emanating from the catchment.

Chapter 7 is a taxonomic list of the algal genera and species identified, and includes a photomicrograph record of many of the genera recorded.

CHAPTER 1

LITERATURE REVIEW

SUCCESSION AND PERIODICITY IN FRESHWATER PHYTOPLANKTON POPULATIONS

1. INTRODUCTION

The taxonomic composition of phytoplankton communities, and the abundance and relative dominance of the different species and groups present, undergo continuous change. This process of continuous community change is termed "succession". Evidence is growing that species successions are of major importance to phytoplankton dynamics and in the coupling of the phytoplankton community to higher trophic levels (Smayda, 1980).

The seasonal succession of algae is a phenomenon which has long attracted the attention of algologists (Smith, 1950). The first assessments of phytoplankton seasonality originated in 1899 (Talling, 1986). Between 1900 and 1945 several studies were made, none of which were of sufficient duration to provide anything more than speculations about algal seasonality. Pearsall established in 1932 that algal populations undergo regular seasonal changes. Since the time of these early studies, a mass of work has been published, principally based on information gleaned from studies of temperate systems.

The primary producers in the hydrosphere belong mostly to the phytoplankton and are almost exclusively unicellular algae (Jorgensen and Vollenweider, 1989). The transfer of food energy to the next stage of the food chain is occasioned by the grazing of phytoplankton by zooplankton and/or their predation by fish. Autotrophic phytoplankton and higher plants (macrophytes) produce biomass from photosynthesis and simple inorganic substances and thus constitute themselves as the photosynthetic primary producers in an aquatic system.

Many of the tenets of periodicity in aquatic systems have been based on the better understood terrestrial succession process (eg Odum, 1971). In the terrestrial model, areas of land are sucessively invaded by recognizable plant communities. This process has distinct sequences ("seres") and passes from pioneer to climax stages (bare ground to forest), with the overall pathway subject to suspension ("plagioclimax"), brought about by sustained maintenance of farmlands, for example, or reversions, occasioned by events such as fires. Such reversions to a more primitive stage in this seral succession do not ultimately affect arrival at the climax stage. Each stage in the successional process alters the environment so that it is prepared for the next, the principal driving process being "autogenic".

Aquatic succession differs from that on land in that environmental selection operates over frequent and much shorter time scales. The "directionality" of terrestrial succession, and emphasis of the need for an improved understanding of directionality in aquatic systems, is excellently described by C.S.Reynolds in a number of publications (eg. 1976; 1980), and in his book (Reynolds, 1983; Chapter 8). "Pioneer" algal species in the epilimnion become progressively nutrient- and light limited, and better suited species, although having lower absolute growth rates, gain the advantage. As long as the water column remains stable, segregation into an upper, nutrient-deficient layer and a lower, light-deficient one takes place. Such responses are, as in the case of terrestrial succession, "autogenic", and are considered by Reynolds (1983) to be equatable with strict succession. Responses to mixing and other "allogenic" forcing-factors bring about short-lived perturbations, or "reversions", whereas sustained events occasion "shifts", and a new community, which is out of the successional sequence, is the outcome. It is therefore necessary to distinguish between autogenic successional progression and allogenic changes (Reynolds, 1982).

One of the typical features of most phytoplankton populations is their relatively short duration. After the population has reached maximal density it, typically, disappears rapidly, the growth and decline cycle lasting (on average) 4 - 8 weeks. The best known example of this is the spring growth of diatoms in temperate waters. Successive populations may grow and then decline at various periods throughout the year, producing the phenomenon known as "phytoplankton succession". In certain cases the successional sequence remains relatively constant for a specific water body from year to year (Golterman, 1975). It is common for a single species to dominate, although it is also quite common for other species to be present in larger or smaller numbers (see Section 4.3).

The composition of phytoplankton communities undergoes continuous changes in response to various stimuli. These range from reorganizations in response to wind-induced mixing and variations due to temperature stratification, to rainfall-generally behave induced flushing (increased hydraulic throughput) and nutrient enrichment. Such changes can vary from short term duration (mixing) to long term floristic changes caused, for example, by increased run-off or by increased nutrient loading as a consequence of morphological changes or anthropogenic effects (eg. Reynolds, 1983).

Determining the composition and successional features of the algal community in a water body provides an insight into the reaction of that system to environmental perturbations (eg. light, turbulence, temperature, throughflow), being imposed upon it. The seasonal succession in most waterbodies forms one of the important indices of the stability of the plankton community, and the extent of its adaptation to habitation conditions (Trifonova, 1986). In addition to the naturally occurring imposed forces of light, temperature, wind and rainfall, most lakes and vleis, especially those situated near to major or developing cities, are subject to varying degrees of nutrient imbalance as a result of point and non-point source pollution leading to nutrient enrichment (eutrophication). Socially, the occurrence of large scums of algae, or "green" waterbodies, results in user-avoidance with possible economic and other problems.

Variability within phytoplankton populations is considered to be a problem in using them for assessing the eutrophication of lakes (Rott, 1984), although Reynolds (1983) has put forward the view that algal populations may follow predictable pathways which are controlled by mechanisms common to all. Changes in the phytoplankton composition, measured against a reference (data base) of the algal succession in a particular system, provide a measure of the degree of perturbation to which that system has been subjected and supplies insights as to the way in which the system will respond to additional stresses. Studies of the phytoplankton populations resident within a particular system must be viewed as forming part of a dynamic entity with respect to the monitoring of changes within that system in response to seasonal or pollution events (see Section 6).

C.S. Reynolds, in his treatise entitled "Ecology of the Freshwater Phytoplankton" (1983) provides an excellent overview of most, if not all, of the aspects pertaining to algal ecology and periodicity, as well as the factors affecting the periodic sequences. For this reason, this work is extensively referred to in this review.

2. PHYTOPLANKTON

Reynolds (1983) describes plankton as "the community of plants and animals adapted to suspension in the sea or in freshwaters and which is liable to passive movement by wind and current". Plankton occurs mainly near the surface (epilimnion) where the plants obtain suitable illumination. As yet, no generally accepted universal taxonomic classification system exists for the algae, and several of those in existence are constantly in a state of flux as classifications are reviewed and names are changed. In addition to this existence of a variety of taxonomic systems existing for the classification of algae, additional systems have been proposed for their further classification according to the type of water body (eg lake, river) which they inhabit. Certain species show considerable overlap with respect to where they occur, and some dispute still exists concerning the overlap of certain classes, eg dinoflagellates, which are both phagotrophic and autotrophic. Further classification is provided by grouping the phytoplankton according to size. Reynolds (1983) proposes that the terms net- and nano-plankton are sufficient in this respect, provided that adequate quantification of the size ranges is supplied.

Plankton communities comprise bacteria, phytoplankton and zooplankton, as well as the infective stages of certain actinomycetes and fungi (Reynolds, 1983). Of these, the algae are the most obvious and will form the subject of this review. The importance of the other forms, however, should not be ignored as the contribution of bacterial biomass (bacterioplankton) to a dynamic system, may be quite considerable (see Pedros-Alio, 1989). The faculty of autotrophy is a defining characteristic for inclusion under the heading of phytoplankton.

Also, not all algae are planktonic. For the purposes of this review the characteristics of being photo-autotrophic and "free-floating" or flagellated (eg. *Euglena* or *Cryptomonas* spp.) will be considered sufficient for inclusion under the term "phytoplankton".

3. SUCCESSION AND PERIODICITY

The term "seasonal succession" implies an annual repetition of events in response to the stresses imposed upon a system by the climatic events seasonally characteristic of a particular region of the world. Ashton (1985) points out that the term "seasonal succession" is derived originally from higher (terrestrial) plant systems and represented changes brought about by nutrient and habitat variations. Used thus in the aquatic context, it can imply that annual changes are in response to nutrient availibility and therefore does not account for changes in the physical environment. Ashton (*ibid.*) goes on to point out that it is now accepted that physical, chemical and biotic factors are involved in the successional process. The terrestrial successional process is considered to be directional, predictable and self-regulating (Smayda, 1980). In aquatic systems, however, frequent unpredictable changes occur, for example wind-induced mixing, which can disrupt the entire system within a very short time. This aquatic seasonal succession process does not coincide with concepts of terrestrial succession in that strongly directional components are not easily definable within a phytoplankton assemblage (Lewis, 1978).

Reynolds (1984) viewed the term "seasonal succession" as misleading, and suggested that periodicity (periodic change in species composition) should be adhered to. The term "seasonal periodicity", in this context, may in turn be misleading as it may be confused with changes in growth rates as the seasons change (Golterman, 1975). "Succession" is a widely-accepted biological concept which, according to Reynolds, implies a strongly pre-determined bias in the sequence regarding which species or groups will dominate a community. Reynolds (1984) proposed that the term "succession" be used to describe autogenic sequences and that it should not be used synonymously with periodicity as the latter can be driven by allogenic variables.

Work by Lewis (1978,1978a,1986), Reynolds (1983 and 1984) and Reynolds *et al* (1983) has shown that other physical factors, such as water column stability and mixing processes, are controlling factors in successional sequences with respect to freshwater phytoplankton populations. These factors will be dealt with under the heading "Factors affecting phytoplankton periodicity." The term "periodicity", as used by these two authors, implies a repetitive cycle of events and they distinguish between autogenic changes brought about by the phytoplankton, and allogenic changes caused by external influences (see Odum, 1971).

Smayda (1980) defined succession as the "process of continuous community reorganization". He further illustrated that a progression within a community can result from two different "primary mechanisms", these being "succession", whereby change originates from a change in a physical, chemical or biological nature, or "sequence", where the origin is a change in water-mass type. This implies that successional events originate from within the system, whilst sequential changes originate from external (allochotonous) inputs. Smayda pointed out that true succession and sequencing rarely occur, and that what actually takes place is a series of successional and sequential events producing the observed seasonal progression. Lewin (1962) pointed out that changes in the algal floras of different water bodies can seldom be attributed to a single factor, and that such changes can be greater than is suggested by the analysis of the major inorganic nutrients. Notwithstanding this, there exists a hierarchial sequence of factors, which, in descending order, move from interactions involving physical factors, to chemical and then to biotic factors (Reynolds, 1984).

Sommer (1989) provided a fresh perspective by observing that succession can have two different meanings: the "*loose concept*", which defines succession as a time series of species replacements; and the "*restrictive concept*", which reserves the term "succession" for those events, in a chain of species replacements, that are a consequence of preceeding ones. Shifts in direct response to external forcing factors do not qualify as succession.

Trifonova (1986) divided succession into two types:- general or main succession, associated with the evolution of the lake or waterbody; and seasonal succession, brought about by the periodic dominance of successive algal populations in the annual cycle.

Several authors have shown that algal periodicity (succession) cycles are similar in geographically remote lakes, ie. that such patterns are common to whole series of water bodies sharing similar properties of morphometry and trophic status. Reynolds (1984) showed that a high degree of similarity existed amongst periodic cycles between temperate lakes at high and low latitudes, as well as in rivers. Lewis (1978,1978a) has illustrated the similarity of seasonal phytoplankton events between tropical and temperate lakes. This aspect of "seasonal paradigm" similarity will be considered below (see also Ashton, 1985; Sommer *et al.*, 1986).

Succession implies a change in the relative abundance of species in a community and that such change is directional in nature (Lewis, 1978a).In an attempt to provide a measure with which to compare communities, the concept of "succession rate" (ie. the rate of change of phytoplankton species composition) was introduced (Jassby and Goldman, 1974). Lewis (1978a) introduced a new measure of succession rate which reduces the reliance made on certain assumptions in the Jassby-Goldman index.

4. FRESHWATER PHYTOPLANKTON PERIODICITY

This section of the review will address the concept of phytoplankton periodicity as it has been studied by other researchers. Methodology, duration of studies, the factors affecting phytoplankton periodicity and comparisons between seasonal cycles, observed in temperate and tropical climates, with those in sub-tropical and Mediterranean climates, will be considered.

The scarcity of available data for sub-tropical (Southern Africa in particular) and Mediterranean regions will be highlighted against the mass of data which has arisen from a long European involvement in algal periodicity studies. In addition, this review illustrates the fact that a scarcity of data exists regarding phytoplankton succession in small water bodies such as ponds and vleis.

The aim of this review has not been to reexamine all the facets of phytoplankton periodicity, but to consider the thrust of investigations since *circa* 1975. Aspects of phytoplankton periodicity studied prior to the 1970's are excellently reviewed by Hutchinson (1967). Additional works pertaining to phytoplankton studies on the African continent may be found in the Limnological Bibliography for Africa south of the Sahara (numbers 1-40), compiled by A. Jacot-Guillarmod and P. Eva under the auspices of the Limnological Society of Southern Africa (now the South African Association of Aquatic Scientists), and the mammoth directory and bibliography on African wetlands and shallow water bodies by Burgis and Symoens (1987), and Davies and Gasse (1987), respectively.

4.1 Extent of studies and global coverage

The considerable literature on seasonal periodicity is largely concerned with qualitative aspects of species and community succession, or changes in some measure of algal abundance such as chlorophyll (eg. Lewin, 1962).

The periodicity of phytoplankton populations has been reviewed at length by Hutchinson (1967), Reynolds (1983) and Smayda (1980). Smayda's review covered succession in oceanic, coastal (both shallow and deep) and other habitats, as well as addressing the factors which regulate species succession. Succession in plankton communities in general has recently been reviewed by Sommer (1989).

Ashton (1985) compared the factors affecting seasonal patterns of algal abundance and species composition in equatorial and low-latitude temperate regions of the Southern Hemisphere, with similar features in the Northern Hemisphere. He found that a common sequence existed at class level, despite the gross variations in climate. In his paper, Ashton stated that few quantitative investigations have been undertaken on Southern Hemisphere phytoplankton populations, and none on seasonal changes in phytoplankton community structure in South African rivers. Ashton (1985) conceded that much of the information in his review had been extracted from eutrophication-related studies, in which phytoplankton-population analysis had played a relatively minor role. Despite this, Ashton found that there were enough data from chlorophyll a measurements and algal observations to permit comparisons to be made with Northern Hemisphere studies. He pointed out, however, that whilst chlorophyll a concentrations provide an easy method of following changes in phytoplankton biomass, there are obvious shortcomings with the method, as chlorophyll a levels are dissimilar for different classes of phytoplankton, and may vary with varying nutrient levels. With respect to the use of chlorophyll a measurements in phytoplankton studies, Reynolds (1983) stated that there is a *"need to know more about individual common organisms, and not convenient correlations of total biomass"*'.

Talling (1986) reviewed the seasonality of phytoplankton in African lakes, and found that whilst numerous studies had been made in the equatorial region, only four studies were listed for Southern Hemisphere, two of which formed part of the same extended study involved primarily with the study of hyper-eutrophication in Hartbeespoort Dam, South Africa, the third was conducted before 1930 on a small artificial lake, Florida Lake, Transvaal (Schuurman, 1932) and the fourth at Lake Sibaya, Natal (Hart and Hart, 1977). Reynolds (1984) estimated that, since the review of Hutchinson (1967), some 200 articles relating to succession had been published, of which 160 related to Europe and North America with the remainder concentrating on African and Australian systems.

Schindler (1978) reviewed a variety of world lakes in order to produce a regression analysis for various parameters based on global data. Whilst the lakes reviewed represented wide ranges of area, mean depth and nutrient state, only three out of 64 were situated outside the temperate region, and only one of these was in the Southern Hemisphere. Thus, the findings were heavily weighted for temperate, Northern Hemisphere lakes (see "Factors affecting phytoplankton production").

In the development of the Plankton Ecology Group (PEG) model (Sommer *et al.*, 1986; Section 6), 24 lake systems were compared to an "ideal" lake (temperate, large, deep and stratifying). In an attempt to establish a global dichotomy, 24 water bodies were compared, with only two of these (Lakes Le Roux and Sibaya) being from a sub-tropical Southern Hemisphere region.

A survey of articles contained in the South African Waterlit Database from 1975 to 1989 revealed 76 articles pertaining to studies of algal succession. Of these, 62 were undertaken in northern temperate regions, 9 in sub-tropical regions, 3 in mediterranean climates (Europe and South America) and 2 in the tropics (personal observation).

Thornton (1986) has stated that the role of phytoplankton in the nutrient cycling of shallow lakes is virtually unknown. Studies of eutrophic lakes tend only to afford minor attention to the dynamics of phytoplankton populations and their interrelationships with water quality and environmental conditions. This makes it difficult to assess with any precision whether or not observed trends are increasing or decreasing.

A large number of studies have been made of phytoplankton periodicity, but few have attempted to explain why the observed patterns occur (Reynolds, 1983). Some classical studies on individual lakes or groups of lakes have established clear year to year similarities, and to a lesser extent, lake to lake similarities. The available data, principally for the Northern Hemisphere, show that the periodic patterns are broadly repeated in geographically remote lakes having similar morphometric, climatological and chemical properties. Lake Windermere (UK) has shown similar successional cycles for 30 successive years.

With respect to lakes at lower latitudes (ie. nearer the equator), the phytoplankton populations of these generally behave in a manner similar to their temperate counterparts, with the exception that irradiance intensities may be higher, surface water temperatures are correspondingly higher and temperature controlled density gradients will be more stable (Reynolds, 1983).

Despite their absolute abundance in the world, very few small water bodies (ponds, vleis) have been studied to permit any generalized assessment of the ecology of their phytoplankton populations (Reynolds, 1983). Much of the information on small ponds has largely concentrated on fish aquaculture systems and, in addition, has been performed on experimental systems. Pond systems change rapidly and successional trends may not be evident from year to year. In addition, as the size of the pond decreases, the influence of epiphytes increases (Russo, 1978).

The general features of phytoplankton growth, both in lakes and in the sea, as well as phytoplankton succession and periodicity, are clearly and concisely presented in Fogg (1975). The increase of diatoms in temperate waters during the spring is particularly well described. In chapter 8 of this work, Fogg (*loc cit.*) discussed the factors affecting phytoplankton distribution and seasonal succession.

Kalff and Knoechel (1978) have made the observation that much of the work conducted in the field of algal periodicity has been confined to observational studies and subjected to correlation analysis, without any deliberate attempt to define the mechanisms and causal relationships behind the observed successional or periodic events. It is the opinion of this author that this general lack of a mechanistic approach may be attributed, partially, to two factors: one, the inherent difficulties (logistic and taxonomic) in undertaking long-term investigations of algal periodicity, and secondly, that the need for defining the algal assemblage, on a "once-off" seasonal basis in a particular lake or impoundment, may (logically) be recognized by water quality managers as sufficient basis for their management decisions. The further involvement of research programmes to investigate causal relationships in algal periodicity may, in all probability, be beyond the financial limitations of management budgets, and difficult to motivate in non-scientific environments such as municipalities or local authorities. Kalff and Knoechel (1978) advocated the need for a more holistic approach to the problems of algal distribution and biomass in relation to various environmental and trophic states. They proposed that more laboratory simulation, allowing for the testing of "articulated hypotheses", be undertaken.

4.2 Methodology and duration of studies

The papers reviewed for this literature survey revealed that most authors used the inverted microscope techniques (or variations and modifications thereof) of Lund *et al* (1958) and/or Utermohl (1958). Lugol's iodine was the preservation and sedimentation agent of choice in the counting and identification of collected phytoplankton samples. Collection of samples was achieved with Van Dorn or Ruttner bottles, integrated tube samplers or net hauls. Most authors preserved samples as soon as possible, with several examining fresh material as soon as possible after collection in order to observe for flagella, motility and fine structures. Identification of the phytoplankton present usually extended to genera, especially where the succession was being linked to environmental parameters, although a number of studies were carried out to species level. Rott (1981), in his study of inter-laboratory counting calibrations gave an excellent summary of phytoplankton sampling and observation techniques. This adequately covers the methods used by the reviewed authors.

Nearly all of the studies reviewed provided detailed data sets of the phytoplankton concentrations, whether by biomass or by individual organism. Several of the papers provided comprehensive analyses of the author's findings, with respect to individual species counts and relationships to various environmental and other parameters.

Apart from some intensive short duration studies, the articles reviewed represented study periods from six months in duration to as much as 20 years. Sampling intervals were on average 14 days, and only in exceptional cases had the researchers maintained weekly sampling throughout their surveys. Most of the articles reviewed provided adequate reference to morphology, climatic conditions and trophic state of the water body being studied.

4.3. SPECIES DIVERSITY AND THE "PARADOX OF THE PLANKTON"

In 1961, Hutchinson (see Smayda, 1980), posed the question as to how a number of species may co-exist in a relatively unstructured (isotropic) environment, all competing for the same food sources. This apparent "paradox" has been explained by the approach that neither the environment, nor the phytoplankton, are unstructured (Golterman, 1975). Micro-niches (patchiness) occur in the spatial distribution of many algal species. This indicates that the rate of mixing is slow enough in relation to algal growth rate to enable micro-niches (habitats) to occur. Thus, in any particular patch, one species has a competitive advantage relative to the others. It has also been shown (Golterman 1975), that complete competition can occur, albeit for limited periods only. The "plankton paradox" is thus based on the supposition of equilibrium situations, whereas the natural situation probably consists of rapid changes from one state to another. Paerl (1982) attributed the fact that a wide diversity of microorganisms may coexist, in an otherwise physically and chemically uniform water column, to two factors:- that whilst such a water column may appear to be spatially uniform, rapid temporal changes may occur, with the column still remaining uniform at each interval within a given space. Secondly, a vast number of "microenvironments" occur within a specific water column, undetectable by the sampling techniques commonly employed.

Reynolds (1983) further addressed this paradox by observing that coexistence might be attributable to species simultaneously experiencing different specific limiting controls; ie. they are not in direct mutual competition. Resource fluctuations will allow more than one species to coexist in the same environment (Tilman *et al.*, 1982). During the 1970's, the concepts of "top-down" control of plankton communities (eg. Porter, 1977., cited in Sommer, 1989) together with "bottom-up" models were introduced into the theory of resource competition. "Top-down" control assumes that herbivores control seasonal biomass patterns and species composition of the phytoplankton, whilst "bottom-up" theory centers around competition for resources (Sommer, 1989). The concept of resource competition and community structure is analysed in Tilman (1982).

Carney *et al.* (1988) addressed in detail interspecific competition occurring within phytoplankton populations. Their results indicated that resource-limited phytoplankton growth and interspecific competition during stratification (see 4.4.3, below) were important. This paper serves to illustrate the differences of opinion which exist with regard to the subject of interspecific competition, and the authors suggested that a possible integration of the existing viewpoints and methodologies may be the best way to positively address this problem in the future.

4.4. FACTORS AFFECTING PHYTOPLANKTON PERIODICITY

4.4.1 INTRODUCTION

Phytoplankton succession is episodic in nature, each episode being initiated by abrupt changes in physico-chemical conditions, and resulting in a sudden change in the composition of the phytoplankton, which then remains unchanged until a new episode occurs. Traditionally, the primary regulating factors in phytoplankton succession were considered to be physical (light, temperature, turbulence etc). Later work showed that nutrients and grazing losses were major factors controlling seasonal shifts. Light, temperature and nutrients are, with exceptions, the most important factors affecting algal seasonality in temperate regions, whilst in the tropics and sub-tropical regions, light is in abundance and succession is dominated by the effects of wind and rain (Pollingher, 1986). The major patterns of algal seasonality are dictated by interactions between temperature and supplies of P, N, Si (Tilman *et al.*, 1982).

Factors which influence species succession can be grouped into three catagories:- allogenic, autogenic and sequential. Allogenic factors include salinity, temperature, light, turbulence and anthropogenic substances, whilst autogenic factors include life-cycles, nutrients, water quality, ectocrines (organic substances or decomposition products which inhibit or stimulate plant life) and predation (Smayda, 1980). Hydrographic disturbances, as well as environmental modifications, account for the principal sequential factors. Smayda (*ibid.*) emphasized that these listings are not mutually exclusive because certain factors exhibit a certain degree of overlap. Furthermore, factors such as sinking rate are primarily neither autogenic nor allogenic.

Golterman (1975), in his text on physiological limnology, listed and discussed in detail the factors controlling population growth, and hence periodicity, as follows:-

FACTORS AFFECTING PHYTOPLANKTON PERIODICITY (after Golterman, 1975)		
PHYSICAL	(BIO)CHEMICAL	BIOLOGICAL
light temperature turbulence through flow	inorganic nutrients organic nutrients other organic compounds	parasitism predation competition

Hutchinson (1967) presents a very similar list of factors, together with a detailed review of examples of each.

Reynolds (1983) introduced the terminology of "autogenic successions, shifts and reversions" which occur during succession. Autogenic (internal) succession takes place under conditions of persistent water column stability, thus implying increasing biological control. Reversions are the result of short duration disturbances, for example wind-induced mixing. Such reversions result in repetition of earlier successional periods. Long term disturbances, such as total mixing of a lake as a result of long periods of wind action, result in shifts in species composition. Long term floristic changes are brought about by changes in climate, urban development and changes in run-off potential, as well as natural, autochotonous, limnological processes.

Reynolds (1983) further described a successional sequence, in the early stages, as being characterized by small species, having high surface area (SA) to volume (V) ratios. Such species have high potential rates of increase. During the later stages, larger species predominate with lower SA/V ratios and slower growth rates. Also, in the later stages, the proportion of motile species increases. Throughout the process, productivity decreases and diversity increases. The smaller species can be described as being opportunistic or colonizing, and according to the concept of *r*- and *K*- selection, proposed by MacArthur and Wilson (1967), would be classified as *r*- selected species. *K*-selected species, on the other hand, are those which are slower growing and can make better use of the available resources.

Reynolds (1983) also showed that a successional sequence is coupled to "directionality". Many indices are used to illustrate the extent of change but give no indication as to its direction. Smayda (1980) reviewed the work of Margalef (1958) in coupling directionality to phytoplankton assemblages, and listed the four stages of a generalized successional pattern as observed in marine conditions. Smayda also described the importance of directionality (ie. representing a coordinated pathway for energy flow, trophic interactions and cycling in phytoplankton successions), in food-web dynamics and phytoplankton cycling.

Round (1973) identified four "shock-periods" during which phytoplankton growth conditions undergo rapid change, these being spring circulation, spring stratification, the summer growth period and the autumn growth period.

Individual studies of factors affecting phytoplankton periodicity and succession have been broadly grouped (Section 4.4.2) according to the factors listed above. It must, however, be borne in mind that changes in succession and periodicity are the result of a combination of effects, and more than one factor, therefore, may be included under a particular sub-heading. In particular, the complex aspect of spatial and temporal heterogeneity is one which is integrally involved with other factors as, for example, size and temporal, as well as spatial distribution, partly determine the grazing behaviour of primary consumers.

4.4.2 PHYSICAL FACTORS

In assessing physical factors and the response of the phytoplankton thereto, it is important to remember that conditions at the time of sampling are not necessarily those which brought about the particular assemblage of algae being collected. As stated by Allen and Koonce (1973; cited in Sommer, 1989), "*today's assemblage is not the product of today's environment, but is rather yesterday's assemblage altered by a factor determined by yesterday's environment*". Sommer (1989) went on to state that "the most significant advances in understanding the ecology of phytoplankton will come from a knowledge of how the rates of growth and attrition of individual species are affected by environmental variability".

Abdul-Hussein and Mason (1988) found that temperature was the principal factor accounting for variation in phytoplankton biomass in a eutrophic reservoir (Ardleigh, UK), whilst pH was a lesser determinant. Prevailing winds were responsible for the concentration of algae in certain areas of the reservoir. Horizontal aggregation of algae was associated with the spring and summer blooms of Chlorophyta and Cyanophyta respectively, and vertical aggregations were most marked during the summer blooms of Cyanophyta.

Viner (1985) provided an impressive interpretation of the relationship between thermal stability patterns of phytoplankton and the underwater light climate through which the algae are moved or to which they are allowed to adapt. He discussed the mathematical equations relating to light attenuation and sinking, with emphasis being placed on the impact of diel periodicity on certain lake systems, and how such periodicity can dominate the phytoplankton dynamics and distribution. The enhancement of blue-green algal growth in stable water column conditions was noted.

Earle *et al.* (1987) analysed the factors influencing the distribution of phytoplankton in 97 oligo- to dystrophic headwater lakes in Newfoundland. The variables of dystrophy, hardness, salinity, lake-size, season, watershed and phosphate were correlated against 23 physical, chemical and morphometric variables. Spearman correlations showed several relationships between species distributions and the seven derived environmental factors.

Duthie and Stout (1986) hypothesized that the seasonal inputs of glacial silt to the Waitaki Lakes in New Zealand absorbed light and effectively reduced photosynthesis. This would account for variations in phytoplankton assemblages between the upper and lower lakes, the latter not receiving any silt.

In the Nile River, poor light penetration coupled with high current velocity (washout) was found to be the sole factors controlling phytoplankton development (Sinada and Abdel-Karim, 1984, 1984a and 1984b). Algal populations increased when the current subsided and the silt settled out. The growth of *Eichhornia crassipes* , and its effect on light penetration in the White Nile, was linked to a decrease in phytoplankton counts.

An effective light climate for algae depends on both the amount and quality of the available light, as well as on the vertical position of the algal cell in the water and the water's transparency (Sommer, 1987). *Microcystis* species of blue-green algae are common inhabitants of eutrophic waterbodies. Scott (1979) showed that light saturation for this genus is reached at relatively low light intensities, and that its ability to grow fast under low light conditions imparts a competitive advantage over other algae. In addition to low-light conditions impairing algal growth, high light intensities may induce photoinhibition (eg. Foy *et al.*, 1976; Rhee, 1982). Certain species of blue-green algae can counteract photoinhibition by increasing the synthesis of carotenoids which protect chlorophyll a from direct photo-oxidation (see Paerl and Ustach, 1982).

In developing a model to predict algal growth as a function of light received and subsequent attenuation by phytoplankton, tripton and background colour, Rijkeboer and Gons (1990) showed that phytoplankton growth in a shallow, turbid and eutrophic Dutch lake was significantly influenced by light availability. Low levels of chlorophyll a were attributed to competition for available light between the algae and a high concentration of tripton in the lake.

The dominance of blue-green algae is generally linked to a varied combination of factors, including nutrients, physical factors, mixing, hydraulics and biotic factors (this review). Hartbeespoort Dam (South Africa), a grossly perturbed (hyper-eutrophic) impoundment, is dominated year-round by large populations of *Microcystis aeruginosa* (NIWR, 1985). Hyperscums of this alga typically form in winter, and accumulations, covering more than a hectare can contain up to 2 tons of chlorophyll a (Zohary and Breen, 1989; see Section 5). Zohary and Robarts (1989) showed that because *Microcystis* maintained itself within shallow, diurnal mixed layers, it was ensured easy access to light, which was in this case the major limiting resource. This condition persisted for up to 10 months a year during the study period. Zohary and Breen (1989) investigated the environmental factors favouring the enhancement of *Microcystis* scums in Hartbeespoort Dam, and arrived at a list of preconditions for these algal accumulations (see Section 4.6).

Sedimentation of *Microcystis* spp. in a shallow, hypertrophic Japanese lake (Lake Kasumigaura) was found to occur subsequent to the collapse of a summer bloom of these blue-green algae (Takamura and Yasuno, 1988). *Microcystis* did not sink during the early part of the bloom. Diatoms were seen to sink as live algae, whereas *Microcystis* sank as detritus after having been decomposed or consumed in the water. The sedimentation of green algae showed the same tendency as the diatoms, with *Scenedesmus* spp. sinking during the early summer. Takamura and Yasuno (*ibid.*) pointed out that other studies had shown that in contrast to the Lake Kasumigaura findings, the sedimentary flux of

Microcystis was greatest at the time of greatest abundance (eg. Reynolds and Wiseman, 1982). This apparent discrepancy was attributed to the shallowness of Lake Kasumigaura and the absence of a permanent thermocline, allowing for easy resuspension of the *Microcystis* colonies.

The dominance of eutrophic waters by species of blue-green algae has been linked to a number of factors such as:- decreased turbulence, increased othrophosphate concentrations and temperature, and increasing light. Paerl and Ustach (1982) linked cyanophyte-scum formation to depletion of carbon dioxide in stratified surface waters. They concluded that under such conditions, cyanophyte algae form scums at the surface, enabling them to utilize carbon-dioxide at the air-water interface.

4.4.3. NUTRIENTS

Available information on taxonomic trends in nutrient competition stems largely from work conducted on three algal divisions:- diatoms, green algae and cyanobacteria (eg. Sommer, 1989). Diatoms are regarded as superior P-competitors, and dominate at high Si:P ratios, whilst as N-competitors they are subordinate to cyanophyte algae which dominate at low N:P ratios. Green algae are the poorest N competitors, whilst in P competition they dominate cyanophytes but are subordinate to diatoms.

Tilman *et al.* (1982) reviewed the role of limiting nutrients in phytoplankton community ecology. Their work provided a review of the effect of limiting nutrients, major ions, pH and other physical factors on an algal population, and showed that the net effect exerted on a specific population is a combination of these. In their illustrative model, light, nitrogen, phosphorus and silica were considered essential. The authors suggested that resource competition is a central mechanism controlling phytoplankton communities, although they conceded that their approach needed to be broadened (see Carney *et al.*, 1988). They identified spatial and temporal heterogeneity as a stumbling block in the assessment of short spatial and time scales, and stated that other workers should consider devoting attention to seasonal population dynamics and succession, rather than to the causes of species diversity.

For the phytoplankton, carbon is rarely limiting, and therefore only the N:P ratio needs to be examined. N:P ratios of less than 16 indicate nitrogen limitation, whilst larger ratios indicate limitation by phosphorus (Rhee, 1982). In tests with the green alga *Scenedesmus* spp., Rhee (1978) found an optimum N:P ratio of 30, with growth above and below this value being determined by limitation of phosphorus and nitrogen, respectively (see also Walmsley and Butty, 1980).

In a detailed overview of the three environmental factors:- nutrients, light and temperature, Rhee (1982) emphasized that the concept of optimum nutrient ratios, such as the Redfield ratio (C:N:P atomic ratio of 106:16:1) provides a basis for understanding coexistence and competitive exclusion. Although the effects of light and temperature are generally considered to be clear, Rhee regarded the adaptation with time to fluctuations in these factors as requiring additional study.

Dominance of urban-impacted waterbodies by blue-green algae is often linked to low prevailing N:P ratios (see Kalff and Knoechel, 1978). As the ratio falls below 10 there is a tendency for dominance by species such as *Oscillatoria* or *Microcystis*, with values below 2:1 favouring N-fixing species such as *Anabaena* (see Walmsley and Butty, 1980; Thornton, 1987; Ashton, 1979 and 1981). The derivation of the N:P ratio, from total or inorganic nitrogen and phosphorus components is important, however, as particulate and total N:P ratios fluctuate the least, and are closest to the true cellular ratios, while inorganic ratios fluctuate the most, and their validity for overall lake characterization is questionable (Barica, 1990). Reference to "nutrient-limited" waterbodies must be treated with care when considering phytoplankton response, as individual algae, and not lakes, are limited by a particular nutrient (Edmondson *et al.*, 1970).

Owens and Esaias (1976) reviewed literature, prior to 1976, concerning four major elements of the aquatic environment: phosphorus, nitrogen, carbon and light. Apart from a thorough discussion of these factors, they concluded in their paper that methods should be developed for "simple, precise, short-term determinations of both the algal response and the environmental factor without perturbing the dynamics of the system.

In studies of nutrient enrichment in the Patuxent River estuary (USA), Sanders *et al* (1987) stated that nutrient flux and chemical form are the most difficult factors to predict and are also the most subject to alteration by man. Other authors referred to (*loc cit.*) have proposed that nutrient flux and nutrient ratios influence the dominance of certain taxonomic groups (eg. that diatoms are promoted by high and flagellates by low nutrient fluxes). Nutrient patchiness or the chemical species of the nutrient may influence the dominance of one species over another. Using large-scale, continuous cultures of phytoplankton, Sanders *et al.* (1987) demonstrated that N-enrichment brought about large changes in species and species-successions during the summer and autumn, whilst P-enrichment had no effect at any time of the year. These authors showed that further enrichment, even in already nutrient-enriched systems, could affect phytoplankton growth and community structure.

An eighty percent reduction in phosphorus levels to Onondaga Lake (USA), as a consequence of a ban on phosphorus-containing detergents, resulted in a reversion from cyanophyte species to chlorococcal green algae, the Cyanophyta requiring a low N:P ratio (Sze, 1980). Diversion of sewage effluent from Lake Washington, between 1963 and 1969, and the resultant lowering in phosphorus concentrations, brought about a marked change in the phytoplankton, with chlorophyll levels being reduced by 80%, and Secchi transparency increasing from 1.0 m to 2.8 m (Edmondson, 1970).

Abdul-Hussein and Mason (1988) found that a significant correlation between levels of *Microcystis* biomass and ammonia concentration. *Microcystis* blooms were found to form when concentrations of ammonia and phosphorus were high and nitrate was low, with the N:P ratio correlated significantly (negatively) with Cyanophyta and Cryptophyta and positively with Chlorophyta. Kappers (1980) found that ammonia was the only form of nitrogen which *Microcystis* would utilize, although no such relationship was detected in the *Microcystis*-dominated Hartbeespoort Dam (see Allanson *et al.*, 1990).

Wehr (1989) showed that bacterium-sized phytoplankton used nutrients more efficiently compared with larger species, and that they were superior competitors within mixed communities (see also size/volume ratios in Reynolds, 1983; page 18).

It is extremely difficult to establish the effect of a specific nutrient at the community level. Because phytoplankton respond so readily and rapidly to changes in their environment, changes in their community composition might reveal aspects not observable using conventional chemical analyses. Tinnberg (1978) used the concept of succession rate (Jassby and Goldman, 1974) to assess changes in the recovery of a polluted, isolated bay in the Baltic Sea, following diversion of sewage effluent to a treatment works. Succession rates were low during the summer, and high in the spring and during the onset of cyanophyte blooms. Succession rates calculated in the laboratory were shown to be valuable in predicting changes in natural populations (Tinnberg, 1978).

Schindler (1978) drew together data from 64 lakes and produced a regression analysis based on global data for phytoplankton production, chlorophyll and certain nutrient parameters. He found that a high proportion of the variance observed in phytoplankton production and chlorophyll levels was related to phosphorus loading. He also showed that the effect of stratification on the concentration of phosphorus was insignificant compared to external sources of phosphorus. Furthermore, Schindler (*ibid.*) found some indication of a correlation between latitude and nutrient input, with the input of nutrients appearing to be important in the control of primary production. As indicated earlier (Section 4.1) Schindler's work relied heavily on data obtained from temperate systems, the absence of suitable data from tropical lakes being attributed as the reason for the lack of a significant correlation between latitude and phytoplankton production.

Wood and Talling (1988) studied chemical and algal relationships with respect to salinity in tropical Africa. They found that lakes with high salinity-alkalinity relationships were typically very productive in terms of phytoplankton biomass and photosynthetic rates. Many of the species observed could be characterized according to the salinity- alkalinity range in which they occurred. As had been observed by other workers, *Microcystis aeruginosa* was found to be able to tolerate a wide salinity range. Their paper listed a variety of lakes studied covering a wide range of conductivities and alkalinities, and specified the dominant algae present in each.

Correlation coefficients between phosphate concentration and the numerical quantity of green algae have been found to be significant. Similarly, the relationships of phytoplankton, pH and carbonate were found to be highly significant (Jana, 1979). Phosphorus limitation was found to be the limiting factor ending a spring increase in numbers of the small, centric diatom *Stephanodiscus hantzschii var. pusillus* in Lake Erken, Sweden (Pettersson, 1990), with silicon, rarely decreasing below concentrations of 0.5 mg Si l^{-1}, shown to be non-limiting.

A 25-50 percent drop in desmid taxa was attributed to the eutrophication of two oligotrophic moorland-nature reserves in the western part of Berlin. Certain widespread taxa became dominant, while some rare taxa disappeared altogether (Weddigen and Geisler, 1980).

4.4.4. MIXING AND SPATIAL DISTRIBUTION

There may be considerable horizontal heterogeneity in the distribution of algae, and this spatial heterogeneity is thought to preclude fixed sampling sites from being representative of a particular water body. Heaney (1976) compared population estimates from samples at a single site with those from random sites over an entire lake. The results showed that for the dinoflagellate being studied, clumping definitely occurred. The distribution was also found to be non-uniform in the vertical plane. This finding introduces complications to sampling methods attempting to achieve quantitative population estimates and the mechanisms of algal distribution within a lake body.

Robarts (1984) separated the major factors controlling primary production in Hartbeespoort Dam (South Africa) into two categories: high levels of nitrogen and phosphorus (which were never limiting), ie. a nutrient category; and wind effects, which determined the spatial and temporal changes which occurred within the system. Because nutrients were never limiting, Hartbeespoort Dam provided an ideal system in which to study the effects of non-nutrient factors which exerted an effect on primary production (see Zohary and Breen, 1989; Zohary and Robarts, 1989).

Several authors have proposed that variations in water-column stability constitute one of the principle variables driving the characteristic periodic cycles of phytoplankton in temperate lakes (Reynolds *et al.*, 1983). Sommer (1985), in studies on succession in the very large and deep (mean depth 100m) Lake Constance, concluded that whilst temperature, light, stratification, sedimentation, nutrient limitation and competition, grazing, algal size and fungal parasitism played important roles in the seasonal succession, there was a hierarchial sequence amongst them. Also, the most important variable for a deep system was found to be stratification, with very little significant algal growth occurring during the well-mixed winter period. During this period, the biological factors of grazing and competition played no role. Once the water column became stable with the onset of stratification, phytoplankton growth started and nutrients were depleted, water transparency decreased and grazing commenced. Sommer (*ibid.*) found the aspects of sedimentation and temperature to play less of a role than would be traditionally assumed.

Studies on Lake Victoria (area 69 000 km^2) showed that despite its nearness to the equator, seasonal periodicity was marked and related to the stratification cycle. Diatoms developed during periods of vertical mixing, whereas Cyanophyta became dominant during periods of stratification (Talling, 1987). The major source of algal loss was due to sedimentation. In his paper, Talling (*ibid.*) included a useful comparison of Lake Victoria with other large lakes.

Reynolds *et al.* (1983) studied the effects of artificial mixing on the dynamics of phytoplankton populations. They found that the increase of certain species such as *Sphaerocystis* and *Anabaena* occurred faster under calmer, stratified conditions, whereas mixing favoured the increase of diatoms. The sequences which they observed corresponded closely to generally-accepted successional pathways. They concluded that stratification in the euphotic zone selects in favour of motile and buoyant species, and against those which are non-motile and negatively buoyant.

It is evident from the above that stability of the water column plays a major role in phytoplankton diversity and community composition. In temperate lakes, a typical succession in summer would be from diatoms in the spring to species able to survive within a stratified system (Trimbee and Harris, 1984). This study examined the effect of intermittent mixing on succession in Lake Guelph, Canada, and found that mixing of the deeper waters perturbed the *status quo* with respect to diatoms in a stratified system. The effect of intermittent mixing (destratification) was to shift the late-summer dominance from non-nitrogen fixing, *k*-selected blue-green algae, such as *Microcystis* spp., to that of nitrogen-fixing, *r*-selected blue-greens such as *Aphanizomenon*.

In further studies on the allogenic effects of wind, Harris and Trimbee (1986) found that day-to-day changes in species composition occurred as a result of intermittent mixing of the surface waters in a small Canadian reservoir. Community changes were seen as a function of advection and growth, with two scales of change evident:- a short-term one associated with mixing; and a longer term aspect associated with growth. This system provided an example of physical/biological coupling.

Nienhuis and Caballero (1985) found that the distribution and density of microphytoplankton (<=25 $_u$m maximal diameter) in the semi-estuarine conditions of a lagoon complex (Magdalena Lagoon Complex, Baja California) were related to the presence of nutrient-rich water pockets and prevailing winds. The Magdalena complex was described as being productive and in which high microphytoplankton densities were recorded from November to May 1980/81. The structure, succession and stability of the phytoplankton assemblages were examined.

Much less is known about the periodicity of the dinoflagellates than is the case for other members of the phytoplankton (Pati and Brook, 1987). Diel depth-distribution patterns of the dinoflagellate *Ceratium hirundinella* were found to be related to wind stress, upwelling, vertical swimming of the organism and illumination (Frempong, 1984). In studies of the vertical and horizontal distribution of *C. hirundinella*, George and Heaney (1978) observed that distribution patterns were related to horizontal variations in specific conductance and pH, and to the vertical distribution of temperature and oxygen. Daily mean wind speeds of 11m s^{-1} were found to be sufficient to break down patches of phytoplankton with values of less than 6m s^{-1} allowing the formation of surface patches. Working on the same organism, Pati and Brook (1987) defined the conditions of temperature, pH and conductivity during which exponential growth was recorded. Doubling times of approximately 7 days were noted. Pati and Brook (1987) also compared the periodic trends exhibited by certain dinoflagellates in four lakes, and provided details of their occurrence in relation to various physico-chemical conditions.

Small water bodies such as ponds are typically shallow, and there is little expanse of open water in relation to the containing basin or perimeter (Reynolds, 1983). Such systems are infrequently stratified, but tend to be fully mixed almost continuously, with short periods of micro-stratification under the influence of solar warming. These shallow depths enable a higher concentration of organisms (as opposed to larger lakes) to be maintained, with a correspondingly more severe attenuation of light (Reynolds, 1983; Moss, 1980).

Ganf (1974a) found that, as a result of wave action on the sediments of Lake George (Uganda), the phytoplankton within the sediments was a major determinant of observed fluctuations in algal biomass. Samples taken in the water column after strong winds showed an increase in numbers of *Microcystis* and other cyanophyte algae by a factor of two to seven. Species of chlorophytes or diatoms showed no significant increase (Burgis *et al.*, 1973).

4.4.5. HYDRAULIC THROUGHPUT AND MORPHOLOGY

Russo (1978) observed that diatom growth in an English pond appeared to be related to periods of rainfall, and linked this to nitrate levels in rainfall run-off. The occurrence of *Volvox* in high numbers was coupled to low levels of nitrate in the pond following periods of heavy rainfall.

Lewis (1978), in his comparison of a tropical and temperate lake system, pointed out that, whilst phytoplankton successional sequences in temperate lakes are primarily seasonally driven, the greater frequency of variation in the supply of resources from rainfall run-off to tropical lakes accounted for a greater incidence of successional episodes in the latter.

Whilst current velocity was found to be a controlling factor in phytoplankton density (Sinada and Abdel-Karim, 1984a and 1984b) the construction of a dam on the Blue Nile was considered as being the reason for a change in algal flora from Bacillariophyta to Cyanophyta. The apparent inability of cyanophyte algae to establish themselves and dominate an otherwise hyper-eutrophic lake (Lake Brundall, Norfolk Broads) was attributed to flushing (Leah *et al.*, 1980). This lake was described as having a "vigorous" flushing regime, preventing the large colonial blue-green algae (eg. *Microcystis*) from forming substantial populations.

Eutrophication, brought about by the artificial lowering of the water level in Lake Sevan (USSR), was accompanied by changes in the structure and dynamics of the phytoplankton communities (Parparov, 1990). The eutrophication process was retarded by stabilization of the water level, since 1981, by means of channeling water to the lake from a river. Prior to the lowering of the water level, diatoms were the most abundant division, along with summer blooms of blue-green algae. Subsequent to the lowering and stabilization, green algae became dominant, with a sharp decrease in numbers of cyanophyte species.

4.4.6. LATITUDE

Traditionally it is thought that seasonal variation in phytoplankton is reduced at low latitudes by virtue of the minimal variations in seasonal radiant energy inputs. In terms of latitude, African lakes lying above the twenty-degree parallel exhibit characteristics of marked seasonality with respect to their algal populations. Such systems are influenced by marked changes in the amount of radiant energy that they receive, and also by the effects of seasonal water input (Talling, 1986). Generally, successional patterns in African lakes, including those within the tropical belt, are dominated by their hydrological features or aspects of their water-column structure and circulation (hydrographic).

Talling (*ibid.*) found that in African lakes, the amplitude of phytoplankton population density, expressed as orders of magnitude, was a measure of seasonal variability. He found examples where amplitudes of three orders of magnitude were observed both in lakes with short retention times and in lakes having long water retention times. In the case of shallow, hydrologically unstable systems, he found that seasonal changes were more of an inter-annual nature (ie changes on a non-seasonal time scale and greater than one year).

Kalff and Watson (1986) concluded that there was no evidence for the postulation that phytoplankton species-abundance declined with latitude from the temperate to the tropical regions; that seasonal variations in the tropics were not systematically lower than in the temperate zone, and that overall, there was no evidence that freshwater tropical phytoplankton compositions differed fundamentally from those observed in temperate lakes during the summer.

Lake George provides an example of an extreme habitat (highly productive) in which models, derived from experimental observations, may be tested (Ganf, 1974a). Lake George lies on the equator, is very shallow (*ca.* 2.25 m) and experiences a constant climate, as well as a continuous hydraulic inflow which offsets two dry seasons (Viner, 1969; Moss, 1980). Between 90% and 95% of the plankton biomass was made up by phytoplankton, with 80% of this amount being comprised of six species of blue-green algae such as (colonial) *Microcystis* spp. and *Aphanocapsa* spp., or (filamentous) *Anabaenopsis* spp. and *Lyngbya* spp. (Burgis *et al.*, 1973; Moss, 1980). The occurrence of diatoms, *Melosira* spp., around the shore areas was correlated with inflow providing sufficient turbulence for growth. Overall, the same species of algae were dominant throughout the year and from one year to the next (Burgis *et al.*, *ibid.*). Diurnal changes were shown to have an overwhelming influence upon the metabolism and distribution of the phytoplankton in Lake George (Ganf, 1974a; Ganf and Horne, 1975; Ganf and Viner, 1973). The phytoplankton was found to be uniformly distributed in the water column at dawn, sinking from *ca.* 10h00 with the onset of stratification and lying below the euphotic zone from 16h00. General redistribution of the algae occurred thereafter

(Burgis *et al.*, 1973). The limnological cycle of Lake George is described by Ganf and Horne (1975) as having many of the physical characteristics of the temperate cycle, although they are compressed into a 24h period.

4.4.7. BIOTIC AND ABIOTIC FACTORS

Youngman *et al.* (1976) provided a rare and interesting study of the effects of fungal parasitism on algal populations. They studied the growth and decline of algal populations in an English reservoir, and found a high incidence of parasitism of certain species. Light, turbulence, zooplankton grazing and nutrients (apart from silica which limited diatoms) appeared unimportant. The authors stated that, although other researchers had indicated the possible modifying effect of parasitic fungi on algae, very little research had been directed towards this aspect. Van Donk (1989) reviewed the role of fungal parasites in phytoplankton succession, and concluded that the fungal parasitism could have a significant effect on the process. Fungal parasites may prevent or delay algal blooms and reduce algal abundance (Van Donk, *ibid.*). The parasitic infection process is complex, and a significant amount of research is still required to quantify the effects of parasitic involvement in phytoplankton succession.

With respect to competitive exclusion, growth rates play an important role in the competition between species. As growth rates are dependent on algal size, this enables small algae to grow faster than larger ones, although smaller algae are more easily consumed by zooplankton (Golterman, 1975). Sommer (1989) regarded the assumption that smaller algae are better competitors as being somewhat incorrect and based on insufficient data (see Sommer, 1989, page 76).

Livingstone and Reynolds (1981) observed the effects of the relationship between sedimentation and phytoplankton periodicity in Rostherne Mere (UK), using recordings from sediment traps to reflect the periodicity which had occurred. The results showed that resuspension by turbulence occurred infrequently, with entrapment occurring during or after periods of maximum phytoplankton abundance. *Microcystis* spp. accounted for 45-75% of the input volumes to the sediments, with the *Microcystis* cells showing little degradation (see also Takamura and Yasuno, 1988; Section 4.4.2).

Olrik (1981) proposed that allelopathic factors, (*allelopathy* - the influence or effect of one living plant upon another) such as the production of inhibiting substances, could account for the dominance of green algae over cyanophytes in a eutrophic system. Other authors (see Olrik, 1981) have indicated that the opposite is the case and that by-products from *Chlorella* spp. promote the growth of *Microcystis* and *Anabaena*, and that extracellular products of the latter inhibit *Chlorella*. Sommer (1989) regarded the knowledge of phytoplankton allelopathy as being grossly deficient and that "more research was needed".

Certain fish species can contribute to the succession of phytoplankton. Bream, eel roach and carp, for example, dredge the bottom sediments and thus increase water turbidity (shading) and the resuspension of algae (Olrik, 1981). In an interesting combination of physical (flushing) and biological (grazing) events, zooplankton grazing of phytoplankton in a hyper-eutrophic lake in the Norfolk Broads, UK (Leah *et al.*, 1980) reduced phytoplankton growth to the extent where aquatic macrophytes were able to establish themselves. A control basin, in the same lake, to which planktivorous fish had free access, showed no phytoplankton reduction and no macrophyte community established itself (see also Moss, 1980, page 189; Anderson *et al.*, 1978; Shapiro, 1979a,b). Leventer (1979) reported that the phytoplanktivorous silver carp, *Hypopthalmicthys molitrix*, could reduce algal biomass by 25%, and that this fish species could feed on *Microcystis*. Poulet and Marsot (1978), as well as Rassoulzadegan *et al.* (1984), found that *Microcystis* had only poor palatability and nutritional value for *Daphnia* spp.

Conversely, fish may aggravate eutrophication conditions by reducing herbivorous zooplankton populations, resulting in a shift to smaller zooplankton (Nakashima and Leggett, 1980). This effect reduces zooplankton grazing pressure on the algae and leads to algal blooms (Anderson *et al.*, 1978; Shapiro, 1979a,b).

A considerable volume of work has been published concerning the effects of zooplankton grazing on phytoplankton succession. The most recent review of the role of grazers is that by Sterner (1989). In South Africa, Jarvis (1987) studied zooplankton feeding ecology and resource utilization in Hartbeespoort Dam. *Microcystis* spp., common inhabitants of eutrophic systems, are generally regarded as being inedible for zooplankton by virtue of their large colony size. Jarvis (1987) showed that *Daphnia* fed significantly on *Microcystis* colonies up to 60-100m in size. Cyclopoid copepods were shown to be able to ingest and assimilate *Microcystis* (Burgis *et al.*, 1973), although this ability was restricted by the colony size of the blue-green alga.

The collapse of phytoplankton populations has frequently been attributed to zooplankton grazing (eg. Sommer *et al.*, 1986). The predominance of *Cryptomonas* spp. is peculiar to such "clear water" phases in meso- to eutrophic lakes (Sommer, 1987). This is attributed to a slower decline in numbers of Cryptophyceae rather than an increase (Sommer, 1987). Experimentation with zooplankton community grazing, following the controlled removal of planktivorous and benthivorous fish species in a small, hypertrophic lake (Lake Zwemlust, Holland), showed that zooplankton grazing pressure reduced chlorophyll a and algal abundance to low levels (Van Donk *et al.*, 1990). This was achieved despite high nitrogen and phosphorus concentrations. Sterner (1989) listed six examples of field case-studies of the effects of grazers on algal succession.

Zooplankton grazing was estimated to reduce algal biomass by up to 4% in Lake Norrviken, equivalent to a reduction in total phosphorus of 0.17 mg l^{-1} (Shapiro, 1979a). In Lake Washington, Shapiro (1979b) recorded decreasing algal density and increasing water transparency with increasing *Daphnia* populations. The reduction of the proportion of blue-green algae present by the introduction of large zooplankton species was demonstrated by Schoenberg and Carlson (1984).

The role played by zooplankton in providing a source of phosphorus was shown to determine only the abundance of blue-green algae (Ejsmont-Karabin and Spodniewska, 1990). This finding was attributed to the lower zooplankton grazing pressure on blue-green algae as compared with other, more edible classes of algae. The results of this work supported the hypothesis that P-uptake by algae is directly affected by the rate of supply of available phosphorus forms, rather than the total-P concentration. This was borne out by the finding that the actual biomass was much lower than that calculated from the total-P concentration. Van Liere *et al.* (1990) showed that excretion by zooplankton satisfied 20-30% of the daily phytoplankton phosphorus demand in the Loosdrecht Lakes (Netherlands). Herbivore grazers provide low Si:P ratios because the Si is not released in available form, as is phosphorus. Herbivores should therefore adversely affect diatom dominance (Sterner, 1989).

4.5. OBSERVED SUCCESSIONAL TRENDS

The aim of this section of this literature survey has been to identify the principal periodic sequences as they occur in various regions of the world and, principally, those in shallow, eutrophic systems. The author recognizes the importance of a mechanistic approach to the dynamics of phytoplankton periodicity, but is of the opinion that the intricacies of these mechanisms would constitute the basis for an entirely separate study. In addition, such investigations were beyond the scope [financially and logistically] of the limnological work programme of which this manuscript forms part. The importance of simulated, laboratory studies to elucidate the interactions of various factors (eg. light, temperature and nutrients) has been emphasized by several authors (eg. Tilman *et al.*, 1982; Rhee, 1982; Reynolds, 1983; Foy *et al.*, 1976; Ganf, 1974 and 1975).

Practically all successional studies, with certain exceptions, show a spring maximum of diatoms, sometimes followed by a second maximum in the autumn, an early summer maximum of Chlorophyceae and a late summer maximum of Cyanophyta (Smith, 1950). This sequence represents what is generally regarded as forming the traditional "Seasonal paradigm" of phytoplankton succession. Reynolds (1983) illustrated 12 successional sequences and described an elegant hypothetical matrix, incorporating water-column stability and nutrient stress, to accommodate several algal assemblages.

Lewis (1978) provided a comprehensive study of phytoplankton succession and dynamics in a tropical lake (Lake Lanao, Phillipines). He showed that the niche space was divided temporally on the basis of nutrient and light availability, with diatoms and cryptomonads occurring during periods of low light and high nutrient availability, and chlorophytes, cyanophytes and dinoflagellates occurring towards the high light and low nutrient end of the spectrum. Loss mechanisms played a more significant role in affecting individual species succession than in affecting the total biomass. Lewis (*ibid.*) also showed that, as in other systems, diatoms and cryptomonads showed a tendency to exist during periods of maximal turbulence, cyanophytes and dinoflagellates under conditions of minimal turbulence, with chlorophytes occupying a broad middle range of conditions. More importantly, he showed that the overall pattern in a tropical lake differed from that seen in temperate lakes, in that the number of abiotic changes was more numerous in tropical than in temperate lakes. Within a specific episode, however, events were similar to those observed in temperate lakes. Lewis (1978) further observed that this increased occurrence of episodes in the successional sequence occurred despite the reduced amplitude of seasonal weather changes. Variations in annual biomass were much less in tropical than in temperate lakes, with greater reduction in cell numbers in temperate lakes resulting from winter losses.

In a five-year study on another tropical system (Lake Valencia), Lewis (1986) tested the seasonal paradigm of succession (diatoms to chlorophytes to cyanophytes to dinoflagellates) using a nitrate-mapping procedure. Nitrate concentrations were recorded on the days of entry and departure of a given taxon from the successional sequence, with the successional position of each major taxon then being mapped on the spectrum of nitrate concentrations for the lake. The successional pattern thus obtained compared well with one derived using mixing events, in relation to water column stability, to pinpoint the onset of a successional event. He concluded that there was a generalized pattern in the phytoplankton succession of the mixed layers of temperate and tropical lakes. As with Lake Lanao, Lewis (*ibid.*) found that, although the sequence of appearance of taxa compared with that observed in temperate systems, the number of events was greater. In his Lake Lanao work, Lewis (1986) found that, although the driving variable was frequent changes in nutrient resources, the cause in the Lake Valencia study was irregular weather variations, which induced changes in the thickness of the mixed layer.

The soda lakes of tropical Africa are grouped amongst the world's most productive systems. Lakes such as L. Aranguadi and L. Kilotes (Ethiopia) are alkaline, saline and typically have pH values in excess of 9. Persistent seasonal stratification is common in the deeper lakes (eg. Lake Aranguadi) (Talling *et al.*, 1973). Areal concentrations of chlorophyll a are reported as reaching maxima of 200-300 mg m^{-2}, with isolated peaks of 2000 mg m^{-3} in the densest populations (Talling *et al.*, *ibid.*).

Cyanophyte dominance is common. Njuguna (1988) studied seasonal variation in relation to nutrients in Lake Sonachi, Kenya. Five species, belonging to the algal divisions Cyanophyta and Chrysophyta, dominated the phytoplankton. Nutrient concentrations and primary productivity levels were found to be lower than for other soda lakes, and algal biomass was found to be phosphorus limited.

Algal abundance was greatest at the end of the rainy season.

The abundance and seasonal occurrence of planktonic algae in Lake Kinneret, Israel, led to their being characterized into two groups:- algae which are abundant during a specific annual period, and algae which are present throughout the year (Pollingher, 1986). The algal assemblage was principally comprised of Pyrrhophyta and Chlorophyta, supplemented by Cyanophyta from time to time. Four stages of algal succession occurred, starting with thermal and chemical destratification and ending with stratification. The succession cycle began with an increase in nutrients and decrease in temperature and ended with the depletion of nutrients and maximal temperatures.

Reynolds (1984) reviewed the periodic cycles of algal species in a wide variety of temperate lakes. By ascribing individual species to assemblages, he demonstrated a high incidence of similarity between periodic cycles. Lakes and rivers, at both high and low latitudes, conformed to parts of the same broad patterns. Reynolds (*ibid.*) recognized two types of change:- autogenic and unidirectional (responding to changing resource-ratio gradients); and allogenic, responding to changes in the physical environment. His review illustrated four successional patterns related to trophic state and season. Reynolds (1984) also attempted to reconcile the lack of information for highly eutrophic, shallow systems by comparing them to the epilimnia of stratified, deep waters and suggested that shallower, more productive systems, are typically dominated by Cyanophyta.

Rott (1984) studied 40 Tyrolean lakes and related the observed successional trends to the trophic state of each system. His work showed no clear succession in ultra-oligotrophic systems, whilst in oligotrophic systems, the changes were from pennate diatoms (spring) to small centric diatoms (summer) and dinoflagellate species in late summer. In mesotrophic systems the succession was from small Chrysophyta (spring) to small centric diatoms/chlorococcal species in summer, to dinoflagellates or Cyanophyta in late summer, with reversion to Chrysophyta in autumn. In eutrophic systems, Rott observed trends similar to the mesotrophic systems with differing species composition and with the occurrence of water blooms (Chlorophyta or Cyanophyta). In highly eutrophic systems, species composition did not change in the summer. Rott (1984) concluded that the same basic autogenic sequence occurred in meso- and eutrophic systems.

Reynolds (1978) observed a dramatic change in the typically dominant phytoplankton in Rostherne Mere (UK), with a diatom *Ceratium-Aphanizomenon-Coelosphaerium* sequence changing to one dominated by light-limited populations of *Microcystis aeruginosa* during the summer and autumn. The cause of the change, although not firmly established, was attributed to a possible qualitative response to eutrophication, although the elimination of bottom fauna by 'guanotrophy' (ammonia-poisoning) as a result of the nearby establishment of a gull roost (see Brinkhorst and Walsh, cited in Reynolds, 1978) was also implicated.

Russo (1978) observed successional trends in a macrophyte-dominated shallow pond in southern England. Diatoms were present throughout the year but only became abundant in autumn and spring, almost disappearing in the summer. *Cryptomonas* species were abundant during autumn and spring and present in the summer. In the early spring, the dinoflagellate *Peridinium* was abundant. *Volvox* was the dominant large species in autumn, exhibiting a second peak in the summer. *Dinobryon* and *Spirogyra* were abundant during the summer with Cyanophyta appearing during the late-summer.

Moustaka-Gouni (1988) studied the structure and dynamics of phytoplankton assemblages in a Greek lake (Mediterranean). Her studies showed that the successional trend which she observed did not fit any of the generalized successional pathways in lakes of different trophic states. Three annual peaks were detected. In the spring, Bacillariophyta and Cryptophyta were present, in the summer Cyanophyta and Bacillariophyta, and Cyanophyta in the autumn. The combination of diatoms and Cyanophyta is unusual (cf. Trimbee and Harris, 1984).

Her data indicate pH levels adequate for cyanophyte requirements all year round. No statements about wind and mixing events, which might have had some bearing on the year-round occurrence of Cyanophyta (see Section 4.4.4 above), were included.

In the deep, temperate Lake Constance, Sommer (1985) found that succession started after the winter in water that was rich in nutrients (see Sommer, under "Factors affecting succession", above). During this stage, algae with high growth rates were dominant. Following this, competition and interaction with heterotrophs became dominant selective forces. Grazing resulted in a clear water phase which marked the transition between spring and summer, with nutrient competition playing a dominant role in the summer. With the deepening of the water layer in the autumn, nutrient competition decreased, favouring algae with low light requirements. Sommer (1987) described, in a stepwise fashion, the main sequence of phytoplankton seasonality in Lake Constance. This idealized scheme provides an informative overview of the events which occur during an annual cycle in a north-temperate lake, and can be extrapolated to systems in other climatic regions. Sommer (*ibid.*) also gave details of species seasonality in Lake Constance, as well as a description of the stages of seasonal development.

Talling, in his 1986 review of seasonality in African lakes, described the observed patterns with respect to latitude, hydrological and hydrographical stability. He also commented on the horizontal variations in succession observed in very large systems. With respect to African lakes, Talling (1986) considered the establishment of a link between population response and biological and/or environmental factors, as being an area which had received only minimal attention.

Moed and Hoogveld (1982) studied seasonal periodicity in a shallow, eutrophic and alkaline Dutch lake. Diatoms and green algae (*Scenedesmus* spp.) were abundant for most of the year, with several blue-green species dominating throughout the year. Diatoms developed during February-March (spring), with a second population maximum in the autumn. Cyanophyta developed in March with maxima in May and June with a second maximum in November. *Scenedesmus* spp. exhibited several maxima.

A phytoplankton community, consisting almost entirely of chlorococcal species, was found in the shallow, eutrophic and well-mixed Lake Arreso, Denmark (Olrik, 1981). Neither nitrogen nor phosphorus were limiting at any stage. The mean Secchi depth was 0.5 m, falling to 0.2 m in summer, with light being the primary limiting factor for growth. Certain chlorophyte species were dominant throughout the year (eg. *Scenedesmus* and *Pediastrum* spp.). Succession occurred amongst the rest of the chlorococcal species. The conditions of high nutrient availability and shallow depth traditionally indicate a cyanophyte-dominated system (eg. Barica, 1981). Cyanophytes were present throughout the year, highest in the autumn, but were never dominant. Diatoms were present throughout the year. Albeit that the observed phytoplankton community is typical of a hypertrophic system, Olrik (1981) posed the question why Lake Arreso is not cyanophyte dominated, and addressed the factors of wind, temperature, pH, allelopathic factors and fish stocks. The combination of frequent mixing, low pH and temperature was found to favour Chlorophyta over Cyanophyta. The action of certain fish species in dredging the sediments was implicated, whilst allelopathic factors were excluded.

Munawar and Munawar (1976) recorded seasonal events in Lake Erie, USA. The lake was divided into three basins, with inshore and offshore sampling stations in each. A large number of species, 125-150, were observed in each basin. Diatoms were abundant in the spring, Chlorophyta in the summer and Cyanophyta in the autumn. A second diatom peak was also recorded in the autumn. Significant variations in inshore-offshore (spatial) phytoplankton compositions were found.

In the largest (area) freshwater lake in the world, Lake Superior, 285 alga taxa were recorded (Munawar and Munawar, 1978). Lake Superior is ultra-oligotrophic, and has low summer and mean-annual temperatures. Mean phytoplankton-biomass levels were homogenous across the lake, with no inshore- offshore variation. Overall biomass concentrations were very low. Phytoflagellates and diatoms dominated the phytoplankton composition, with Chlorophyta and Cyanophyta contributing the least. Lake Superior has a unique thermal regime, with the lowest summer surface temperatures of the Great Lakes, long periods of deep vertical mixing and short periods of stratification. As a result, the usual terms spring, summer and autumn do not apply to Lake Superior. For this reason, succession was studied along stratification lines and was expressed as species occurring under stratified and non-stratified conditions. No marked seasonal trends were observed, and Munawar and Munawar (1978) suggested that this lack of a clear, seasonal maximum of phytoplankton could well be an indicator of ultra-oligotrophic or pristine waters.

In 1982, Munawar and Munawar produced a comparative synthesis of phytoplankton seasonality in the North American Great Lakes. This in-depth work reviewed the well-developed seasonal peaks of high biomass in the eutrophic/mesotrophic Lower Great Lakes, as opposed to the low biomass found in the oligotrophic Upper Great Lakes. As mentioned above, the ultra-oligotrophic Lake Superior exhibited an absence of any marked seasonal trends. Munawar and Munawar's (1982) work described the inter-lake differences in detail, with the results being presented as a general review, and with a case study illustrating of the lakes. In the case-study of a meso-eutrophic system, diatoms were abundant in the winter and in spring, with Chlorophyta and Cyanophyta appearing in the late summer. Some inshore-offshore variations in amounts of each algal division were apparent. Size composition was also included in the analysis. Certain species were described as being seasonally unselective and eurytopic (wide geographical range) in their distribution.

The algal flora of the ultra-oligotrophic estuarine portion of the Rio Cruces (Chile) was found to have high diversity combined with low total counts

(Durrschmidt, 1980). Some 382 algal taxa were identified. Succession was found to be chrysophyte dominated in the winter, Chlorophyta (principally desmids) in the spring, with a surge in diatoms and green algae in the summer. Intrusion of salt water into this estuary in the autumn altered the algal composition and favoured the growth of halophilic diatoms

Comparison of oligotrophic lakes in New Zealand and Canada showed that four times fewer algal taxa occurred in the New Zealand systems (Duthie and Stout, 1986). The periodicity of the phytoplankton was found to be greatly influenced by seasonal inflows of glacial silt into the New Zealand lakes (see 4.4.2). Three hypotheses were proposed to explain the algal composition and periodicity. These centered on:- light control as influenced by inputs of silt; nitrogen limitation during non-light limited periods, and zooplankton grazing effects.

In studies on three ponds in India, Rao (1977) found that the (dominant) diatoms could be classified according to their tolerance of the varying salt contents of the ponds, and that temperature was observed to be the most important factor in their periodicity. Certain green algal *Trachelomonas* spp. developed under conditions of iron richness and low organic matter. Several species could be grouped as seasonal forms, whilst others appeared indifferent to fluctuations in chemical and/or seasonal changes. Species of Euglenaceae were dominant during the summer months. With respect to the Cyanophyta, they were found to occur during all the seasons, but the dominant species varied from season to season. Certain indifferent species (with respect to their seasonal occurrence) were identified.

Ahmed *et al.* (1986,1986a) provided a detailed data set of algal counts and chlorophyll a variations obtained from a two-year study of phytoplankton in the Nile River. The algae are grouped into three catagories:- constants, ie. present all year round; ephemerals, which appeared in large numbers during certain seasons and then disappeared, and rare genera, appearing occasionally in small numbers. Ahmed *et al.* (1986) supported the view that whilst chlorophyll gives a good idea of crop size, it provides no information on the algal components, and varies with varying nutrient concentrations and algal species (see Ashton, 1985). Ahmed *et al.*'s (1986) data were presented in tables showing monthly variations, and whilst no discussion was made of periodicity, it was apparent that although the Chlorophyta contributed the greatest number of genera, diatoms were always dominant.

Bailey-Watts (1978 and 1982) provides two lengthy and comprehensive reports on long-term phytoplankton studies conducted on Loch Leven (Scotland). Loch Leven is a shallow, eutrophic and non-stratifying system. The 1978 study represents nine years of data. It was found that Cyanophyta and Bacillariophyta were dominant in both studies, but that species composition and the times of population maxima varied from year to year. *Microcystis* appeared in the late summer and autumn, with a nitzschioid diatom species occurring in large numbers associated with the outer mucilage of the *Microcystis* colonies. The work focussed on those environmental parameters which were most closely related to phytoplankton changes. Significant changes were related to water chemistry (nutrient supplies) and zooplankton. An increase in *Daphnia* numbers was related to increased grazing of small algae modifying the size distribution of the phytoplankton. The dominance shown by the Cyanophyta in this (well-mixed) system was contrary to expectations (refer also to Moustaka-Gouni (1988) and Olrik (1981)).

A ten-year study conducted at Lough Neagh (Ireland) revealed that the phytoplankton was dominated by diatoms in the early spring, and by blue-green algae at most other times (Gibson and Fitzsimons, 1982). Phosphorus concentration, the size of the overwintering algal crop and the activity of grazing herbivores were implicated in the annual phytoplankton of this large, shallow, eutrophic lake. *Oscillatoria* spp. were the dominant cyanophytes present, with the almost perpetual crop resulting in a "closed canopy" of phytoplankton (Gibson and Fitzsimons, 1982). Increases in nitrogen inputs to the lake during the study period resulted in a change from N-fixing (*Anabaena flos-aquae*) species to *Oscillatoria agardhii.*

Algal succession in the Mississippi River was similar to that of adjacent local lakes (Baker and Baker, 1981). Diatoms exhibited the characteristic two periods of dominance (spring and autumn), with Cyanophyta becoming dominant in the summer. Green algae were always present but never exceeded 21% of the total algal biomass. Use of a diversity index showed that greatest diversity occurred during the summer months. Baker and Baker (*ibid.*) found that the installation of locks and dams on the river had resulted in large increases in total counts (ponding effect).

A repetitive annual pattern of algal succession has been recorded over a twenty-year period for Lake Vechten, Netherlands (Blaauboer, 1982). Early spring maxima were caused by diatoms and some green algae, the summer was dominated by chrysophyte and dinoflagellate species, as well as some species of Chlorophyta. The end of the summer showed a second diatom maximum, and the winter period exhibited several species of cryptophytes and chrysophytes. Blaauboer (*ibid.*) observed a shortening of the annual period of minimum phytoplankton biomass and attributed this to a slight eutrophication of the system over the past twenty years.

Succession in Harveys Lake (Pennsylvania, USA) also fitted the traditional seasonal paradigm, with diatoms dominant in winter and spring, Chlorophyta in summer and autumn, and Cyanophyta in late summer, autumn and winter (Casterlin and Reynolds, 1977). The lake was found to contain many pollution-tolerant forms such as *Anabaena* spp.

Phytoplankton succession in the eutrophic lakes of the upper Q'Appelle River system (Canada) showed cyanophyte dominance in the summer and autumn with diatom dominance in the spring. Chlorophyta were always present but did not form a significant portion of the biomass (Hammer, 1983). This lake system had been subjected to high nutrient loads for several decades and high soluble-phosphate levels, combined with high temperatures, were attributed as being the cause of cyanophyte scums. The reason for the low levels of green algae, which in other successional patterns fill the space between diatoms and cyanophytes, was not found.

Abdul-Hussein and Mason (1988) studied the dynamics of a eutrophic reservoir over a two-year period. Diatoms dominated the winter and early spring, being replaced by Chlorophyta and then by a cyanophyte bloom during late spring. The phytoplankton was dominated (characteristically) by only one or two species at any given time.

Hecky and Kling (1987) provided an illustrative analysis of phytoplankton succession in five lakes of the Central African Rift Valley. The lakes were compared using a variety of parameters and sketches were included of the phytoplankton species occurring in each, and reasons were presented to account for variations in phytoplankton diversity observed between the lakes.

Hopkins and Lea (1982) conducted a ten-year study of phytoplankton in a bay in Lake Erie, Canada. A strong similarity in the composition of the algal community was observed from year to year. Again, the seasonal sequence of diatoms (and, in this case cryptophytes) dominated in the spring, cryptophytes and green algae were dominant during the summer period with cyanophytes in the late summer. Reversion to cryptophytes and diatoms occurred in the autumn.

No distinct seasonal maxima were observed in a humic and acidic lake in Canada (Janus and Duthie, 1979). The biomass in this system was very low and maximal populations succeeded one another and did not co-exist.

The phytoplankton community structure in a reservoir Lamingo Dam (Nigeria, West Africa), was found to be Bacillariophyceae > Chlorophyceae > Dinophyceae, with *Nitzschia* spp. forming the most important diatom genus. Migratory tendencies for *Nitschia* and *Scenedesmus* spp. were apparent (Khan and Ejike, 1984).

The periodicity of the dinoflagellate *Peridinium* spp. was similar to that in other, adjacent dams. Diatoms dominated the reservoir during the rainy season, whilst the dinoflagellates proliferated during the rainy period.

The seasonal variation of phytoplankton in the eutrophic Lake McIlwaine (Zimbabwe) during 1975/6, has been described by Robarts *et al.* (1982). *Microcystis aeruginosa* dominated the phytoplankton production of the lake for most of the year, particularly during the summer. *Anabaena* and/or *Anabaenopsis* spp. were also prevalent, particularly during the spring, and *Melosira* spp. increased during early winter. The winter and spring periods in Lake McIlwaine showed the greatest algal diversity.

The seasonal and main succession of phytoplankton in eight lakes of the Karelian isthmus, USSR, ranging from oligotrophic to hyper-eutrophic, was comprehensively described by Trifonova (1986). Characteristics of the seasonal phytoplankton succession, as a function of the degree of eutrophication, were discussed.

4.6 SOUTH AFRICAN PHYTOPLANKTON PERIODICITY STUDIES

As has been stated in Section 4.1, the greater volume of work on phytoplankton periodicity has been confined to lakes in the Northern Hemisphere, with fewer studies conducted in the equatorial and sub-tropical regions, and only a handful of publications emanating from South Africa (Ashton, 1985). The differences between the forces driving phytoplankton periodicity in the Northern and Southern Hemisphere are reviewed in Ashton (1985).

South Africa is poorly endowed with natural lakes, and shallow pans (vleis) occur sporadically along the coast, as well as in the Karroo, the Orange Free State and the southern and eastern Transvaal (Hutchinson *et al.*, 1932). Of the coastal vleis, only two have been subjected to phytoplankton periodicity studies:- Lake Sibaya (Hart and Hart, 1977) and Swartvlei (Robarts, 1973; Howard-Williams and Allanson, 1981). The most detailed of these studies is regarded as being that by Hart and Hart on Lake Sibaya (Allanson *et al.*, 1990) Other phytoplankton periodicity studies in South Africa have formed part of investigations undertaken on, chiefly, large impoundments such as Rietvlei Dam (Ashton, 1979 and 1981), Hartbeespoort Dam (eg. NIWR, 1985; Jarvis, 1987; Zohary and Robarts, 1989; Zohary and Breen, 1989), Roodeplaat Dam (Pieterse and Rohrbeck, 1990), Rhenosterkop Dam (Heath *et al.*, 1988; Robarts *et al.*, in press), Lake Midmar (Breen, 1983) and Lake le Roux (Allanson and Jackson, 1983). In addition, a number of reports concerning phytoplankton in the Vaal River have been published (Pieterse *et al.*, 1986; Pieterse, 1987; Pieterse and Roos, 1987 and 1987a; Pieterse and van Zyl, 1988). Some limited, non-periodic observations of the phytoplankton in an estuarine coastal lake were made by Begg (1974). Some attempts were made to gather together information on plankton successions (see Scott, 1976) but no evidence of further progress has been evident. The degree of awareness and concern regarding the extent of problems caused by algae in South African waters is apparent in CSIR (1989).

Broadly summarized, the South African studies show that phytoplankton periodicity in the eastern, summer rainfall region broadly conforms to the seasonal paradigm. Swartvlei, although oligotrophic, semi-estuarine, macrophyte-dominated and situated in a winter-rainfall region, also appears to follow the generally-accepted cyclical trend. Earliest records of algal assemblage in the vleis of the south-western Cape Province stem from the work of Hutchinson *et al.* (1932) and Stephens (1929). More recent and comprehensive observations, made at Zeekoevlei and Princess Vlei, and giving some limited indication as to the seasonality of the phytoplankton therein, are to be found in Harrison (1962). A macrophyte-phytoplankton interaction is described for Zeekoevlei (see also Howard-Williams, 1976; Bickerton, 1982), whilst Princess Vlei was reported as being colonized in the summer by green algae (*Micractinium* spp.) with a winter-spring appearance of *Microcystis* spp.

algal counts in Lake Midmar during 1981, along with increased numbers of *Microcystis* colonies (Breen, 1983). Diatom species, chiefly *Melosira granulata* were very common during the winter, declining with the onset of spring (Breen, *ibid.*).

The phytoplankton community of Rhenosterkop Dam was found to contain 59 taxa representing six major taxonomic groups (Heath *et al.*, 1988). Dinoflagellates, cryptophyes and chlorophytes comprised more than 80% of the total phytoplankton volume. Cyanophyta and diatoms were never dominant but occasionally co-dominant (Heath *et al.*, *ibid.*). A seasonality pattern was indistinct for the population as a whole. The abundance, species composition and productivity could not be related to water temperature, solar irradiance or penetration, and it was concluded that this relatively new (completed 1984) impoundment had not yet reached equilibrium, and that successional changes unrelated to seasonal changes were occurring.

Nitrogen has been identified as being the growth-limiting nutrient in the eutrophic Rietvlei Dam, Transvaal (Ashton, 1979). Algal blooms of both nitrogen and non-nitrogen fixing species have occurred, often escalating during the summer months. Green algae utilized much of the epilimnetic nitrogen during the spring and early summer, with the resultant low N:P ratios (approx 1:1), and elevated water temperatures promoting summer bloom development of the nitrogen fixing species *Anabaena circinalis* (Ashton, 1979and 1981). Ashton (1979) reported that succession in Rietvlei Dam was highly correlated with water temperature. *Microcystis* spp. succeeded the *Anabaena* peak, similar to the sequence observed in Lake le Roux (Allanson and Jackson, 1983), with release of nitrogen from the death of the *Anabaena* cells fueling growth of the *Microcystis* spp. (Ashton, 1979).

Hartbeespoort Dam, a biogenically turbid reservoir (Allanson *et al.* 1990), has recently been the subject of an intensive limnological investigation (NIWR, 1985) and for which the effects of reduced nutrient inputs have been evaluated

(Chutter, 1989). *Microcystis aeruginosa* dominated Hartbeespoort Dam in terms of numbers and cell volume throughout the study (Robarts and Zohary, 1984). *Microcystis* spp. became apparent during mid- to late October, increasing rapidly so that by December *Microcystis* accounted for over 90% of the phytoplankton (Robarts and Zohary, 1984; Chutter, 1989). This dominance remained until early winter, whereupon sedimentation losses, as a result of low water temperatures, brought about a significant reduction in *Microcystis* numbers. *Oocystis* spp. were dominant during the spring, together with other chlorophytes (NIWR, 1985). *Melosira granulata* usually appeared for short periods during the winter or early spring (NIWR, *ibid.*).

The formation of hyperscums in Hartbeespoort Dam has been linked to several factors, including decreased turbulence. Zohary and Breen (1989) have shown that hyperscums of *Microcystis* in Hartbeespoort Dam form, typically, in winter, and are dependent on the following preconditions being met:

a). The pre-existence of a large standing crop of cyanophyte algae
b). That the algae (a) are buoyant
c). low-wind speeds over long periods of time (weeks)
d). shore morphometry providing sheltered accumulation sites
e). high incident solar radiation

Microcystis has been shown to dominate the phytoplankton population of Hartbeespoort Dam not only in the summer (characteristic of temperate lakes), but also during the winter (NIWR, 1985). Zohary and Robarts (1989) investigated the involvement of diurnal mixed layers in the long-term dominance of *Microcystis* in Hartbeespoort Dam. Amongst a variety of factors contributing to the long-term dominance of this blue-green alga, they concluded that, by maintaining itself within diurnal mixed layers shallower than the euphotic zone, and by aggregating into large colonies, *Microcystis* was able to compete for available light. At the same time, grazing losses were minimized.

5. THE PEG MODEL OF SEASONAL SUCCESSION

The Plankton Ecology Group (PEG) proposed a model consisting of 24 sequential statements describing the seasonal events occurring in both the phytoplankton and zooplankton of an "ideal" lake (Lake Constance) (Sommer *et al.*, 1986; Sommer, 1989). This was circulated amongst 30 participants world-wide, who then tested it against a well studied system of their own (see 4.1 above). It was found that biological interactions (see 4.4.1) played a dominant role in the observed successional patterns, and that physical forces were not dominant during stratified periods, although they were considered to impose random noise upon the autogenic succession process. Reynolds' (1980) definition of succession (see 3, above, and as cited in Sommer, 1986) was found to hold true. Succession, generally, was understood to be predictable and directional, although subject to disturbance by irregular physical events.

According to the PEG model, transition between lakes with and without a summer growth of phytoplankton was found to lie along the oligotrophic-eutrophic gradient, although the actual mechanism of the transition is still unclear. Amongst other conclusions, high flushing rates and the absence of thermal stratification were found to result in deviations from the standard model. Flushing was found to favour the smaller, *r*- selected organisms. Shallowness also precluded predictability, and the windier the shallow lake, the moreoften the endogenous successional trend is broken. The paper by Sommer *et al.* 1986 provides an excellent overview of the factors affecting the successional cycle, and emphasizes the similarities in phytoplankton periodic cycles between climatologically and morphologically- different bodies of water.

6. PHYTOPLANKTON AS TROPHIC STATE INDICATORS

In the aquatic environment, the phytoplankton community is recognised as being one of the most sensitive indicators of change. In order to assemble base-line data on a region faced with hydroelectric development, Janus and Duthie (1979) carried out a three-year study on a Canadian Lake. Once the dam was constructed, it was proposed that this data base would be used for comparing observed changes in the phytoplankton periodicity (subsequent publication not identified).

The use of algae in indicator assays, phytoplankton assemblage bioassays, as indicators of soil fertility and heavy metal contamination, as well as in industry and for the assay of industrial effluents are reviewed in Shubert (1984). This is a very practical publication, covering a broad range of topics such as the characteristics of phytoplankton assemblages, *in situ* bioassays, experimental enclosures and sampling techniques, as well as relevant laboratory methods. Throughout the publication emphasis is placed on the utility of qualitative data, as well as data synthesis and interpretation.

Hutchinson (1967) included a comprehensive ecological classification of phytoplanktonic associations, listing dominant and characteristic species in various trophic water types. He listed a range of 13 associations, progressing from oligotrophic desmid plankton to bacterial (photosynthetic) plankton in saline, hydrogen-sulphide rich lakes.

Rott (1984) stated that the two basic factor-complexes used to define trophic state:- mineral nutrient and organic substance content (static); and the dynamic processes of auto- and allochotonous supply of organic nutrients, are not independent of each other. The amount of organic nutrient is the result of dynamic processes such as production and decomposition, whilst such processes are affected by the inorganic nutrient level. Rott (1984) concluded that phytoplankton populations follow general patterns which are determined to an extent by the trophic status of the system in question, and that phytoplankton studies provide a sensitive measure of changes occurring within a specific system.

In the development of the PEG model (see Section 5), it was concluded that the observed highly variable taxonomic composition might be related to differing trophic status as well as to variations in the hydrographic regimes of the various systems. Cyanophyta numbers were found to be high in eutrophic systems, irrespective of thermal stratification. Dinoflagellates were found to be absent from non-stratifying systems. Diatoms have long been used as indicators of river water quality and levels of eutrophication (eg. Schoeman, 1976 and 1979), and the multitude of publications and books by Cholnoky (eg. Cholnoky, 1968) concerning diatoms and their ecology are too numerous to be included in this review. Diatom periodicity in itself merits a separate review of the literature which has been amassed to-date. The presence of various groups of diatoms can be indicative of the oxygen and/or nitrogen concentrations present in the water, or indicate the level of pollution. In the development of the PEG model (Sommer *et al* ., 1986), however, no consistent trend between trophic state and diatoms was found for any of the lake systems reviewed.

The Jassby-Goldman Index (Jassby and Goldman, 1974) has been identified as being a potentially useful diagnostic tool in pollution studies. This parameter, defining the rate of change of species composition, enables a simple, quantitative description of the course of succession in ecosystems.

Variations in the total biomass of Lake Erie allowed it to be divided into three basins graded according to trophic state (Munawar and Munawar, 1976). *Melosira, Stephanodiscus, Anabaena spiroides* and *Aphanizomenon* were regarded as eutrophic indicator species.

Rao (1977), in studying freshwater ponds in India, found three species of *Oscillatoria* to be indicative of eutrophic conditions.

Casterlin and Reynolds (1977) investigated phytoplankton succession in a lake receiving raw domestic sewage, and which had become severely polluted. Several algae, described as being "pollution-tolerant", were observed. This work formed the first such study on the lake, and, as changes to the sewer system were expected, monitoring of the system with respect to phytoplankton species and diversity in the future should have revealed the changes concomitant with decreasing levels of eutrophication.

7. USE OF DIVERSITY INDICES IN PHYTOPLANKTON SUCCESSION STUDIES

The use of indices, such as those developed by Jassby and Goldman (1974) or Lewis (1978a), for expressing directionality have been referred to above. Where phytoplankton periodicities have been linked to environmental factors, some measure of the trophic state of the water body under study has usually been employed. Such indices are well reviewed in the United States Environmental Protection Agency publication on Lake and Reservoir Classification Systems (Maloney, 1979). Most attempts to relate species composition to lake trophy are centered around the concept of species diversity. This appears to be fundamentally in error, as such methods rely heavily on the taxonomic competence of the observer in being able to identify all the species present (Kalff and Knoechel, 1978). Kalff and Knoechel (*ibid.*) regarded such indices as "ecologically obscure", and suggested that they rather be computed on the basis of biomass rather than cell numbers.

Washington (1984) provided a detailed review of several diversity, biotic and similarity indices with special reference to aquatic systems. Hutchinson (1967) reviewed several phytoplankton indices, based on numbers of species per algal division, as well as related to lake productivity.

Several articles have been produced by Pieterse (1987), Pieterse and Roos (1987, 1987a) and Pieterse and Van Zyl (1988) using different diversity indices to study a variety of algological factors in the Vaal River at Balkfontein, South Africa. These works cover the application of various indices, and their relationship to various factors such as turbidity, discharge, temporal trends and environmental factors.

8. CONCLUSIONS

It is clear that periodic sequences follow (with exceptions) a similar pattern, even in spite of gross morphological and climatic differences. It is also apparent that the nature and direction of phytoplankton periodicity may be "masked" by random events impinging upon the cycle. This may render the interpretation of the directional aspect of phytoplankton periodicity much more difficult.

Deep, stratifying, north-temperate systems have been comprehensively studied, and the phytoplankton periodic cycles are well understood. Small, polymictic and shallow tropical, sub-tropical and south-temperate, as well as Mediterranean waterbodies have received less attention, although there is strong evidence that the seasonal paradigm of phytoplankton periodicity still applies. There is, however, much scope for research in these less-well understood systems. The overall greater frequency of periodic events in small bodies of water renders them that much more valuable as study areas for investigating causal relationships between environmental factors and algal periodic response.

The problem of the paucity of information on phytoplankton periodicity in Southern African, and in particular, South African lakes and vleis, needs to be addressed. In addition to numerous large reservoirs, South Africa has a number of shallow systems, including coastal lakes and estuaries, some of which are severely impacted by anthropogenic pollution. Many of these lakes and vleis form the focal point of regional recreational developments, and there exists a need to maintain an acceptable degree of water quality. South African limnologists, therefore, are exposed to a unique area in which to study the responses and periodicity of phytoplankton in shallow, well-mixed systems of varying trophic state. The potential value of the findings thereof, in the disciplines of phytoplankton ecology as well as water quality management, is significant.

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CHAPTER 2

THE LIMNOLOGY OF ZEEKOEVLEI

1981-1990

INTRODUCTION

South Africa has a number of shallow, natural lakes (vleis) which lie adjacent to the coastline (Noble and Hemens, 1978). These coastal lakes are found in the southern and south-western Cape and in northern Natal where they extend into the wetland/floodplain systems of Mozambique (see Figure 1A). The lake systems of the Natal region contribute the major portion of the total South African lake surface.

These lakes are chiefly estuarine in character, such as the Kosi Lake system, with 196 estuaries listed for the South African coastline (Noble and Hemens, 1978); others display intermittent or semi-estuarine regimes, such as Swartvlei or Zandvlei (southern and south-western Cape, respectively), while some are isolated from the coastline and are freshwater systems, eg. Lake Sibaya.

Several of these waterbodies have been the focus of intensive studies, the results of which were reviewed in Allanson *et al.*, 1990, and referenced in the extensive bibliography and directory of African shallow lakes and wetlands (Burgis and Symoens, 1987; Davies and Gasse, 1988, respectively; see also Chapter 1). Particular attention has been devoted to the Natal region, with studies of the Kosi and St Lucia lake systems, as well as Lake Sibaya. Along the southern coast, Swartvlei and the Wilderness Lakes complex (Figure 1A) have also been investigated.

In contrast, very little attention has been paid to the coastal vleis of the south-western, mediterranean-climate, winter-rainfall region (see Mepham, 1987), and no comprehensive account of the limnology of these waterbodies has yet been

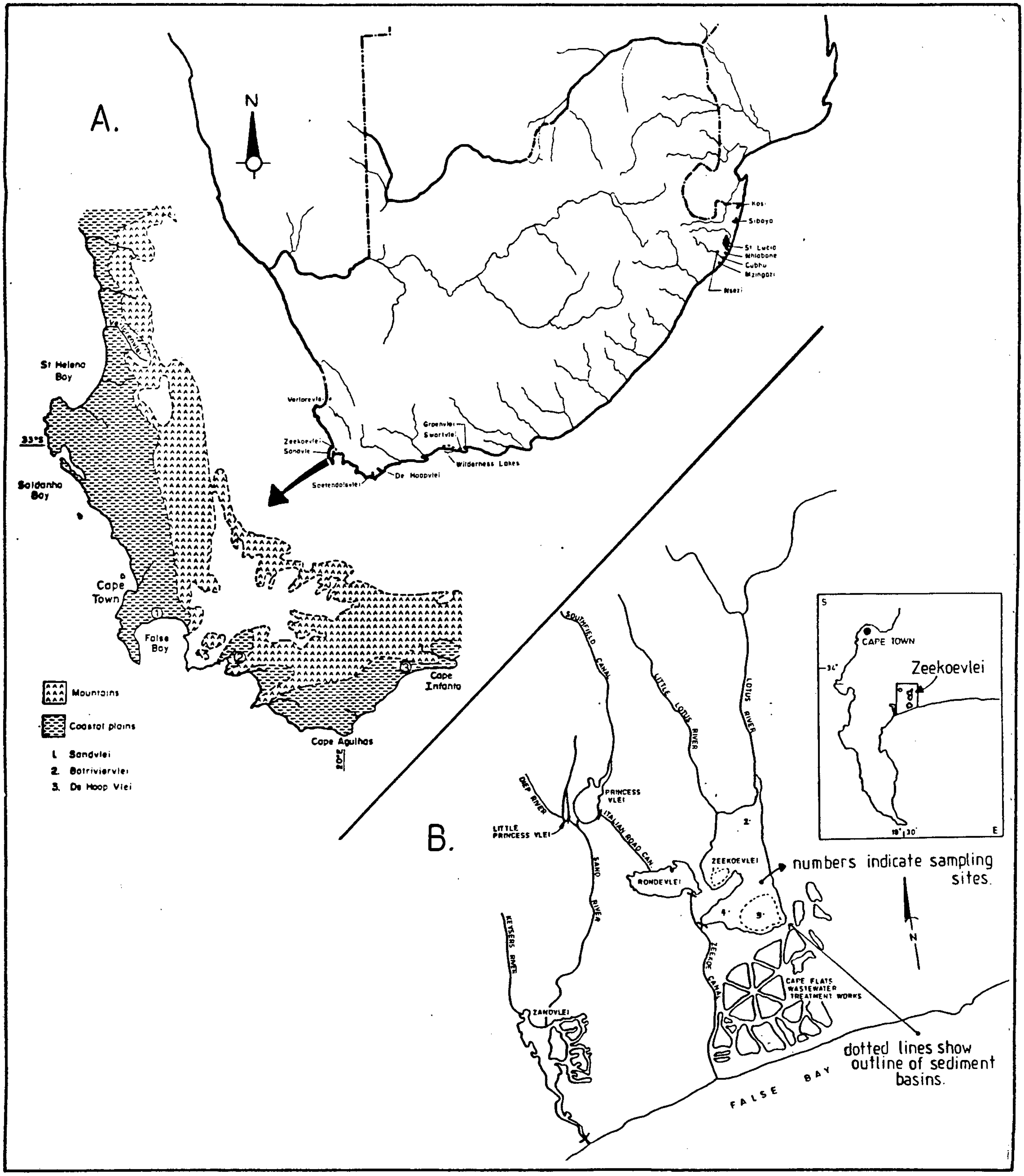

FIGURE 1. (A) Map showing position of South African coastal lake systems (after Noble and Hemens, 1978); and (arrowed) the south-western Cape coastal plains and vleis as described by Mepham in Burgis and Symoens, (1987).

(B) Map showing the position of Zeekoevlei in relation to the Cape Peninsula (insert); and the sampling sites, sediment basins and its position in relation to the other coastal vleis referred to in the text.

published. The Directory of South African Shallow Lakes and Wetlands (Burgis and Symoens, 1987) lists three lakes in this region under the heading of "Wetlands of the south-western Cape", these being Sandvlei (*sic*) and Botriviervlei, both semi-estuarine; and De Hoop Vlei, an isolated, blind estuarine system (see Figure 1A). To these may be added Kleinriviersvlei, a blind estuary near Botriviervlei; Zeekoevlei, Princess Vlei, Little Princess Vlei, Langevlei and Rondevlei, all situated on the Cape Flats northeast of Zandvlei; and Rietvlei, a lagoon-system to the north of Cape Town. Zeekoevlei, Princess Vlei and Rondevlei are freshwater systems, draining to other vleis or to the sea (refer to Figure 1B).

Zandvlei, Zeekoevlei, Princess Vlei, Little Princess Vlei and Rondevlei are small, shallow, permanent lakes which lie on the Cape Flats coastal plain adjacent to the Cape Peninsula (see Figure 1B). Of the five, only details of Zandvlei, a semi-estuarine system, have been published largely due to the development of a marina along its eastern shoreline (see Begg, 1976; Morant and Grindley, 1982). Despite the fact that Zandvlei, Zeekoevlei and Princess Vlei have been monitored for some years by the Cape Town City Council, relatively little data (see Davies and Gasse, 1987) other than City Council departmental and consultancy reports, have been published. The phosphorus dynamics of Rondevlei have been studied by Semmelink (1990) and the chemistry is routinely monitored by the Western Cape Regional Services Council (M. Taljaard, personal communication). Rondevlei formed part of a study by Gardiner (1988).

No attempts have been made to collate the available information for these shallow systems into a concise, limnological entity. This chapter presents the results of the past ten years of physico-chemical monitoring at Zeekoevlei, and introduces the findings of recently introduced phytoplankton investigations. This chapter was compiled to support the interpretation of the first comprehensive phytoplankton study conducted at Zeekoevlei which commenced during April of 1989. The results of the first two years of phytoplankton studies at

Zeekoevlei, from April 1989 to March 1991, are presented in Chapter 4.

STUDY AREA

Zeekoevlei is a large (256 ha), shallow (mean depth 1.9 m) coastal vlei situated on the Cape Flats of the Cape Peninsula (Figure 1A). Aspects of the vlei's limnology have been reviewed by Bickerton (1982) in a synopsis of the available information on the Zeekoevlei estuary. Early work was conducted by Stephens (1929) and Hutchinson *et al.* (1932). More recently, various investigations have been conducted by Harrison (1962), van Wyk (1970), King (1973), Curtin *et al.* (1975), Howard-Williams (1976), Hamman *et al.* (1977), Brummer (1981), Davies (1983), Rudnick (1986), Dick (1990), Hall (1990) and Harding (1990a-d). In addition, the results of the routine CCC water chemistry monitoring programme are summarized annually in reports of the Cape Town City Engineer. Details of the catchment geology can be found in Brummer (1981), Bickerton (1982) or Gardiner (1988).

Zeekoevlei has for many years been characterized as being "pea-soup green" in colour, as a consequence of excessive algal growth. This feature is reported as far back as the 1920s (Stephens, 1929). From the information supplied by Harrison (1962), it is evident that prior to 1947, the aquatic flora was dominated on a cyclical basis by phytoplankton or the macrophyte, *Potamogeton pectinatus* (L.), with the controlling variable being the hydraulic flushing of the vlei during winter rainfall (see Harrison, 1962). Construction of an outlet weir increased the overall maximum depth of the vlei by approximately 1 m (Cape Divisional Council Plan 26670 of 1952) and thus provided additional depth for year-round sailing and other aquatic pursuits. It also greatly reduced flushing and increased the water-retention time of the vlei. Until 1958, Zeekoevlei was connected to Rondevlei (Figure 1B), and phytoplankton blooms originating in the latter invariably seeded similar conditions in Zeekoevlei (Bickerton, 1982).

The effect of the weir on the physical dynamics of Zeekoevlei, and the reduced hydraulic ability of the vlei to rid itself of its algal population, was exacerbated by a further concession to the sailing fraternity in the form of a decision to rid the vlei of *Potamogeton* by spraying with sodium arsenite (CCC, 1951; see also Allanson, 1978a-c). The resultant nutrient input to the system from the tonnes of decaying plant material fuelled a massive cyanophyte bloom, and the vlei has been dominated by blue-green algae ever since (Dick, 1990; CCC, unpublished records).

At weir crest, 5.18m AMSL, Zeekoevlei has a volume of 5 million m^3 and is fed by two rivers, the Big and Little Lotus (Figure 1B), which drain a catchment of approximately 8000 ha. The bulk of the catchment area falls under the jurisdiction of the Western Cape Regional Services Council (see Bickerton, 1981). Of the total catchment area, the shore and the Little and Big Lotus River sub-catchments comprise 6, 13, and 81% respectively. Zeekoevlei's outlet weir is situated to the south-west (Figure 1B) and overflows only during the winter, with the vlei level fluctuating by an average of 0.5 m between winter and summer as a result of evaporation. Vlei bathymetry (Harding, 1990a) highlighted the presence of two large basins (Figure 1B) which, over the years, have become filled with organically rich sediments such that the vlei presently (1990) contains 1.1 million m^3 of accumulated material, equivalent to 21% of the total vlei volume. These basins are ideally placed for deposition of sediments as the dividing peninsula (Figure 1) provides sheltered conditions, depending on the direction of the prevailing winds (either NW or SE).

A limited dredging operation in the northern bay was undertaken during 1983 to accommodate the requirements of the local yachtclub by increasing the water depth (Hill, Kaplan and Scott, 1980; Civil Engineering Reporter, 1982; CCC, 1983). This dredging removed approximately 200 000m^3 of material (sand and sediment) and created a deep "hole" for future sediments to accumulate in. Seven years later a survey of the bottom profile showed that accumulation had occurred and that the hole was almost full (Harding, 1990a). Apart from increasing the water depth, dredging produced no visible change in the appearance of the water (Davies and Day, 1986; CCC, unpublished records).

Zeekoevlei sediments have phosphorus concentrations virtually identical to those recorded in the hyper-eutrophic Hartbeespoort Dam (Dick, 1990). The contribution of these sediments to the nutrient dynamics of Zeekoevlei is presently under investigation. In a shallow system such as this, one would expect a continuous loading of the euphotic, trophogenic zone with phosphate (ILEC, 1989). In addition to the riverine loading, seepage from the sewage works to the south-east (Figure 1B) has, for a long time, been implicated in the eutrophication of Zeekoevlei (Harrison, 1962; King, 1973; Howard-Williams, 1976; Noble and Hemens, 1978). Overflow channels used to exist between the wastewater treatment plant and Zeekoevlei (King, 1973), but these have since been filled in. Seepage through the dividing berm, together with the impact of seepage from residential conservancy tanks on the Zeekoevlei Peninsula is not, however, regarded as significant to the present overall nutrient loading of Zeekoevlei (Harding, 1990b). Contributions from conservancy tanks have been estimated at 1.6kg person^{-1} y^{-1} where phosphorus-based detergents are in use (EPA, 1980). Given that there are approximately 100 houses on the peninsula, the total contribution, assuming correctly-functioning septic systems and allowing for soil-type variations, would be small in comparison to Zeekoevlei's estimated total annual P-load of 11 000kg P y^{-1} (Quick, *in litt*.). If each household had four occupants, the total contribution (100 houses) would be approximately 6% of the total estimated phosphorus loading of Zeekoevlei.

The polymictic nature of Zeekoevlei precludes stratification of the water column and development of the symptoms characteristic of hyper-eutrophic lakes described by Barica (1981; see also Chapter 4). The situation within the sheltered reed beds in the vlei is somewhat different. On days with little or no wind, ebullition of hydrogen sulphide gas from the sediments purges all trace of oxygen from the water and causes isolated fish kills (personal observation).

Algal scums aggregate amongst the reeds and can form surface layers up to 0.03 m thick (personal observation).

The influent rivers drain residential, industrial and horticultural areas, and a large percentage of the residential areas consist of sub-economic housing (Quick, *in litt*). Horticultural use is the principal land-use type of the Big Lotus River catchment, whilst that of the Little Lotus is chiefly residential.

The vlei is fringed by dense growths of emergent aquatic macrophytes, *Typha latifolia*, *Scirpus australis* and *Phragmites* sp. These reed beds, insofar as their growth along the vlei edge is concerned, are a frequent source of complaint by shoreline property-owners and anglers as the reeds obscure a view of the vlei and prevent access to the water. Excessive reed removal is discouraged by the Cape Town City Council in order to offset bank erosion caused by wind-driven wave action. Large areas of reed beds within the body of the vlei serve as breeding areas for many species of birds (Brummer, 1981). An investigation of bulrush growth and its importance to Zeekoevlei was conducted by Davies (1983) and subsequently, studies have been completed by Hall (1990). Dense growths of *Eichhornia crassipes* (Mart.) (Solms) occur in the reed beds to the south-east of the vlei. These are removed at regular intervals by the Cape Town City Council. Vegetation communities have been reviewed by Brummer (1981), Bickerton (1982) and Hall (1990).

Zeekoevlei's fish population has been surveyed by Van Wyk (1970) and Hamman *et al*. (1977). Large numbers of fish were caught, principally *Sarotherodon mossambicus* , now *Oreochromis mossambicus* , and *Cyprinus carpio*. being the major species present. In addition, van Wyk reported on aspects of the zooplankton. References to zooplankton are also contained in Hutchinson *et al*. (1932) and Harrison (1962). A study of the diversity and periodicity of the zooplankton in Zeekoevlei was added to the monitoring programme in October 1989 and the results will be reported elsewhere (Combrink, *in litt.*).

Zeekoevlei is a popular recreational area and supports a variety of both water- and shoreline-based sporting and family activities (Brummer, 1981; Zeekoevlei User Survey, 1990; see also Chapter 6). A burgeoning housing development on the eastern shore will, no doubt, increase the demands on this amenity, as will growth of the Cape Town metropolitan area in general. As the inevitable increase in loading, both pollutant- as well as user-derived, occurs, so the need to effectively address the problems of the vlei will intensify.

METHODOLOGY

Sampling programme and frequency

Zeekoevlei has been routinely monitored with respect to physico-chemical and bacteriological (sewage-indicator) parameters since 1981, with intermittent sampling between 1984 and 1986; phytoplankton since April 1989, and zooplankton since October 1989. Heavy metal analysis (water and sediments) was introduced on a quarterly basis in December 1989, with heavy metal analyses having been conducted twice before 1989 (Dick, 1982 and 1983). The 1989/90 sampling programme was made up of fortnightly physical, bacteriological and plankton collection, and monthly chemical sampling. With the exception of the plankton, the influent rivers (Figure 1B) were monitored according to the same schedule of variables, whilst on the vlei itself, four sampling stations (Figure 1B) were sampled from a boat. Sampling was invariably carried out during the morning.

Integrated water column samples were collected at each vlei sampling station using a 2.0 X 0.04 m clear PVC tube fitted at the upper end with a 0.04 m PVC ball valve. The sampler was lowered vertically into the water as far as possible with the valve open. The valve was then closed, the sampler withdrawn from the water and the contents transferred to a bucket. This procedure was repeated in triplicate at each station. Samples for analysis at the laboratory were transferred to and transported in two litre HDPE acid-washed bottles.

The physical, chemical and biological methodologies employed are listed in Tables 1 and 2. Water temperatures, pH, dissolved oxygen and conductivity measurements were made *in situ*. All other analyses were performed on the same day at the laboratory.

Total phosphorus in sediment samples was determined according to the method described by Andersen (1976).

Rainfall data were obtained from a CCC rainfall gauge situated at the adjacent Cape Flats Wastewater Treatment Works (Figure 1B). Wind speed data from a recorder at the same site had to be discarded due to an instrument malfunction. Supplementary wind, rainfall, sunshine and incident solar radiation data were obtained from the meteorological office of the South African Transport Services, DF Malan Airport, Cape Town.

Sediment samples for heavy metal analysis were collected using a stainless-steel Birge-Ekman grab with a bite area of 0.0225 m^2 and a penetration depth of 0.15 m. Samples were then transported in plastic buckets to the laboratory and aliquots thereof dried at 105 ^{o}C prior to digestion and analysis. Similarly, integrated water column samples were collected in high density polyethylene bottles and preserved with nitric acid (see Table 1).

Phytoplankton samples were collected using the tube sampler technique already described. All of the phytoplankton cells present in pre-calibrated sedimentation-chamber transects were identified and counted. Colonial species such as *Microcystis* spp. were disrupted prior to counting using the method of Zohary and Pais Madeira (1987). Other colonial species such as *Chroococcus*, *Merismopedia* and *Aphanocapsa* were not enumerated as individual cells owing to their resistance to disruption into identifiable, individual cells. With certain exceptions, identification was to genus level only, and a photomicrograph record of the genera observed was made using a Zeiss

Photomicroscope (see Appendix 1).

TABLE 1. ANALYTICAL METHODS		
CONSTITUENT	METHOD	REFERENCE
pH	Hanna Model HI8424 pH meter with auto temperature compensation	-
Temperature	YSI Model 57 DO meter or Hanna pH meter thermistor probes	-
Windspeed	Deuta hand-held anaemometer	-
Water transparency	0.15m Secchi disc	-
Total alkalinity	Sulphuric acid titration, as mg l^{-1} $CaCO_3$	DWA 1988
Dissolved oxygen	YSI 57 DO meter	-
Oxygen saturation	Calculated using the formulae of Green and Carrit (1967)	J.Mar.Res 1967
Conductivity	T & C 2001 conductivity meter with auto temperature compensation	-
Heavy metals	Atomic absorption spectrophoto-metrically for As, Cd, Cu, Ni, Cr, Fe, Zn, Pb, Al, Hg and Mn.	NIWR 1974
Water hardness	Atomic absorption spectro. for Ca and Mg, converted to $CaCO_3$	NIWR 1974
Sediment composition	Sedigraph analysis Gravimetric/ignition at 600°C	TMH 1986 APHA 1985
Kjeldahl -N	Digestion and conversion to ammonium sulphate	EPA 1979
Ammonia -N	Boric acid distillation	EPA 1979
Nitrate and nitrite -N	Cadmium reduction and autoanalyzer colorimetry	EPA 1979
Silica	Molybdate reduction	NIWR 1974
Total and total-dissolved -P	Persulphate digestion followed by SRP analysis	EPA 1979
Ortho-P (SRP)	Ascorbic acid method	EPA 1979
Suspended solids	Gravimetric	EPA 1979
Chlorophyll *a*	Acetone extraction, results corrected for phaeophytins	ASTM 1979

TABLE 2. BIOLOGICAL METHODS		
CONSTITUENT	METHOD	REFERENCE
1. Bacteriology (Sewage pollution indicator)	Membrane filtration followed by incubation on McConkey agar at 44.5°C (faecal coliforms)	EPA 1978
2. Phycology		
a. Phytoplankton collection and enumeration	Integrated water-column sampler; (2 x 0.04 m), followed by preservation with Lugol's iodine and inverted microscope examination.	Utermohl 1958 Lund 1958
b. Primary production	Light and dark bottle oxygen method.	Vollenweider 1975

RESULTS

Meteorology

Long-term wind (1975-1986) data for the Cape Peninsula (as measured at DF Malan Airport) are shown in Figure 2a. The Cape Peninsula has a bi-modal wind regime, with spring-summer winds predominately from the S and SSE, and during the winter from the N and NW. DF Malan Airport has a marked incidence of winter calms (Figure 2b), reflected as hours per day with a mean wind speed of <1 m s^{-1}. Fuggle (1978) found a marked absence of calms (measured as hours d^{-1} <0.3 m s^{-1}) in the Zeekoevlei area. While it is apparent that the False Bay coastline has an overall "windier" annual regime when compared with more northerly parts of the Peninsula, it is well known that the calmest periods, with "mirror-like" vlei surfaces, occur during the winter. Wind speeds measured at the vlei surface at the time of sampling (1989/90) ranged from zero to 8.1 m s^{-1}. Minimum and maximum monthly mean velocities were 3.1 m s^{-1} (June and July) and 6.1 m s^{-1} (February), respectively.

The rainfall period lasts from April to October, and coincides with the period of lowest overall wind speeds and highest incidence of calm periods (Figure 2a-c). Annual rainfalls for the years 1986-1989 were 740, 530, 377 and 539 mm, respectively. Heaviest rainfalls fell during June 1986 (240 mm); August 1987 (143 mm) and August 1989 (106 mm), with no clear maximum recorded for 1988 (CCC records; Figure 2c).

Sunshine and incident (global) solar radiation for the periods 1981-1990 and 1989-1990, respectively, are given in Figure 2d,e. Minimum hours of sunlight, <6 h d^{-1}, and solar radiation, <10 MJ m^2 d^{-1}, were recorded during the months of June and July, with maxima during January, 11.1 h d^{-1} and 29.5 MJ m^2 d^{-1}, respectively.

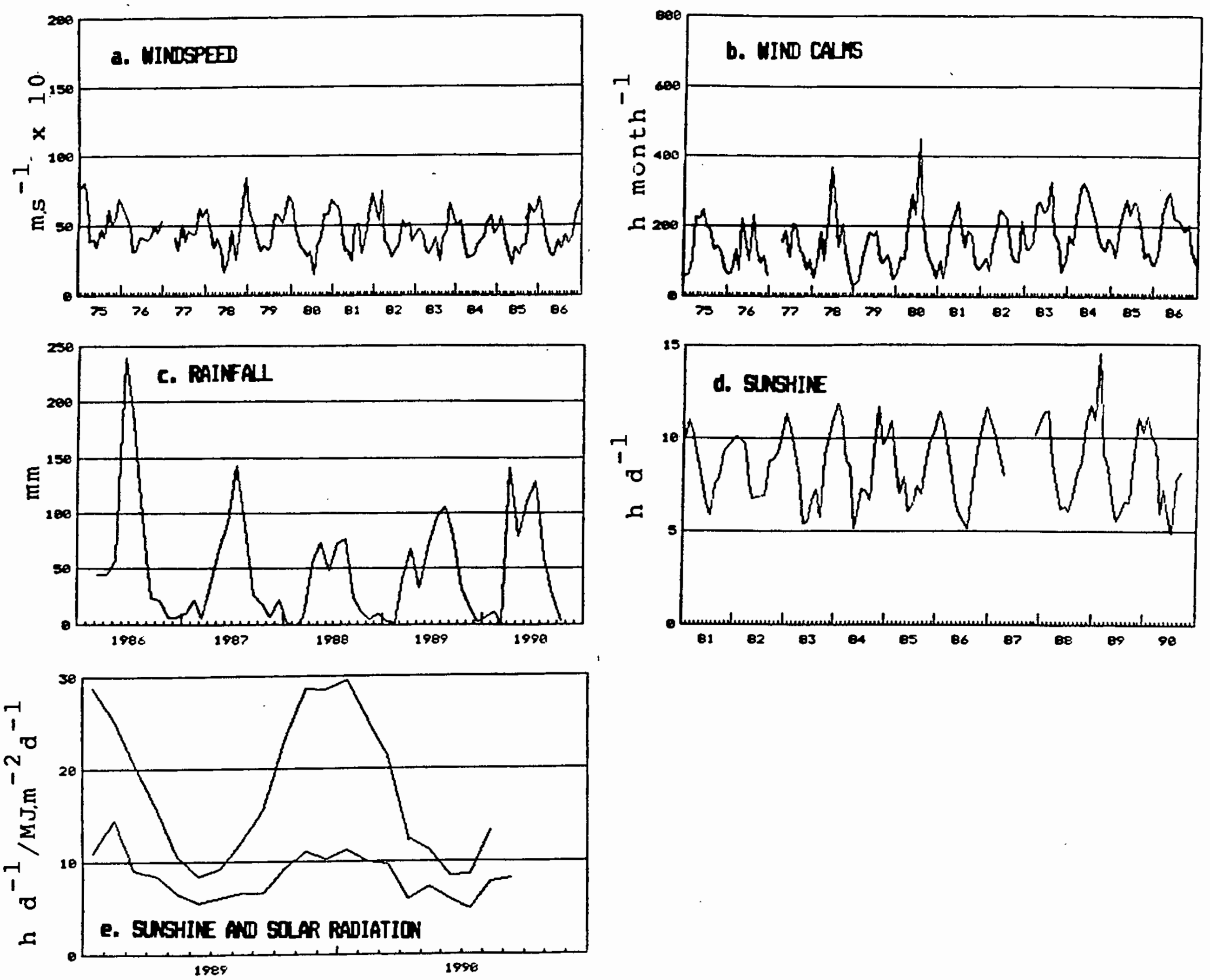

FIGURE 2: Long term climatic trends for the Zeekoevlei region (a), (b), (d) and (e) measured at D.F. Malan Airport, Cape Town; and (c) measured adjacent to Zeekoevlei at the Cape Flats Wastewater Treatment Plant.

Water chemistry

Physico-chemical results for Zeekoevlei and water chemistry data for the Big and Little Lotus Rivers are presented in Tables 3-5. Consolidated data tables for the period 1981-1990 are included at the end of this chapter. Physical parameter measurements for the influent rivers were not tabulated but are included in the text. Tabulated data are given for those years when sufficient readings were taken to provide a representative result. Consequently, the physical data for the vlei spans the period 1983-1990, whilst chemical data for the vlei and the two rivers represents the period 1986-1990. Data is presented from April to March for each annual period in order to facilitate comparison of the water chemistry with the results of the first year of phytoplankton results (see also Chapter 4). In addition, physico-chemical trends, incorporating all the available data, for the vlei and rivers for the period 1981-1990 are presented graphically in Figures 3-6.

TABLE 3 ZEEKOEVLEI. YEAR BY YEAR COMPARISON OF CERTAIN PHYSICAL AND CHEMICAL RANGES AND MEAN VALUES FOR THE PERIOD 1983 - 1990						
RANGES						
YEAR (April-March)	Temperature (^{o}C)	Dissolved Oxygen ($mg\ l^{-1}$)	Oxygen sat. (%)	pH	Cond ($mS\ m^{-1}$)	Secchi trans. (m)
1983-84	11.5-25.0	5.3-18.5	50-139	7.7-10.2	108-327	0.01-0.39
1984-85	11.9-22.6	7.2-19.8	75-205	7.4-10.3	120-263	0.18-0.48
1985-86	11.9-27.8	5.0-18.1	52-191	7.8-10.4	81-214	0.14-0.38
1986-87	12.0-24.0	3.0-11.9	33-135	8.9-10.0	97-225	0.16-0.47
1987-88	12.1-23.5	4.0-14.2	43-137	8.0-11.0	103-349	0.14-0.45
1988-89	12.0-25.0	4.3-13.1	41-137	no data	110-207	0.10-0.37
1989-90	10.0-23.5	7.1-16.6	55-171	8.9-10.6	93-202	0.10-0.41
MEANS						
YEAR (April-March)	Temperature (^{o}C)	Dissolved Oxygen ($mg\ l^{-1}$)	Oxygen sat. (%)	pH	Cond ($mS\ m^{-1}$)	Secchi trans. (m)
1983-84	17.8	8.7	91	9.4	189	0.24
1984-85	16.2	10.9	108	9.3	171	0.28
1985-86	17.9	9.4	98	9.5	140	0.24
1986-87	18.9	7.6	80	9.5	176	0.23
1987-88	18.1	9.0	98	9.6	159	0.25
1988-89	17.8	8.8	86	no data	151	0.25
1989-90	18.3	9.9	102	9.7	136	0.26

From the data in Tables 3-5 it is apparent that conditions in both the vlei and its influent rivers have not changed appreciably during the period reviewed. Nitrate and nitrite -N and phosphorus concentrations in the vlei were higher during 1986/7 when compared to subsequent years (Table 4), but no such variation was apparent for the rivers (Table 5). In addition, in so far as the vlei is concerned, no significant interstation differences could be found for any of the variables using linear regression analysis ($p < 0.001$). The results are therefore presented as the pooled means of all four stations.

Zeekoevlei water temperatures ranged from 11.6 ^{o}C in winter to 24.5 ^{o}C in summer (Figure 3a), with a similar range of 11-28 ^{o}C in the rivers. pH values were lower in the two rivers, ranging from 7.3 to 8.4. Dissolved oxygen levels in the vlei were high, with a mean saturation close to or exceeding 100%

(Table 3). No stratification was observed, except for some microstratification recorded on calm days when windrows of blue-green algae were present on the vlei surface. Maximum dissolved oxygen levels in the rivers were lower than in the vlei, ranging from 3.5-9.9 mg l^{-1}, representing percentage saturations of 33 to 101%. Although the continuity of the pH data was somewhat disjointed due to instrument unavailability and malfunctions, overall pH means were high, in excess of 9 (Table 3, Figure 3c).

Vlei conductivities rarely exceeded 200 mS m^{-1}, and decreased during the rainfall period (Figure 3d). In the Big & Little Lotus rivers, conductivities ranged from 20-120 mS m^{-1}. Secchi disk transparencies were very low (Table 3) and have not exceeded 0.5 m since monitoring began in 1981. Water transparency minima appear to have occurred annually during the late winter-early spring period (Figure 3e).

Zeekoevlei exhibited very high total phosphorus concentrations, with mean values close to or exceeding 0.5 mg l^{-1} (Table 4). N:P ratios, both for total and inorganic nitrogen and phosphorus components were very low, and seldom exceeded 10:1 (Figure 4h,i). High winter concentrations of phosphorus were evident in the water entering the vlei via the Big Lotus River, >0.5 mg l^{-1}, and to a considerably lesser extent, >0.1 mg l^{-1}, in the Little Lotus River (Table 5 and Figures 5 and 6, c-e). Peaks of nutrient inputs (N and P) in both the vlei and the rivers coincided with the peak rainfall period and hence, peak catchment runoff (Figures 3 and 4). The kinetics of phosphorus loading from the sediments must still be investigated, but estimations made by Dick (1990) indicated a massive reserve of phosphorus, present as orthophosphate in the interstitial water and as bound phosphorus in the sediments. Seepage from the wastewater treatment works to the south (Figure 1B) was not regarded as significant; nor was the potential contribution by residential septic tanks (Harding, 1990b).

Mean chlorophyll a concentrations usually exceeded 100 $_{u}g$ l^{-1} with maxima approaching 500 $_u$g l^{-1} at times (Table 4). Chlorophyll a peaks correlated significantly ($p > 0.01$) with peak orthophosphate concentrations (Figure 4e,f). An absence of elevated orthophosphate concentrations (>0.2 mg l^{-1}) in the vlei during 1988 coincided with the absence of a high chlorophyll a level (>100 $_u$g l^{-1}) for that year (Figure 4e,f; see also Chapter 6). Summer peaks of chlorophyll a were observed during 1983 and 1986 (Figure 4f). Suspended solids concentrations in the vlei were 5-8 times greater than in the rivers (Tables 4 and 5).

TABLE 4
ZEEKOEVLEI. YEAR BY YEAR COMPARISON OF CHEMICAL VARIABLES RANGES AND MEAN VALUES FOR THE PERIOD 1986 - 1990

CHEMICAL PARAMETER RANGES (*)								
YEAR (April-March)	TKN	NH3	NOx	TP	TSP	SRP	ss	Chl a
	(mg l^{-1})							ug l^{-1}
1986-87	1.0-8.9	0.10-0.47	0.00-2.20	0.26-1.05	0.07-0.98	0.21-0.86	14-180	40-199
1987-88	0.0-13	0.00-0.20	0.01-1.16	0.16-0.73	0.04-0.41	0.02-0.39	34-266	43-316
1988-89	1.0-7.7	0.00-0.25	0.00-0.05	0.27-0.66	0.05-0.25	0.02-0.19	44-120	39-155
1989-90	1.7-6.6	0.03-0.38	0.01-0.94	0.29-0.95	0.01-0.51	0.01-0.45	14-153	57-468
CHEMICAL PARAMETER MEANS (*)								
YEAR (April-March)	TKN	NH3	NOx	TP	TSP	SRP	ss	Chl a
	(mg l^{-1})							ug l^{-1}
1986-87	3.1	0.18	0.44	0.68	0.35	0.29	94	100
1987-88	4.0	0.11	0.15	0.46	0.16	0.14	92	132
1988-89	3.5	0.08	0.02	0.47	0.13	0.09	72	81
1989-90	3.9	0.13	0.17	0.56	0.19	0.15	68	168

(*) KEY TKN = Total(Kjeldahl) -N ; NH3 = Ammonia -N ; NOx = Nitrite & Nitrate -N
TP = Total -P ; TSP = Total soluble -P ; SRP = Soluble reactive (ortho) -P
ss = Suspended solids ; Chl a = Chlorophyll a (corrected for phaeophytins)

Total alkalinity and reactive silica data were not tabulated as they were representative of only a portion of the 1989-1990 period. Riverine alkalinities, expressed as mg l^{-1} $CaCO_3$, were of the same order as those measured in Zeekoevlei, with mean concentrations of 221, 135 and 160 mg l^{-1} for the Big Lotus River, Little Lotus River and Zeekoevlei, respectively. Total alkalinity ranges for the rivers and vlei were 179-270, 113-170 and 132-181 mg l^{-1}, respectively. Silica in the rivers (1.1-10.7 mg l^{-1}) was much higher than in the vlei (0.01-2.16 mg l^{-1}) indicating either a change in form or utilization by species of Bacillariophyta.

Trophic State

Zeekoevlei occupied a position at the upper end of Carlsons (1979) continuum scale of trophic state, with TSI (trophic state index) values of 80, 81 and 96 for Secchi disk transparency, chlorophyll a and total-P, respectively. According to the trophic state classification of the OECD (1982) Programme, Zeekoevlei bridged or exceeded the eutrophic/hypertrophic boundaries for total-P, total-N, chlorophyll a and Secchi transparency. N:P ratios were almost exclusively <10:1 (Figure 4h,i).

Heavy Metals

Heavy metal concentrations in the sand and sediments of Zeekoevlei were low (Table 6), and were in line with values for relatively unpolluted lakes, such as those at the Wilderness, Southern Cape (Watling, 1977). Data are included for two other coastal vleis on the Cape Peninsula:- Zandvlei and Princess Vlei.

The upper 0.2 m layer of the sediment in Zeekoevlei was found to be predominately siltaceous in nature, having a particle size range of 0.001-0.04 mm. The sediment composition was found to be 94% water, and on ignition, the dried sediments were found to contain 35% organic matter (Harding, 1990c). Nitrogen and phosphorus contents of the dried sediments were calculated as being 16000 and 1300 mg kg^{-1}, respectively (n=7, standard deviation for N = 2160 mg kg^{-1}, and P = 760 mg kg^{-1}, Harding, 1990d).

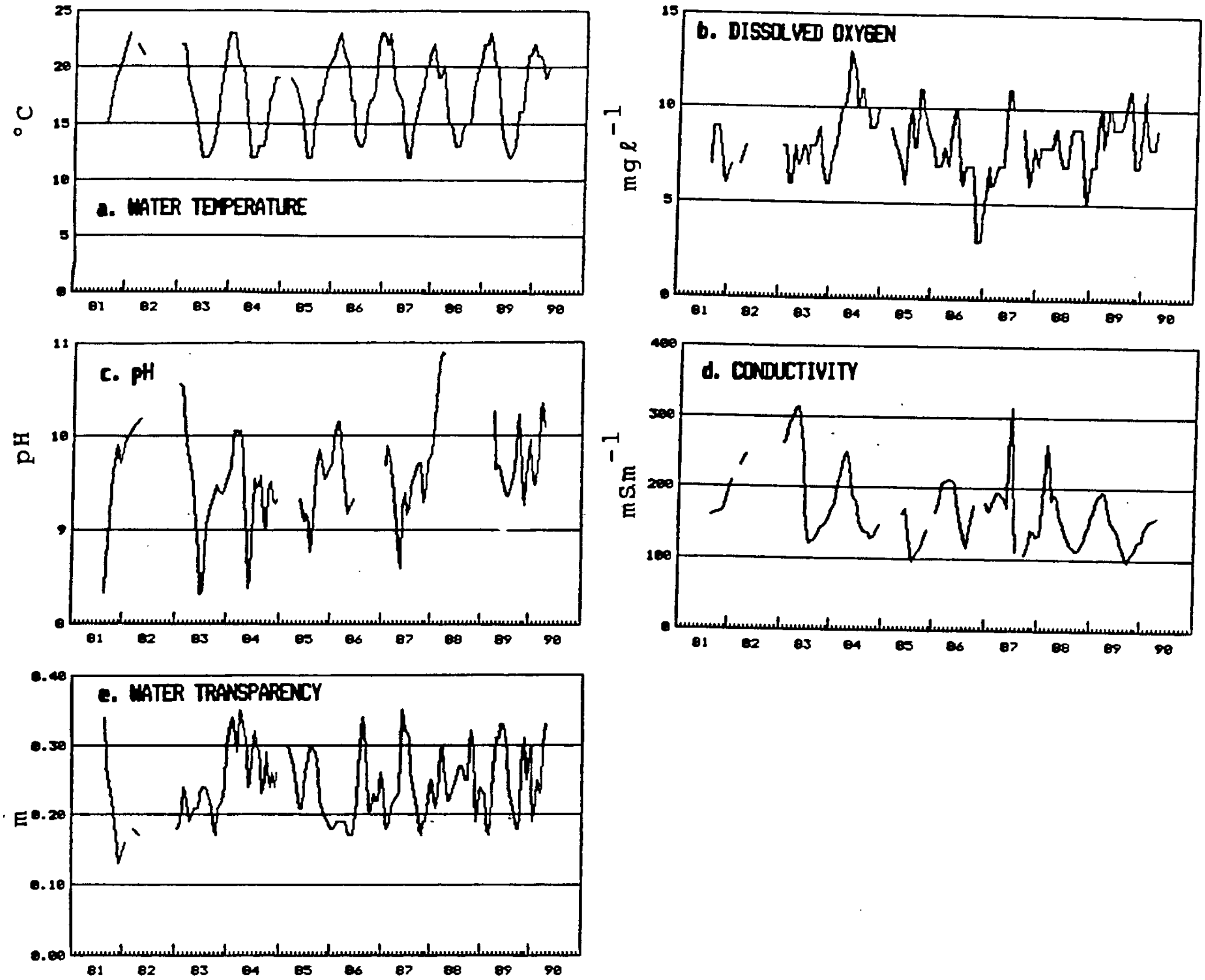

FIGURE 3 : Physical parameter trends for Zeekoevlei 1981-1990. Graphs indicate mean (all stations) values for water (a) water temperature; (b) dissolved oxygen; (c) pH; (d) conductivity; (e) Secchi-depth.

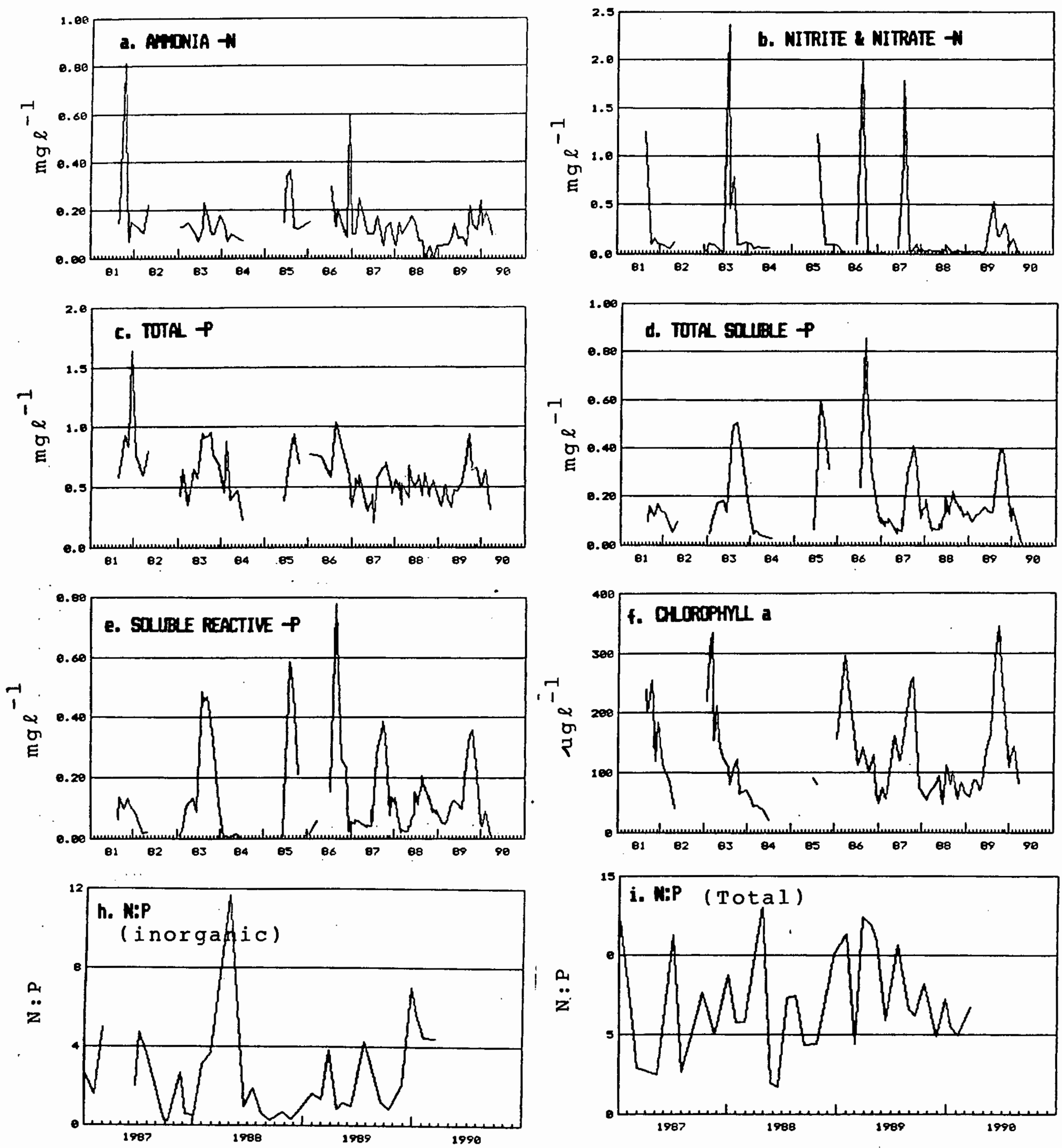

FIGURE 4 : Long-term chemical parameter trends for Zeekoevlei. Graphs show mean (all stations) concentrations for (a) ammonia -N; (b) nitrite & nitrate -N; (c) total -P; (d) total soluble -P; (e) soluble reactive -P; (f) chlorophyll a; (h) N:P ratio (inorganic); (i) N:P ratio (total).

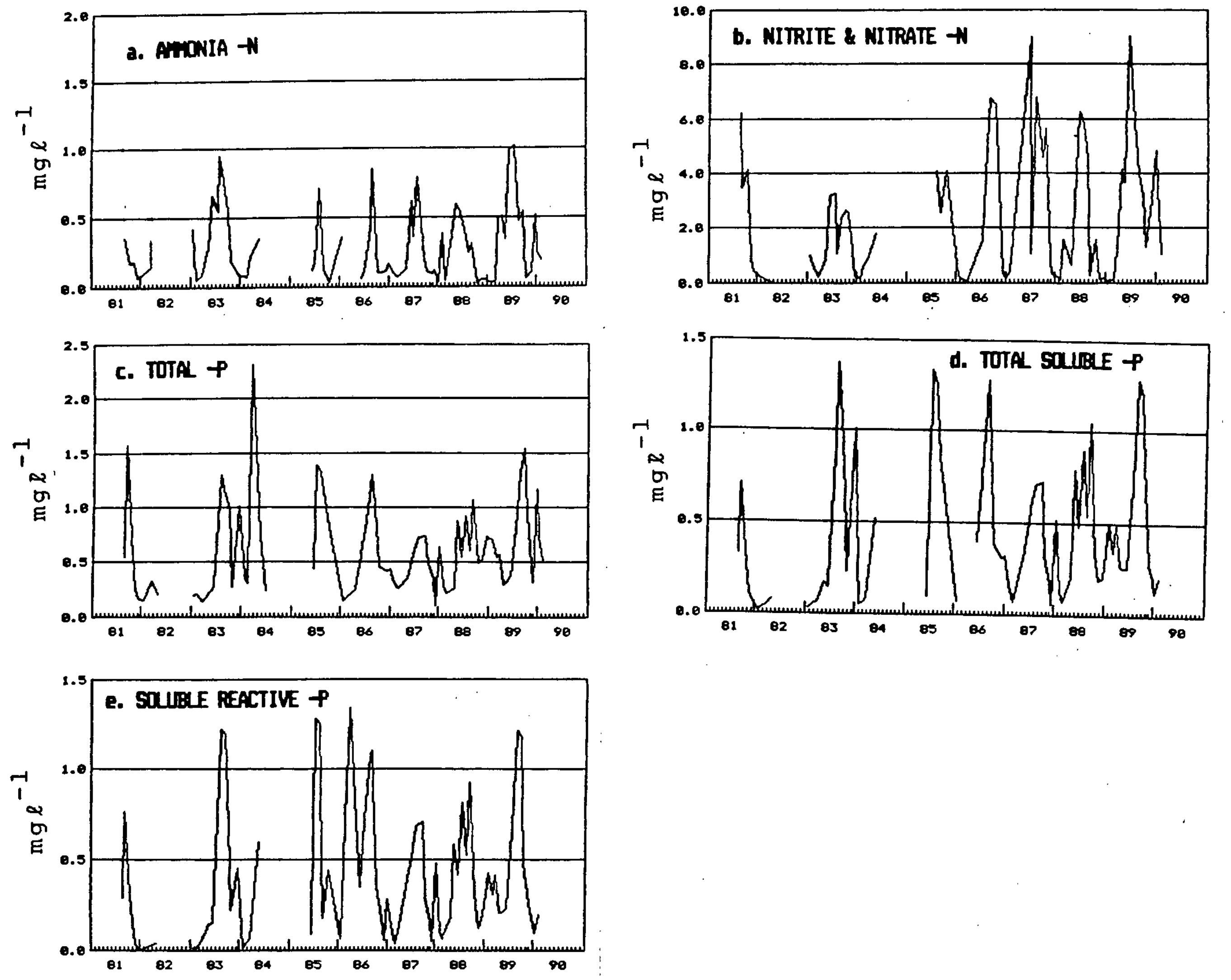

FIGURE 5 : Long-term chemical parameters for the Big Lotus River. (a) ammonia -N; (b) nitrite and nitrate -N; (c) total -P; (d) total soluble -P; (e) soluble reactive-P.

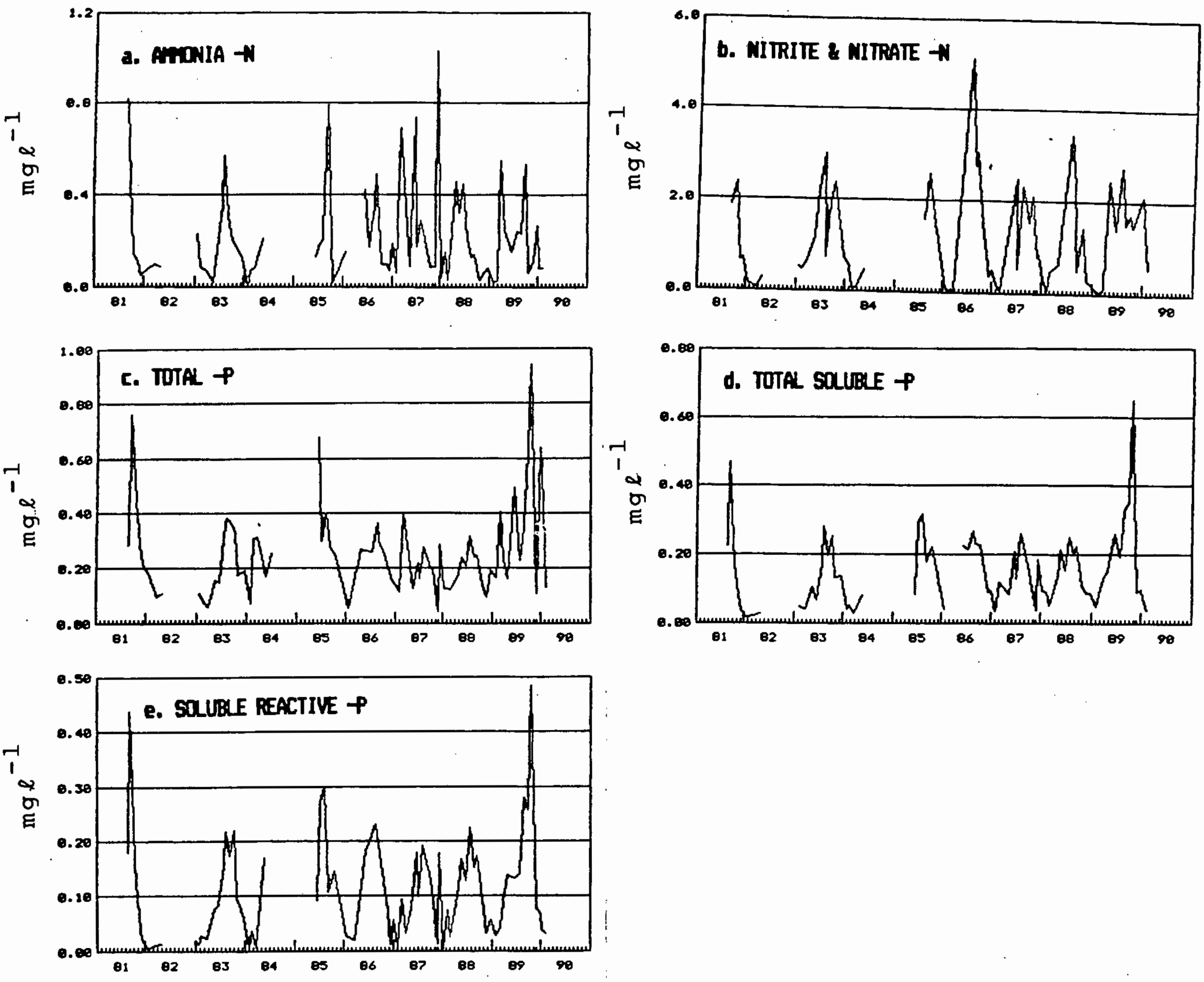

FIGURE 6 : Long-term chemical parameters for Little Lotus River.
(a) ammonia -N; (b) nitrite and nitrate -N;
(c) total -P; (d) total soluble -P;
(e) soluble reactive -P.

TABLE 5

ZEEKOEVLEI. YEAR BY YEAR COMPARISON OF INFLUENT RIVER CHEMICAL PARAMETER RANGES AND MEAN VALUES FOR THE PERIOD 1986 - 1990

BIG LOTUS RIVER - CHEMICAL PARAMETER RANGES						
YEAR (April-March)	TKN	TIN	TP	TSP	SRP	ss
	(mg l^{-1})					
1986-87	0.5-5.1	0.32-7.60	0.25-1.30	0.07-1.28	0.04-1.10	nd
1987-88	0.4-6.0	0.13-9.75	0.11-0.74	0.05-0.72	0.05-0.71	8-36
1988-89	0.7-2.7	0.05-6.90	0.27-1.06	0.19-1.05	0.12-0.93	4-64
1989-90	1.3-4.0	1.10-9.10	0.29-1.54	0.12-1.29	0.10-1.20	4-35
LITTLE LOTUS RIVER - CHEMICAL PARAMETER RANGES						
YEAR (April-March)	TKN	TIN	TP	TSP	SRP	ss
	(mg l^{-1})					
1986-87	0.9-3.3	0.07-5.80	0.01-0.40	0.03-0.27	0.01-0.23	nd
1987-88	0.3-8.7	0.11-2.50	0.04-0.28	0.04-0.26	0.00-0.19	5-30
1988-89	0.5-2.0	0.05-4.00	0.12-0.41	0.05-0.25	0.03-0.23	4-40
1989-90	1.0-2.5	0.61-3.30	0.11-0.95	0.04-0.65	0.03-0.49	5-70
BIG LOTUS RIVER - CHEMICAL PARAMETER MEANS						
YEAR (April-March)	TKN	TIN	TP	TSP	SRP	ss
	(mg l^{-1})					
1986-87	2.1	3.30	0.61	0.53	0.43	nd
1987-88	2.2	3.26	0.46	0.37	0.35	15
1988-89	1.9	2.14	0.65	0.50	0.44	27
1989-90	2.3	4.40	0.75	0.51	0.44	14
LITTLE LOTUS RIVER - CHEMICAL PARAMETER MEANS						
YEAR (April-March)	TKN	TIN	TP	TSP	SRP	ss
	(mg l^{-1})					
1986-87	1.6	2.00	0.25	0.17	0.11	nd
1987-88	2.7	1.40	0.17	0.13	0.10	12
1988-89	1.4	1.20	0.22	0.14	0.11	18
1989-90	1.6	1.95	0.42	0.22	0.17	14

(*) KEY TKN = Total(Kjeldahl) -N ; TIN = Total inorganic nitrogen
TP = Total -P ; TSP = Total soluble -P ; SRP = Soluble reactive -P
ss = Suspended solids : nd = np data

TABLE 6. HEAVY METAL CONCENTRATIONS IN ZEEKOEVLEI SEDIMENTS AND COMPARISON WITH OTHER VLEIS

SAMPLE and reference	Concentration of metal (mg kg^{-1})							
	Cd	Cu	Ni	Cr	Fe	Zn	Mn	Pb
ZEEKOEVLEI (sludge *)	1.6	21	14	19	3100	154	87	nd
(sand **)	0.1	3	2	5	470	16	5	nd
ZANDVLEI 1. (sand)	0.9	6	6	10	nd	50	23	34
WILDERNESS LAKES 2.	0.2	4	4	5	5800	15	50	nd
PRINCESS VLEI 3.	1.0	14	5	11	1950	150	40	90

SOURCE 1 - Harding (unpublished data) * ex Station 3
2 - Watling (1977) ** ex Station 2
3 - Chapter 3 (see Study Area)

Primary production

Highest measurements of primary production (A_{max}) ranged from 30 to 431 mg C m^{-3} h^{-1}. The highest rate was recorded during September 1989 and the lowest during February 1990. Mean daily production was 1100 mg C m^{-2} d^{-1}. A_{max} readings were recorded between the surface and 0.2 m, with rapid cut-off with any further increase in depth (see Harding, 1990d). Daily production exceeded the limit for eutrophic systems as given by Thornton (1987). No investigations of the underwater light climate were undertaken.

Bacteriology

Zeekoevlei bacteriology was limited to water quality monitoring in terms of the faecal coliform (fc) indicator. Year by year results are presented in Table 6. Counts are expressed as positive colonies $100ml^{-1}$ and are listed against the SANCOR requirements which call for <100fc $100ml^{-1}$ (50%ile) or <400fc $100ml^{-1}$ (90%ile) (Lusher, 1984). Faecal coliform counts in the Big and Little Lotus Rivers were exceptionally high, ranging from 1400 to

155000 $100ml^{-1}$, whilst those in the vlei were two orders of magnitude lower (Table 7). Mean riverine and vlei faecal coliform counts are presented in Figure 7 clearly showing an increase and decrease in numbers coinciding with the increase and decrease in annual rainfall (Figure 2c).

Phytoplankton

A detailed analysis of the phytoplankton diversity and periodicity in Zeekoevlei from April 1989 to March 1991 is covered in Chapter 4. The algal assemblage in Zeekoevlei was principally composed of representatives of three divisions:- blue-green algae (Cyanophyta), diatoms (Bacillariophyta) and green algae (Chlorophyta) (Table 8). Representatives of these were present in the vlei year-round. Overall diversity was low. The high algal growth level in Zeekoevlei was reflected in the year-round high pH, dissolved oxygen, suspended solids, chlorophyll a concentrations and low water transparencies. In terms of total numbers and cell volume, the Chlorophyta and Bacillariophyta were almost insignificant when compared with the Cyanophyta (Table 8).

Chlorophyta (principally *Scenedesmus* spp.) were present year-round, and the Bacillariophyta were poorly represented, apart from a marked increase in a small, centric species (*Thalassiosira* sp.) during the winter. A graph depicting total algal cells ml^{-1} in Zeekoevlei would virtually mirror the graph for total cyanophyte algae (Figure 8).

Species of cryptophytes (*Cryptomonas* spp.) appeared in very low numbers during the winter. Species of dinoflagellates and Euglenophyta were present on rare occasions.

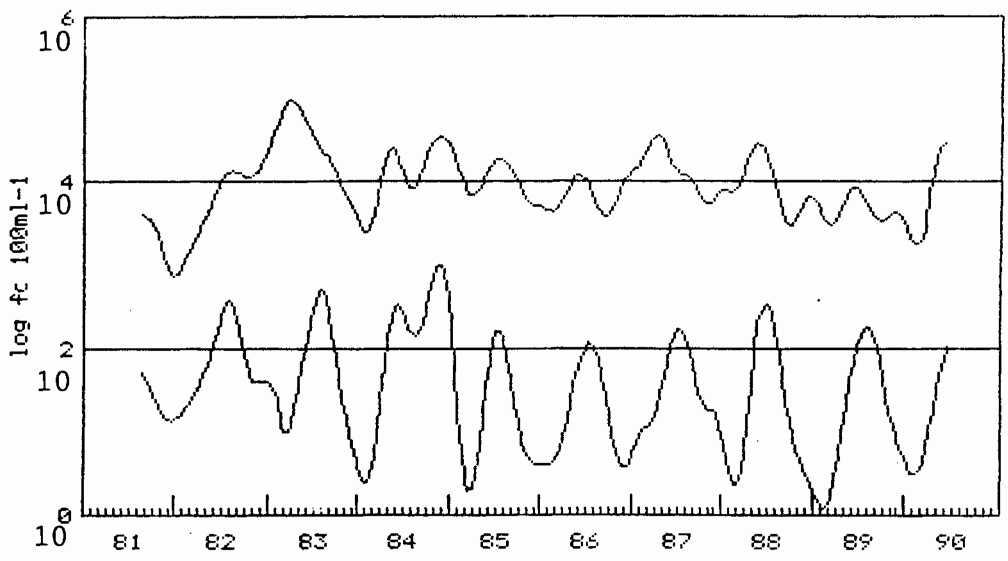

FIGURE 7. Mean faecal coliform levels in the Big & Little Lotus Rivers (upper line) and in Zeekoevlei (lower line)

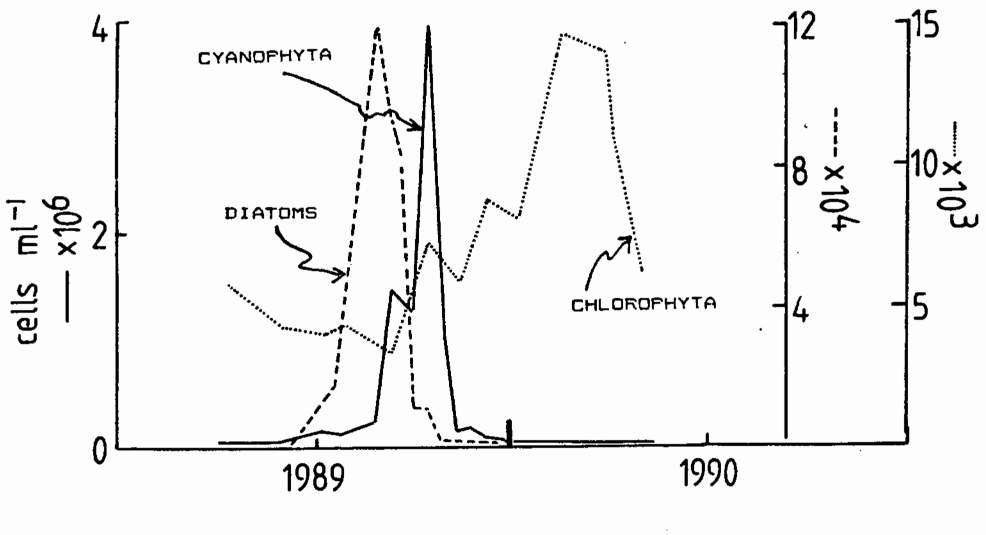

FIGURE 8. Zeekoevlei phytoplankton seasonality

TABLE 7.
ZEEKOEVLEI-BACTERIOLOGY. FAECAL COLIFORM MEAN AND PERCENTILE (AS AGAINST SANCOR CRITERIA*) COUNTS
1981 - 1989
Allowed limits:fc 100ml-1 : 50% (100); 90%(400)

YEAR	% ile *	RIVERS		VLEI STATIONS			
		LLR	BLR	1	2	3	4
		CELLS $100ml^{-1}$					
1981	x	2400	1400	35	20	15	nd
	50	3000	1400	35	15	15	nd
	90	6300	2600	125	40	20	nd
1982	x	5100	7800	60	90	55	nd
	50	6900	8700	50	80	55	nd
	90	21000	23500	400	490	230	nd
1983	x	34000	20000	25	140	75	15
	50	47000	19500	15	120	65	10
	90	155000	56000	275	1900	830	95
1984	x	9100	17000	75	150	70	105
	50	12300	15500	130	340	150	190
	90	15900	110000	1000	850	620	810
1985	x	9800	11500	20	30	15	5
	50	8100	13000	15	25	10	5
	90	29000	40000	200	590	65	85
1986	x	9500	4800	15	30	10	10
	50	9100	4700	15	20	5	10
	90	22000	6500	90	360	70	55
1987	x	18000	10000	15	65	40	20
	50	2200	8500	10	50	35	20
	90	37000	32000	95	380	140	120
1988	x	7800	9500	15	40	10	15
	50	10200	6000	5	35	10	10
	90	17500	43000	150	1300	130	200
1989	x	3800	5600	20	35	10	5
	50	3000	5900	32	40	10	3
	90	9500	9300	100	1000	110	60

* SANCOR = Water Quality Criteria for the South African Coastal Zone, Lusher (1984)
x = mean value; BLR=Big Lotus R; LLR=Little Lotus R.

These results represented the first year of continuous observations of phytoplankton made at Zeekoevlei. The blue-green algae showed a marked seasonal increase during the early spring period, whilst the diatoms increased during the winter, and the Chlorophyta increased during the warmer, windier spring and summer period (Figure 8). The cyanophyte increase correlated significiantly ($p > 0.01$) with peak orthophosphate concentrations (see Chapter 4) and peak counts of *Microcystis* correlated significantly with chlorophyll a concentrations. A small increase in numbers of *Anabaena circinalis* sp. occurred following the collapse of the *Microcystis* bloom, and corresponded to a minimum in the N:P ratio. Large quantities of *Aphanocapsa* spp. occurred during the summer of 1989. Overall, total phytoplankton numbers in Zeekoevlei correlated significantly with total soluble and ortho-P and chlorophyll a ($p > 0.01$), using linear regression analysis.

TABLE 8.
PRINCIPAL ALGAL DIVISIONS, AS CELLS ml^{-1}, PRESENT IN ZEEKOEVLEI PER SAMPLING OCCASION.
(percentage of total cell count in brackets)

Sampling date	Cyanophyta	Diatoms	Chlorophyta	Total
1989-04-10	3600 (24)	2000 (14)	9100 (62)	14700
1989-04-23	15200 (60)	400 (2)	9600 (38)	25200
1989-05-15	37000 (80)	2000 (4)	7000 (15)	46000
1989-05-29	30000 (80)	2500 (7)	4900 (13)	37400
1989-06-12	76000 (87)	160 (<1)	11000 (13)	87160
1989-07-12	163000 (91)	11000 (6)	6000 (3)	180000
1989-07-24	79000 (74)	19000 (18)	8300 (8)	106300
1989-08-30	262000 (68)	120000 (31)	4700 (1)	386700
1989-09-12	1500000 (94)	91000 (6)	2600 (<1)	1593600
1989-09-21	1290000 (94)	82000 (6)	5700 (<1)	1377700
1989-10-03	1260000 (99)	10200 (<1)	5500 (<1)	1275700
1989-10-16	3950000 (99)	10500 (<1)	10200 (<1)	3970700
1989-10-30	1070000 (99)	1100 (<1)	10500 (<1)	1081600
1989-11-13	148000 (91)	1300 (1)	13000 (8)	162300
1989-11-27	167000 (91)	600 (<1)	15000 (8)	182600
1989-12-11	70000 (84)	650 (1)	12500 (15)	83150
1989-12-28	34000 (72)	300 (1)	13000 (27)	47300
1990-01-08	25000 (68)	600 (2)	11000 (30)	36600
1990-01-22	9000 (42)	650 (3)	12000 (55)	21650
1990-02-05	24000 (54)	550 (1)	20000 (45)	44550
1990-02-19	20000 (53)	350 (1)	17000 (46)	37350
1990-03-06	32000 (64)	1000 (2)	17000 (34)	50000
1990-03-20	41000 (69)	1100 (2)	17600 (29)	59700

RSD - relative standard deviation
Chlorophyta - 22% Cyanophyta - 12% Diatoms - 11%

DISCUSSION

As with Hartbeespoort Dam (Robarts, 1984), Zeekoevlei would appear to be an ideal system for studying the effects of physical forcing-factors on algal periodicity and succession. Nutrients, both N and P, are non-limiting, and the presence of the considerable volume of sludge, coupled with its high phosphorus content, most probably fuels the system internally. Loading models currently being applied to the Zeekoevlei system indicate a large discrepancy between input and output of phosphorus, and it is surmised that this "missing input" is attributable to sediment loading (Thornton and Quick, *in litt.*). A considerable volume of physico-chemical data has been amassed for Zeekoevlei during the past 10 years. Unfortunately, and despite the advice of a consultant limnologist (see Allanson, 1978a-c), it has been only recently that attention has been devoted to an investigation of the nutrient loading of the system. Thus, much still remains to be discovered regarding the nutrient dynamics of Zeekoevlei.

Total phosphorus loading to Zeekoevlei from the Big and Little Lotus rivers and the shore runoff have been provisionally estimated as being 6000, 500 and 100 kg y^{-1}, respectively. (Quick, *in litt*.). In addition, soluble reactive phosphorus release from the sediments was estimated to occur at a mean rate of 14.2 g ha^{-1} h^{-1}, or 8500 kg SRP y^{-1}, based on the results of the NIWR (1985) study and the surface area of the sediment basins (Dick, 1990). Total nitrogen loading for the rivers and the shore was calculated to be 53000, 5000 and 600 kg y^{-1}, respectively (Quick, *in litt.*). Vlei outflow volumes ranged from 11400-21000 Ml y^{-1} with a mean outflow of 17500 Ml y^{-1}. Incorporating mean annual (total) N and P concentrations, this reflected a mean outflow of 59500 kg N and 9450 kg P y^{-1}.

The rivers, especially the Big Lotus, deliver huge amounts of nitrogen and phosphorus to the vlei, mainly during the winter rainfall period. This indicates uncontrolled catchment pollution, the sources of which are currently the subject of a combined Cape Town City Council/Regional Services Council investigation.

Physico-chemical data since 1981 indicate that the vlei has been remarkably stable during the past ten years. The fact that chlorophyll a and soluble reactive-P maxima correlate significantly indicates that algal blooms have occurred annually during the late winter, although the peaks of chlorophyll a recorded during summers of 1983 and 1986 indicate that the timing of blooms in Zeekoevlei has not always been confined to the winter period. The new information gleaned from the algal studies show that cyanophyte species are responsible for the spring bloom. The absence of orthophosphate-P and chlorophyll a maxima for 1988 is significant, as this implies that a reduction in the soluble reactive phosphorus concentration would bring about a significant reduction in the amount of algal material produced. The absence of the chlorophyll a peak, and by implication, increased algal biomass, may be due to other causes, such as increased wind speed (see Chapters 4 and 6).

The high nutrient concentrations, and the year-round low N:P ratios provide ideal conditions for cyanophyte algal dominance. Historical data and anecdotal information indicates that cyanophyte-species have been associated with Zeekoevlei since *ca* 1920, along with the establishment of wastewater treatment ponds in the vicinity. Hydraulic flushing, which appeared to have been the controlling variable in managing the balance between macrophyte and algal dominance, has been negated by the construction of a weir. Further reductions in the N:P ratio could lead to dominance by N-fixing species (*Anabaena*) such as is the case in Rietvlei (Transvaal, Ashton, 1979).

The occurrence of a blue-green algal maximum during the winter does not fit the seasonal paradigm of algal periodicity for temperate and tropical lake systems (Reynolds, 1983). This aspect is discussed in Chapters 1 and 4. Reduced turbulence appears to play a crucial role in the timing and the degree of development of cyanophyte blooms in the vlei. *Microcystis* spp. require calm conditions in order to be able to grow optimally (eg. Hutchinson, 1967). Such conditions occur at Zeekoevlei during mid-winter, and high, sustained wind speeds during the summer may prevent the alga from proliferating under more optimum conditions of higher light and temperature. Fuggle (1978) showed that the Zeekoevlei coastal region has less calm periods relative to DF Malan, a natural factor influencing the extent of bloom formation (Zohary and Breen, 1989). Windier conditions during the winter, and the 1988 situation, above, may be a case in point, would reduce the degree of bloom formation. The converse is also true. Less wind during the winter or summer will enhance *Microcystis* development.

Zeekoevlei receives very high numbers of faecal coliform organisms in the water entering via the rivers. This indicates sewage pollution and therefore increased phosphorus inputs, although catchment-derived orthophosphate has been shown to originate chiefly from fertilizers used in horticultural allotments and detergents (EPA, 1980; Welch, 1984). The almost incredible die-off between the rivers and the vlei shows the ability of Zeekoevlei to cope with bacteriological pollution, to the extent that the vlei largely complies with the SANCOR criteria for contact recreation.

Heavy metal concentrations in both the sediments and the sandy bottom of the vlei are low, and show no adverse signs of pollution by trace elements. The concentrations recorded in the sediments closely match those of Princess Vlei (see Chapter 3). Concentrations measured in the Zeekoevlei sand sample drawn at Station 2 (Figure 1B) were within the ranges reported earlier by Dick (1982 and 1983), whilst levels in the sediments showed higher levels of each trace metal measured. The higher levels recorded in the sediments reflect the deposition of particulate matter from the catchment.

CONCLUSIONS

Zeekoevlei is an interesting example of a hyper-eutrophic shallow lake. The trophic state is sustained from year to year by high nutrient loads from the catchment, as well as internal P-loading from the accumulated sediments in the vlei. Generation of algal biomass in the system is controlled to a large extent by physical factors (mixing, turbulence, long retention times), in the absence of limiting nutrients. Conditions are ideally suited for *Microcystis* proliferation and the long term colonization of Zeekoevlei by Cyanophyta.

Any remedial measures to restore the vlei will have to be drastic, as conventional techniques may be inadequate in a self-sustaining system such as this (see Barica, 1981). Whilst there is more than sufficient data on nutrient concentrations, much still remains to be understood regarding nutrient loading rates, wind-algal interactions, fluid dynamics and biophysical factors. The elucidation of the nutrient loading dynamics of Zeekoevlei will provide valuable information essential for predicting any post-remedial changes.

Zeekoevlei is a very attractive waterbody, with considerable potential as a prime recreational venue. Shallow lakes such as this are at a premium in the Western Cape and should be preserved. The rehabilitation of Zeekoevlei will be expensive, and should the Cape Town City Council decide that restoration has merit, a comprehensive, integrated programme, starting in the catchment and culminating in the vlei (see Chapter 6), will be required. Any half-measures will amount to a squandering of ratepayers money.

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LOTUS RIVER - PHYSICO-CHEMICAL DATA SUMMARY 1981 - 1990															
YEAR		°C	pH	Cnd	DO	%OS	TKN	NH3	NOx	TIN	TP	TSP	SRP	TPP	ss
1981	n	5	5	5	2	2	5	5	5	5	5	5	5	5	5
	min	15.0	6.4	64	8.3	82	1.9	0.07	0.69	0.76	0.21	0.07	0.02	0.14	10
	max	26.5	9.6	185	9.7	156	3.8	1.61	9.96	11.57	1.58	0.71	0.76	0.86	61
	mean	20.9	8.2	141	9.0	113	3.0	0.31	2.44	2.79	0.52	0.23	0.16	0.28	18
	std dev	4.7	1.3	49	1.0	52	0.8	0.65	3.75	4.36	0.55	0.26	0.29	0.22	21
1982	n	3	3	3	0	0	3	3	3	3	3	3	3	3	3
	min	22.0	9.0	170	-	-	2.8	0.09	0.07	0.22	0.18	0.02	0.00	0.13	15
	max	26.0	9.7	182	-	-	4.5	1.85	0.28	2.13	0.33	0.08	0.04	0.29	29
	mean	24.3	9.5	177	-	-	3.7	0.29	0.17	0.54	0.23	0.04	0.01	0.18	20
	std dev	2.1	0.4	6	-	-	0.9	1.00	0.11	1.07	0.08	0.03	0.02	0.29	7
1983	n	20	20	19	20	15	9	11	11	11	11	10	11	10	11
	min	10.0	7.4	54	6.5	61	3.8	0.08	0.68	0.76	0.14	0.04	0.01	0.01	4
	max	24.4	9.6	202	13.8	152	9.7	0.95	3.25	3.81	1.30	1.37	1.22	0.32	52
	mean	16.0	8.3	130	9.8	96	6.4	0.31	1.47	1.85	0.45	0.33	0.21	0.07	12
	std dev	3.8	0.5	43	2.0	27	1.8	0.30	1.03	1.19	0.47	0.49	0.47	0.15	15
1984	n	24	24	22	22	22	5	4	4	4	5	4	4	4	5
	min	10.5	7.0	79	3.9	43	4.1	0.07	0.53	0.61	0.25	0.05	0.01	0.23	5
	max	23.5	9.0	171	16.3	184	7.1	0.35	1.80	2.15	2.31	0.52	0.60	2.23	224
	mean	16.1	8.1	136	9.0	94	5.2	0.14	0.83	0.98	0.54	0.11	0.06	0.44	31
	std dev	3.6	0.5	29	3.4	40	1.3	0.13	0.59	0.72	0.87	0.23	0.28	0.08	90
1985	n	14	12	12	14	14	5	5	3	3	5	5	5	5	3
	min	11.5	7.4	37	3.7	41	1.2	0.03	2.59	3.38	0.68	0.10	0.09	0.05	90
	max	21.0	8.2	208	14.2	139	3.3	0.79	4.08	4.78	1.39	1.33	1.28	0.58	400
	mean	15.4	7.7	89	7.9	79	2.1	0.21	3.50	4.05	1.00	0.62	0.41	0.13	240
	std dev	2.7	0.3	46	2.5	25	0.9	0.36	0.86	0.70	0.32	0.50	0.58	0.04	175
1986	n	21	10	11	21	21	7	8	7	6	7	7	8	6	6
	min	13.5	7.0	45	4.8	50	1.1	0.10	0.01	0.49	0.15	0.07	0.06	0.02	3
	max	28.5	9.4	324	12.6	150	5.1	0.85	6.75	7.60	1.30	1.28	1.34	0.15	76
	mean	19.3	8.0	108	7.8	83	2.3	0.24	1.03	2.82	0.52	0.44	0.32	0.07	23
	std dev	3.9	0.9	74	1.9	26	1.6	0.26	3.18	3.15	0.46	0.45	0.52	0.22	24
1987	n	19	18	18	18	18	11	11	9	9	11	11	12	11	11
	min	12.0	7.3	22	5.9	62	0.4	0.09	0.37	0.47	0.28	0.12	0.09	0.01	4
	max	24.5	8.8	157	11.0	131	8.7	1.03	8.96	9.70	0.74	0.72	0.71	0.28	80
	mean	18.7	8.1	97	7.9	82	1.7	0.28	1.81	2.27	0.45	0.32	0.27	0.07	18
	std dev	3.8	0.4	36	1.4	19	2.3	0.34	2.25	3.39	0.16	0.22	0.22	0.98	21
1988	n	24	7	24	24	24	12	12	11	11	12	12	12	12	12
	min	13.0	7.5	44	4.5	44	0.6	0.03	0.10	0.28	0.21	0.07	0.08	0.01	12
	max	25.0	10.0	218	12.5	140	6.1	0.60	6.25	6.78	1.06	1.05	0.93	0.53	64
	mean	17.2	8.8	92	8.8	90	1.9	0.16	0.86	1.19	0.53	0.34	0.30	0.09	24
	std dev	3.4	0.7	37	1.6	20	1.4	0.21	2.36	2.47	0.27	0.32	0.28	0.09	16
1989	n	23	15	17	17	17	10	10	10	10	10	10	10	10	10
	min	11.3	7.8	73	5.4	51	1.3	0.06	1.23	1.36	0.29	0.07	0.14	0.02	4
	max	25.0	10.9	152	19.4	233	4.0	1.02	9.02	10.00	1.54	0.20	1.21	0.96	55
	mean	18.6	8.4	120	9.8	101	2.0	0.38	3.46	3.91	0.63	0.46	0.38	0.09	12
	std dev	4.2	0.7	22	3.1	42	0.8	0.31	2.26	2.52	0.46	0.41	0.40	0.08	12
1990	n	21	28	28	33	32	13	13	12	12	13	13	13	13	12
	min	12.5	7.1	72	5.9	62	1.0	0.07	1.04	1.17	0.22	0.11	0.09	0.05	6
	max	27.3	8.8	171	16.2	197	7.8	1.67	6.91	7.61	1.25	0.97	0.97	0.79	105
	mean	18.3	8.1	136	9.8	102	2.4	0.34	2.70	3.11	0.62	0.33	0.28	0.21	19
	std dev	5.2	0.5	26	3.1	43	1.8	0.50	1.72	2.04	0.36	0.33	0.31	0.30	28
ALL	n	174	142	159	171	165	80	82	75	74	82	80	83	79	78
	min	10.0	6.4	22	3.7	41	0.4	0.03	0.01	0.22	0.14	0.02	0.00	0.01	3
	max	28.5	10.9	324	19.4	233	9.7	1.85	9.96	11.57	2.31	1.37	1.34	2.23	400
	mean	17.7	8.2	116	8.9	92	2.6	0.27	1.59	2.16	0.54	0.31	0.24	0.12	20
	std dev	4.2	0.6	42	2.6	34	2.1	0.39	2.42	2.61	0.42	0.38	0.37	0.30	66

Cnd = conductivity (mS m^{-1}); DO = daytime dissolved oxygen (mg l^{-1});
%OS = oxygen saturation (%); TKN = Kjeldahl -N; NH3 = ammonia -N;
NOx = nitrate & nitrite -N; TIN = total inorganic -N; TP = total -P;
TSP = total soluble -P; SRP = soluble reactive (ortho) -P;
TPP = total particulate -P; ss = suspended solids (all mg l^{-1})

LITTLE LOTUS RIVER - PHYSICO-CHEMICAL DATA SUMMARY 1981 - 1990

YEAR		°C	pH	Cnd	DO	%OS	TKN	NH3	NOx	TIN	TP	TSP	SRP	TPP	ss
1981	n	5	5	5	2	2	5	5	5	5	5	5	5	5	5
	min	15.5	6.6	107	7.8	78	1.2	0.05	0.44	0.49	0.17	0.03	0.01	0.06	13
	max	27.0	10.2	160	12.8	121	3.1	0.82	16.22	17.04	0.76	0.47	0.44	0.30	34
	mean	21.4	8.2	128	10.0	97	2.2	0.19	1.83	2.05	0.33	0.14	0.10	0.16	20
	std dev	5.0	1.4	19	3.5	30	0.7	0.32	6.71	7.01	0.24	0.17	0.17	0.10	10
1982	n	3	3	3	0	0	3	3	3	3	3	3	3	3	3
	min	21.0	9.4	134	-	-	1.9	0.07	0.04	0.13	0.10	0.02	0.00	0.08	14
	max	28.0	10.3	165	-	-	3.6	0.10	0.14	0.21	0.15	0.03	0.01	0.13	28
	mean	24.5	9.7	149	-	-	2.5	0.09	0.07	0.16	0.11	0.02	0.01	0.09	20
	std dev	3.5	0.5	16	-	-	0.9	0.02	0.06	0.04	0.03	0.01	0.08	0.03	7
1983	n	20	20	19	20	15	10	11	11	11	11	11	11	11	11
	min	10.0	6.8	16	6.1	59	2.3	0.02	0.19	0.26	0.06	0.03	0.01	0.02	2
	max	23.4	9.6	173	13.0	125	7.0	0.57	3.01	3.36	0.38	0.28	0.22	0.19	37
	mean	15.7	8.1	112	9.4	88	3.8	0.14	0.92	1.12	0.18	0.11	0.07	0.07	10
	std dev	3.7	0.6	34	2.0	24	1.4	0.16	0.99	1.06	0.12	0.09	0.08	0.05	10
1984	n	24	24	22	22	22	5	4	4	4	5	4	4	4	5
	min	11.1	7.2	34	3.8	43	2.6	0.00	0.07	0.15	0.07	0.03	0.01	0.03	11
	max	25.0	8.8	164	13.4	149	28.2	0.21	0.47	0.68	0.31	0.08	0.17	0.28	50
	mean	16.5	8.0	108	7.8	79	4.6	0.03	0.14	0.22	0.19	0.05	0.02	0.12	22
	std dev	3.6	0.6	28	3.4	39	11.3	0.09	0.19	0.26	0.10	0.02	0.08	0.12	17
1985	n	14	12	12	14	14	5	5	3	3	5	5	5	5	3
	min	11.9	6.9	42	4.6	47	0.8	0.02	1.58	1.71	0.24	0.08	0.09	0.01	25
	max	19.5	8.0	173	13.6	133	1.7	0.21	2.55	2.68	0.44	0.32	0.30	0.35	190
	mean	15.6	7.5	115	7.8	78	1.2	0.10	1.90	2.02	0.32	0.20	0.16	0.05	88
	std dev	2.2	0.4	37	2.5	26	0.5	0.07	0.53	0.54	0.08	0.09	0.10	0.14	85
1986	n	21	10	11	21	21	7	8	7	6	7	7	9	6	6
	min	14.5	4.0	79	3.1	33	0.5	0.06	0.01	0.21	0.06	0.04	0.01	0.02	5
	max	28.0	8.8	164	12.0	150	3.3	0.49	3.06	3.55	0.37	0.27	0.72	0.10	72
	mean	19.3	7.4	123	6.6	73	1.4	0.14	0.47	1.22	0.21	0.16	0.09	0.04	16
	std dev	3.7	1.5	27	2.3	28	1.0	0.15	1.26	1.36	0.10	0.09	0.22	0.03	25
1987	n	19	18	19	18	18	11	11	10	10	11	11	12	11	11
	min	12.0	7.3	61	5.1	55	0.3	0.06	0.01	0.08	0.04	0.03	0.01	0.00	8
	max	24.1	8.7	167	11.6	132	3.0	0.61	2.48	3.09	0.28	0.26	0.19	0.19	94
	mean	18.8	7.9	124	7.3	81	1.2	0.14	0.47	0.73	0.15	0.10	0.06	0.03	17
	std dev	4.0	0.3	27	2.2	27	0.9	0.16	0.98	1.09	0.07	0.07	0.06	0.05	25
1988	n	24	7	24	24	24	12	12	11	11	12	12	12	12	12
	min	13.0	8.6	18	3.5	33	0.5	0.02	0.08	0.18	0.10	0.05	0.00	0.01	5
	max	24.5	9.0	202	12.7	133	6.0	0.45	3.46	3.67	0.32	0.25	0.23	0.11	40
	mean	17.4	8.8	112	8.3	84	1.4	0.10	0.52	0.69	0.18	0.13	0.07	0.04	18
	std dev	3.5	0.1	35	2.2	24	1.4	0.16	1.18	1.25	0.07	0.07	0.07	0.03	13
1989	n	23	15	18	18	18	10	10	10	10	10	10	10	10	10
	min	10.9	7.6	35	4.8	47	1.0	0.06	0.14	0.69	0.09	0.07	0.07	0.01	4
	max	25.0	8.8	104	15.1	178	19.4	4.03	2.75	5.68	1.00	0.20	0.68	0.98	70
	mean	18.2	8.0	75	9.2	96	1.9	0.29	1.41	2.06	0.24	0.46	0.18	0.10	12
	std dev	4.7	0.4	16	2.8	36	5.7	1.20	0.71	1.35	0.29	0.41	0.32	0.31	21
1990	n	24	19	19	22	32	8	13	8	8	8	8	8	8	12
	min	13.0	7.1	51	6.3	62	0.6	0.08	0.55	0.63	0.04	0.11	0.03	0.02	6
	max	27.8	8.8	128	14.2	155	3.2	0.68	4.33	5.01	1.04	0.97	1.00	0.75	27
	mean	18.9	8.1	79	9.1	94	1.6	0.22	1.41	1.68	0.14	0.33	0.11	0.13	13
	std dev	5.0	0.7	17	2.0	28	0.9	0.26	1.46	1.68	0.33	0.33	0.32	0.26	21
ALL	n	177	133	152	161	155	76	77	72	71	77	76	79	75	78
	min	10.0	4.0	16	3.1	33	0.3	0.00	0.01	0.08	0.04	0.02	0.00	0.00	2
	max	28.0	10.3	202	15.1	178	28.2	4.03	16.22	17.04	1.98	1.04	1.00	0.98	190
	mean	17.8	8.0	105	8.2	84	1.8	0.14	0.70	1.01	0.23	0.12	0.08	0.07	16
	std dev	4.2	0.8	34	2.6	30	3.8	0.47	2.06	2.23	0.28	0.18	0.17	0.16	29

Cnd = conductivity (mS m^{-1}); DO = daytime dissolved oxygen (mg l^{-1});
%OS = oxygen saturation (%); TKN = Kjeldahl -N; NH3 = ammonia -N;
NOx = nitrate & nitrite -N; TIN = total inorganic -N; TP = total -P;
TSP = total soluble -P; SRP = soluble reactive (ortho) -P;
TPP = total particulate -P; ss = suspended solids (all mg l^{-1})

ZEEKOEVLEI - PHYSICO-CHEMICAL DATA SUMMARY 1981 - 1990																
YEAR	°C	pH	Cnd	DO	%OS	ST	TKN	NH3	NOx	TIN	TP	TSP	SRP	TPP	ss	CHLa
1981 n	20	20	20	20	20	20	20	19	20	19	20	20	20	20	18	20
min	14.8	7.1	149	4.9	53	0.07	4.5	0.05	0.05	0.10	0.42	0.09	0.06	0.11	7	177
max	22.1	10.4	180	13.9	150	0.40	12.5	0.21	1.52	1.69	1.75	0.31	0.29	1.61	332	695
mean	18.5	9.0	165	8.4	90	0.21	7.0	0.10	0.22	0.51	0.79	0.14	0.11	0.62	84	317
std dev	2.8	1.0	10	3.0	31	0.10	2.5	0.05	0.49	0.21	0.38	0.05	0.05	0.39	95	138
1982 n	8	12	12	12	8	11	12	12	12	12	12	12	12	12	11	12
min	19.0	9.4	220	6.4	79	0.12	6.0	0.05	0.02	0.07	0.50	0.04	0.01	0.45	84	53
max	26.0	10.5	250	10.4	114	0.25	10.1	0.26	0.17	0.34	0.89	0.17	0.13	0.73	168	277
mean	22.8	9.9	230	7.9	95	0.18	7.4	0.10	0.06	0.17	0.68	0.08	0.02	0.59	116	119
std dev	3.0	0.4	9	1.1	11	0.04	1.4	0.06	0.04	0.10	0.13	0.05	0.05	0.10	28	71
1983 n	80	80	80	80	60	80	40	44	44	44	44	44	44	44	44	56
min	11.5	7.7	108	5.4	55	0.10	7.6	0.01	0.01	0.03	0.25	0.37	0.01	0.07	17	88
max	24.6	11.4	337	12.6	117	0.34	21.1	0.40	3.21	3.35	1.06	0.60	0.68	0.88	108	609
mean	17.3	9.5	198	8.6	88	0.22	11.6	0.10	0.13	0.28	0.73	0.22	0.17	0.45	70	237
std dev	4.1	0.7	77	1.7	15	0.05	3.5	0.09	0.71	0.72	0.19	0.17	0.20	0.14	20	139
1984 n	96	96	88	88	88	96	20	19	19	19	20	20	20	19	20	20
min	12.0	7.2	120	7.0	72	0.18	3.9	0.05	0.04	0.09	0.18	0.03	0.00	0.15	27	29
max	23.2	10.3	265	19.8	205	0.48	16.0	0.15	0.08	0.20	0.55	0.09	0.04	0.49	86	100
mean	17.0	9.3	173	10.5	107	0.28	9.8	0.08	0.06	0.14	0.41	0.04	0.01	0.37	62	66
std dev	3.5	0.8	44	2.3	23	0.06	3.1	0.03	0.01	0.04	0.11	0.02	0.01	0.10	18	21
1985 n	56	48	48	56	56	55	20	20	12	12	20	20	20	20	13	8
min	11.5	7.8	81	5.7	56	0.16	0.8	0.02	0.06	0.08	0.27	0.00	0.00	0.06	33	90
max	20.0	10.2	206	18.1	191	0.38	3.6	0.42	1.90	2.28	1.04	0.95	0.95	0.62	565	182
mean	16.0	9.3	126	9.9	100	0.26	1.9	0.14	0.32	0.47	0.60	0.19	0.12	0.30	193	142
std dev	2.5	0.4	29	2.5	27	0.06	0.9	0.12	0.51	0.60	0.25	0.24	0.24	0.13	201	32
1986 n	81	40	44	79	79	80	25	25	24	20	25	24	30	21	21	29
min	12.0	8.9	97	3.1	37	0.14	0.7	0.05	0.00	0.06	0.56	0.02	0.01	0.06	14	114
max	28.5	10.4	227	13.6	160	0.47	8.9	0.57	2.22	2.33	1.05	0.98	0.86	0.86	168	544
mean	18.6	9.6	173	7.9	84	0.21	3.2	0.13	0.09	0.45	0.82	0.12	0.10	0.38	80	236
std dev	3.8	0.5	42	2.3	26	0.06	2.2	0.11	0.69	0.69	0.16	0.33	0.29	0.26	41	114
1987 n	75	71	71	71	71	79	43	43	39	39	43	44	44	43	43	43
min	13.0	8.0	104	4.4	43	0.14	0.0	0.00	0.00	0.02	0.16	0.04	0.01	0.10	12	68
max	24.1	10.1	222	14.5	148	0.45	11.0	0.30	4.26	4.46	0.79	0.42	0.42	0.57	188	537
mean	18.6	9.5	156	8.6	92	0.23	2.1	0.10	0.03	0.21	0.47	0.12	0.09	0.31	88	195
std dev	3.8	0.5	30	2.5	24	0.08	2.9	0.07	0.72	0.73	0.16	0.12	0.13	0.11	39	127
1988 n	96	28	96	96	96	92	48	48	44	44	48	48	48	48	48	48
min	12.0	8.0	110	4.0	29	0.10	1.0	0.00	0.00	0.01	0.23	0.05	0.02	0.18	38	66
max	24.0	10.1	355	12.0	138	0.37	13.0	0.40	0.20	0.42	0.75	0.37	0.36	0.60	241	264
mean	17.3	10.6	149	8.6	85	0.25	3.5	0.06	0.23	0.11	0.52	0.13	0.09	0.38	77	122
std dev	3.3	0.5	49	1.7	20	0.06	2.2	0.10	0.03	0.11	0.11	0.07	0.07	0.11	36	46
1989 n	96	64	76	72	72	76	40	45	40	40	40	40	40	40	40	40
min	10.3	9.5	93	5.1	58	0.10	2.4	0.03	0.01	0.04	0.29	0.07	0.05	0.17	14	97
max	25.0	11.0	202	16.7	171	0.41	6.6	0.33	0.94	0.99	0.95	0.51	0.45	0.56	106	796
mean	18.0	9.6	133	9.6	97	0.25	4.2	0.09	0.09	0.23	0.54	0.18	0.14	0.34	58	254
std dev	3.8	0.3	33	1.8	20	0.07	1.2	0.08	0.20	0.21	0.18	0.12	0.12	0.11	20	172
1990 n	109	113	113	136	132	113	57	55	55	51	57	52	59	52	48	89
min	10.9	7.9	88	7.2	68	0.17	1.4	0.04	0.00	0.06	0.26	0.01	0.01	0.03	24	95
max	23.6	10.6	164	13.9	163	0.58	5.3	1.26	3.55	3.78	1.25	1.12	1.07	0.57	153	695
mean	17.5	9.3	127	9.7	100	0.29	2.9	0.15	0.16	0.33	0.57	0.16	0.14	0.30	60	258
std dev	3.7	0.5	20	1.3	16	0.09	1.0	0.27	0.77	0.80	0.26	0.28	0.25	0.10	27	147
ALL n	717	572	648	710	682	702	325	325	309	300	329	324	337	319	306	365
min	10.3	7.1	81	3.1	29	0.07	0.0	0.00	0.00	0.01	0.16	0.00	0.00	0.03	7	29
max	28.5	11.4	355	19.8	205	0.58	21.1	1.26	4.26	4.46	1.75	1.12	1.07	1.61	565	795
mean	17.6	9.5	153	9.1	94	0.25	4.1	0.10	0.08	0.23	0.58	0.14	0.09	0.37	75	200
std dev	3.7	0.7	51	2.1	23	0.08	3.9	0.14	0.58	0.59	0.24	0.20	0.20	0.18	69	146

KEY: Cnd = conductivity ($mS\ m^{-1}$); DO = daytime dissolved oxygen ($mg\ l^{-1}$); %OS = oxygen saturation (%); ST = Secchi transparency (m); TKN = Kjeldahl -N; NH3 = ammonia -N; NOx = nitrate & nitrite -N; TIN = total inorganic -N; TP = total -P; TSP = total soluble -P; SRP = soluble reactive (ortho) -P; TPP = total particulate -P (all $mg\ l^{-1}$); ss = suspended solids ($mg\ l^{-1}$); CHLa = chlorophyll a (corrected for phaeophytins) ($\mu g\ l^{-1}$)

CHAPTER 3

THE LIMNOLOGY OF PRINCESS VLEI

1983 - 1990

INTRODUCTION

The coastal sandflats of the Cape Peninsula, South Africa, once abounded in vleis, these being mostly of a temporary nature (Hutchinson *et al.*, 1932). Along with the growth and concomitant drainage requirements of the Cape Town Metropolitan area, most of these have disappeared. Princess Vlei is the third largest perennial vlei remaining, and falls under the control of the Cape Town City Council (CCC); the other two are Zeekoevlei (the largest) and Zandvlei.

These water bodies serve as flood buffers in the Cape Peninsula drainage system and, in addition, are extensively utilized by the public for a variety of recreational pursuits. Together, they form the only substantial, naturally-occurring, inland waters within the Cape Town Municipal area, serving a population of 940 000 people (CCC, 1990). The City Council has, since the early 1980s, been addressing the existing and potential future water quality problems of each vlei, with a view to formulating recommendations for maintaining or improving the existing conditions in terms of water quality conducive to improved recreational amenity value.

This report on conditions at Princess Vlei stemmed partially from concern by anglers regarding a perturbation to the resident fish population, and also coincided with the completion of the first year of a comprehensive phytoplankton observation programme made at Princess Vlei.

A general lack of information on phytoplankton periodicity in Southern African systems has been identified (eg. Ashton, 1985; Talling, 1986). Data on primary production in Southern African lakes are very limited (Allanson *et al.*, 1990). In addition, there is very little available information on algal periodicity in small, shallow systems such as the coastal vleis mentioned here (Reynolds, 1983). Other coastal vlei systems in South Africa, such as the Wilderness Lakes group, are macrophyte dominated, and research there has been directed towards aspects of zooplankton ecology rather than phytoplankton (eg. Coetzee, 1980, 1981, 1983). In the majority of cases, chlorophyll measurements have been employed to monitor changes in algal biomass. This convenient measure, as opposed to the enumeration of individual organisms, has been criticised due to its inherent shortcomings in being unable to describe the components of the phytoplankton assemblage (eg. Reynolds, 1983; Ashton, 1985).

Seasonal periodicity of phytoplankton in temperate and tropical lake systems has been shown to follow a similar seasonal paradigm (eg. Smith, 1950; Lewis, 1978, 1978a, 1986; Reynolds, 1984; see also Chapter 1). In addition, annual periodic cycles may remain relatively constant from year to year (eg. Golterman, 1975). The phytoplankton data presented in this paper, as well as in Chapters 4 and 5, form part of a comprehensive study started in April 1989 and conducted at all three vleis mentioned above. This aim of this study was to establish the nature of the phytoplankton composition, diversity, and periodicity in each vlei, the relationships to environmental conditions, and the degree of adherence of the observed periodicity to the traditional seasonal paradigm. This paper is also the first detailed account of the limnology of Princess Vlei.

STUDY AREA

Princess Vlei is a small (29 ha), shallow (*ca.* 2.3 m), permanent, freshwater coastal lake (as defined by Davies & Day, 1986), situated in the Southfield area of Cape Town, South Africa (latitude 34^{o} 03'S, 18^{o} 28'E; Figure 1). It was classified in the 1920s and again during the 1940s as alkaline and eutrophic (respectively, Stevens, 1929; Harrison, 1961). Princess Vlei lies on sandflats which were originally submerged beneath the sea (Shand *et al.*, cited in

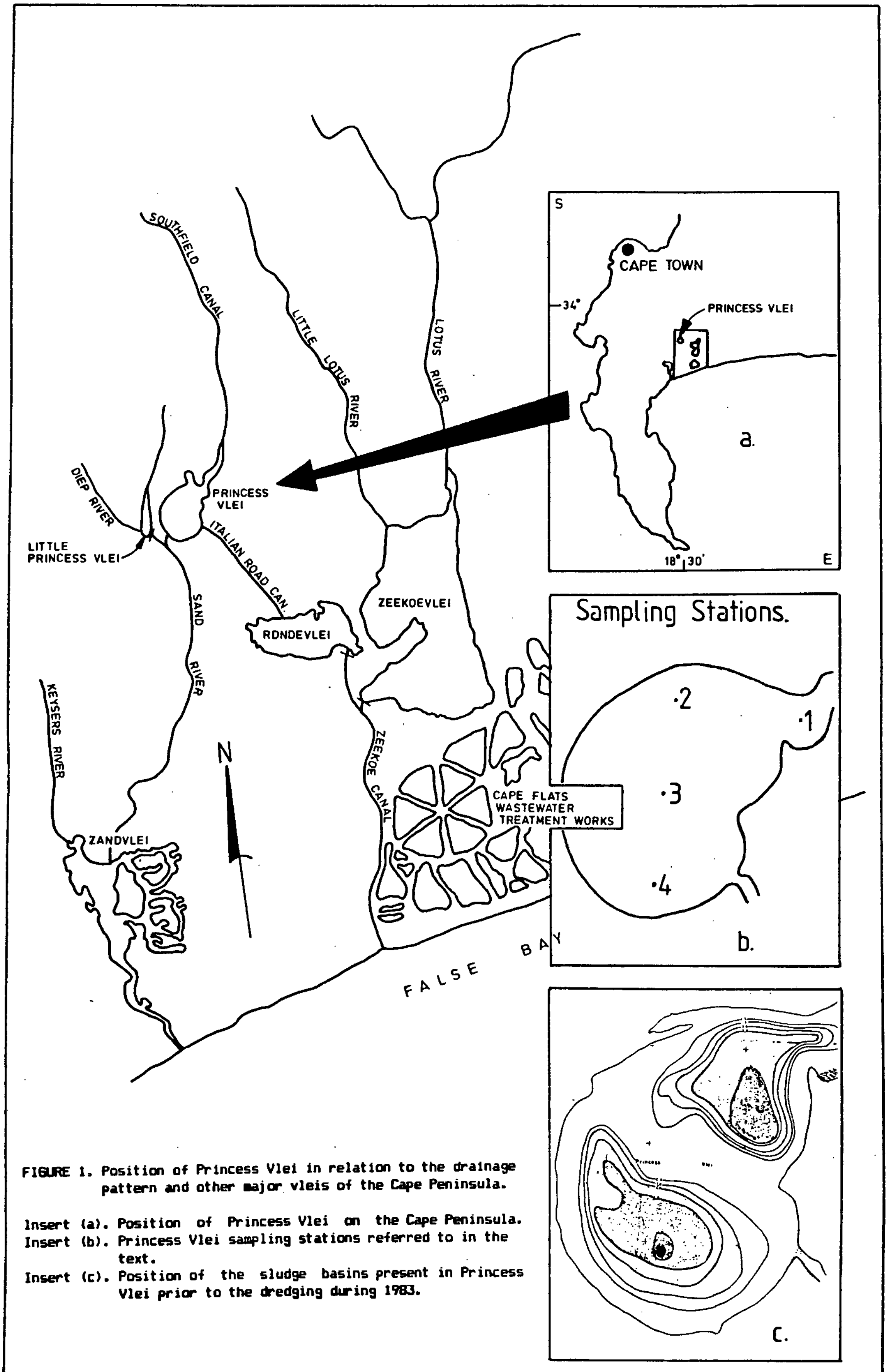

FIGURE 1. Position of Princess Vlei in relation to the drainage pattern and other major vleis of the Cape Peninsula.

Insert (a). Position of Princess Vlei on the Cape Peninsula.
Insert (b). Princess Vlei sampling stations referred to in the text.
Insert (c). Position of the sludge basins present in Princess Vlei prior to the dredging during 1983.

Hutchinson *et al.*, 1932). Of the four largest vleis on the Cape Peninsula, viz:- Zeekoevlei, Zandvlei, Rondevlei (under Regional Services Council Control) and Princess Vlei, Princess Vlei is the smallest and probably the oldest (Hutchinson, 1932). It is fed by the Southfield Canal, which enters from the northeast (Figure 1), and which drains an urban catchment of approximately 800 ha (Cape Town City Council records). Thus, all water entering the vlei originates as urban or industrial runoff, and can be expected to be high in nutrients, as well as containing pollutants of various types (eg. EPA, 1980). An outlet weir, constructed during 1990 and having a crest height of 6.6 m AMSL, lies to the south-east and drains into a canal linking Princess Vlei to Rondevlei (Figure 1). Prior to this, a temporary weir with a crest height of 6.45 m AMSL restricted the outlet. A flood-prevention overflow weir, with a crest height of 7.4 m AMSL, is positioned to the south-west and drains into the Sand River, terminating ultimately in Zandvlei (Figure 1).

In addition to the inflow from the Southfield Canal, several stormwater pipes enter the vlei at various points around its perimeter. Outflow from Princess Vlei only occurs during the rainy season, from April to October. The Cape Town City Council has three sewage pumping stations in the Princess Vlei catchment which, during times of malfunction or overloading (during the rainy months), are designed to overflow into the Southfield Canal. Prior to 1985, such overflows were relatively frequent with 51 recorded overflows between 1973 and 1984. Subsequent modifications to the pump stations have greatly reduced the incidence of overflow events, and only three overflows occurred between January 1986 and December 1990 (CCC Sewerage Branch records, unpublished).

The vlei is bordered to the north by residential and small-scale industrial areas, to the east and west by public open space and to the south by a small residential development. Vegetation bordering the vlei is sparse, with grass and stands of semi-aquatic reeds (*Typha* sp.), as was recorded by Harrison (1962). The inlet bay, where Sampling Station 1 is situated (Figure 1), has denser fringes of *Typha*, and is subject to year-round infestation by water hyacinth, *Eichhornia crassipes* (Mart) (Solms). Control of these plants is carried out at intervals using herbicides and physical removal.

Princess Vlei has not yet been fully developed as a recreational/water sport venue (see Hill, Kaplan and Scott, 1980), but is utilized on a regular basis by casual and club anglers, especially during the winter months. Water is abstracted from the vlei by CCC for irrigation of the surrounding public open space. According to the terms of reference of an ecological management survey of Cape Peninsula waters (Howard-Williams, 1976), Princess Vlei was accorded a low priority with respect to research needs. At that time, attention was directed towards the removal of water hyacinth.

Princess Vlei was dredged between March and July of 1983 to remove a shallow sand-bar, running from north-west to south-east across the middle of the vlei (Figure 1). It was at this time that CCC limnological monitoring of the vlei commenced. Prior to the dredging, the sand-bar divided the vlei into two basins (Figure 1). Sludge accumulation, with fine, black, organically-rich silt overlying white to buff-coloured medium-grained sands in these basins, was, on average, between 2 and 3 m thick, reaching as much as 5 m deep in places (Hill, Kaplan and Scott, 1980). The bathymetry of Princess Vlei has recently been resurveyed (Harding, *in litt.*) and the results show that the shallow ridge has been replaced with a central deepening of the vlei and some redistribution of the sediments. The volume of the vlei is approximately 671 000 m^3, with the sediments accounting for approximately 140 000 m^3 or 21% of the vlei volume (1991 estimates, Harding, *in litt.*). During pre-dredging surveys it was found that the sludge composition resembled that of the sediment found in Zeekoevlei (Hill, Kaplan & Scott, 1980) and that it was unsuitable for horticultural purposes (Fedmis, report dated 1980-01-09, appended to Hill, Kaplan & Scott, 1980). During the dredging operation, water transparencies were reduced to <0.05 m. To counteract this, the dredge spoils were dosed with ferric sulphate to settle out fine suspended matter. whereupon the treated water was returned to the vlei. Approximately 15 000 l of ferric sulphate and 188 000 m^3 of dredged material (mainly sand) were respectively used or removed (Hill, Kaplan & Scott, 1980; Dredging Contract records, unpublished).

METHODOLOGY

Sampling programme and frequency

The Scientific Services Branch (SSB) of the Cape Town City Council routinely conducts limnological surveys at four coastal vleis, these being Zeekoevlei, Zandvlei, Princess Vlei and Little Princess Vlei. Princess Vlei has been routinely monitored with respect to limnological and bacteriological parameters since 1982, with intermittent sampling between 1984 and 1986; phytoplankton since April 1989 and zooplankton from October 1989. Heavy metal analyses (water and sediments) commenced on a monthly basis as from December 1989. The sampling programme comprised fortnightly physical, bacteriological and plankton collections, and monthly chemical sampling. Except for plankton, the influent Southfield Canal (Figure 1) was similarly monitored. On the vlei itself, four sampling stations (Figure 1) have been sampled from a boat since October 1988. Prior to this most of the sampling was conducted from the shore. Sampling was invariably carried out between 09h00 and 11h30. Depths of water at Stations 1 to 4, assuming a water level of 6.45 m AMSL, were *ca*. 0.9, 2.1, 3.2 and 1.5 m, respectively, measured using a calibrated ranging pole.

Sampling of physical and chemical variables

The methods used for sampling the physical and chemical variables of Princess Vlei are listed in Table 1. Integrated water column samples were collected at each vlei sampling station using the method described in Chapter 2. Water temperatures, pH, dissolved oxygen and conductivity measurements were made in the field, while all other analyses were performed in the laboratory on the day of collection.

TABLE 1. ANALYTICAL METHODS

VARIABLE	METHOD	REFERENCE
pH	Hanna Model HI8424 pH meter with auto temperature compensation	-
Temperature	YSI Model 57 DO meter or Hanna pH meter thermistor probes	-
Windspeed	Deuta hand-held anaemometer	-
Water transparency	0.15m Secchi disc	-
Total alkalinity	Sulphuric acid titration, as mg l^{-1} $CaCO_3$	DWA 1988
Dissolved oxygen	YSI 57 DO meter	-
Oxygen saturation	Calculated using the formulae of Green and Carrit (1967)	J.Mar.Res 1967
Conductivity	T & C 2001 conductivity meter with auto temperature compensation	-
Heavy metals	Atomic absorption spectrophotometrically for As, Cd, Cu, Ni, Cr, Fe, Zn, Pb, Al, Hg & Mn.	NIWR 1974
Water hardness	Atomic absorption spectro. for Ca & Mg, converted to $CaCO_3$	NIWR 1974
Sediment composition	Sedigraph analysis Gravimetric/ignition at 600°C	TMH 1986 APHA 1985
Kjeldahl -N	Digestion and conversion to ammonium sulphate	EPA 1979
Ammonia -N	Boric acid distillation	EPA 1979
Nitrate & nitrite -N	Cadmium reduction and autoanalyzer colorimetry	EPA 1979
Silica	Molybdate reduction	NIWR 1974
Total and total-dissolved -P	Persulphate digestion followed by SRP analysis	EPA 1979
Ortho-P (SRP)	Ascorbic acid method	EPA 1979
Suspended solids	Gravimetric	EPA 1979
Chlorophyll *a*	Acetone extraction, results corrected for phaeophytins	ASTM 1979

TABLE 2. BIOLOGICAL METHODS

CONSTITUENT	METHOD	REFERENCE
1. Bacteriology (Sewage pollution indicator)	Membrane filtration followed by incubation on McConkey agar at 44.5°C (faecal coliforms)	EPA 1978
2. Phycology		
a. Phytoplankton collection and enumeration	Integrated water-column sampler; (2 x 0.04 m), followed by preservation with Lugol's iodine and inverted microscope examination.	Utermohl 1958 Lund 1958
b. Primary production	Light and dark bottle oxygen method.	Vollenweider 1975

Total phosphorus in sediment samples was determined according to the method described by Andersen (1976).

Rainfall data were obtained from a CCC rainfall gauge situated on the northern shore of the vlei. On-site wind speed recordings were limited to surface measurements made at the time of sampling. Supplementary wind, rainfall, sunshine and incident solar radiation data were obtained from the meterological office of the South African Transport Services, DF Malan Airport, Cape Town.

Sediment samples for heavy metal analysis were collected using a stainless-steel Birge-Ekman grab with a bite area of 0.0225 m^2, and a penetration depth of 0.15 m. Samples were then transported in plastic buckets to the laboratory and aliquots thereof dried at 105 ^{o}C prior to digestion and analysis. Similarly, integrated water column samples were collected in high density polyethylene bottles and preserved with nitric acid prior to heavy metal analysis (Table 1). Heavy metals in fish liver and muscle tissues were analysed by the Department of Sea Fisheries (Cape Town).

No nutrient loading or flow data were available at time of writing. Semmelink (1990) has reported on estimates of Princess Vlei outflow volumes in relation to water flowing into Rondevlei.

Biological monitoring

All of the phytoplankton cells present in pre-calibrated sedimentation-chamber transects were identified and counted. Colonial species such as *Microcystis* spp. were disrupted prior to counting using the method of Zohary & Pais Madeira (1987). Other colonial species such as *Chroococcus*, *Merismopedia* and *Aphanocapsa* were not enumerated as individual cells owing to their resistance to disruption into identifiable, single units. Apart from certain exceptions, identifications were to genus level only, and a comprehensive photomicrograph record of the genera observed was made using a Zeiss Photomicroscope (see Appendix 1).

Chlorophyll a samples were collected throughout the study period using the integrated column sampler.

Primary production was determined on 4 occasions using the oxygen method described by Vollenweider (1974). Light and dark bottles were suspended (Station 3, Figure 1) below a float at depths of 0.2, 1.0, 1.5 and 2.0 m for a period of five hours.

RESULTS

Climatic details

Prevailing winds in the south-western Cape are predominantly north-westerly in winter and southerly in summer (Fuggle, 1978). Measurements made at the time of sampling gave a mean surface wind speed of 4.5 m s^{-1} (Table 1). Wind speeds were 0.5 m s^{-1} or greater on each occasion that the vlei was visited during 1989-90. This observation, coupled with an observed lack of stratification (RI Dick, personal communication), tends to indicate a well-mixed waterbody. The Cape Peninsula experiences highest wind speeds (southerly) during the summer, and lowest speeds and greatest incidence of periods of calm during the winter (Fuggle, 1978).

Rainfall events (as monthly totals) for the period 1987-1990 are presented in Figure 2. Good agreement was found between gauges in the catchment and the gauge at Zeekoevlei (I. Morrison, *in litt.*). From these it is evident that the bulk of the annual rain fell between April and October, with peak falls during April and August.

The incident solar radiation pattern for the Cape Peninsula, as measured at DF Malan Airport, showed maximum and minimum levels during January and June/July, respectively (see Chapter 2).

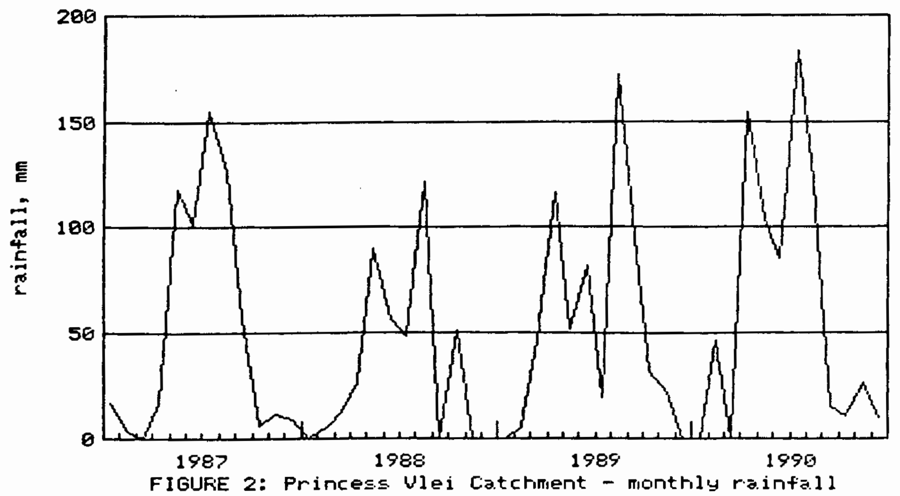

FIGURE 2: Princess Vlei Catchment - monthly rainfall

Physico-chemical characteristics

Data for Princess Vlei and the influent Southfield Canal are summarized in Tables 3 and 4, respectively, whilst Table 5 contains a comparison of values in the canal and the vlei before the dredging. Comprehensive data tables for the vlei and the Southfield Canal are appended at the end of the chapter. The results for the vlei are expressed as a mean value for all 4 stations. The data are presented so as to correspond to and facilitate comparison with the period of phytoplankton sample collection from April-March.

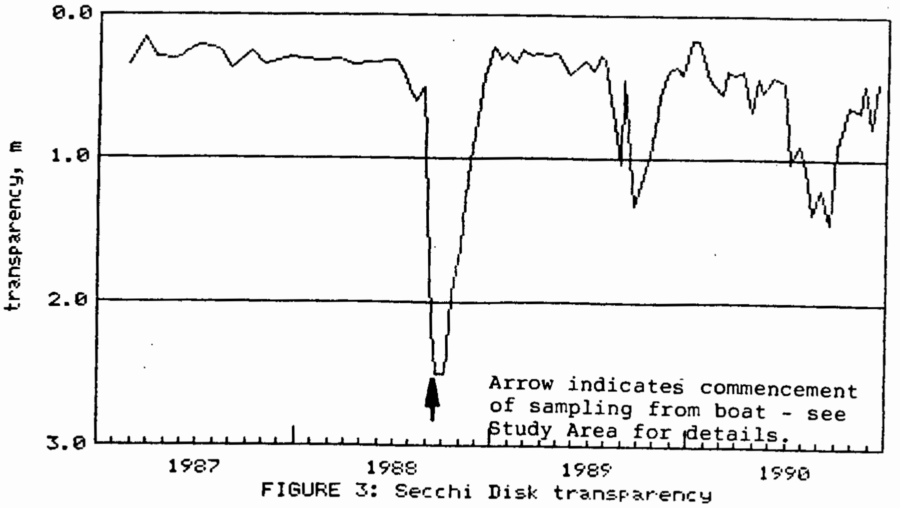

FIGURE 3: Secchi Disk transparency

TABLE 3. PHYSICO-CHEMICAL REGIME - PRINCESS VLEI
SEPTEMBER 1983-MARCH 1989 AND APRIL 1989-MARCH 1990

VARIABLE	RANGE 1983-1989	MEAN 1983-1989	RANGE 1989-1990	MEAN 1989-1990
Temperature ^{o}C	12.0-26.0	18.0	12.0-25.0	18.0
Dissolved O_2 mg l^{-1}	4.0-12.0	7.9	6.1-17.8	9.7
pH	7.1-10.1	8.9	7.1-9.8	8.9
Transparency m	0.15-3.00	0.50	0.25-1.55	0.58
Conductivity mS m^{-1}	18-130	63	28-81	53
Susp. solids mg l^{-1}	3-102	41	3-74	31
TKN mg l^{-1}	1.4-13.6	3.3	1.0-3.4	2.1
NH3 mg l^{-1}	0.02-0.93	0.20	0.04-0.80	0.26
NOx mg l^{-1}	0.00-1.75	0.32	0.01-0.88	0.22
TP mg l^{-1}	0.05-0.65	0.19	0.11-0.30	0.19
TSP mg l^{-1}	0.01-0.61	0.04	0.01-0.16	0.05
SRP mg l^{-1}	0.00-0.16	0.02	0.00-0.15	0.03
SRSi mg l^{-1}	no data	-	0.03-2.50	0.83
Alkalinity mg l^{-1}	no data	-	65-125	97
Chlorophyll a μg l^{-1}	1-219	51	6-118	64
Wind speed m s^{-1}	no data	-	1-8	4.5

KEY: TKN = Kjeldahl nitrogen NOx = nitrate & nitrite -N
TP = Total phosphorus TSP = total soluble phosphorus
SRP = Soluble reactive phosphorus SRSi = reactive silica

Water quality in the vlei closely resembled that of the Southfield Canal. Water temperatures reached the middle 20^{o}s by February, decreasing to below 15 C in July. Dissolved oxygen concentrations consistently exceeded half-saturation, and pH levels ranged between 7 and 10. Conductivities were low, having minima and maxima in winter and summer, respectively, with a mean of 53 mS m^{-1} (1989-1990). Peak concentrations of nitrogen and phosphorus coincided with the peak winter rainfall period from July to September. During this time, chlorophyll a and suspended solids concentrations were at an annual minimum, and, correspondingly, Secchi Disk transparencies showed a marked increase (Figure 3). These increases in water clarity were not recorded earlier than 1988, this being ascribed to the practice of shore sampling.

Total N:P ratios ranged from 10 to 40 with a mean of 20. Application of the trophic state index (TSI) formulae of Carlson (1979) to the mean Secchi Disc transparency, chlorophyll a and total phosphorus levels of Princess Vlei yielded a TSI range of 70 to 80. On Carlson's "continuum" scale of 0 to 110 (0 =

ultra oligotrophic) this indicates a eutrophic system. According to the parameters for trophic state laid down by the OECD (1982), Princess Vlei was eutrophic with respect to concentrations of phosphorus, nitrogen and chlorophyll a.

TABLE 4. PHYSICO-CHEMICAL REGIME - SOUTHFIELD CANAL
SEPTEMBER 1983-MARCH 1989 AND APRIL 1989-MARCH 1990

VARIABLE	RANGE 1983-1989	MEAN 1983-1989	RANGE 1989-1990	MEAN 1989-1990
Temperature °C	13.0-32.0	20.3	12.7-28.4	20.3
Dissolved O_2 mg l^{-1}	3.2-15.9	8.7	7.1-12.0	9.1
pH	7.1-9.9	8.3	7.3-8.9	8.1
Conductivity mS m^{-1}	8-133	70	19-87	61
Susp.solids mg l^{-1}	2-52	19	3-74	17
TKN mg l^{-1}	0.7-11.2	3.1	0.7-2.3	1.4
NH3 mg l^{-1}	0.02-1.62	0.35	0.02-0.48	0.21
NOx mg l^{-1}	0.05-7.03	3.1	0.59-5.00	3.3
TP mg l^{-1}	0.08-0.62	0.17	0.07-0.31	0.16
TSP mg l^{-1}	0.04-0.30	0.11	0.04-0.18	0.10
SRP mg l^{-1}	0.02-0.26	0.10	0.03-0.18	0.07
SRSi mg l^{-1}	no data	-	1.05-5.03	3.55
Alkalinity mg l^{-1}	no data	-	96-289	135

KEY: TKN = Kjeldahl nitrogen NOx = nitrate & nitrite -N
TP = Total phosphorus TSP = total soluble phosphorus
SRP = Soluble reactive phosphorus SRSi = reactive silica

In general, the physico-chemical regime of Princess Vlei exhibited a cyclical year to year pattern which remained constant over the post-dredging period. Where significant changes were apparent, however, was shown by comparing pre- and post-dredging data. Comparison of the data in Table 5 with that in Tables 3 and 4 showed that while the pre- and post-dredging water chemistry of the SFC has remained largely unchanged, marked differences had occurred in the vlei itself. Whilst the pre-dredging data is based on only seven sampling investigations, they showed that after the dredging, mean concentrations of total nitrogen and phosphorus decreased markedly from 8.4 to 3.0 mg l^{-1} and 0.42 to 0.19 mg l^{-1}, respectively. Secchi transparencies increased from 0.17 to 0.50 m and chlorophyll a experienced massive reductions with respect to both range and mean concentrations (compare Tables 3 and 5).

TABLE 5. PHYSICO-CHEMICAL REGIMES
(PRINCESS VLEI AND SOUTHFIELD CANAL) - PRE-DREDGING

VARIABLE	PRINCESS VLEI		SOUTHFIELD CANAL	
	RANGE	MEAN	RANGE	MEAN
Temperature °C	14.0 - 23	19	15 - 27	19
Dissolved O_2 mg l^{-1}	4.7 - 7.8	6.7	id	-
pH	8.6 - 10.6	9.6	7.4 - 10.1	8.4
Transparency m	0.09 - 0.24	17	-	-
Conductivity mS m^{-1}	id	-	id	-
Susp.solids mg l^{-1}	53 - 154	97	id	-
TKN mg l^{-1}	3.7 - 12.7	8.4	1.4 - 4.1	2.3
NH3 mg l^{-1}	0.10 - 0.20	0.12	0.01-0.21	0.11
NOx mg l^{-1}	0.06 - 0.10	0.08	1.62-4.27	3.20
TP mg l^{-1}	0.26 - 0.68	0.42	0.08-0.55	0.21
TSP mg l^{-1}	0.01 - 0.03	0.02	0.04-0.13	0.08
SRP mg l^{-1}	0.001-0.009	0.003	0.03-0.11	0.06
Chlorophyll a ug l^{-1}	70 - 602	273	-	-

KEY: id = insufficient data
TKN = Kjeldahl nitrogen NOx = nitrate & nitrite -N
TP = Total phosphorus TSP = total soluble phosphorus
SRP = Soluble reactive phosphorus

With respect to bacteriological water quality, mean annual counts of faecal coliforms entering the vlei via the Southfield Canal between 1984 and 1989 ranged between 50 and 15000 organisms 100 ml^{-1}. These counts decreased significantly from north to south down the vlei, but did not comply with either the European Economic Community Directive on Bathing Waters:- 100 faecal coliforms 100 ml^{-1} [80 percentile] (EEC, 1976); or the South African Coastal Zone Criteria of 100 or 400 faecal coliforms 100 ml^{-1} at the 50 & 90 percentiles, respectively, (Lusher, 1984; see Table 6). The counts showed an improvement during 1988 and 1989.

TABLE 6. FAECAL COLIFORMS PER 100ML (80 PERCENTILE)
PRINCESS VLEI 1984 - 1989

YEAR	SAMPLING POINT					
	SFC	1	2	3	4	n
1984	32000	4300	3100	1900	1500	25
1985	18000	2700	400	400	160	24
1986	4800	3000	900	400	1100	27
1987	11000	7900	2600	3500	1300	25
1988	500	500	1400	350	270	28
1989	100	150	300	700	1200	26

KEY: SFC = Southfield Canal
1-4 = Vlei Sampling Stations 1 - 4
n = number of samples
EC requirement : < 100 organisms at 80th percentile

Heavy metal analyses of the water and sediments of Princess Vlei were carried out on 10 occasions between December 1989 and December 1990. The results are presented in Table 7, together with some comparative values for other western and southern-Cape systems. Analysis of the sediment composition revealed a 30% silt content having a particle size range 0.001-0.1 mm, with the remainder being fine to medium sand with a particle size range of 0.1-0.43 mm. The mean water and organic contents of these samples were 80% and 14%, respectively.

Aluminium, mercury and arsenic concentrations in the sediments had mean concentrations of 2400, <0.3 and 1.1 mg kg^{-1}, respectively. The mean concentration of aluminium in the water was 320 mg l^{-1}. The water hardness, as calcium carbonate, was found to be <150 mg l^{-1}.

TABLE 7. HEAVY METAL CONCENTRATIONS IN PRINCESS VLEI WATER AND SEDIMENTS AND A COMPARISON WITH LEVELS IN THE SEDIMENTS OF OTHER WATER BODIES

SAMPLE source in ()	Concentration of metal (water = $\mu g\ l^{-1}$, sediments = $mg\ kg^{-1}$)							
	Cd	Cu	Ni	Cr	Fe	Zn	Mn	Pb
SEDIMENTS								
Princess Vlei	1.0	14	5	11	1950	150	40	90
Zeekoevlei (1)								
(sludge)	1.6	21	14	19	3100	154	87	nd
(sand)	0.1	3	2	5	470	16	5	nd
Zandvlei (1)								
(sand)	0.9	6	6	10	nd	50	23	34
Wilderness Lakes (2)	0.2	4	4	5	5800	15	50	nd
WATER								
Princess Vlei	1.0	3	4	5	340	10	25	10

SOURCE 1 - Harding (unpublished data)
2 - Watling (1977)

Primary production rates were determined on four occasions. The maximum rate of photosynthesis, Amax, occurred at a depth of 0.2 m on all occasions, and ranged from a minimum of 40 mg C m-3 h-1 during August, to a maximum of 261 mg C m^{-3} h^{-1} during February.

The results of the phytoplankton monitoring, presented as total cells ml^{-1} per algal division, are presented in Table 8. A full discussion of the phytoplankton periodicity of Princess Vlei is given in Chapter 5. The major components of the phytoplankton were comprised of genera of Cyanophyta, Chlorophyta and Bacillariophyta (Chrysophyta). Low levels of cryptomonads (Table 8) were present between June and September 1989, as well as isolated occurrences of dinoflagellates and euglenophytes between November and December of 1989. Desmids and dinoflagellates were extremely rare, appearing on only one or two occasions. Maximum numbers of phytoplankton were recorded during the summer, with lowest levels during the winter (Table 8) corresponding to the period of increased water transparency (see Figure 4).

TABLE 8. PHYTOPLANKTON DENSITIES (cells ml^{-1}) IN PRINCESS VLEI. - APRIL 1989 TO MARCH 1990

SAMPLING DATE	PHYTOPLANKTON PER DIVISION (*)						
	CHL	DIAT	CYAN	CRP	PYR	EUGL	TOTAL
1989-04-12	15300	1480	4030	0	0	0	20810
1989-04-27	2290	340	2650	60	0	0	5340
1989-05-23	8490	4880	2260	0	0	0	15630
1989-06-08	6730	9740	2940	160	5	0	19575
1989-06-21	15300	6980	5290	30	0	0	27600
1989-07-05	8230	2970	710	0	5	0	11915
1989-07-18	10100	4400	1680	10	10	0	16200
1989-07-26	8830	3700	0	30	0	0	12560
1989-08-30	950	20	0	300	0	0	1270
1989-09-04	570	20	0	100	0	0	690
1989-09-25	780	20	0	90	0	0	790
1989-10-11	440	70	0	0	0	0	510
1989-10-25	70	890	0	0	0	0	960
1989-11-08	1830	260	5420	90	15	0	7615
1989-11-22	11740	130	0	0	0	20	11890
1989-12-06	19270	300	0	0	30	0	19600
1989-12-18	2410	320	60	0	0	15	2745
1990-01-04	3560	2000	880	0	0	0	6440
1990-01-15	2650	1830	1090	10	0	0	5580
1990-02-01	2980	1930	0	15	0	0	4925
1990-02-12	3700	1110	110	35	0	0	4920
1990-03-01	9270	360	640	390	0	0	10660
1990-03-12	7040	380	60	295	0	0	7775
1990-03-27	7280	810	140	125	0	0	8355
1990-04-09	11100	1320	660	60	0	0	13150

(*) KEY:
CHL=Chlorophyta DIAT=Bacillariophyta
CYAN=Cyanophyta CRP=Cryptophyta
PYR=Pyrrophyta EUGL=Euglenophyta
RSD (relative standard deviation) = 11%

Phytoplankton diversity, in terms of genera recorded per sampling occasion, n=25, ranged from 11 to 24, with a mean of 18 genera. The Chlorophyta (green algae) were the most numerous, followed by the Cyanophyta and the Bacillariophyta. The genera recorded are listed in Table 9.

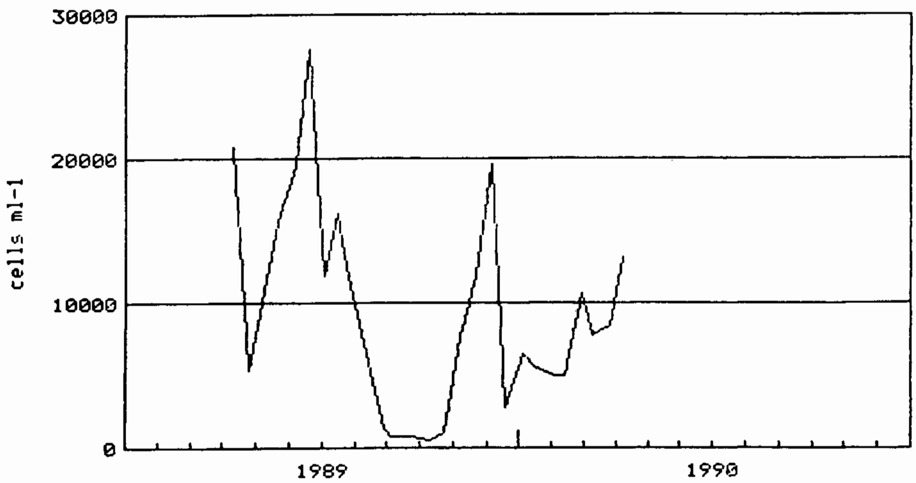

FIGURE 4: Total phytoplankton count - April 1989-March 1990

TABLE 9
COMPOSITION OF THE PRINCIPAL PHYTOPLANKTON DIVISIONS PRESENT IN PRINCESS VLEI

Chlorophyta	Cyanophyta	Bacillariophyta
Actinastrum	*Anabaena*	*Cocconeis*
Ankistrodesmus	*Anabaenopsis*	*Cyclotella*
Carteria	*Aphanocapsa*	*Fragilaria*
Chlamydomonas	*Chroococcus*	*Melosira*
Chlorella	*Merismopedia*	*Navicula*
Chodatella	*Microcystis*	*Nitzschia*
Coelastrum	*Pseudanabaena*	
Golenkinia	*Raphidiopsis*	
Gloeocystis	*Spirulina*	
Micractinium		
Oocystis		
Pediastrum		
Phacotus		
Scenedesmus		
Schroederia		
Selenastrum		
Sphaerocystis		
Tetraedron		

Within the division Chlorophyta, *Scenedesmus* spp. were present on 90% of occasions, with species of *Pediastrum, Micractinium, Tetraedron, Oocystis, Golenkinia* and *Actinastrum* frequently recorded throughout the year. Species of *Gloeocystis, Sphaerocystis* appeared during the spring of 1989. *Schroederia* was present in low numbers, <600 cells ml^{-1}, during the period of increased water clarity. Small numbers of desmids, *Staurastrum* sp., occurred irregularly during the summer months. Other green algal genera recorded in Table 9 appeared on rare occasions.

Microcystis spp. made up the greater portion of the cyanophyte assemblage, with *Chroococcus* sp. and *Anabaena circinalis* present to a much lesser extent. Species of *Aphanocapsa* (not enumerated) were ubiquitous throughout the year, reaching a maximum during the spring. *Spirulina* species were almost always present, but in very low numbers except during June and July of 1989 when they increased markedly. Casual observations of the vlei littoral on the sheltered western shoreline showed a late winter increase of *Microcystis*, appearing as clumps up to 10 mm in diameter.

The Bacillariophyta were poorly represented, with nitzschioid and naviculoid species making up the bulk of the total cell count for this division, together with smaller numbers of *Melosira* and *Cyclotella* spp. Species of Euglenophyta, principally *Euglena, Trachelomonas* and *Phacus* were observed on one or two occasions. During the periods of clear water (Figure 3), dense mats of *Rhizoclonium* and *Spirogyra* spp. were observed around the edges as well as on the vlei bed.

Data pertaining to catches of fish made during angling competitions held at Princess Vlei between 1984 and 1989 are presented in Table 10.

TABLE 10. DETAILS OF FISH CATCHES MADE AT PRINCESS VLEI BY THE WPFWAA FROM 1984 - 1989 (Source WPFAA)

Date	Number of anglers	Mean catch per angler (fish > 200g)	Mean mass per fish in grams (live weight)
84-05-19	57	6	400
84-06-16	59	5	500
84-07-21	54	6	500
84-08-25	54	7	400
85-01-26	72	4	500
85-05-11	54	5	500
85-06-15	63	5	350
85-07-13	54	9	350
85-08-17	52	9	400
86-05-24	71	7	400
86-07-19	57	6	350
87-06-13	65	7	350
87-07-18	82	3	350
87-08-15	76	5	350
88-07-23	71	2	450
88-08-20	84	0.5	450
89-05-27	97	0.6	1100
89-08-19	82	0.1	4700

Catches are of common carp, *Cyprinus carpio*

The results of the gill and seine nettings conducted in November 1989 yielded exceptionally low numbers of fish. With respect to the gill nets, a single barbel (700 mm in length) was caught on the first night, whilst only three mozambique bream, *Oreochromis mossambicus* , ranging from 70 to 100 mm in length, were caught on the second night. Use of the seine nets also yielded very low numbers of fish. Apart from a large carp which escaped, only a juvenile mosquito fish, *Gambusia* sp., three mozambique bream, one juvenile carp and numerous larval barbel were caught.

DISCUSSION

The physico-chemical characteristics of the water entering Princess Vlei, via the Southfield Canal, have not altered significantly since monitoring of the vlei began in 1982. Compared with the historical information (eg. Harrison, 1962) and pre-dredging data (this report), Princess Vlei, although eutrophic, appears to be currently less nutrient enriched than was the case prior to the dredging in 1983.

The action of the dredging removed the sill separating the two basins and would have improved the flushing action of hydraulic flows through the vlei. Dick (1982), as well as Benkenstein (1982), reported that before the dredging took place, elevated concentrations of nitrogen and phosphorus were present in the pore water of the Princess Vlei sediments. CCC tests carried out during June 1990 showed that the total P concentration of the pore water was approximately three times less than that recorded by Benkenstein (1982). The treatment of the dredge spoils with ferric sulphate, and the return of the settled water to the vlei would have effectively "sealed" the bottom sediments and removed a source of internal phosphorus loading (eg. EPA, 1980). The presence of organically-rich sediment (Hill, Kaplan and Scott, 1980) in the vlei may have served as a source of internal phosphorus loading, and enabled the vlei to sustain larger populations of phytoplankton, as indicated by the high chlorophyll *a* concentrations, than is currently the case.

In its present condition, Princess Vlei is still eutrophic, although the reduced availability of inorganic nitrogen and phosphorus during the summer months results in mesotrophic conditions. Any improvements which might be brought about to reduce phosphorus inputs from the catchment will further improve the water quality. The converse is also true, in other words that any increase in nutrient loading will increase phytoplankton dominance and reduce water quality. The high N:P ratios serve to offset cyanophyte-algal dominance (eg. Thornton, 1987). Primary production levels support the conclusions as to the trophic state of the system by exceeding the upper limit for mesotrophy in tropical systems as given by Thornton (1987).

Although flow data were not available, the effect of rainfall-induced flushing on this small vlei was readily apparent, as seen by the dramatic increase in water clarity (Figure 3), decreases in phytoplankton numbers (Figure 4), concentrations of chlorophyll a and suspended solids. This physical forcing factor appears to be an important controlling factor in the dynamics of this waterbody. The flushing occurs annually at a time when the nearby, hyper-eutrophic Zeekoevlei, which is not subject to observable (transparency) wash-out, experiences maximal nutrient levels as well as marked increases in phytoplankton numbers (see Chapters 2, 4 and 6).

Bacteriological water quality has shown considerable improvement in recent years. This is attributed to improvements made at sewage pumping stations which have reduced both the number and severity of overflows. The bacteriological water quality does not, however, meet the requirements for general contact recreation.

The concentrations of trace metals in the Princess Vlei sediments are very similar to those recorded for Zeekoevlei (see Chapter 2). These levels are probably consistent with the trace metal inputs which would be expected from the catchments feeding Princess Vlei and Zeekoevlei. The elevated iron levels are generally regarded as non-critical with respect to toxicity (Forstner and Wittman, 1981). The concentrations of metals in Princess Vlei comply with the benchmark levels of the Dutch Guidelines for Soil Sanitation (Rang and Schouten, 1989). In addition, heavy metal concentrations in the water of Princess Vlei do not exceed the limits specified by the EC Guidelines for the Protection of Freshwater Life (Mance, 1986).

During February 1987, complaints of plants dying when irrigated with yellow-coloured water revealed chromium concentrations of 30 mg l^{-1} in water from a borehole in the residential area to the north of the vlei (CCC, 1990a). Five months later, measured concentrations of Cr in this same borehole were 28 mg l^{-1}. At the time it was found that the origin of high Cr concentrations in the groundwater could have been as a result of the activities of an adjacent lumber-treatment plant (CCC, 1990b). Subsequent monitoring of this borehole revealed much reduced levels, and in January of 1990 and 1991 the Cr concentrations were 3 and 5 mg l^{-1}, respectively (J. Stow, personal communication). The elevated concentrations appear to be restricted to the vicinity of the timberyard, as water drawn from boreholes closer to the vlei revealed Cr levels of <0.5ppm (RI Dick, personal communication). No investigations of metal concentrations in Princess Vlei were carried out at that time [1987], but it was thought possible that the contaminated groundwater may have reached the vlei, either by upwelling or seepage, or via the stormwater drains during pumping-out of the borehole. Timber treatment process preservatives, typically chrome-copper-arsenic or pentachlorophenol-tributyltin mixtures, can be particularly destructive to life in aquatic ecosystems (eg. McNeill, 1989). Investigations are currently under way to determine the nature and direction of groundwater flows in the vicinity of Princess Vlei. The analysis of heavy metals in sediment cores collected in and around Princess Vlei during 1990 revealed no evidence of any heavy metal poisoning events during the recent past (Van der Heyden, 1990). The analysis of fish liver and muscle tissue from carp specimens from Princess Vlei showed no trace of heavy metal accumulation.

The phytoplankton divisions which are present, and the composition of the Cyanophyta and Chlorophyta are characteristic of a eutrophic waterbody (Hutchinson, 1967). The levels (cells ml^{-1}) are low in comparison with Zeekoevlei (see Chapter 4), and the water does not, except for some sheltered littoral areas, attain a "green" colour. The high N:P ratios and the annual removal from the vlei of a significant fraction of viable algal biomass through hydraulic flushing, prevent cyanophyte species from becoming established. The chlorophyte species are favoured during the summer as a result of the warm temperatures, wind-induced mixing and high light levels (Hutchinson, 1967).

Historical data on the phytoplankton assemblage of Princess Vlei are limited to the *ad hoc* observations of Stevens (1929), Hutchinson (1932) and Harrison (1962) on samples collected in the littoral zone during the 1920s and 1940s. Nonetheless, the profiles recorded by these researchers are similar to those noted during the 1989-1990 period (see Chapter 4). Algal blooms were reportedly common in Princess Vlei. This was still the case in more recent years as Furness (1979) reported a severe bloom of *Microcystis aeruginosa* during the winter of 1979. The available information indicates that blooms of *Micractinium* spp. occurred during the summer (Harrison, 1962). Summer blooms of phytoplankton have been recorded for the similarly-sized Rondevlei (Gardiner, 1988). City Council officials have reported that the vlei used to be a year-round green colour prior to the time of the dredging (personal communications), but algal blooms and the green colouration have not been recorded since 1983. Stevens (1929) and Hutchinson (1967) both regarded the alkalinity of Princess Vlei as a factor precluding the development of desmid and dinoflagellate populations.

The documented and *ad hoc* historical information concerning the abundance of fish in Princess Vlei indicates that substantial populations were present until recently. Hutchinson (1932) observed that "fish are common in the [Princess] vlei". Hutchinson also mentioned that kurper (*Anabas capensis* L.) were present, that carp had been introduced and that trout had flourished in the vlei prior to a sewage spill; and Harrison (1962) recorded that european carp (*Cyprinus carpio* L.) were abundant during the spring periods of 1946 and 1947. Local Cape Town residents have reported that carp used to be so abundant in the vlei that they were caught and sold alongside the road to passing motorists (*ca*. 1950). This practice continued until the early 1970s (JA Day, personal communication). Barbel (*Clarius gariepinus* Burchell) were introduced into Princess Vlei by the Angling Association (WPFAA) during 1987 (C. Garrow, personal communication). Surveys conducted at the other major vleis of the Cape Peninsula have indicated substantial fish populations (see Hamman *et* *al.*, 1977; Gaigher and Thorne, 1979 and Quick and Bennett, 1989). In addition, there was clear evidence that carp are abundant in Little Princess Vlei, although no data are available on the population structure (personal observations).

The data in Table 10 indicates that the change in the Princess Vlei fish population occurred between 1987 and 1988, in the form of a reduction in numbers of fish caught per angler. Between 1988 and 1989 the catch per angler was further reduced, and the mean mass per fish increased dramatically. This was still the situation in January 1991 (Garrow, personal communication). There was no available evidence linking fish-kills, illegal netting, chemical spills and heavy metal poisoning events to the observed perturbation. Formal angling competitions conducted by the WPFAA at Princess Vlei were on a "catch, weigh and return alive" basis, and did not, therefore, contribute to the observed decline in numbers. The introduction of barbel into Princess Vlei, however, may have brought about a bottom-up depletion of smaller fish, thereby disrupting the resident population. Barbel have been described as "omnivorus scavengers, feeding on almost anything including small fish" (Jubb, 1967), and their illegal introduction into the vleis and waterways of the Western Cape have recently (1991) been declared cause for concern by the freshwater angling community.

The alteration in the biodiversity of Princess Vlei was found to be not limited to the fish. Investigations by McShane (1989) and a year later by Henderson and Davies (1990) revealed extraordinarily low levels of chironomid and other insect larvae, as well as benthic macroinvertebrates in general. Although Zeekoevlei was similarly found to have low numbers of benthic insects, Henderson and Davies (1990) expressed their concern regarding the ecologically-disturbed appearance of Princess Vlei.

CONCLUSIONS

Princess Vlei is a well mixed, eutrophic water body which currently exhibits a very low level of biodiversity. The partial dredging of the vlei during 1983 served to improve the overall nutrient water quality and reduce phytoplankton biomass as a result of sediment sealing and hydraulic alterations to the vlei bottom.

The lack of benthic macroinvertebrates and the depletion of an until recently "normal" fish population indicates a seriously perturbed system, the exact cause of which is unclear. The presence of extremely predatory fish species such as the barbel which were introduced during 1987 may well be implicated here. The introduction of the barbel is also chronologically linked to the observed perturbation in the Princess Vlei fish population.

The lack of historical biological data, as well as the absence of a reference framework with respect to heavy metals, makes comparisons with earlier years impossible. These deficiencies highlight the need for comprehensive limnological monitoring of water bodies if events, such as those which might have led to the present conditions in Princess Vlei, are to be correctly interpreted.

The introduction of a "mark and recapture" procedure with the remaining as well as any newly-introduced fish would assist in monitoring the recovery of the fish population. Tissue analysis of fish still present in Princess Vlei could well contribute to discovering the cause. Princess Vlei should be restocked once it has been established that there is no danger to the introduction of young fish.

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SOUTHFIELD CANAL - PHYSICO-CHEMICAL DATA SUMMARY 1982 - 1990													
YEAR		C	pH	Cnd	DO	%OS	TKN	NH3	NOx	TP	TSP	SRP	ss
1982	n	5	5	0	0	0	4	5	5	5	5	4	4
	min	15.0	7.4	-	-	-	1.3	0.01	1.97	0.08	0.04	0.03	0
	max	19.5	9.0	-	-	-	4.1	0.21	4.27	0.21	0.13	0.08	8
	mean	17.2	8.0	-	-	-	2.1	0.08	2.93	0.14	0.07	0.05	2
	std dev	1.9	0.6	-	-	-	1.3	0.08	1.09	0.05	0.03	0.02	4
1983	n	7	7	3	7	3	6	6	6	5	5	5	5
	min	13.0	7.6	90	3.8	45	1.5	0.07	0.08	0.11	0.05	0.04	4
	max	27.3	10.1	133	13.1	112	79.0	3.56	3.79	8.72	6.18	5.40	116
	mean	18.4	8.2	110	8.6	73	5.4	0.70	1.36	0.47	0.21	0.17	14
	std dev	5.5	0.9	22	2.8	34	30.9	1.30	1.29	3.78	2.72	2.38	48
1984	n	7	7	6	7	7	5	6	6	5	6	4	6
	min	15.0	7.9	39	5.5	58	0.1	0.08	0.15	0.10	0.06	0.04	2
	max	26.8	9.7	120	15.9	183	11.2	1.46	3.44	0.52	0.28	0.14	12
	mean	21.3	8.4	75	9.0	101	1.4	0.34	0.81	0.15	0.09	0.07	5
	std dev	4.7	0.6	27	3.7	48	4.5	0.65	1.39	0.18	0.09	0.04	4
1985	n	3	3	2	3	0	2	2	0	2	2	2	1
	min	14.5	7.5	85	3.2	-	2.6	0.59	-	0.09	0.07	0.04	-
	max	19.9	7.9	101	7.6	-	3.2	0.85	-	0.14	0.08	0.05	-
	mean	16.5	7.6	93	5.5	-	2.9	0.71	-	0.11	0.08	0.05	-
	std dev	2.9	0.2	11	2.4	-	0.4	0.18	-	0.04	0.01	0.01	-
1986	n	4	0	2	4	4	5	5	7	5	5	5	5
	min	14.9	-	68	4.6	45	1.4	0.09	3.23	0.09	0.05	0.04	3
	max	24.0	-	86	9.2	108	5.3	0.81	7.03	1.03	0.58	0.42	49
	mean	18.4	-	76	5.7	60	2.2	0.36	4.42	0.18	0.11	0.09	18
	std dev	3.9	-	13	2.2	29	1.6	0.30	1.53	0.41	0.23	0.16	18
1987	n	10	10	7	10	10	10	10	9	10	10	10	10
	min	13.9	7.1	32	4.8	47	0.7	0.08	0.12	0.08	0.04	0.03	6
	max	27.5	9.0	68	12.2	145	10.0	0.56	5.28	0.23	0.19	0.15	29
	mean	19.7	8.2	55	7.7	84	2.2	0.21	1.55	0.14	0.11	0.08	14
	std dev	4.3	0.6	12	2.3	30	2.7	0.15	1.86	0.06	0.06	0.04	8
1988	n	18	3	18	18	18	11	8	8	11	11	11	11
	min	15.0	8.8	8	7.2	71	0.9	0.02	0.01	0.09	0.05	0.02	3
	max	26.0	9.9	94	14.0	170	7.5	1.46	6.20	0.62	0.30	0.26	52
	mean	19.2	9.4	63	9.0	98	2.0	0.19	0.71	0.15	0.08	0.06	16
	std dev	3.4	0.6	18	1.9	27	2.0	0.47	2.76	0.15	0.07	0.07	17
1989	n	21	14	21	21	21	9	9	9	10	10	10	9
	min	12.7	7.3	19	7.1	70	0.8	0.06	0.01	0.07	0.04	0.03	3
	max	32.0	9.2	87	12.6	173	2.6	0.48	4.50	0.31	0.23	0.18	74
	mean	20.0	8.0	58	9.1	100	1.4	0.14	0.44	0.16	0.09	0.08	12
	std dev	4.9	0.5	13	1.6	27	0.5	0.14	1.81	0.09	0.07	0.05	23
1990	n	24	24	24	24	23	11	11	11	11	11	11	11
	min	13.9	6.8	34	6.3	61	0.7	0.01	2.38	0.07	0.04	0.03	3
	max	28.4	8.9	75	10.7	138	4.3	0.82	6.31	0.45	0.23	0.21	206
	mean	19.7	7.7	61	8.2	90	2.1	0.18	4.06	0.16	0.08	0.06	17
	std dev	4.3	0.6	9	1.2	21	1.0	0.24	1.14	0.13	0.07	0.05	79
ALL	n	99	73	84	94	86	63	62	60	64	65	62	62
	min	12.7	6.9	8	3.2	45	0.1	0.01	0.01	0.07	0.04	0.02	1
	max	32.0	10.1	133	15.9	183	79.0	3.56	7.03	8.72	6.18	5.40	206
	mean	19.4	8.0	64	8.3	92	2.1	0.23	1.48	0.16	0.10	0.07	12
	std dev	4.3	0.7	18	2.2	29	9.8	0.57	1.90	1.08	0.76	0.04	39

Cnd = conductivity (mS m^{-1}); DO = daytime dissolved oxygen
%OS = oxygen saturation (%); TKN = Kjeldahl -N; NH3 = ammonia -N;
NOx = nitrate & nitrite -N; TP = total -P; TSP = total soluble -P;
SRP = soluble reactive (ortho) -P; ss = suspended solids
(all mg l^{-1})

PRINCESS VLEI- PHYSICO-CHEMICAL DATA SUMMARY 1982 - 1990														
YEAR	°C	pH	Cnd	DO	%OS	ST	TKN	NH3	NOx	TP	TSP	SRP	ss	CHLa
1982 n	20	20	4	20	0	20	16	20	20	20	20	16	16	20
min	13.0	7.4	57	4.1	-	0.09	3.3	0.02	0.01	0.22	0.01	0.000	29	21
max	22.0	10.6	62	8.6	-	0.31	14.0	0.86	0.34	0.70	0.07	0.021	170	507
mean	17.7	9.4	58	6.4	-	0.18	6.2	0.12	0.07	0.35	0.02	0.001	73	121
std dev	3.1	0.9	3	1.4	-	0.06	3.7	0.23	0.08	0.16	0.02	0.005	45	152
1983 n	28	26	14	27	12	26	24	22	22	20	20	20	20	28
min	13.0	7.4	81	5.6	58	0.07	2.5	0.03	0.03	0.07	0.00	0.000	21	2
max	24.0	10.4	130	9.2	99	0.39	14.0	0.19	3.17	0.53	0.12	0.033	134	646
mean	17.9	8.7	97	7.1	76	0.20	6.4	0.09	0.44	0.25	0.02	0.004	45	36
std dev	4.4	1.0	19	0.9	14	0.10	3.3	0.04	1.07	0.18	0.03	0.008	39	239
1984 n	27	14	28	27	27	27	24	12	12	24	24	24	24	24
min	14.0	5.9	60	4.0	40	0.18	2.1	0.04	0.04	0.15	0.01	0.000	18	0
max	25.2	9.1	108	11.2	122	0.39	13.6	0.25	0.65	0.44	0.05	0.007	65	81
mean	19.7	8.2	90	7.2	78	0.25	5.4	0.10	0.11	0.23	0.02	0.001	41	22
std dev	4.2	0.9	15	2.1	28	0.06	3.3	0.08	0.23	0.06	0.01	0.002	13	28
1985 n	11	6	5	11	0	4	4	4	2	4	4	4	2	4
min	14.0	7.3	32	3.6	-	0.23	1.1	0.10	0.79	0.14	0.01	0.001	20	1
max	19.1	9.2	71	9.4	-	0.29	3.7	0.25	1.35	0.23	0.12	0.080	34	106
mean	15.6	8.5	54	7.0	-	0.25	2.4	0.16	1.03	0.17	0.05	0.006	26	23
std dev	2.0	0.7	16	1.8	-	0.03	1.1	0.07	0.40	0.04	0.05	0.037	10	43
1986 n	12	0	6	12	12	12	15	10	10	15	15	15	15	15
min	14.0	-	41	5.2	54	0.28	0.6	0.03	0.00	0.13	0.02	0.002	45	1
max	24.8	-	55	11.0	129	0.49	4.9	0.30	1.39	2.22	0.42	0.120	96	54
mean	18.3	-	49	6.7	71	0.39	1.9	0.08	0.14	0.28	0.05	0.013	62	22
std dev	4.0	-	6	2.1	29	0.08	1.3	0.09	0.53	0.76	0.13	0.035	16	18
1987 n	33	21	24	33	33	32	33	22	20	33	33	33	33	30
min	13.0	7.5	29	3.7	35	0.15	0.4	0.03	0.01	0.08	0.01	0.001	7	11
max	25.0	10.1	72	10.2	121	0.38	9.5	0.71	0.95	0.26	0.08	0.035	83	219
mean	18.6	9.0	51	7.3	77	0.27	2.5	0.14	0.05	0.15	0.02	0.004	42	68
std dev	4.1	0.7	12	1.6	22	0.06	1.6	0.18	0.30	0.05	0.02	0.007	22	55
1988 n	59	6	58	59	59	49	35	26	26	35	35	35	35	35
min	13.0	9.6	18	2.4	23	0.15	0.7	0.02	0.01	0.07	0.01	0.001	6	2
max	26.0	10.0	85	11.4	141	3.00	6.6	2.02	6.78	0.65	0.61	0.460	98	79
mean	18.4	9.8	60	7.3	78	0.64	2.5	0.24	0.18	0.16	0.03	0.009	25	21
std dev	3.1	0.2	13	1.7	19	0.86	1.3	0.54	1.43	0.13	0.10	0.080	23	21
1989 n	88	60	88	88	88	88	40	40	36	40	40	40	40	40
min	12.3	7.1	28	6.1	62	0.20	1.0	0.02	0.01	0.05	0.01	0.003	3	6
max	26.5	9.8	80	17.8	208	1.55	4.3	0.82	0.88	0.33	0.16	0.146	102	118
mean	17.7	8.8	55	9.4	99	0.42	2.2	0.17	0.07	0.18	0.04	0.016	21	57
std dev	4.1	0.8	13	2.0	25	0.32	0.8	0.22	0.26	0.06	0.04	0.032	24	30
1990 n	96	96	96	96	92	94	44	44	46	44	44	46	44	56
min	11.6	7.1	36	4.6	52	0.15	0.8	0.00	0.05	0.07	0.01	0.002	3	2
max	24.8	9.6	81	11.5	135	1.54	3.4	0.62	1.61	0.27	0.14	0.132	165	158
mean	18.0	8.4	56	8.0	86	0.58	1.8	0.14	0.14	0.14	0.04	0.025	26	22
std dev	3.6	0.7	10	1.3	16	0.35	0.6	0.16	0.23	0.05	0.04	0.038	40	40
ALL n	374	249	323	373	323	352	235	200	194	235	235	233	229	252
min	11.6	5.9	18	2.4	23	0.07	0.4	0.00	0.01	0.05	0.00	0.001	3	1
max	26.5	10.6	130	17.8	208	3.00	14.0	2.02	6.78	2.22	0.61	0.460	170	646
mean	18.1	8.7	60	7.8	85	0.40	2.9	0.14	0.13	0.19	0.03	0.009	34	36
std dev	3.8	0.8	18	1.9	23	0.47	2.8	0.27	0.74	0.23	0.06	0.042	32	107

KEY: Cnd = conductivity (mS m^{-1}); DO = daytime dissolved oxygen (mg l^{-1}); %OS = oxygen saturation (%); ST = Secchi transparency (m); TKN = Kjeldahl -N; NH3 = ammonia -N; NOx = nitrate & nitrite -N; TP = total -P; TSP = total soluble -P; SRP = soluble reactive -P ss = suspended solids (all mg l^{-1}); CHLa = chlorophyll a (corrected for phaeophytins) (ug l^{-1})

CHAPTER 4

PHYTOPLANKTON DIVERSITY AND PERIODICITY IN ZEEKOEVLEI.

1989 - 1991

INTRODUCTION

Phytoplankton periodicity commonly refers to a repeated cycle of growth and decline within the algal community of a particular waterbody. Increases in numbers of algae, followed by die-off and subsequent growth of other species may be periodic with respect to both the algal division(s) as a whole, as well as to the individual components of a division or genus. These cyclical events occur in response to various environmental variables, imposed both autochotonously and allochotonously upon the system in question, and may be natural or anthropogenically induced. Similar repetitive events have been identified in morphologically and climatically dissimilar lakes, in temperate, tropical and sub-tropical regions, this feature leading to the establishment of a "seasonal paradigm" for phytoplankton periodicity. The basis of this paradigm is heavily reliant on data from studies conducted in north-temperate regions, and to a lesser extent from tropical latitudes, with few comprehensive studies emanating from further south (Chapter 1). Many of the documented phytoplankton-periodicity investigations have been carried out on deep, stratifying systems, and there is a scarcity of information for small systems such as ponds and shallow lakes or coastal vleis (eg. Hutchinson, 1967; Reynolds, 1984; Talling, 1986).

Phytoplankton periodicity studies in South Africa have formed part of investigations undertaken chiefly on large impoundments such as Rietvlei Dam (Ashton, 1979 and 1981), Hartbeespoort Dam (NIWR, 1985; Zohary and Robarts, 1989; Zohary and Breen, 1989), Roodeplaat Dam (Pieterse and Rohrbeck, 1990); Rhenosterkop Dam (Heath *et al.*, 1988; Robarts *et al.*, in press), Lake Midmar (Breen, 1983), Lake le Roux (Allanson and Jackson, 1983) and on two large, coastal lakes, Lake Sibaya (Hart and Hart, 1977) and Swartvlei (Robarts, 1973; Howard-Williams and Allanson, 1981). In addition, Pieterse *et al.* (1986), Pieterse (1987), Pieterse and Roos (1987 and 1987a) and Pieterse and van Zyl (1988) have reported on aspects of phytoplankton ecology of the Vaal River. The most detailed of these studies is regarded by Allanson *et al.* (1990) as being that of Hart and Hart (1977) on Lake Sibaya. Summarized, these studies show that phytoplankton periodicity in the eastern, summer rainfall region broadly conforms to the seasonal paradigm as described by Reynolds (1983, 1984; see Chapter 1). Swartvlei, which is oligotrophic, semi-estuarine, macrophyte-dominated and situated in a winter-rainfall region, also appears to follow the generally-accepted cyclical trend. No detailed phytoplankton studies have been conducted in the south-western Cape or on eutrophic coastal systems.

When considering periodicity in aquatic systems, it is relevant first to examine this phenomenon in the more readily understood terrestrial situation. As far as terrestrial plant ecology is concerned, terminological differences arise with respect to the concepts of "seasonal succession" and "seasonal periodicity". "Succession" on land implies a strong directional bias, through which a piece of bare earth, initially colonized by a "pioneer" plant community, will finally support a "climax" vegetation, usually forest (Reynolds, 1983). This process is characterized by increasing species diversity and declining productivity. The main driving process is, however, autogenic, and can be considered to be directional, predictable and self-regulating. Reversals can and do occur in this successional sequence, and allogenic factors (fires, tree-felling) result in a return to an earlier successional stage, at which point the sequence resumes, or can be maintained ("plagioclimax") by sustained human activity. What is observed in the terrestrial sense is, therefore, strict seral succession. The difficulties of attempting to treat phytoplankton periodicity using the same terminology are obvious, due to the very nature of the aquatic situation. With respect to time, terrestrial successional cycles usually require many decades to reach the "climax stage", whilst for planktonic communities the succession repeats itself on annual, or shorter, cycles.

The traditional "seasonal paradigm" is characterised by a spring maximum of Bacillariophyta, an early summer maximum of Chlorophyta and a late-summer maximum of Cyanophyta. This typical seasonal cycle of phytoplankton periodicity in temperate regions is well illustrated by Fogg (1975) in his chapter on the spring increase of phytoplankton in temperate waters. During autumn and early winter, nutrient concentrations in temperate lakes increase as a result of heterotrophic bacterial activity. Little algal growth occurs during this well-mixed period (Sommer, 1985). Assuming the presence of viable propagules, algal reinoculation of the water occurs. Some algal growth is supported by the available light and warmth during mid-winter, but the conditions are far from optimal for vigorous multiplication of cell numbers. Cell losses, either by sedimentation (loss of whole cells) or respiration (loss of biomass), probably balance the increase in cell numbers produced by new growth. Increasing light and warmth, coupled with the availability of nutrients, culminates in a burst of algal growth, usually bacillariophyte species, during early spring, with the timing of this increase showing marked similarity from year to year in many cases (eg. Petterson, 1990). As the numbers of cells in the water increases, light penetration concomitantly decreases, chiefly as a result of self-shading by the presence of algal cells. As nutrient depletion takes place, species selection occurs in favour of slower-growing, *K*-selected and conservative species which are better adapted to nutrient scarcity. In the absence of vertical mixing, the water becomes separated into an upper, nutrient-deficient layer (epilimnion) and a lower, light-deficient one (hypolimnion). Thus, the features controlling the sequence up to this point are autogenic, result from biotic activity and, according to Reynolds (1983, page 317), should be the only phytoplankton-related sequences to which the term "succession" may be applied. Succession should not be used as a synonym of "periodicity", as the latter is driven by allogenic as well as by autogenic variables (Reynolds, 1984).

This "successional" trend of the phytoplankton may be interrupted at any time by externally-imposed (allogenic) "forcing factors" or variables, the most important of these being wind-induced mixing. Washout, sedimentation, grazing, autoinhibitors and/or parasitism all contribute to disturbance of the sequence, as do anthropogenic inputs of sewage or other pollutants. Whereas in the case of terrestrial succession, returns to earlier stages (seres) do not affect the ultimate arrival of the seral succession at the same climax, sustained perturbations in aquatic systems can result in a new line of development being followed, and constitutes a "shift" as opposed to a "reversion"; reversions result in the original pathway being followed after recovery from the disturbance (Reynolds, 1983).

In temperate lakes, the spring maximum is usually followed by a period of two or so months where the phytoplankton standing crop remains at a relatively constant level. This fall-off in growth is attributable to a depletion of nutrients brought about by the sedimentation of most of the cells produced during the spring maximum or the onset of summer stratification. Stratification generally selects in favour of buoyant, motile species and against those species which are non-motile and negatively buoyant (Reynolds *et al.*, 1983). Mixing generally favours increases in bacillariophyte numbers (eg. Talling, 1987; Reynolds, 1983), with autumnal increases in mixed depth frequently resulting in a second bacillariophyte maximum. It has been stated that this "double-maximum" peak occurs only in lakes which show the summer depletion of nutrients. Over-enrichment may tend to obliterate spring and autumn peaks with an extended mid-summer peak, the form of which is dictated by light and temperature.

What value is gained from studies of algal periodicity? Phytoplankton forms the base of the pelagic food chain. If an excess of nutrients is present, rapid overdevelopment of the algal standing crop of a particular waterbody can have severe repercussions in both the social and economic spheres. Quantification of nutrient loadings to lakes and rivers does not indicate what the algal response will be, nor does it provide information on which genera will predominate. Algal assays can, however, be employed to determine the biological availability of nutrients, the sensitivity to N- and P-loading and the environmental impact of effluent discharges on receiving streams. Changes in aquatic algal populations may provide as much information about water chemistry as the chemical determinations themselves (Pipe and Schubert, 1984). Despite a knowledge of mean levels of biomass, it is the peaks in the biomass which cause problems, and these may be compounded by the dominant species of algae present (Reynolds, 1983).

What advantage does the monitoring of algal periodicity, as monitored by the sedimentation and counting of algal cells (Utermohl, 1958; Lund *et al.*, 1958) have over monitoring conventional physical and chemical variables? Although the algal content of water bodies can be easily and conveniently measured using techniques such as water transparency (Secchi Disk), pigment analysis (chlorophyll a), algal biomass (gravimetric methods) or primary production (light and dark bottle or carbon-14 techniques), these determinations all have inherent drawbacks. Secchi transparency can be negatively influenced by suspended or resuspended matter other than live algae, especially after periods of heavy rainfall or sustained periods of wind-induced mixing. The chlorophyll a content of various algal genera varies, as does the chlorophyll a content of specific taxa under differing nutrient conditions. There are also methodological problems with the determination of chlorophyll a (see Chapter 1). Biomass determinations can be offset by the inclusion of other suspended solids, and indeed, other organisms such as zooplankton in the sample. Similarly, respiration in the light and dark bottle primary production technique may include zooplankton and bacterial input, and therefore represents "community respiration" rather than that due to the phytoplankton alone. In addition, encasing a sample creates an artificial "niche-space", with respect to nutrient accessibility, unlike that experienced by a freely-floating algal cell. With regard to elucidating the specific components of the phytoplankton assemblage, none of the above techniques tell us which species of algae are present in a particular sample, let alone in what numbers or in what "direction" the assemblage may be changing. Naturally occurring algal communities are very seldom "unialgal" in nature, and the number of species present may range from a few to several hundred, the level of diversity decreasing as the degree of eutrophication increases. The determination of the components of a particular algal population requires a time-consuming, dedicated process of microscopic examination, identification and counting of the algae present. This is probably the single most significant reason why so few studies of this nature are attempted.

Algae which are vastly morphologically-different can and do co-exist within the same waterbody, suggesting that if varying structural characteristics are present together, then the controlling factors, *i.e.* the response of the various phytoplankton species to environmental variables, will be very different. For this reason alone, the use of correlates such as chlorophyll a to monitor algal periodicity are inadequate.

With respect to the factors which affect the periodicity of the phytoplankton, no single determinative parameter can be singled out. Early studies, between 1904 and 1932, tended to consider algal periodicity as being the nett result of physical interactions. Since then, the concepts of nutrient-competition, parasitism and grazing have been accepted as forming part of a multi-factorial process determining the sequence of aquatic periodic events (see Sommer, 1987). There does, however, appear to be a hierarchial sequence which is based upon the degree or the extent of the community response, invoked by certain factors (Reynolds, 1984). This sequence, in descending order, is from physical interactions, to chemical, nutrient availabilities and gradients, and then biotic parameters such as grazing and parasitism. Selection occurs within each level, according to the relative growth potentials of the phytoplankton present. Each of the various factors are discussed in Hutchinson (1967), Fogg (1975), Smayda (1980) and Reynolds (1983), to name some of the most prominent works.

This study represents the first comprehensive study of phytoplankton periodicity in Zeekoevlei. The results are those of the first two years of data collection, over the period from April 1989 to March 1991.

STUDY AREA AND METHODOLOGY

A description of the study area, methodologies and results of the physico-chemical monitoring of Zeekoevlei between 1981 and 1990 are presented in Chapter 2. The results presented in this chapter represents the collection of phytoplankton at Zeekoevlei and relevant physico-chemical data for the period April 1989 to March 1991.

Integrated water column samples (see Chapter 2 for description of method) were collected at each of four vlei stations at fortnightly intervals during the first year of the study, and at two stations during the second year. Sampling frequency was increased to weekly during the spring of 1990. Samples were invariably collected between 0900 and 1100. Aliquots (250 ml) from the composite of three columns per sampling station were immediately preserved with Lugols-iodine (Vollenweider, 1975) and stored in the dark until examined. Algal identification and counting was carried out in sedimentation chambers using the inverted microscope techniques of Utermohl (1958) and Lund (1958). Colonial species were disrupted using the method of Zohary and Pais-Madeira (1987). Samples were examined using a range of magnifications, and all the cells present in pre-calibrated transects were counted. Cells as small as 1 m in diameter were routinely recorded. Colonial species, such as *Merismopedia* and *Aphanocapsa*, were not enumerated as individual cells because of their very small size, their resistance to mechanical disruption and the difficulty of identifying them as individual cells. Results are expressed as cells ml^{-1} of sample.

Identification of algal genera was made by reference to one or more of the following texts: Fritsch (1932); Smith (1950); Huber-Pestalozzi (1955); Davis (1955); Fott (1959); Ward and Whipple (1959); Shillinglaw (1980); Streble and Krauter (1985); Truter (1987), and APHA (1989).

As this study concentrated on the dominant phytoplankton periodic patterns, details of rare species observed are not included. The occurrence of rare species were, however, recorded as part of a photomicrograph database.

The determination of chlorophyll a differs from that presented in Chapter 2. An evaluation of the acetone pigment-extraction was compared with one using ethanol as the extractant (Harding, 1990b). This work revealed that in Zeekoevlei, use of the acetone-based method resulted in an under-estimation of the chlorophyll a concentration by as much as 70%. As from May 1990, the ethanol-extraction technique (DWA, 1988) replaced the acetone method, and the chlorophyll a concentrations presented in this chapter are those obtained using the new method, as well as the results from April 1989 to May 1990 were multiplied by a factor of 1.7 before being included here. The results were corrected for phaeophytins using the equations in DWA (1988).

Correlation of the algal cell counts with prevailing environmental parameters was made using linear regression analyses.

Calculation of cell volumes of the dominant species were made using the volumes arrived at by Nauwerck (cited in Vollenweider, 1975) or by measurement and calculation using the formulae described in Rott (1981),

Whilst some uncertainty exists as to the correct terminology to be used when referring to the blue-green algae, it was felt that the term "cyanobacteria", although commonly used, has led to confusion, especially in para- or non-scientific arenas. Therefore the synonomous designation, "Cyanophyta" (=Myxophyta) is used throughout when referring to genera and species of blue-green algae.

Meteorological data pertaining to sunlight and wind patterns were obtained from the Weather Bureau at D F Malan Airport. Wind data obtained from a recorder at the Cape Flats Wastewater Treatment Plant, adjacent to Zeekoevlei, had to be disregarded due to an instrument malfunction. Measurements of wind speed were limited to surface readings made using a hand-held anaemometer at the time of sampling. Rainfall measurements were taken from a guage situated at the aforementioned treatment works.

RESULTS

Meteorological and physico-chemical regimes

Daily hours of sunlight and incident solar radiation patterns were consistent with those reported in Chapter 2, as was the trend for wind speed and direction, noted from recordings at D F Malan Airport (Figure 1). Maximum hours of sunlight, 11.1-11.2 h d^{-1}, were recorded during January of both years, with minima of 5.5 and 4.9 h d^{-1}, during June 1989 and July 1990, respectively. The wind pattern varied from 1989 to 1990 with the rate of the increase from the mid-winter minimum being more pronounced during 1990 than was the case during 1989 (Figure 1). Buoyant *Microcystis* spp. cells become mixed into the water column at wind speeds in excess of 3.7 m s^{-1} (Scott *et al*., 1969) and the interaction of wind on cyanophyte cell numbers has been discussed in Chapter 6. The maximum monthly rainfalls of 106 and 141 mm, recorded at the adjacent wastewater treatment plant (see Chapter 2) fell during August 1989 and April 1990, with lowest falls (<2 mm) during December of both years (Figure 1). Total falls for the two periods were 552 and 560 mm, respectively.

Estimates of hydraulic outflows became available during early 1991 (Morrison *in litt.*), and the calculated total annual weir outflows for Zeekoevlei are presented in Table 1. These flow volumes are also expressed relative to the total volume of the vlei, including the sediments; and the water volume alone. An appreciable amount, 22% of Zeekoevlei's volume, is taken up by accumulated sediments, and the option of dredging these to improve water quality is currently under consideration (see Chapters 2 and 6). The mean retention time from 1986-1990, expressed relative to the water volume was 2.4 months, with a range of 1.8 to 4.2 months. The annual hydraulic flow pattern expressed as weir outflow for 1989 and 1990, is shown in Figure 1.

TABLE 1: ZEEKOEVLEI WEIR OUTFLOWS, 1986 - 1990

YEAR	Flow, Ml	Exceeds total volume	Exceeds water volume
1986	20246	4.0 X	5.1 X
1987	18213	3.7 X	4.6 X
1988	11286	2.3 X	2.9 X
1989	18930	3.8 X	4.8 X
1990	27309	5.5 X	6.9 X

Total volume of Zeekoevlei = 4.97 million m3
Water volume of Zeekoevlei = 3.86 million m3
(Harding, 1990a)

The physico-chemical regime of Zeekoevlei during the first two annual periods of phytoplankton periodicity monitoring, between April 1989-March 1990 and April 1990-March 1991, is summarized in Table 2.

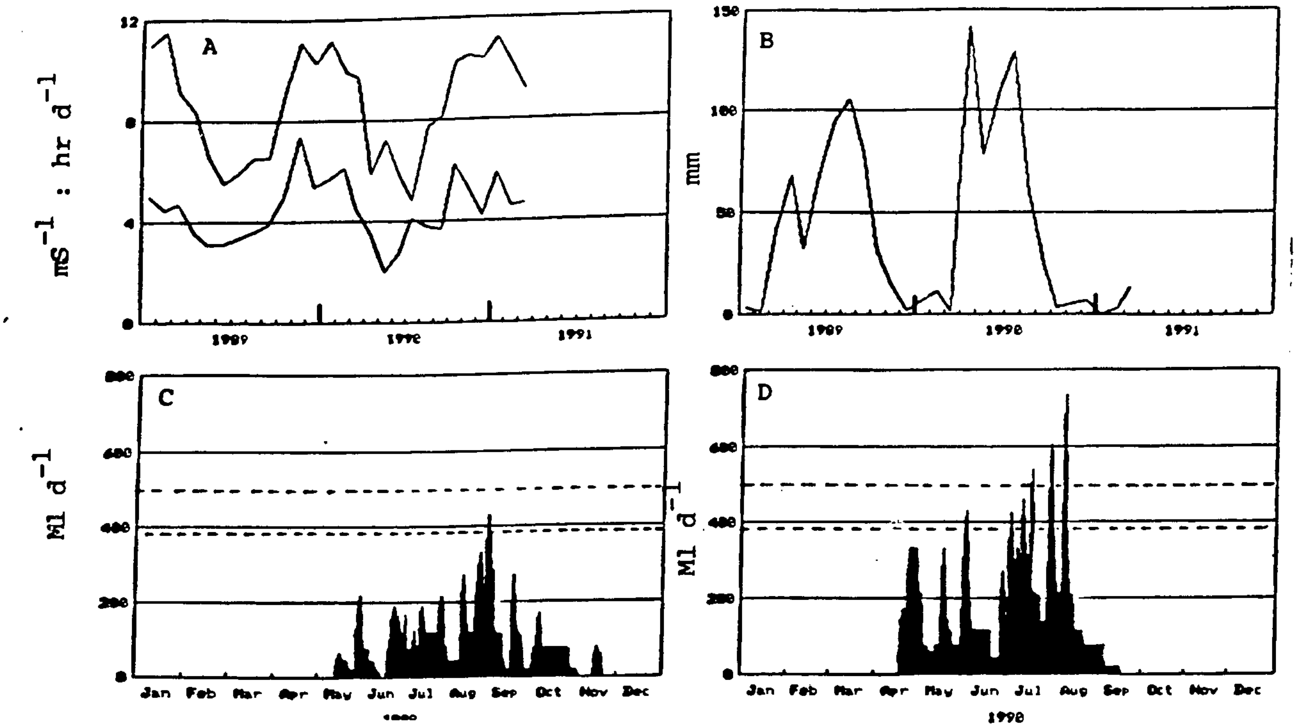

FIGURE 1 : (A) Wind speed (lower line) and sunlight (upper line) regimes as measured at D F Malan Airport.

These data have been taken as representative of conditions at Zeekoevlei, in lieu of other more direct measurements.

(B) Monthly total rainfall measured adjacent to Zeekoevlei.

(C) and (D) Vlei outflow volumes, for 1989 and 1990. Upper and lower broken lines, respectively, represent 10% of vlei total and effective (minus sediment) water volumes.

TABLE 2: ZEEKOEVLEI - SUMMARY OF PHYSICO-CHEMICAL MONITORING DURING THE FIRST TWO YEARS OF PHYTOPLANKTON MONITORING

PARAMETER		1989 - 1990		1990 - 1991	
		RANGE	MEAN	RANGE	MEAN
Temperature	^oC	10.3-23.5	18.6	10.9-23.6	17.8
Dissolved O_2	mg l^{-1}	5.1-16.7	9.6	7.2-12.8	9.6
Oxygen satur.	%	58-171	100	68-131	101
Secchi transp.	m	0.1-0.41	0.26	0.17-0.58	0.32
pH		8.9-10.6	9.7	7.9-10.5	9.3
Conductivity	mS m^{-1}	93-202	143	88-184	130
Susp. solids	mg l^{-1}	14-153	69	24-88	54
Total (K)-N	mg l^{-1}	1.7-6.6	4.2	1.4-6.6	3.5
NH3 -N	mg l^{-1}	0.03-0.42	0.13	0.01-1.26	0.21
NOx	mg l^{-1}	0.00-0.94	0.15	0.01-2.80	0.31
Total -P	mg l^{-1}	0.29-0.95	0.54	0.26-1.25	0.62
TSP	mg l^{-1}	0.01-0.51	0.18	0.03-1.12	0.32
SRP	mg l^{-1}	0.01-0.45	0.15	0.02-1.07	0.28
SR Silicon	mg l^{-1}	0.01-0.98	0.45	0.12-3.28	0.67
Tot. Alk.	mg l^{-1}	104-181	154	82-219	149
Chlorophyll <u>a</u>	ug l^{-1}	97-796	270	69-409	183

KEY NOx = nitrate and nitrite -N; TSP = total soluble -P; SRP = soluble reactive (ortho) -P; SR = soluble reactive; Tot. Alk. = total alkalinity; (K) = Kjeldahl.

Comparison with data for previous years (Chapter 2) showed that while the physico-chemical regime for 1989-1990 was consistent with respect to ranges and means of earlier data, the 1990-1991 study period was not comparable. During the period under review, the mean depth of water transparency increased slightly from 0.26 m to 0.32 m. While total nitrogen concentrations were lower during 1990, ammonia and nitrate-N as well as nitrite-N fractions increased, and the upper limits of the phosphorus-component ranges were higher than had been previously recorded (Table 2 and Figure 2; see also Chapter 2, Tables 3 and 4). The weight ratios of nitrate-N and SRP to chlorophyll <u>a</u> were also higher during the second year, even at the time of the cyanophyte algal maximum (Figure 2).

Although it is not immediately apparent from an examination of the ranges and mean data provided in Table 2, 1990 winter pH levels for both the influent rivers and for Zeekoevlei were much lower than for the corresponding 1989 period

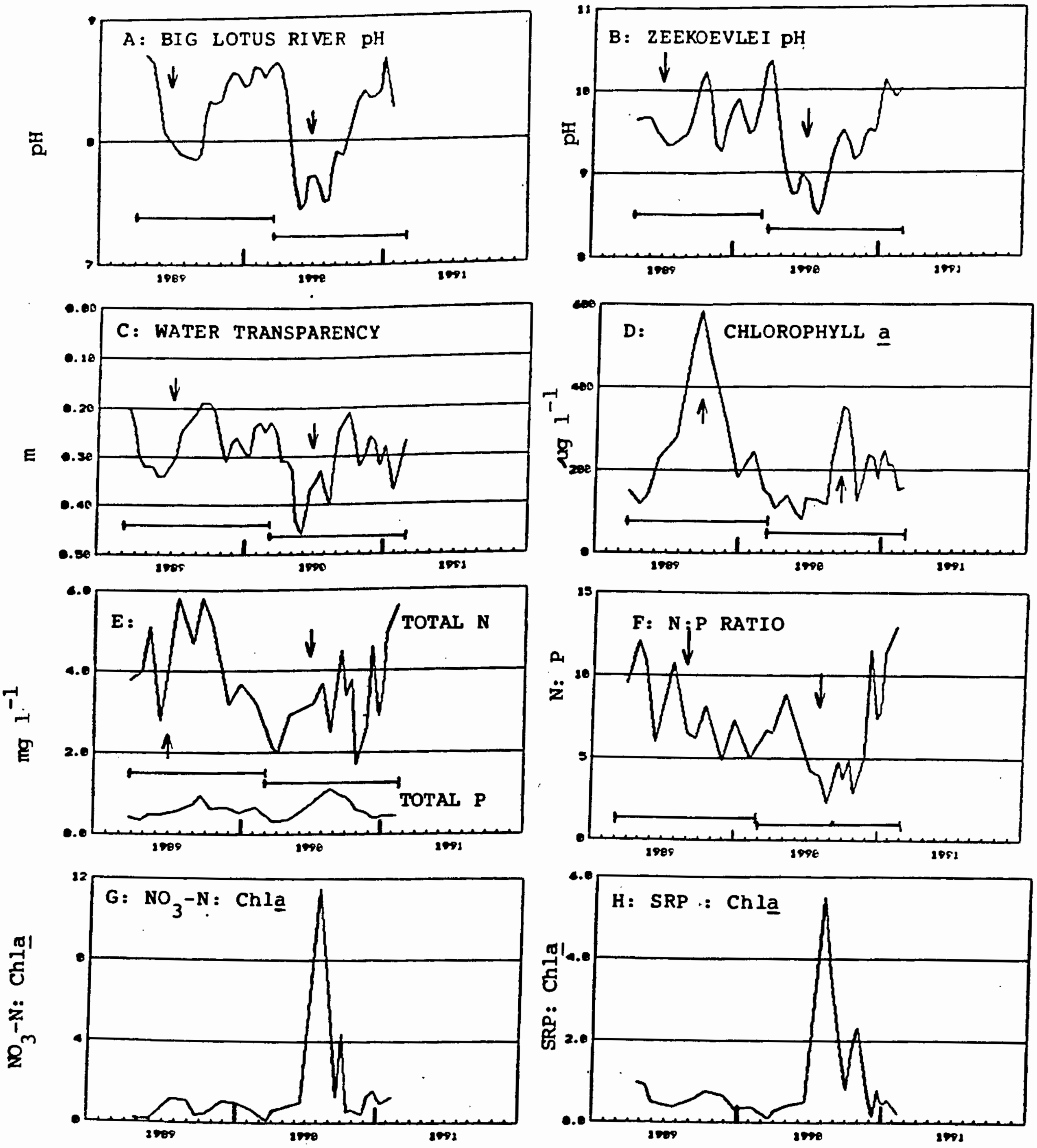

FIGURE 2 : Physico-chemical parameters, as indicated, for the two years of study 1989-1991. Horizontal bars delineate the individual years of the survey while arrows indicate corresponding chronological positions as described in the text.

(Figure 2). Concomitantly, lower total alkalinity levels were recorded in both the rivers and in the vlei during 1990. During the same season, water transparencies were much higher during 1990 than was the case during 1989 (Figure 2). In contrast to the elevated nitrogen and phosphorus concentrations mentioned earlier, mean concentrations of suspended solids and chlorophyll a decreased from 69 to 54 mg l^{-1} and from 270 to 183 $ug\ l^{-1}$, respectively, over the two years of the study. Total N:P ratios were much lower during 1990 compared to 1989, falling from approximately 6 to 4 (Figure 2). Consequently, the physico-chemical regimes of the individual years of the study period, reported here, differed markedly from each other.

The timing of the reductions in pH, chlorophyll a and suspended solids was coincident with increases in water transparency, phosphorus concentration and the winter-rainfall period of the Zeekoevlei region.

Other measured parameters for the vlei and its influent rivers (results not shown here) remained within the ranges and means described by the data for earlier years (see Chapter 2). Reactive silicon, monitored over a complete annual cycle for the first time during 1990, reached maximum concentrations during winter (Figure 3).

Zeekoevlei is a hyper-eutrophic vlei as measured against any of the well-known standards of eutrophication (eg. OECD, 1982; German Technical Standard as reviewed in Thornton, 1987; Carlson, 1969; Vollenweider and Kerekes, 1980), with year-round non-limiting concentrations of both nitrogen and phosphorus (Table 2). Overall low N:P ratios of between 2 and 14 are indicative of cyanophyte-algal dominance (eg. Walmsley and Butty, 1980; Thornton, 1987a). The low water transparencies and shallow depth of the vlei indicate that light plays a limiting role in primary production, an observation borne out by the fact that 90% of the photosynthetic activity takes place between the surface and 0.2 m (Harding, 1990).

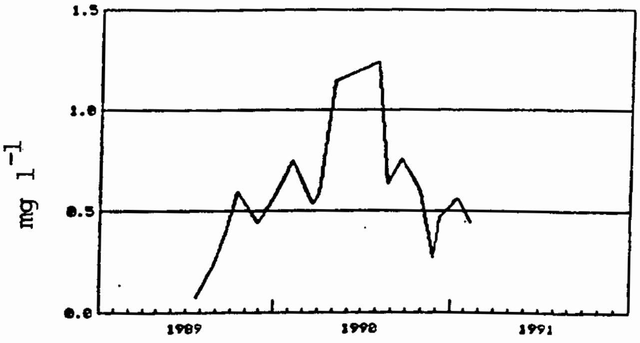

Figure 3: Pattern of reactive silicon availability in Zeekoevlei.

Phytoplankton assemblages, diversity and periodicity

The overall phytoplankton diversity in Zeekoevlei was low, with a range of 11-24 regularly recorded genera and a mean of 17. The coefficient of variation was 16%. Phytoplankton composition was dominated by three divisions:- Cyanophyta, Bacillariophyta (Division Chrysophyta) and Chlorophyta. Of these, the Cyanophyta, and in particular *Microcystis* spp., predominated in terms of total cell numbers, comprising more than 50% of the total cell count on 51 out of 53 occasions and exceeding 80% of the total population on 30 occasions (Tables 3 and 3a).

TABLE 3.
CELLS ml^{-1} OF PRINCIPAL ALGAL DIVISIONS PRESENT IN ZEEKOEVLEI, ON EACH SAMPLING OCCASION.
First year of monitoring
(percentage of total cell count in brackets)

Sampling date	Cyanophyta	Bacillariophyta	Chlorophyta	Total
1989-04-10	3600 (24)	2000 (14)	9100 (62)	14700
1989-04-23	15200 (60)	400 (2)	9600 (38)	25200
1989-05-15	37000 (80)	2000 (4)	7000 (15)	46000
1989-05-29	30000 (80)	2500 (7)	4900 (13)	37400
1989-06-12	76000 (87)	160 (<1)	11000 (13)	87160
1989-07-12	163000 (91)	11000 (6)	6000 (3)	180000
1989-07-24	79000 (74)	19000 (18)	8300 (8)	106300
1989-08-30	262000 (68)	120000 (31)	4700 (1)	386700
1989-09-12	1500000 (94)	82000 (6)	2600 (<1)	1584600
1989-09-21	1290000 (98)	20000 (2)	5700 (<1)	1315700
1989-10-03	1260000 (99)	10200 (<1)	5500 (<1)	1275700
1989-10-16	3950000 (99)	10500 (<1)	10200 (<1)	3970700
1989-10-30	1070000 (99)	1100 (<1)	10500 (<1)	1081600
1989-11-13	148000 (91)	1300 (1)	13000 (8)	162300
1989-11-27	167000 (91)	600 (<1)	15000 (8)	182600
1989-12-11	70000 (84)	650 (1)	12500 (15)	83150
1989-12-28	34000 (72)	300 (1)	13000 (27)	47300
1990-01-08	25000 (68)	600 (2)	11000 (30)	36600
1990-01-22	9000 (42)	650 (3)	12000 (55)	21650
1990-02-05	24000 (54)	550 (1)	20000 (45)	44550
1990-02-19	20000 (53)	350 (1)	17000 (46)	37350
1990-03-06	32000 (64)	1000 (2)	17000 (34)	50000
1990-03-20	41000 (69)	1100 (2)	17600 (29)	59700

Standard Deviation - Chlorophyta & Bacillariophyta 11 %
- Cyanophyta 22 %

TABLE 3a
CELLS ml^{-1} OF PRINCIPAL ALGAL DIVISIONS PRESENT IN ZEEKOEVLEI, ON EACH SAMPLING OCCASION.
Second year of monitoring
(percentage of total cell count in brackets)

Sampling date	Cyanophyta	Bacillariophyta	Chlorophyta	Total
1990-04-04	52000 (77)	150 (<1)	15000 (22)	67150
1990-04-17	35000 (68)	650 (1)	16000 (31)	51650
1990-05-02	30000 (77)	600 (2)	8300 (21)	38900
1990-05-14	37000 (79)	1100 (2)	8900 (19)	47000
1990-05-29	33000 (83)	1150 (3)	5700 (14)	39850
1990-06-11	33700 (80)	1600 (4)	7000 (16)	42300
1990-06-18	132800 (73)	42000 (23)	7800 (4)	182600
1990-07-05	65200 (80)	10200 (12)	6600 (8)	82000
1990-07-19	51000 (62)	26000 (31)	5600 (7)	82600
1990-07-31	53000 (45)	53000 (45)	13000 (10)	119000
1990-08-14	101300 (50)	97000 (48)	3400 (2)	201700
1990-08-22	81200 (88)	4200 (5)	6500 (7)	91900
1990-09-03	528000 (98)	60 (<1)	11000 (2)	539000
1990-09-07	504000 (98)	220 (<1)	7700 (2)	512000
1990-09-18	1625500 (99)	150 (<1)	9400 (1)	1635000
1990-10-01	1044000 (98)	600 (<1)	17500 (2)	1062000
1990-10-16	746000 (99)	450 (<1)	9500 (1)	756000
1990-10-29	280200 (97)	150 (<1)	7200 (3)	287600
1990-11-15	194200 (96)	300 (<1)	7900 (4)	202400
1990-11-26	209000 (94)	150 (<1)	13500 (6)	222700
1990-12-10	95600 (94)	100 (<1)	6100 (6)	102000
1990-12-20	40600 (91)	150 (<1)	4000 (9)	44750
1990-12-27	62200 (90)	80 (<1)	6700 (10)	69000
1991-01-04	36800 (77)	300 (<1)	11000 (23)	48100
1991-01-14	31500 (79)	170 (<1)	8200 (21)	39900
1991-01-28	61700 (82)	2200 (3)	11700 (15)	75600
1991-02-11	60700 (83)	1000 (1)	11500 (16)	73200
1991-02-26	45000 (80)	360 (1)	10700 (19)	56100
1991-03-14	51300 (82)	1300 (2)	10000 (16)	62600

&bStandard Deviation&n - Chlorophyta & Bacillariophyta 11 %
- Cyanophyta 22 %

In addition to the above divisions, small numbers, (<3000 ml^{-1}), of *Cryptomonas* species were recorded during the winters of both years. Species belonging to the Euglenophyta appeared on two occasions, with counts <100 ml^{-1}. Within the division Pyrrophyta, some unidentified species of dinoflagellates were observed on six occasions. The euglenophytes and dinoflagellates made a negligible contribution (<0.01%) to the total cell count.

The genus composition of each of the principal divisions present in Zeekoevlei are shown in Table 4, with the ranges and means of cell numbers ml^{-1} of the dominant genera presented in Table 5.

TABLE 4
COMPOSITION OF THE PRINCIPAL PHYTOPLANKTON DIVISIONS PRESENT IN ZEEKOEVLEI
(* denotes presence in 80% of samples)

Cyanophyta		Chlorophyta		Bacillariophyta	
Anabaena		*Actinastrum*		*Chaetoceros*	
Anabaenopsis		*Ankistrodesmus*		*Cyclotella*	
Aphanocapsa	*	*Carteria*		*Melosira*	
Chroococcus	*	*Chlamydomonas*		*Navicula*	*
Microcystis	*	*Chlorella*		*Nitzschia*	
Merismopedia	*	*Coelastrum*		*Thalassiosira*	
Pseudanabaena		*Crucigenia*			
Raphidiopsis		*Golenkinia*	*		
Spirulina	*	*Kirchnierella*			
		Micractinium	*		
		Oocystis	*		
		Pediastrum	*		
		Phacotus			
		Scenedesmus	*		
		Selenastrum			
		Tetraedron	*		

The genera of *Aphanocapsa, Merismopedia, Chroococcus* and *Spirulina* were present throughout the year. *Pseudanabaena* cells were frequently associated with the *Microcystis* colonies (see Appendix 1). *Rhaphidiopsis* spp. appeared during the summer of 1990. In terms of algal biomass, individual *Microcystis* cells with a mean diameter of 4 μm were calculated to have a mean cell volume of 34 μm^3 (see Rott, 1981 for calculation methods). Thus, *Microcystis* dominated the vlei in terms of volume as well as in terms of numbers, even when compared to the large *Scenedesmus* coenobia; the latter were estimated as having a mean cell volume of 1000 μm^3 $cell^{-1}$.

Cyanophyte periodicity showed early spring maxima during both years of the study (Figure 4), reaching a mean (all 4 stations) maximum level of 4 million cells ml^{-1}, and an individual station maximum of 7 million cells ml^{-1}, during 1989. The maximum level was much lower during 1990, with cyanophyte numbers peaking at 1.6 million cells ml^{-1}. During both years, the collapse of the *Microcystis* peak was followed by the appearance of *Anabaena* *circinalis* (Kutz) Rab. whose numbers reached 2500 filaments ml^{-1}. Lower numbers of *Anabaena solitaria* as well as *Anabaenopsis* (the latter distinguishable by its terminal heterocysts), were concomitantly observed with the spiral form. This development of *Anabaena* spp. was more sustained and pronounced after the 1990 peak of *Microcystis* cells. Numbers of *Aphanocapsa* colonies were seen to increase during January in both years, reaching bloom conditions, which included huge, globular shoreline accumulations recorded during January and February of 1990. *Raphidiopsis* spp. reached maximum numbers (4800 filaments ml^{-1}) during March 1990 while *Merismopedia* was most dense during the *Microcystis* bloom.

Cyanophyte cell numbers were significantly correlated with the concentration of nitrogen and phosphorus in the vlei, r = 0.376 and 0.336, (n = 51), respectively.

The Bacillariophyta, apart from peak growth periods during the winters of 1989 and 1990, were poorly represented, both with respect to diversity as well as to numbers. Only five genera were routinely recorded (see Table 4), and with the exception of *Chaetoceros* spp., all were present in more than 50% of the samples collected. The naviculoid and nitzschioid species were always very small, <14 m in length. The winter peaks of bacillariophyte growth (Figure 4) resulted from the rapid proliferation of a very small (<4.0 m in diameter), centric diatom which was identified as *Thalassiosira nana* (R. Archibald and R. Norris, personal communications). This species did not appear at other times of the year. Total bacillariophyte numbers were significantly negatively correlated with temperature, r = -0.426, (n =46). and positively with total nitrogen and phosphorus concentrations, r = 0.434 and 0.400, (n = 24), respectively. Apart from the contribution made by *Thalassiosira* sp., combined total counts of the other bacillariophyte genera were usually less than 1000 ml^{-1} (Table 5).

TABLE 5: RANGES AND MEDIAN CELL (TWO YEARS) NUMBERS OF DOMINANT ALGAL GENERA IN ZEEKOEVLEI - 1989-1991			
DIVISION and GENUS	RANGE cells ml^{-1}	MEDIAN cells ml^{-1}	Present (% samples)
CYANOPHYTA			
Anabaena	0-2500	140	83
Raphidiopsis	30-3600	550	40
Microcystis	3200-3950000	62000	100
CHLOROPHYTA			
Scenedesmus	2000-15500	6600	100
Pediastrum	100-3000	750	100
Tetraedron	10-2300	250	100
Golenkinia	20-220	70	80
Micractinium	50-650	340	80
BACILLARIOPHYTA			
Navicula	0-2000	170	80
Nitzschia	0-500	80	60
Melosira	0-300	90	50
Cyclotella	0-800	85	70

As stated earlier, the Chlorophyta constituted the most diverse group, with 16 genera recorded for this Division alone (Table 4). In terms of numbers, fluctuations were low, with less than a single order of magnitude separating the extremes, and a range of 4 000 to 20 000 cells ml^{-1}. *Scenedesmus* spp. were numerically dominant, with species of *Golenkinia* , *Micractinium* , *Oocystis* (chiefly *O. eremosphaera*) , *Pediastrum* and *Tetraedron* (a mixture of *T. muticum, T. minimum, T. trigonum and T. caudatum*) present in 80% of samples. With the exception of *Scenedesmus* spp., the total combined counts of the other chlorophyte taxa rarely exceeded 2000 ml^{-1}. Maximum total counts for the Chlorophyta, 20 000 ml^{-1}, were reached during the summer of 1990, with lowest numbers recorded at the onset of spring in 1989. During the second year of study, the Chlorophyta reached an early spring maximum which coincided with the peak of cyanophyte activity; a second peak occurred during the summer (Figure 4). Significant correlations were obtained between the Chlorophyta algae and temperature, r = 0.364, (n = 46).

The temporal sequence, coincident for both years of the study, can be summarized as follows: a mid-winter increase in numbers of Bacillariophyta; an early-spring maximum of Cyanophyta, principally *Microcystis* spp., followed by a much smaller increase in numbers of *Anabaena* spp. and a spring/summer maximum of Chlorophyta, chiefly *Scenedesmus* spp.

Due to the large variation in numbers of cells between the three divisions, the periodic trend described by the cyanophyte algae completely masked the characteristics and contributions of the Bacillariophyta and Chlorophyta.

The periodicity of some individual genera are presented in Figure 5. These, with the exception of *Golenkinia* spp., which showed no distinct seasonality, conformed to the overall trend for each Division.

Total algal numbers in Zeekoevlei were significantly correlated with chlorophyll a, r = 0.650, (n = 33), this correlation being enhanced by the cyanophyte contribution.

DISCUSSION

Influence of the physico-chemical regime on phytoplankton biomass development

The observed variation of the physico-chemical regimes between the individual years of this study was brought about by the reduced pH and increased volume of water entering the vlei during 1990. Apart from the subsequent overall reduction in pH during the winter of 1990, lower total nitrogen concentrations, combined with increased phosphorus availability, resulted in a sustained lowering of the N:P ratio during the same period. Whilst these differences had no effect on the timing of the phytoplankton periodicity in Zeekoevlei (see below), the intensity of cyanophyte development was markedly affected. The factors which support the perennial dominance of *Microcystis* in Zeekoevlei are discussed in Chapter 6.

It was postulated in Chapters 2 and 6 that the broad, shallow nature of Zeekoevlei precluded effective hydraulic flushing or washout of algal cells, and thereby facilitated the existence of a permanent cyanophyte population. This

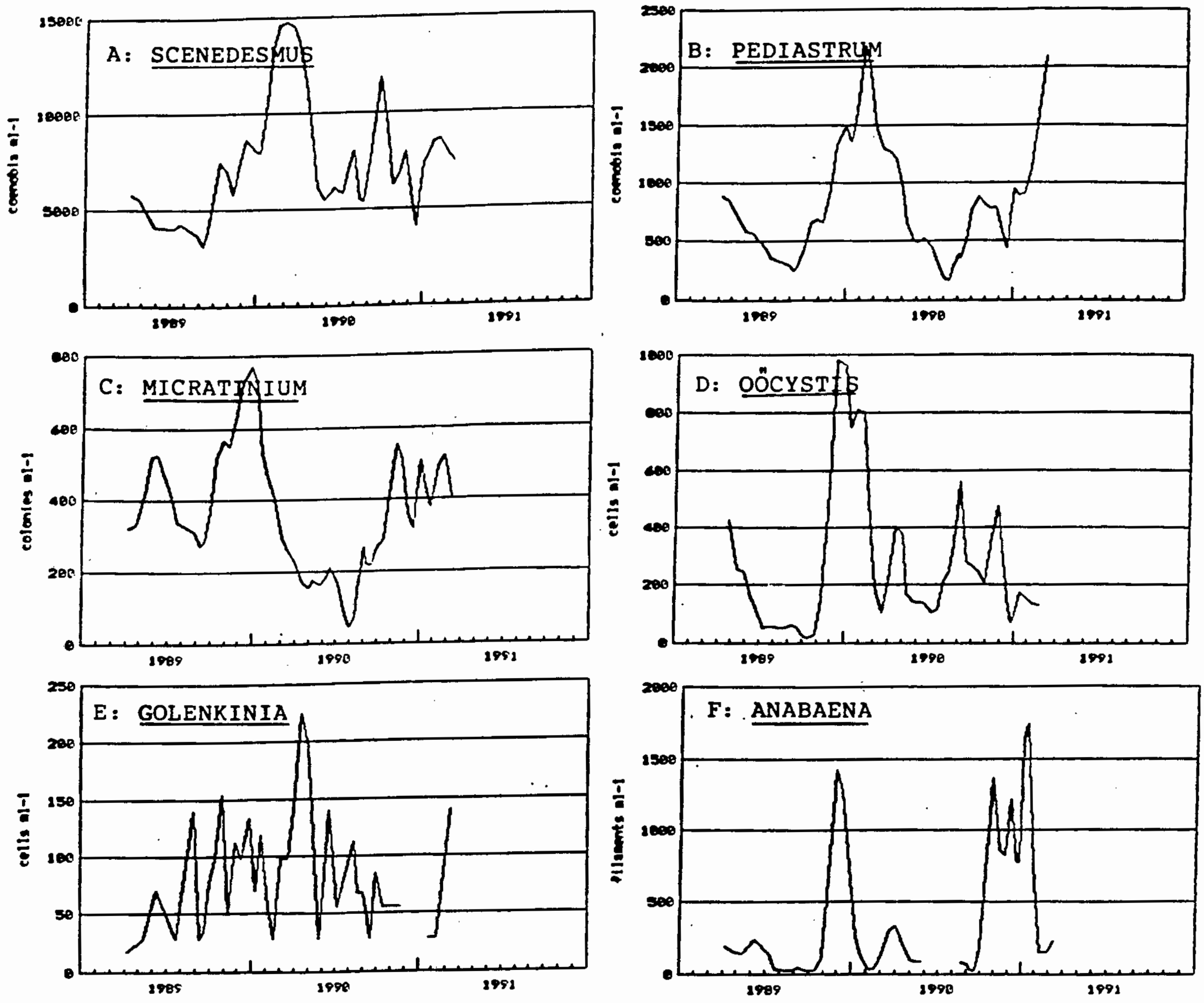

FIGURE 5 : Periodic sequences of certain phytoplankton genera present in Zeekoevlei.

assumption was made in the absence of any hydraulic flow data. Once flow figures became available, it was apparent that the volume of water which passed through Zeekoevlei during 1990 was 44% higher than for 1989; equivalent to a decrease in retention time from 0.21 y to 0.15 y. Washout did not appear to have a significant effect on the degree of development of the Cyanophyta because:- (a) daily flows only attained or exceeded the 10% of vlei volume per day necessary to bring about a washout of algal biomass (Welch, 1984) on 10 occasions (Morrison, *in litt* ., see Figure 1); (b) if washout was a prevailing forcing factor during 1990, then all algal divisions present should have been equally affected. This was not the case as the Chlorophyta exhibited a nett increase in numbers, coinciding with the peak of Cyanophyta (Figure 4); (c) rainfall and outflow had almost ceased by the end of August 1990, ie. before the peak of *Microcystis* and (d) the size of the cyanophyte inoculum in the vlei at the onset of spring 1990 was of the same order as that prevailing at the equivalent period in 1989.

The morphometry of, and the nutrient status and wind regime prevalent at Zeekoevlei may provide the basis for a "reactor" or chemostat-type situation, with the complete integration of the algal assemblage throughout the well-mixed waterbody (Figure 6). Under the proposed model, growth rates would be high enough to resist the effects of hydraulic flushing or washout of cells and a dense population would be maintained during the rainfall period. Nutrient release from the sediments would sustain the system at high biomass levels during the dry summer period, with the sheltered reed beds which fringe the vlei acting as "nurseries" for seeding the vlei with cyanophyte species. Figure 6 depicts the features of the Zeekoevlei system which lend themselves to such a chemostat-type theory.

High pH (8 to 10) levels, combined with N:P ratios of 7 to 10 are well known to be conducive to the development of cyanophyte populations in eutrophic water bodies (eg. Kalff and Knoechel, 1978; Ashton, 1979, 1981;

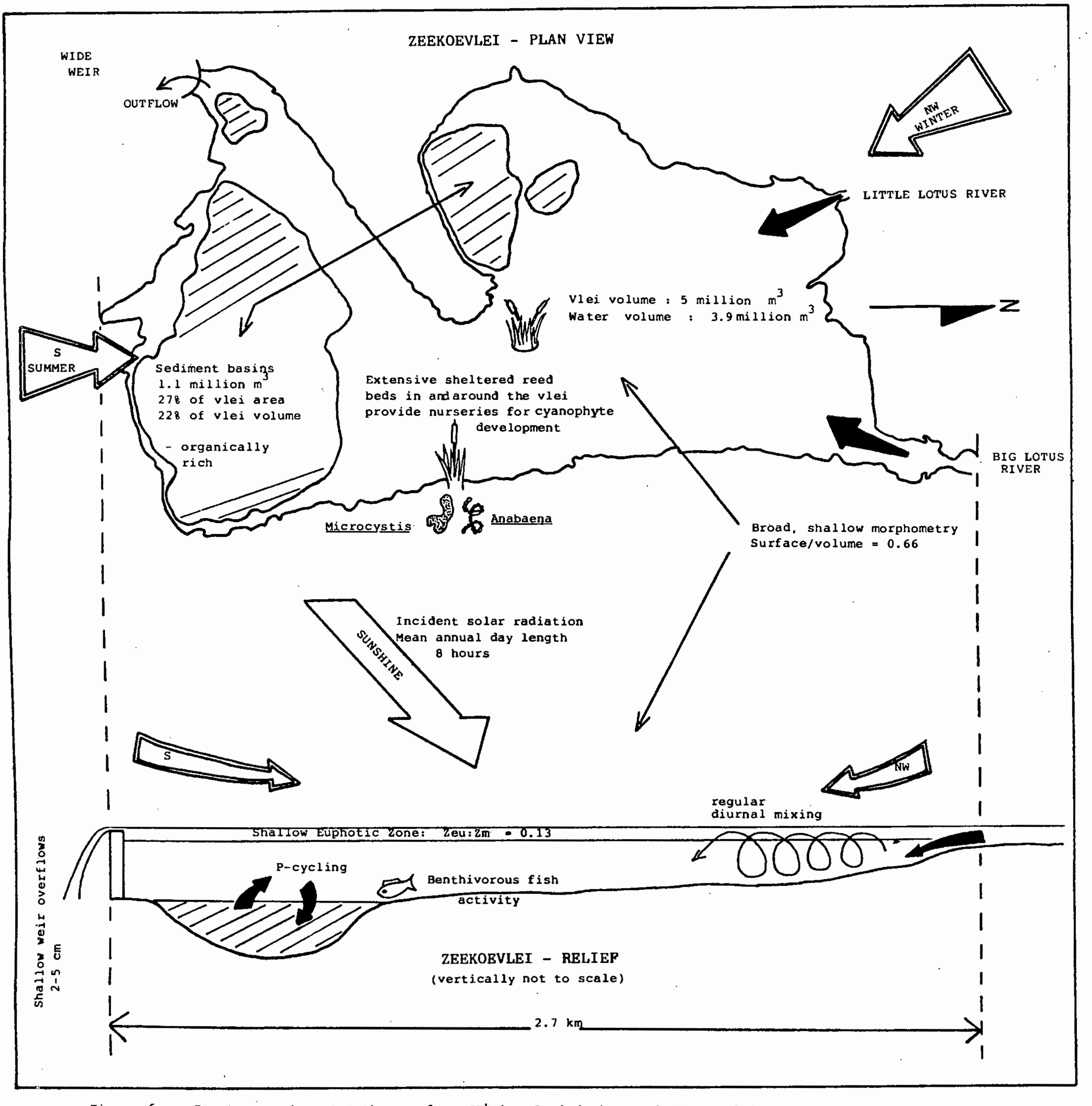

Figure 6 : Reactor or chemostat theory of cyanophyte algal dominance in Zeekoevlei: Double-edged arrows indicate prevailing wind directions, filled arrows indicate nutrient inputs. The vlei is well mixed throughout the year, with no spatial variations in the physico-chemical or algal regimes. An aliquot of nutrient-rich water entering the vlei at A will be retained for, on average, 0.2y. During this time it is constantly mixed throughout the vlei, and becomes rapidly colonised by Microcystis. Despite the shallow (0.26m) photic depth, regular mixing through this zone allows enough photosythetic activity to sustain development and reduce available light to other genera of algae. Sediment-nutrient release sustains the system during the dry summer period. (Original).

Walmsley and Butty, 1980; Thornton, 1987). Such conditions prevailed in Zeekoevlei during 1989, but were conspicuously absent during 1990. Lowering of the N:P ratio towards 1:1 is often accompanied by the development of N-fixing populations of *Anabaena* or *Oscillatoria* spp., although in Zeekoevlei nitrogen concentrations did not fall to the point where *Anabaena* would have a competitive growth advantage.

The coincident timing of the chlorophyll a, nitrate-N and SRP peaks during 1989 and 1990 can be compared to the spring of 1987 when a similar event occurred (see Chapter 2). Examination of the data for 1988 revealed the absence of marked increases in these parameters (Chapter 2). In addition, very little rain fell during 1988, this being the lowest recorded hydraulic flow for the five-year period from 1986 to 1990 (this chapter). This suggests that the available nutrient concentrations during 1988 determined the intensity of the cyanophyte algal development. This assumption, however, is complicated by the fact that, despite the nett increase in phosphorus in Zeekoevlei during 1990 compared with 1989, the peak of *Microcystis* counts was lower and less intense during 1990. Using the approach of Bailey-Watts (1987), the ratios of nitrate-N:chlorophyll a and SRP:chlorophyll a in the water of Zeekoevlei during 1990 were found to exceed the normal algal cell contents of 6:1 and 1:1, respectively, (Bailey-Watts, 1987) at the time of the *Microcystis* maximum. This indicates that there was reserve nitrogen and phosphorus available for further cell development. Thus, nutrient concentrations alone did not control the intensity of algal development.

Whilst the influence of phosphorus release from the sediments of Zeekoevlei is thought to be substantially implicated in sustaining the perennial dominance of *Microcystis* in Zeekoevlei (RI Dick, *in litt.*), the precise nature of the sediment-water interaction is inadequately understood at the present time.

In the absence of adequate supporting data, no assumptions can be made regarding the influence of the prevailing wind regime on the development of algal populations in Zeekoevlei. As is made clear in Chapter 6, it is highly probable that the influence of wind action constitutes a key variable in the phytoplankton dynamics of Zeekoevlei, especially with regard to the degree of development of a particular population. The influence of water column stability and wind-induced mixing has been demonstrated in other waterbodies as being crucial to the development of dense populations of Cyanophyta (eg. Viner, 1985; Trimbee and Harris, 1984; Scott, 1969; Robarts and Zohary, 1989; Zohary and Breen, 1989). Lowest wind speeds and the highest incidence of periods of calm weather occurred during the winter, whilst the opposite was the case for the summer season (Figure 1). Conversely, cyanophyte development would be retarded and that of Chlorophyta favoured during the summer (see Chapter 1) when, although water temperatures might be adequate for genera of both Divisions to grow, regular and sustained mixing of the water column occurs due to the prevailing southerly winds and precludes the formation of large cyanophyte populations (see Burgis *et al.*, 1973). The degree of spring development of *Microcystis* in Zeekoevlei will thus in part be dependent upon the wind regime at that time. It is felt that the influence of diurnal mixing patterns, with calms from midnight to mid-morning, followed by increasing wind speed, will be most significant in favouring the development of buoyant cyanophyte populations in Zeekoevlei (see Ganf and Viner, 1973 and Ganf and Horne, 1975).

Factors dictating the phytoplankton periodicity of Zeekoevlei

The phytoplankton assemblage observed in Zeekoevlei from April 1989 to March 1991 was typically representative of a eutrophic waterbody (eg. Hutchinson, 1967), and was very similar to that recorded in the *Microcystis*-dominated, eutrophic systems of Lake George (Burgis *et al.*, 1973) and Hartbeespoort Dam (NIWR, 1985). The low overall diversity of genera further highlighted the elevated nutrient status of this shallow vlei.

During the winter, nutrient-rich catchment run-off entered the vlei such that by the end of the rainfall period concentrations of nitrogen and phosphorus had attained their annual maxima. During the same period, reactive silicon concentrations increased, and additionally, the prevailing northerly winds provided the necessary turbulence to maintain benthic-littoral bacillariophyte species circulating in the water column. This combination of conditions promoted the observed development of *Thalassiosira* . Silicon concentrations were quite low, with 0.5 mg l^{-1} generally regarded as limiting (eg. Pettersson, 1990), and thus silicon availability and depletion would probably have determined the timing and duration of the bacillariophyte maximum. *Thalassiosira* may have a competitive advantage over the other bacillariophyte genera present with respect to nutrient uptake by virtue of it's small size (eg. Wehr, 1989; Reynolds, 1983). Winter water temperatures in Zeekoevlei were more than adequate to support bacillariophyte growth. It is this Division of algae which is most commonly responsible for post-thaw spring blooms in north-temperate lakes (eg. Fogg, 1975) because of their ability to thrive at relatively low temperatures.

At the onset of spring, a large inoculum of *Microcystis* cells was present in the nutrient-rich waters of the vlei, as a result of the high level of perennial dominance of Zeekoevlei by this organism. Whilst *Microcystis* growth becomes inhibited below 12 ^{o}C to 15 ^{o}C (see Robarts and Zohary, 1989), Zeekoevlei water temperatures only fall briefly below this level (see Chapter 2). *Microcystis* spp. are characteristically slow growing, *K*-selected algae (see Reynolds, 1983), and the presence of an already large number of cells at the outset of spring would enable them to proliferate more competitively. Cell counts of *Microcystis* increased concomitantly with increasing hours of sunlight and water temperatures, whilst low overall windspeeds would have supported dense population development. A similar combination of factors has been recorded for Hartbeespoort Dam (NIWR, 1985). Extended periods of calm conditions and/or diurnal mixing (see Ganf and Horne, 1975) will support the formation of surface blooms. After the *Microcystis* peak, N:P ratios fell and the limited, sub-dominant development of nitrogen-fixing cyanophyte algal species was favoured.

As summer temperatures and southerly windspeeds continued to increase, conditions became suitable for growth of chlorophyte species. The Chlorophyta are generally slow-growing and conservative, well-adapted to growing under conditions of low nutrient supply. They are, however, subject to loss through sedimentation, and, like the Bacillariophyta, require mixing of the water column to remain competitively in suspension. At the end of the summer, decreasing temperatures caused a decline in the numbers of Chlorophyta. Cyanophyte blooms are common elsewhere during the summer (see Chapter 1), and the facility of luxury-uptake (see Lewin, 1964; Reynolds, 1983) allows cyanophyte algae to accumulate nutrients such that they are then able to form blooms under, paradoxically, low nutrient conditions. Summer nutrient concentrations in Zeekoevlei were sufficient to support dense growth of species such as *Microcystis*, but as was indicated above, the almost-continuous wind conditions prevented the development of large populations in the open water areas. Thick scums and aggregations of *Microcystis* and *Anabaena* spp. do, however, occur during the summer in the dense, sheltered reed beds which fringe Zeekoevlei (see Chapter 2).

It is important, however, to bear in mind that the growth and periodicity of chlorophyte algae, as well as that of the bacillariophytes in Zeekoevlei was completely masked by the numbers of Cyanophyta present. As such, there was no clear seasonal progression from one division to another, but the bacillariophyte and chlorophyte periodicities were evident as muted, sub-dominant progressions beneath the "canopy" of *Microcystis* (see Figure 7). Neither the bacillariophytes nor the Chlorophyta dominated the system at any time during the two-year period. While on the one hand, the dense *Microcystis* population was capable of selectively adjusting its depth and light requirements, by the same process it shades out other species and reduces their growth potential. Trophic conditions in Zeekoevlei are, and have been for some time, conducive to the year-round dominance of the system by Cyanophyta (see Chapters 2 and 6).

A typical phytoplankton-periodicity cycle in Zeekoevlei is presented in Figure 7.

CONCLUSIONS

1. In terms of phytoplankton composition, Zeekoevlei is characteristic of an anthropogenically-impacted urban lake having elevated, non-limiting nutrient concentrations. The vlei is hyper-eutrophic and receives the bulk of its nutrient input during the winter rainfall period from April to September.

2. The system is dominated year-round by a large population of *Microcystis* cells. This large inoculum enables the slow-growing *Microcystis* to form maxima and occasional bloom conditions during early spring, a period when ambient concentrations of nitrogen and phosphorus are at their maximum. At other times of the year the dense *Microcystis* population is maintained by the high nutrient levels and regular mixing of the cells throughout the euphotic zone.

3. In addition to (2), the formation of dense populations and blooms of *Microcystis* are enhanced by the alga's inherent buoyancy control mechanism, together with low overall wind speeds and degree of water column mixing, and increasing daylength and water temperatures.

4. Winter maxima of bacillariophytes are driven by availability of silicon and wind-induced mixing of benthic-littoral species into the water column.

5. Chlorophyte and bacillariophyte algae are effectively precluded from attaining any significant degree of dominance as a result of the competitive advantage *Microcystis* enjoys by virtue of its population size and its ability to monopolise the euphotic zone.

6. As a consequence of the combination of effects in (2), (3) and (4), the

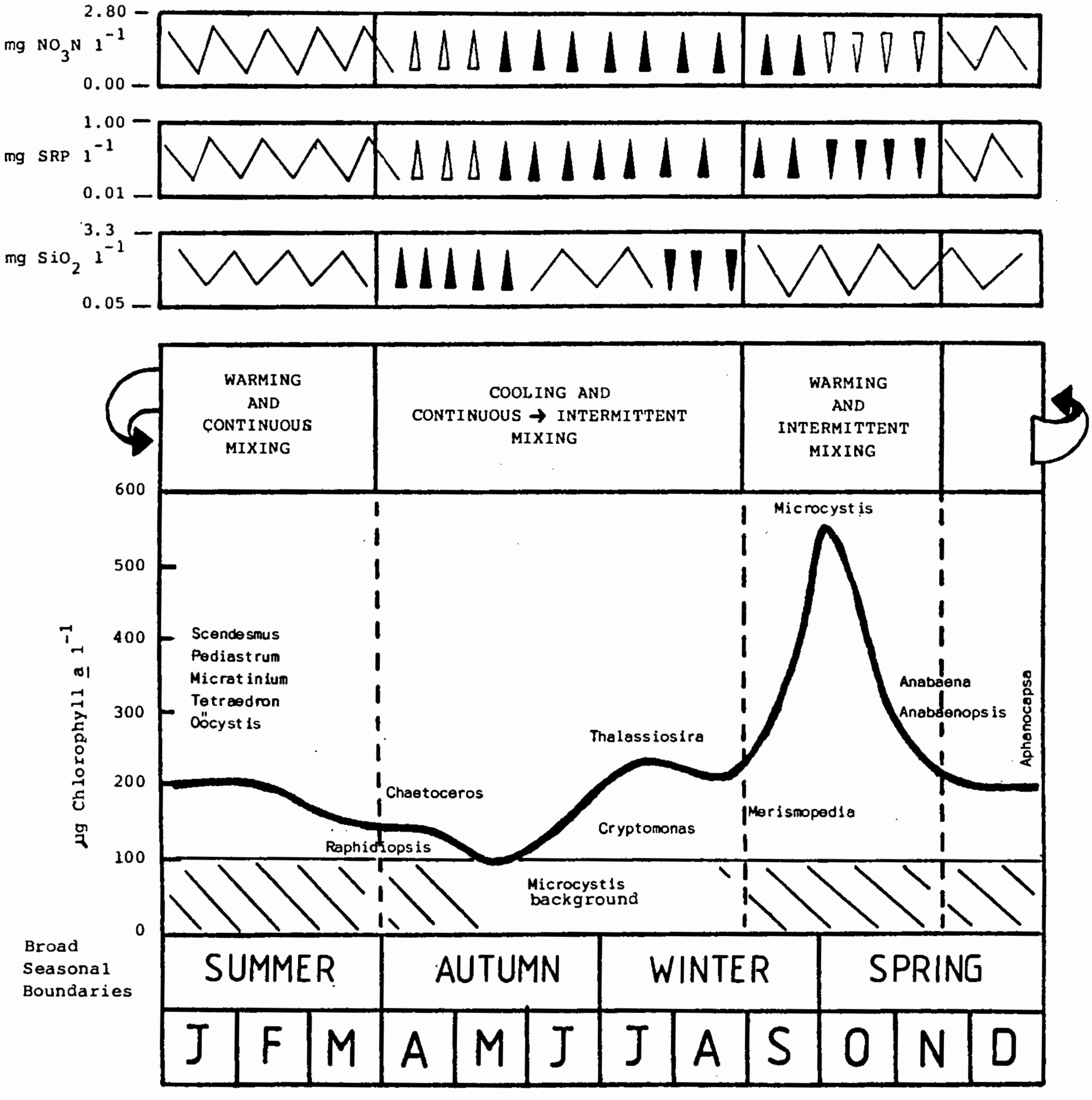

Figure 7 : Schematic representation of a typical phytoplankton periodicity cycle in Zeekoevlei, related to the principal states of the water column and nutrient concentrations. Minimal shifts in nutrient concentrations are indicated by zig-zag lines; minor and major changes by open and filled arrows, respectively. (Layout after Bailey-Watts, 1987)

seasonal phytoplankton periodicity cycle in Zeekoevlei differs from that in other regions of the world, including the summer rainfall region of South Africa. This variation is manifest in the spring maximum of cyanophyte algae, as opposed to summer/late-summer in other regions; and a winter maximum of Bacillariophyta, compared with spring elsewhere.

7. The interactions of wind, especially on a diurnal basis, and the release of phosphorus from the sediments on the phytoplankton dynamics in Zeekoevlei are inadequately understood at present and merit further study. In addition, an understanding of the rate of loss of algal biomass to the sediments would compliment this research, as would an improved knowledge of the interactions of zooplankton and fish with the phytoplankton. Modelling of the nutrient loading of the system is currently underway and the details of this should be available in the near future.

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CHAPTER 5

PHYTOPLANKTON PERIODICITY IN PRINCESS VLEI

1989-1991

INTRODUCTION

Very little documented information exists on the phytoplankton of Princess Vlei; that which is available is limited to *ad hoc* observations or to short-duration investigations conducted during the first half of the 20th-century.

Hutchinson *et al.* (1932) collected samples from Princess Vlei during January, February and June of 1928. The water of the vlei was described as turbid and strongly alkaline, with the pH exceeding 9 during the summer, falling to neutral during the winter. The most common phytoplankton collected by these workers were *Scenedesmus protuberans*, *Golenkinia radiata* and *Pediastrum boryanum*. *Microcystis flos-aquae* was also reported present on all the sample dates.

Harrison (1962) carried out studies at Princess Vlei from April 1946 to January 1948. The pH of the vlei water was reported to lie between 8.0 and 9.6, with maxima during the summer. The water was described as turbid and green all year round, with a conspicuous abundance of *Micractinium* and *Microcystis*. *Micractinium* was abundant during the summer months, extending into the winter of 1946. *Micractinium* and *Microcystis* were common during the spring, with *Microcystis* becoming less so during the summer. *Scenedesmus* was also reported as "very common", while the presence of *Pediastrum* and *Anabaena* spp. was also noted. Some years later, Furness (1979) reported a dense winter bloom of *Microcystis aeruginosa*.

Since these early observations, anecdotal information gleaned from Cape Town residents and City Council officials has indicated that, historically, Princess

Vlei has been "green and turbid" for many years. Regular monitoring of the water quality by the Cape Town City Council (CCC) began during 1982, and chlorophyll a concentrations during the summer of 1983 exceeded 600 g l^{-1} (see Chapter 3). Dredging operations and ferric sulphate treatment carried out during 1983 resulted in improved hydraulic flows and, possibly, a reduction in the autochotonous supply of nutrients from the substantial accumulations of organically-laden sediments, with a concomitant reduction in chlorophyll a concentrations (see Chapter 3).

This chapter presents the findings of the first long-term, comprehensive phytoplankton study conducted at Princess Vlei.

METHODOLOGY

Phytoplankton sampling, preservation, identification and counting methods employed at Princess Vlei are essentially the same as those already described for Zeekoevlei (Chapter 4). The methods employed for the meteorological and physico-chemical monitoring are described in Chapter 3.

RESULTS

The results presented here pertain to two annual cycles of phytoplankton growth in Princess Vlei, between April 1989 and March 1990, and April 1990 and March 1991. The limnology of Princess Vlei between 1983 and 1990 is detailed in Chapter 3 of this thesis.

Meteorological and physico-chemical regimes

Because of the close geographical proximity of Princess Vlei to Zeekoevlei, it has been assumed that the wind and solar radiation patterns (already detailed in Chapters 2 and 3) are similar. However, rainfall (and hence hydraulic flushing) was felt to be important and therefore specific details of rainfall over the study period are included here.

Rainfall records, obtained from a guage situated on the northern shore of Princess Vlei, showed that of the major portion of the total annual rainfall, between 67 and 77% fell between April and August of both 1989 and 1990. During 1989, 636 mm were measured, with peak falls of 116 and 172 mm $month^{-1}$ recorded during April and August. In 1990, 715 mm of rain fell, with highest falls of 154, 183 and 121 mm measured during April, July and August, respectively (Figure 1). Negligible falls (<10 mm $month^{-1}$) were measured between December and February of each study period.

No data pertaining to hydraulic flows were available, due to the absence of guaging weirs at the inlet or outlet to Princess Vlei during this study (see Chapter 3), and no simulations were made.

The physico-chemical regimes of Princess Vlei and the influent Southfield Canal during the first two annual periods of this phytoplankton periodicity study are summarized in Tables 1 and 2. The data for each period did not differ from previous annual data ranges and means for Princess Vlei (see Chapter 3).

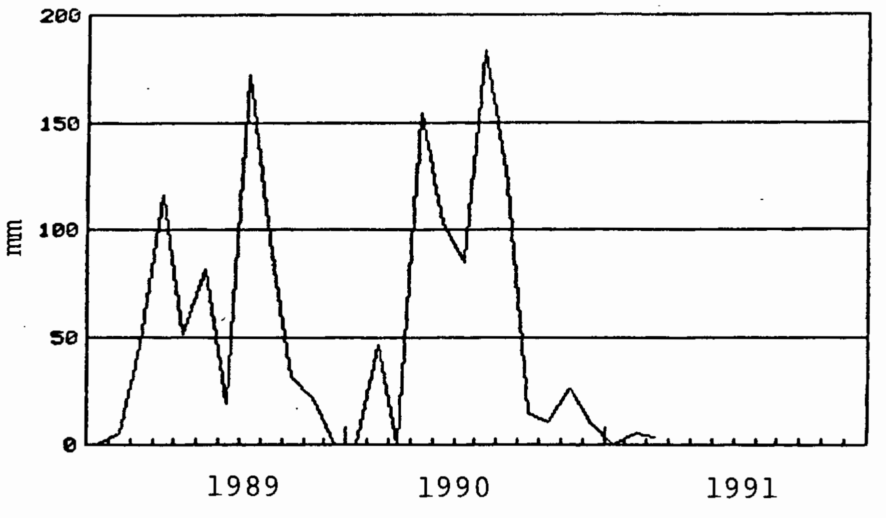

FIGURE 1: Rainfall pattern at Princess Vlei depicted as monthly totals (mm)

TABLE 1: PRINCESS VLEI-SUMMARY OF PHYSICO-CHEMICAL MONITORING DURING THE FIRST TWO YEARS OF PHYTOPLANKTON MONITORING

PARAMETER		1989 - 1990		1990 - 1991	
		RANGE	MEAN	RANGE	MEAN
Temperature	°C	12.6-24.4	18.4	12.2-22.8	18.3
Dissolved O2	mg l^{-1}	5.2-15.9	9.4	6.5-12.2	8.3
Oxygen sat.	%	59-189	100	61-140	89
Secchi transp.	m	0.17-1.30	0.49	0.22-1.44	0.64
pH		7.5-9.6	8.9	7.5-9.7	8.5
Conductivity	mS m^{-1}	36-75	56	39-74	58
Susp. solids	mg l^{-1}	4-80	36	4-100	41
Total (K)-N	mg l^{-1}	1.2-3.2	2.1	1.5-3.6	2.2
NH3 -N	mg l^{-1}	0.06-0.61	0.27	0.01-0.58	0.15
NOx	mg l^{-1}	0.01-0.65	0.21	0.05-1.61	0.30
Total -P	mg l^{-1}	0.09-0.25	0.19	0.09-0.24	0.16
TSP	mg l^{-1}	0.02-0.12	0.05	0.01-0.11	0.05
SRP	mg l^{-1}	0.00-0.10	0.03	0.00-0.11	0.04
SR Silicon	mg l^{-1}	0.14-0.80*	0.78*	0.13-0.98	0.50
Tot. Alk.	mg l^{-1}	72-143	104	72-130	103
Chlorophyll a	ug l^{-1}	10-101	56	5-282	127

KEY NOx = nitrate and nitrite -N; TSP = total soluble -P;
SRP = soluble reactive (ortho) -P; SR = soluble reactive;
Tot. Alk. = total alkalinity; (K) = Kjeldahl.
* = data for 8 months only

TABLE 2: SOUTHFIELD CANAL: SUMMARY OF PHYSICO-CHEMICAL MONITORING DURING THE FIRST TWO YEARS OF PHYTOPLANKTON MONITORING

PARAMETER		1989 - 1990		1990 - 1991	
		RANGE	MEAN	RANGE	MEAN
Temperature	°C	12.7-28.4	20.7	13.9-25.6	19.8
Dissolved O2	mg l^{-1}	6.6-12.0	8.9	6.3-12.4	8.4
Oxygen sat.	%	70-138	99	61-148	93
pH		7.3-8.9	8.1	6.9-9.5	7.8
Conductivity	mS m^{-1}	19-87	61	34-89	62
Susp. solids	mg l^{-1}	3-74	17	3-54	16
Total (K)-N	mg l^{-1}	0.7-2.70	1.5	1.1-4.3	2.23
NH3 -N	mg l^{-1}	0.00-0.82	0.24	0.02-0.48	0.22
NOx	mg l^{-1}	0.59-6.31	3.61	2.38-5.06	3.82
Total -P	mg l^{-1}	0.07-0.31	0.15	0.09-0.45	0.20
TSP	mg l^{-1}	0.04-0.23	0.09	0.04-0.23	0.10
SRP	mg l^{-1}	0.03-0.18	0.07	0.03-0.21	0.07
SR Silicon	mg l^{-1}	1.10-9.70*	4.32*	1.50-4.90	3.00

KEY NOx = nitrate and nitrite -N; TSP = total soluble -P;
SRP = soluble reactive (ortho) -P; SR = soluble reactive;
Tot. Alk. = total alkalinity; (K) = Kjeldahl.
* = data for 8 months only

Statistical comparison using linear regression analyses of the measured parameters during each of the two annual periods showed no significant variations, apart from increases in the vlei of mean Secchi transparency, from 0.49 to 0.64 m and in the mean concentration and range of chlorophyll a, doubling from 56 to 127 $_{u}$g l^{-1} (see Table 1). Water temperatures reached maxima and minima during February and July, respectively, whilst pH, conductivity, water transparency and chlorophyll a reached minima that coincided with the period of peak rainfall (Figure 2). The winter reduction in pH was more marked and sustained during 1990 than was the case during 1989, indicating a greater inflow of water during 1990. Reactive silicon concentrations increased concomitantly with the developing winter rainfall period (Figure 2). Total nitrogen and phosphorus concentrations in both the canal and the vlei were highest during the winter, with a second peak during the summer of 1990 (Figure 2).

As was pointed out in Chapter 3, Princess Vlei is a eutrophic waterbody. At times the vlei tends towards phosphorus limitation as evidenced by the low mean soluble reactive phosphorus concentrations of <0.05 mg l^{-1} recorded during the spring, autumn and summers of 1989, 1990 and 1991. In the light of this it may well be more correct to describe Princess Vlei as intermittently eutrophic.

Total N:P ratios showed no distinct seasonality, ranging from 7:1 to 18:1, with a mean of 13, whilst inorganic N:P ratios increased significantly from a mean of 15 to >150:1 during the spring and summer periods of 1989 and 1991, respectively (Figure 3).

Total N:P ratios were at the upper limit of the range (7-14) which is generally accepted as indicating conditions that will allow cyanophyte dominance (Walmsley and Butty, 1980; Thornton, 1987).

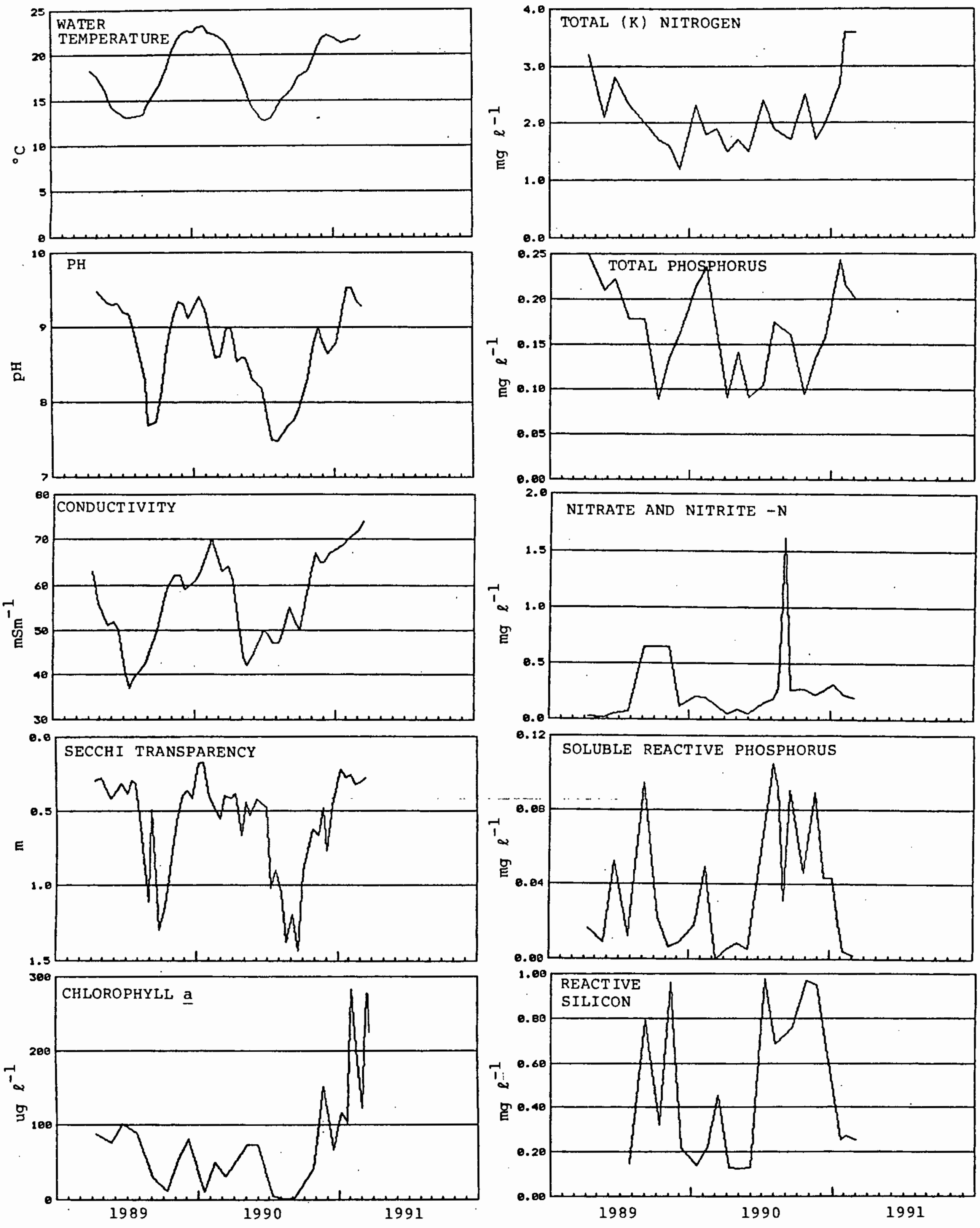

FIGURE 2: TRENDS OF CERTAIN PHYSICO-CHEMICAL PARAMETERS MEASURED AT PRINCESS VLEI BETWEEN APRIL 1989 AND MARCH 1991

Phytoplankton diversity, assemblages and periodicity

The diversity of phytoplankton genera present in Princess Vlei was low, with a mean of 15 and a range of 5-24 regularly recorded (48 sampling occasions). Other genera appeared on rare, infrequent occasions and in insignificant numbers. A full list of all recorded genera is presented in Appendix 1. The total number of genera present was lowest between August and October of each year, corresponding to a period of increased water transparency. This was most evident during 1990, when the number of genera recorded reached a minimum of 5, compared with 13 at the same time during 1989 (Figure 4).

The phytoplankton composition was dominated by the divisions Chlorophyta, Cyanophyta and Bacillariophyta (Division Chrysophyta). The ranges of the individual cell counts for the three dominant divisions were very similar:- Chlorophyta 60-20 000 cells ml^{-1}; Cyanophyta 0-27 000 cells ml^{-1}; and Bacillariophyta 0-25 000 cells ml^{-1}. Median counts for each division over the two-year study were respectively 3200, 290 and 540 cells ml^{-1}, indicating that, in terms of numbers, the Chlorophyta was the dominant division, comprising in fact in excess of 50% of the total cell count on 71% of 48 sampling occasions (see Table 3).

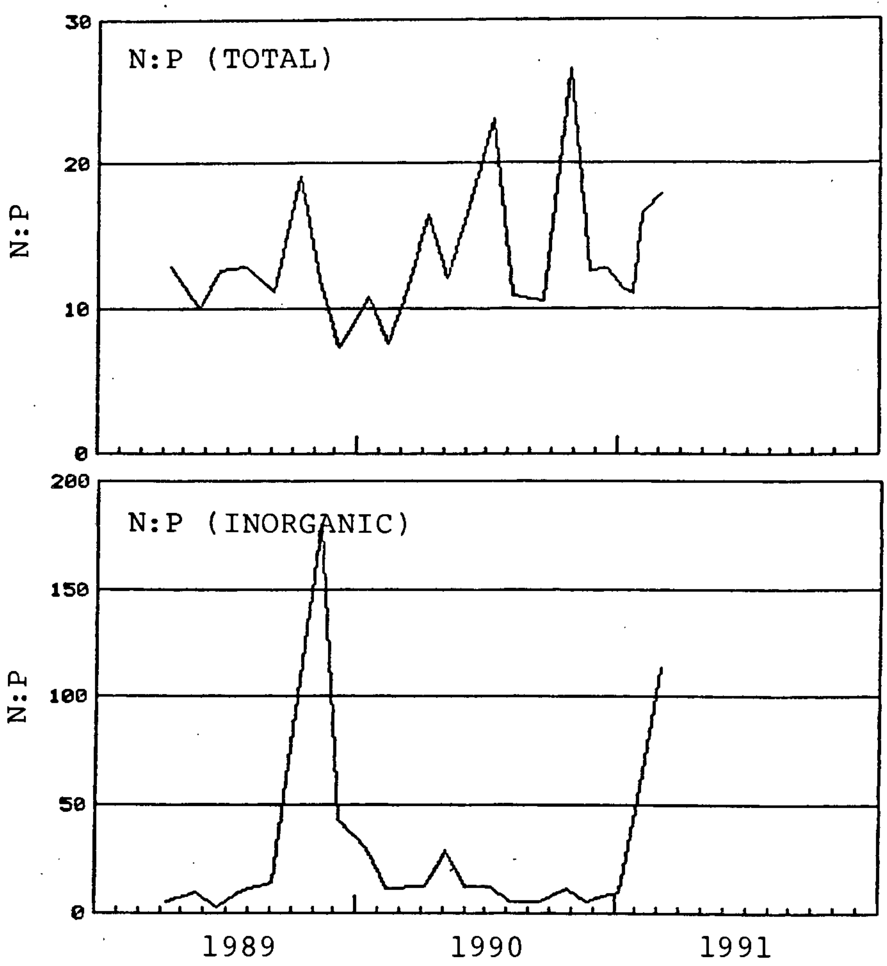

FIGURE 3: Nitrogen to phosphorus ratios of total and inorganic nitrogen and phosphorus components.

TABLE 3: CELL COUNTS (cells ml^{-1}) OF DOMINANT PHYTOPLANKTON DIVISIONS PRESENT IN PRINCESS VLEI BETWEEN APRIL 1989 AND MARCH 1991 (percentage of total count in brackets)

Sample date	Cyanophyta	Bacillariophyta	Chlorophyta	TOTAL
1989-04-12	4000 (19)	1500 (7)	15300 (74)	20800
1989-04-27	2700 (51)	340 (6)	2300 (43)	5340
1989-05-23	2300 (15)	4900 (31)	8400 (54)	15600
1989-06-08	3000 (15)	9800 (50)	6700 (35)	19500
1989-06-21	5300 (20)	7000 (25)	15300 (55)	27600
1989-07-05	700 (6)	3000 (25)	8200 (69)	11900
1989-07-18	1700 (10)	4400 (27)	10100 (63)	16200
1989-07-26	0 (0)	3700 (30)	8800 (70)	12500
1989-08-30	0 (0)	20 (2)	950 (98)	970
1989--9-04	0 (0)	20 (3)	570 (97)	590
1989-09-25	0 (0)	20 (3)	700 (97)	720
1989-10-11	0 (0)	70 (14)	440 (86)	510
1989-10-25	0 (0)	890 (93)	70 (7)	960
1989-11-08	5400 (73)	260 (3)	1800 (24)	7460
1989-11-22	0 (0)	130 (1)	11750 (99)	11880
1989-12-06	0 (0)	300 (2)	19300 (98)	19600
1989-12-18	60 (2)	320 (12)	2400 (86)	2780
1990-01-04	880 (14)	2000 (31)	3560 (55)	6440
1990-01-15	1100 (20)	1830 (33)	2650 (47)	5580
1990-02-01	460 (8)	1930 (36)	3000 (56)	5390
1990-02-12	110 (2)	1110 (23)	3700 (75)	4920
1990-03-01	640 (6)	360 (4)	9200 (90)	10200
1990-03-12	60 (1)	380 (5)	7000 (94)	7440
1990-03-27	140 (1)	800 (10)	7300 (89)	8240
1990-04-09	660 (5)	1320 (10)	11100 (85)	13080
1990-04-24	60 (2)	140 (5)	2600 (93)	2800
1990-05-07	140 (3)	1070 (18)	4600 (79)	5810
1990-05-17	620 (9)	280 (4)	6100 (87)	7000
1990-06-04	7500 (19)	24400 (65)	5900 (16)	37800
1990-06-27	7600 (67)	360 (3)	3400 (30)	11360
1990-07-10	0 (0)	15 (20)	60 (80)	75
1990-07-24	10 (3)	40 (13)	270 (85)	320
1990-08-06	0 (0)	5 (1)	450 (99)	455
1990-08-20	0 (0)	10 (6)	150 (94)	160
1990-09-04	160 (27)	60 (10)	370 (63)	590
1990-09-19	420 (29)	30 (2)	1000 (69)	1450
1990-10--3	30 (3)	0 (0)	1040 (97)	1070
1990-10-25	0 (0)	700 (47)	790 (53)	1490
1990-11-12	0 (0)	360 (8)	4200 (92)	4560
1990-11-22	0 (0)	280 (5)	5350 (95)	5630
1990-12-03	0 (0)	1350 (43)	1800 (57)	3150
1990-12-17	1800 (49)	800 (22)	1060 (29)	3660
1991-01-07	3800 (43)	760 (9)	4230 (48)	8790
1991-01-24	1090 (29)	730 (19)	1940 (52)	3760
1991-02-04	6220 (67)	730 (8)	2300 (25)	9250
1991-02-19	5320 (51)	3250 (31)	1800 (18)	10370
1991-03-05	26880 (87)	760 (2)	3360 (11)	31000
1991-03-18	28500 (79)	170 (1)	7200 (20)	35870
1991-04-02	3300 (8)	32800 (80)	5000 (12)	41100

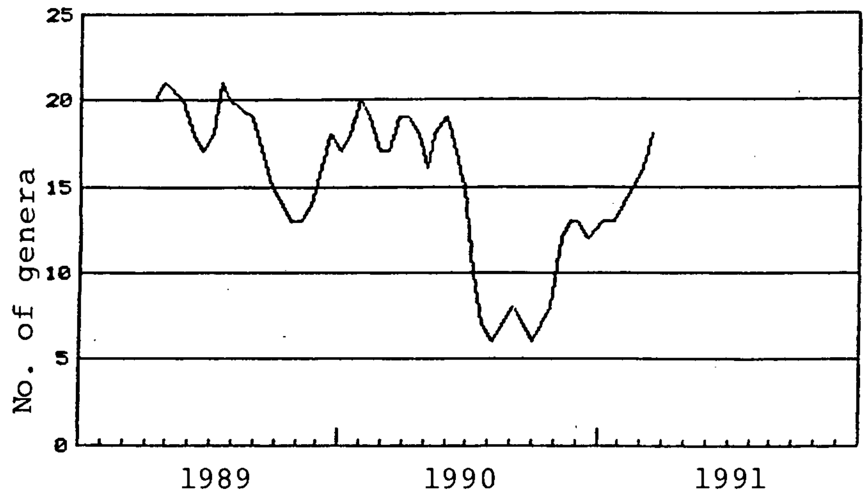

FIGURE 4: Phytoplankton diversity in Princess Vlei expressed as the number of Genera recorded per sampling occasion.

Cryptomonas spp. counts ranged from 0-3300 cells ml^{-1}. Species of Euglenophyta, desmids (*Staurastrum*, Division Chlorophyta) and dinoflagellates (Pyrrophyta) were observed on irregular and rare occasions (<10%).

The generic compositions of each of the principal divisions recorded from Princess Vlei are presented in Table 4.

TABLE 4
COMPOSITION OF THE PRINCIPAL PHYTOPLANKTON DIVISIONS PRESENT IN PRINCESS VLEI (* indicates rare)

Chlorophyta		Cyanophyta		Bacillariophyta	
Actinastrum	*	*Anabaena*		*Cocconeis*	*
Ankistrodesmus		*Anabaenopsis*	*	*Cyclotella*	
Carteria	*	*Aphanocapsa*		*Fragilaria*	*
Chlamydomonas	*	*Chroococcus*	*	*Melosira*	
Chlorella	*	*Merismopedia*		*Navicula*	
Chodatella		*Microcystis*		*Nitzschia*	*
Coelastrum	*	*Pseudanabaena*		*Thalassiosira*	
Golenkinia		*Raphidiopsis*	*		
Gloeocystis		*Spirulina*			
Micractinium					
Oocystis					
Pediastrum					
Phacotus	*				
Scenedesmus					
Schroederia					
Selenastrum	*				
Sphaerocystis					
Tetraedron					

Phytoplankton periodicity, expressed as total cells ml^{-1} per sampling occasion, as well as the periodicities of the dominant component divisions, are depicted in Figure 5. The overall periodicity showed:-

(a) winter (June-July) maxima;

(b) a spring maximum during 1989 and

(c) a summer maximum during 1991 with a smaller summer peak evident during the summer of 1990 (Figure 5A).

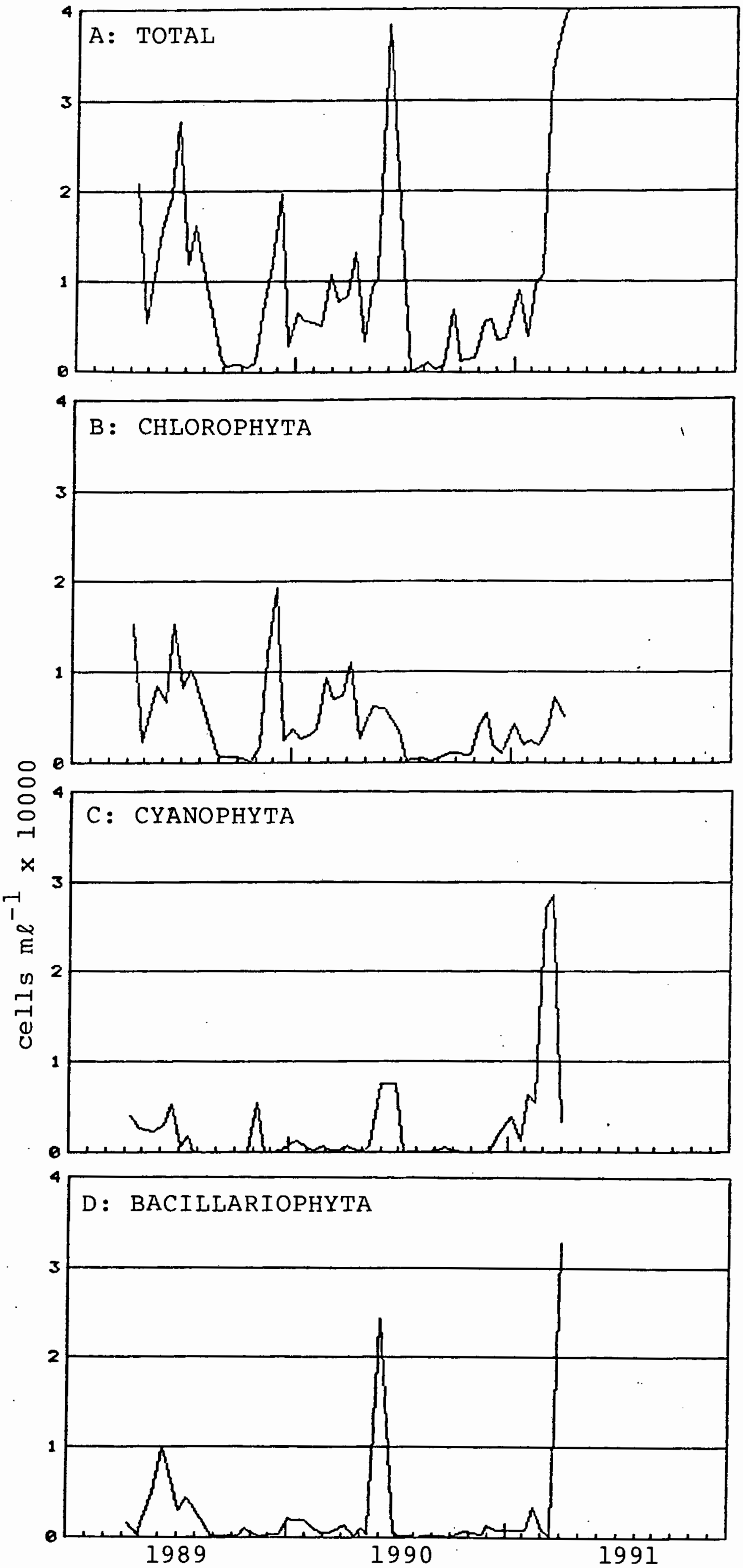

FIGURE 5: Phytoplankton periodicity of Princess Vlei showing (A) as total cell count and (B)-(D) Cell counts of the individual dominant divisions.

Examination of the periodicities of the three dominant divisons (Figure 5, B-D) shows the following:-

(a) the winter peaks resulted from increases in all three divisions, with the Bacillariophyta contributing 66% of the total count during 1990;

(b) The spring maximum during 1989 was a consequence of chlorophyte proliferation, as was the 1990 summer maximum, and

(c) the 1991 summer peak was brought about by prolific development of *Anabaena* spp., with a concomitant increase in numbers of *Microcystis* cells.

Seasonal variation in the phytoplankton assemblage

The phytoplankton study commenced at the end of the summer in 1989, when water temperatures, conductivity and nutrient concentrations were decreasing (Figure 2). By mid-winter (June-July) of 1989, water temperatures were at their annual minimum (<15 ^{o}C), and concentrations of inorganic phosphorus and nitrogen began to increase as nutrient-rich runoff entered the system.

At the start of the study, the phytoplankton assemblage primarily comprised Chlorophyta, with species of *Pediastrum* being gradually replaced by species of *Scenedesmus*, *Micractinium* and *Ankistrodesmus* as temperatures decreased. In addition, species belonging to the bacillariophyte genera of *Cyclotella* and pennate species (mainly Nitzschia and *Navicula* spp.), as well as an isolated, short-lived appearance of *Thalassiosira nana* were also recorded during June 1989. The bacillariophyte *Melosira* spp. was ubiquitous throughout the study, and occurred mostly as short fragments (<100 m).

Microcystis was the dominant cyanophyte, with *Anabaena circinalis*, *A. solitaria* , *Aphanocapsa* , *Merismopedia* and *Spirulina* spp. always present in low numbers. *Pseudanabaena* sp. cells were commonly associated with the *Microcystis* colonies. *Microcystis* cells were present between 1000 and 5000 cells ml-1 from the start of the study until November of 1989, at which time they almost disappeared from the assemblage before reappearing during the winter of 1990. Although not dominant in the open water phytoplankton assemblage, *Microcystis* cells formed dense populations of clumped colonies along the west and south-western shores during the late summer and winter months. This assemblage prevailed until the onset of increased water clarity (Figure 2) whereupon it disappeared and was replaced by low numbers of *Schroederia* sp. (up to 600 cells ml^{-1}). With the onset of spring, the assemblage reverted to one dominated by chlorophyte species of *Pediastrum*, *Gloeocystis* , *Sphaerocystis* , *Actinastrum* and *Tetraedron* (Figure 6).

A second peak of naviculoid bacillariophyte development was observed during the summer of 1990, together with an increase in *Aphanocapsa* colonies, which reached maximum numbers during mid-January. The *Gloeocystis-Sphaerocystis* assemblage was replaced during February of 1990 by a group of Chlorophyta:- *Chodatella*, *Micractinium* , *Scenedesmus* and *Ankistrodesmus* spp. This assemblage persisted until the middle of 1990 when the small, centric *Thalassiosira nana* reappeared in large numbers (peaking at 24000 cells ml^{-1}), for a short period of less than 14 days. *Scenedesmus* spp., some naviculoid species and *Microcystis* spp. were also present at this time. The winter composition was again followed by a clear water period during which *Schroederia* was again noted. The spring of 1990 saw the re-emergence of an assemblage of *Gloeocystis* sp. cells, together with increasing numbers of *Pediastrum*, *Sphaerocystis*, *Chodatella*, *Micractinium*, *Actinastrum* and *Tetraedron* spp. and some naviculoid species (Figure 6).

The 1991 summer assemblage was marked by the sudden and prolific development of the nitrogen-fixing, cyanophyte species, *Anabaena circinalis* followed by *Anabaena solitaria*, with total counts reaching 25 000 cells ml^{-1}.

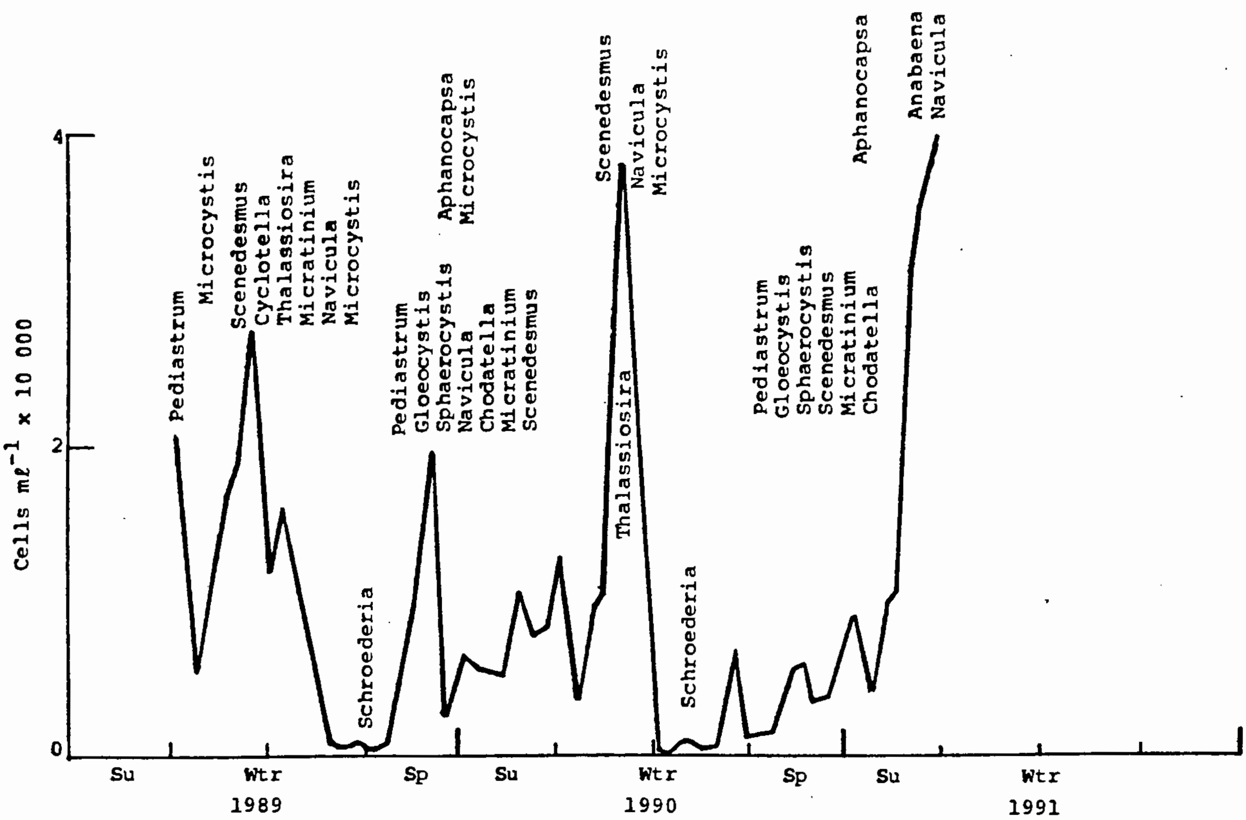

FIGURE 6: Phytoplankton periodicity of Princess Vlei, depicted as total cell count; showing composition and timing of the various phytoplankton assemblages referred to in the text.

Microcystis cells also increased at this time, with maxima of up to 8 000 cells ml^{-1} recorded. As was the case during the previous (1990) summer, *Aphanocapsa* colonies reached peak numbers during January 1991. *Pediastrum* and *Scenedesmus* species were recorded concurrently with the development of cyanophyte algae, although in low numbers (<400 and <4000 cells ml^{-1}, respectively). The collapse of this assemblage was immediately followed by an increase in naviculoid and nitzschioid species of Bacillariophyta (Figure 5).

DISCUSSION

Phytoplankton periodicity trends in Princess Vlei between April 1989 and March 1991 were forced by the prevailing winter-rainfall pattern. Hydraulic flushing of the vlei by nutrient-rich water reduced phytoplankton biomass to the extent that regrowth and development of the assemblage took place only after the cessation of the winter season. Subsequently, the growth of phytoplankton reduced the available nutrients and limited the degree of algal biomass development. A noticeable change in this pattern was the emergence of a large population of nitrogen-fixing cyanophyte algae during the summer of 1991.

The background assemblage of chlorophyte species was very similar to that recorded in Zeekoevlei (see Chapter 4), with the notable difference that *Scenedesmus* species were more evident during the winter than during the summer, as would be expected (eg. Hutchinson, 1967). Higher potential growth rates may have allowed *Schroederia* cells to predominate during the clear water phases of both years of the study. The composition and timing of the chlorophyte-assemblages was almost identical during both years.

The sudden, short-lived appearance of the small, centric bacillariophyte species, *Thalassiosira nana*, occurred at the same as in Zeekoevlei during both years of the study (see Chapter 4) and although no statistical correlation was obtained coincided increasing concentrations of reactive silicon.

The phytoplankton assemblages present in Princess Vlei essentially contained the same components as those reported by Hutchinson *et al.* (1932) and Harrison (1962). Seasonal pH ranges noted by these researchers were also in line with those reported on here and in Chapter 3. This indicates that conditions in Princess Vlei may not have markedly altered during the past sixty years.

The clear water phases observed during 1989 and 1990 may not be solely due to the effect of hydraulic flushing on biomass. In Chapter 3 it was shown that a similar phase occurred during 1988, despite the fact that 1988 was an uncharacteristically dry year for the Cape Peninsula (see Chapter 4).

The reasons for the appearance of cyanophyte algae towards the end of this study are presently unclear. The "green" conditions, commonly indicative of dense cyanophyte populations, have not been evident in Princess Vlei since 1983 (see Chapter 3). During the spring and summer of 1990/91, the surface of the upper reaches of the inlet channel became completely choked with a dense growth of *Eichhornia crassipes* Mart (Solms.). This floating weed was killed by treatment with herbicide, and the bulk of the plant matter was allowed to decay in the water. The breakdown of plant tissue would have elevated the phosphorus concentration of the vlei at a time when ambient concentrations of this element are normally relatively low. Accordingly, the annual spraying of *Eichhornia* might have to be reevaluated, if the plant material cannot be removed from the vlei. The summer development of dense populations of nuisance algae such as *Anabaena* or *Microcystis* are common elsewhere in the summer-rainfall and temperate climatic regions of the world. In addition, the hyper-eutrophic Zeekoevlei system, although dominated year-round by an almost uni-algal assemblage of *Microcystis*, showed maximum development of this genus during spring (see Chapter 4). Gardiner (1988) reported summer blooms of cyanophyte algae in Rondevlei, which is smaller than Zeekoevlei but is situated adjacent to it (see Chapter 2). The constraints of size and area/volume may be instrumental in influencing these seasonal variations.

Ashton (1979) reported that whilst increasing temperatures favoured the development of *Anabaena* spp., subsequent cooler, wet weather resulted in cell die-off, with the concomitant release of fixed nitrogen into the system. It is, therefore, expected that the early April rains common to the Cape Peninsula may initiate this process, and that this early release of additional nutrients may progressively lead to increased development in, and dominance of Princess Vlei by, nuisance-genera such as *Microcystis*. The release of nitrogen generated from dead cells during the collapse of the *Anabaena* population probably initiated the increased bacillariophyte growth observed at the end of the study.

CONCLUSIONS

Princess Vlei was historically regarded as a pea-soup green, cyanophyte-algal dominated waterbody until the partial dredging and sediment treatment undertaken during 1983 appeared to improve the water quality. Subsequently, overall algal biomass levels have been relatively low and the occurrence of cyanophyte algae do not constitute a problem.

This phytoplankton periodicity study has revealed a periodic trend influenced significantly by the hydraulic cycle, as would be expected in a small waterbody. Very similar algal assemblages were recorded at corresponding times of each year of the work.

The appearance of increased numbers of cyanophyte cells towards the end of the study may indicate a successional change towards a less-acceptable, cyanophyte-dominated assemblage such as that prevailing in Zeekoevlei, and which may well have been the case in Princess Vlei prior to 1983. The question of whether or not the trophic state of Princess Vlei is worsening will have to verified by continuing to monitor the system. It may be that progressively larger (more numerous) overwintering populations of cyanophyte species are producing a greater number of viable cells to seed the system, once conditions for growth become favourable after the winter flush.

Princess Vlei is currently regarded as being biologically disturbed. The results from the continued phytoplankton monitoring of the vlei may help to predict or interpret any observed improvements in or worsening of the systems trophic state and biological condition.

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CHAPTER 6

THE CYANOPHYTE-ALGAL DOMINANCE OF ZEEKOEVLEI. THE OPTIONS FOR REHABILITATION AND WATER QUALITY MANAGEMENT.

INTRODUCTION

The need for knowledge of the phytoplankton dynamics, composition and periodicity in Zeekoevlei was identified in 1976 (Howard-Williams, 1976) as crucial to an overall understanding of the system (see also Allanson, 1978a-c). but apart from isolated, littoral-zone samples collected prior to 1950 (Stephens, 1929; Hutchinson *et al.*, 1932; Harrison, 1962), no comprehensive, long-term study of phytoplankton periodicity has been conducted in Zeekoevlei prior to 1989 (see Chapter 4). During 1989, Zeekoevlei was selected as the subject of a study by a Cape Town City Council (CCC) multidisciplinary working group, charged with the task of evaluating the chemical and biological condition of the vlei, and the formulation of suitable rehabilitation options to produce an acceptable standard of recreational water quality (CCC, 1990).

Historically, Zeekoevlei has been plagued by blue-green algae for several decades (see Harrison, 1962), and reports of pea-soup green conditions can be found almost as far back as the turn of the century (see Stephens, 1929). Increasing catchment urbanization, in the form of medium- to sub-economic housing, has progressively compounded the problem of elevated nutrient inflows to the vlei. Modifications to the hydraulics of the vlei, combined with the chemical control of aquatic macrophytes (see Chapter 2) exacerbated the conditions. Algal growth during the past 40 years has led to the accumulation of a substantial amount of organically-rich sediments, comprising more than 20% of the vlei volume, in two basins with sediment depths of up to 3m in places (Harding, 1990a).

The process of cultural eutrophication degrades the quality of lakes through, amongst other changes, increased algal concentrations and decreased water transparency (Welch, 1984). The problem of blue-green algal dominance in eutrophic waterbodies is not a new phenomenon. Similarly, lake restoration is developing into a science and descriptions and methods of rehabilitation techniques and management aspects abound in the literature (eg. Thornton, 1987; Ryding and Rast, 1986; Thornton *et al.*, 1986; Welch, 1984; Hayes, 1983; Chapra *et al.*, 1983; Kennedy and Cooke, 1982; OECD, 1982; Benndorf *et al.*, 1981; Effler *et al.*, 1981; Lee *et al.*, 1978; Schindler, 1974). The comprehensive review of the reversibility of man-induced eutrophication by Ryding (1981), as well Welch's (1984) overview of lake restoration results, are particularly informative.

Blue-green (cyanophyte) algae, typically species of *Microcystis*, *Anabaena* or *Oscillatoria*, are commonly associated with eutrophic water bodies exhibiting low (<10:1), N:P ratios (eg. Thornton, 1987; Stewart, 1978). Excessive growth of such algae invariably leads to discoloured ("green"), turbid water with the formation of unsightly surface scums and offensive odours generated by the decomposing algal material. In large impoundments, where the water is abstracted for drinking or domestic purposes, the need to remove excessive amounts of algal biomass, using filtration, sedimentation or floatation techniques, usually results in large financial expenditure. Similarly, in so far as recreational water bodies are concerned, the presence of "pea-soup green" water, accumulations of malodourous decaying cells and the build-up of organically rich sediments lead to user avoidance with associated problems and financial implications for water quality managers (see Bruwer, 1979; Chutter, 1989a).

Persistent blooms of toxic cyanophyte species imply water quality problems and health risks, and may also lead to an impoverishment of the fauna in lakes (Lindholm *et al.*, 1989). In South Africa, 24 species of cyanophyte (cyanobacterial) algae are known to be capable of producing toxins, but most algal-related poisonings are caused by the blue-green alga *Microcystis aeruginosa* (Scott, 1989 and 1991; CPFAC, 1990). The extent and nature of algal toxins in South Africa form the subject of a book (Scott, in press). Apart from an *ad hoc* assay for the presence of *Microcystis* toxins (result pending), extracellular phytoplankton metabolites have not been studied in Zeekoevlei.

Once a cyanophyte phytoplankton population has become firmly established in a water body, its removal, or the alteration of the physico-chemical regime to favour an alternative algal assemblage, is not easily achieved. The extensive work conducted at Hartbeespoort Dam illustrates this well (NIWR, 1985). Invariably, catchment options to control point- and diffuse sources of nutrient enrichment, especially orthophosphate, are required (eg. Chutter, 1989). In-lake options, such as whole-lake mixing; bottom-sealing with alum or ferric sulphate; or dredging may also have to be employed (EPA, 1980).

Zeekoevlei represents a unique and fresh opportunity for investigating the interactions between environmental variables and phytoplankton with a view to lake management. Situated in a Southern Hemisphere, Mediterranean-climate region, it is a shallow, well-mixed, hyper-eutrophic system (see Chapter 2). Phytoplankton interactions in such systems have received only scant scientific attention (see Chapter 1).

In an area poorly endowed with suitable expanses of open water suitable for aquatic sport and recreation, Zeekoevlei is a popular regional focal-point (Brummer, 1981; CCC, 1990a) used for a wide range of activities, ranging from national watersport competitions to family recreation. Zeekoevlei, as stated earlier, is characteristically green in colour, with very low mean water transparencies (see Chapter 2). It has been clearly shown (Thornton *et al.*, 1989; Thornton and McMillan, 1989), that the influence of water quality on user-avoidance is significantly inversely correlated with the visual appearance thereof. Algal-rich waters will be unacceptable for water contact sports such as skiing, and may render potential angling sites aesthetically unacceptable (eg. Haynes *et al.* 1989).

This chapter not only examines the restoration techniques applicable to Zeekoevlei, but also strives to emphasize the crucial importance of an in-depth understanding of the phytoplankton dynamics before any action can be taken. The implementation of any rehabilitation choices may require pilot-scale testing or laboratory simulation before any scale-up is attempted. The incorporation of predictive computer-modelling programmes will be essential. As stated in Ryding and Rast (1986), *"the OECD (1982) international eutrophication survey illustrated that it is possible to assess the response of a water body to nutrient inputs, by studying the statistical behaviour of a large number of similar systems"*. As pointed out above as well as in Chapter 4, studies of phytoplankton responses in shallow, S.Hemisphere lakes have not received much attention. This makes the potential impact of the success or failure of remedial measures applied to Zeekoevlei so much more significant. The results may not only be applicable to an increased knowledge of the nutrient dynamics and biological character of shallow systems, but also to the epilimnia of stratifying lakes. It is planned that this paper will be followed at a later date by Part II, which will address the options ultimately selected and their impact on the prevailing conditions in Zeekoevlei.

Remedial measures do not always meet with success, and it may be wise to review some comments made by other researchers as, whilst a variety of techniques exist which are plausible in theory, many have not been sufficiently proven in practice to develop sound design procedures (Welch, 1984). Allen (1980) observed *"that despite the application of [these] remedial measures, perturbations in phytoplankton biomass will remain such that, on any particular day during the open-water [north-temperate systems] period, short-term algal blooms or scums will still be sufficiently intense for long-term improvements not to be clearly evident"*. Allen further stated that *"taxpayers who make* *use of a body of water are at the forefront of public action groups requesting improvements in water quality. Assessments are made by observation from cottages, beaches and boat launching ramps. Considerable emotion and little science is involved in these visual assessments."*

Curiously enough, the appearance of the water in Zeekoevlei is such that it can be classified, even by non-scientists, as being of poor quality without invoking any emotion whatsoever. Of the recent opinion survey conducted at the vlei (CCC, 1990a), the greater portion (59%) of respondents advocated clear, non-turbid water free of algae as desirable of good water quality. 47% of those polled regarded Zeekoevlei as a vlei with poor water quality. These percentages may well have been higher as the questionaire concentrated on day-visitors and did not include the numerous local and provincial clubs of on-water sportsman and shoreline fishermen.

A description of the Zeekoevlei study area and the limnology of the vlei since 1981 is given in Chapter 2. Details of the phytoplankton assemblage and periodicity are presented in Chapter 4. Suffice to say, Zeekoevlei is 256 ha in extent, has a mean depth of 1.9 m and typical mean annual N and P concentrations of 3.90 mg l^{-1} and 0.56 mg l^{-1}, respectively, with chlorophyll a concentrations of up to 600 $_{u}g\ l^{-1}$. The catchment area covers approximately 8 km^2, and water residence time is estimated at 0.2 y. Two separate local authorities are involved with the management of the catchment and the vlei itself. The catchment and most of the area adjacent to the vlei falls under the control of the Regional Services Council, whilst responsibility for the vlei itself is that of the Cape Town City Council.

DISCUSSION

REASONS FOR THE DOMINANCE OF *Microcystis* IN ZEEKOEVLEI

The physico-chemical conditions in Zeekoevlei are, and evidently have been for some time, conducive to sustained, year-round dominance by species of Cyanophyta (see Chapters 2 and 4). The eutrophic conditions, coupled with the consistently low N:P ratios are suitable for a blue-green algal dominated system (eg. Walmsley and Butty, 1980; Barica, 1981; Thornton, 1987).

Why has this dominance been in force for so long? From the historical information available (see Chapter 2), it is apparent that blue-green algal blooms have occurred from time to time in the past, but that hydraulic flushing served as a mechanism to clear the vlei of algae and to allow sufficient light for the macrophyte *Potamogeton pectinatus* to become established. Reversion to algal dominance occurred with the formation of a bloom in the northern basin, gradually encompassing the whole vlei and reducing the sunlight available to the macrophyte. Thus, a natural cyclical rehabilitation mechanism took place in Zeekoevlei. The growing human population, and the concomitant need for both improved flood control and increased water depths for recreation, culminated in the construction of the present outlet weir. This action radically reduced the effects of flushing, increased retention times and, in one fell swoop, served to offset the natural periodic cycling of phytoplankton and macrophyte flora in Zeekoevlei.

The absence of marked flushing may well have contributed to an increased incidence of algal blooms which may, in time, reached a density where light restrictions would have precluded macrophyte growth in the vlei. However, further efforts to accommodate the sailing fraternities' complaints concerning the presence of the *Potamogeton* were made, culminating in a decision to treat the macrophyte with sodium arsenite (CCC, 1951). An area approximate to 30% of the vlei area was treated, an area equivalent to the surface area of Zandvlei. The treated plant material was not removed from the vlei and would have resulted in a large accumulation of phosphorus emanating from the decaying tissue. This fuelled an algal bloom (see Harrison, 1962; CCC, unpublished records), and, supported by high nutrient loads from the rivers. heralded the onset of the present-day domination by blue-green algae. Deposition of particulate material and the sedimentation of algal biomass have resulted in the accumulation of 1.1 million m^3 of organically-rich sediment (Harding, 1990a). Investigations into the nutrient dynamics of Zeekoevlei are still in their early stages, and whilst the internal loading potential of this sediment must still be calculated, initial estimates (Dick, 1990; Harding, 1990b) indicate that it is substantial (see Chapter 2). The contribution of seepage from the adjacent sewage works, and from residential conservancy tanks is not regarded as being significant to the overall nutrient loading of Zeekoevlei (Harding, 1990c).

The first two years of the present study of algae and algal-periodicity events in Zeekoevlei (Chapter 4), provided an insight into the mechanisms which may have been operating during past years. Zeekoevlei was seen to be dominated year-round by *Microcystis* spp., with genera of Chlorophyta and diatoms showing population maxima during the summer and winter, respectively (see Chapter 4) and a cyanophyte bloom during the early spring.

Zeekoevlei experienced a *Microcystis* bloom during the spring period of 1989. The bloom occurred at a time when incident solar radiation, water temperatures and concentrations of nitrogen and phosphorus in the vlei were increasing and overall wind speeds were low, with lengthy periods (>1day) of calm weather between wind-mixing events. Okada *et al.* (1982) noted that algal cells would rapidly take up phosphorus after the inflow of P-rich water heavy rain. Robarts and Zohary (1984) proposed that the reasons why *Microcystis aeruginosa* was dominant in Hartbeespoort Dam were the ability of the alga to maintain itself in the upper part of the water column, as well as an increase in colony size as the population accumulated at the surface with any decrease in mixing and turbulence. Changes in the colony size of *Microcystis aeruginosa* moderated the effect of chlorophyll a on light attenuation. The euphotic zone depth increased with colony size increase, and *vice versa* (see also Paerl and

Ustach, 1982). This work was further elucidated by Zohary and Breen (1989) who investigated the environmental factors governing the formation of *Microcystis* hyperscums in Hartbeespoort Dam. They concluded that the development of such scums was dependent on the following preconditions being met (*ibid.*, pg 187):-

> *(a) The pre-existence of a large standing stock of blue-green algae*
> *(b) That the algae are buoyant*
> *(c) Low windspeeds over long periods of time*
> *(d) Suitable shore-morphometry providing sheltered accumulation sites*
> *(e) High incident solar radiation*

With the inclusion of the enhanced nutrient levels which prevailed during the winter and spring of 1989, all of the above conditions were complied with in Zeekoevlei. A large population of *Microcystis* cells was present in Zeekoevlei year-round, these cells being obviously buoyant as seen by their ability to form thin surface layers and windrows, as well as scums in sheltered areas around the perimeter of the vlei. The morphometry of Zeekoevlei provides natural, sheltered accumulation sites for *Microcystis* to proliferate and seed the main vlei body. Although data reflecting wind conditions at Zeekoevlei, especially the period immediately prior to the bloom, were not available, it is well known that periods of low wind speed prevail in the area from mid-winter to mid-spring. It has been shown by other authors (eg. Scott, 1969) that wind-speeds in excess of 3.7 m s^{-1} mix algae into the water column, and offset the ability of blue-green algae to form surface aggregations.

Seasonally, by September mean hourly days of sunlight were increasing, and mean water temperatures had exceeded the critical 12-15 ^{o}C limit below which *Microcystis* growth is grossly retarded, and loss of cells by sedimentation takes place (Thomas and Walsby, 1986).

The 1989 spring bloom of *Microcystis* correlated significantly ($p > 0.01$)

with increases in levels of soluble reactive P introduced by the rivers (see Chapter 4). With respect to increased nutrient levels, elevated algal crops have been related to phosphorus inputs in other waterbodies (eg. Garnier and Montesanto, 1988), and sudden increases in blue-green algae have been significantly correlated with soluble reactive phosphorus concentrations (eg. Chang and Rossman, 1988). Apart from the nutrient inputs from the rivers, the internal loading from the considerable sediment accumulations must play a significant role in the supply of phosphorus. Indeed, such a sediment-rich system may become self-sustaining (see Allanson *et al.*, 1990). Schindler (1974) disagreed with this viewpoint, and was of the opinion that sediment-fuelling of the water column would not significantly delay recovery where riverine nutrient sources had been controlled. In a contrasting finding, Cooke *et al.* (1977) showed that internal loading could account for 65-100% of summer phosphorus increases in eutrophic lakes, and that this loading delayed recovery after nutrient diversion. In Lake Talquin, reactive P- and dissolved inorganic N- inputs were found to account for 25 to 30% of measured levels, with recycling of nutrients and N-fixation accounting for the balance (Turner *et al.*, 1983). Otsuki *et al.* (1981) emphasized the importance of internal loading in shallow, highly eutrophic, non-thermally stratifying lakes. It has been demonstrated that *Microcystis aeruginosa* Kutz. can utilize sediment-bound phosphorus for growth (Thornton, 1980). Whether or not this is significant in a non-stratifying system such as Zeekoevlei, is unknown.

RESTORATION OPTIONS AND IMPLICATIONS FOR WATER QUALITY MANAGEMENT

Ideally, Zeekoevlei water quality management programmes should strive towards ultimately obtaining a favourable balance between macrophyte and algal growth. Phosphorus is the most important element governing the trophic state of most lakes (eg. Dillon *et al.*, 1978; Lee *et al.*, 1978), and Golterman (1980) emphasized that "phosphate removal is the only cure for the devasting effects of lake blooms". Phosphorus-chlorophyll and nitrogen-phosphorus, N:P, relationships have become well established for predicting both the size and expected composition of a particular phytoplankton standing crop (Dillon and Rigler, 1974; Rhee, 1978; Smith, 1982). Reduced P-loading generally leads to decreased phytoplankton biomasses, shortened bloom periods and a change in the algal assemblage. Shallow systems may, however, prove contradictory and become dominated by filamentous, N-fixing forms (*Anabaena* spp.) or small-celled colonial forms such as *Aphanocapsa* spp. (Willen, 1987).

South Africa currently finds itself experiencing times of increasing financial stringency in which all available and excess funds are being channelled into socio-economic programmes. It is generally accepted that the priorities accorded to water usage are, in decreasing order:- potability, agriculture, industry and recreation (Haynes *et al.*, 1989). With respect to conditions at Zeekoevlei, restoration of the vlei would not appear to be practical without the input of massive amounts of capital for lake-, catchment-, education- and on-going remedial measures. In the absence of a total "all-encompassing" programme, the "do-nothing" option exists at the opposite end of the scale. The amenity value of Zeekoevlei (see Introduction), seen on the spectrum of limited availability of inland recreational water resources in the Cape Town municipal area, and given the present unsightly, unpleasant and potentially toxic condition of the vlei, tends to indicate that some corrective measures should be taken. Whatever measures are adopted, however, will have to have some longlasting visible effect in order to satisfy both the ratepayer and the water-user.

What should such measures entail? Golterman (1980) noted that *"the early limnologists' solution to the problem [of excessive algal growth] was simple common sense: decrease the input step by step, starting, for instance, with a 50% reduction and let the resulting phytoplankton populations indicate the need for further steps, if necessary"*. Several standard options exist for lake restoration (eg. EPA, 1980), the scale, adaptation or combination of methods necessary for a particular waterbody being dependent on the severity of the conditions. Uttormark and Hutchins (1978) divided restoration techniques into three groups:- (1) those to reduce nutrient inflow; (2) those to disrupt internal nutrient cycles; and (3) those to accelerate nutrient outflow. The applicability of certain of these techniques, as seen in the Zeekoevlei context, will be considered below under the headings of "catchment" or "in-lake" options. Options such as hypolimnetic discharge or aeration, which are relevant only to deep stratifying systems, have been excluded.

Progress towards the development of clear design procedures has been aided by the use of mass-balance models (see Orlob, 1984; Welch, 1984). Whilst such models have been proved capable of predicting general lake response to remedial treatment, they have been shown to be less reliable in shallow lakes having large internal sources of phosphorus. The implementation of such models for the Zeekoevlei situation is still in the early stages, and it is hoped that the results derived therefrom will fundamentally assist the decision-making process.

CATCHMENT OPTIONS

On a preventative basis, the identification and curtailment of pollution problems within the catchment itself have merit as being a point of departure for a rehabilitation programme. Whilst an investigation of the Zeekoevlei catchment, especially the Big Lotus River, is still to be undertaken, the seasonality of phosphorus increases in the rivers (see Chapter 2) would tend to indicate a diffuse origin. The observed delay period between the onset of the rainy season and the peak orthophosphate concentrations may be due to a rising water-table effect within the catchment (see Chapter 2). The fact that the chronological appearance of phosphate and nitrogen peaks in the Little Lotus catchment (primarily residential), mirrors that of the Big Lotus River (which has a large horticultural land-use) may be relevant here since it has been argued that the increase in ortho-P is primarily of agricultural origin (CCC, unpublished records). In addition, rising groundwater levels may enhance seepage from the tertiary treatment ponds of a wastewater treatment plant near the source of the Big Lotus River. High ortho-phosphate:total-P ratios suggest some wastewater input in the Big Lotus River (see Chapter 2 for data). Ambuhl (1966) stated that *"the major part of [phosphorus] eutrophizing matters is not carried out into lakes with sewage, but is washed out of cultivated fields by rain or infiltration water, and gets into lakes by way of ground water or streams. We know today [1966] that amounts of phosphorus arriving into lakes in this way are equal to normal discharges of sewage; as regards nitrogen, these amounts are even superior to those of sewage"*.

Nutrient diversion and pre-lake treatments

The successful use of diversion techniques relies upon the availablity of an alternative receiving water which can cope with the nutrient load. In the absence of effective within-catchment control, diversion of the nutrient rich waters is an alternative (EPA, 1980). In the case of Zeekoevlei, an alternative supply of appropriately treated water from another source, such as the adjacent sewage works, would be required to "top-up" the vlei and to provide necessary hydraulic flow-through. Wastewater soluble reactive phosphate (SRP) concentrations are higher than in the river, and would be unsuitable for level control purposes.

Lake Washington is regarded as a classic example of what can be achieved with nutrient diversion (Edmondson, 1972; Edmondson and Lehman, 1981). Amounts of effluents reaching the lake were reduced to zero over a five-year period. During the subsequent seven-year period, this previously eutrophic system recovered. Nutrient levels, amounts of phytoplankton and the proportion of blue-green algae decreased. In a second example, an 80% reduction in P- loads to Shagawa Lake, Minnesota, resulted in 40-80% reductions in total and soluble reactive P-concentrations, and a greater than 50% reduction in chlorophyll a (Larsen *et al.*, 1979). Similarly, diversion of sewage effluent from Lakes Waubesa and Kegonsa (Sonzogni and Lee, 1974) resulted in a considerable improvement in lake water quality.

No measurable reductions in total P-, chlorophyll a, phytoplankton biomass or Secchi transparency were recorded in Lake Sammamish following the diversion of nutrients, but the blue-green algal component decreased by 50% (Welch, 1977; Welch *et al.*, 1980). High, anaerobic release of phosphorus from the sediments was implicated in the maintenance of lake trophic stability.

The option of dilution, that is by introducing nutrient-poor water to a eutrophic lake, requires the presence of a suitable source of water (eg. Welch and Patmont, 1980; Welch, 1981). No such alternative exists for Zeekoevlei (see comments on diversion). Flushing, even using nutrient-rich water, may be utilized if sufficiently high flows can be realized. Flushing would bring about "wash-out" of algal cells. Generally, flushing rates should exceed 10% of lake volume per day in order to be effective as a biomass control (Welch, 1984). Increased flushing rates may also be counterproductive, as in the case of Lake Talquin, USA, where phytoplankton productivity increased by 70% in response to a higher flushing rate (Turner *et al.*, 1983).

The application of phosphorus standards has been shown to have effect in reducing the nutrient loading flux to lakes (NIWR, 1985; Chutter, 1989), but can be a long term process, such as in in the case of Lake Erie (USA) where an intended 35% reduction in P-loading was estimated to require at least 25 years to achieve (Richards, 1985).

The option of treating input water biologically (wetland) or chemically (treatment works) before it enters the vlei is a reactive measure, and the required land space, plant and cost make this very unsuitable for the Zeekoevlei situation, although dephosphorization has been used with success in other parts of the world (eg. Van Liere *et al.*, 1990). Zeekoevlei receives the bulk of its nutrient input during the winter rainfall period, and it is at such times of peak flows that wetland and "in-line" flow systems of nutrient removal are at their least efficient. Fiala and Vasata (1982) showed that P-elimination in a pre-reservoir was dependent on detention time, whilst Ryding and Forsberg (1976) suggested that reduction in nutrient input may not improve shallow, hyper-eutrophic lakes.

Product substitution or modification is an attractive option when one considers that 50% of the phosphorus in sewage originates from detergents (eg. EPA, 1980; Welch, 1984). This line of approach can meet with resistance, especially in third-world or rural communities. Substitution of non-phosphorus detergents in Zimbabwe had to be revoked as detergent "sudsing" was equated with cleaning-ability by the non-white community (J. Thornton, personal communication).

Legislation

A discussion of the complexities of water laws and pollution would merit a separate publication. Any attempt to control pollution within a catchment necessitates a thorough knowledge of the conditions contributing to the problem. The absence of receiving-water standards for effluent disposal further compounds the problem. Extensive on-going public education programmes would be necessary to emphasize the necessity for good catchment-housekeeping. The status of South African water-laws and management was recently the subject of a symposium (see SAJAS, 1989).

IN-LAKE OPTIONS

Dredging

In the case of a lake such as Zeekoevlei, the removal or inactivation of sediments, and/or the amelioration or diversion of nutrient-rich inflows, would be essential for reducing P- levels and long-term improvement (eg. EPA, 1980). The technique is regarded as most appropriate for lakes whose high phosphorus content and eutrophic state are sustained by an internal supply of phosphorus from bottom sediments, even after the inflow of phosphorus has been reduced

(Welch, 1984). Apart from its role as an internal nutrient source, the presence of the sludge in Zeekoevlei presents a physical hindrance to yachtsmen and waterskiers (see Howard-Williams, 1976). In addition, odours (hydrogen sulphide) emanating from the sludge, especially on calm days, are not only objectionable but bring about fish deaths in the more sheltered areas (see Chapter 2).

The cost of removing the sediment from Zeekoevlei was estimated during 1990 at R10 million and would necessitate a large-scale programme, requiring the importation of dredging plant. In addition, the drying and disposal of the dredged material is anticipated as being a significant problem. Removal should drastically reduce the internal nutrient loading with a subsequent decrease in overall numbers of algae and an increase in water clarity. Once dredging was completed, however, what would be the long term prognosis for the vlei?

Assuming the absence of significant inputs of phosphorus from the treatment works, the rivers, in their present, unaltered, nutrient-rich state would continue to pollute the vlei. Therefore, algal growth and sediment build-up, in this hydraulically-unaltered system, would probably continue to be cyanophyte dominated. Overall, in-lake phosphorus concentrations might be lower than at present but, with time, the system would return to the state that existed in the pre-dredging era. The success, therefore, of any dredging option will be crucially and directly related to the parallel control of the external nutrient sources (see Davies and Day, 1986). The cost of a dredging exercise alone to accomodate, in real terms, a comparatively small number of water-users, would be difficult to justify given the present economic conditions.

Large scale "once-off" dredging could be replaced by long-term, small scale "continuous" programmes, akin to macrophyte harvesting. This would significantly prolong the amount of time required before an noticeable effect would be apparent and would lay such an effort open to public criticism. In addition, the economies of scale gained with a large-scale programme would be lost in a long-term project using plant of lower capacity (M. Lief, personal communication).

With any dredging effort, the problems of transporting, storing and drying the sludge have to be answered (see Davies and Day, 1986). The large amount of material in Zeekoevlei compounds the scale of this option. The disadvantages of dredging include cost, temporary phosphorus release from the sediment, increased phytoplankton productivity, noise, lake drawdown, temporary reduction in benthic fish food organisms, the potential for toxic material release to the overlying water and the potential for environmental degradation at the dredged material disposal site (Peterson, 1982).

Sediment treatment

If the catchment problems (see Catchment Options) could be alleviated or corrected, then actions to begin restoring the vlei itself would lend themselves to justification.

The bottom sealing of sediments, using low or non-toxic chemical or mineral additives such as lime, alum or iron, is a relatively inexpensive option, but would obviously not accommodate the Zeekoevlei water-user in that the sediment would still be present, and the process would require "topping-up" treatments from time to time. Sanville *et al.* (1976) suggested that this type of treatment may be required in shallow lakes, even in spite of external supplies of excess nutrients being prevented from entering the system. Cooke *et al.* (1982) applied aluminium sulphate, following nutrient diversion, to two lakes, and recorded an increase in water transparency with a concomitant decrease in algal biomass. No deleterious side-effects were observed. Francko and Heath (1980) found that alum was unable to remove complex phosphorus compounds from the water column itself. Alum treatment of a shallow lake (mean depth 2m), and approximately half the area of Zeekoevlei, curtailed P loading and blue-green algal dominance for a one-year period (Welch *et al.*, 1982). Return of macrophytes, and their subsequent decay, was attributed as being the reason for the restoration of internal P-loading.

In-lake nitrogen fertilization could be employed to alter the N:P ratio to one which would support a different phytoplankton assemblage. This costly technique, requiring frequent re-dosing, has met with mixed success in other parts of the world (eg. Lathrop, 1988; see also Schindler, 1975). Shapiro *et al.* (1983) showed that in a total of 70 experiments, pH-lowering resulted in a shift from blue-green algae to green algae, principally *Scenedesmus* spp.

Biological

Biological (biomanipulatory) controls, other than harvesting, seem to have received only scant attention as restoration options (see Shapiro *et al.*, 1983), although the impact of biotic interactions has been found to be significant in a number of cases (eg. van Liere *et al.*, 1990; Leah *et al.*, 1980). One gains the impression that biological controls are only considered as "fine-tuning" options for already substantially restored systems. Although the prevailing situation in Zeekoevlei tends to indicate the necessity for radical physical remedial actions, the work of Keating (1976) into the allelopathic impact of algal "metabolites", may be relevant. Keating (*ibid.*) showed that extracellular products of bloom dominant algae play a significant role in the bloom sequences of eutrophic waters, and that the inhibition of diatom growth by blue-green algal metabolites may be a widespread freshwater phenomenon. Keating (*ibid.*) proposed a strategy for bloom control, incorporating the elimination of winter, blue-green algal blooms using algicides such as copper-sulphate, and the enhancement of diatom growth by the addition of silica.

Biotic harvesting has received much attention in the field of macrophyte control, whilst algal floatation and fish harvesting still have to have their potential as removers of phosphorus fully evaluated (Welch, 1984). The elimination of bottom-feeding fish in Lake Marion (172 ha; mean depth 1.98 m) revealed that fish excretion provided approximately half the phosphorus input to the lake (Shapiro *et al.*, 1983). Reduced densities of planktivorous fish, and the concomitant development of dense cladoceran populations were shown to prevent the appearance of blue-green algal blooms (Spencer and King, 1987).

Certain biotic factors may be implicated in the sediment release of phosphorus from the upper 0.1m of sediments. Apart from the physical mixing brought about by turbulence and gas ebullition, benthic fish, such as carp, continually stir up the sediments. Recreational and other motorboats have been shown to increase turbidity and phosphorus concentrations (Yousef *et al.*, 1980). The impact of nutrient excretion by fish and zooplankton, albeit small, will have to be calculated in a final analysis of the rehabilitation of Zeekoevlei's water quality. The zooplankton grazing/algal size interaction, as well as the planktivorous fish/zooplankton dynamic will also have to be factored into the final management plan for the rehabilitation of Zeekoevlei.

Does an example of restoration in a similar situation exist ?

Lake Trummen (Sweden) presents an interesting example of what might be achieved with Zeekoevlei (ILEC, 1989). Lake Trummen is smaller than Zeekoevlei, being 100 ha in area, mean depth of 1.6 m and a volume of 1.26 million m^3. Water residence time was equivalent to 0.4 y, and the catchment area encompassed 13 km^2. Lake utilization included fisheries, tourism and recreation. Since the turn of the century, increases in the pollutant loads to this lake changed the trophic state from oligo- to eutrophic. Annual blue-green algal blooms (*Anabaena* and *Microcystis* spp.) occurred, causing unsightly conditions, offensive odours and fish-kills. Excessive reed growth further complicated the situation. During the 1950's, wastewater (municipal sewerage and industrial wastewater) diversions had no effect. A restoration programme (1970-1971), comprising suction dredging, removed 600 000 m^3 of sediments from the lake.

The total cost (dredging and other aspects) of the project (SA Rands, 1990 equivalent) was of the order of R6 million. The result was a drastic decrease in phytoplankton biomass (85-90%), with the dominant blue green algae being reduced to 5% of the pre-restoration value. The improved light conditions, resulting from the decrease in algal biomass, allowed the re-establishment of submerged plants such as *Potamogeton* and *Nitella*. Concentrations of P- and N- were reduced by 90% and 70% respectively.

Lake Trummen is regarded as the first successful example of whole-lake restoration on a large scale and has drawn world-wide attention. The need to divert the nutrient rich inputs to the lake, followed by in-lake treatments mirrors the Zeekoevlei situation closely and provides an excellent example of what might be achieved in the latter, given the requisite financial input.

In another example, mismanagement of Lake Apopka (Florida, USA), in the form of the construction of an outlet, converted the natural lake to a managed reservoir. A subsequent combination of factors led to the formation of dense algal blooms, as well as coarse fish dominance (Golterman, 1975). An unconsolidated bottom sediment covered 90% of the lake bottom, reaching 10m thick in places, with an average depth of 1.5 m. Dredging, lake drawdown to induce oxidation and diversion of inputs comprised the restoration plan, the results of which were not identified by this dissertation's literature survey.

Locally, the dredging of Princess Vlei (1983), a small coastal vlei situated to the north-west of Zeekoevlei, appears to have radically altered the degree of phytoplankton growth (see Chapter 3). Treatment of the dredge spoils with ferric sulphate, with the intention of settling out fine suspended matter, may have sealed the bottom sediments and temporarily removed a significant source of autochotonous loading of orthophosphate-P. In addition, removal of a hydraulically-restrictive underwater sill increased overall flow rates through the vlei (see Chapter 3). Whilst no variation in external nutrient-loading of the system was apparent prior and subsequent to the dredging taking place, algal biomass levels in Princess Vlei, as measured by Secchi disk transparency and mean concentrations of chlorophyll a were significantly altered, with transparency increasing from a mean depth of 0.17 m to 0.50 m, and mean chlorophyll a decreasing from 270 to 50 $\mu g\ l^{-1}$. Princess Vlei was well known to be green and turbid all year round prior to 1983. This has certainly not been the case since (see Chapters 3 and 5).

CONCLUSIONS

The rehabilitation of Zeekoevlei poses a difficult problem for those tasked with the formulation of a restoration plan. The hyper-eutrophic conditions, coupled with excessive nutrient pollution from the catchment and the sheer magnitude of the volume of accumulated sediments, seem almost insurmountable. Any measures which are adopted to restore Zeekoevlei will require considerable financial input and public-education programmes, as well as functional cooperation between both local authorities. Financial limitations dictate that Zeekoevlei's restoration should not form the basis of an experiment, but that decisive, longlasting remedial action be taken.

It is clearly evident that pre-lake water treatment will be confined to the improved control of nutrient pollution within the catchment area. The identification of the major sources of soluble reactive phosphate are crucial in this respect. Feasible options for the vlei itself are few. Alternative sources of water for nutrient diversion or dilution are unavailable, and the chemical treatment of influent waters would not only be prohibitively expensive, but would have to be sufficiently large to cope with peak hydraulic flows during the winter.

Zeekoevlei is presently endowed with a resilience to any minor attempts to alter the phosphorus balance in the vlei. Phosphorus inactivation and bottom-sealing of the sediments would therefore only be practicable in conjunction with a dredging operation to remove the bulk of the sediment volume. It is expected that the application of input-output mass-balance models will confirm this postulation. Once the major sources of phosphorus have been either removed or controlled, then supportive, biomanipulatory controls, such as control of dominant fish species or the establishment of macrophyte beds, could be brought into play.

Paramount to the making of any decisions regarding the restoration of Zeekoevlei will be the reconciliation of cost, water-user requirements and conservation factors. The successes attained in the Lake Trummen case are indicative of what might well be achieved with Zeekoevlei. A long-term planning viewpoint should be adopted, and the implementation of measures which will only provide short-term, cosmetic relief should be avoided.

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APPENDIX 1

A LIST AND PHOTOMICROGRAPH RECORD OF THE PHYTOPLANKTON TAXA IDENTIFIED IN WATER COLUMN SAMPLES COLLECTED FROM ZEEKOEVLEI AND PRINCESS VLEI, 1989-1991

Introductory Note.

It was not the intention of this study, neither did time allow full taxonomic classification of the phytoplankton taxa as far as species and nomenclator. The list presented here, however, does extend to some individual identifications as far as species, where the obvious structure of the alga allowed.

This list also includes rare species observed on single or infrequent occasions and which were not included in the individual chapters of this thesis on the periodicity of the two vleis.

The photomicrographs displayed here are not intended as an exhaustive record of the phytoplankton of Princess Vlei and Zeekoevlei. Representative examples of the dominant genera have been included, and in certain cases more than one picture of a particular taxon have been included for purposes of clarity.

The classifications made here are according to Smith (1950), "*The Freshwater Phytoplankton of the United States.*"

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1. LIST OF PHYTOPLANKTON TAXA

S = seasonally abundant, R = infrequently abundant, - = infrequently present,

+ = frequently present, D = perenially dominant.

Z = Zeekoevlei, P = Princess Vlei.

DIVISION: CYANOPHYTA (=CYANOBACTERIA)	Abundance/Location
Order: Chroococcales	
Family: Chroococcaceae	
Aphanocapsa sp. not determined	S/Z,P
Merismopedia spp. not determined	+/Z,P
Chroococcus sp. not determined	-/Z
Microcystis spp. not determined	(D/Z)(+/P)
Order: Oscillatoriales	
Family: Oscillatoriaceae	
Oscillatoria sp. not determined	-/Z
Spirulina spp. not determined	-/Z,P
Pseudanabaena sp. not determined	+/Z
Suborder: Nostochineae	
Family: Nostocaceae	
Anabaena circinalis	S/Z,P
Anabaena spp. not determined	S/Z,P
Anabaenopsis sp. not determined	-/Z
Family: Rivulariaceae	
Raphidiopsis sp. not determined	R/Z
DIVISION: CHLOROPHYTA	
Order: Volvocales	
Family: Chlamydomonadaceae	
Chlamydomonas spp. not determined	-/Z
Carteria spp. not determined	-/Z
Family: Phacotaceae	
Phacotus spp. not determined	-/Z,P
Order: Tetrasporales	
Family: Palmellaceae	
Gloeocystis sp. not determined	S/P
Sphaerocystis sp. not determined	S/P

Order: Chlorococcales

Family: Micractiniaceae

Golenkinia spp. not determined	+/Z,P
Micractinium spp. not determined	+/Z,P

Family: Characiaceae

Schroderia sp. not determined	S/P

Family: Hydrodictyaceae

Pediastrum spp. not determined.	+/Z,P

Family: Oocystaceae

Oocystis eremosphaera	+/Z,P
Oocystis spp. not determined	+/Z,P
Chodatella sp. not determined	-/Z
Tetraedron muticum	+/Z,P
Tetraedron minimum	+/Z,P
Tetraedron caudatum	-/Z,P
Tetraedron trigonum	-/Z,P
Ankistrodesmus spp. not determined	+/Z,P
Selenastrum sp. not determined	-/Z
Chlorella sp. not determined	-/Z
Treubaria sp. not determined	-/Z,P
Pachycladon umbrinus	-/P

Family: Coelastraceae

Coelastrum sp. not determined	-/Z,P

Family: Scenesdesmaceae

Crucigenia spp. not determined	-/Z
Scenedesmus spp. not determined	S+/Z,P
Actinastrum spp. not determined	+/Z,P

Order: Cladophorales	
Family: Cladophoraceae	
Rhizoclonium	R,P
Order: Zygnematales	
Family: Zygnemataceae	
Spirogyra spp. not determined	R,P
Family: Desmidiaceae	
Staurastrum sp. not determined	-/P

DIVISION: CHRYSOPHYTA

Class: Bacillariophyta	
Order: Centrales	
Suborder: Coscinodiscineae	
Family: Coscinodiscaceae	
Melosira spp. not determined	(-/Z)(+/P)
Cyclotella spp. not determined	+/Z,P
Thalassiosira nana	S/Z,P
Suborder: Biddulphineae	
Family: Chaetoceraceae	
Chaetoceros spp. not determined	-/Z
Suborder: Fragilarineae	
Family: Fragilariaceae	
Fragilaria spp. not determined	-/Z
Asterionella sp. not determined	-/Z
Suborder: Achnanthineae	
Family: Acthnanthaceae	
Cocconeis sp. not determined	-/Z
Suborder: Surirellineae	
Family: Nitzschiaceae	
Nitzschia spp. not determined	+/Z,P

Unidentified pennate diatoms	+/Z,P

DIVISION: <u>PYRROPHYTA</u>

Order: Gymnodiniales

Family: Gymnodiniaceae

Gymnodinium sp. not identified	-/Z

Order: Peridiniales

Family: Peridiniaceae

Peridinium sp. not identified	-/Z

DIVISION: <u>EUGLENOPHYTA</u>

Order: Euglenales

Family: Euglenaceae

Euglena spp. not determined	-/Z,P
Phacus sp. not determined	-/Z,P
Trachelomonas sp. not determined	-/Z,P

DIVISION: <u>CRYPTOPHYTA</u>

Order: Cryptomonadales

Family: Cryptochrysidaceae

Rhodomonas sp. not identified	+/Z,P
Chroomonas sp. not identified	+/Z,P

Family: Cryptomonadaceae

Cryptomonas spp. not identified	+/Z,P

2. PHOTOMICROGRAPH RECORD

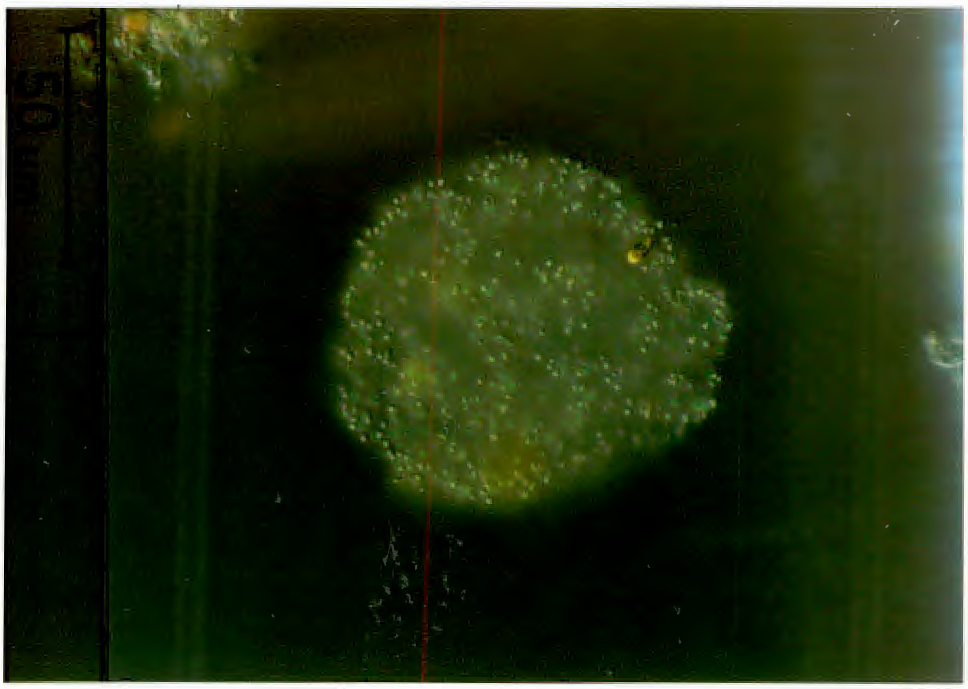

FIGURE 1: Aphanocapsa sp.

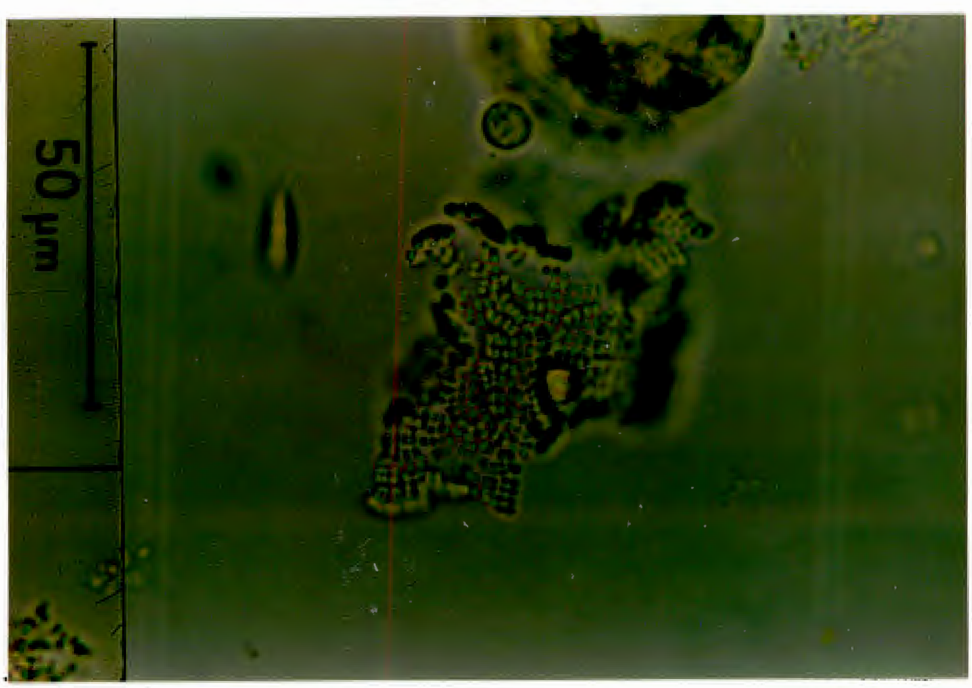

FIGURE 2: Merismopedia sp.

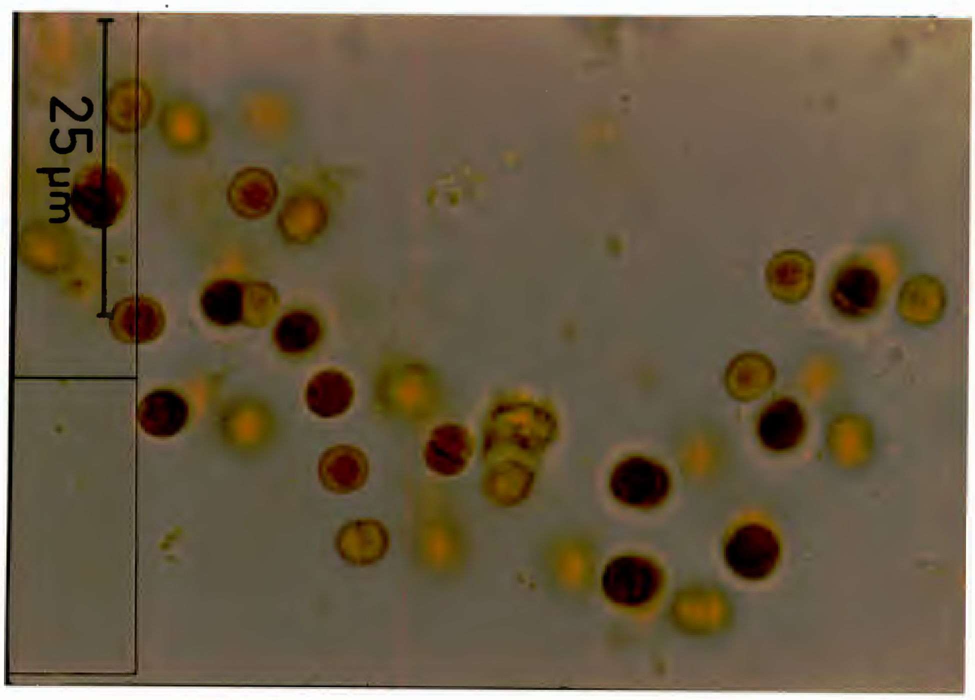

FIGURE 3: Chroococcus sp.

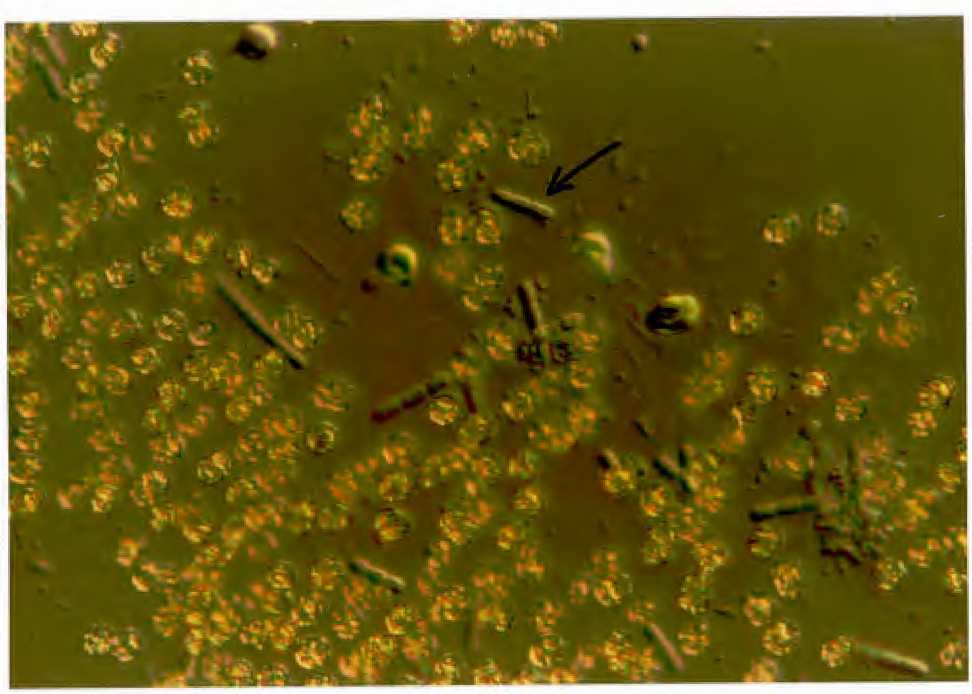

FIGURE 4: Microcystis sp. with Pseudanabaena sp. (arrowed)

FIGURE 5: <u>Oscillatoria</u> sp.

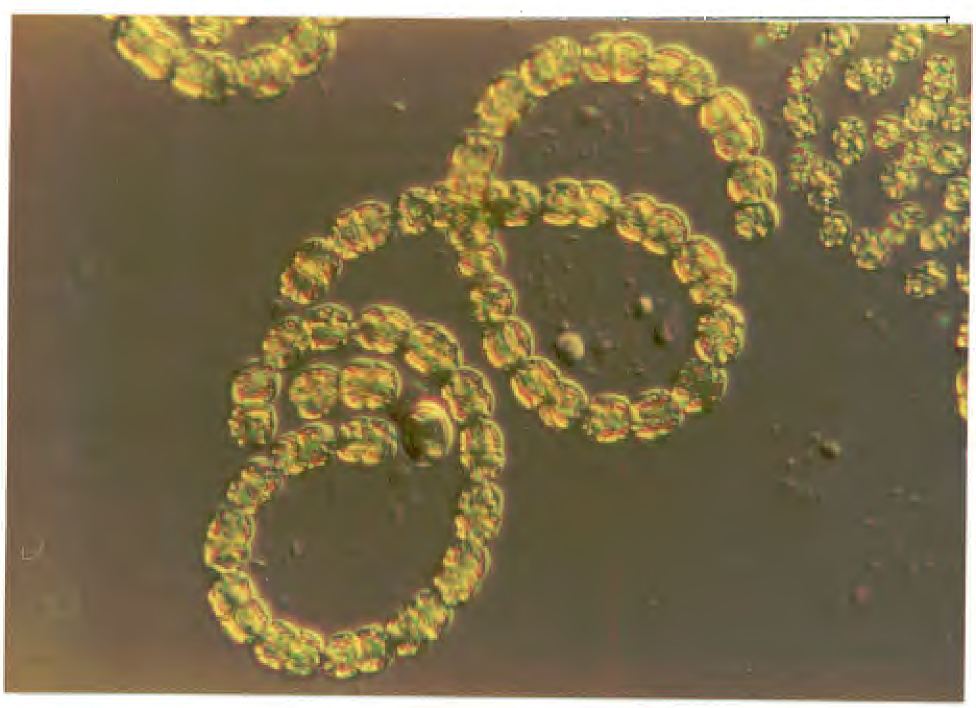

FIGURE 6: <u>Anabaena circinalis</u>

FIGURE 7: Anabaena sp.

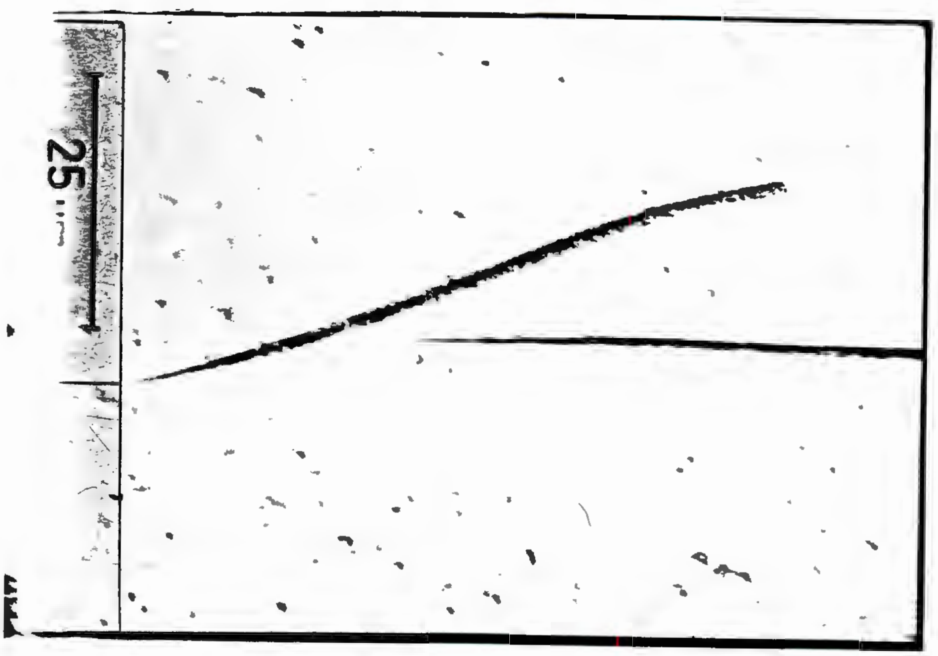

FIGURE 8: Raphidiopsis sp.

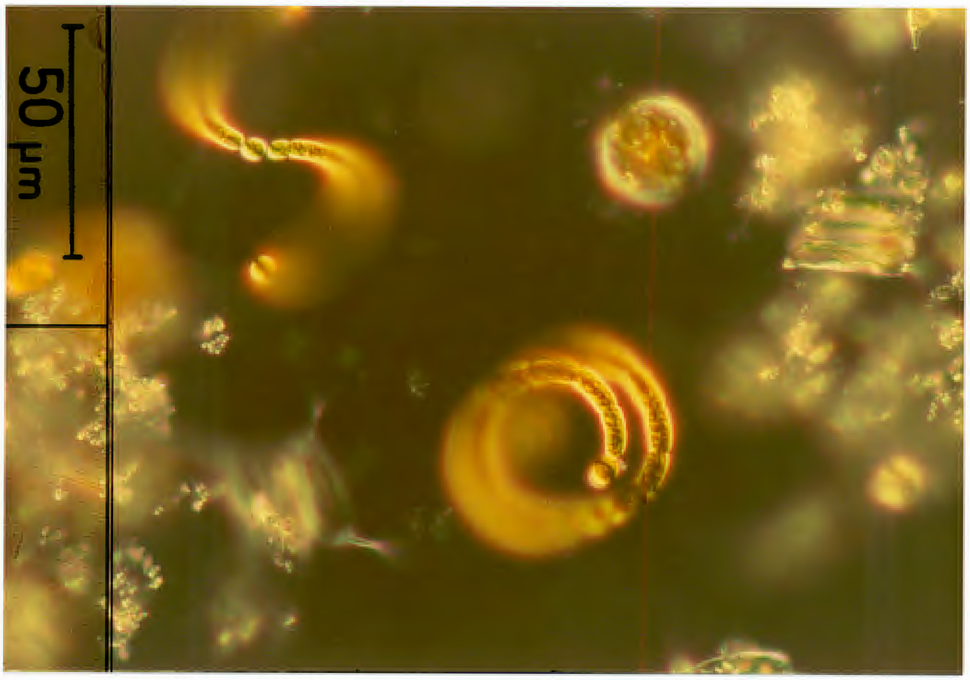

FIGURE 9: Anabaenopsis sp.

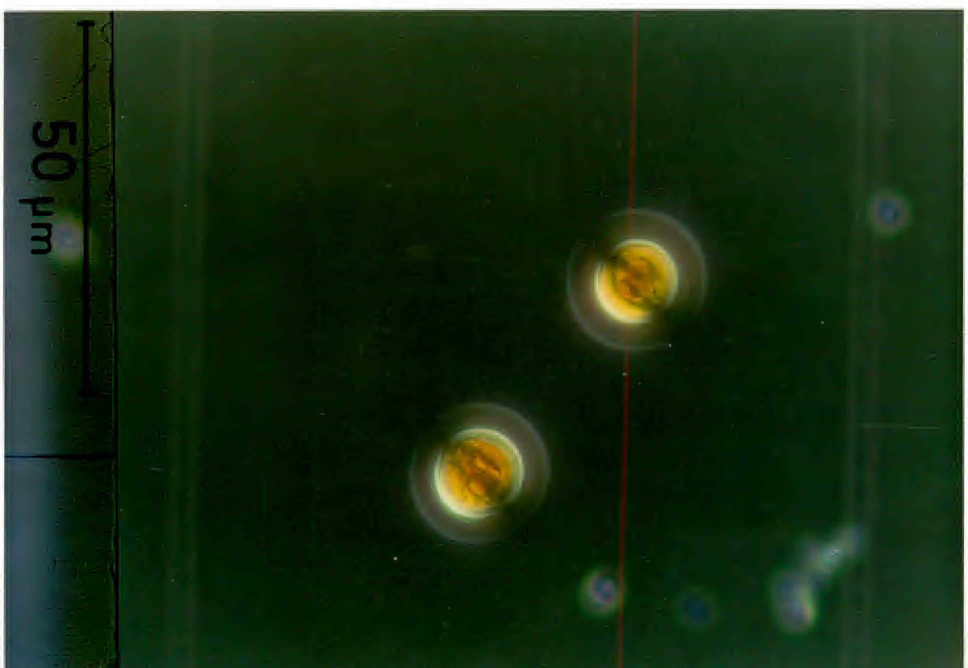

FIGURE 10: Gloeocystis sp.

FIGURE 11: Sphaerocystis sp.

FIGURE 12: Actinastrum sp.

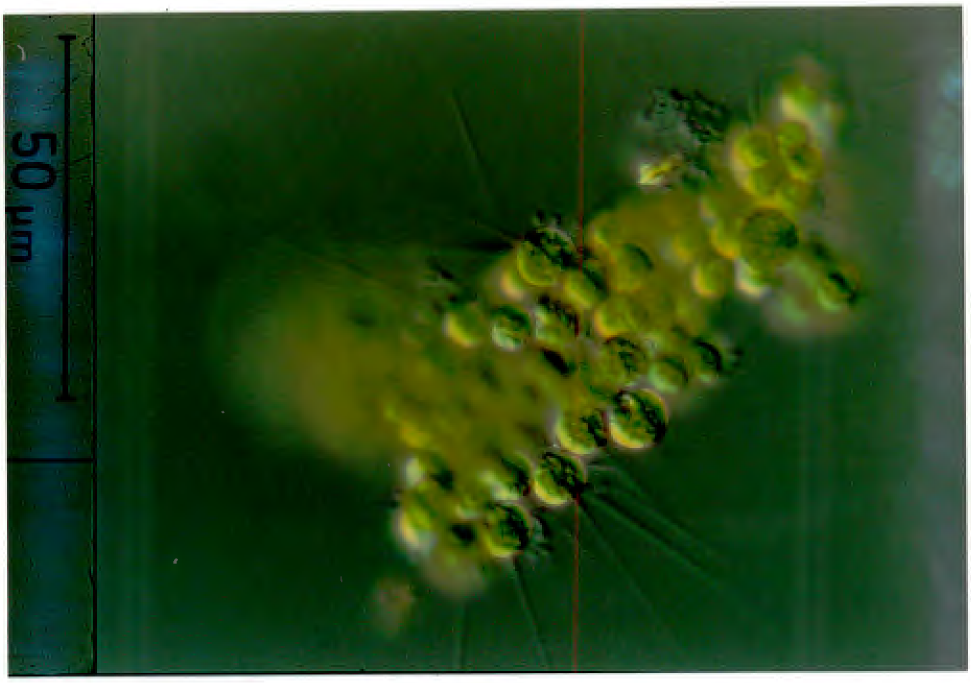

FIGURE 13: Micratinium sp.

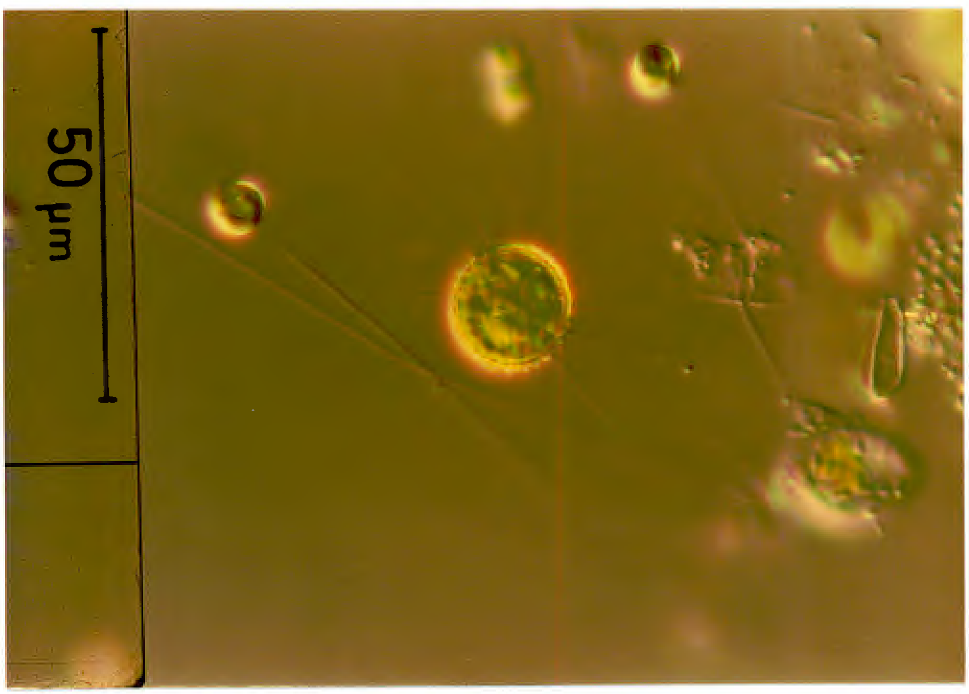

FIGURE 14: Golenkinia sp.

FIGURE 15: Schroederia sp.

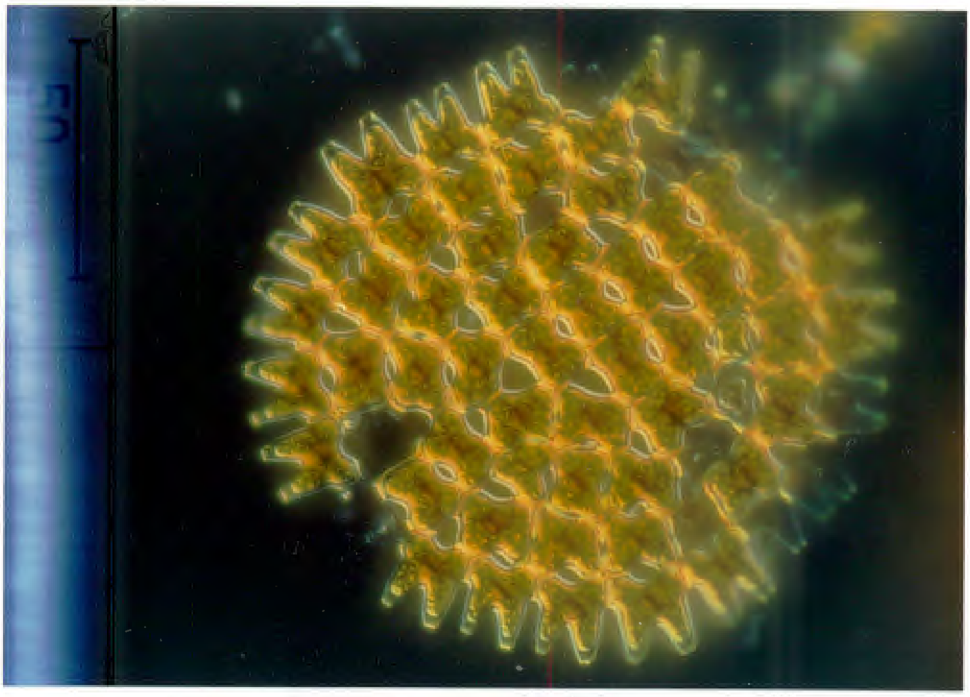

FIGURE 16: Pediastrum sp.

FIGURE 19: Tetraedron trigonum

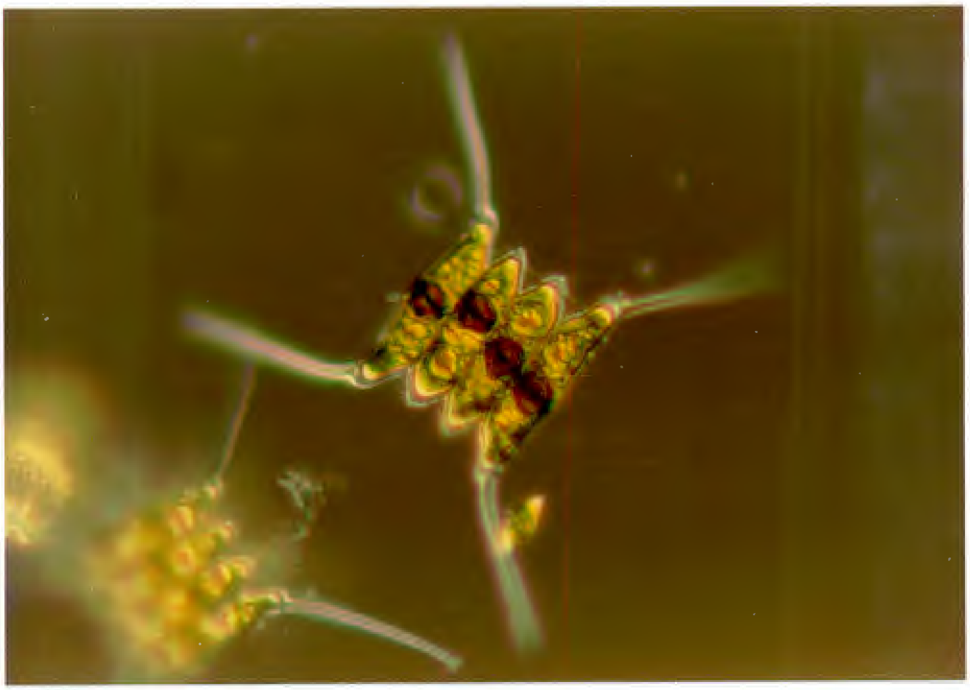

FIGURE 20: Scenedesmus sp.

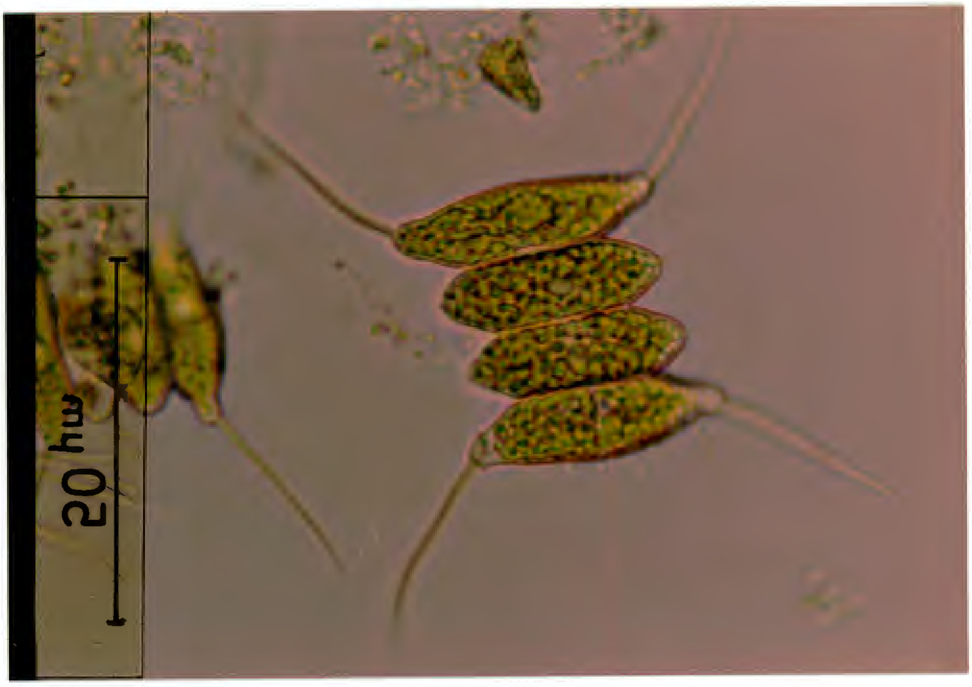

FIGURE 21: Scenedesmus sp.

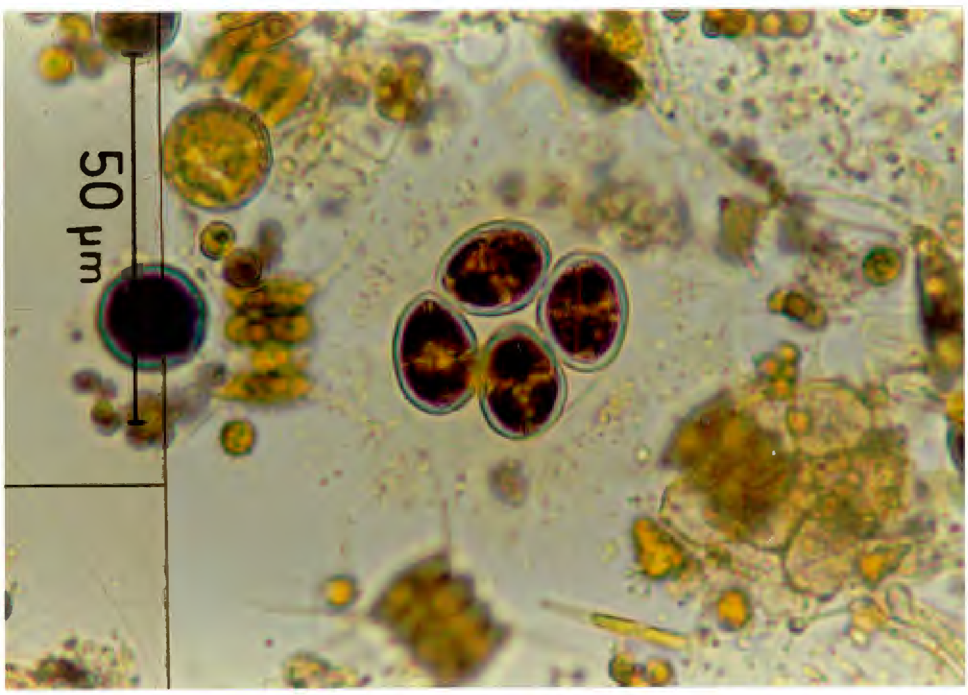

FIGURE 22: Oöcystis sp

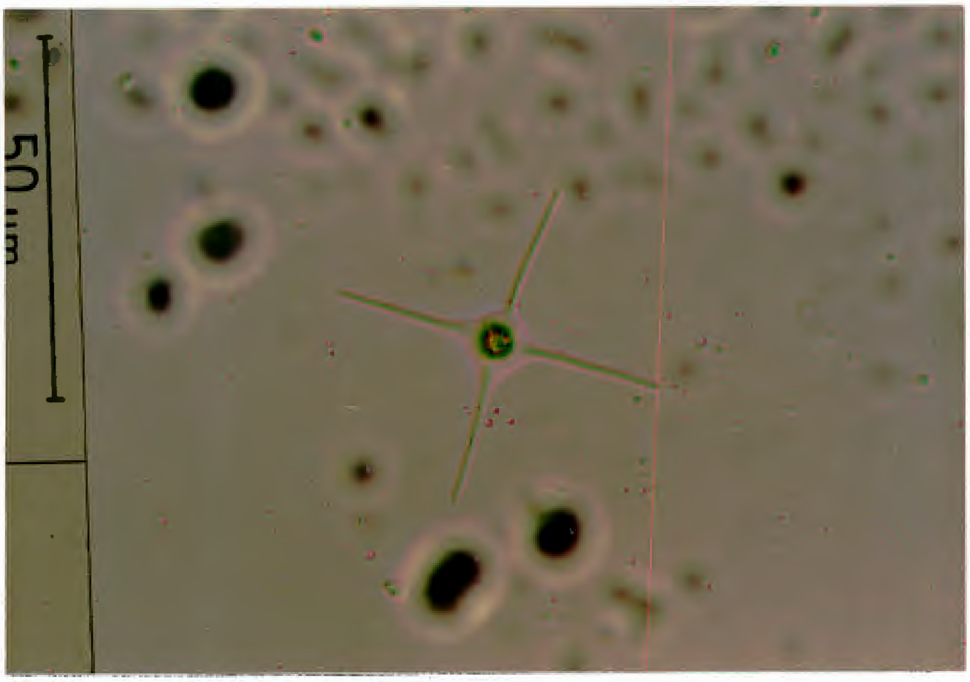

FIGURE 23: Pachycladon umbrinus (Oöcystaceae)

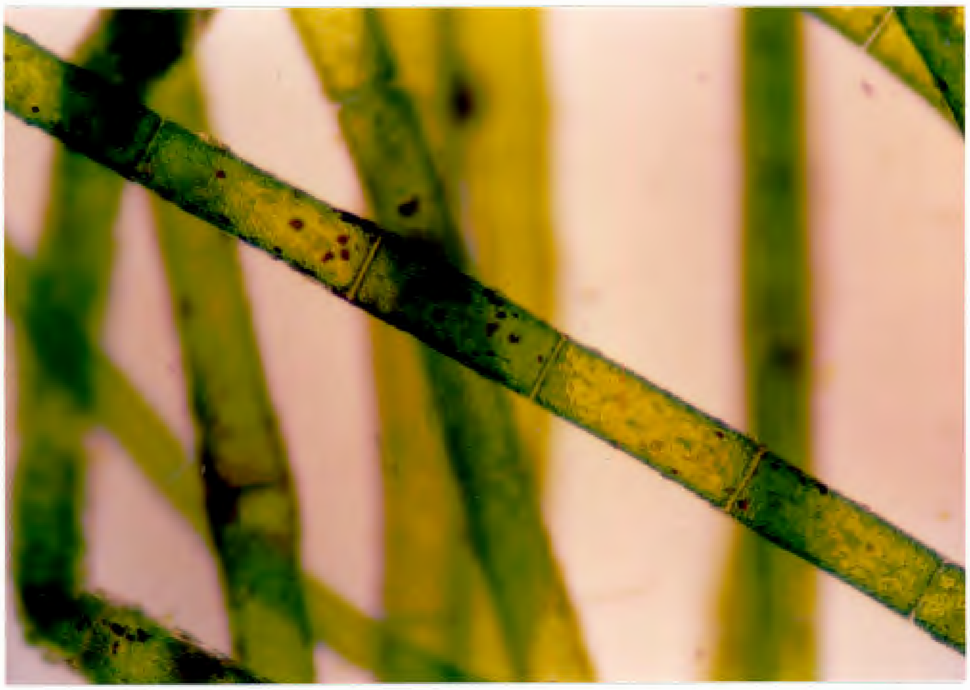

FIGURE 24: Rhizoclonium sp.

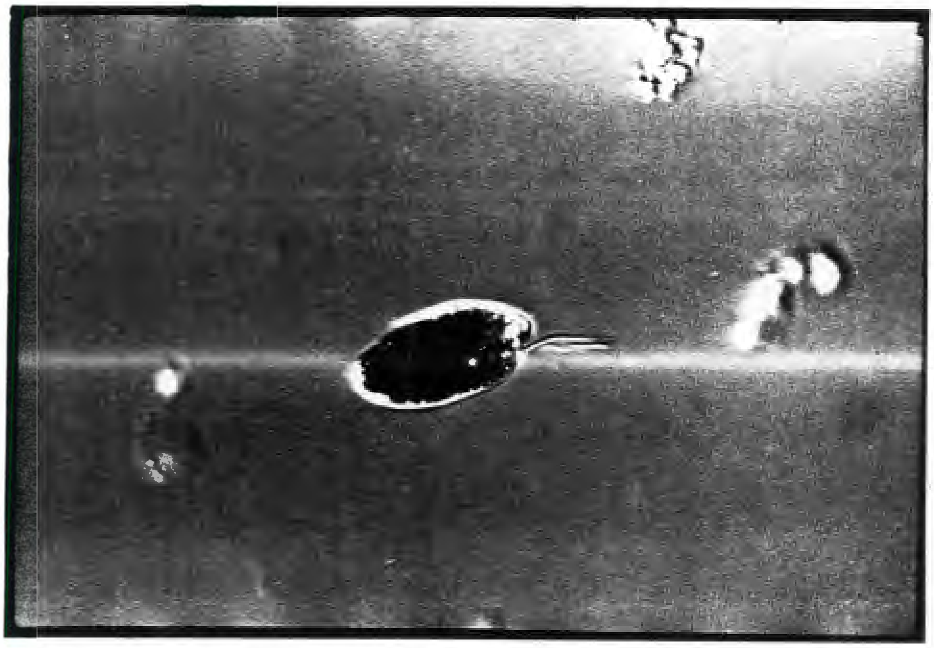

FIGURE 25: Cryptomonas sp.

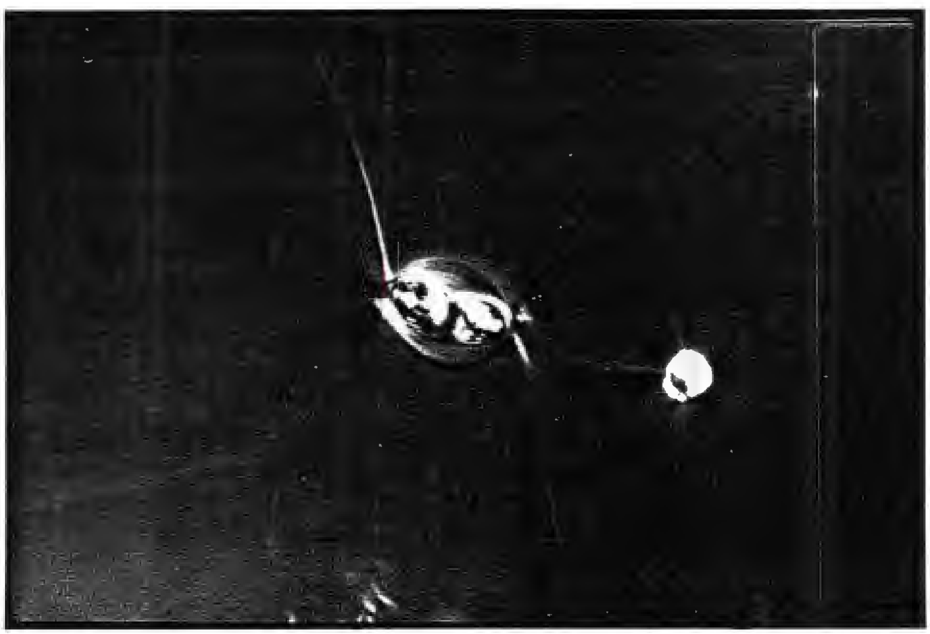

FIGURE 26: Chodatella sp.

FIGURE 27: Melosira sp.

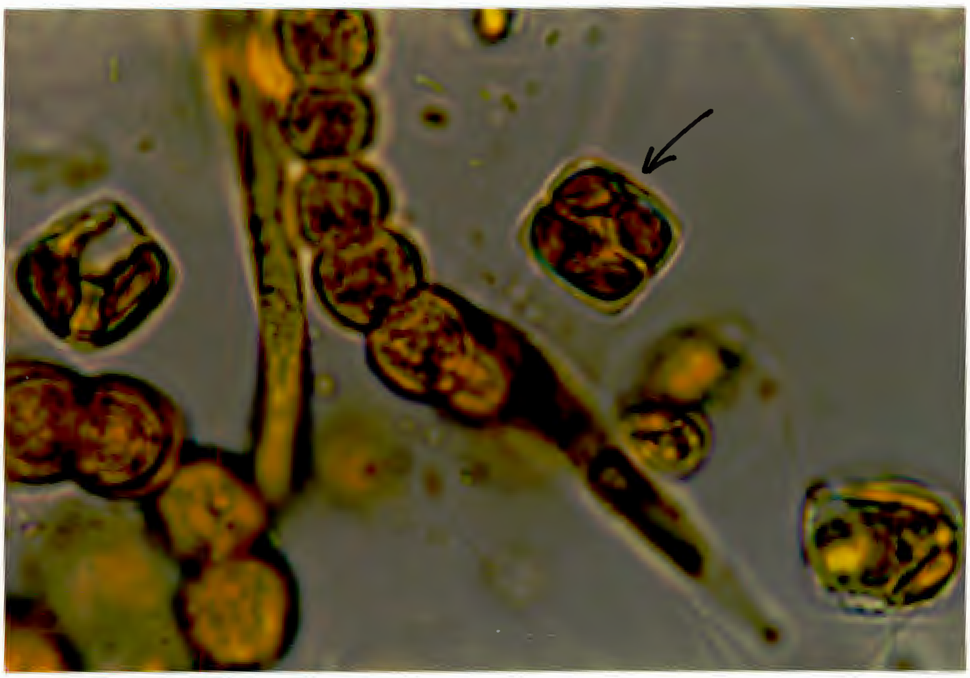

FIGURE 28: Thalassiosira nana (arrowed)

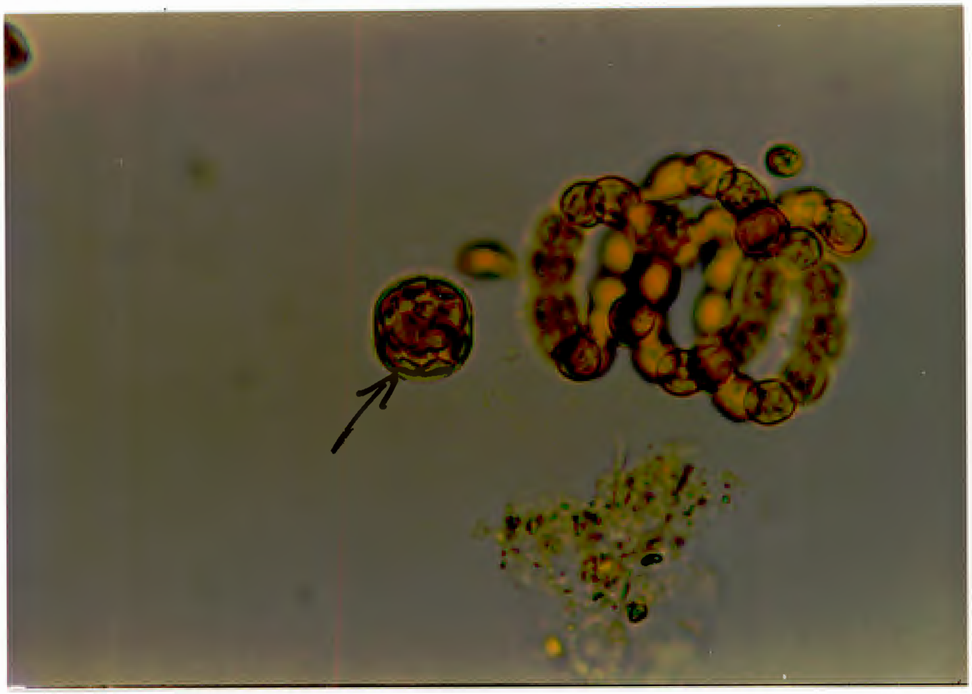

FIGURE 29: *Thalassiosira nana* (arrowed)

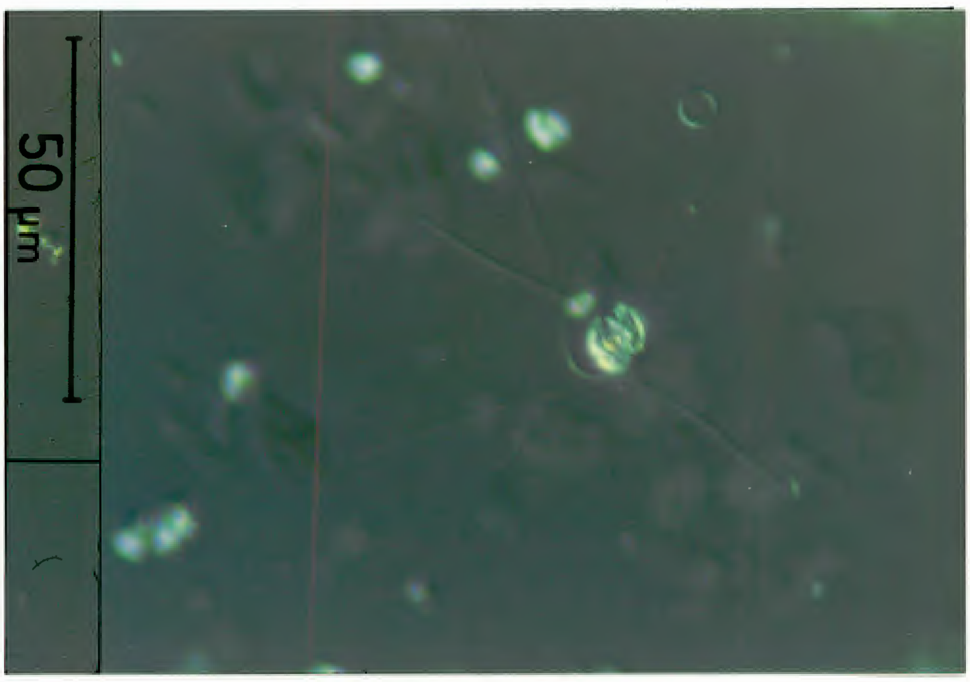

FIGURE 30: *Chaetoceros* sp.

FIGURE 31: Asterionella sp.

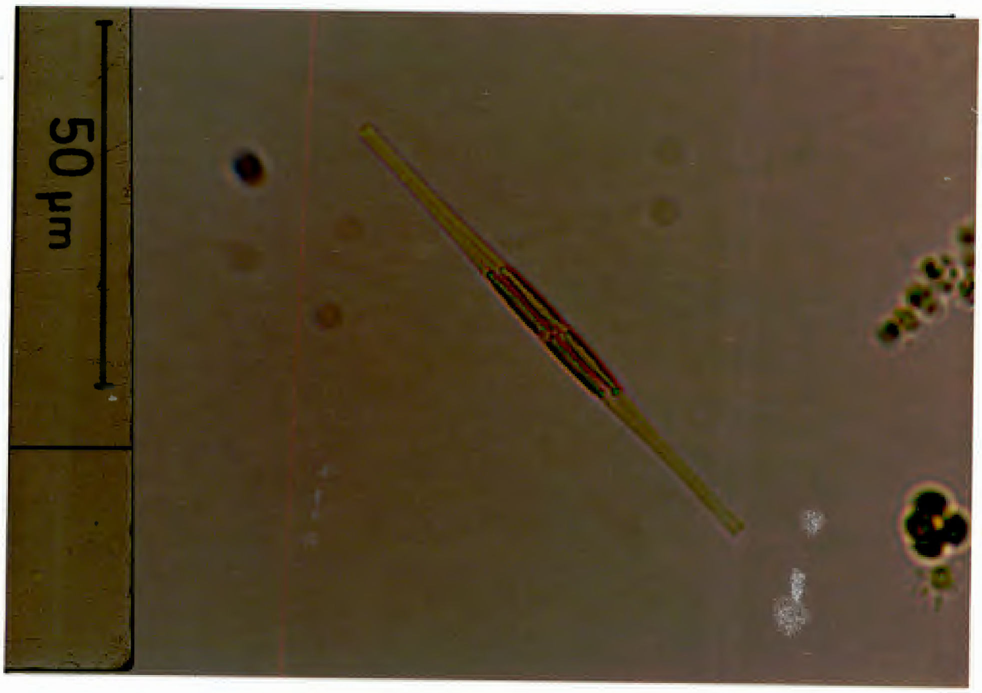

FIGURE 32: Nitzschia sp.

FIGURE 33: Nitzschia sp.

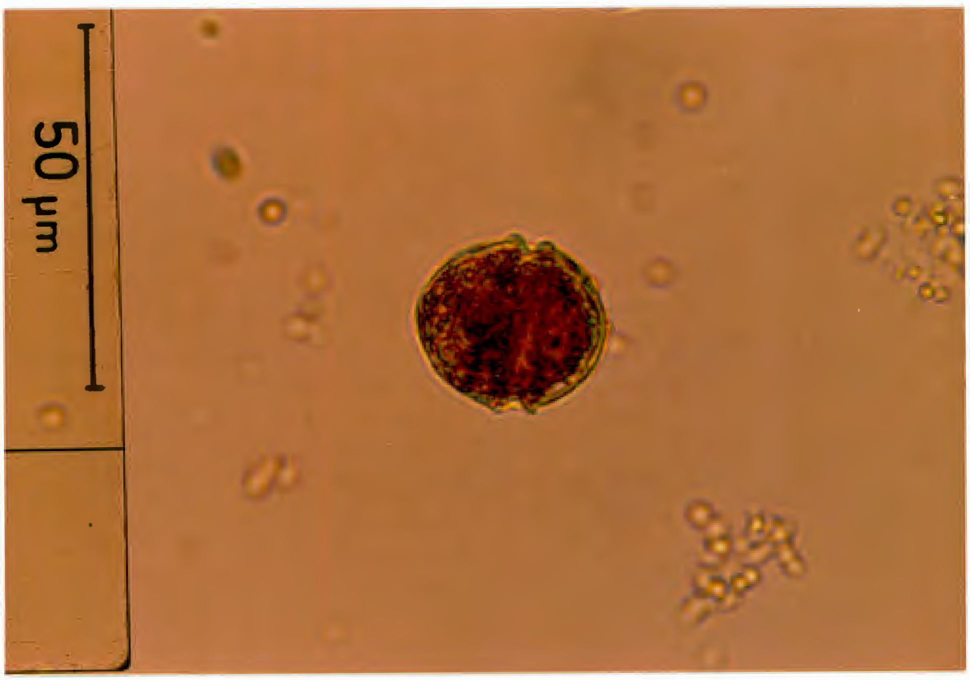

FIGURE 34: Dinoflagellate (unidentified)

FIGURE 35: Euglena sp.

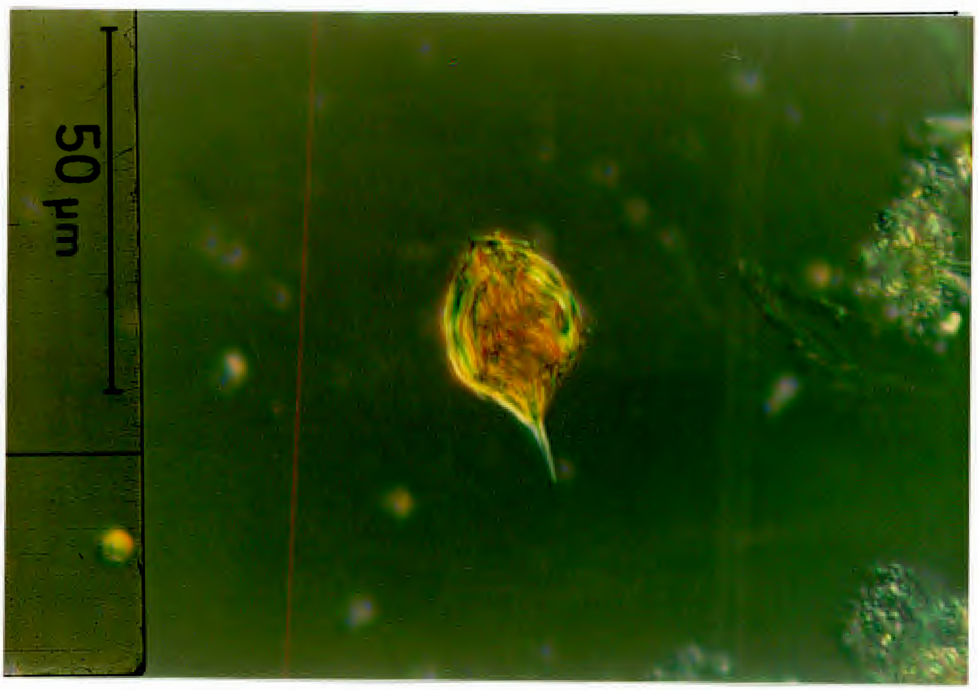

FIGURE 36: Phacus sp.