MODELLING THE WATER QUALITY IN IMPOUNDMENTS WITHIN THE UMGENI WATER OPERATIONAL AREA AND THE CONSEQUENCES FOR POTABLE WATER TREATMENT COSTS

Final Report to the

Water Research Commission

by

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EXECUTIVE SUMMARY

Introduction

Based on numerous years worth of water quality (including algal) and water treatment cost data, available at Umgeni Water, this study undertook to better understand the water quality relationships (particularly as they affected algae) in lakes within the company's operational area and to see how this water quality affected the cost of treating water from these lakes.

The principal aims of the study were:

1. Establish the key environmental variables influencing the distribution and abundance of problematic algae in lakes in the Umgeni Water operational area.

2. Establish a predictive model(s) relating algae to the environment for the major lakes in the Umgeni Water operational area.

3. Build an economic model relating water treatment costs to the types and numbers of algae likely to be found in lakes.

Models were developed relating algal abundance's with important water quality variables. In most cases, the models developed were related to algae that were known to adversely affect water treatment.

Thereafter lake water quality was statistically examined to determine which factors were most impacting on water treatment, and hence treatment costs, at selected waterworks (WW). Models were developed relating raw water quality entering respective water works with costs incurred in treating that water.

Algae/environment relationships

Lake Shongweni appears to be an extreme case of eutrophication - both in terms of its physico-chemistry as well as its algal composition. This created problems in data analyses (swamping the data) and it was therefore dropped from analyses. The remaining seven lakes viz. Midmar, Albert Falls, Nagle, Inanda, Henley, Nungwane and Hazelmere formed the focus of the study.

Many of the environmental variables investigated in this study were highly correlated with each other. This created problems in analysis of the data. The variation of the original large number of environmental variables (53) could be reasonably accounted for by a smaller number of 'key' environmental variables identified as conductivity, secchi depth, silicon, total inorganic nitrogen, total phosphorus, inflow, temperature, percentage dissolved oxygen and stability. These variables represented the primary aspects of variation in the environmental data and had intuitive biological appeal in that they are often implicated in the literature as influencing algal populations.

Low conductivity, low turbidity, 'inland' lakes (Midmar, Albert Falls, Nagle and Henley) were identified as distinct from more turbid 'coastal' lakes (Hazelmere, and to a lesser extent, Nungwane). Inanda was characterised by generally higher conductivities but low turbidities. Lakes Midmar, Albert Falls and Nagle neatly demonstrate the change in water quality with progression down the Mgeni River catchment. This progression is characterised by increased conductivities. Inanda, the last lake on the Mgeni system cascade, had the highest conductivities.

Weaker gradients (characterised by total inorganic nitrogen, total phosphorus and inflows) distinguished between Midmar, Nagle and Albert Falls (higher total phosphorus) and Nungwane and Henley (higher total inorganic nitrogen). Inanda was relatively 'mixed', experiencing a range of values for total inorganic nitrogen, total phosphorus and inflows.

Lakes with similar water-quality are more likely to respond similarly to management/perturbation.

The reduced set of 'key' environmental variables explained a low (16%), but statistically significant ($P < 0.01$) portion of the variability in the algal data. Of these variables, total inorganic nitrogen, silicon, temperature, inflow and secchi were the most important in explaining algal variability. This low amount of explained variation is not unusual for large multi-genera ecological data. Not all algae had appreciable amounts of their variability explained by analyses.

Anabaena and *Microcystis* (important blue-green algae) were responding to the higher (20–25°C) temperatures and inflow volumes associated with late summer conditions (January to April). They were also generally more abundant at the lower end of the total inorganic nitrogen (TN) gradient (low TN:TP ratio, < 20). Under these conditions they may become sufficiently abundant to cause water treatment problems (taste and odour formation).

Navicula, *Spermatozopsis* and *Mallomonas* were responding to higher silicon (> 5mg/ℓ) and TN (> 0.5mg/ℓ) and lower temperatures (15-20°C) and inflows. Cool (15-20°C), clear waters (with high secchi depths i.e. >1.5m), with low total phosphorus (<20µg/ℓ), favour *Crucigena* whilst waters generally low in TN (<0.5mgN/ℓ) and Si (<5mg/ℓ) favours *Melosira, Scenedesmus, Cyclotella* and *Tetraedron*. These waters are also generally clear (secchi > 2.0m) and have lower water column stability. *Cyclotella* and *Cosmarium* are abundant in autumn (March/April) whilst *Spermatozopsis* is likely to be more abundant in spring (August to October).

Unfortunately little may be said about *Chlorella*, a dominant or sub-dominant species in many lakes, as its variability is not well explained by the measured environmental variables. Some (unmeasured) factors, associated with seasons, appeared to be important in terms of its abundance and distribution.

From an algal composition point of view, Lakes Hazelmere, Nungwane and Inanda (and to a lesser extent Nagle) are most dissimilar from each other.

The difference appears primarily associated with low water clarity (high turbidities or low secchi depths). Given that they are all on entirely different river systems (except Nagle and Inanda on the Mgeni River), with different water qualities, this is not surprising. There is an interesting trend, as illustrated by the algal composition of lakes, from generally upper catchment (Henley), down the Mgeni system sequentially to the coastal lakes (Nagle and Inanda).

Within the bounds of the data *Chlorella* and *Anabaena* are the only algae which are ever really numerically and proportionally abundant in lakes.

There are large shifts in algal populations during the late summer period (February/March) through to midwinter (June/July) with another large shift again in early summer (September to November) through to late summer. The following genera most exemplify these shifts: *Chlorella* and *Anabaena* (increase in abundance in late summer), *Cyclotella* and *Cosmarium* (increase in autumn - March/April) and *Spermatozopsis* (increase in spring). These shifts are most probably associated with stratification changes in the water column.

Classical multiple regression modelling of important algae against environmental variables was unsuccessful with the predictive ability of all multiple regression models poor ($R_a^2 < 0.5$). The semi-quantitative empirical models, developed in ordination analyses, provided the best available predictive models for algae/environment relationships.

Water quality impacts on treatment costs

Lake water-quality clearly has a significant impact on the cost of treating water in each of the major waterworks (WW) examined.

The cost of treating water per mega litre (Mℓ) is highest at the Hazelmere WW (R41) followed by the Durban Heights (R 28), DV Harris (R25) and Wiggins

WW (R22). The cost of treating water in the Hazelmere system is almost double the others.

Within the range of the data analysed, abiotic water quality factors generally affected water treatment more significantly than algae, except where potentially powerful taste and odour forming algae (principally *Anabaena*) were present. The Nagle/Durban Heights WW system is most affected by taste and odour problems.

The model derived for the Hazelmere WW explains 79% of the variation in chemical treatment costs. The model predicts actual costs quite well and can be easily applied in simulation exercises.

Abiotic water quality factors have a particularly significant impact on treatment costs at the Hazelmere WW. Treatment costs increase when turbidity, total aluminium, manganese, suspended solids, potassium, sulphates, and total organic carbon concentrations in Lake Hazelmere water increase. Likewise, costs rise with lower water pH and alkalinity levels. Algae have a relatively minor impact on treatment costs at the Hazelmere WW.

Hazelmere is the only system analysed with water treatment problems associated with manganese (necessitating the use of a powerful oxidant, such as chlorine dioxide - which also increases treatment costs). During periods of lake turnover (when the water column de-stratifies) manganese (in the reduced form) should be very carefully monitored to limit its potential impact on water treatment (and hence costs).

A management strategy that reduces the turbidity of Lake Hazelmere would reduce water treatment costs at the Hazelmere WW.

The model estimated for the Durban Heights WW explains some 64% of the variation in chemical treatment costs. The model predicts actual costs well (except during occasional peak cost periods) and can be easily applied in simulation exercises. Treatment costs increased when levels of turbidity, suspended solids, total organic carbon, conductivity, total water hardness, potassium, nitrates and coliform bacteria rise in the raw water. Treatment costs rise with a fall in raw water pH and alkalinity (increasingly acidic conditions, requiring greater lime dosages to achieve a 4mg/ℓ $CaCO_3$ precipitation potential).

High numbers of the algae *Anabaena* and *Microcystis* in Lake Nagle has a major impact on treatment costs at the Durban Heights WW, particularly when they are producing taste and odour compounds. The results show that iron, manganese, total phosphorus, and *E. coli* do not add significantly to treatment costs. Initially the policy implications may be that resources should not be wasted on these apparent problems. However it is a well-known fact that total phosphorus has the potential to have a marked effect on algal abundances (particularly the blue-green algae which traditionally cause taste and odour problems). The results of algae/environment models presented in the first half of this report support this view.

The DV Harris WW model explains 67% of the variation in chemical treatment costs. Treatment costs increase when levels of alkalinity, total hardness, manganese and conductivity in Lake Midmar fall. Treatment costs also rise with declining numbers of *Chlorella*. Conversely, costs rise with higher concentrations of potassium and numbers of coliforms and *E.coli*. Results show that turbidity, silicon, suspended solids and total organic carbon do not significantly affect treatment costs at the DV Harris WW. This indicates that raw water in this system is traditionally clean with costs principally driven by the need to disinfect and stabilise (lime) the water. The "trend variable" in the DV Harris model indicates that over time treatment costs have been increasing in this system.

The Wiggins WW model explains 79% of the variation in chemical treatment costs. Treatment costs at the Wiggins WW increase with an increase in water turbidity, total aluminium, iron, suspended solids, nitrates, total organic carbon, total dissolved solids, silicon, coliform numbers, conductivity, total water hardness, potassium, nitrates, *Microcystis* and *Anabaena*. Conversely, treatment costs diminish with an increase in water pH and dissolved oxygen in the water. Again the "trend variable" indicates that over time treatment costs have been increasing in this system.

The study quantifies how an integrated catchment management strategy that would reduce both point and diffuse nutrient loads and turbidity in the lakes could reduce water treatment costs at the respective WW.

Water treatment cost prediction models developed have the potential to assist in catchment management by providing the tools for cost/benefit type analyses of the impact of land-use change on water treatment costs. Understanding of how catchment processes impact on in-lake processes is necessary however.

Various recommendations are presented for future data storage and accessibility (particularly associated with water treatment), whilst future research needs are highlighted.

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CHAPTER 1
INTRODUCTION

1.1 Background to the project

Likens (1988) has observed that long term monitoring data are sadly lacking for most aquatic systems and that monitoring programmes must continue for many years before any statistically defensible approaches can detect trends. Umgeni Water is in the fortunate situation in having more than seven years of continuous weekly limnological and algal data from all of the major lakes[1] in Umgeni Waters' operational area (Figure 1.1). This is probably the most complete and exhaustive long term monitoring data set available in the country for algae and their environment. This data covers eight lakes in Umgeni Waters' operational area and represents a range of nutrient states - from typically mesotrophic, in the upper catchments, to eutrophic conditions in the lower reaches. There are also records of the costs incurred in treating these waters for potable consumption.

This, therefore, provides a large and robust data set with which to begin modelling the algal populations for these lakes, as well as to begin building economic models of the various algal and water quality loadings on respective water treatment works (WW). There is also the potential to identify those alga (and their abundance) likely to occur under different water quality regimes. This will be of particular economic and planning benefit, where problematic algae (taste and odour forming, filter clogging etc.) are concerned, where these algae impact on the operation of water treatment works.

[1] The convention used for all impounded reservoirs studied in this report was 'lake'

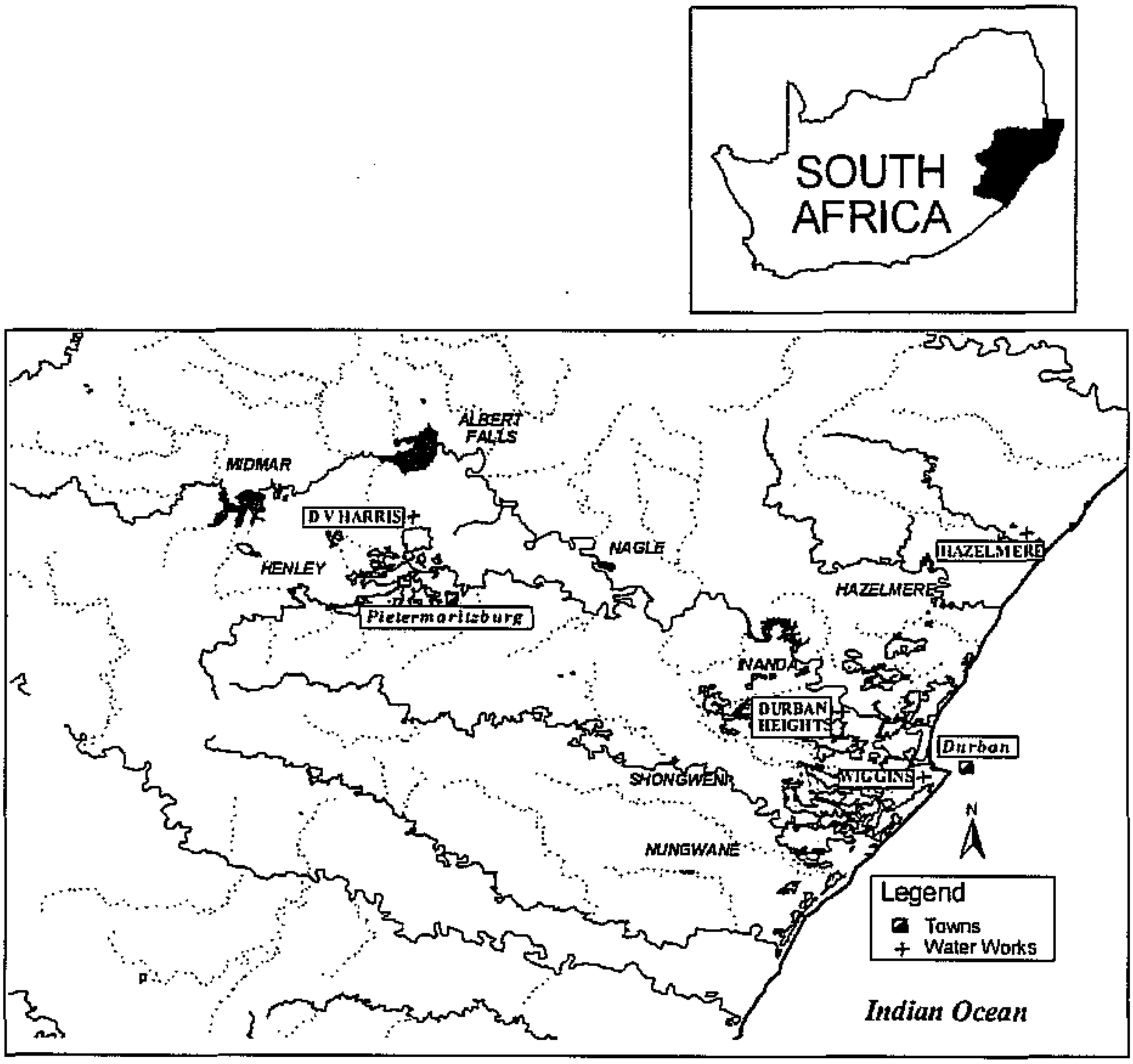

Figure 1.1 Geographical position of lakes and key water works studied in kwaZulu/Natal

Previous work (e.g. Varis *et al.* 1989; Dixit *et al.* 1992) has clearly demonstrated that algae are sensitive to many environmental characteristics, but that certain environmental variables have a larger and more significant impact than others. These variables tend to limit the distribution and abundance of the algae. Once algae/environment models have been established these may be integrated with economic models to provide a useful and powerful tool for catchment managers responsible for the provision of potable water and maintenance of environmental quality.

As noted by the South African authors, Grobler & Silberbauer (1984) well defined relationships for water quality variables which are able to be quantitatively related to water quality problems associated with eutrophication are sparse. This is a major limitation in predicting the impact of eutrophication control measures on water quality in SA. These authors go further to state that 'research to establish such relationships should receive a high priority.' This study begins to address these needs.

1.2 Project aims

The key project aims for this project are as follows:

1. Establish the key environmental variables influencing the distribution and abundance of problematic algae in lakes in the Umgeni Water operational area.

2. Establish a predictive model(s) relating algae to the environment for the major lakes in the Umgeni Water operational area.

3. Build an economic model relating water treatment costs to the types and numbers of algae likely to be found in lakes.

1.2.1 Report layout

This report is divided into six chapters of which this introductory chapter (covering the background to the work and the aims of the project) is the first.

Chapter 2 provides a brief summary of the study area, sources of the data used as well as summary statistics for the respective lakes studied. This covered both the abiotic (physico-chemical) and biotic (algal) nature of the different systems.

Chapter 3 deals with the analytical methods employed in analyses of both algae, and their relationship with their environment, as well as the water treatment cost models.

Chapter 4 provides a summary discussion of the relationships between environmental variables and how these relate to algal populations. This satisfies the first two aims of the project i.e. establishing the key environmental variables influencing algae and the predictive models relating algae to the environment. The limitations of classical regression modelling for this type of data were also noted in this chapter, as were the reasons for the development of more semi-quantitative models. These models covered most of the traditionally problematic algae affecting water treatment in the Umgeni Water operational area.

Chapter 5 covers the final aim i.e. building economic models relating treatment costs to water quality. Details on the derivation of models used here are to be found in Appendix 4.

Finally Chapter 6 provides a detailed summary of the study with conclusions. Recommendations for further work are also included in this chapter.

Appendix 1 describes in detail the sources, collection and manipulation of the data prior to statistical analyses. The approach to missing data, rationalisation of the number of different algal genera, and the calculation of nutrient loads is also dealt with in Appendix 1. Appendix 2 provides a detailed insight into the water quality and abiotic (physico-chemical) conditions of lakes studied. Statistical derivations of results covering the environmental effects on algal populations are covered in Appendix 3. Details on the derivation of economic models relating water quality variables to water treatment costs in the respective water works (WW) are presented in Appendix 4.

Appendices and other sections of the text are referred to in the body of the report with the appropriate section symbol §. Appendices are to be found at the end of this report.

CHAPTER 2
LAKES STUDIED

2.1 Introduction

This chapter provides a broad background to the lakes in the study and includes detail on their catchments and lake physical characteristics. A statistical summary is provided on their physico-chemistry as well as algal composition with the primary aim to describe the types of lake systems being considered in this study. The sources of the data used in analyses are also presented here. Greater detail on methods of manipulation and handling of the data prior to statistical analyses is presented in Appendix 1.

2.2 Study area

The extent of the study area, as well as the location of the eight lakes and various water works, has already been shown in Figure 1.1.

Except for Lakes Inanda and Nungwane detailed descriptions for all lakes may be found in Walmsley and Butty (1980) and for Midmar in Breen (1983). The Mgeni Catchment Management Plan (MCMP) document (1996) provides supplementary details. A general description of the catchments and their lakes, as they relate to this study, is presented below with more detailed information presented in Table 2.1. Summary statistics for the general physico-chemical condition of respective lakes over the study period are presented in Table 2.3. Further summary statistics are graphically portrayed where appropriate in the body of the report.

Table 2.1 Summary catchment and physical characteristics of the lakes studied

Parameters	Henley	Midmar	Albert Falls	Nagle	Inanda	Hazelmere	Nungwane	Shongweni
River system	Msunduze	Mgeni	Mgeni	Mgeni	Mgeni	Mdloti	Nungwane	Mlazi
Year completed	1960	1963	1975	1963	1989	1975	1978	1927
Altitude (m a.s.l.)	918	1021	630	300	115	61	346	300
Latitude (deg,min,sec)	29 37 23	29 29 42	29 25 50	29 35 31	29 42 29	29 36 00	30 00 26	29 51 39
Longitude (deg,min,sec)	30 14 15	30 12 16	30 25 39	30 37 41	30 52 04	31 02 37	30 44 43	30 43 17
Maximum depth (m)	10	22	26	34	44	24	24	14
Full supply level (FSL) (m)	24.1 *	22.2	21.6	24.1	31.2	24.9	16.7	22.5
Max volume (Mm^3)	3.74	177.76	290.72	24.61	251.75	17.81	2.24	7.16
Total catchment (km^2)	219	928	1644	2535	4082	377	58	786
Incremental catch (km^2)	220	927	721	886	1322	375	59	786
Max lake area (km^2)	0.321	15.64	23.87	1.56	14.63	1.81	0.29	0.81
FSL volume/area ratio	11.64	11.37	12.18	15.77	17.21	9.84	7.72	8.84

* Note the dam wall at Henley was lowered in 1991 to 24.1m from its previous height of 31.1m.

2.2.1 General catchment characteristics

The Mgeni River system (which has on it five of the lakes studied here) is of particular strategic significance in the province of kwaZulu-Natal (KZN) being one of the most developed catchments in South Africa. The lakes on this system supply the major Pietermaritzburg-Durban complex with some 45% of the population of the province dependent upon it. It also supports some 20% of the industrial output from the whole country (Town and Regional Planning Commission 1973) and 65% of the total economic production in KZN (MCMP 1996). The other major lakes studied (Nungwane and Hazelmere) are important sources of water for the KZN south and north coast regions respectively. Shongweni, on the Umlaas River system, although included in this study is no longer of significance as a water resource due its decommissioning in 1993.

To reiterate, the basic characteristics of respective lakes and their catchments are described in Table 2.1 with a statistical summary of the water physico-chemistry for the study period described in Table 2.3 as well as Appendix 2 § A2.2 & A2.3.

2.2.1.1 Midmar

Lake Midmar is sited in a broad valley in the upper Mgeni catchment. The Mgeni River here (which is the principal river feeding this lake) has an estimated mean annual runoff of $158.5 \times 10^6 m^3$ of generally good quality water with low suspended solids, low total dissolved solids and low nutrient concentrations (Walmsley & Butty 1980). Generally the soils in this catchment have a high phosphate (P) binding capacity (Scotney 1976) which makes P concentrations and loads low (Furness 1974; Walmsley & Butty 1980). Van der Zel (1975) identified that more than 50% of the catchment remains undeveloped grassland with most of the rest forestry, agriculture and stock raising. Scotney (1970) has identified the area as having a high rating for intensive agriculture. Nutrient concentrations entering the lake from other tributaries are generally low except for the Mthinzima Stream that drains the Mpophomeni township.

Walmsley and Butty (1980) describe the lake as a warm monomictic system with Hemens *et al.* (1977) indicating that it is oligo-mesotrophic. Walmsley (1977) confirmed this general observation and later noted that although not turbid by South African standards, the lake was unusual in increasing in turbidity in winter. Walmsley & Butty (1980) ascribe this to a combination of fine silt suspension from loose marginal and bottom sediments and intense water circulation of the wind exposed system.

2.2.1.2 Albert Falls

This, the largest lake on the Mgeni system, is situated below the town of Howick, between Midmar and Nagle. Its primary function is for potable water supply, acting as a storage lake and releasing water to the Mgeni River when required for the smaller Lake Nagle downstream.

Walmsley and Butty (1980) have classified this clear water, oligotrophic, phosphate limited lake as a warm monomictic system displaying normal pattern of summer stratification, autumn turnover and isothermal winter conditions. Unlike Midmar, turbidity in this system does not appear to increase in winter.

2.2.1.3 *Nagle*

This lake is midway down the Mgeni system, between Albert Falls and Inanda. It was the first reservoir to be built on the Mgeni (1950) to supplement supplies for the growing demands of Durban. It has a unique diversion weir and control gates at the head of the lake which allow floodwaters (with high suspended solid and nutrient loads) to be diverted around the lake. This, in combination with Albert Falls and Midmar upstream of it on the Mgeni, has resulted in it having a unique hydrological regime. It is now essentially a holding reservoir being maintained almost at full supply level by compensation water discharge releases from Albert Falls upstream. From here water is abstracted to a major water treatment works (Durban Heights Water Works) in the Durban metropolitan area.

Walmsley & Butty (1980) describe this reservoir as being a warm monomictic system with summer stratification, autumn turnover and a winter period of isothermal conditions. They go further to describe it as an oligotrophic phosphate limited system. Nevertheless, severe algal related problems have been experienced intermittently since 1987. This study illustrates some of the impacts of these algal related problems on water treatment (Chapter 5).

2.2.1.4 *Inanda*

This is the lowermost lake on the Mgeni River and was completed relatively recently in 1989. It boasts a large catchment area (Table 1.1) drained by the Mgeni and its major tributary the Msunduzi river. Activities in this catchment include extensive and intensive agriculture, urban development and informal settlements which supply significant nutrient loadings to the lake. The major point sources of nutrient loadings into the lake are from Darvill Wastewater Works in Pietermaritzburg and Cato Ridge Abattoir. Because of the high initial loads of Phosphorus (80 tonnes per year), and the retention of up to 80 % of this load, Inanda has been classified as eutrophic (Umgeni Water 1991). Consequently relatively high concentrations of algae persist throughout the year.

In terms of temperature and oxygen profiles, this lake is described as a warm monomictic system with summer stratification, an autumn turnover and uniform conditions during winter.

2.2.1.5 Shongweni

This is the oldest man made lake in kwaZulu-Natal (completed in 1927) but which is now essentially decommissioned as far as water supply is concerned. This decommissioning was primarily due to low yields and to the high allocthonous nutrient loads (and excessive algal growth) on this system. These loads are principally from an industrial complex and domestic sewage works in the catchments draining into this lake. This has made the water from this lake expensive to treat (Wilson 1992).

The lake is situated in a valley just below the original confluence of the Mlazi, Sterkspruit and WekeWeke rivers in an area dominated by quartzite and shales of the Table Mountain series of the Cape system. There are small outcrops of Dwyka tillite and shales of the Ecca series of the Karoo system in the upper catchment (Walmsley & Butty 1980).

Shongweni was included in this study as it was anticipated that it would usefully represent the upper end of the enrichment axis due to the extreme loadings. Table 2.3 indicates that this lake had the highest chlorophyll 'a' concentration (monthly mean 31μg/l) of any lake considered in this study.

This agrees with Walmsley and Butty's (1980) observation about the enriched state of this lake.

Walmsley and Butty (1980) note that the Mlazi (which drains 81% of the catchment) is frequently rich in nutrients since this catchment is dominated by agricultural activities as well as having a domestic wastewater works (WWW) discharging treated sewage directly into this river. The Sterkspruit (which only drains some 15% of the catchment) is also rich in nutrients (particularly nitrogen) having an industrial WWW discharging into this river. Very high conductivities (and hence mineralisation) in this lake (Table 2.3) are primarily associated with inputs from this latter river. This mineralised state was highlighted in the study (see § 4.2 & Appendix 2 § A2.2).

2.2.1.6 Hazelmere

This coastal lake, situated on the Mdloti River, drains an essentially undeveloped catchment with sugar cane the dominant agricultural interest. The Mdloti is the only major input into this lake. It was completed in 1977 making it one of the younger lakes in this study.

Walmsley and Butty (1980) identified high silt loadings from the catchment as well as occasionally high nutrient loadings. The former they attribute to poor soil conservation in the catchment making for generally turbid conditions for much of the year. Of all the lakes studied this had the highest recorded average monthly silicon concentrations (9.2mg/ℓ) with Walmsley and Butty (1980) noting it to be a turbid system for most of the year and certainly one of the most turbid systems in kwaZulu-Natal. This was borne out in this study where it was also shown as a principal factor affecting water treatment costs.

Walmsley and Butty (1980) classified the lake as a warm monomictic system with phosphate likely to be the limiting nutrient.

2.2.1.7 Henley

This is a relatively small lake ($3.7x10^6m^3$) situated in the upper catchment of the Msunduzi River which was originally designed and built (1943, wall raised 1959) for potable water supply to Pietermaritzburg. It is currently (1997) not used for water supply purposes. The mean annual runoff from the Msunduzi (some 80% of the total inflow to the lake (Walmsley & Butty, 1980)) is seven times the capacity of the lake and therefore greatly influences the quality of the water in the system.

Walmsley and Butty (*op. cit.*) note the lake to be a warm monomictic system with a long period of summer stratification, a short overturn and a period of isothermal conditions during winter before reformation of stratification in summer. These authors classify the lake as oligo-mesotrophic although cautioning that this may change in dry years when inflows are reduced. This is primarily because the system is so dependent on its flushing rate (a function of the inflow and small capacity).

2.2.1.8 Nungwane

This is the smallest of the lakes (Table 1.1) studied here which supplies water to the coastal areas just south of Durban after it has been treated at Amanzimtoti Waterworks. The lake is relatively high up in its catchment on the Nungwane River. The river has a few minor tributaries before draining into the Lovu River just below the lake. The catchment area is mainly (86 %) extensively cultivated land with the remainder natural trees and bush (Umgeni Water 1994).

Unfortunately there are no gauging weirs measuring the nutrient loads into the lake but installation of these is currently (1997) under way. Therefore all the data available on loads had to be estimated using a model which indicates that phosphorus loads into the lake are generally low (maximum of 2 tones per year). The temperature and oxygen profiles indicate that the lake has a warm monomictic system with summer stratification, late autumn turnover and is isothermal in winter.

2.3 Sources of data

Umgeni Water has an extensive water quality monitoring programme covering a range of sites in all of the major lakes and waterworks (WW) within its operational area. This provided most of the data used in analyses for this study. Water chemistry determinands and algal counts are accredited in terms of ISO/IEC Guide 25.

The modelling of algae/environment relationships was based on sites monitored in the lakes' *main-basins*, for the five-year period from 1990 to 1994. By contrast, the economic models developed used, wherever possible, the water quality measurements made on the *raw-water* inlets to the respective WW (for the seven year period from 1990 to 1996). Abstracted (raw) water and lake main-basin water quality's are likely to differ in certain respects.

Further supplementary environmental variables (e.g. weather) had to be derived from other sources. Several new determinands were derived from those present in the original data set. For example: Total Inorganic Nitrogen (TNE3), from the summation of nitrite (NO_2), nitrate (NO_3) and ammonia (NH_3); and ratios from some of the original determinands (e.g Total inorganic Nitrogen and Total Phosphorus ratios, TN:TP).

Chemical cost data were determined at December 1996 prices (Appendix 4, Table A4.1). Prices relate to the brand of chemicals most frequently used in the treatment of water at respective WW. Costs were expressed in South African Rands per mega-litre (Mℓ) of water treated, and refer only to expenditure on chemicals. Unfortunately no operational cost data, such as electricity consumption, backwash times etc. were available for respective

WW. Data on water quality recorded at specified sample points at each plant were expressed in monthly terms to coincide with average monthly measures of treatment chemical usage.

The names (acronyms, units and an indication of their source) of all environmental variables considered in this study are presented in Table 2.2. Summary descriptive statistics for these data in respective lakes is provided in Table 2.3 with an indication of the algal composition in respective lakes shown in Figure 2.1.

The acronyms used to represent algal genera, as well as their potential impact on water treatment, are also shown in Table 2.4. The complete list of 89 algae analysed by Umgeni Water and initially considered for analyses is presented in Appendix 1. The number of algal genera considered in analyses was rationalised from 89 to 32. The protocol adopted in rationalising the algae in this study is detailed in Appendix 1 (§ A1.5.1). This reduced the algal data set by some 64% where the remaining algae (Table 2.4) were determined to be the generally more abundant and, from a water treatment point-of-view, problematic algae. If a genus was in low abundance (rare) but the literature considered it to significantly affect water treatment then it was retained in the data set.

Summary abundance statistics for key genera in all lakes, except for Shongweni, are summarised by class and presented in Figures 2.2 to 2.4. It should be noted that three algal genera (*Microcystis, Anabaena* and *Chlorella*) made up the bulk of the total algal count (Fig. 2.2a) in this study. For the most part the blue-green algae (*Microcystis* and *Anabaena*) dominated the total algal count in Lake Shongweni (Appendix 2).

Table 2.2 Summary of all environmental variables used in analyses along with their relevant method of extraction, acronyms, units and source

Environmental variables	Extraction technique	Variable acronyms	Units	Derived from LIMS	Modified from LIMS data	Derived from supplementary sources
Water column stability index		StabE4	s^{-2}		Yes	
Wind speed		WnSp	m/s			Yes
Wind direction		WnDir	°			Yes
Sun hours		SHrs	hours			Yes
Total Phosphorus load		TPLDE-1	kg/ha/yr		Yes	
Soluble Reactive P load		SRPLD	kg/ha/yr		Yes	
Total inorganic Nitrogen load		TNLDE-3	kg/ha/yr		Yes	
Total inorganic Nitrogen		TNE3	mgN/ℓ	Yes		
Photic-zone Temperature		Temp	°C		Yes	
Chlorophyll 'a'		Chl	ug/ℓ	Yes		
Secchi depth		Secc	m	Yes		
pH		pH		Yes		
Turbidity		turb	NTU	Yes		
Conductivity		cond	ms/m	Yes		
Total Aluminium	acid	TAl	ug/ℓ	Yes		
Alkalinity		alkal	mg/ℓ $CaCO_3$	Yes		
Hardness		hardness	mg/ℓ $CaCO_3$	Yes		
Calcium	acid	Ca	mg/ℓ	Yes		
Magnesium	acid	Mg	mg/ℓ	Yes		
Sodium	acid	Na	mg/ℓ	Yes		
Potassium	acid	K	mg/ℓ	Yes		
Iron	acid	Fe	mg/ℓ	Yes		
Manganese	acid	Mn	mg/ℓ	Yes		
Silicon	acid	Si	mg/ℓ	Yes		
Nitrate		NO_3	mgN/ℓ	Yes		
Nitrite		NO_2	mgN/ℓ	Yes		
Ammonia		NH_3	mgN/ℓ	Yes		
Chloride		Cl	mg/ℓ	Yes		
Fluoride		F	ug/ℓ	Yes		
Sulphate		SO_4	mg/ℓ as SO_4	Yes		
Total Phosphorus	total acid	TP	ugP/ℓ	Yes		
Soluble Reactive P		SRP	mgP/ℓ	Yes		
Total N : Total P ratio		TN/TP			Yes	
Total N : Soluble Reactive P ratio		TN/SRP			Yes	
Total N : Si ratio		TN/Si			Yes	
Total P : Si ratio		TP/Si			Yes	
Sol. Reactive P : Si ratio		SRP/Si			Yes	
Total Dissolved Solids		TDS	mg/ℓ	Yes		
Suspended Solids		SS	mg/ℓ	Yes		
Copper	acid	Cu	mg/ℓ	Yes		
Zinc	acid	Zn	mg/ℓ	Yes		
Lead	acid	Pb	ug/ℓ	Yes		
Cadmium	acid	Cd	ug/ℓ	Yes		
Chrome	acid	Cr	ug/ℓ	Yes		
Mercury	total acid	Hg	ug/ℓ	Yes		
Selenium	total acid	Se	ug/ℓ	Yes		
Nickel	acid	Ni	ug/ℓ	Yes		
Total Organic Carbon		TOC	mg/ℓ as C	Yes		
Biological Oxygen Demand		BOD	mg/ℓ O_2	Yes		
Dissolved Oxygen		DO	mg/ℓ O_2	Yes		
Percent Dissolved Oxygen		% DO	%	Yes		
Total Kjeldahl Nitrogen		TKN	mgN/ℓ	Yes		
Inflow (adjusted for lagging effect)		inflowa	Mℓ/day		Yes	Yes (for Shongweni)

Table 2.3 Summary descriptive statistics for lake physico-chemistry

Physico-chemical variable	Units	Albert Falls monthly data summary N	Min	Max	Mean	CV	Hazelmere monthly data summary N	Min	Max	Mean	CV	Henley monthly data summary N	Min	Max	Mean	CV	Inanda monthly data summary N	Min	Max	Mean	CV
Stability	s^{-1}	60	-0.3	9.5	3.1	80.2	54	-0.5	9.2	4.1	72.5	59	0.1	18.9	4.9	92.6	59	-0.2	5.5	2.0	80.4
Wind speed	m/s	60	1.0	5.7	2.3	41.5	54	1.0	7.1	3.7	36.4	59	1.0	7.0	2.5	44.0	59	1.3	6.5	3.8	33.2
Wind direction	degrees	60	25.7	203.3	84.3	46.8	54	32.0	262.3	128.5	42.8	59	23.5	228.7	94.1	40.8	59	45.0	224.7	129.0	36.5
Sunhours	hours	60	0.6	10.6	7.3	30.1	54	0.5	11.4	6.4	27.4	59	3.6	11.1	7.9	22.6	59	0.9	10.8	6.9	31.1
TP load	kg/ha/yr	60	78	5840	719	1477	54	16	1439	249	1238	59	3	4133	632	1448	59	430	24241	3015	1371
SRP load	kg/ha/yr	60	15	934	112	134	54	4	154	33	108	59	1	112	18	119	59	186	6352	1131	104
TN load	kg/ha/yr	60	630	67490	7332	54583	54	210	17640	3664	17312	59	860	11660	13266	26379	59	1570	95480	23669	37621
Total Inorganic Nitrogen	mgN/l	60	0.058	0.995	0.358	0.043	54	0.192	1.962	0.704	0.051	59	0.353	1.652	0.800	0.040	59	0.062	0.785	0.360	0.052
Temperature	degrees	60	13.7	27.1	20.6	18.9	54	15.6	26.8	22.5	15.6	59	11.1	25.9	19.1	21.7	59	15.5	27.9	22.0	15.8
Chlorophyll a	ug/l	60	0.6	10.5	3.8	58.7	54	0.4	42.3	4.6	162.7	59	0.6	25.7	4.7	92.6	59	0.8	23.6	5.8	67.7
Secchi	m	60	0.2	2.2	1.3	38.9	54	0.1	1.1	0.4	60.8	59	0.1	4.2	1.7	52.4	59	0.7	2.7	1.7	28.1
pH		60	7.2	8.4	7.7	3.4	54	7.2	8.1	7.7	2.7	59	6.4	8.1	7.5	3.7	59	6.6	8.5	7.9	4.0
Turbidity	NTU	60	2.4	57.5	14.7	96.2	54	13.6	235.0	59.7	78.0	59	1.7	193.0	16.0	167.7	59	1.1	79.6	6.1	182.0
Conductivity	mS/m	60	6.5	8.9	7.8	9.7	54	13.3	24.9	17.8	14.8	59	6.0	12.2	8.3	15.0	59	12.5	29.0	21.7	18.6
Total Aluminium	ug/l	60	21.0	1008.3	138.3	122.8	54	53.3	1345.3	483.8	66.1	59	19.0	1136.3	140.0	146.0	59	7.3	179.0	48.7	65.2
Alkalinity	mg/l $CaCO_3$	60	21.3	31.1	25.6	10.2	54	24.4	59.7	41.5	23.3	59	12.6	44.2	27.3	22.7	59	24.8	66.1	53.6	15.2
Hardness	mg/l $CaCO_3$	60	18.3	28.9	24.3	10.0	54	15.4	50.5	37.8	19.2	59	16.5	37.3	24.8	16.8	59	32.1	78.1	53.6	16.6
Calcium	mg/l	60	4.0	5.7	4.7	10.0	54	2.1	8.3	5.9	21.9	59	3.0	7.7	4.7	18.9	59	6.2	16.5	11.0	19.9
Magnesium	mg/l	60	2.4	3.6	3.0	10.2	54	4.2	7.6	5.6	15.2	59	2.1	4.3	3.1	15.7	59	4.0	8.9	8.2	14.1
Sodium	mg/l	60	4.1	7.3	5.3	12.3	54	15.4	26.6	20.3	14.1	59	4.2	8.5	6.2	17.2	59	12.3	31.0	22.5	23.5
Potassium	mg/l	60	0.8	1.9	1.4	18.3	54	0.9	3.1	2.1	21.9	59	0.5	2.5	1.2	30.0	59	1.4	3.9	2.6	23.8
Iron	mg/l	60	0.1	2.5	0.6	73.9	54	0.6	5.5	2.1	55.2	59	0.1	1.8	0.4	77.5	59	0.0	0.7	0.2	78.6
Manganese	mg/l	60	0.0	0.1	0.0	52.6	54	0.0	0.2	0.1	74.6	59	0.0	0.3	0.0	100.0	59	0.0	0.2	0.0	87.7
Silicon	mg/l	60	2.4	5.8	4.0	19.7	54	5.9	13.2	9.2	13.4	59	3.5	8.7	5.7	17.1	59	0.5	6.7	2.8	56.3
Nitrate	mgN/l	60	0.0	0.9	0.3	47.6	54	0.1	1.8	0.6	56.8	59	0.1	1.4	0.6	50.9	59	0.0	0.7	0.3	61.1
Nitrite	mgN/l	60	0.0	0.0	0.0	0.0	54	0.0	0.0	0.0	0.0	59	0.0	0.1	0.0	25.3	59	0.0	0.0	0.0	4.3
Ammonia	mgN/l	60	0.0	0.1	0.0	58.4	54	0.0	0.2	0.1	73.8	59	0.0	0.8	0.2	90.0	59	0.0	0.2	0.0	85.3
Chloride	mg/l	60	4.6	7.9	5.8	12.9	54	19.4	38.9	25.8	15.9	59	5.3	8.1	6.4	10.2	59	14.6	38.0	27.6	22.3
Flouride	ug/l	60	27.9	69.4	41.4	18.3	54	37.5	158.0	59.6	49.2	59	20.7	38.8	35.5	11.1	59	37.5	175.0	62.0	62.1
Sulphate	mg/l as SO_4	60	2.7	4.8	3.5	13.3	54	3.7	12.9	5.5	39.9	59	2.1	4.4	2.6	16.8	59	6.6	20.4	12.3	25.3
Total Phosphorus	ugP/l	60	7.5	94.7	28.4	71.0	54	7.5	98.2	33.4	58.7	59	7.5	98.3	25.1	70.1	59	7.5	53.0	16.5	63.9
Soluble Reactive Phosphorus	ugP/l	60	1.5	10.9	3.5	66.1	54	1.5	18.0	5.9	56.1	59	1.5	11.5	3.9	67.5	59	1.5	16.2	3.5	73.2
TN:TP		60	4.1	84.2	24.3	79.4	54	8.4	239.1	37.7	90.3	59	10.0	184.2	55.2	73.3	59	1.8	105.1	35.8	88.1
TN:SRP		60	17.0	663.3	141.3	77.2	54	34.4	605.3	204.1	57.8	59	77.4	907.8	354.4	52.6	59	17.4	398.9	168.8	58.2
TN:Si		60	0.0	0.2	0.1	33.9	54	0.0	0.2	0.1	43.7	59	0.1	0.4	0.1	37.8	59	0.0	0.9	0.2	90.2
TP:Si		60	0.0	0.0	0.0	73.4	54	0.0	0.0	0.0	53.7	59	0.0	0.0	0.0	62.9	59	0.0	0.0	0.0	84.2
SRP:Si		60	0.0	0.0	0.0	66.9	54	0.0	0.0	0.0	54.0	59	0.0	0.0	0.0	71.3	59	0.0	0.0	0.0	66.1
Total Dissolved Solids	mg/l	60	30.0	81.6	52.9	16.6	54	35.3	196.4	135.4	15.6	59	32.6	109.5	64.6	23.8	59	48.6	213.6	124.5	19.8
Suspended Solids	mg/l	60	2.0	48.2	10.8	81.1	54	2.8	134.0	25.9	96.3	59	2.0	116.7	11.8	145.2	59	2.0	43.1	6.3	101.5
Copper	mg/l	60	0.0	0.3	0.0	162.0	54	0.0	0.0	0.0	42.3	59	0.0	0.0	0.0	47.4	59	0.0	0.0	0.0	53.9
Zinc	mg/l	60	0.0	0.0	0.0	42.9	54	0.0	0.1	0.0	62.1	59	0.0	0.1	0.0	92.9	59	0.0	0.1	0.0	81.9
Lead	ug/l	60	0.5	2.3	0.7	42.7	54	0.5	7.2	1.7	66.4	59	0.5	10.0	1.7	102.1	59	0.5	2.5	0.7	63.2
Cadmium	ug/l	60	0.5	0.5	0.5	0.0	54	0.5	0.5	0.5	0.0	59	0.5	0.5	0.5	0.0	59	0.5	0.5	0.5	0.0
Chrome	ug/l	60	2.2	11.4	5.4	47.0	54	3.2	29.1	10.8	47.7	59	0.6	23.6	4.8	81.5	59	0.0	16.5	3.9	77.3
Mercury	ug/l	60	0.3	1.9	0.3	75.0	54	0.3	1.3	0.4	51.7	59	0.3	3.5	0.6	95.2	59	0.0	1.0	0.1	236.9
Selenium	ug/l	60	0.3	2.1	0.5	64.9	54	0.3	1.2	0.3	43.6	59	0.3	0.6	0.3	19.9	59	0.0	1.1	0.1	236.3
Nickel	ug/l	60	0.3	10.7	2.4	89.6	54	0.3	10.1	3.6	67.1	59	0.3	8.0	1.9	89.7	59	0.0	16.6	1.7	158.5
Total Organic Carbon	mg/l as C	60	1.5	4.3	2.4	27.0	54	1.9	7.8	3.5	27.7	59	1.1	3.9	2.4	33.2	59	2.1	5.9	3.3	23.1
Biological Oxygen Demand	mg/l O_2	60	0.4	9.8	1.9	97.8	54	0.1	7.1	1.3	87.1	59	0.5	4.3	1.3	51.5	59	0.5	2.2	0.9	42.3
Dissolved Oxygen	mg/l O_2	60	5.7	10.0	8.1	12.0	54	4.4	9.7	7.6	15.8	59	5.5	10.4	7.6	13.2	59	3.6	10.8	8.0	18.4
% DO	%	60	66.6	120.8	97.1	9.9	54	50.6	113.4	88.9	15.2	59	65.9	121.3	94.6	11.9	59	41.0	118.7	92.6	19.2
Total Kjeldahl Nitrogen	mgN/l	60	0.1	2.1	0.8	59.0	54	0.2	3.9	1.1	77.2	59	0.1	4.2	0.8	83.5	59	0.2	3.4	0.7	88.0
Partial retention		60	2	31	13	43	54	1	15	6	52	11	1	6	3	47	59	1	68	20	62
Inflow	Ml/day	60	65	5185	568	150	54	20	691	150	101	58	7	526	74	121	59	136	8368	778	164

Physico-chemical variable	Units	Midmar monthly data summary N	Min	Max	Mean	CV	Nagle monthly data summary N	Min	Max	Mean	CV	Nungwane monthly data summary N	Min	Max	Mean	CV	Shongweni monthly data summary N	Min	Max	Mean	CV
Stability	s^{-1}	59	0.0	9.9	2.6	91.6	59	-0.2	8.0	3.1	60.8	59	-0.2	12.9	6.0	69.5	58	-0.3	11.9	4.7	63.4
Wind speed	m/s	59	1.0	5.5	2.4	39.6	59	1.0	4.7	2.3	36.8	59	1.3	7.3	3.9	34.5	58	1.0	6.7	3.7	35.1
Wind direction	degrees	59	22.5	197.3	90.7	38.4	59	25.7	189.0	86.3	36.4	59	26.7	243.3	127.5	38.1	58	59.3	239.0	141.8	33.7
Sunhours	hours	59	2.1	10.2	6.9	27.4	59	1.9	11.1	7.4	29.7	59	1.3	38.9	7.3	60.5	58	1.6	10.9	6.9	32.6
TP load	kg/ha/yr	59	56	7341	664	1765	59	172	1267	474	495	59	1	993	47	3294	58	12	2617	484	1188
SRP load	kg/ha/yr	59	7	1507	141	188	59	12	263	74	66	59	1	393	20	312	58	6	1020	231	116
TN load	kg/ha/yr	59	240	35640	5519	38987	59	1240	20730	5578	75485	59	20	15530	978	48863	58	0	25930	3692	50728
Total Inorganic Nitrogen	mgN/l	59	0.208	0.758	0.327	0.029	59	0.142	0.742	0.346	0.035	59	0.275	1.720	0.731	0.043	58	0.063	4.005	0.800	0.107
Temperature	degrees	59	10.6	25.6	18.7	21.1	59	13.0	27.6	21.6	17.6	59	12.5	26.3	20.6	18.4	58	11.8	27.8	21.2	20.3
Chlorophyll a	ug/l	59	1.1	59.3	4.3	177.3	59	0.3	10.8	3.4	69.6	59	1.0	12.9	4.3	53.0	58	1.0	227.9	31.0	136.7
Secchi	m	59	0.4	4.0	1.3	49.0	59	0.3	2.6	1.2	38.1	59	0.6	1.7	1.1	22.9	58	0.1	2.4	0.9	59.9
pH		59	7.1	8.1	7.6	3.1	59	7.1	8.1	7.7	3.1	59	7.0	7.9	7.6	2.7	58	7.2	8.8	8.0	4.3
Turbidity	NTU	59	2.3	22.1	10.5	51.9	59	4.4	79.2	13.7	91.6	59	2.5	122.7	10.8	149.6	58	2.2	200.0	30.5	125.8
Conductivity	mS/m	59	5.9	8.0	6.6	8.7	59	5.9	12.5	8.8	10.2	59	10.3	18.1	13.4	12.5	58	28.8	161.6	79.8	46.2
Total Aluminium	ug/l	59	23.3	373.0	109.7	55.0	59	24.7	603.3	113.2	86.4	59	15.7	614.0	79.6	101.6	58	7.0	540.0	112.2	112.0
Alkalinity	mg/l $CaCO_3$	59	21.2	29.2	25.0	7.9	59	25.3	33.2	28.8	6.5	59	16.8	33.3	24.8	16.1	58	38.6	190.0	106.3	38.1
Hardness	mg/l $CaCO_3$	59	18.0	25.7	22.0	7.5	59	24.3	33.8	27.6	9.5	59	16.1	35.3	25.5	14.8	58	48.8	108.4	77.2	20.5
Calcium	mg/l	59	3.1	5.3	4.4	9.2	59	4.3	6.5	5.2	10.0	59	2.3	5.8	3.8	18.4	58	8.0	22.7	14.6	25.8
Magnesium	mg/l	59	2.3	3.2	2.6	7.8	59	3.1	4.3	3.4	9.4	59	2.5	5.5	3.9	12.9	58	6.8	15.9	9.6	17.7
Sodium	mg/l	59	3.8	5.5	4.4	8.8	59	5.5	9.7	6.6	11.5	59	11.7	20.6	15.6	11.8	58	18.8	298.0	129.3	59.2
Potassium	mg/l	59	0.7	2.4	1.3	19.2	59	1.0	3.8	1.5	29.8	59	0.7	3.6	1.6	33.2	58	1.3	21.7	9.3	53.7
Iron	mg/l	59	0.2	1.0	0.6	34.5	59	0.2	1.6	0.5	46.0	59	0.5	2.6	1.0	36.5	58	0.1	3.5	1.0	95.5
Manganese	mg/l	59	0.0	0.0	0.0	43.3	59	0.0	0.0	0.0	54.3	59	0.0	0.4	0.1	125.8	58	0.0	0.7	0.2	83.6
Silicon	mg/l	59	2.6	5.4	4.2	17.7	59	2.6	6.8	4.1	19.6	59	5.5	11.5	7.4	12.2	58	3.2	8.3	5.3	28.3
Nitrate	mgN/l	59	0.1	0.7	0.3	34.0	59	0.1	0.6	0.3	34.8	59	0.1	1.4	0.6	54.8	58	0.0	3.2	0.6	106.6
Nitrite	mgN/l	59	0.0	0.0	0.0	4.3	59	0.0	0.1	0.0	17.0	59	0.0	0.0	0.0	6.0	58	0.0	0.0	0.0	4.4
Ammonia	mgN/l	59	0.0	0.1	0.0	52.6	59	0.0	0.3	0.0	112.2	59	0.0	0.4	0.1	61.0	58	0.0	2.2	0.1	223.0
Chloride	mg/l	59	3.5	5.4	4.4	10.9	59	6.1	13.5	7.8	17.4	59	17.4	33.0	25.6	12.6	58	35.5	190.0	95.1	39.2
Flouride	ug/l	59	27.3	46.1	36.9	9.4	59	27.3	61.3	38.6	13.5	59	17.4	63.8	39.3	21.8	58	37.5	179.0	59.2	60.6
Sulphate	mg/l as SO_4	59	1.5	3.9	2.1	17.8	59	3.1	7.5	4.0	21.1	59	1.4	11.3	3.6	66.1	58	38.5	355.0	142.3	56.6
Total Phosphorus	ugP/l	59	7.5	52.0	24.1	46.1	59	7.5	72.0	25.8	60.8	59	7.5	64.0	21.8	61.0	58	17.2	582.7	101.7	100.3
Soluble Reactive Phosphorus	ugP/l	59	1.5	10.7	3.8	54.3	59	1.5	14.0	3.9	66.7	59	1.5	12.0	5.3	49.6	58	3.0	94.0	20.6	82.7
TN:TP		59	5.1	51.8	20.9	54.1	59	5.4	61.7	24.7	70.8	59	4.3	140.2	57.8	63.3	58	0.2	55.6	13.7	91.6
TN:SRP		59	36.6	505.6	135.0	54.2	59	30.9	529.8	165.4	48.6	59	51.1	543.4	234.8	52.1	58	1.2	256.3	66.6	82.1
TN:Si		59	0.0	0.2	0.1	29.8	59	0.1	0.1	0.1	23.7	59	0.0	0.2	0.1	42.2	58	0.0	0.8	0.1	106.2
TP:Si		59	0.0	0.0	0.0	59.2	59	0.0	0.0	0.0	63.0	59	0.0	0.0	0.0	67.1	58	0.0	0.1	0.0	103.2
SRP:Si		59	0.0	0.0	0.0	63.6	59	0.0	0.0	0.0	71.5	59	0.0	0.0	0.0	49.1	58	0.0	0.0	0.0	94.6
Total Dissolved Solids	mg/l	59	30.4	113.5	56.6	18.8	59	38.8	150.0	71.9	26.0	59	48.8	165.0	82.3	17.4	58	207.6	940.0	507.5	42.5
Suspended Solids	mg/l	59	2.0	16.5	7.4	50.1	59	2.0	41.5	9.3	77.8	59	2.0	60.3	7.2	108.5	58	2.0	142.6	23.1	123.0
Copper	mg/l	59	0.0	0.0	0.0	47.8	59	0.0	0.0	0.0	47.4	59	0.0	0.0	0.0	47.0	58	0.0	0.1	0.0	76.2
Zinc	mg/l	59	0.0	0.1	0.0	74.4	59	0.0	0.0	0.0	58.3	59	0.0	0.1	0.0	70.8	58	0.0	0.4	0.0	207.1
Lead	ug/l	59	0.5	5.3	1.1	78.6	59	0.5	2.0	0.9	55.3	59	0.5	2.4	0.9	39.4	58	0.5	6.7	2.0	76.6
Cadmium	ug/l	59	0.5	1.0	0.5	14.7	59	0.5	2.0	0.7	82.5	59	0.5	0.5	0.5	0.0	58	0.5	1.6	0.5	31.8
Chrome	ug/l	59	2.2	36.0	7.9	74.8	59	1.3	81.8	7.4	117.2	59	1.7	8.7	4.0	30.1	58	1.0	30.0	6.0	83.4
Mercury	ug/l	59	0.3	2.0	0.4	72.6	59	0.3	0.3	0.3	0.0	59	0.3	0.6	0.3	19.9	58	0.3	2.4	0.4	92.8
Selenium	ug/l	59	0.3	0.3	0.3	0.0	59	0.3	0.9	0.3	34.9	59	0.3	0.3	0.3	0.0	58	0.3	0.5	0.5	0.0
Nickel	ug/l	59	0.3	9.9	2.6	83.8	59	0.3	4.8	1.8	83.1	59	0.3	2.9	1.5	32.0	58	0.7	26.5	6.1	88.4
Total Organic Carbon	mg/l as C	59	1.5	4.3	2.6	22.4	59	1.4	4.6	2.4	28.9	59	2.1	6.3	3.8	29.7	58	4.9	19.9	8.7	35.9
Biological Oxygen Demand	mg/l O_2	59	0.0	3.9	1.0	69.1	59	0.1	6.6	1.2	79.1	59	0.3	6.4	1.4	60.8	58	0.5	122.0	9.1	200.6
Dissolved Oxygen	mg/l O_2	59	6.7	10.9	8.3	11.1	59	5.9	10.9	8.1	13.1	59	5.9	10.4	8.1	11.5	58	2.7	12.5	7.2	27.5
% DO	%	59	81.2	118.6	101.5	8.7	59	72.1	133.1	96.6	12.3	59	66.4	127.8	94.4	12.2	58	33.9	159.7	85.2	30.6
Total Kjeldahl Nitrogen	mgN/l	59	0.1	11.1	1.5	124.1	59	0.1	4.3	0.8	97.5	59	0.4	4.9	0.9	78.5	58	0.5	4.9	1.8	63.3
Partial retention		59	2	269	23	157	59	1	3	2	24	59	0	43	6	122	10	93	14562	2293	208
Inflow	Ml/day	59	61	4057	464	144	59	144	679	444	34	59	3	473	34	220	60	2	1192	138	142

Insert Table 2.3 Summary statistics for respective lake water physico-chemistry

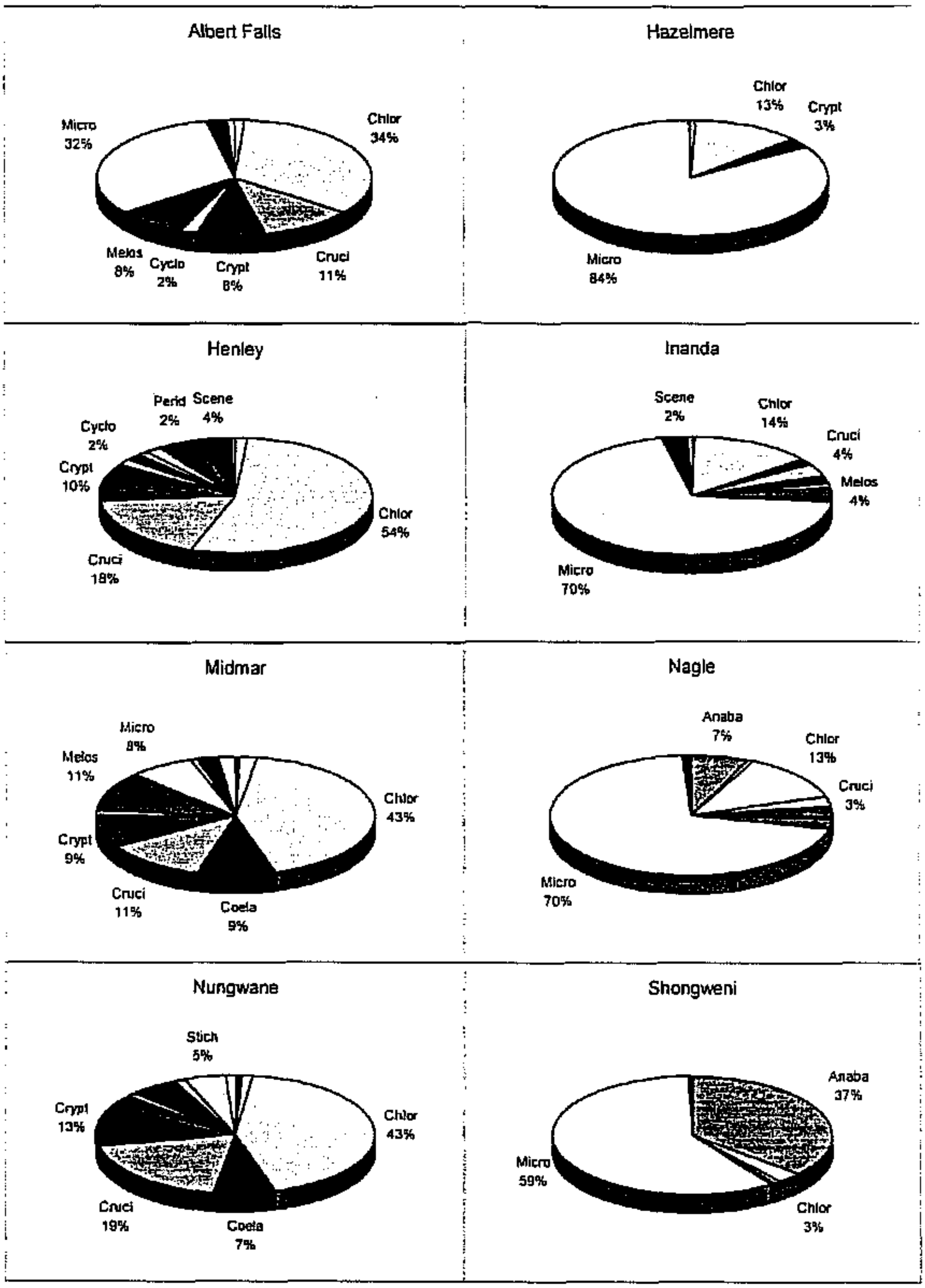

Figure 2.1 Proportional composition (as a percentage of the total median) for respective lakes for the duration of the study period (Chlor=Chlorella; Crypt=Cryptomonas; Cruci=Crucigena; Melos=Melosira; Anab=Anabaena; Micro=Microcystis; Coel=Coelastrum; Stich=Stichococcus; Perid=Peridinum; Scene=Scenedesmus; Cyclo=Cyclotella).

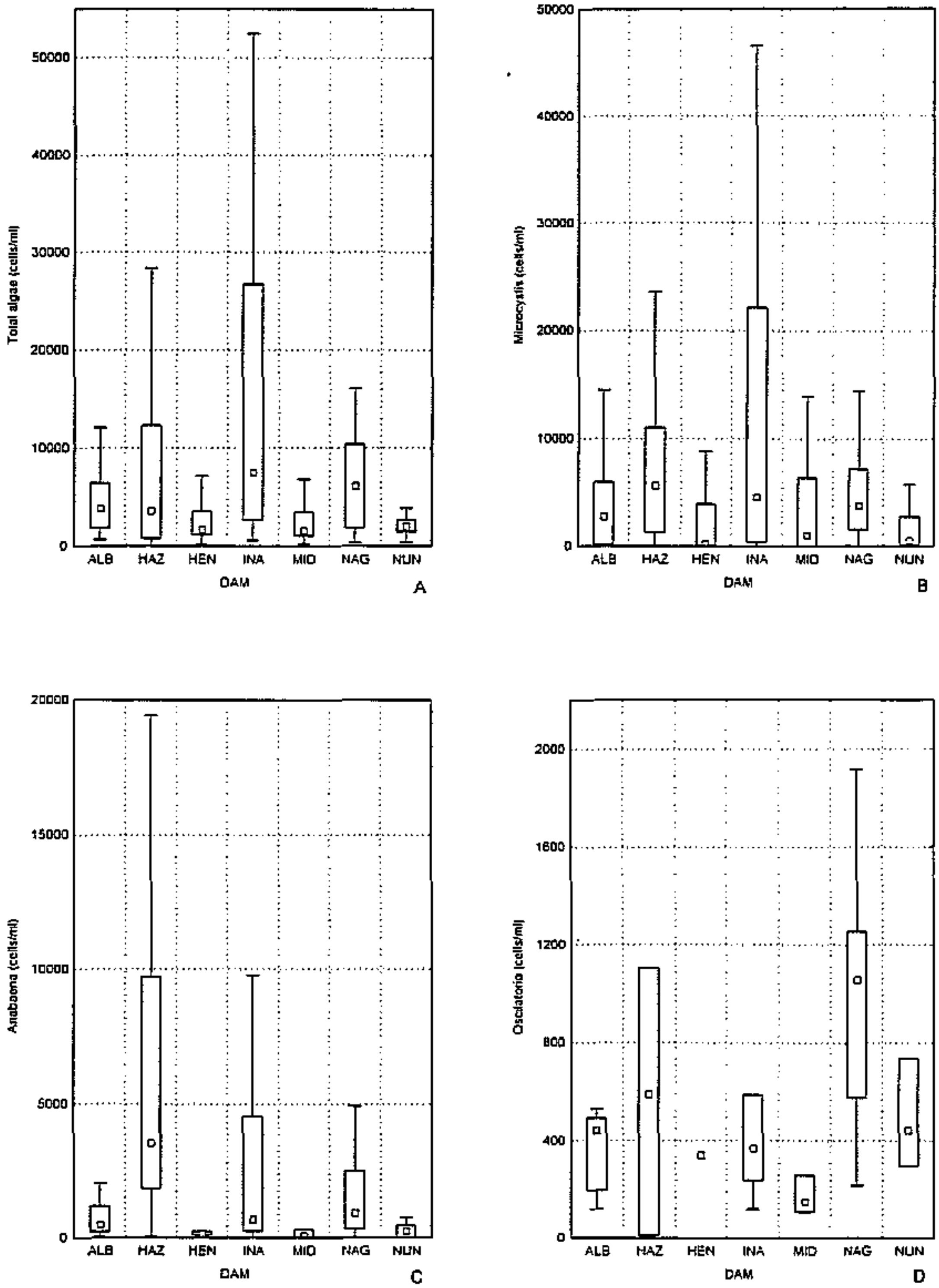

Figure 2.2 Summary abundance statistics (median, 25&75 percentiles & non-outlier minimum & maximum) of Total Algae and key blue-green algal genera in the lakes of interest.

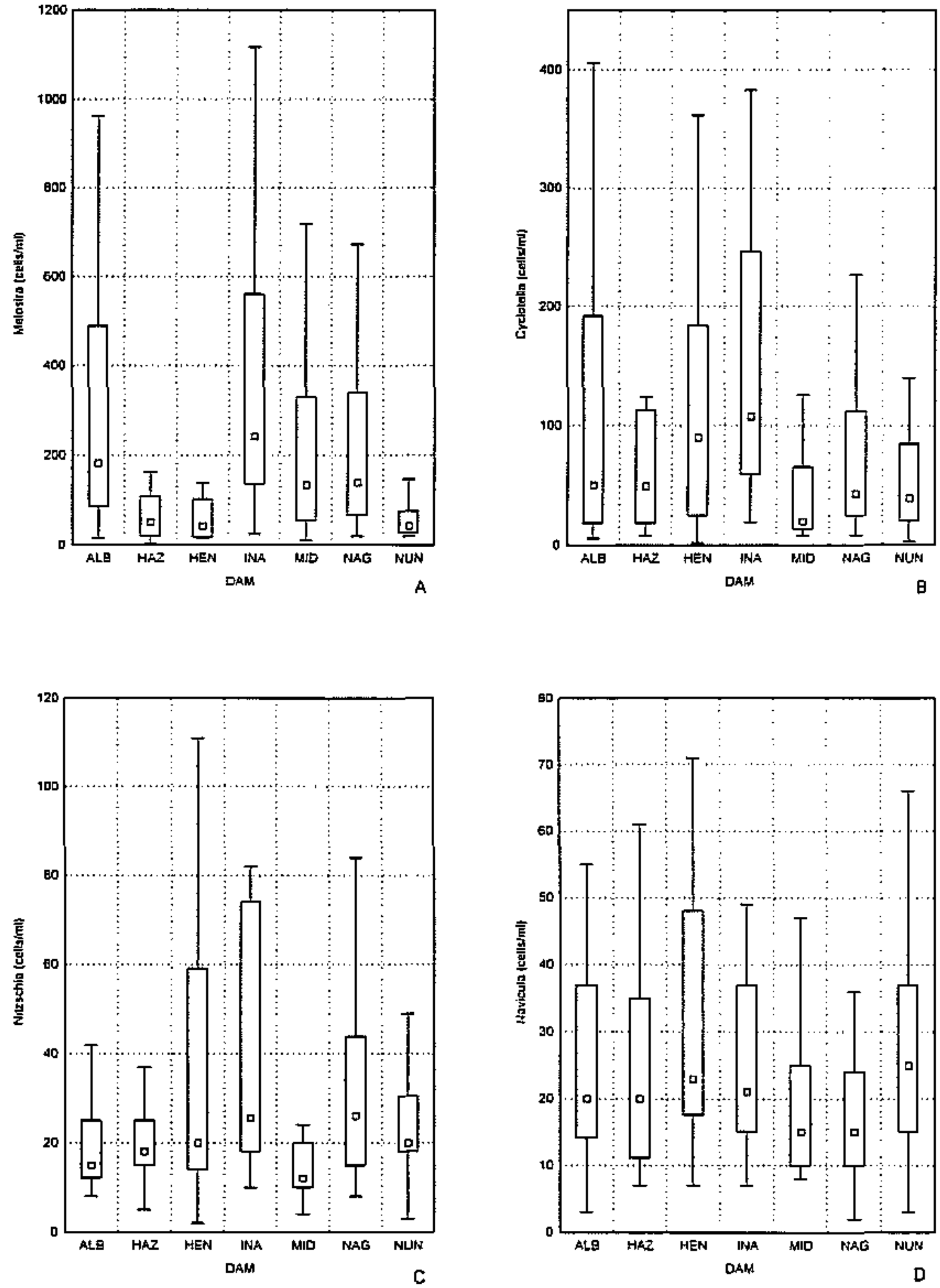

Figure 2.3 Summary abundance statistics (median, 25&75 percentiles & non-outlier minimum & maximum) of key diatom genera in the lakes of interest.

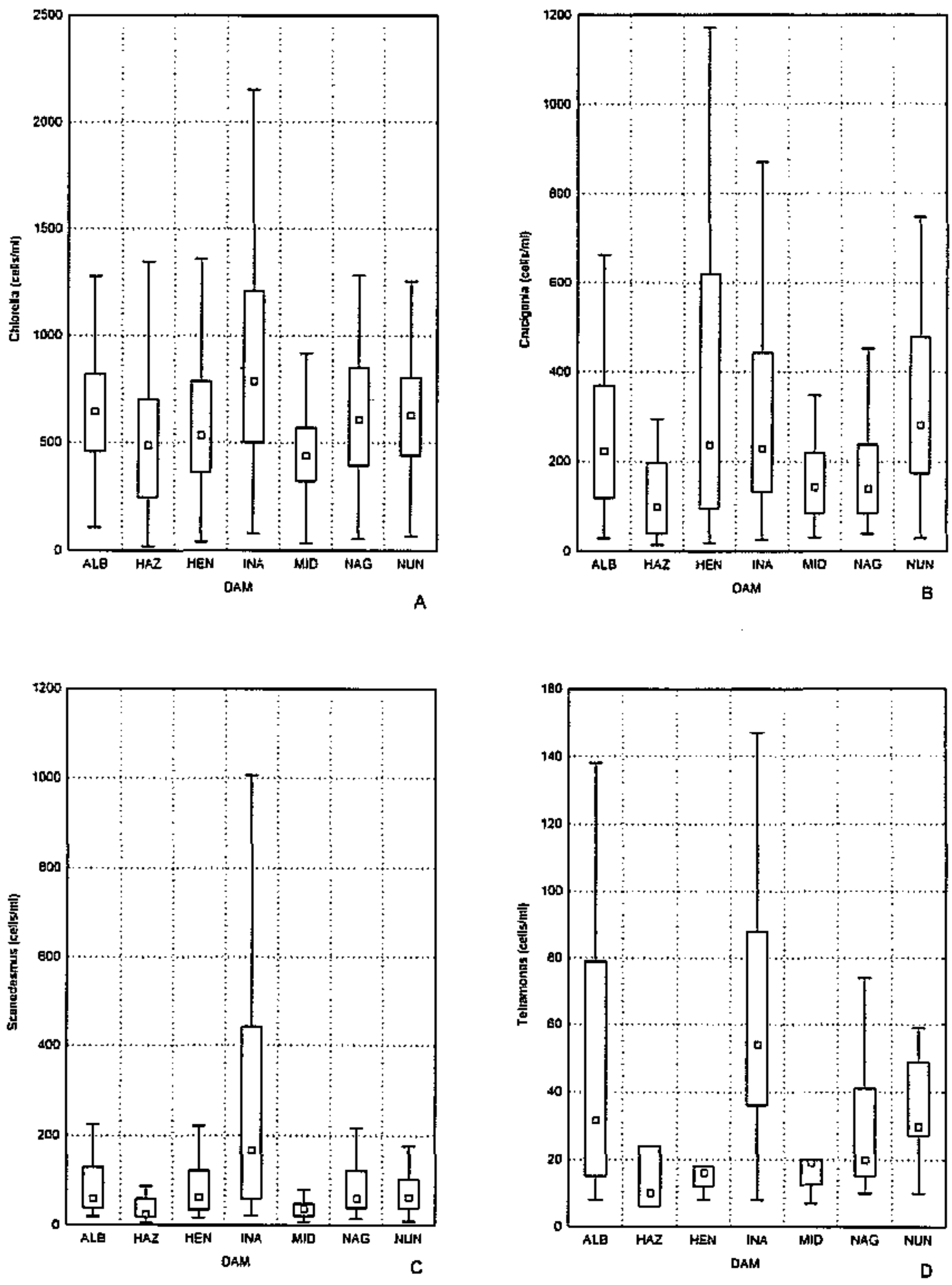

Figure 2.4(A-H) Summary abundance statistics (median, 25&75 percentiles & non-outlier minimum & maximum) of key green algal genera in the lakes of interest.
(Figure continued overleaf)

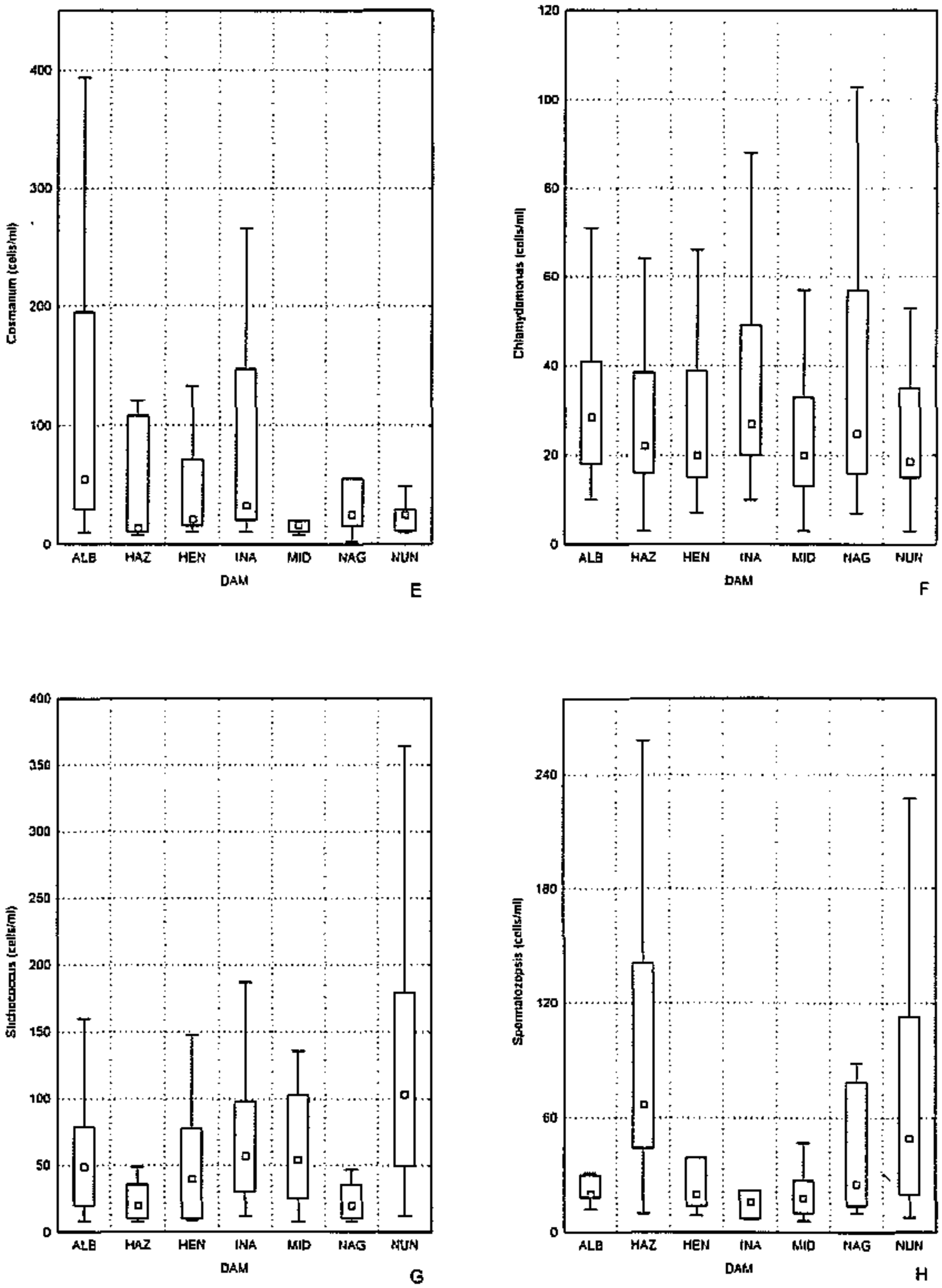

Figure 2.4(a-h) Summary abundance statistics (median, 25&75 percentiles & non-outlier minimum & maximum) of key green algal genera in the lakes of interest.

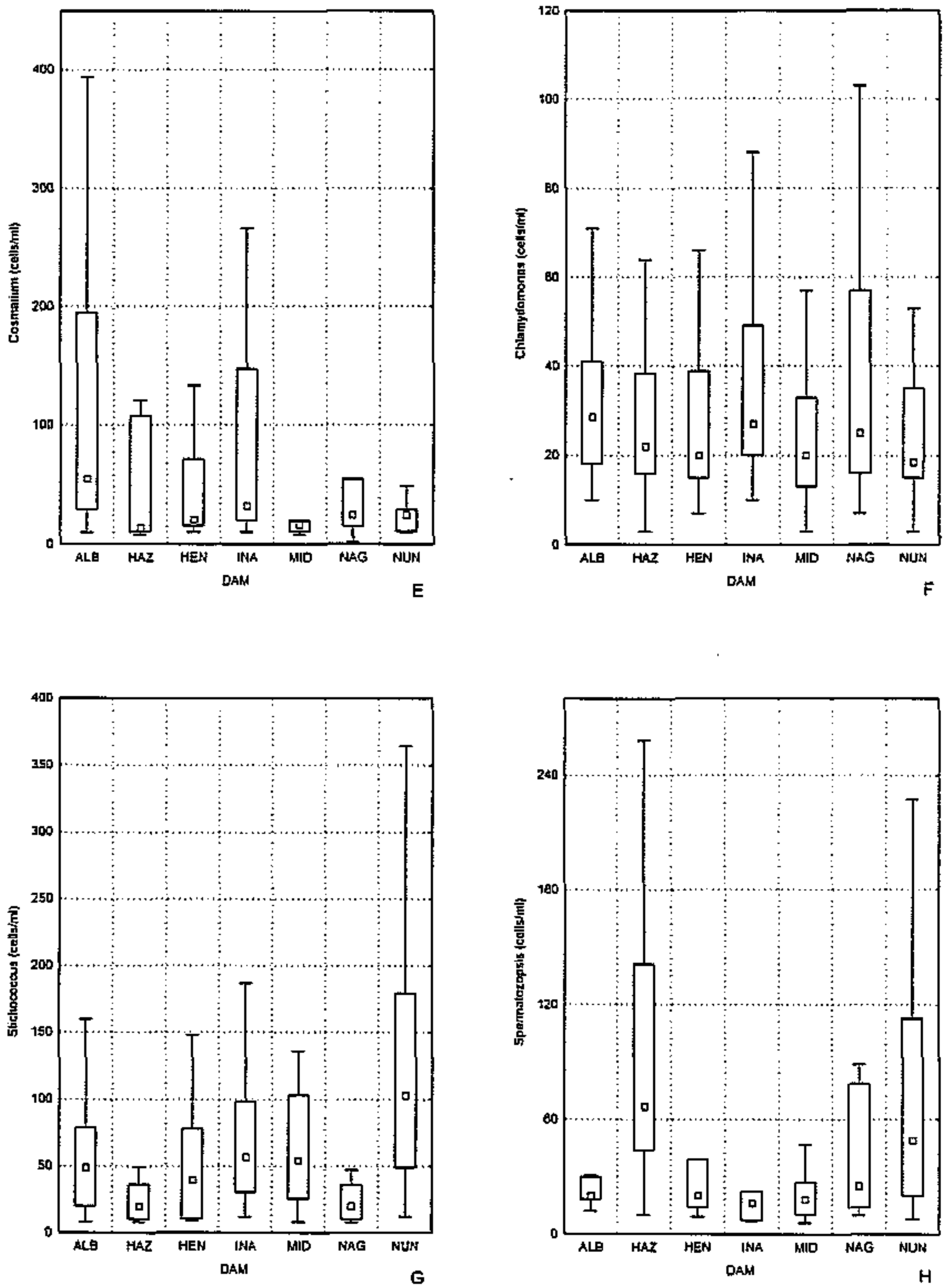

Figure 2.4(a-h) Summary abundance statistics (median, 25&75 percentiles & non-outlier minimum & maximum) of key green algal genera in the lakes of interest.

Table 2.4 Rationalised list of algae used in analyses. Acronyms, genera names, class and potential to cause water treatment problems indicated

Algal genera (acronyms)	Algal genera (scientific name)	Algal class	Potential treatment problems
Anaba	*Anabaena*	*blue-green*	*taste and odour*
Ankis	*Ankistrodesmus*	*green*	
Botry	*Botryococcus*	*green*	
Chlam	*Chlamydomonas*	*green*	*taste and odour*
Chlel	*Chlorella*	*green*	*filter clogging*
Coela	*Coelastrum*	*green*	
Cosma	*Cosmarium*	*green*	*taste and odour*
Cruci	*Crucigenia*	*green*	*filter pentetration*
Crypt	*Cryptomonas*	*brown flagellate*	*taste and odour*
Cyclo	*Cyclotella*	*diatom*	*taste and odour, filter clogging*
Dicty	*Dictyosphaerium*	*green*	*taste and odour, filter clogging*
Eugle	*Euglena*	*green flagellate*	*taste and odour*
Mallo	*Mallomonas*	*golden brown*	*taste and odour*
Melos	*Melosira*	*diatom*	*filter clogging*
Micro	*Microcystis*	*blue-green*	*taste and odour*
Navic	*Navicula*	*diatom*	*filter clogging*
Nitzs	*Nitzschia*	*diatom*	*filter clogging*
Oocys	*Oocystis*	*green*	
Oscil	*Oscillatoria*	*blue-green*	*taste and odour, filter clogging*
Pando	*Pandorina*	*green*	*taste and odour*
Pedia	*Pediastrum*	*green*	*taste and odour*
Perid	*Peridinium*	*armoured flagellate*	*filter clogging*
Ptero	*Pteromonas*	*green*	
Scene	*Scenedesmus*	*green*	*taste and odour*
Sperm	*Spermatozopsis*	*green*	
Sphae	*Sphaerocystis*	*green*	
Stich	*Stichococcus*	*green*	
Syned	*Synedra*	*diatom*	*taste and odour, filter clogging*
Synur	*Synura*	*golden brown*	*taste and odour*
Tetra	*Tetraedron*	*green*	
Trach	*Trachelomonas*	*green flagellate*	*filter clogging*

CHAPTER 3
METHODS OF DATA ANALYSIS

3.1 Introduction

A brief introduction to the methods of data analysis used in the various phases of the study is presented here. All the methods have been widely used in various fields of ecological and econometric research although some of the methods and their application to environmental problems in the South African context appear little explored. Detail is provided on the interpretation of figures (ordinations) emanating from the algae/environment models. To assist the reader a summary of this explanation is presented again in Appendix 3 (§ A3.2.2) where these figures are discussed in detail.

It is widely acknowledged (e.g. Jongman *et al.* 1987) that ecosystems are generally complex, consisting of many interacting biotic (biological) and abiotic (non-biological) components. Furthermore, environmental conditions are often difficult to characterise exhaustively. As noted by Borcard *et al.* (1992), considering multi-species and environmental data (as in this study), the amount of unexplained variation in the biotic data is always fairly high. They also note that it may not always be possible to measure all the environmental variables (in the broad sense covering biological interactions and external environmental factors) that are relevant in an ecological study such as was undertaken here. Lynam (1997) elegantly summarises this problem when he states: *"The more variables there are affecting the behaviour of a system, the more complex the web of interactions and dependencies. As analysts we can either turn a blind eye to these dependencies or we can attempt to identify their relative contributions to system performance. It is however, an extremely difficult task analytically, to separate complex interactions in ways that are reliable and have meaning in the world in which we make our observations."*

3.2 Methods used in determining algae/environment relationships

Due to the multivariate nature of this type of this study i.e. numerous environmental variables with the potential to simultaneously influence numerous members of an algal community in lakes, appropriate multivariate analytical techniques were required (e.g. Manly 1994). The techniques used to illuminate different aspects of the algae/environment relationships were Principal Components Analysis, Correspondence Analysis and Redundancy Analysis. All of these could be classified as ordination methods.

Ordination is the collective term used to describe multivariate techniques that ***arrange sites*** along axes ***on the basis of the species composition at respective sites***. The general result of an ordination analysis is an ordination diagram in which sites are represented by points. Sites, which are closer together, will have a greater biological similarity compared to sites further apart on the diagram. The ordination represents a graphical summary of the biological data.

Between the classical regression analysis approach (where the primary focus is on the detailed relationship between a single species and the environment), and typical ordination techniques (where one gains a more global picture of how a community of species is related to each other), stand the canonical ordination techniques. These deal with many species and many environmental variables with the central aim to detect the main patterns in the relations between the two. They were the primary analytical tools used in this study - principally to elucidate the relationships between algae observed in the various lakes and their environment.

3.2.1 Principal Components Analysis – to detect the principal aspects of variation in the environmental data

It was noted in this study that many of the environmental variables considered were highly inter-correlated (both positively and negatively) with each other (Table A2.1 - correlation table), or in other words were multi-collinear. This is not unusual with environmental data of this nature (Jongman *et al.* 1987) and, as was also noted in the economic models developed, this causes problems for multiple regression analysis. To overcome this, as well as to simplify the understanding of the correlation structure of the data, standardised Principal Components Analysis (PCA) was used to produce a few key variables i.e. Principal Components, PCs, which describe most of the variation in the environmental data. The result of this approach is a degree of economy in that the variation in the original large number of variables is concisely accounted for by a smaller number of variables or PCs. Another way of viewing this approach is as a reduction in the dimensionality of the data. The reduced dimensionality of the data also obviously assists in the understanding of the problem as the variability in algae may now be described by fewer key environmental parameters. The reduced set of key environmental variables has close (and known) associations with many of the remaining variables.

Essentially PCA takes a number of variables (environmental parameters in this case) and finds linear combinations of these to produce new variables or components (PCs) that are un-correlated. This ensures that the components are measuring different 'dimensions' or variability in the data. The PCs are also ordered in such a way that the first PC (PC_1) displays the largest amount of variation, PC_2 the second largest amount of variation, and so on (Manly 1994). Because of multi-collinearity, with the increase in variance accounted for by successive axes, relatively fewer axes are required to represent the majority of variation in the environmental data set (Figure A2.1 elegantly illustrates this point).

3.2.2 Redundancy Analysis for examination of algae/environment relationships

Due to the nature of the data (relatively short environmental axes - likely to represent **linear** relationships between algae and the environment), Jongman *et al.* 1987, advise Redundancy Analysis (RDA) as the preferred technique to perform the multivariate ordinations on log transformed algal data.

The aim of these ordination analyses (see § 3.3) was to arrange lakes sites (represented by points on an ordination diagram) such that points that are close together correspond with sites that are similar in algal composition. Obviously sites that are further apart on ordinations are more dissimilar in algal composition. The ordination of algae in RDA methods results in an ordination diagram where the arrows corresponds with the rate of change in abundance of respective algae over ordinated lake sites. The interpretation of these diagrams is described in §3.3 below.

3.2.3 Kriging of environmental and algal data

At each ordinated lake site there are corresponding quantitative values available on environmental variables. In an effort to develop predictive models relating algae to the environment kriging was employed. This essentially takes quantitative values for environmental variables of interest, at respectively ordinated lake sites, and creates "best fit" contours of similarity over the ordination diagram. In other words as the values for an environmental variable change at respective sites over an ordination diagram, contours are created to represent this trend surface (in rate, value and direction) over the ordination. In the same way as kriging was used to fit **environmental** trend-surfaces across the ordination diagrams an **algal** abundance trend-surface could also be fitted. This provides a more general indication than the algae/environment biplot (e.g. Fig. 3.1) as to where algal abundances could be expected to be highest and under what environmental conditions. Kriging therefore provided semi-quantitative models relating algae to key environmental elements. Results for this are summarised in Table 4.1 (summary by genera of algae/environment relations).

3.3 Interpretation of ordination figures

As many of the results were dependent on this type of analysis a brief summary, to be used in the interpretation of all ordination figures presented in Appendix 3, is presented here. To reiterate, the aim of ordination analyses is to arrange lakes sites (represented by points on an ordination diagram) such that points that are close together correspond with sites that are similar in algal composition. As the algal composition changes across lake sites (and hence the ordination diagram), the position of arrows representing respective algae also changes. This corresponds with the rate of change in abundance of algae over ordinated lake sites. As an example Figure 3.1 illustrates many of features of ordination diagrams. The interpretation of this diagram is described below.

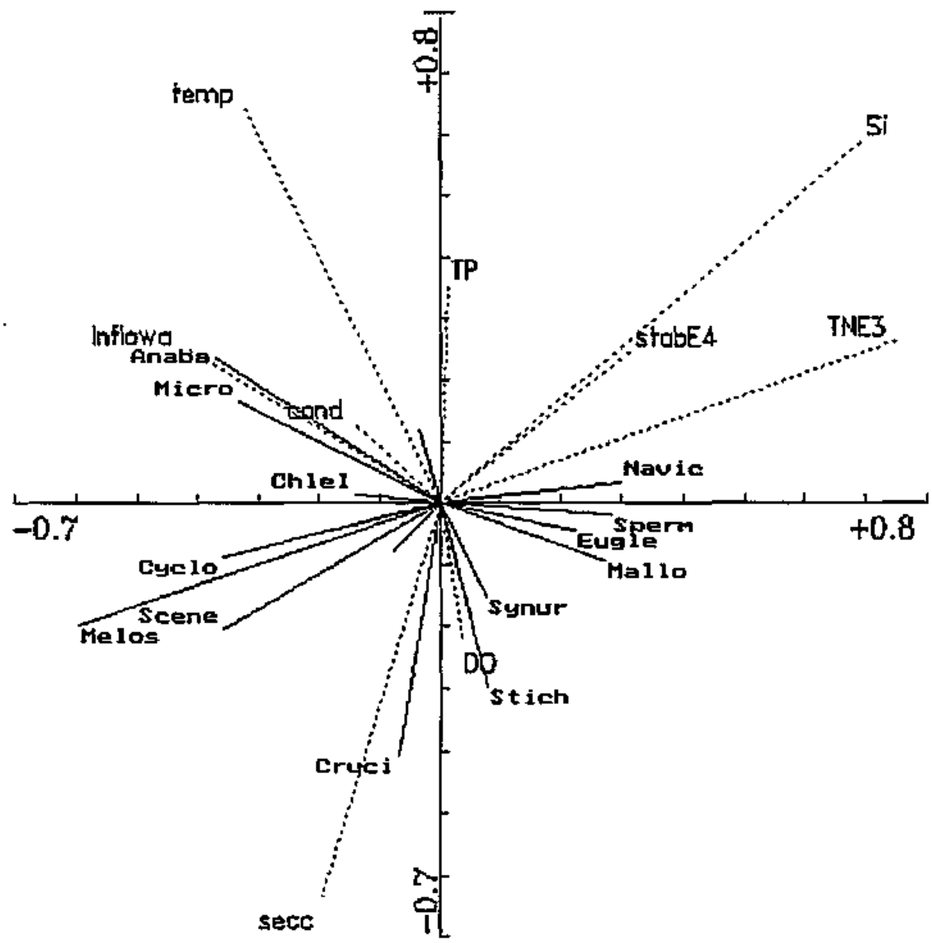

Figure 3.1 Biplot ordination of algae and key environmental variables (summary of Fig. A3.1a & b). Algal genera are: Anaba=*Anabaena*, Micro=*Microcystis*, Navic=*Navicula*, Sperm=*Spermatozopsis*, Eugle=*Euglena*, Mallo=*Mallomonas*, Synur=*Synura*, Stich=*Stichococcus*, Cruci=*Crucigena*, Scene=*Scenedesmus*, Melos=*Melosira*, Cyclo=*Cyclotella* and Chlel=*Chlorella*. Environmental variables are: TP=Total Phosphorus, Si=Silicon, stabE4=stability, TNE3=Total Inorganic Nitrogen, DO=%Dissolved Oxygen, cond=conductivity, Inflowa=inflow and temp=temperature.

In the interpretation of RDA ordination figures, algal genera should strictly be represented as arrows as the rationale underlying the technique assumes that there is a linear change of algal abundance across the ordination diagram. However, for visual clarity genera in some ordination figures were represented by dots (the position of dots representing the ends of the respective arrows). Algae grouped closely together on an ordination diagram are more similar in their response to their environment compared to algae further apart on an ordination diagram. For example in Figure 3.1 the algae *Microcystis* and *Anabaena* are grouped together in the upper left quadrant of the ordination diagram. They therefore have similar environmental requirements and, as the ordination diagram shows, generally tend to favour warmer temperatures and higher inflows compared to the other algae displayed on the ordination. Environmental (and algal) variables are positively correlated (e.g. temperature and inflow) if their arrows subtend a small angle, uncorrelated (independent) if their arrows are at 90° (e.g. temperature and total inorganic nitrogen), and negatively correlated if their arrows are in opposite directions (temperature and % dissolved oxygen). Environmental variables with the longest arrows relative to an axis have the greatest influence on that axis – for example temperature and inflow compared to conductivity. Successive ordination axes account for successively lower proportions of algal variability i.e. the first axis accounts for more of the total algal variability compared to the second axis, and so on. Algae with long arrows (distance from the origin of ordinations) have a greater proportion of their variability explained by the ordination than do algae closer to the origin (e.g. *Anabaena* & *Microcystis* compared to say *Chlorella*). They are consequently responding more strongly (rate-of-change) to the measured environmental variables. The order of response of genera along any environmental gradient is obtained by dropping a perpendicular bisector from the end of the arrows (points), representing algal genera, to the extended line of an environmental arrow.

3.4 Methods used in determining relationships between treatment costs and water quality

3.4.1 The linear regression model

In order to identify the most important factors (environmental and algal) affecting water treatment costs in water treatment works (WW) studied in the Umgeni Water operational area, a multiple linear regression model (expressed in equation 1) was estimated. This used all variables that were identified as significantly correlated with water treatment cost for each of the selected WW systems (i.e., Hazelmere, Durban Heights, DV Harris and Wiggins).

$$Cost = \alpha_0 + \alpha_1 X_1 + \alpha_2 X_2 + \ldots\ldots\ldots\ldots\ldots \alpha_n X_n \quad (1)$$

where;

Cost = Water treatment cost in 1996 Rands per mega litre (R/Mℓ) terms

X_i = Variables selected as affecting water treatment costs

α_i = Estimated regression coefficients

3.4.2 Principal Components Analysis (PCA)

The high intercorrelations between explanatory variables X_i (termed multicollinearity - Appendix 4), created statistical problems in the estimated models. This implied that the relationship between individual variables and treatment cost could not be estimated. Therefore in order to investigate how each variable was affecting treatment cost, principal component analysis (PCA) was applied to solve the multicollinearity problem (see Appendix 4) for the details of this procedure).

CHAPTER 4

DISCUSSION OF RELATIONSHIPS BETWEEN ENVIRONMENTAL VARIABLES & HOW THEY RELATE TO ALGAE

4.1 Introduction

Due to the statistically technical nature of the results pertaining to the algae/environment relations, these were confined to the appendices (Ap. 2 & 3) whilst this chapter summarises and consolidates the key findings from this aspect of the study. Firstly (§ 4.2 & 4.3), the environmental variables themselves were considered, how these varied between lakes, and the implications of this, and then secondly (§ 4.4), the relationships of algae to these various facets of the environment. The source in the appendices of each set of results used for each discussion is indicated by the appropriate section symbol, §.

4.2 The physico-chemical environment of all lakes studied (summarised from Appendix 2 § A2.2)

Many of the environmental variables in this study were highly correlated with each other. Analytical techniques were implemented to counter this which resulted in a degree of economy in that the variation of the original large number of environmental variables (53) could be reasonably accounted for by a smaller number of Principal Components (PCs). The dimensionality (or complexity) of the environmental data was therefore reduced and assisted in the understanding of the relationships between algae and the environment.

A series of analyses identified that Shongweni appeared to be an extreme outlier at the end of an eutrophication gradient, both in terms of its physico-chemical as well as biological composition. It was therefore dropped from further analyses. The distinction between Shongweni and all other lakes in the study was based primarily on its high conductivity waters. High conductivities in the Shongweni waters reflected a range of variables (e.g. potassium, chloride, sodium, total dissolved solids and sulphate) that had highly elevated concentrations compared to all other lakes studied. This picture of poor water quality in Shongweni could be traced to catchment activities (primarily textile industries).

Highly elevated algal counts of the blue-green algae *Microcystis* and *Anabaena* appeared to account for the biological distinction between Shongweni and the other lakes. These algae were also proportionately abundant in Shongweni. Amongst other reasons this poor water quality (both abiotic and biotic) in Shongweni contributed to its decommissioning as a potable water supply source in 1993

The focus of the study then concentrated on the remaining seven lakes viz. Midmar, Albert Falls, Nagle, Inanda, Henley, Nungwane and Hazelmere.

4.3 The physico-chemical environment of all lakes studied (excluding Shongweni, from Appendix 2 § A2.2)

Analyses after the exclusion of Shongweni data indicated that most of the variability in the remaining environmental data set could be explained by five key axes or PCs. These captured some 52% of the variability in the environmental data. Certain 'key' environmental variables (viz. conductivity, secchi depth, silicon, total inorganic nitrogen and total phosphorus, inflow, temperature, % DO and stability), which represented a primary component of variation in the data set and acted as surrogates for this variation, were uniquely and strongly associated with these PCs. These were used in further analyses relating algae to the environment. The reduced set (53 to the nine listed above) of environmental variables also had intuitive biological appeal in that they are often implicated in the literature as influencing algae in some way. This reduced set of environmental variables were then used in analyses to determine which variables appeared to be most significant at influencing the observed algal populations in the remaining lakes.

Before considering the algae/environment relationships in detail however, an examination of the abiotic environmental data across all lakes in the study produced some interesting findings. A distinct group of relatively low conductivity, low turbidity 'inland' lakes (Midmar, Albert Falls, Nagle and Henley) were identified. These contrasted with more highly turbid 'coastal' lakes (Hazelmere and to a lesser extent Nungwane). Inanda was apparently quite different from the other lakes (and distinct from previous groupings) in being characterised by higher conductivity but low turbidity. From a physico-chemical point of view, Inanda and Hazelmere are the most dissimilar lakes in the study (excluding Shongweni). On the other hand Midmar, Albert Falls and Nagle are the most similar when compared to the other lakes in the study. They also neatly demonstrate the change in lake water quality with progression down the cascade of lakes on the Mgeni River. Relative catchment position places Henley close to this group of lakes in terms of its water quality. Although not on the Mgeni River itself it is on a major tributary of the Mgeni system and shares a similar catchment position compared to the upper Mgeni lakes. Not surprisingly, progression down catchments was characterised by increased conductivities with Inanda, the lowest lake on the Mgeni system generally having the highest conductivities.

Having examined lakes in terms of their relation to the 'turbidity' and 'conductivity' gradients in the environmental data, further (though weaker) distinctions between lakes in relation to gradients characterised by total inorganic nitrogen, total phosphorus and inflows were possible. Midmar, Nagle and Albert Falls appeared to be characterised by relatively high total phosphorus, whilst Nungwane and Henley had higher total inorganic nitrogen. Inanda was relatively 'mixed', experiencing a range of values for total inorganic nitrogen, total phosphorus and inflows.

Use of PCs helped to objectively identify lakes that could be considered to have similar physico-chemistry (water quality) and therefore would be likely to respond similarly to management/perturbation.

4.4 The effect of environmental conditions on algal populations (from Appendix 3 § A3.3)

The heterogeneity that may be observed in communities between spatially different sites generally has various origins (Borcard *et al.* 1992). Two classic models have been given in the literature (e.g. May 1984) to describe this spatial heterogeneity. Firstly, the environmental control (where environmental variables have the primary control over the observed variations) and secondly the biotic control model (where links among organisms e.g. competition or predation are considered to be the primary factors structuring communities (Southwood 1987)). These models have often been viewed as competing or mutually exclusive hypotheses (May 1984). Quinn and Dunham (1983) propose viewing the alternative models in terms of the relative contribution of each to explaining the causes of community variation.

Within this understanding of the range and complexity of potential models analyses were conducted to determine which aspects of the environment (measured environmental variables (§ A3.3), effects unique to different lakes (§ A3.4) and seasonality (months, § A3.5) were playing the most significant part in explaining the observed algal variability. Each of these analyses revealed a different aspect of how the environment was influencing the distribution and abundance of algae (first objective of this study, § 1.2). From this, interpretations could be made about the conditions favouring problematic algae (this chapter).

Due to the multivariate nature of the problem, i.e. numerous different types of algae and numerous environmental effects potentially affecting them, analyses based on ordination techniques were used. Essentially algae are not independent, i.e. do not exist alone in aquatic systems, as there is always a range of biological interactions taking place in these communities - be it competitive exclusion, luxury nutrient uptake, predation, etc. (e.g. Lampert *et al.* 1986; Sommer 1989; Shapiro 1997). Therefore attempts to model individual algal genera, as independent factors, against a range of environmental parameters will always be fraught with problems if the interaction effects are ignored. Soudant *et al.* (1997) note that due to the inherent complexity of this type of algal data and the high variabilities often associated with algae over time, (generated by processes occurring at different spatial and temporal scales), static regression models are not suitable for this type of analysis. Multiple regression ordination techniques elegantly surmount this problem and consider the response of algae to the environment at the community level i.e. how are ***all*** the algae responding to the environment as a whole?

Analyses (Appendix 2, § A2.3) had identified a reduced number of environmental variables that appeared to describe the principal elements of variability in the strictly environmental data set almost as well as well as the complete set. This reduced set (53 to 9), colloquially referred to as 'key' environmental parameters, covered the major physico-chemical processes known to affect algae and were taken forward to investigate their effects on the algal populations in the lakes under study. Not all of them were necessarily related to the observed variability in the algae however.

4.4.1 Effects of 'key' environmental variables on algal populations

Key environmental variables explained some 16% of the variability in the algal data. Of the variables, total inorganic nitrogen, silicon, temperature, inflow and secchi appear to be the most important in accounting for the environmentally explainable variability in the algal data. Had other environmental variables been quantified (e.g. predation, competition effects etc.) more algal variability may have been accounted for.

It is not unusual for low amounts of explained variation in large sets of multi-genera ecological data, particularly with many zero values in the data (e.g. Stevenson *et al.* 1991; Agbieti 1992). As a check on the significance of this apparently low explained variability, in all facets of the analyses the environmental effects were Monte Carlo permutation tested (ter Braak 1987-1992) and found be significantly related ($P < 0.01$) to the variation in the algal data. It could thus be said that variables identified in the analyses (total inorganic nitrogen, silicon, temperature, inflow and secchi) account for a statistically significant proportion of the variability in the observed algal data. In other words, of all the supplied environmental variables, these just listed form the primary gradients (axes) along which the observed algae appear to be responding to the environment.

Of the algal genera apparently responding to the supplied environmental gradients (Fig A3.1a&b) *Anabaena* and *Microcystis* (blue/green algae) were responding to the higher temperatures, inflow volumes and, though not as significant, conductivities, that one would expect with summer conditions. The temperatures (20–25°C) leading to the greatest abundances of the blue-green algae *Anabaena* and *Microcystis* (Table 4.1) in this study were in accordance with those noted in the literature. Hammer (1964) found *Anabaena* blooming at 15 to 20°C with *Microcystis* blooming in a wide range of temperatures, from 19 to 25°C. Reynolds & Walsby (1975), Dawes *et al.* (1987) and Varis (1993) also noted this dominance of blue-green algae in the warmer summer months.

It should be emphasised that the few 'key' environmental variables are closely associated/correlated with specific groups of other variables, i.e. their variations in the environmental data set are not singular, and because of this all the associated variables are useful in interpretations of algae and environment. The Principal Components Analysis undertaken in Appendix 2 covers this in detail. Positively associated with the total inorganic nitrogen axis was the TN:TP ratio (Appendix 2 Table A2.3). This implies that at low TN concentrations there are also likely to be low TN:TP ratios. The blue-green algae (*Anabaena* and *Microcystis*) in this study appeared to be more abundant at the lower end of this TN (low TN:TP ratio, < 20) gradient (see Figure A3.6). The literature supports this observation (e.g. Schindler 1977; Tilman *et al.* 1982, 1986) with Jensen *et al.* (1994) noting blue-green algae seldom dominant above a TN:TP ratio of 32. The level of around 20 noted in this study is also not far off the critical level of 29 observed by Smith (1983) for differentiating blue-green dominated lakes.

Higher silicon and total inorganic nitrogen levels appear to affect them less than other algal genera.

Although with much lower amounts of their variability explained by the key environmental variables, *Navicula*, *Spermatozopsis* and *Mallomonas* were responding to higher Si (> 5mg/ℓ) and TN (> 0.5mg/ℓ) and lower temperatures (15-20°C) and inflows. Cool (15-20°C), clear waters (with high secchi depths i.e. >1.5m) with low total phosphorus (<20µg/ℓ) favour *Crucigena* whilst waters generally low in TN (<0.5mgN/ℓ) and Si (<5mg/ℓ) favour *Melosira*, *Scenedesmus*, *Cyclotella* and *Tetraedron*. These waters are also generally clear (secchi > 2.0m) and have low water-column stability. Reynolds & Walsby (1975) note that conditions of stable stratification (stable water-column) select against diatoms and non-motile green algae. Therefore in water-columns with low stability (for example during winter and in systems subjected to wind induced mixing) diatoms may be expected to dominate. The potentially filter clogging diatom genera, *Melosira* and *Cyclotella*, dominating in water-columns with low stability, supports the previous authors observations.

Unfortunately not much may be said about *Chlorella*, a dominant or sub-dominant genera in many lakes (Fig. 2.1 - proportional composition figures for lakes), as its variability is not well explained by the measured key environmental variables.

A summary of the key environmental conditions favouring respective key algae is presented in Table 4.1. Only the more abundant algal genera, with significant amounts of their variability explained by analyses are presented. Appendix 3 (Figs. A3.20 to 3.24) provides a good graphical representation of the response of key algae (with 95% confidence bands) to various important environmental parameters identified in the analysis. These figures were used to supplement the summary provided by Table 4.1. Only algae displaying a strong and meaningful response to the different environmental parameters are plotted in the figures in Appendix 3 § A3.6. Note that not all environmental parameters presented in these figures are displayed on the ordinations (§ A3.3). Most of these 'other' variables were strongly correlated with key environmental parameters identified in the Principal Components Analysis (PCA -§ A2.3).

The direct plotting of algae against the various environmental variables (in Appendix 3 § A3.3) also gives an indication of the range of applicability of the models developed i.e. the abundances (of algae) and values (of environmental variables) for which the ordination models hold true.

Table 4.1 Summary of key environmental variable conditions favouring the maximal abundance of algae. Only more abundant algal genera with appreciable amounts of their variability explained by key environmental variables (long arrows on ordination figures) are presented.

	Units	*Anabaena*	*Microcystis*	*Melosira*	*Crucigena*	*Scenedesmus*
Algal abundance	cells/ml	>100	>1000	>100	>100	>100
# Silicon (2)	mg/l	<5	<5	<5 (1-4)	<5	<5 (0.5-3)
# Secchi (2)	m	0.5-1.5	0.5-1.5	>2.0	>2.0	>2.0
Tot.Aluminum (2)	ug/l				(<200)	
Turbidity (2)	NTU				(<20)	
Iron (2)	mg/l				(<1)	
# Tot.Inorg.N (3)	mgN/l	<0.5	<0.5	<0.5 (<0.25)	<0.5	<0.5 (<0.25)
TN:TP ratio (3)			(<10)			
TN:SRP ratio (3)			(<50)			
Nitrate (3)	mgN/l				<0.5 (<0.25)	
# Tot.Phosphorus (3)	ug/l	20-40	20-40	<20	>20	<20
TP:Si ratio (3)				(>0.01)		
# Temperature (4)	degrees	20-25 (26-27)	20-25 (25-27)	20-25	15-20	20-25
# Inflow (4)	Ml/day	>1000 (500-1000)	>1000 (500-1500)	100-500	100-500	100-500
Stability (5)	s^{-2}			<0		

NOTES: ALGAL ABUNDANCE IN THE TABLE REFERS TO THE *MINIMUM* ALGAL COUNT THAT COULD BE EXPECTED IN A SAMPLE UNDER SPECIFIED KEY ENVIRONMENTAL CONDITIONS.
KEY ENVIRONMENTAL VARIABLES IDENTIFIED IN RDA ORDINATION ANALYSES (§ A3.3)
NUMBERS IN BRACKETS (?) AFTER ENVIRONMENTAL VARIABLES REFERS TO THE PRINCIPAL COMPONENT (PC - OR MAJOR AXIS OF VARIATION IN THE ENVIRONMENTAL DATA). FOR EXAMPLE THE FIRST 5 ENVIRONMENTAL VARIABLES ARE ASSOCIATED WITH PC AXIS 2 AND IS ESSENTIALLY A WATER CLARITY OR TURBIDITY AXIS.
ONLY ALGAE DISPLAYING GOOD RESPONSES TO THE RESPECTIVE ENVIRONMENT VARIABLES ARE DISPLAYED.
VALUES IN BRACKETS (UNDER THE ALGAE) REFER TO THEIR RESPONSE AFTER DIRECT GRAPHING AGAINST RESPECTIVE ENVIRONMENTAL VARIABLES (§ A3.6)

After analysing the response of algae to environmental variables it was possible to examine the distribution of the actual lakes and seasons (months) in relation to these same variables. It is apparent that the spatial variation among lakes is more important than seasonal or yearly differences. Hazelmere (Fig A3.1c), in the early part of the summer rainy season (September to December), is dominated by factors associated with high silicon and total inorganic nitrogen and low water clarity (low secchi and high turbidity). The algal variability observed in Henley and Nungwane appear to be related to relatively high silicon and total inorganic nitrogen and correspondingly low temperatures and inflow volumes associated with spring (August to September). Having just come through the winter, where water temperatures and inflows are at their lowest, this would be a reasonable explanation for this observed pattern. Inanda and Nagle on the other hand appear to have higher temperatures and inflows and lower silicon and total inorganic nitrogen dominating their algal distribution and hence ordination, particularly during the late summer period from January through to April.

Algal genera which had a significant proportion (>10%) of their variance accounted for by the different aspects of the environment are summarised in Table 4.2. These results show the ranked response of genera (in terms of variance explained) to the supplied environmental variables. Clearly, for the first analysis where key environmental variables were considered, *Melosira* has more of its variability explainable compared to *Euglena*. The higher this percentage variance, the greater the confidence that the supplied key environmental variables, lake unique or temporal effects (months) are important in explaining observed variability in the algal populations.

Table 4.2 Ranked algal responses in terms of their cumulative % variance accounted for by respective analyses i.e. key environmental variable, lake unique (spatial), and seasonal (temporal) effects

Key environmental effects		Lake unique effects		Seasonal (temporal) effects	
Genera	Cum. % variance	Genera	Cum. % variance	Genera	Cum. % variance
Melosira	49.42	*Melosira*	54.42	*Chlorella*	20.52
Anabaena	22.39	*Mallomonas*	32.58	*Spermatozopsis*	20.13
Tetraedron	22.26	*Peridinium*	26.46	*Cyclotella*	17.23
Cyclotella	21.94	*Tetraedron*	26.13	*Cosmarium*	15.37
Crucigena	20.26	*Crucigena*	25.72	*Cryptomonas*	13.43
Scenedesmus	19.48	*Scenedesmus*	23.66	*Anabaena*	12.71
Peridinium	18.81	*Anabaena*	22.92		
Spermatozopsis	16.98	*Stichococcus*	22.22		
Microcystis	16.68	*Microcystis*	19.48		
Stichococcus	16.09	*Spermatozopsis*	18.57		
Mallomonas	15.83	*Trachelomonas*	18.12		
Cosmarium	14.10	*Coelastrum*	15.17		
Coelastrum	13.28	*Euglena*	15.12		
Navicula	12.72	*Cyclotella*	14.86		
Cryptomonas	12.24	*Navicula*	10.67		
Botryococcus	11.26	*Chlorella*	10.65		
Euglena	10.87				

Melosira appears to have a significant proportion of its variance explained by both key environmental and lake unique effects. Figures 2.1 (proportional composition) and 2.3 (abundance) indicate that this genus is really only in significant numbers and proportionally abundant in lakes on the Mgeni system viz. Albert Falls, Inanda, Midmar and Nagle. If in significant numbers, this potentially problematic genus causes reduced filter runs during water treatment.

4.4.2 Differences unique to individual lakes and the effect of this on algae (§ A3.4)

Analyses to determine the response of algae to the 'uniqueness' of individual lakes revealed that there were processes operating in the lakes which were not accounted for by environmental variables measured (or quantified) in this study. These processes, captured by the spatial separation of the lakes, were statistically significant.

Hazelmere appears distinctly different from all other lakes studied. Of all the lakes studied Hazelmere, Nungwane and Inanda (and to a lesser extent Nagle) were biologically most dissimilar from each other. Given that they are all on entirely different river systems (except Nagle and Inanda on the Mgeni River) this is not surprising.

There is an interesting trend in the lakes from generally upper catchment (Henley), down the Mgeni system sequentially to the coastal lakes (Nagle and Inanda). Nungwane is an apparent anomaly in this trend as it could be geographically classified as a 'coastal' lake. It appears however to have a greater affinity to the upper catchment lakes and indeed is situated relatively high up in its catchment.

Again algal genera with a significant proportion (>10%) of their variance explained by the effects unique to different lakes are indicated in Table 4.2. As with the previous analysis, *Melosira* has a significant proportion of its variance explained by effects unique to different lakes. This genus is only in significant numbers and proportionally abundant in Albert Falls, Inanda, Midmar and Nagle Dams. This genus, potentially problematic to the water industry where it can reduce filter runs, appears to be most significant on the Mgeni system lakes. *Navicula, Euglena, Spermatozopsis, Trachelomonas, Peridinium* and *Mallomonas* appear to be restricted to Henley and Nungwane Dams. These genera are generally never numerically abundant in these lakes and (*ceteris paribus*) are therefore unlikely to negatively impact water treatment.

4.4.3 Seasonal changes in lakes and the effects of this on algal populations (§ 4.5)

Seasonal successional trends (within the year, i.e. on a monthly basis) and annually (i.e. over the duration of the study) were examined to determine if these were significantly affecting algal populations in the study lakes. When compared to all other effects (key environmental and spatial) seasonality accounts for a relatively small amount of algal variability. This said however there ***is*** still a clear and significant seasonal pattern in the algal data. The annual successional trends are less significant than monthly patterns and show no strong unidirectional trend within the time-period of the study. This indicates that there was no overall successional trend in the algal populations in the lakes under study during this five-year period.

Fewer algal genera have significant portions of their variability explained in the 'seasonal' analysis compared to either of the previous two analyses (key environmental and spatial (lake) variables, Table 4.2). This emphasises the lower importance seasonality has on algal populations compared to pure environmental and effects uniquely associated with different lakes.

Chlorella had a greater proportion of its variability explained by seasonal changes than could be explained by either key environmental or spatial (lake) effects. This is significant when it is considered that this genus was a dominant to subdominant genus in many lakes. This implies that there is some unmeasured factor(s) in the environment, of either biotic or abiotic origin, which is explaining some of this genus' variability. This factor(s) would appear to fluctuate seasonally.

As a generalisation, in terms of genera having ***appreciable*** amounts of their variability explained by seasonal effects, the abundance of *Chlorella* and *Anabaena* is highest in summer, in the early part of the calendar year, when inflows and temperatures are greatest. *Cyclotella* and *Cosmarium* are abundant in autumn (March/April) whilst *Spermatozopsis* is likely to be more abundant in spring (August to October) when dissolved oxygen concentrations in the water appear to be highest.

Of the algae responding to seasonal changes in the lakes, in terms of numbers that may be expected to impact on water treatment it is only really *Chlorella* and *Anabaena* which are ever really numerically and proportionally abundant. Of these two the latter is the more significant to the water treatment process due to its potential for producing taste and odour compounds. The analysis indicates that January through to April are the most significant months where this genus may be expected to become abundant and therefore cause treatment problems.

Another noteworthy feature of this seasonal analysis is the apparently large shift in algal populations at certain times of the year associated with changes in season. This was most apparent during late summer (February/March) through to midwinter (June/July) with another large shift again in early summer (September to November) through to late summer. The following genera most exemplify these shifts: *Chlorella* and *Anabaena* (increase in abundance in late summer), *Cyclotella* and *Cosmarium* (increase in autumn - March/April) and *Spermatozopsis* (increase in spring).

This shift in seasonal pattern is most probably associated with changes in the water column physical stability (establishment and breakdown of stratification within the water column). Typically stratification of the water column occurs in early summer with destratification in late summer/winter. These are periods of major physico-chemical change in the water column that could be expected to have a significant impact on algal populations resident there.

4.5 Establishing statistically rigorous predictive models relating algae to the environment

Classical multiple regression modelling (as was applied to the economic models developed in Chapter 6) of important algae against environmental variables was attempted to gain a statistically rigorous model of how the abundance of these algae were affected by the environment. However the predictive ability of all multiple regression models was poor ($R_a^2 < 0.5$) even with appropriate transformations of the response variables (algal abundance data). There were indications that interactions among environmental variables, spatial locations (lakes) and algae themselves were important. In other words, the effects of environmental variables on the different algal genera were not consistent over all lakes. This was not surprising given the variation in physico-chemistry between lakes.

As noted by Borcard *et al.* (1992), considering multi-species and environmental data, as in this study, the amount of unexplained variation in the biotic data is always fairly high. They also note that it may not always be possible to measure all the environmental variables (in the broad sense covering biological interactions and external environmental factors) that are relevant in an ecological study such as was undertaken here. Lynam (1997) elegantly summarises this problem when he states: *"The more variables there are affecting the behaviour of a system, the more complex the web of interactions and dependencies. As analysts we can either turn a blind eye to these dependencies or we can attempt to identify their relative contributions* *to system performance. It is however, an extremely difficult task analytically, to separate complex interactions in ways that are reliable and have meaning in the world in which we make our observations."*

The strict multiple regression modelling of key algae against environmental variables was therefore not successful in this study. The semi-quantitative empirical models developed in the ordination analyses had to suffice for producing predictive models for algae/environment relationships.

CHAPTER 5
AN ECONOMIC EVALUATION OF THE EFFECTS OF LAKE WATER ON WATER TREATMENT COSTS IN THE UMGENI WATER OPERATIONAL AREA

5.1 Introduction

The enrichment of scarce water resources with plant nutrients such as phosphorus and nitrogen, generally known as eutrophication, creates many problems for development in South Africa (e.g. O'Keeffe *et. al.*, 1992). The main consequence of eutrophication is abundant algal growth, which can lead to increased water treatment costs. As per the aims of this project (§ 1.2), this aspect of the study has two objectives: firstly, to identify the main factors or contaminants[2] affecting treatment costs at waterworks (WW) in the Umgeni Water operational area, and secondly, to predict treatment costs from observed levels of contaminants. Treatment costs refer to financial costs incurred in ensuring that the water meets the UW potable water standards. The 1996/97 Umgeni Water Annual Report (year ended 28th February 1997) indicates that over R 8 000 000 was spent on chemicals alone for the purification of drinking water during this period (Umgeni, 1997).

Four WW systems were investigated viz. Hazelmere, Durban Heights, DV Harris and Wiggins. The latter three constituted the top three WW operating within the Umgeni Water operational area during the study period, both in terms of amounts of water processed and costs involved in processing. Hazelmere was included due to its unique (turbid) nature.

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[2] Contaminants refers to those water quality variables or factors which impact on the cost of treating water (these may be physico-chemical and/or biological e.g. algae).

Statistical methods (involving linear regression and principal components analysis-PCA) are used to analyse the cost of treating water at the following waterworks: Hazelmere WW, which draws water from Lake Hazelmere; DV Harris WW, which draws water from Lake Midmar; the Durban Heights WW, which draws water from Lakes Nagle and Inanda, and the Wiggins WW which draws water principally from Inanda. Raw water-quality from the different storage impoundments (lakes) were all generally quite different from one another. For example Lake Hazelmere is highly turbid, while water in the more coastal lakes (Nagle and Inanda) is eutrophic relative to the clean water in Lake Midmar (see Chapter 2, this report). Consequently, treatment processes and hence costs differ between the respective WW. Costs were therefore analysed separately at each WW.

Treated water in the inland (Pietermaritzburg – DV Harris) regions is dosed with lime to achieve a precipitation potential of 4mg/ℓ of calcium carbonate ($CaCO_3$). This limits the corrosive nature of water that is too 'soft'. In the case of the coastal Durban Heights/Wiggins WW systems lime is also dosed. However, the amount added is generally lower due to a request from the Durban Metro (the major bulk purchaser of water in the region) who prefer to have a lower pH to improve disinfection efficiency. To perform valid cost comparisons between the respective WW the theoretical additional lime dose (based on the raw water-quality entering the coastal plants) was calculated to achieve a similar precipitation potential (4 mg/ℓ $CaCO_3$) to that achieved at the DV Harris plant (Thompson pers. com., 1997). This additional dose was then added to that 'actually' used in the Durban Heights and Wiggins WW.

The earlier section of this report presented a model that relates algal populations to various environmental factors. The results of the economic and algae/environment models could be combined in a later study to explore links between land use activities, water quality and treatment costs. Reliable information about the origin of high treatment costs is required to inform both policy and planning decisions as well as to assist with water treatment process refinement.

5.2 Description of selected water treatment systems

For the Hazelmere system, data on water quality parameters recorded at Lake Hazelmere (UW sample point 101.1) and Hazelmere WW (UW raw water sample point 314) were used to analyse this system. Missing data on chemical usage between the months of January to September and December 1993, January, May, June, and September 1994, reduced the number of valid data cases available for analysis from 84 to 71.

For the Durban Heights system, water quality data recorded at Lake Nagle (UW sample point number 431) and Durban Heights site (UW raw water sample point number 316), recorded over the period March 1990 to February 1997 were used, giving rise to 84 valid cases. The DV Harris system was studied based on water quality data recorded at the Midmar site (UW sample point 36.1) and the DV Harris site (UW raw water sample point 324). Data used was from January 1990 to December 1996. Unfortunately, some data on chemical dosage for the months of January 1990, July 1990 - April 1991, March 1993, July 1993, February 1994 - May 1994, September 1994, and October 1994 were missing at this plant, reducing the number of valid observations from 84 to 64. Lastly, the Wiggins system was analysed based on 82 valid water quality data observations recorded at Lake Inanda (UW sample point 55.1) and the Wiggins WW (UW raw water sample point 320).

A broad description of each of the catchments is provided in Chapter 1. More specific information as it pertains to the economics of water treatment of this study is presented here for each of the systems and their respective WW.

5.2.1 The Hazelmere system

As the analysis of algae and environmental variables showed (Chapter 4) Hazelmere is a turbid lake, the mean and maximum turbidity recorded at the WW over the period March 1990 to February 1996 was 87 NTU and 540 NTU respectively (Table 5.1). The turbid water is persistent for most of the summer stratification period after heavy rains result in inflow maxima (Archibald *et. al.*, 1980). The rapid flushing rate and the high turbidity of the water may offset to some extent the summer nutrient input and consequent potential for algal growth (Archibald *op. cit.*). Information describing the quality of the water in the Hazelmere system is summarised in Table 5.1.

Table 5.1 Descriptive statistics showing characteristics of raw water treated at Hazelmere WW (March 1990 February 1997)

Water quality indicator	Units	Minimum	Mean	Maximum
Treatment cost	R/Mℓ	6.00	40.59	111.00
Turbidity	NTU	11.80	87.47	540.90
Total Organic Carbon	mg/l	0.00	3.86	10.80
Suspended Solids	mg/l	2.50	38.99	264.00
Total Aluminium	ug/l	102.00	553.8	2027.00
Alkalinity	mg/l	17.70	37.61	54.20
Nitrate	mgN/l	0.00	0.54	1.32
Sulphate	mg/l	0.00	5.77	10.40
Potassium	mg/l	1.20	2.20	4.00
Inflow	Mℓ/day	12.00	198.50	1769.00
Chrome	ug/l	0.00	9.83	61.20
Total Dissolved Solids	mg/l	0.00	132.3	286.00
Iron	mg/l	0.48	2.07	6.39
Manganese	mg/l	0.01	0.06	0.35
pH		6.66	7.32	7.77
Chlorella	cells/ml	0	77	352
Cryptomonas	cells/ml	0	26	149
Microcystis	cells/ml	0	59	829
Nitzschia	cells/ml	0	3	23
Scenedesmus	cells/ml	0	1	21

The average cost of treating water at Hazelmere WW over the period March 1990 to December 1996 was R40/Mℓ. This cost ranged between R6/Mℓ and R111/Mℓ with changes in water quality (Table 5.1). On average, the cost of polymeric coagulant constitutes the largest proportion (66%) of treatment costs (Figures 5.1 and 5.2).

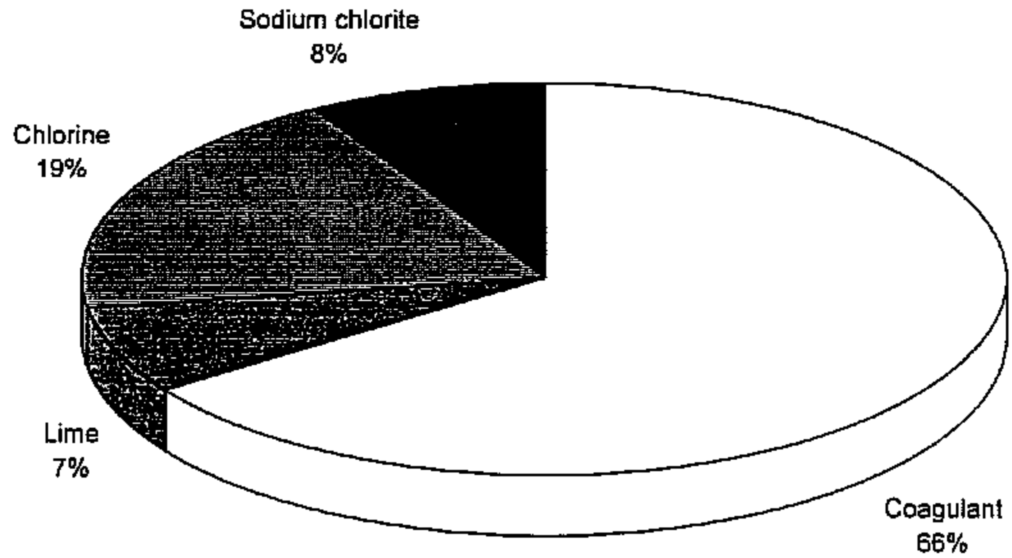

Figure 5.1 Average chemical cost composition at Hazelmere WW (March 1990 - February 1997).

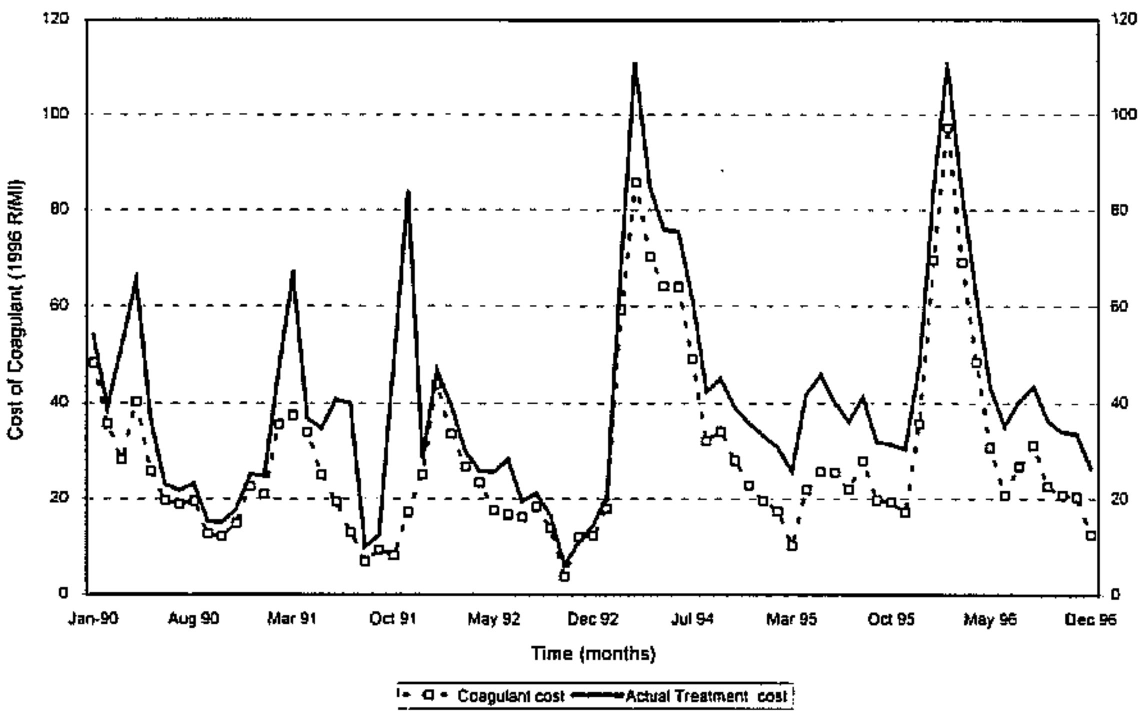

Figure 5.2 Total treatment costs and cost of polymeric coagulant at Hazelmere WW.

5.2.2 The Durban Heights system

The Durban Heights WW plant draws water mainly from Lake Nagle and occasionally from Lake Inanda. Water quality conditions in Lake Nagle are conducive to the formation of occasional blooms of the algal genera *Anabaena* and *Microcystis*. These algae have the potential to form taste and odour compounds requiring advanced (and costly) water treatment processes. A maximum of 16869 cells/mℓl and 6117 cells/mℓ of *Anabaena* and *Microcystis* counts respectively, were recorded in Lake Nagle (Table 5.2).

Table 5.2 Descriptive statistics showing characteristics of raw water treated at the Durban Heights WW (January 1990 - February 1997)

Water quality indicator	Units	Minimum	Mean	Maximum
Treatment cost	R/Mℓ	14.17	24.90	65.24
Turbidity	NTU	6.76	18.28	89.98
Total Organic Carbon	mg/l	1.65	2.74	5.84
Suspended Solids	mg/l	3.28	13.04	44.25
Total Aluminium	ug/l	47.20	158.20	915.30
Nitrate	mgN/l	0.09	0.30	1.38
Secchi	m	0.25	1.18	2.36
Conductivity	mS/m	6.43	9.23	14.58
Sulphate	mg/l	3.09	4.21	9.37
Chloride	mg/l	6.30	8.02	16.74
Sodium	mg/l	5.48	6.85	12.60
Total Hardness	mg/l $CaCO_3$	24.32	28.31	36.93
Calcium	mg/l	4.28	5.36	6.57
Magnesium	mg/l	3.06	3.57	5.09
Potassium	mg/l	0.97	1.65	5.07
Silica	mg/l	1.43	4.05	7.38
Dissolved oxygen	mg/l O_2	6.23	8.23	10.28
Sol. Reactive Phosphorus	ugP/l	1.50	4.08	19.67
Iron	mg/l	0.21	0.58	1.26
Manganese	mg/l	0.01	0.04	0.13
pH		7.19	7.66	7.86
Coliforms	colony counts/100	3	71	566
E.coli	colony counts/100	1	32	239
Anabaena	cells/ml	0	873	16869
Microcystis	cells/ml	0	848	6117
Chlorella	cells/ml	31	407	1023

The cost of treating water at Durban Heights WW was on average is R25/Mℓ, however, this can rise as high as R65/Mℓ (Table 5.2). On average the cost of polymeric coagulant constitutes 45% of treatment costs, followed by the cost of chlorine at 38% (Figure 5.3). This illustrates that treatment costs at Durban Heights are mainly driven by changes in coagulant requirement and water disinfection. The average treatment cost at the Durban Heights WW increases to R28/Mℓ if the final water is adjusted to achieve a final precipitation potential of 4mg/ℓ $CaCO_3$ (more lime). This would change the average cost structure at the Durban Heights WW as illustrated in Figure 5.4. This cost structure again changes (only more dramatically) when powdered activated carbon (PAC) is dosed during periods of taste and odour problems, resulting from blooms of *Anabaena* or *Microcystis* in Lake Nagle (Figure 5.5). For example, in March 1994, the average cost of treating water was R65/Mℓ during a particularly severe period of *Anabaena* generated taste and odour problems.

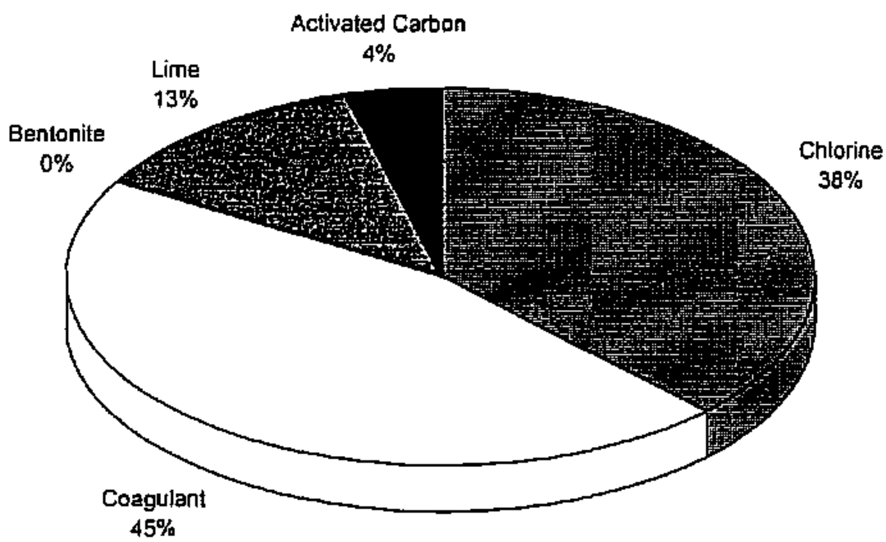

Figure 5.3 Average chemical cost composition at Durban Heights WW (January 1990 – February 1997).

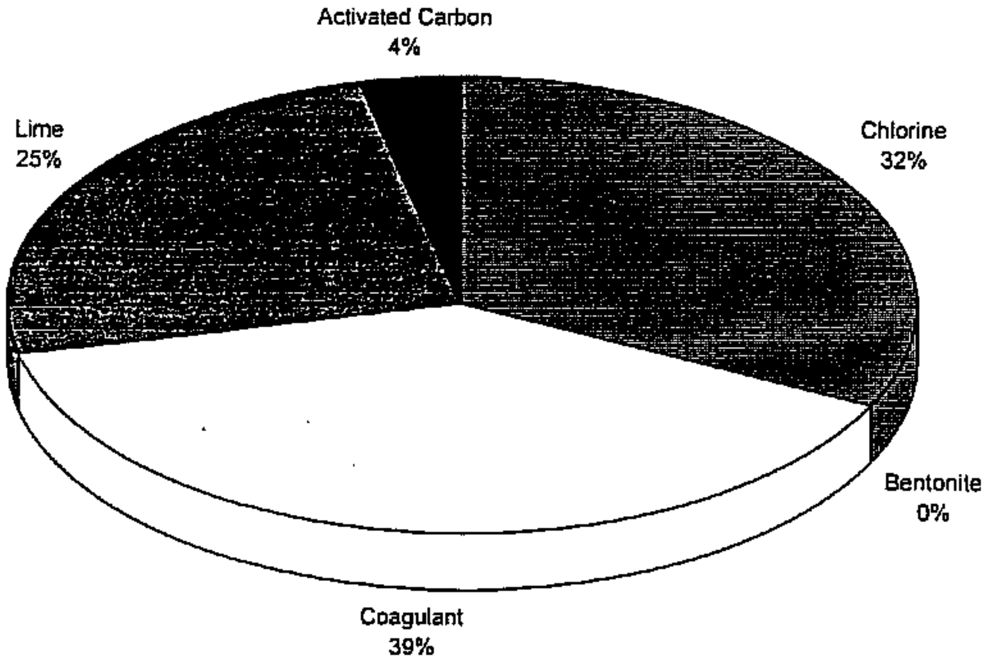

Figure 5.4 Average water treatment cost composition at Durban Heights WW (January 1990 – February 1997) after correction for lime dosages to attain a precipitation potential of 4mg/ℓ $CaCO_3$.

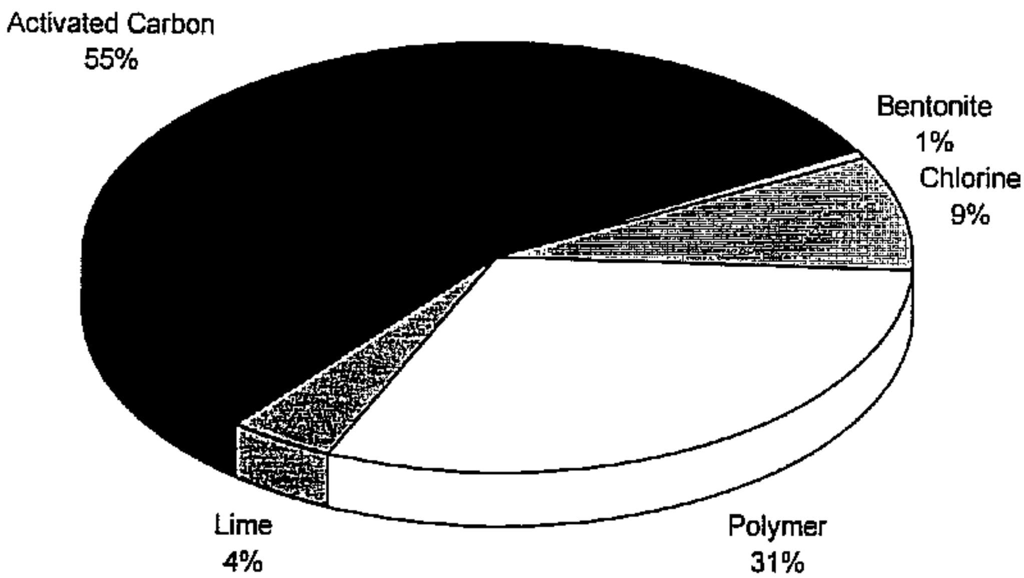

Figure 5.5 Average water treatment cost composition at Durban Heights WW during a particularly severe period of taste and odour formation (March 1994)

5.2.3 The DV Harris system

The DV Harris WW plant draws water from Lake Midmar, an inland impoundment characterised by generally 'clean' water (compared to that treated at Hazelmere and Durban Heights WW). Maximum turbidity of water treated at DV Harris recorded between January 1990 to December 1996 was 52 NTU (Table 5.3). The descriptive statistics showing the condition of raw water treated at DV Harris is given in Table 5.3.

Table 5.3 Descriptive statistics showing the characteristics of raw water treated at the DV Harris WW

Water quality indicator	Units	Minimum	Mean	Maximum
Treatment cost	R/Mℓ	22.64	28.30	49.83
Turbidity	NTU	4.63	23.65	52.46
Total Organic Carbon	mg/l	1.82	2.86	7.85
Suspended Solids	mg/l	3.82	14.96	36.70
Alkalinity	mg/l	19.73	24.83	29.20
Nitrate	mgN/l	0.07	0.31	1.09
Potassium	mg/l	0.69	1.38	2.22
Temperature	°C	11.03	17.20	21.93
Conductivity	mS/m	5.97	6.92	8.09
Total Hardness	mg/l $CaCO_3$	18.02	21.96	25.73
Calcium	mg/l	3.11	4.40	5.31
Magnesium	mg/l	2.24	2.63	3.16
Sodium	mg/l	3.24	4.48	5.55
Silicon	mg/l	2.30	4.53	5.92
Dissolved oxygen	mg/l O_2	6.63	8.39	10.88
Manganese	mg/l	0.01	0.01	0.03
Coliforms	colony counts/100ml	0	16	136
E.coli	colony counts/100ml	0	5	53
Chlorella	cells/ml	12	221	644

The average cost of treating water at DV Harris plant over the period January 1990 to December 1996 was R28/Mℓ, the cost however, ranged between R22/Mℓ and R49/Mℓ with changes in water quality (Table 5.3). The cost of disinfecting the water constituted approximately 50% of total treatment costs (Figure 5.6). The cost of water treatment at DV Harris would therefore appear to be strongly influenced by changes in the requirements of chlorine and ammonia to disinfect the water. More probably however, the polymeric coagulant costs in this relatively 'clean' Lake Midmar water are relatively low compared to the 'apparent' contribution of disinfection costs. This appears to artificially inflate the influence of disinfection on total costs by comparison with more turbid (coagulant) driven systems.

The removal of cost of ammonia, which is only required for distribution purposes of treated water at DV Harris, reduces the average treatment cost to R25/Mℓ. This also changes the cost structure of the DV Harris system as shown in Figure 5.7, compared to that shown in Figure 5.6.

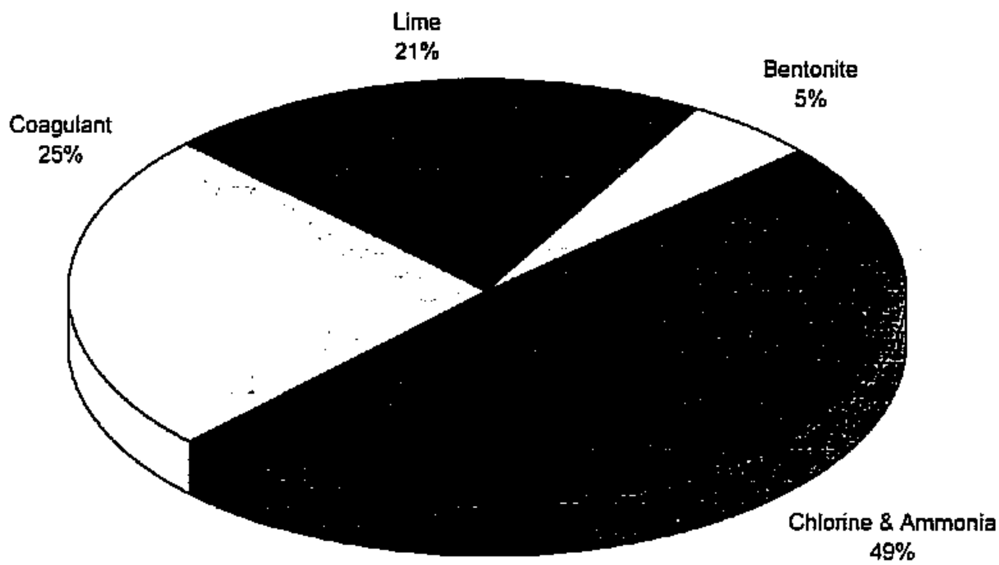

Figure 5.6 Average water treatment cost composition at DV Harris WW.

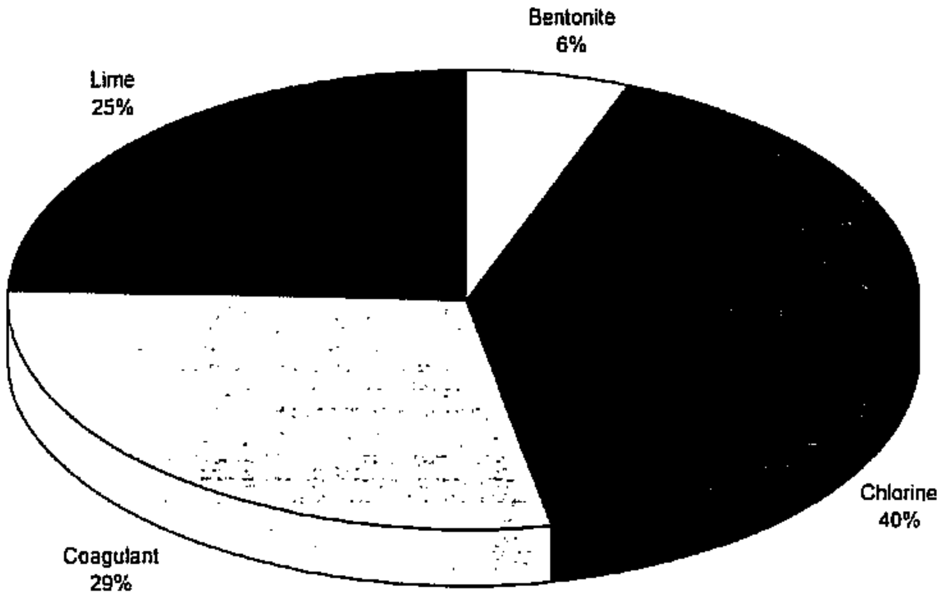

Figure 5.7. Average treatment cost composition at DV Harris WW (with the exclusion of ammonia).

5.2.4 The Wiggins system

The Wiggins WW plant draws water mainly from Lake Inanda and occasionally from Lake Nagle. Water quality conditions in the lake are such that occasional blooms of the algae *Anabaena* and *Microcystis* occur. A maximum of 6310 cells/ml *Anabaena* was recorded in Lake Inanda during the study period (Table 5.4).

Table 5.4 Descriptive statistics showing the characteristics of raw water treated at Wiggins WW (January 1990 - March 1997)

Water quality indicator	UNITS	Minimum	Mean	Maximum
Treatment cost	R/Ml	3.06	20.84	75.32
Turbidity	NTU	2.36	19.19	141.13
Total aluminium	ug/l	3.40	85.46	519.50
Iron	mg/l	0.10	0.56	1.89
Suspended Solids	mg/l	2.00	15.14	88.50
Nitrate	mgN/l	0.03	0.44	2.35
Total Organic Carbon	mg/l	1.62	3.09	5.45
Total Dissolved Solids	mg/l	39.20	117.13	224.00
pH		7.32	7.71	8.11
Secchi	m	0.40	1.65	2.90
Silicon	mg/l	0.50	2.98	7.60
Potassium	mg/l	1.00	2.83	15.00
Coliforms	colony counts/100ml	2.00	157.23	1472.00
Sulphate	mg/l	3.20	11.13	22.00
Temperature	°C	15.22	20.80	25.97
Trachelomonas	cells/ml	0	0	4.00
Chlorella	cells/ml	6	247	726
Cryptomonas	cells/ml	0	35	130
Crucigena	cells/ml	0	74	819
Anabaena	cells/ml	0	151	6310

The average cost of treating water at the Wiggins WW during the period January 1990 to April 1997 was R20/Mℓ. The cost however, ranged between R3/Mℓ and R75/Mℓ, with changes in water quality (Table 5.4). The cost of flocculation constituted approximately 44% of total water treatment costs, followed by disinfection costs, 38%. (Figure 5.8). As with the Durban Heights system the average treatment cost increases (to R22/Mℓ) if the lime dosage is adjusted to attain a precipitation potential of 4mg/ℓ $CaCO_3$. This would change the average cost structure at Wiggins WW as shown in Figure 5.9.

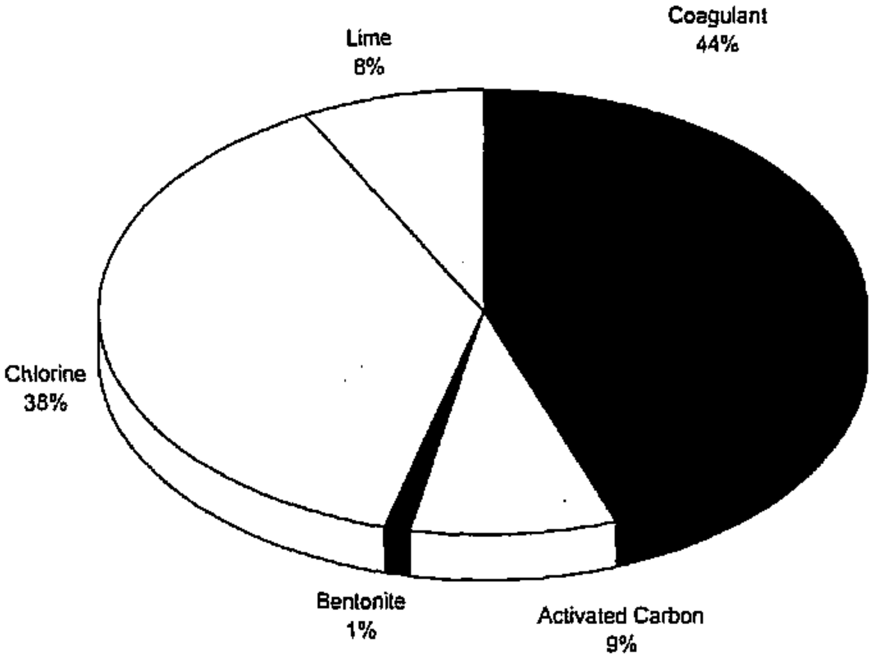

Figure 5.8 Average water treatment cost composition at Wiggins WW (Jan 1990 – Feb 1997).

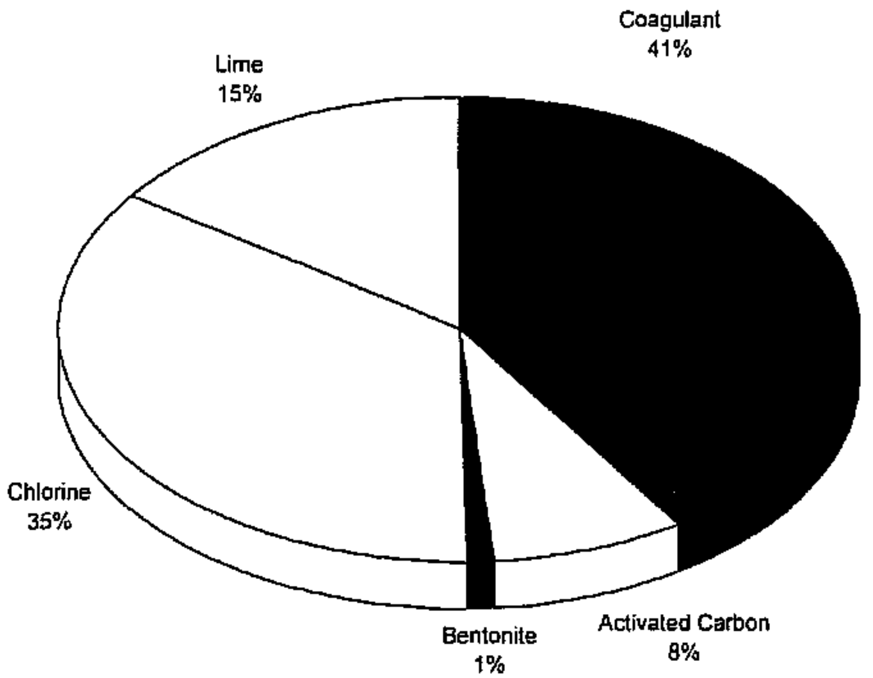

Figure 5.9 Average chemical cost composition at Wiggins WW (Jan 1990 - Feb 97) after adjusting for extra lime required to achieve the 4mg/ℓ $CaCO_3$ precipitation potential.

5.3 Results and discussion

5.3.1 Selection of water quality variables for the modelling of costs at selected waterworks

In order to isolate factors most closely associated with water treatment costs at the selected WW (Hazelmere, Durban Heights, DV Harris and Wiggins), zero-order correlation analysis was performed relating some of the variables anticipated to affect the cost of treating water. Variables with significant correlation (r^2) coefficients were selected for further analysis. Tables showing correlations of these variable with cost are given in Appendix 4, Tables A4.2 to A4.5.

On the basis of the correlation analysis, water quality variables and algae that were anticipated to be affecting the cost of treating water at the selected WW included; turbidity, total organic carbon, suspended solids, total aluminium, alkalinity, nitrates, sulphate, potassium, water inflow, total dissolved solids, iron, manganese, pH, conductivity, iron, secchi, total hardness, silicon, soluble reactive phosphorus, total phosphorus, coliforms, *E.coli*, temperature, manganese, dissolved oxygen, total kjeldahl nitrogen, *Microcystis, Anabaena and Chlorella.*

5.3.2 Water quality variables affecting treatment costs at respective waterworks

Results of the linear regression models fitted for the respective WW are presented in Tables 5.5 to 5.8. Due to the multicollinearity problem (§ 3.4.2), whereby many environmental variables were strongly correlated with each other, there were problems with developing robust statistical models relating water treatment costs to water-quality variables (original model estimates). After removing multicollinearity (final model estimates), the final models were considered a more robust predictor of treatment costs. The lowest R^2 in these final models was still a reasonable 64%.

The figures indicating the match between actual costs and those predicted by the various models illustrate the robustness of these models. Where appropriate, selected additional explanations and graphical presentations are made in the text of some of the important relationships between water quality variables and treatment costs.

A trend variable was considered in each analysis to detect if there was a gradual increase or decrease in treatment costs at respective works. An increase in treatment costs over time would indicate deterioration in raw water quality entering WW (and obviously *visa versa*). In only the DV Harris and Wiggins WW systems was the trend variable found to be significantly affecting treatment costs.

5.3.2.1 The Hazelmere system

Table 5.5 Estimated regression coefficients of factors affecting water treatment costs at Hazelmere WW (before and after removing the multicollinearity problem).

Explanatory Variable	Original model estimates		Final model estimates	
	Coefficients	t-values	Coefficients	t-values
Constant	50.100	1.16	62.330	
pH	-8.150	-1.36	-9.296	-1.84
Turbidity	0.180	4.19**	0.026	5.78**
Total Aluminium	-0.001	-0.18	0.004	3.24*
Alkalinity	-0.147	-0.63	-0.310	-1.53
Potassium	7.210	2.48*	8.026	2.80*
Manganese	145.000	5.95**	135.031	5.67**
Nitrate	23.970	2.93*	22.677	1.01
Sulphate	1.880	2.24*	1.653	2.26*
Suspended Solids	-0.105	-1.55	0.049	4.10**
Total Organic Carbon	-0.420	-0.30	1.633	3.82*
Chlorella	-0.032	-1.71	-0.031	-1.71
R^2		82%		79%
Adj. R^2		80%		76%
Number of cases		71		

* Sig. at 5%, and ** Sig. at 1%.

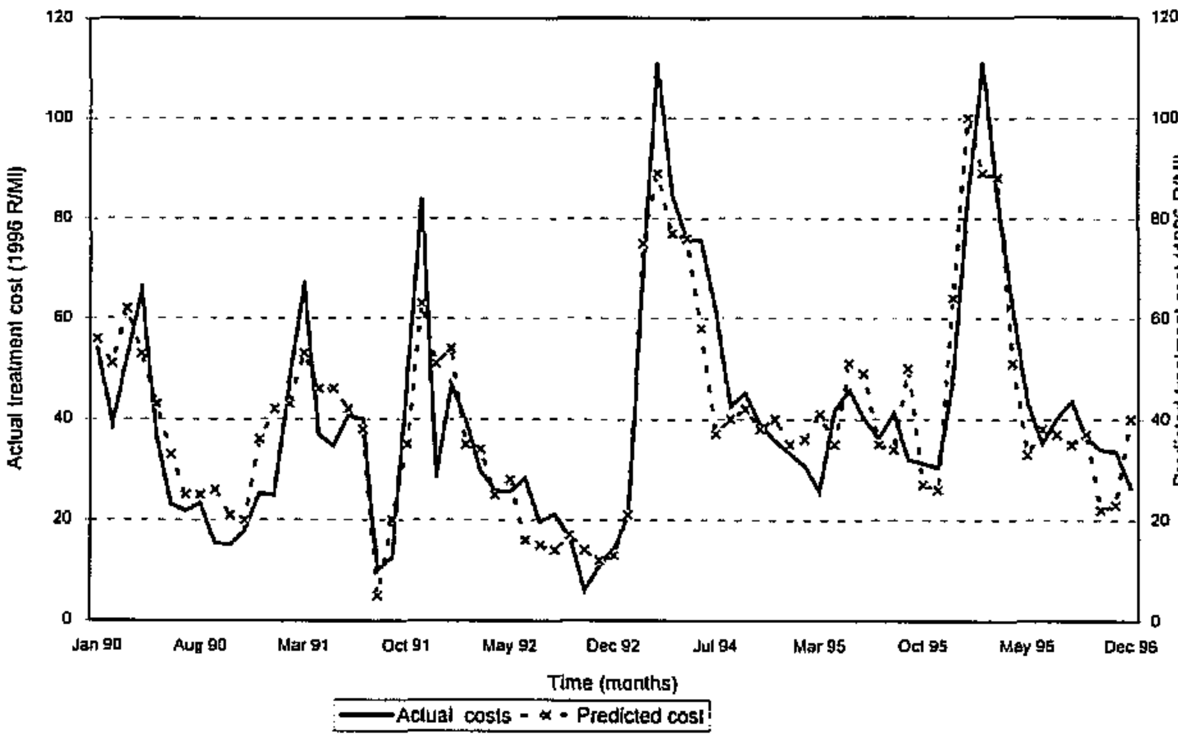

Figure 5.10 Actual versus predicted treatment costs (over time) estimated for the final Hazelmere WW model.

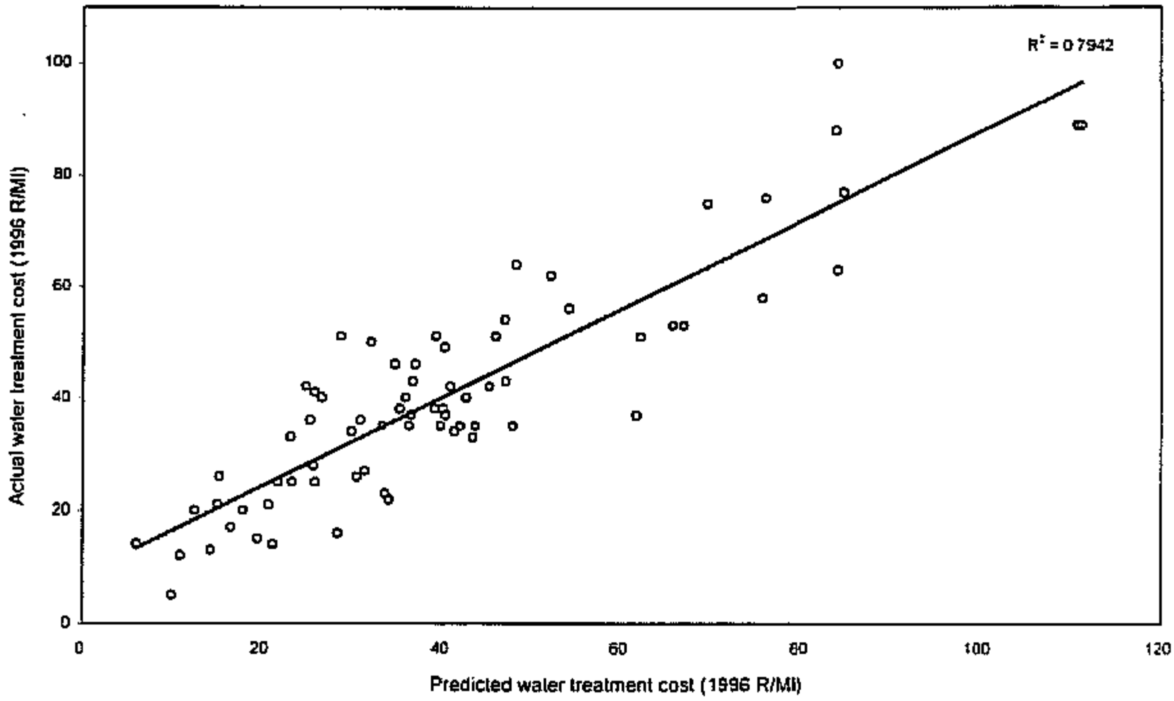

Figure 5.11 Scatterplot of actual versus predicted treatment costs for the Hazelmere WW model.

The algebraic form of the model used to predict water treatment cost at Hazelmere WW is as follows:

Cost = 62.3 + 0.026Turb +135.0Mn + 0.049SS + 1.633TOC + 0.004Al + 1.653SO_4 + 8.026K - 9.296pH - 1.71*Chlorella* - 0.310 Alk + 22.7NO_3

Where:

Cost	=	Predicted water treatment cost
Turb	=	Turbidity
Mn	=	Manganese
SS	=	Suspended Solids
TOC	=	Total Organic Carbon
Al	=	Total Aluminium
SO_4	=	Sulphates
K	=	Potassium
pH	=	pH
Alk	=	Alkalinity
NO_3	=	Nitrates

The results (Table 5.5) suggest that real treatment costs at the Hazelmere WW are closely related to water turbidity in Lake Hazelmere. Increases in cost arise as a result of increased use of polymeric coagulants to treat the elevated turbidity in the raw water (Figure 5.12). It should be noted that highly turbid water in Lake Hazelmere has correspondingly high levels of suspended solids, total organic carbon and total aluminium.

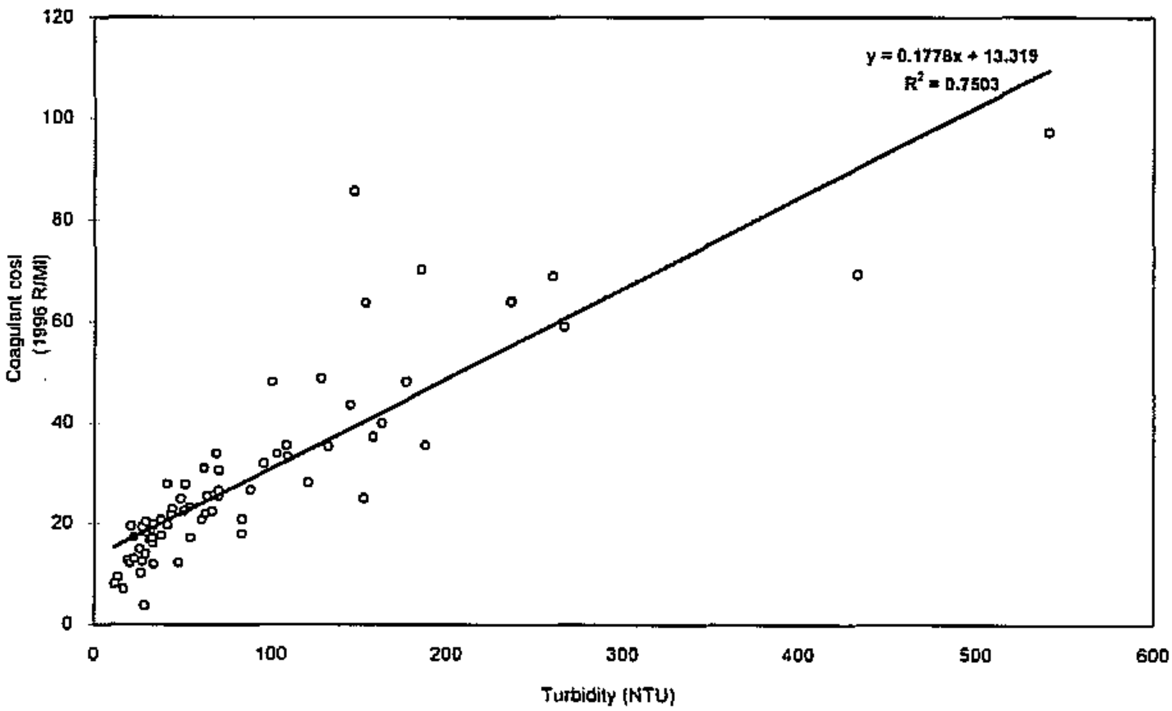

Figure 5.12 Cost of polymeric coagulant versus raw water turbidity at Hazelmere WW.

The positive and significant relationship between treatment costs and manganese shows that manganese is a potentially serious contaminant in Lake Hazelmere water. Manganese in the reduced form may cause aesthetic problems, for example staining. It may also exacerbate bio-film production through the formation of deposits in distribution networks. Treatment for problems associated with manganese normally requires the use of a strong oxidant e.g. chlorine dioxide (formed through the combination of sodium chlorite and chlorine, Freese, pers. comm., 1997).

The results presented in Table 5.5 (negative coefficient and *t*-value) suggests that treatment costs at Hazelmere WW diminish with an increase in abundance of the common green alga *Chlorella*. Lake Hazelmere, unlike other lakes e.g. Midmar and Nagle, has generally highly turbid water that probably suppresses the growth of algae. *Chlorella* abundance, although relatively low, is most apparent during periods of low turbidity when treatment costs are lowest. *Chlorella* is therefore probably a surrogate for water clarity in Lake Hazelmere and helps to explain the negative relationship between treatment costs and increases in *Chlorella* counts in the lake.

There is an apparent inverse relationship between the raw water alkalinity and treatment costs at the Hazelmere WW. This relationship arises from lower lime dosages required as raw water alkalinity levels rise, and *vice versa*. The relationship between pH and treatment costs follows a very similar trend to that of alkalinity for the same reasoning.

5.3.2.2 The Durban Heights system

Results of the regression model estimated for the Durban Heights WW are presented in Table 5.6. The final model fitted for the Durban Heights WW captures a reasonable amount of information (R^2=64%) on factors affecting water treatment costs with a good match shown between actual and predicted treatment costs (Figs. 5.13 and 5.14).

Table 5.6 Estimated regression coefficients of factors affecting water treatment costs at Durban Heights WW (before (original) and after removing the multicollinearity problem (final))

Explanatory Variable	Original model estimates		Final model estimates	
	Coefficients	t-values	Coefficients	t-values
Constant	-106.524	-1.43	67.890	
Temperature	0.692	2.10*	0.383	3.20*
Coliforms	-0.006	-0.71	0.005	2.10*
pH	9.659	1.11	-8.681	-3.62*
Turbidity	0.178	1.39	0.084	8.33**
Iron	-2.461	-0.39	1.613	1.60
Suspended Solids	0.059	0.36	0.084	3.62*
Secchi	-2.239	-0.93	-0.748	-1.42
Conductivity	-0.252	-0.19	0.617	3.14*
Total hardness	0.680	1.49	0.256	3.74*
Potassium	0.420	0.23	0.823	2.58*
Silica	2.922	2.52*	0.577	2.56*
Nitrate	5.431	0.54	3.177	2.40*
Total Organic Carbon	0.314	0.21	0.618	2.65*
Dissolved Oxygen	1.268	1.17	-0.940	-3.30*
Microcystis	0.020	2.11*	0.021	3.25*
Anabaena	0.013	1.97	0.001	2.86*
R^2	70%		64%	
Adj. R^2	62%		62%	

*Sig. at 5%, and **Sig. at 1% level.

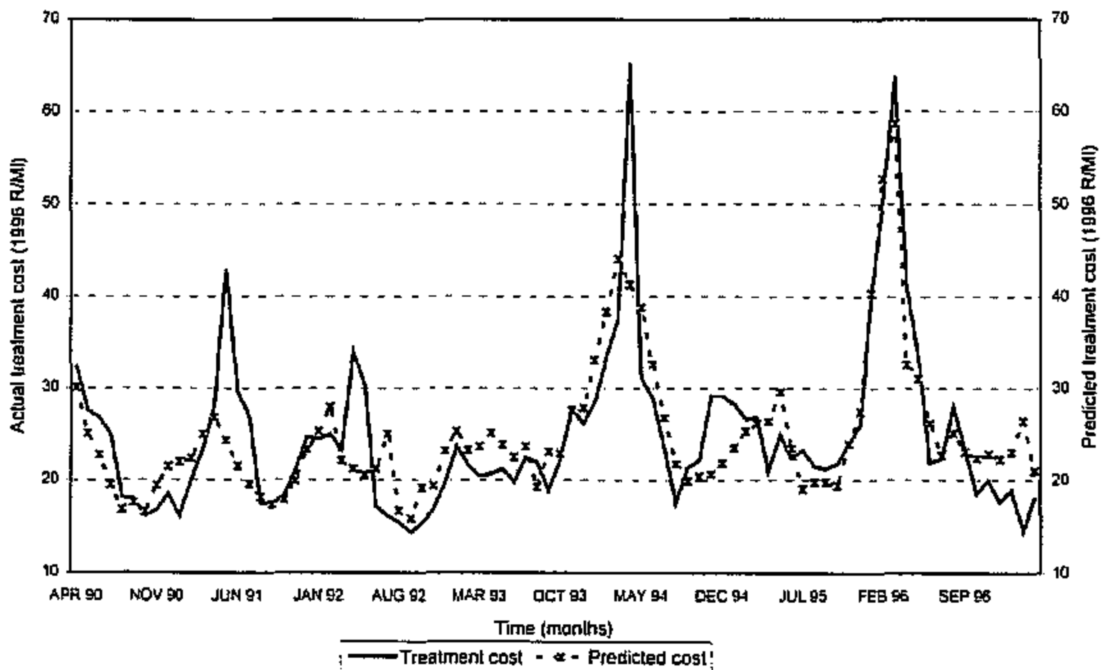

Figure 5.13 Actual versus predicted treatment costs over time fitted using coefficients of water quality variables estimated in the final Durban Heights WW model.

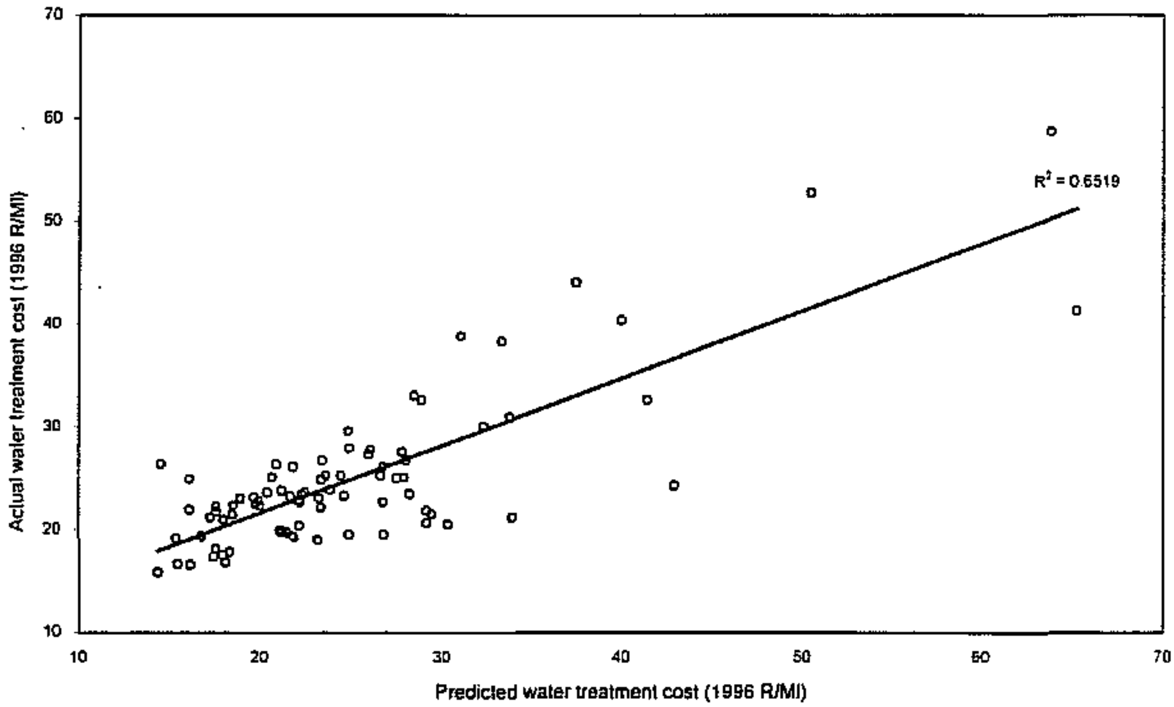

Figure 5.14 Scatterplot of actual versus predicted treatment costs for the Durban Heights WW model.

The algebraic form of the model estimated for the Durban Heights WW is as follows:

$$Cost = 67.9 + 0.383Temp + 0.005Colif - 8.681pH + 0.084Turb + 1.613Fe + 0.084SS - 0.748Secchi + 0.617Cond + 0.256Hard + 0.823K + 0.577Si + 3.177NO_3 + 0.618TOC - 0.940DO + 0.021\textit{Microcystis} + 0.001\textit{Anabaena}$$

Where;

Cost	=	Predicted water treatment cost			
Temp	=	Temperature	Colif	=	Coliforms
pH	=	pH	Turb	=	Turbidity
Fe	=	Iron	SS	=	Suspended Solids
Cond	=	Conductivity	Hard	=	Hardness
K	=	Potassium	Si	=	Silicon
NO_3	=	Nitrates	TOC	=	Total Organic Carbon
DO	=	Dissolved Oxygen			

The results in Table 5.6 show that treatment costs at the Durban Heights WW increase with an increase in water turbidity, suspended solids, silicon, total organic carbon, coliform numbers, conductivity, total water hardness, potassium, nitrates, *Microcystis* and *Anabaena*. These factors are directly related to water pollution of both natural (soil erosion, siltation) and anthropogenic (sewage and agricultural nutrient runoff) origin. Conversely, results show that treatment costs diminish with an increase in water pH and dissolved oxygen in the water.

The cost increases associated with higher water turbidity are a direct result of increased use of polymeric coagulants which is functionally the same relationship as observed in the Hazelmere WW system. The positive coefficient estimated for temperature confirms that treatment costs rise during summer owing to increased rainfall runoff and the attendant deterioration in water quality (generally due to increased turbidity).

High coliform counts are often associated with high runoff (after rains) which washes faecal matter into watercourses and hence lakes. Concurrently turbidity, which is one of the primary determinants of cost, also increases with runoff. Therefore coliforms tend to co-vary with turbidity. Again, as with the Hazelmere WW system, there is an inverse relationship between pH and treatment costs at the Durban Heights WW. The reasoning for this is also the same as expressed for the former system.

Both the blue-green algal genera, *Anabaena* and *Microcystis,* carry positive and significant regression coefficients (Table 5.6), implying that an increase in their abundance leads to increased treatment cost at the Durban Heights WW. Figures 5.15 and 5.16 illustrate this positive relationship between the respective algae and water treatment cost at the WW. *Anabaena*, and to a lessor extent *Microcystis*, are algae widely recognised as causing taste and odour problems (Table 2.4). Advanced (and relatively expensive) treatment procedures e.g. powdered activated carbon (PAC) treatment, are required to remove taste and odour substances from water (Tebbutt, 1992).

In view of previous work which indicates that a large proportion of algae, contained in water abstracted from Lake Nagle, disappears during transport from the lake to the treatment plant at Durban Heights (Dickens, *et. al.* 1996), the Durban Heights model was estimated using flow-weighted algal data collected from the two Lake Nagle abstraction points (UW sample points 17 and 18, § 2.1). These results showed that *Anabaena* was the most important algal genera influencing water treatment cost at Durban Heights WW, while *Microcystis* was insignificant. However, the overall fit of the model was low (R^2 58 %). The reason for the low explanatory power could be attributed to a poor estimate of flow weighted algal counts expected in the raw water at the Durban Heights WW. The algal counts at Durban Heights may in fact have been somewhat different and affected by scarce flow data at the two Lake Nagle abstraction points. Therefore the results reported on here for the Durban Heights WW are based on actual algal data collected at the Durban Heights raw water sample point (UW point 316), because this model provided a better fit.

Clearly the peaks in algal data do not always appear to correspond with peaks in treatment costs indicating that not all blue-green algal blooms have associated taste and odour treatment problems.

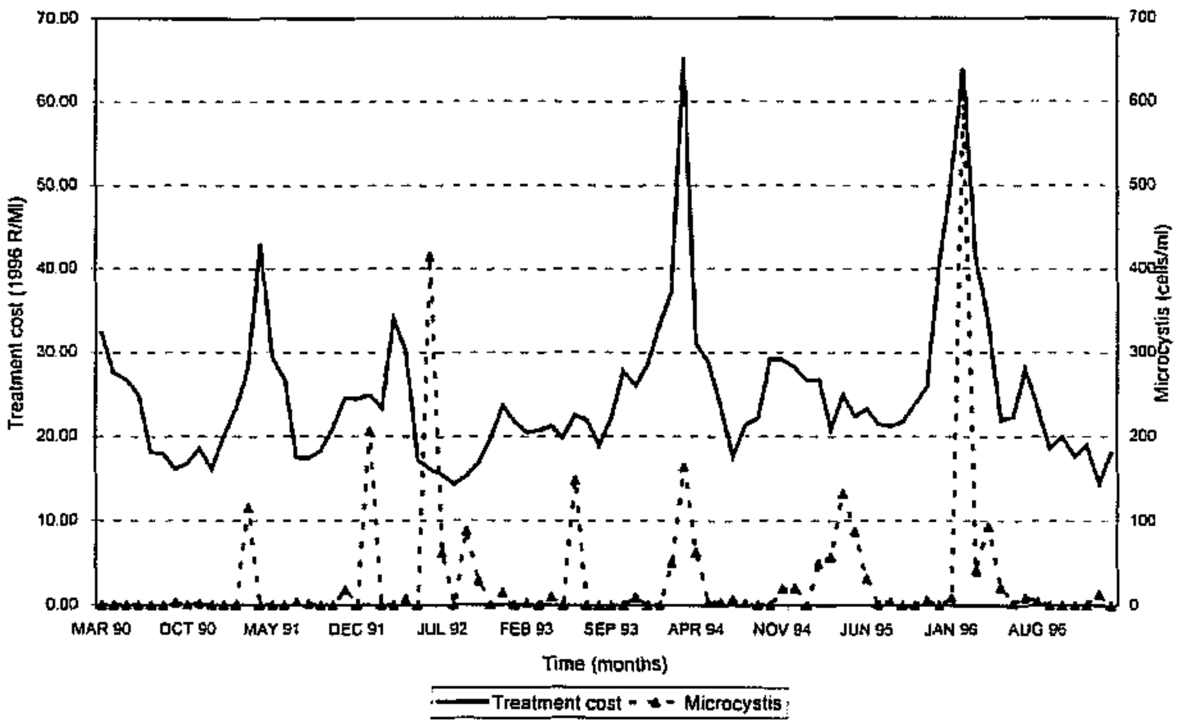

Figure 5.15 Treatment cost versus *Microcystis* counts in the raw water at the Durban Heights WW.

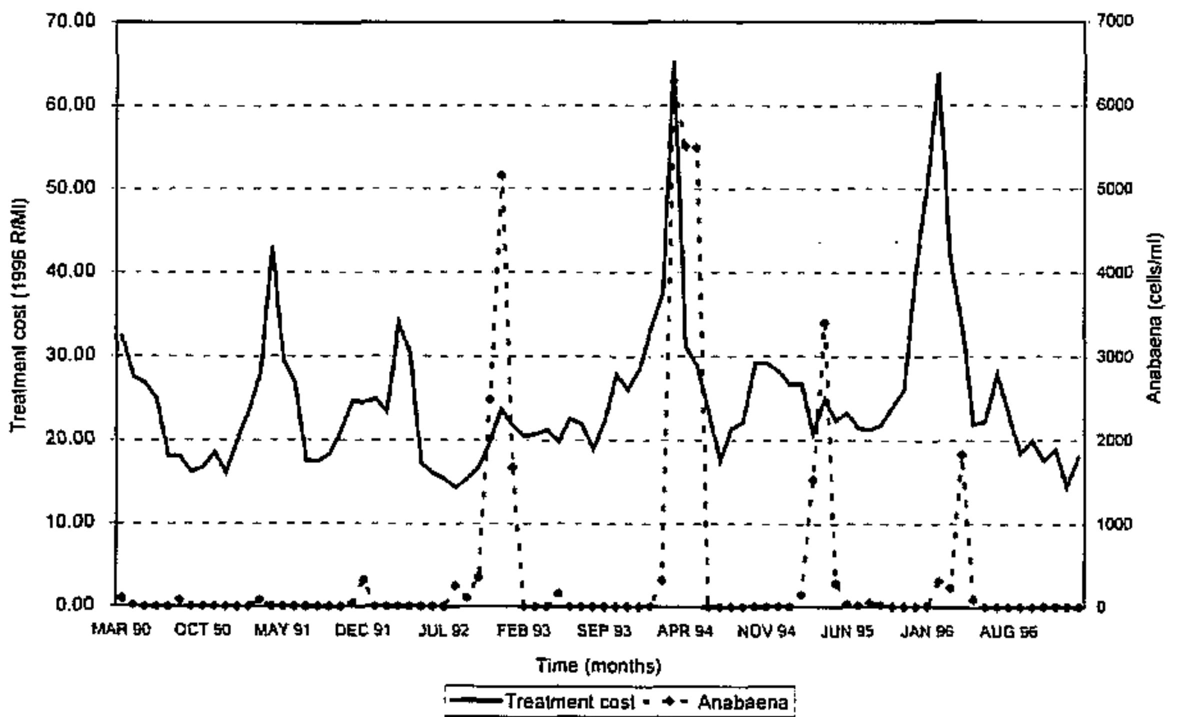

Figure 5.16 Treatment cost versus *Anabaena* counts in the raw water at the Durban Heights WW.

5.3.2.3 The DV Harris system

Results of the regression model estimated for the DV Harris WW are presented in Table 5.7. The final fitted model captures a reasonable amount of information (R^2=67%) on water quality variables affecting water treatment costs at this WW.

Table 5.7 Estimated regression coefficients of factors affecting water treatment costs at DV Harris WW (before and after removing the multicollinearity problem).

VARIABLE	Original model estimates		Final model estimates	
	Coefficients	t-values	Coefficients	t-values
Constant	44.030	2.67*	45.500	
Alkalinity	-0.352	-0.85	-0.415	-6.70**
Coliforms	0.073	2.70*	0.028	6.13**
E.coli	0.026	0.37	0.075	6.12**
Total Hardness	-0.632	-1.44	-0.345	-6.16**
Potassium	3.242	1.24	2.150	3.02*
Trend Variable	0.119	3.09*	0.024	2.86*
Nitrate	6.608	1.98	5.075	3.37*
Manganese	103.724	1.01	-97.369	-4.11*
Conductivity	0.291	0.16	-0.508	-2.19*
Silica	0.008	0.01	0.285	1.50
Dissolved Oxygen	-0.682	-0.86	-0.463	-2.94*
Temperature	-0.051	-0.18	0.165	3.69*
Total Organic Carbon	-0.369	-0.64	0.234	1.27
Suspended Solids	-0.039	-0.45	-0.021	-0.55
Turbidity	0.032	0.43	-0.010	-0.61
Chlorella	-0.003	-0.63	-0.006	-6.53**
R^2		75%		67%
Adj. R^2		67%		64%
Number of cases	64			

*Sig. at 5% and **Sig. at 1%

Figures 5.17 and 5.18, show a reasonably good match between actual costs and those predicted by the model.

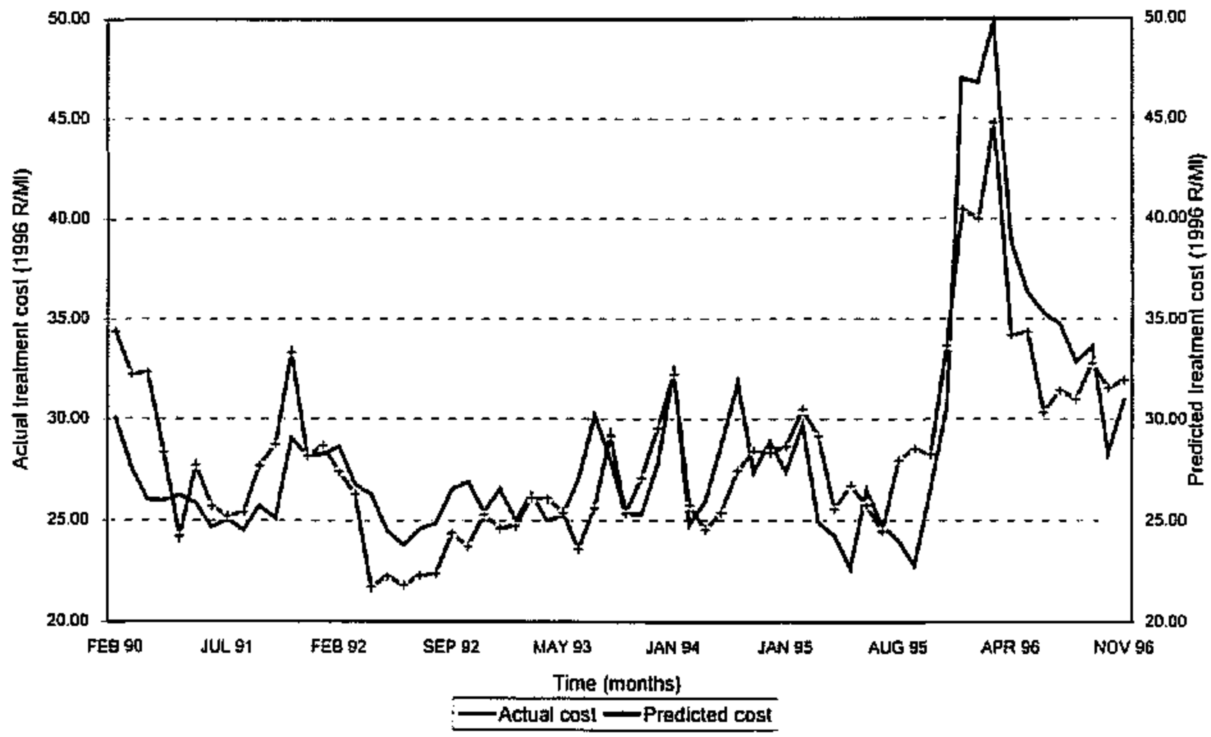

Figure 5.17 Actual versus predicted treatment costs over time fitted using coefficients of water quality variables estimated in the final DV Harris WW model.

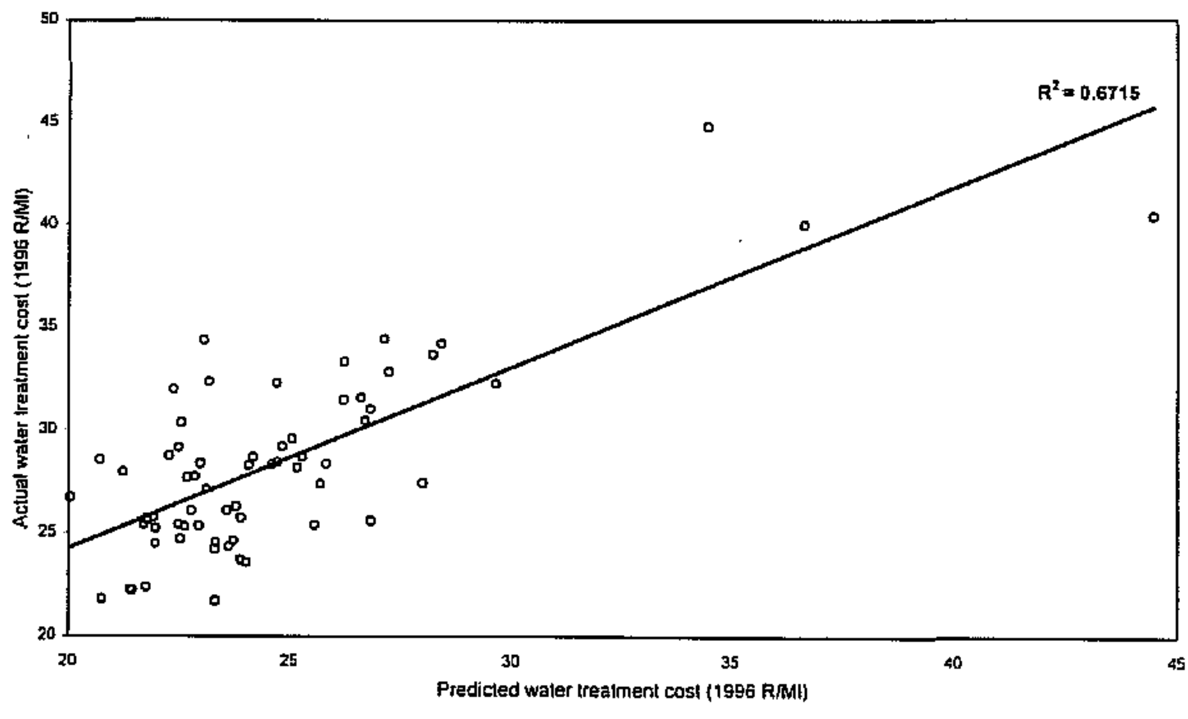

Figure 5.18 Actual versus predicted treatment for the DV Harris WW model.

The algebraic form of the model used to predict water treatment cost at DV Harris WW is as follows:

$$Cost = 45.5 - 0.415Alk + 0.028Colif + 0.075\ E.coli - 0.345Hard + 0.024K + 0.024Trend + 5.075NO_3 - 97.4Mn - 0.508Cond + 0.285Si - 0.463DO + 0.234TOC - 0.021SS - 0.010Turb - 0.006\textit{Chlorella}$$

Where:

Cost	=	Predicted water treatment cost			
Alk	=	Alkalinity	Colif	=	Coliforms
E.coli	=	*E.coli*	Hard	=	Hardness
K	=	Potassium	Trend	=	Trend variable
NO3	=	Nitrates	Mn	=	Manganese
Cond	=	Conductivity	Si	=	Silicon
DO	=	Dissolved Oxygen	Temp	=	Temperature
TOC	=	Total Organic Carbon	SS	=	Suspended Solids
Turb	=	Turbidity			

The results suggest that real treatment costs at the DV Harris plant diminish with an increase in the alkalinity, *Chlorella* and Total Hardness, in Lake Midmar. As with previous systems analysed, an increase in alkalinity (and hardness) of the water means a reduction in lime dosage and hence treatment costs. Likewise the presence of the algae *Chlorella* acts as a surrogate for clean water, so that when the water is turbid, *Chlorella* is less abundant, and the costs of treating such water increase.

Water treatment costs at DV Harris appear to rise significantly with an increase in coliforms and *E.coli* (Figure 5.19) in Midmar. Traditionally cost increases associated with coliforms and *E.coli* in raw water may be expected to be because of a higher chlorine-demand in this water. However a plot of these variables against chlorine costs did not reveal any obvious relationships. An alternative explanation for these relationships may be that these bacteriological variables generally increase with increased rainfall and runoff from catchments. Along with this comes an increase in turbidity and other variables that have a potential chlorine-demand and will therefore increase treatment costs. A plot of total organic carbon (which may have been anticipated to be related to chlorine demand) against chlorine costs did not reveal a close relationship.

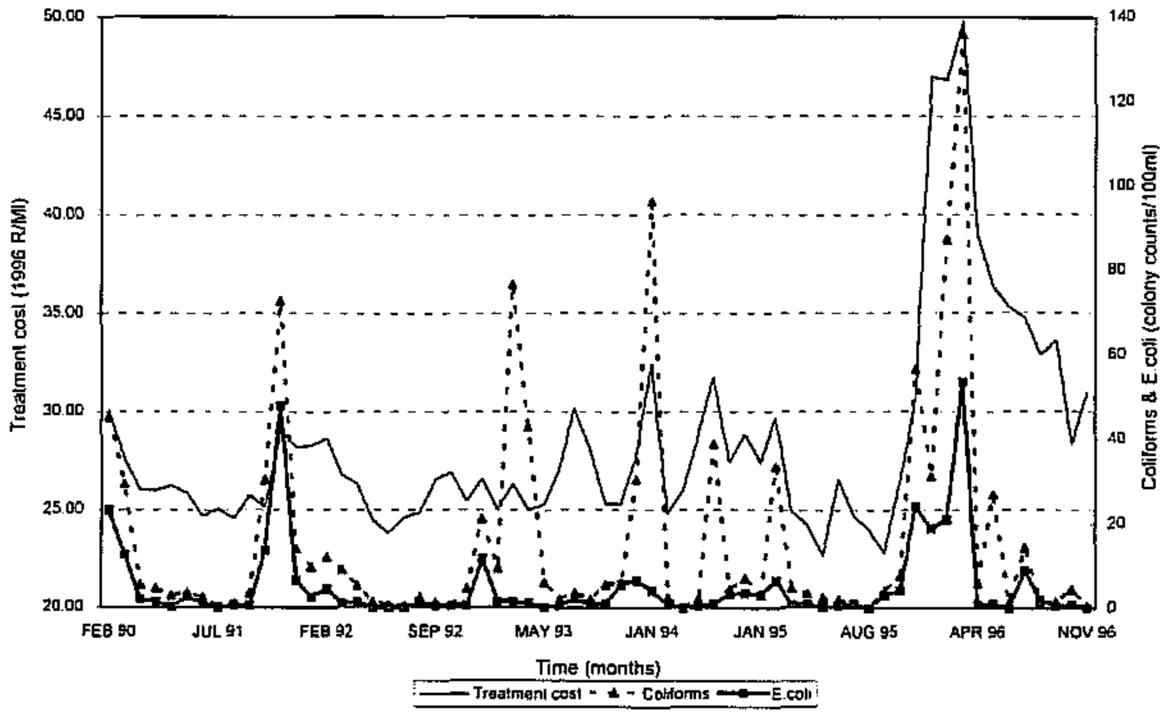

Figure 5.19 Water treatment cost versus number of coliforms & *E.coli* in the raw water to DV Harris WW.

Unlike all other WW considered results indicate that turbidity is not significant in influencing treatment costs in the DV Harris system. In fact costs may increase under low turbidity conditions as bentonite is added to the raw water to increase the efficacy of polymeric coagulants.

The positive coefficient estimated for temperature confirms that treatment costs rise during summer probably owing to increased rainfall runoff and the attendant deterioration in water quality. The significance of the "trend" variable in the DV Harris model shows that over time treatment cost have been increasing in this system. This might be associated with factors other than those included in the model having a significant effect on treatment costs at the DV Harris WW.

5.3.2.4 The Wiggins system

Table 5.8 Estimated regression coefficients of factors affecting water treatment costs at Wiggins WW (before and after removing the multicollinearity problem)

VARIABLE	Original model estimates		Final model estimates	
	Coefficients	t-values	Coefficients	t-values
Constant	-34.288	-0.77	34.087	1.96*
Turbidity	0.303	6.21***	0.091	13.88***
Total Aluminium	0.020	1.35	0.016	6.96**
Iron	4.432	1.55	4.253	4.67***
Suspended Solids	-0.015	-0.19	0.104	3.76***
Nitrate	-3.77	-1.45	3.156	4.33***
Total Organic Carbon	-0.327	-0.30	1.196	5.15***
Total Dissolved Solids	-0.011	-0.47	0.024	3.90***
pH	4.497	0.79	-5.279	-2.32**
Silicon	0.654	1.18	0.486	3.23***
Trend variable	0.084	1.87*	0.032	2.25**
Coliforms	0.006	2.34**	0.009	3.79***
Sulphates	0.404	2.14**	0.090	1.78*
Temperature	-0.051	-0.18	0.465	2.42**
Anabaena	0.001	1.71*	0.001	2.01*
R^2:	92%		79%	
Adj. R^2:	85%		77%	
Number of cases:	82			

*Sig. at 10%, **Sig. at 5% and ***Sig. at 1%

The final model fitted for the Wiggins WW captures a reasonable amount of information (R^2=79%) on factors affecting water treatment costs at this WW. Figures 5.20 and 5.21, show a good match between actual costs and those predicted by the model fitted for this WW.

The algebraic form of the predictive model estimated for the Wiggins WW is as given below:

$$Cost = 34.1 + 0.091Turb + 0.016Al + 4.253Fe + 0.104SS + 3.156NO_3 + 1.196TOC + 0.024TDS - 5.279\ pH + 0.486Si + 0.032Trend + 0.009Colif + 0.090SO_4 + 0.465Temp + 0.001\textit{Anabaena}$$

Where:

Cost	=	Predicted water treatment cost
Turb	=	Turbidity
Al	=	Total Aluminium
Fe	=	Iron
SS	=	Suspended Solids
NO_3	=	Nitrates
TOC	=	Total Organic Carbon
TDS	=	Total Dissolved Solids
pH	=	pH
Si	=	Silicon
Colif	=	Coliforms
SO_4	=	Sulphates
Temp	=	Temperature

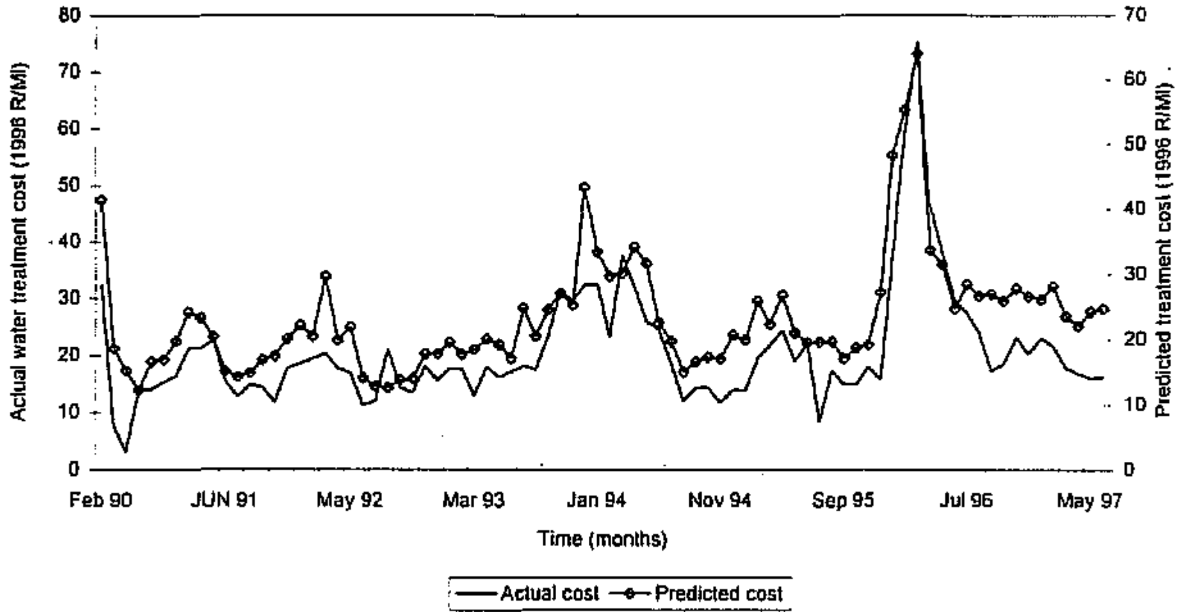

Figure 5.20 Actual versus predicted treatment costs over time fitted using coefficients of water quality variables estimated in the final Wiggins WW model.

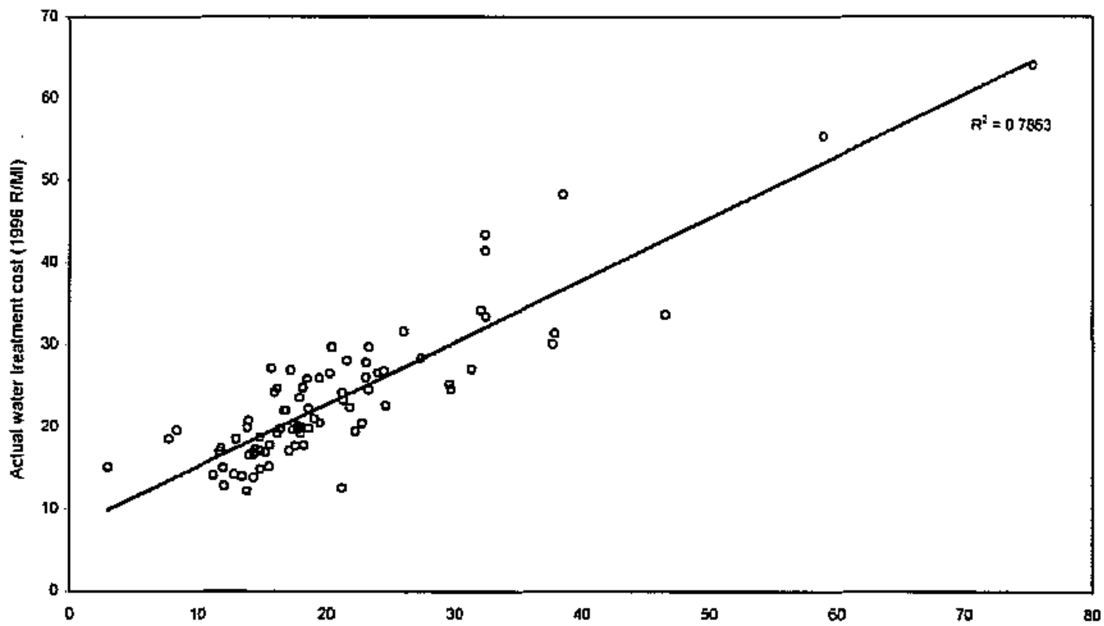

Figure 5.21 Scatterplot of actual versus predicted treatment costs for the Wiggins WW.

The results in Table 5.8 show that treatment costs at the Wiggins WW increase with an increase in water turbidity (e.g. Figure 5.22), total aluminium, iron, suspended solids, nitrates, total organic carbon, total dissolved solids, silicon, coliform numbers, conductivity, total water hardness, potassium, nitrates, *Microcystis* and *Anabaena*. Conversely, results show that treatment costs diminish with an increase in water pH and dissolved oxygen in the water. As with the DV Harris system the significance of the "trend variable" shows that over time treatment costs appear to have been increasing in this system.

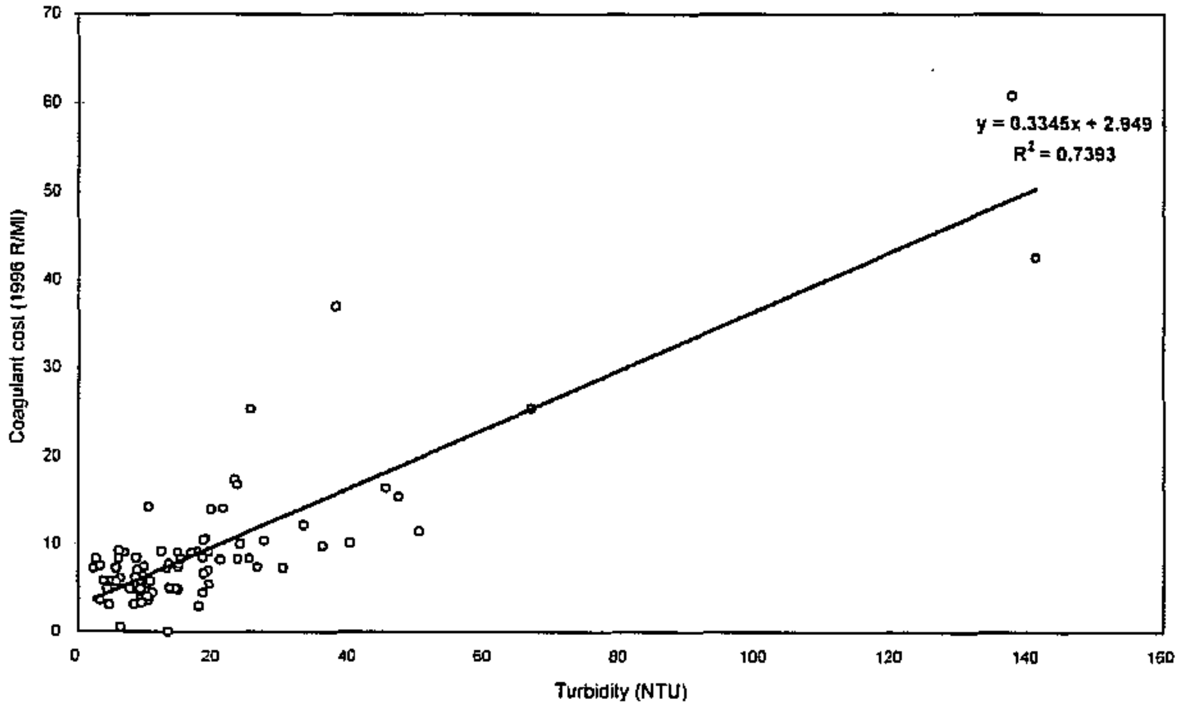

Figure 5.22 Polymeric coagulant cost versus raw water turbidity at the Wiggins WW.

5.4 Application of water treatment cost models

The water treatment cost models presented in section 5.3 may be used practically by WW operators to improve/optimise the WW process. They also quantify for catchment managers and planners those water quality processes that are likely to have an impact on the cost of treating water. Various 'what-if' and prediction type scenarios are possible with these derived models.

5.4.1 Predicting changes in water treatment costs with changes in raw water turbidity – the Hazelmere system

The predictive model developed for Hazelmere WW (in section 5.3.2.1) is a useful management tool. Regression coefficients estimated using ordinary least squares (OLS) and principal components analysis (PCA) quantified the independent effects of each of the WQ variables identified as significantly affecting treatment costs. The model can therefore be used to predict the outcome of a management-induced change in one or more of the explanatory WQ variables. Plausible scenarios can be predicted rapidly using a standard spreadsheet package. As an example, the model was used to predict treatment costs assuming that turbidity is held at different levels. In lakes with abstraction towers allowing a choice of abstraction levels, this would be feasible. Modifications to catchment land-use may also induce changes to lake turbidities, although in a less predictable manner. For example sand-winning operations in this catchment were found to be having an impact on lake turbidity.

Turbidity was identified as playing a significant role in affecting the cost of water treatment at Hazelmere Dam. At the same time it is acknowledged that controlling lake turbidity would have a direct impact on the levels of suspended solids and total aluminium in the lake and that these should also reasonably be allowed to co-vary (as established in a linear regression relationship presented in Appendix 4, Figures A4.1 and A4.2). Therefore treatment costs are predicted at different levels of turbidity, while holding suspended solids and total aluminium at corresponding levels, and allowing other important variables affecting treatment cost in Hazelmere dam to vary with 'real' data. The information used in the prediction exercise is given in Table 5.9, and graphically presented in Figure 5.23.

Table 5.9 Predicted treatment cost, holding turbidity (and corresponding levels of suspended solids and total aluminium) constant, but allowing other factors to vary with real data at Hazelmere WW

Turbidity (NTU)	Suspended Solids (mg/ℓ)	Total Aluminium (ug/ℓ)	Predicted mean cost (1996 R/Mℓ)	Difference in cost from the mean cost (R 40.59)
0	0	22	34.36	6.23
10	0	83	34.85	5.74
20	0	143	35.34	5.25
30	5	204	36.08	4.51
40	11	265	36.87	3.72
50	17	326	37.66	2.93
60	23	387	38.45	2.14
70	29	448	39.24	1.35
80	35	508	40.02	0.57
90	41	569	40.81	-0.22
100	46	630	41.55	-0.96
.	.	.	.	.
.	.	.	.	.
200	106	1238	49.44	-8.85
.		.	.	.
.		.	.	.
550	315	3367	76.98	-36.39

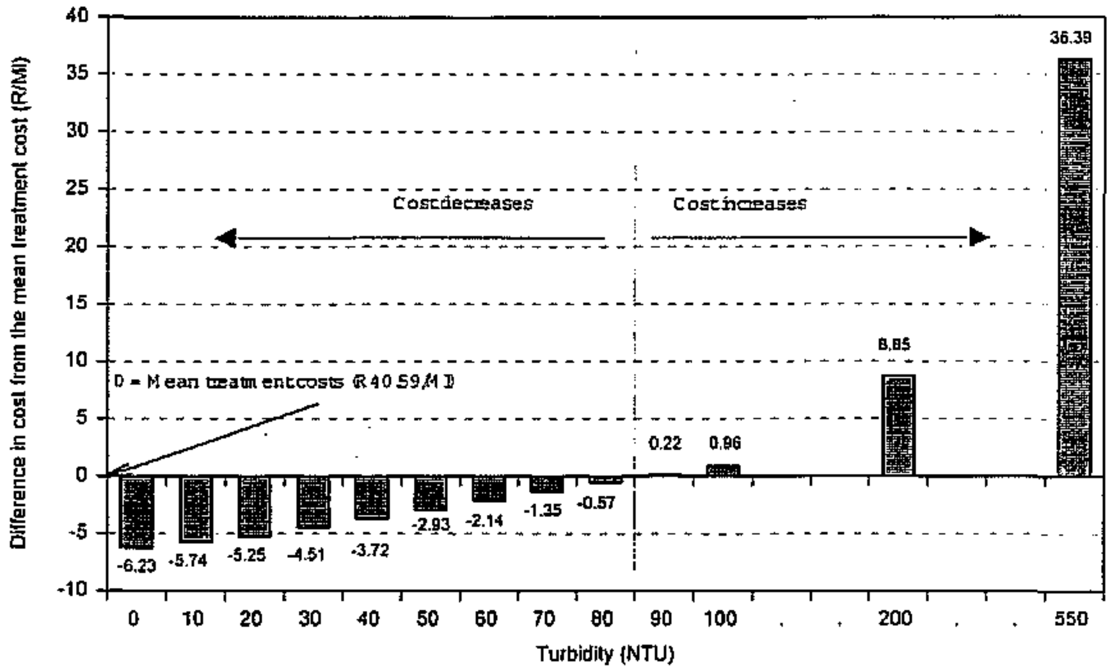

Figure 5.23 Difference in predicted costs from mean treatment cost at different turbidity levels in the Hazelmere WW.

Figure 5.23 illustrates the differences in predicted treatment cost from the mean treatment cost with varying turbidity scenarios. Water treatment costs in this figure are observed to rise above the average (R40.59/Mℓ), recorded at Hazelmere WW over the period January 1990 to December 1996, when turbidity levels exceed 80NTU. Implications are that any management action that keeps the turbidity level below 80 NTU in Lake Hazelmere would lower the average water treatment costs at Hazelmere WW. For example, if turbidity is held at 20 NTU, this could lower average treatment cost by R5.25/Mℓ (*ceteris paribus*). From a financial perspective (based on 1996 chemical treatment costs and approximately 8500Mℓ treated) this could amount to approximately R45 000 annually.

5.4.2 Predicting changes in water treatment costs with changes in raw water turbidity and *Anabaena* abundance – the Durban Heights system

The raw water abstracted from Lake Nagle (and occasionally Inanda) and fed to Durban Heights is characterised as relatively turbid with occasional blooms of *Anabaena* and *Microcystis* that may significantly affect water treatment costs. The model estimated for Durban Heights WW were used to predict possible cost scenarios given changes in water turbidity and *Anabaena* counts. Treatment costs over the period are predicted with turbidity (and corresponding levels of suspended solids) held at different levels (Table 5.10), and allowing other factors to vary with real data. The justification for co-varying suspended solids with turbidity is the same as that applied in the Hazelmere WW system (the linear relationship between suspended solids and turbidity in the raw water treated at Durban Heights is illustrated in Appendix 4, Figure A4.3). Results from analyses of water treatment costs and water quality variables (Table 5.6 (§ 5.3.2.2)) show that total aluminium does not significantly affect treatment costs at the Durban Heights WW.

Results are presented in Table 5.10 and Figure 5.24.

Table 5.10 Predicted treatment cost, holding turbidity at corresponding levels of suspended solids constant, but allowing other factors to vary with real data at Durban Heights WW

Turbidity (NTU)	Suspended Solids (mg/ℓ)	Predicted mean cost (1996 R/Mℓ)	Deviation from mean cost (R 40.59)
0	0	22.23	2.61
6	4	23.06	1.78
10	7	23.65	1.19
20	14	25.06	-0.22
30	21	26.48	-1.64
40	29	27.98	-3.14
50	36	29.40	-4.56
60	43	30.81	-5.97
70	50	32.23	-7.39
80	57	33.65	-8.81
90	64	35.07	-10.23

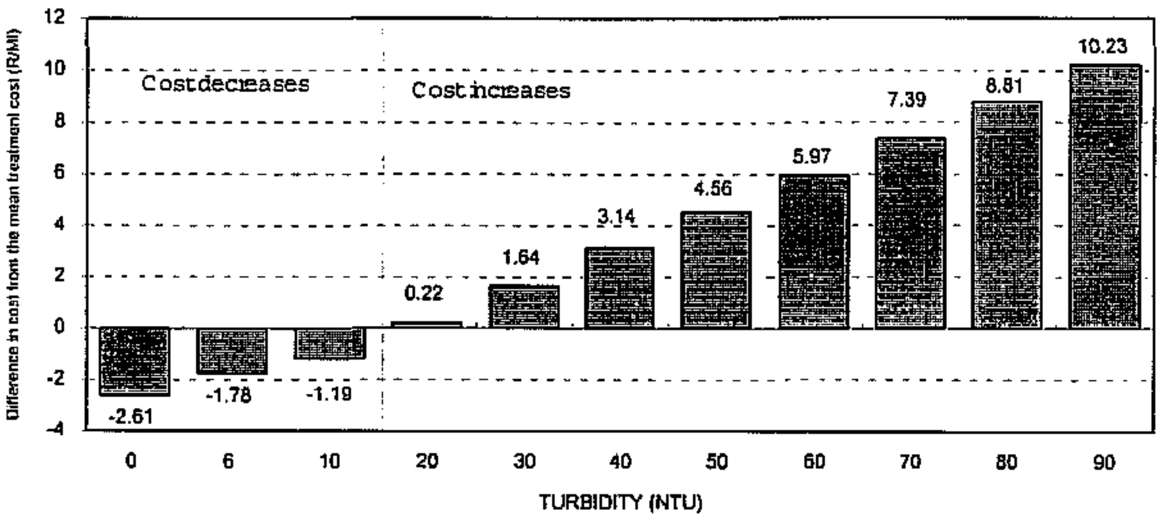

Figure 5.24 Differences in mean treatment cost at different turbidity levels at Durban Heights WW.

Figure 5.24 shows that water treatment costs are observed to rise above the mean (≈R25/Mℓ) water treatment cost recorded at the Durban Heights WW when turbidity levels exceeds 20NTU. Implications are that any management action that keeps the turbidity level below 20NTU at this WW will lower the mean water treatment costs. For example, if turbidity is held at 6NTU, this could lower the mean treatment cost by R1.78/Mℓ. From a financial perspective (based on 1996 figures) this could amount to approximately R350 000 annually, with a total of ≈190 000Mℓ treated. Conversely, as turbidity rises, mean treatment cost will increase by the magnitudes shown in Figure 5.24.

In a similar way the Durban Heights model is also used to predict the possible effects of different numbers of the algae *Anabaena* on cost. Results of these simulations are illustrated in Figure 5.25.

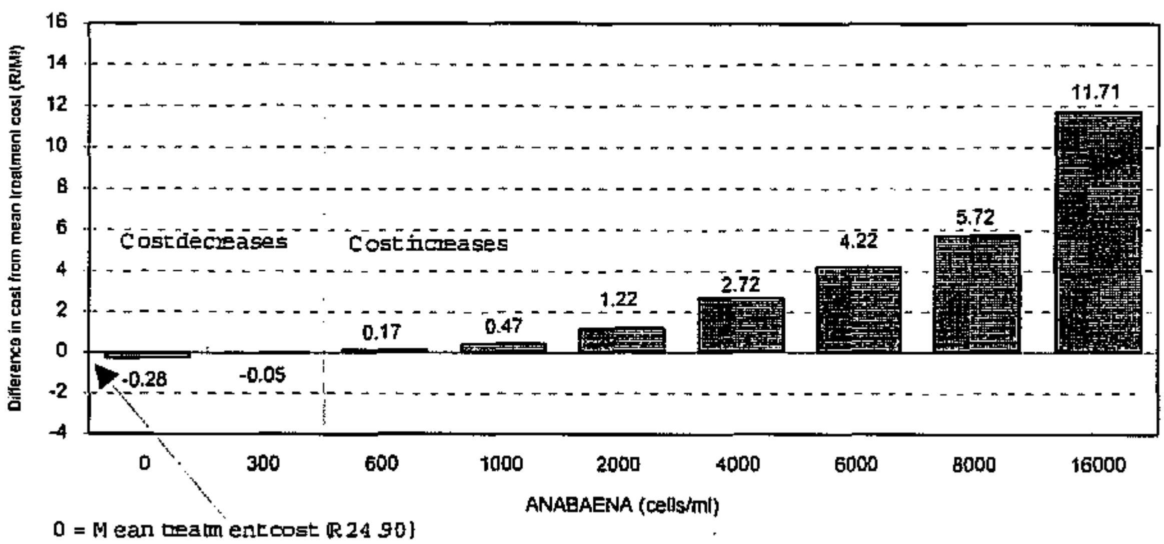

Figure 5.25 Differences in mean treatment cost with different abundances of *Anabaena* in the raw water treated at the Durban Heights WW.

Figure 5.25 illustrates that an increase in the abundance of *Anabaena* beyond ≈600 cells/mℓ would result in an increase in mean treatment cost. For example, treatment costs would increase by approximately R4.22/Mℓ (over the mean treatment cost of ≈R25/Mℓ) if the *Anabaena* counts in the raw water entering Durban Heights WW were 6000 cells/mℓ and causing taste and odour problems. Currently at >1000 cells/mℓ of *Anabaena* a warning is automatically generated advising operators of the WW to be aware of potential taste and odour problems associated with this algae. This 1000 cells/mℓ of *Anabaena* cut-off was derived empirically and appears to correspond well with the results of this simulation.

5.5 Summary discussion

Lake water-quality clearly has a significant impact on the cost of treating water in each of the major WW examined in this study. The study has also shown that the cost of treating water per mega litre (Mℓ) is highest at the Hazelmere WW (R41) followed by Durban Heights WW (R 28), DV Harris WW (R25) and Wiggins WW (R22). These latter three WW are all in a similar 'ballpark,' with respect to treatment costs, whilst the costs in the Hazelmere system are almost double the others.

Important factors contributing to changes in real treatment costs at each water plant are identified in this study. Physico-chemical water quality factors generally affected water treatment more significantly than algae except where potentially powerful taste and odour forming algae (e.g. *Anabaena*) were present, as for example in the Nagle/Durban Heights WW system.

Physico-chemical water quality factors have a particularly significant impact on treatment costs at the Hazelmere WW. Treatment costs increase when turbidity, total aluminium, manganese, suspended solids, potassium, sulphates, and total organic carbon concentrations in Lake Hazelmere water increase. Likewise, costs rise with lower water pH and alkalinity levels. Algae have a relatively minor impact on treatment costs at Hazelmere WW. This is mainly because the high turbidity conditions in Lake Hazelmere allow for only limited algal growth.

The model derived for the Hazelmere WW explains 79% of the variation in chemical treatment costs. The model predicts actual costs quite well and can be easily applied in simulation exercises. The study shows that a management strategy that reduces the turbidity of Lake Hazelmere would reduce water treatment costs at the Hazelmere WW. Control of turbidity in Lake Hazelmere to levels below 10 NTU could however lead to possible algal growth problems. Nevertheless, changing the Hazelmere system from a turbidity-driven system to an algal determined system could lower the costs of treating such water as costs of treating water in the less turbid systems like Durban Heights and DV Harris are lower. However costs could increase if conditions created in Lake Hazelmere favoured the growth of taste and odour forming algae like *Anabaena.*

The model estimated for the Durban Heights WW explains some 64% of the variation in chemical treatment costs. The model predicts actual costs well (except during occasional peak cost periods) and can be easily applied in simulation exercises. The study identifies some important water quality variables contributing to treatment costs at the Durban Heights WW. Results show that environmental and algal contaminants have a marked impact on treatment costs. Treatment costs increased when levels of turbidity, suspended solids, total organic carbon, conductivity, total water hardness, potassium, and nitrates rise in the raw water. Costs also rise with higher numbers of coliform bacteria in the water. Treatment costs rise with a fall in raw water pH and alkalinity (more acidic conditions, requiring greater lime dosages). An increase in *Anabaena* and *Microcystis* numbers in Lake Nagle have a major impact on treatment costs at the Durban Heights WW, particularly when they are producing taste and odour compounds. Costs also appear responsive to an increase in temperature and a fall in dissolved oxygen. The results show that iron, manganese, total phosphorus, and *E. coli* do not add significantly to treatment costs, other factors held constant. Initially the policy implications may be that resources should not be wasted on these apparent problems. However it is an well-acknowledged fact that total phosphorus has the potential to have a marked effect on algal abundances (particularly the blue-green algae which traditionally cause the taste and odour problems). The results of algae/environment models presented in the first half of this report support this view.

The model developed for the DV Harris WW explains 67% of the variation in chemical treatment costs. The results show that treatment costs increase when levels of alkalinity, total hardness, manganese and conductivity in Lake Midmar fall. Treatment costs also rise when numbers of the alga, *Chlorella,* decline. Conversely, costs rise with higher concentrations of potassium and numbers of coliforms and *E.coli.* Results show that turbidity, silicon, suspended solids and total organic carbon do not significantly affect treatment costs at the DV Harris WW. Paradoxically, clean water - typical of Lake Midmar is expensive to treat. The significance of the "trend variable" in the DV Harris model shows that over time treatment cost have been increasing in this system. This might be associated with factors other than those included in the model having a significant effect on treatment costs at the DV Harris WW.

The model fitted for the Wiggins WW explains 79% of the variation in chemical treatment costs. The results show that treatment costs at the Wiggins WW increase with an increase in water turbidity, total aluminium, iron, suspended solids, nitrates, total organic carbon, total dissolved solids, silicon, coliform numbers, conductivity, total water hardness, potassium, nitrates, *Microcystis* and *Anabaena*. These factors are directly related to water pollution of both natural (soil erosion, siltation) and anthropogenic (sewage and agricultural nutrient runoff) origin. Conversely, results show that treatment costs diminish with an increase in water pH and dissolved oxygen in the water. The significance of the "trend variable" shows that over time treatment cost have been increasing in this system. This could be from either a deterioration in raw water quality coming into this WW or from a reduction in efficiency in the operation of the plant and hence a need to dose more chemical to achieve the potable water standards.

The study quantifies how an integrated catchment management strategy that would reduce both point and diffuse nutrient loads and turbidity in the lakes could reduce water treatment costs at the respective WW.

CHAPTER 6
SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary

6.1.1 Introduction

Based on numerous years worth of water quality (including algal) and water treatment cost data, available at Umgeni Water, this study was undertaken to better understand the water quality relationships in lakes within the company's operational area and to see how water quality affected the cost of treating water from these lakes. Briefly the broad aims to the study were; to identify the key environmental variables that were affecting algal populations in lakes, and if these were significant; to establish predictive models relating algae to the water quality. Finally, models relating the water quality in lakes to the cost of treating that water were attempted.

Semi-quantitative models were developed relating algal abundances with important elements in their environment. In most cases, the models developed were related to algae that were known to adversely affect water treatment. Direct algal impact on water treatment was through the production of either taste and odour forming compounds (requiring advanced water treatment e.g. use of activated carbon), or their ability to clog sand filters and so reduce filter run times (requiring more frequent backwashing of filters).

Thereafter lake water quality parameters (which included water physico-chemistry and algae) were statistically examined to determine which factors were most impacting on water treatment and hence treatment costs at selected water works (WW) within the Umgeni Water operational area.

Models were developed relating raw water quality entering respective water works with costs incurred in treating that water.

6.1.2 Lake Shongweni identified as an extreme case

Prior to analyses relating algae to environmental factors it was determined that Lake Shongweni appeared to be an extreme outlier at the end of an eutrophication gradient, both in terms of its physico-chemistry as well as its algal composition. It was therefore dropped from further analyses. The distinction between Shongweni and all other lakes in the study was based primarily on its high conductivity waters. High conductivities in the Shongweni waters reflected a range of variables (e.g. potassium, chloride, sodium, total dissolved solids and sulphate) that had highly elevated concentrations compared to all other lakes studied. This picture of poor water quality in Shongweni could be traced to catchment activities (primarily textile industries) which contributed to the significant conductivity loadings on this lake. Highly elevated algal counts of the blue-green algae *Microcystis* and *Anabaena* appeared to account for the biological distinction between Shongweni and the other lakes.

With Lake Shongweni removed the focus of the study then concentrated on the remaining seven lakes viz. Midmar, Albert Falls, Nagle, Inanda, Henley, Nungwane and Hazelmere.

6.1.3 Reduction in the number of environmental variables used in analyses

Many of the environmental variables investigated in this study were highly correlated with each other. This created problems in analysis of the data and analytical techniques were therefore implemented to counter this. The result was a degree of economy in that the variation of the original large number of environmental variables (53) could be reasonably accounted for by a smaller number of 'key' environmental variables. These were identified as conductivity, secchi depth, silicon, total inorganic nitrogen and total phosphorus, inflow, temperature, percentage dissolved oxygen and stability. The selected variables represented the primary aspects of variation in the environmental data and acted as surrogates for this variation. This set of nine environmental variables also had intuitive biological appeal in that they are often implicated in the literature as influencing algal populations.

6.1.4 Physico-chemical differences between lakes studied

A preliminary investigation of purely physico-chemical differences and similarities between lakes produced some interesting findings. This had potential management and policy implications, as lakes that could be considered to have similar physico-chemistry would be likely to respond similarly to management/perturbation.

A distinct group, of relatively low conductivity, low turbidity, 'inland' lakes (Midmar, Albert Falls, Nagle and Henley) were identified. These were distinct from more turbid 'coastal' lakes (Hazelmere and to a lesser extent Nungwane). Inanda appeared different from either of these previous groupings in that it was characterised by generally higher conductivities but low turbidities. From a physico-chemical point of view, Inanda and Hazelmere are the most dissimilar lakes in the study (excluding Shongweni). On the other hand Midmar, Albert Falls and Nagle are relatively similar when compared to the other lakes in the study. They also neatly demonstrate the change in water quality within lakes with progression down the Mgeni River catchment. Not surprisingly, progression down catchments was characterised by increased conductivities. Inanda, the last lake on the Mgeni system cascade, had the highest conductivities.

Further (though weaker) distinctions between lakes could be identified in relation to gradients characterised by total inorganic nitrogen, total phosphorus and inflows. Midmar, Nagle and Albert Falls appeared to be characterised by higher total phosphorus, whilst Nungwane and Henley had higher total inorganic nitrogen. Inanda was relatively 'mixed', experiencing a range of values for total inorganic nitrogen, total phosphorus and inflows.

6.1.5 Relationships between algae and their environment

The reduced set of 'key' environmental variables (conductivity, secchi, silicon, total inorganic nitrogen, total phosphorus, inflow, temperature, %DO and stability), lake unique effects, and seasonal effects, were then used to determine which aspects of the environment were playing the most significant part in explaining the variability observed in algal populations in the respective lakes. Each of these analyses revealed a different aspect of how environmental variables were influencing the distribution and abundance of algae (first objective of this study). Interpretations were then made about the conditions favouring problematic algae.

The reduced set of 'key' environmental variables explained some 16% of the variability in the algal data. Of these variables, total inorganic nitrogen, silicon, temperature, inflow and secchi appeared to be the parameters accounting for the major portion of the environmentally explainable variability in the algal data. This low amount of explained variation is not unusual for large multi-genera ecological data. As a check on the significance of this relatively low variability explained, the environmental effects were Monte Carlo permutation tested and found be significantly related ($P < 0.01$) to the variation in the algal data. Therefore these variables (total inorganic nitrogen, silicon, temperature, inflow and secchi) appear to account for a statistically significant proportion of the variability in the observed algal data.

Of the algal genera apparently responding to these environmental gradients *Anabaena* and *Microcystis* (blue-green algae) were responding to the higher temperatures and inflow volumes that one would expect with summer conditions whilst they were less affected by higher silicon and total inorganic nitrogen values. The temperatures (20–25°C) leading to the highest abundance of the blue-green algae *Anabaena* and *Microcystis* were in accordance with those noted in the literature.

It was recognised (and should be emphasised) that the reduced set of 'key' environmental variables are closely associated with particular groups of other variables and because of this all the associated variables are useful in interpretations of algae and environment. For example, positively associated with total inorganic nitrogen (TN) was the TN:TP ratio. This implies that at low TN concentrations there are also likely to be low TN:TP ratios. The blue-green algae (*Anabaena* and *Microcystis*) appeared to be more abundant at the lower end of this TN (low TN:TP ratio, < 20) gradient. The literature again supported this finding.

Although with lower amounts of their variability explained by the key environmental variables, conversely *Navicula, Spermatozopsis* and *Mallomonas* were responding to higher Si (> 5mg/ℓ) and TN (> 0.5mg/ℓ) and lower temperatures (15-20°C) and inflows. Cool (15-20°C), clear waters (with high secchi depths i.e. >1.5m), with low total phosphorus (<20µg/ℓ) favour *Crucigena* whilst waters generally low in TN (<0.5mgN/ℓ) and Si (<5mg/ℓ) favours *Melosira, Scenedesmus, Cyclotella* and *Tetraedron*. These waters are also generally clear (higher secchi i.e. > 2.0m) and have lower water column stability.

Unfortunately not much may be said about *Chlorella*, a dominant or sub-dominant species in many lakes, as its variability is not well explained by the measured environmental variables.

6.1.6 The effects of differences unique to individual lakes ('lake unique' differences) on algae

It has to be acknowledged that not all of the parameters that may be affecting algae in a lake can always be measured or quantified. These 'other' parameters may be of a biological, physico-chemical or seasonal nature (or various combinations of all of these). It is this un-quantified element of variability in a lake that prevents one from being able to fully understand, and therefore predict, all the dynamics and processes that result in the abundance and variation in algal populations observed. Often certain parameters may be unique to (e.g. basin morphometry) or vary uniquely (e.g. local weather patterns) in respective lakes, thus giving that lake its unique set of characteristics affecting local algal populations. Analyses to determine the response of algae to this 'uniqueness' of respective lakes (lake unique differences) were conducted. In this way lakes with similar characteristics could be expected to have a similar composition and abundance of algal populations. Concurrent with this, environmental variables were examined to determine possible environmentally based reasons for the differences (or similarities) observed between lakes.

Hazelmere is distinctly different from all other lakes studied. This difference appears primarily associated with low water clarity (high turbidities or low secchi depths). Of all the lakes studied Hazelmere, Nungwane and Inanda (and to a lesser extent Nagle) are biologically most dissimilar from each other. Given that they are all on entirely different river systems (except Nagle and Inanda on the Mgeni River) with different water physico-chemistry this is not surprising.

There is an interesting trend, as measured by the algal composition of lakes, from generally upper catchment (Henley), down the Mgeni system sequentially to the coastal lakes (Nagle and Inanda). Nungwane is an apparent anomaly in this trend as it could be geographically classified as a 'coastal' lake. It appears however to have a greater affinity to the upper catchment lakes and indeed is situated relatively high up in ***its*** catchment. Examination of the environmental data indicates that this trend down the catchment is related to factors associated with increasing inflow, temperature and conductivity approaching the coast on the Mgeni system with parallel decreases in stability and lowered silicon and total inorganic nitrogen values.

Factors associated with silicon and total inorganic nitrogen concentrations appear to be the most important variables associated with the observed spatial differences between the lakes - particularly Henley and Nungwane compared to all the other Mgeni system lakes.

The relatively high importance attached to silicon, as it distinguished between the different lakes in the study, could possibly be related to the respective sizes of the lakes. The main basins of smaller lakes (e.g. Henley and Nungwane) are likely to be more prone to, and therefore influenced to a larger degree by, seasonal fluctuations related to inflow. Larger lakes on the other hand (with their main basins often some distance from the inflow) tend to 'absorb' the impact of floods more readily, with the bulk of the silicon loadings generally confined to the lake inflow area. Associated with seasonally variable inflows (particularly flood type events) are the clay and silt loadings that will affect the silicon concentration in the water. The hypothesised dynamics between lake size and silicon variability appears to be borne out in this study and help elucidate the importance silicon has in explaining the difference (as measured by the algal populations dominating them) between Henley and Nungwane and the other larger lakes.

Lakes at the lower end of the Mgeni river system (Inanda, Nagle and Albert Falls) appear to have less stable water column conditions. The relative size of lakes may explain this as Henley and Nungwane were the smallest studied and therefore potentially less prone to the effects of winds. Generally the smaller the dimensions of the lake, the lower the fetch (uninterrupted distance wind is able to travel across the water body) and hence the lower the impact of wind induced mixing currents on the water column, which obviously affects stability.

6.1.7 The effects of 'season' on algae

'Seasonal' effects account for a relatively small proportion of the observed algal variability as compared to that of the 'key' environmental and 'lake unique' variables. This said however the effect of season is still clear and accounts for a statistically significant portion of the algal variability. Seasonal successional trends (within the year, i.e. on a monthly basis) and annually (i.e. over the duration of the study) were examined to determine how these may be affecting algal populations in the lakes studied.

The annual successional trends are less significant than monthly patterns and show no strong unidirectional trend within the time period of the study. This indicates that there was no overall successional trend in the algal populations in the lakes under study.

Fewer algal genera have significant portions of their variability explained in the 'seasonal' analysis compared to either of the previous two analyses (key environmental and lake unique variables). This emphasises the lower importance seasonal (monthly) effects have on algal populations compared to pure environmental and effects unique to different lakes.

Chlorella had a greater proportion of its variability explained by seasonal changes than could be explained by either key environmental or lake unique effects. This is significant when it is considered that this genus was a dominant to subdominant genus in many lakes. This implies that there is some unmeasured factor(s) in the environment, of either biotic or abiotic origin, which is explaining some of this genus' variability. This factor(s) appears to fluctuate seasonally.

As a generalisation, in terms of genera having ***appreciable*** amounts of their variability explained by seasonal effects, the abundance of *Chlorella* and *Anabaena* is highest in summer, in the early part of the calendar year, when inflows and temperatures are greatest. *Cyclotella* and *Cosmarium* are abundant in autumn (March/April) whilst *Spermatozopsis* is likely to be more abundant in spring (August to October), when dissolved oxygen concentrations in the water appear to be highest.

Of the algae responding to seasonal changes in the lakes, in terms of numbers that may be expected to impact on water treatment it is only really *Chlorella* and *Anabaena* which are ever really numerically and proportionally abundant. Of these two the latter is the more significant to the water treatment process due to its potential for producing taste and odour compounds. The analysis indicates that January through to April are the most significant months where this genus may be expected to become sufficiently abundant and therefore cause treatment problems. Elevated temperatures and inflows are closely associated with this summer bloom of *Anabaena* and *Chlorella*.

Another noteworthy feature of this seasonal analysis is the large shift in algal populations at certain times of the year associated with changes in season. This was most apparent during late summer period (February/March) through to midwinter (June/July) with another large shift again in early summer

(September to November) through to late summer. The following genera most exemplify these shifts: *Chlorella* and *Anabaena* (increase in abundance in late summer), *Cyclotella* and *Cosmarium* (increase in autumn - March/April) and *Spermatozopsis* (increase in spring). This shift in seasonal pattern is most probably associated with changes in the water column physical stability (establishment and breakdown of stratification within the water column). Classically stratification of the water column occurs in early summer with destratification in late summer/winter. These are periods of major physico-chemical change in the water column and which have a significant impact on algal populations resident there.

6.1.8 Establishing statistically rigorous predictive models relating algae to the environment

Classical multiple regression modelling of important algae against environmental variables was attempted to gain a statistically rigorous model of how the abundance of these algae was affected by the environment. However the predictive ability of all multiple regression models was poor ($R_a^2 < 0.5$) even with appropriate transformations of the response variables (algal abundance data). There were indications that interactions among environmental variables, spatial locations (lakes) and algae themselves were important. In other words, the effects of environmental variables on the different algal genera were not consistent over all lakes. This was not surprising given the variation in physico-chemistry between lakes.

The statistically rigorous multiple regression modelling of key algae against environmental variables was therefore not successful in this study. The semi-quantitative empirical models developed in the ordination analyses had to suffice as far as getting predictive models for algae/environment relationships.

6.1.9 Economic models relating water quality to treatment costs at waterworks

This aspect of the study was undertaken to identify the main factors (contaminants) affecting water treatment costs at selected water works (WW) in the Umgeni Water (UW) operational area. The aim was to develop models to predict treatment costs from observed measures of water quality (contaminants). Models of treatment costs are estimated using ordinary least squares (OLS) linear regression and principal component analysis (PCA).

Lake water-quality clearly has a significant impact on the cost of treating water in each of the major WW examined in this study. The study has also shown that the cost of treating water per mega litre (Mℓ) is highest at the Hazelmere WW (R41) followed by Durban Heights WW (R 28), DV Harris WW (R25) and Wiggins WW (R22). These latter three WW are all in a similar 'ballpark,' with respect to treatment costs, whilst the costs in the Hazelmere system are almost double the others.

Important factors contributing to changes in real treatment costs at each water plant are identified in this study. Physico-chemical water quality factors generally affected water treatment more significantly than algae except where potentially powerful taste and odour forming algae (e.g. *Anabaena*) were present, as for example in the Nagle/Durban Heights WW system.

Physico-chemical water quality factors have a particularly significant impact on treatment costs at the Hazelmere WW. Treatment costs increase when turbidity, total aluminium, manganese, suspended solids, potassium, sulphates, and total organic carbon concentrations in Lake Hazelmere water increase. Likewise, costs rise with lower water pH and alkalinity levels. Algae have a relatively minor impact on treatment costs at Hazelmere WW. This is mainly because the high turbidity conditions in Lake Hazelmere allow for only limited algal growth.

The model derived for the Hazelmere WW explains 79% of the variation in chemical treatment costs. The model predicts actual costs quite well and can be easily applied in simulation exercises. The study shows that a management strategy that reduces the turbidity of Lake Hazelmere would reduce water treatment costs at the Hazelmere WW. Control of turbidity in Lake Hazelmere to levels below 10 NTU could however lead to possible algal growth problems. Nevertheless, changing the Hazelmere system from a turbidity driven system to an algal determined system could lower the costs of treating such water as costs of treating water in the less turbid systems like Durban Heights and DV Harris are lower. However costs could increase if conditions created in Lake Hazelmere favoured the growth of taste and odour forming algae like *Anabaena*.

The model estimated for the Durban Heights WW explains some 64% of the variation in chemical treatment costs. The model predicts actual costs well (except during occasional peak cost periods) and can be easily applied in simulation exercises. The study identifies some important water quality variables contributing to treatment costs at the Durban Heights WW. Results show that environmental and algal contaminants have a marked impact on treatment costs. Treatment costs increased when levels of turbidity, suspended solids, total organic carbon, conductivity, total water hardness, potassium, and nitrates rise in the raw water. Costs also rise with higher numbers of coliform bacteria in the water. Treatment costs rise with a fall in raw water pH and alkalinity (more acidic conditions, requiring greater lime dosages). An increase in *Anabaena* and *Microcystis* numbers in Lake Nagle have a major impact on treatment costs at the Durban Heights WW, particularly when they are producing taste and odour compounds. Costs also appear responsive to an increase in temperature and a fall in dissolved oxygen. The results show that iron, manganese, total phosphorus, and *E.coli* do not add significantly to treatment costs, other factors held constant.

Initially the policy implications may be that resources should not be wasted on these apparent problems. However it is an well-acknowledged fact that total phosphorus has the potential to have a marked effect on algal abundances (particularly the blue-green algae which traditionally cause the taste and odour problems). The results of algae/environment models presented in the first half of this report support this view.

The model developed for the DV Harris WW explains 67% of the variation in chemical treatment costs. The results show that treatment costs increase when levels of alkalinity, total hardness, manganese and conductivity in Lake Midmar fall. Treatment costs also rise when numbers of the alga, *Chlorella,* decline. Conversely, costs rise with higher concentrations of potassium and numbers of coliforms and *E.coli.* Results show that turbidity, silicon, suspended solids and total organic carbon do not significantly affect treatment costs at the DV Harris WW. Paradoxically, clean water - typical of Lake Midmar is expensive to treat. The significance of the "trend variable" in the DV Harris model shows that over time treatment cost have been increasing in this system. This might be associated with factors other than those included in the model having a significant effect on treatment costs at the DV Harris WW.

The model fitted for the Wiggins WW explains 79% of the variation in chemical treatment costs. The results show that treatment costs at the Wiggins WW increase with an increase in water turbidity, total aluminium, iron, suspended solids, nitrates, total organic carbon, total dissolved solids, silicon, coliform numbers, conductivity, total water hardness, potassium, nitrates, *Microcystis* and *Anabaena*. These factors are directly related to water pollution of both natural (soil erosion, siltation) and anthropogenic (sewage and agricultural nutrient runoff) origin. Conversely, results show that treatment costs diminish with an increase in water pH and dissolved oxygen in the water. The significance of the "trend variable" shows that over time treatment cost have been increasing in this system. This could be from either a deterioration in raw water quality coming into this WW or from a reduction in efficiency in the operation of the plant and hence a need to dose more chemical to achieve the potable water standards.

The study quantifies how an integrated catchment management strategy that would reduce both point and diffuse nutrient loads and turbidity in the lakes could reduce water treatment costs at the respective WW.

6.2 Conclusions

6.2.1 Conclusions related to algae and their environment

- The study has highlighted the use of a suite of statistical techniques that has assisted in reducing a complex multivariate problem (many different types of algae and many environmental variables) into something more comprehensible. The complex community of algae in lakes has been able to be graphically summarised into associations of algae showing similar responses to important environmental variables.

- Lake Shongweni appears to be an extreme outlier at the end of an eutrophication gradient, both in terms of its physico-chemistry as well as its algal composition. This created problems in data analyses and it was therefore dropped from analyses.

- The remaining seven lakes viz. Midmar, Albert Falls, Nagle, Inanda, Henley, Nungwane and Hazelmere formed the focus of the study.

- Many environmental variables investigated were highly correlated with each other. This created problems in data analysis with statistical techniques implemented to counter this. The original large number of environmental variables (53) could be reasonably accounted for by a smaller number of 'key' environmental variables identified as conductivity, secchi depth, silicon, total inorganic nitrogen, total phosphorus, inflow, temperature, percentage dissolved oxygen and stability. These variables represented the primary aspects of variation in the environmental data and acted as surrogates for this variation.

- A distinct group, of relatively low conductivity, low turbidity, 'inland' lakes (Midmar, Albert Falls, Nagle and Henley) were identified as distinct from more turbid 'coastal' lakes (Hazelmere and to a lesser extent Nungwane). Inanda was characterised by generally higher conductivities but low turbidities.

- Inanda and Hazelmere are the most dissimilar lakes in the study (excluding Shongweni). Midmar, Albert Falls and Nagle are relatively similar when compared to the other lakes in the study and neatly demonstrate the change in water quality within lakes with progression down the Mgeni River catchment. Not surprisingly, progression down catchments was characterised by increased conductivities. Inanda, the last lake on the Mgeni system cascade, had the highest conductivities.

- Further, weaker distinctions between lakes could be identified in relation to gradients characterised by total inorganic nitrogen, total phosphorus and inflows.

- The reduced set of 'key' environmental variables explained some 16% of the variability in the algal data. Of these variables, total inorganic nitrogen, silicon, temperature, inflow and secchi were the most important explaining algal variability. The environmental effects were significantly related ($P<0.01$) to the variation in the algal data.

- *Anabaena* and *Microcystis* (blue-green algae) were responding to the higher temperatures and inflow volumes that one would expect with late summer conditions. They are also more abundant at the lower end of the TN (low TN:TP ratio, < 20) gradient.

- With lower amounts of their variability explained *Navicula*, *Spermatozopsis* and *Mallomonas* were responding to higher Si (> 5mg/ℓ) and TN (> 0.5mg/ℓ) and lower temperatures (15-20°C) and inflows. Cool (15-20°C), clear waters (with high secchi depths i.e. >1.5m), with low total phosphorus (<20µg/ℓ) favour *Crucigena*. Waters low in TN (<0.5mgN/ℓ) and Si (<5mg/ℓ) favours *Melosira, Scenedesmus, Cyclotella* and *Tetraedron*. These waters are also generally clear (secchi > 2.0m) and have lower water column stability.

- *Chlorella*, a dominant or sub-dominant species in many lakes, does not have its variability well explained by measured environmental variables. Its variability is better explained by some (un-quantified) seasonal factor(s).

- Hazelmere is distinctly different from all other lakes studied – the difference primarily associated with low water clarity. Furthermore Hazelmere, Nungwane and Inanda (and to a lesser extent Nagle) are biologically most dissimilar from each other.

- There is a trend from generally upper catchment (Henley), down the Mgeni system sequentially to the coastal lakes (Nagle and Inanda).

- 'Seasonal' effects account for a relatively small proportion of the observed algal variability compared to 'key' environmental and 'lake unique' variables. The effect of season is still clear however and accounts for a statistically significant portion of the algal variability.

- The annual successional trends are less significant than monthly patterns and show no strong overall successional trend in the algal populations in the lakes under study.

- January through to April are the most significant months where *Anabaena* may be expected to become sufficiently abundant and therefore cause treatment problems. Factors associated with elevated temperatures and inflows are closely associated with these summer highs of *Anabaena* and *Chlorella*.

- There are large shifts in algal populations during the late summer period (February/March) through to midwinter (June/July) with another large shift again in early summer (September to November) through to late summer. The following genera most exemplify these shifts: *Chlorella* and *Anabaena* (increase in abundance in late summer), *Cyclotella* and *Cosmarium* (increase in autumn - March/April) and *Spermatozopsis* (increase in spring). This seasonal pattern is most probably associated with changes in the water column physical stability (establishment and breakdown of stratification within the water column).

- Classical multiple regression modelling of important algae against environmental variables was unsuccessful with the predictive ability of all multiple regression models poor ($R_a^2 < 0.5$).

- The semi-quantitative empirical models developed in ordination analyses were the best available predictive models for algae/environment relationships.

6.2.2 Conclusions related to the cost of water treatment

- Lake water-quality clearly has a significant impact on the cost of treating water in each of the major WW examined.

- The cost of treating water per mega litre (Mℓ) is highest at the Hazelmere WW (R41) followed by the Durban Heights (R 28), DV Harris (R25) and Wiggins WWs (R22). The costs in treating water in the Hazelmere system are almost double the others.

- Within the range of the data analysed here physico-chemical water quality factors generally affected water treatment more significantly than algae, except where potentially powerful taste and odour forming algae (principally *Anabaena*) were present. The Nagle/Durban Heights WW system is most affected by taste and odour problems.

- The model derived for the Hazelmere WW explains 79% of the variation in chemical treatment costs. The model predicts actual costs quite well and can be easily applied in simulation exercises.

- Physico-chemical water quality factors have a particularly significant impact on treatment costs at the Hazelmere WW. Treatment costs increase when turbidity, total aluminium, manganese, suspended solids, potassium, sulphates, and total organic carbon concentrations in Lake Hazelmere water increase. Likewise, costs rise with lower water pH and alkalinity levels. Algae have a relatively minor impact on treatment costs at Hazelmere WW.

- Hazelmere is the only system analysed that appeared to suffer from problems associated with manganese (necessitating the use of a powerful oxidant such as chlorine dioxide).

- A management strategy that reduces the turbidity of Lake Hazelmere would reduce water treatment costs at the Hazelmere WW. During periods of lake turnover (when the stratification of the water column breaks down) manganese (in the reduced form) should be very carefully monitored to reduce its potential impact on water treatment (and hence costs).

- The model estimated for the Durban Heights WW explains some 64% of the variation in chemical treatment costs. The model predicts actual costs well (except during occasional peak cost periods) and can be easily applied in simulation exercises. Treatment costs increased when levels of turbidity, suspended solids, total organic carbon, conductivity, total water hardness, potassium, nitrates and coliform bacteria rise in the raw water. Treatment costs rise with a fall in raw water pH and alkalinity (more acidic conditions, requiring greater lime dosages).

- An increase in *Anabaena* and *Microcystis* numbers in Lake Nagle have a major impact on treatment costs at the Durban Heights WW, particularly when they are producing taste and odour compounds. The results show that iron, manganese, total phosphorus, and *E. coli* do not add significantly to treatment costs, other factors held constant. Initially the policy implications may be that resources should not be wasted on these apparent problems. However it is a well-known fact that total phosphorus has the potential to have a marked effect on algal abundances (particularly the blue-green algae which traditionally cause the taste and odour problems). The results of algae/environment models presented in the first half of this report support this view.

- The model developed for the DV Harris WW explains 67% of the variation in chemical treatment costs. The results show that treatment costs increase when levels of alkalinity, total hardness, manganese and conductivity in Lake Midmar fall. Treatment costs also rise with declining numbers of *Chlorella*. Conversely, costs rise with higher concentrations of potassium and numbers of coliforms and *E.coli*. Results show that turbidity, silicon, suspended solids and total organic carbon do not significantly affect treatment costs at the DV Harris WW. This indicates that raw water in this system is traditionally clean with costs principally driven by the need to disinfect and stabilise (lime) the water. The "trend variable" in the DV Harris model shows that over time treatment cost have been increasing in this system.

- The model fitted for the Wiggins WW explains 79% of the variation in chemical treatment costs. The results show that treatment costs at the Wiggins WW increase with an increase in water turbidity, total aluminium, iron, suspended solids, nitrates, total organic carbon, total dissolved solids, silicon, coliform numbers, conductivity, total water hardness, potassium, nitrates, *Microcystis* and *Anabaena*. Conversely, treatment costs diminish with an increase in water pH and dissolved oxygen in the water. The significance of the "trend variable" shows that over time treatment cost have been increasing in this system.

- The study quantifies how an integrated catchment management strategy that would reduce both point and diffuse nutrient loads and turbidity in the lakes could reduce water treatment costs at the respective WW.

6.3 Recommendations

The following recommendations for future research and management strategies were highlighted by the preceding work.

6.3.1 Recommendations with respect to algae and their environment

- Lakes could be grouped into similar entities based on their water-quality. These groups are likely to respond more similarly to changes in water-quality because of policy or management changes than are lakes in different groupings. Changes in water-quality would also affect algae resident in lakes.

- Water temperature and inflow to lakes (and factors associated with these environmental variables) appear to be the more important variables controlling the occurrence and abundance of the important blue-green algae, *Anabaena* and *Microcystis*. Most of these variables are beyond management control. However, they also appeared to favour low total inorganic nitrogen concentrations (and low TN:TP ratios, i.e. <20). Therefore, wherever possible, management should aim to keep the TN:TP ratio above 20 to avoid incidences of these problematic algae.

- The data base should be re-analysed when it is larger to determine if the trends and associations identified in analyses still hold, or are systems changing and responding to different patterns in water-quality and climate. The different drought cycles (and their impact on water-quality) could also be considered in this analysis. For example at the end of this study the regional climate system appeared to be entering a wet phase, with overall lake capacities at an all time high (1996 –1997). The statistical tools to perform these analyses are now sufficiently well understood (and documented here) to perform this at any future date.

- Efforts need to be applied to determining what other environmental parameters are important which may assist in better explaining algae/environment relationships i.e. attempt to improve the amount of algal variability explainable by environmental parameters. These parameters may be of either an abiotic (purely physico-chemical) or biotic (e.g. predation, competitive exclusion etc.) nature. The degree of interaction between algae (and to what extent this is accounting for observed algal variability) also needs further investigation.

- Further work is required on elucidating the features of the environment, which were unique, or sufficiently different between lakes, to account for the different patterns of algal variability observed between different lakes.

- A reduced suite of variables, that explains the main axes of variation in the environmental data set almost as well as the entire data set, was identified. From a water-quality monitoring perspective this may allow a reduction in monitoring intensity and hence costs for sample analyses. With a known correlation structure in the environmental data set it appears that monitoring a reduced number of 'key' environmental variables would allow a reasonable picture to be determined of how other unmonitored variables may be co-varying.

- The algae/environment models developed should be tested against 'new' data to determine their predictive ability.

- The models should also be tested in other systems to determine their applicability in those systems.

6.3.2 Recommendations with respect to water treatment

- Treatment cost models were developed based on only chemical usage for coagulation, stabilisation and disinfection. Obviously "dirtier" water would require more frequent backwashing and which would incur increased costs. Records of electricity used or backwash times for the relevant treatment periods were generally absent or inaccessible. To improve models attempts to build in these factors should be made. This improvement would obviously be dependent on the availability of these records.

- On a more general note, the accessibility of water treatment dosage (and hence cost) information was in some instances difficult and once located rather patchy. This system should be revised and standardised across WW to assist in updating treatment cost models as well as making valid comparisons across WW. A central, electronic database, of this information would assist in this process.

- Models were developed describing the impact of in-lake processes on water treatment costs for most of the major WW. To make the connection between catchment management activities and water treatment costs, work is required on determining the relationships between catchment and in-lake processes. This should, as far as possible, be determined quantitatively. For example, how are catchment activities (e.g. farming practices) influencing in-stream turbidity and hence in-lake turbidity. Changes to in-lake turbidity now have a known impact on treatment costs. With these relationships better understood there is a greater possibility of determining the "costs" (from a water treatment point-of-view) of catchment management (or lack of it). From here valid 'cost/benefit' analyses could be made in terms of alternative catchment management strategies.

- Other examples of possible application of these treatment cost models would be in determining the impact of inter-basin transfers, raising dam walls etc. on treatment costs. This would be on the assumption that these procedures had a known and quantified impact on in-lake processes.

- The sensitivity of the treatment cost models, with and without the trend variable (where it was shown to be a significant factor affecting cost – the DV Harris and Wiggins WW) needs to be tested. The future application of these models would be more useful without having to insert an estimate for the 'trend variable' into the equation for the prediction of costs.

- An economic analysis of water-quality variables over the combined data set from all waterworks systems would possibly be more generally useful to other water authorities. This would result in a more generalised model of how water quality factors are impacting on water treatment costs. Within this type of analysis sub-models to cater for the various aspects of the treatment process should be formulated i.e. coagulation, stabilisation (liming) and disinfection (chlorination) sub-models. An Umgeni Water internal project proposal is currently (1998) being formulated to address these issues.

- Economic models developed should be tested for their predictive ability against raw water-quality and WW systems in other parts of the country.

- Water treatment costs are principally driven by abiotic water-quality variables e.g. turbidity, except during periods of intense taste and odour formation which appears to be principally related to the blue-green alga *Anabaena*. Manganese in the reduced form will also cause treatment problems and increase costs. Therefore management actions to reduce the concentration of these variables in the raw water-quality arriving at WW will reduce treatment costs.

APPENDIX 1
DATA COLLECTION AND MANIPULATION

A1.1 Introduction

This appendix provides some of the detail on the methods of data collection (including procedures used to handle missing data and data at the detection limit of analytical instrumentation) and then various manipulations performed on the data to set it into the correct format for analyses.

A1.2 Screening and cleaning procedures

Results recorded at the detection limit for a specific analyte (or determinand) were halved so as not to over-emphasise their significance in analyses. If the detection limit changed during the period of the study then the project steering committee felt that the lower of the detection limits be selected and half this value returned as some estimate of the actual value for that period. Results that were below the detection limit were often only a minor proportion of the total data set available for that determinand. As the analyses ran, variables with data at their detection limit did not appear to be significant factors in explaining observed algal or treatment cost variability.

A1.3 Missing Data

Even with the monthly averaging of certain weekly data, there were a number of environmental variables that still had some missing data. This generally applied to environmental variables that were only monitored on a quarterly basis. This was dealt with by substituting the best possible estimate (by month and lake) for the respective variable in the place of missing data. As Manly (1991) notes, "doing something about missing values is by no means a straightforward matter". This is particularly problematic with multivariate data and his suggestion is to use "common sense" methods of estimation and that this procedure should work satisfactorily "providing that only a small proportion of values are missing."

A summary of the extent of missing data encountered in this data set is presented in Table A1.1. Key findings from this investigation were that only 14% of the total data set were missing. Furthermore, the majority of this missing data was for heavy metals and other variables which traditionally did not vary much and which the literature does not generally acknowledge as significantly affecting algal dynamics or water treatment. For this reason this data was generally only monitored on a quarterly basis. If this type of data was removed from the calculations of missing data the percentage of missing data dropped to only 1% of the entire data set.

Table A1.1 Summary of the percentage of the entire environmental data-set which comprised 'missing' data (summarised by lake and environmental variable)

Environmental variables	*Midmar*	*Nagle*	*Albert Falls*	*Inanda*	*Henley*	*Shongweni*	*Hazel-mere*	*Nungwane*	Average over all lakes
StabE4									
WnSp		2	8	7	8	5		8	5
WnDir		2	6	7	8	5		6	5
SHrs		2	8	8	8	5		8	5
TPLDE-1					2	2			
SRPLD					2	2			
TNLDE-3					2	2			
TNE3								2	
Temp									
Chl				2	3	9	25		5
Secc	5	7	32		14		22	43	15
pH			2						
turb									
cond									
TAl			2						
alkal									
hardness	3	37	28	2	8	5	5	5	12
Ca	3	36	28	2	8	5	7	7	12
Mg	3	36	30	2	8	5	7	7	12
Na	3	36	30	3	8	7	5	5	12
K	3	36	28	2	8	5	5	5	12
Fe									
Mn									
Si									
NO_3								2	
NO_2									
NH_3									
Cl									
F	69	71	68	66	68	67	67	67	68
SO_4	5	7	7	5	5	7	3	3	5
TP									
SRP									
TN/TP								2	
TN/SRP								2	
TN/Si									
TP/Si									
SRP/Si									
TDS	69	68	68	66	68	69	70	67	68
SS									
Cu	69	73	68	3	68	16	68	67	54
Zn	69	73	68	3	68	9	67	67	53
Pb	69	75	72	10	68	12	67	70	55
Cd	69	73	68	5	68	16	67	67	54
Cr	69	73	68	7	69	12	67	67	54
Hg	69	73	70	5	69	16	67	67	54
Se	69	73	68	5	68	14	73	67	55
Ni	69	73	68	5	69	16	68	67	54
TOC				5		9	5		2
BOD	71	71	68	68	71	64	75	67	69
DO				2			18		3
% DO				2					
TKN	15	15	17	15	15	17	17	17	16
Overall average									14
Average (excluding quarterly data)									1

A1.4 Physico-chemical environmental data

A1.4.1 Data available from LIMS

As noted earlier (§ 2.1) much of the environmental data was available from the Umgeni Water LIMS database system. Most of the environmental variables from this database were used 'as is', although some had to be manipulated for various reasons. Temperature was a case in point. Original algae/environment modelling efforts had used the surface water temperature as available from LIMS. The project steering committee felt however that some measure of the average temperature in the photic-zone would be more appropriate. Accordingly new temperature data was derived by taking the average temperature in the water column, limited to the secchi depth, in respective samples. This was on the assumption that the photic-zone was estimated as being approximately that of the secchi depth. Table 2.1 (Chapter 2) reflects the origin of variables.

A1.4.2 Nutrient loads on lakes

Nutrient loads for respective lakes were estimated using the FLUX model (Walker 1987). This essentially combines a grab sample, for nutrient concentration, from the inflow to respective lakes with the inflow rate to create a 'best estimate' of nutrient loads on the system. Monthly nutrient loads were calculated for all lakes for total inorganic nitrogen (TNLD-3), total phosphate (TPLDE-1) and soluble reactive phosphate (SRPLD).

A1.4.2.1 Derivation of data for use in nutrient load calculations in Shongweni

No nutrient load data was available for Shongweni because of a lack of gauging weirs on its three main catchments (the Umlaas, Sterkspruit and

Wekeweke). Without this inflow data nutrient loads were unable to be calculated for the respective rivers draining into Shongweni. Therefore, flow estimates were made using ACRU (1995). With these flow estimates nutrient loads could be calculated.

One of the rivers flowing into Shongweni was the Sterkspruit. This travels through the Hammarsdale industrial area and at times has a significant proportion of its flow increased by the addition of return flows from the Hammarsdale Wastewater Works (WWW). The monthly average WWW inflow volumes were added to the respective monthly ACRU estimates for the Sterkspruit to derive an estimated total inflow arriving at Shongweni from this catchment. The Sterkspruit was on average 10% WWW return flow with a maximum of 65% and minimum of 3% (for the study period of 1990 to 1994).

A1.4.2.2 Lagging of nutrient loads

Previous work by Pillay (1994) indicated that there might be a lag effect whereby the impact of nutrient loads, calculated at the head of the lake, took time to reach the lake main-basin. This was really only an issue in the larger lakes, particularly Inanda, due its length. A correlation analysis, between nutrient loads and certain numerically dominant algal genera revealed that a five-week lag gave the highest correlations with the algae selected and hence all the load data were offset forward by this period in all further analyses involving Inanda data.

A1.4.2.3 Relationships between inflow, nutrient concentrations and nutrient loads

Two potentially biologically important variables, nutrient concentration in the water column and mass flow of water (represented as lake 'inflow' in this study), were confounded when they were 'collapsed' into a single composite variable called 'nutrient load'. (Nutrient loads are a function of the concentration of a nutrient (taken from a grab sample at the inflow to the lake) and the inflow rates (mass flow of water into the lake)). Analyses involving this variable directly were therefore avoided due to its composite nature i.e. it would prove difficult to determine the unique effect 'nutrient loads' may be having on algae. Analyses therefore separated nutrient loads into its respective components of inflow and nutrient concentration.

Inflow can affect algae both directly (i.e. the mass movement of water) and indirectly (i.e. through its effect on the concentration/dilution of nutrients in the water column). So whilst on the one hand increased inflow may increase the nutrient loads on lakes it may also be diluting the concentration of respective nutrients within a system. Figure A1.1 illustrates these relationships.

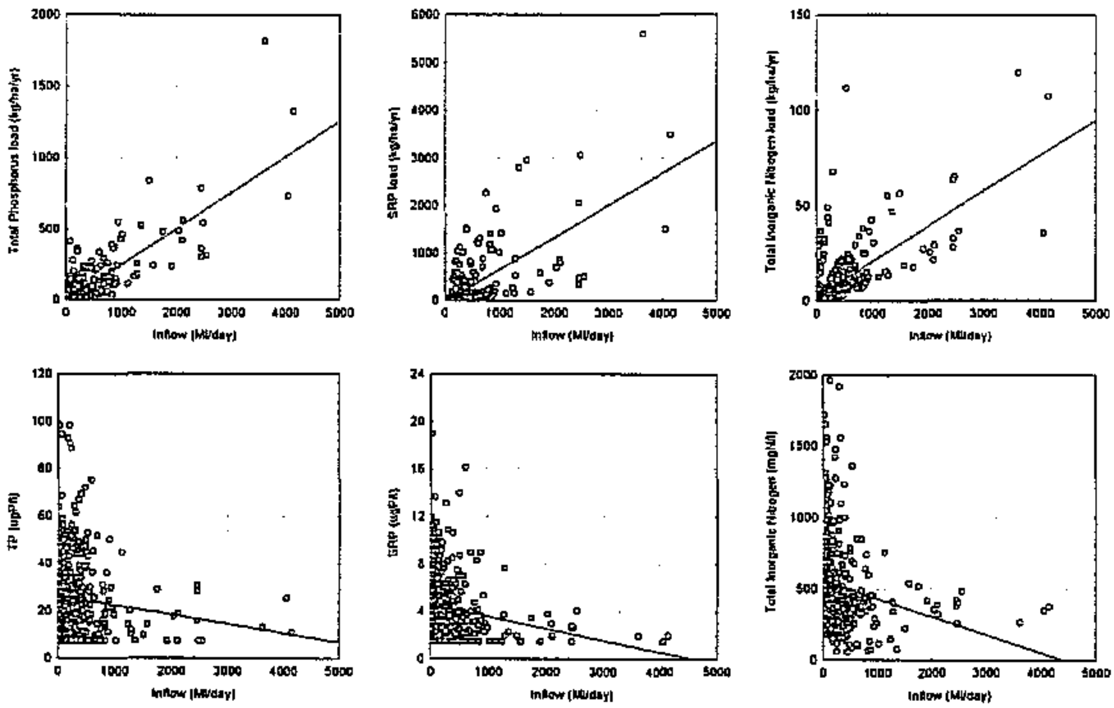

Figure A1.1 Scatterplots illustrating the relationship 'inflow' has with both nutrient loads and nutrient concentrations for all lakes.

A1.4.3 Weather data

This aspect of the study was designed to identify those Weather Bureau (WB) stations providing detailed weather data that could be used to infer weather conditions at respective lakes where this data was unavailable or deficient from Department of Water Affairs and Forestry (DWAF) lake meteorological stations. Rainfall was used to demonstrate correlations between WB station readings and those taken at the different lakes by the DWA&F. The appropriate WB data was then used to feed into the environmental data set derived for the respective lakes. This WB data includes wind speed, wind direction and sun hours.

A basic assumption made in this study was that rainfall was a representative variable co-varying with a range of weather conditions, e.g. temperature, wind and cloud cover (and hence sunshine hours). If there was a good relationship between rainfall at the WB and DWAF stations, then it was assumed that the other weather variables of interest for this study could be reasonably extrapolated from the closest WB weather station.

Weather data from various weather stations and lakes in kwaZulu-Natal were obtained from the WB and DWAF in Pretoria respectively. An initial sorting of weather stations into classes was conducted to isolate those that would be able to provide the most detailed weather information. These classes (first, second and third) were after the Weather Bureau's classification.

DWAF monitor rainfall and temperature (amongst other parameters) at the following lakes in the Umgeni Water operational area: Midmar, Albert Falls, Nagle, Inanda, Hazelmere and Shongweni. Nungwane and Henley are unmonitored.

A correlation analysis was run taking monthly rainfall data from each of the lakes (Albert Falls, Midmar, Hazelmere and Nagle) and comparing this with data from the WBs stations for the same period. The stations used were Cedara, Pietermaritzburg, Durban Airport and Mount Edgecombe. Pearson's *r* correlation coefficient was used to measure the strength of relationships between these two sets of data.

The distribution of the data was checked and found to be generally log-normally distributed. This cautioned against the use of parametric correlation methods (e.g. Pearson's *r*) particularly in the interpretation of the significance of the correlation coefficient. However, as acknowledged in various texts, because the sample sizes were reasonably large (i.e. >50) serious biases are unlikely. The results of the correlation analysis are therefore reasonably reliable and were worthy of further interpretation. The results are summarised in the following correlation table.

Table A1.2 Table of correlation coefficients (*r*) for rainfall comparisons between WB and DWAF weather stations. (*All correlation coefficients significant at *P<.01* except for PmbRf & InandRf *P=.07*)

	CedRf	PmbRf	AlbRf	MidmRf	InandRf	HazelRf	NaglRf	ShngRf	DurbRf	MtEdRf
CedRf	1.00									
PmbRf	.90	1.00								
AlbRf	.92	.93	1.00							
MidmRf	.95	.90	.93	1.00						
InandRf	.80	.67*	.71	.78	1.00					
HazelRf	.73	.81	.71	.67	.91	1.00				
NaglRf	.85	.93	.86	.83	.86	.92	1.00			
ShngRf	.61	.70	.64	.58	.73	.73	.71	1.00		
DurbRf	.70	.84	.73	.71	.88	.79	.83	.70	1.00	
MtEdRf	.65	.75	.65	.64	.97	.87	.82	.73	.84	1.00

Explanation of codes

Code	Explaination of codes used and source of data
CedRf	Cedara rainfall (Weather Bureau)
PmbRf	Pietermaritzburg rainfall (Weather Bureau)
AlbRf	Albert Falls rainfall (Dept. Water Affairs)
MidmRf	Midmar rainfall (Dept. Water Affairs)
InandRf	Inanda rainfall (Dept. Water Affairs)
HazelRf	Hazelmere rainfall (Dept. Water Affairs)
NaglRf	Nagle rainfall (Dept. Water Affairs)
ShngRf	Shongweni rainfall (Dept. Water Affairs)
DurbRf	Durban Airport rainfall (Weather Bureau)
MtEdRf	Mt. Edgecombe rainfall (Weather Bureau)

Geographically there are two distinct groups of lakes - the inland (Midmar and Albert Falls) and the coastal lakes (Hazelmere and Shongweni). Nagle and Inanda fall somewhere between these two groups. Not unexpectedly the inland lakes are most closely correlated with the Cedara and Pietermaritzburg WB stations whilst the coastal lakes are most closely correlated with the coastal WB stations at Durban airport and Mt. Edgecombe.

From these results it appears reasonable to assume that the Cedara weather station is most closely reflecting weather conditions for the following lakes: Midmar, Albert Falls and Nagle. Hazelmere, Inanda and Shongweni, on the other hand, are more strongly correlated with the Durban Airport and Mt. Edgecombe stations. Inanda, which is geographically lower down in the catchment and hence closer to the coast and Durban Airport and Mt. Edgecombe weather stations, is more strongly correlated with these coastal WB stations, particularly the latter. Unfortunately however the Mt. Edgecombe data set was not as complete as the Durban Airport one so this latter station was chosen to represent weather conditions at the various lakes indicated in Table A1.3. Henley and Nungwane did not have any available DWAF weather data to compare with the WB station data but due to their geographical position are expected to be most strongly correlated with Cedara and Durban Airport (or Mt. Edgecombe) weather stations respectively. This analysis indicated that weather data for the various lakes in this study might be inferred with some confidence from the closest high order WB weather stations indicated in Table A1.3.

Table A1.3 Groupings of lakes in relation to best available Weather Bureau weather station data records

CEDARA WEATHER STATION	DURBAN AIRPORT WEATHER STATION
Albert Falls	Inanda
Henley	Hazelmere
Midmar	Nungwane
Nagle	Shongweni

It was reasoned that sun hours would affect algae because of their widely acknowledged (e.g. Round 1973) photosynthetic dependence on light. Wind speed and direction was seen as a possibly important variable due to their effect of inducing turbulence in the upper layers of water surfaces, which are the regions of algal growth.

It was reasoned that sun hours would affect algae because of their absolute photosynthetic dependence on light (e.g. Round 1973). Wind speed and direction was seen as an important variable due to their effect of inducing turbulence in the photic zone (and beyond) of water bodies, which are the regions of algal growth.

A1.4.4 Stability index

As a measure of the physical stability of the water column at respective sites the Brunt-Väsäilä buoyancy frequency squared term (N2) was calculated (Patterson et al.1984; Viner 1985) from equation 1.

$$N^2 = (-g/\rho_0)(\partial\rho/\partial z) \qquad (1)$$

where g = 9.81 ms^{-1} and

$(\partial\rho/\partial z)$ = the density gradient for the entire water column, of mean density ρ_0.

Values of N^2 have units' s^{-2}.

Water density (ρ) was calculated using the following polynomial equation (Hart 1992).

ρ = 1000.0873+(0.0215*T)-(0.0057*T2) (2) where T = temperature (°C) at the respective water depth

Temperature profiles, routinely monitored and captured into LIMS for respective lakes, were used to derive the stability index (using equations 1 and 2).

A1.5 Algal data

All the algal data used in this study were extracted from the LIMS database. Genera used in analyses after removal of rare and, from a water treatment point-of-view, unimportant algae are summarised in Chapter 2, Table 2.4. The acronyms used to represent algal genera, as well as their potential impact on water treatment, are also shown in this table. The complete list of 89 algae analysed by Umgeni Water is presented in this appendix as Table A1.4.

The median proportional composition of algae in respective lakes during the study period is presented in Figure 2.1. Summary abundance statistics for important genera in all lakes, except for Shongweni, are summarised by class and presented in Figures 2.2 to 2.4. It should be noted that three genera of algae (Microcystis, Anabaena and Chlorella) made up the bulk of the total algal count (Fig. 2.2A) in this study. Analyses (§ A2.2) indicated that Shongweni had its total algal count for the most part dominated by blue-green algae. This data is presented in more detail in Appendix A2.2.

A1.5.1 Rationalisation of the number of algal genera investigated

Due to the size of the data set it was necessary to rationalise the number of algae examined. Therefore those with a low abundance and particularly those which the literature acknowledged as not adversely affecting water treatment were removed and only the more abundant and common algae were taken forward in further analyses.

In total 89 algal genera are potentially enumerated in any one algal sample analysed by Umgeni Waters' Hydrobiology laboratory. Many of these genera are only rarely encountered in any sample and if encountered are often in low abundance. Typically less than twenty different algal genera will be found in any one sample. It was therefore postulated that the "rare" algae did not significantly add to the picture or relationships that may be developed for the more commonly encountered and abundant algae. The question was then - "what constituted a "rare" algae and at what level to draw the distinction between rare and abundant algae?"

To deal with this question, monthly averages for all algal genera were considered over all months and over all the study sites (lakes) i.e. a matrix of over 89 X 469 was examined. The number of times the genus was encountered in the data set was compared with the theoretical maximum possible encounters (469). Those rare genera (encountered less than 10% of the time over the entire data set) were eliminated from further analyses after checking that none of these genera were known to be important with respect to water treatment. Several rare (but acknowledgeably important algal genera) were included in this data set (e.g. *Synura* - a potentially powerful taste and odour forming algae even at low abundances (Palmer 1959)). This reduced the algal data set by some 64% (from 89 to 32 genera).

The full list of 89 genera enumerated by the Umgeni Water Hydrobiology laboratory is presented in Table A1.4 with the reduced set taken forward in analyses indicated in Chapter 2 as Table 2.4.

Table A1.4 Complete alphabetical list of algal genera routinely monitored by Umgeni Water in lakes within its operational area

Genus	Genus
Achnanthes	*Lepocinclis*
Actinastrum	*Mallomonas*
Amphipleura	*Melosira*
Amphiprora	*Meridion*
Anabaena	*Merismopedia*
Ankistrodesmus	*Micractinium*
Ankyra	*Micrasterias*
Asterionella	*Microcystis*
Biddulphia	*Microspora*
Botryococcus	*Navicula*
Ceratium	*Nitzschia*
Chaetoceros	*Oedogonium*
Chlamydomonas	*Oocystis*
Chlorella	*Oscillatoria*
Chlorogonium	*Pandorina*
Chodatella	*Pediastrum*
Chroococcus	*Peridinium*
Cladophora	*Phacotus*
Closterium	*Phacus*
Cocconeis	*Pleurococcus*
Coelastrum	*Pteromonas*
Cosmarium	*Scenedesmus*
Crucigenia	*Schroederia*
Cryptomonas	*Selenastrum*
Cyclotella	*Siderocelis*
Cymatopluera	*Spermatozopsis*
Cymbella	*Sphaerocystis*
Diatoma	*Spirogira*
Dictyosphaerium	*Staurastrum*
Didymogenes	*Stephanodiscus*
Dinobryon	*Stichococcus*
Elakatothrix	*Stigeoclonium*
Euastrum	*Surirella*
Eudorina	*Synedra*
Euglena	*Synura*
Fragilaria	*Tabellaria*
Gloeocapsa	*Tetraedron*
Golenkinia	*Tetrastrum*
Gomphonema	*Thalassiosira*
Gomphosphaeria	*Trachelomonas*
Gonium	*Ulothrix*
Gyrosigma	*Volvox*
Haematococcus	*Westella*
Hydrodictyon	
Kirchneriella	

APPENDIX 2
WATER QUALITY AND ENVIRONMENTAL CONDITIONS OF THE LAKES STUDIED

A2.1 Introduction

Preliminary investigations of the data indicated that many of the environmental variables considered were highly inter-correlated (both positively and negatively) with each other (Table A2.1 - correlation matrix), or in other words were multi-collinear. This is not unusual with environmental data of this nature (Jongman *et. al.* 1987) and, as was also noted in the economic models developed later (Ch. 6), this causes problems for multiple regression analysis. To overcome this, as well as to simplify the understanding of the correlation structure of the data, standardised Principal Components Analysis (PCA) was used on the data to produce a few key variables i.e. Principal Components, PCs, which describe most of the variation in the environmental data. The result of this approach is a degree of economy in that the variation in the original large number of variables is accounted for by a smaller number of variables or PCs (reduction in the dimensionality of the data). The reduced dimensionality of the data also obviously assists in the understanding of the problem as the variability in algae may now be described by fewer key environmental parameters (i.e. reduced from 52 environmental variables to 9 in this study). These 9 variables have close (and known) associations with many of the remaining 43 variables.

Essentially PCA takes a number of variables (environmental parameters in this case) and finds linear combinations of these to produce new variables or components (PCs) that are un-correlated. This ensures that the components are measuring different 'dimensions' or variability in the data. The PCs are also ordered in such a way that the first PC (PC_1) displays the largest amount of variation, PC_2 the second largest amount of variation, and so on (Manly 1994). Theoretically, with 52 environmental variables, 52 PCs are possible, but because of multicollinearity, with the increase in variance accounted for by successive axes, relatively fewer axes are required to represent the majority of variation in the environmental data set. Table A2.2 clearly illustrates this point. The first 5 axes account for over 50% of the variation in the environmental data set, with this figure only rising to 77% with 13 axes included.

Table A2.1 Correlation matrix of all environmental variables

Note: Environmental variables as per Table 2.2, Correlations significant at P < 0.05 marked *

	STABE4	WINSP	WNDIR	SHRS	TIDE-1	SRFLD	TIDE-3	TIES	TEMP	CHL	SECC	PH	RFB	COND	TAL	ALKAL	HARD	CA	MG	NA	K	FE	MN	SI	NO3	NO2	NH4
STABE4	1																										
WINSP	.32*	1																									
WNDIR	0.01	.45*	1																								
SHRS	-.18*	-.15*	-.20*	1																							
TIDE-1	0.04	-0.01	0	-0.09	1																						
SRFLD	-0.04	0.07	0.04	-.10*	.91*	1																					
TIDE-3	0.05	-.09*	-0.03	-0.09	.86*	.79*	1																				
TIES	-0.02	-0.01	.13*	.10*	-.11*	-.14*	0	1																			
TEMP	.63*	.25*	0	-.18*	.28*	.22*	.27*	-.17*	1																		
CHL	0.04	0.07	.16*	-0.04	0.02	0.07	0.01	.10*	0.05	1																	
SECC	-.10*	-0.06	-0.07	.10*	0.08	.11*	0.05	-.22*	-.13*	-.20*	1																
PH	.13*	.23*	.17*	-0.02	.14*	.19*	0.07	-.16*	.21*	.28*	0	1															
RFB	.14*	0.03	0.06	-.10*	-0.02	-0.06	0.02	.31*	.18*	.34*	-.56*	0.05	1														
COND	0.09	.29*	.36*	-0.03	-0.04	0.04	-.11*	.15*	0.05	.61*	-.13*	.47*	.19*	1													
TAL	.14*	0.09	0	-0.09	-0.04	-.12*	-0.02	.27*	.18*	0.02	-.63*	-0.06	.80*	-0.05	1												
ALKAL	0.02	.31*	.37*	-0.03	-0.01	.10*	-.10*	0.05	0.05	.58*	-0.08	.50*	.14*	.86*	-0.08	1											
HARD	0.01	.36*	.39*	-0.07	0.08	.24*	-0.02	.11*	.12*	.51*	-0.08	.46*	.15*	.86*	-0.05	.92*	1										
CA	-0.03	.30*	.34*	-0.07	.14*	.20*	0.03	0.05	.10*	.53*	0	.49*	.11*	.84*	-.10*	.91*	.98*	1									
MG	0.05	.41*	.41*	-0.07	0.03	.17*	-0.07	.17*	.13*	.47*	-.16*	.47*	.20*	.85*	0.03	.90*	.99*	.92*	1								
NA	0.06	.23*	.34*	-0.03	-0.05	0.02	-.11*	.18*	0.01	.63*	-.14*	.42*	.21*	.97*	-0.04	.97*	.81*	.79*	.80*	1							
K	0.05	.22*	.33*	-0.03	-0.04	0.03	-.11*	.21*	0.01	.66*	-.18*	.41*	.25*	.94*	-0.02	.90*	.82*	.61*	.70*	.95*	1						
FE	0.08	.11*	0.08	-0.06	-.15*	-.17*	-.14*	.45*	0.05	.18*	-.82*	-0.05	.69*	.11*	.74*	0.05	0.06	-0.03	.15*	.14*	.15*	1					
MN	-.14*	0.08	.24*	0.08	-.11*	-0.06	-.12*	.46*	-.17*	.37*	-.21*	0.07	.23*	.54*	0.08	.53*	.52*	.48*	.55*	.56*	.57*	.35*	1				
SI	.17*	.13*	.10*	-0.03	-.17*	-.22*	-0.08	.45*	0.05	0.04	-.47*	-.19*	.45*	-0.03	.48*	-.12*	-.13*	-.27*	0.02	0	-0.03	.63*	.21*	1			
NO3	0	0.01	.11*	0.08	-.10*	-.13*	0.02	.55*	-.12*	0.09	-.26*	-.16*	.34*	.10*	.31*	-0.02	0.08	0.01	.14*	.13*	.15*	.46*	.38*	.47*	1		
NO2	-0.01	0.02	0.01	-0.01	0.02	0	0.01	.11*	0.02	-0.01	0.02	-0.03	0.01	-0.03	0.05	-0.03	-0.03	-0.05	-0.03	-0.03	-0.03	0.01	0		0.05	1	
NH4	-0.05	-0.04	.13*	.12*	-0.08	-0.08	-0.06	.60*	-.22*	0.09	0	-0.06	0.04	.23*	0.02	.21*	.15*	.14*	.16*	.28*	.25*	.18*	.44*	.18*	.34*	.21*	1
CL	.10*	.35*	.40*	-0.04	-0.05	0.05	-.12*	.21*	0.07	.59*	-.19*	.48*	.21*	.98*	-0.02	.85*	.88*	.84*	.89*	.95*	.93*	.16*	.44*	.57*	.16*	-0.04	.25*
F	-0.01	0.02	0.03	-.13*	.21*	.34*	.20*	.19*	.13*	-0.02	-.10*	0.02	.17*	0.08	.12*	0.07	.21*	.16*	.24*	0.06	0.07	.18*	.09*	.15*	.22*	-0.02	-0.01
SO4	0.07	.20*	.30*	-0.03	-0.06	0	-.11*	.21*	0	.63*	-.14*	.41*	.21*	.97*	-0.05	.91*	.79*	.78*	.77*	.95*	.95*	.12*	.54*	-0.05	.15*	-0.02	.27*
TP	0.06	.10*	.16*	-0.03	-0.06	-0.05	-.10*	.16*	0.01	.60*	-.24*	.28*	.35*	.62*	.15*	.58*	.48*	.47*	.47*	.61*	.67*	.19*	.36*	0.06	.13*	-0.03	.17*
SRP	0.02	.14*	.22*	-0.04	-0.05	-0.04	-.13*	.24*	-0.05	.43*	-.15*	.29*	.20*	.66*	0.04	.62*	.54*	.51*	.55*	.64*	.67*	.14*	.39*	0.07	.20*	-0.02	.22*
TN:TP	-.11*	-0.02	0.01	0.08	-0.09	-0.06	0.04	.43*	-.20*	-.20*	.18*	-.28*	-.18*	-.74*	-.11*	-.28*	-.25*	-.28*	-.21*	-.22*	-.25*	0	-0.02	.31*	.44*	.13*	.18*
TN:SRP	-0.02	-0.08	-0.04	.12*	-0.06	-.11*	.15*	.40*	-.09*	-.19*	0.08	-.28*	0	-.32*	0.03	-.35*	-.32*	-.33*	-.30*	-.29*	-.30*	0.01	-.10*	.25*	.40*	.12*	.18*
TN:SI	-.15*	0.01	.17*	0.06	-0.01	0.02	0.02	.61*	-.16*	0.05	.10*	0.03	0.02	.15*	-0.01	.16*	.28*	.31*	.24*	.18*	.21*	0.05	.27*	-.18*	.57*	.10*	.41*
TP:SI	0.01	.10*	.16*	-0.02	-0.03	0	-.11*	-0.01	0	.50*	-0.08	.37*	.20*	.60*	-0.01	.60*	.52*	.54*	.47*	.67*	.63*	-0.01	.23*	-.24*	-0.04	-0.03	0.08
SRP:SI	-0.01	.15*	.20*	-0.03	-0.04	0.02	-.12*	0.06	-0.03	.35*	0.01	.36*	0.05	.54*	-0.09	.63*	.57*	.57*	.54*	.60*	.62*	-0.05	.26*	-.21*	0.02	-0.02	.12*
TDS	.11*	.29*	.34*	-0.04	-0.04	0.04	-.10*	.17*	0.08	.61*	-.18*	.44*	.25*	.95*	0.01	.94*	.85*	.82*	.85*	.94*	.92*	.17*	.55*	0.03	.13*	-0.04	.21*
SS	.12*	0.07	0.08	-0.07	0.01	-0.02	0.02	.25*	.16*	.45*	-.47*	.10*	.87*	.28*	.63*	.24*	.24*	.22*	.25*	.31*	.37*	.51*	.25*	.32*	.27*	0.05	0.07
CU	-.11*	-.10*	-0.06	0.05	-0.07	-0.07	-.10*	-0.04	-.12*	0.01	0.01	-0.02	-0.05	-0.05	-0.06	-0.05	-0.07	-0.04	-.09*	-0.04	-0.02	-0.04	-0.01	-.12*	-0.03	0.02	-0.03
ZN	-0.03	0.03	0.04	-0.05	-0.02	0.03	-0.01	.28*	-0.01	0.07	-.11*	-0.09	0.04	0.04	-0.02	0	0.06	0.04	0.06	0.03	0.06	0.06	.10*	.14*	.27*	0.01	.11*
PB	0.08	0.08	.12*	-0.01	-0.08	-.11*	-0.07	.22*	-0.02	.18*	-.12*	0.06	.22*	.25*	.15*	.23*	.19*	.18*	.22*	.27*	.27*	.14*	.25*	.21*	.22*	-0.01	.10*
CD	-.10*	-.11*	-0.07	-0.01	-0.03	-0.05	-0.03	-0.04	0.07	-0.02	0.01	-.13*	0.06	-0.01	-0.07	-0.02	-0.06	-0.04	0.07	0	-0.02	-0.06	-0.04	-0.06	-0.05	.18*	-0.02
CR	0.01	-.14*	-.12*	-0.07	0.05	0	0.06	.14*	0.02	-0.02	-.31*	-.16*	.37*	-0.08	.37*	-.10*	-.09*	-.12*	-0.08	-0.06	-0.05	.40*	0.07	.27*	.16*	-0.02	0.01
HG	0	-.17*	-0.06	-0.01	-.16*	-.21*	-.13*	.27*	-.13*	.23*	-.20*	-.29*	.23*	0.02	.22*	-0.04	-0.07	-0.08	-0.05	0.04	0.05	.22*	.13*	.24*	.25*	0.06	.17*
SE	0.04	-.18*	-.18*	0.03	-.16*	-.23*	-.14*	0.02	0	-0.06	-.10*	-.18*	.09*	-.11*	.09*	-.17*	-.24*	-.25*	-.21*	-.09*	-.10*	.10*	-0.06	.14*	0.01	-0.02	0.02
NI	.10*	0.04	.08*	-0.06	-0.04	0	-.10*	.21*	0.03	.49*	-.35*	.19*	.49*	.55*	.30*	.50*	.45*	.45*	.43*	.56*	.60*	.37*	.37*	.11*	.17*	0.03	.20*
TOC	.19*	.33*	.31*	-0.02	-0.05	0.02	-.13*	.13*	.11*	.57*	-.24*	.38*	.28*	.88*	0.06	.84*	.77*	.73*	.79*	.98*	.87*	.21*	.48*	0.09	.11*	-0.02	.15*
BOD	-0.01	0.01	0.02	0	-0.04	-0.02	-0.04	.34*	-0.01	0.06	-.15*	0.01	0.03	.23*	0.04	.14*	.20*	.17*	.22*	.20*	.24*	.15*	.23*	0.09	.38*	0.01	0.06
DO	0.04	.13*	-0.04	-0.01	-0.02	-0.01	-0.05	-.25*	-.23*	-0.07	.18*	.23*	.23*	-0.07	-.22*	-0.07	-.14*	-.12*	-.18*	-0.07	-0.09	-.24*	-.32*	-.17*	-.26*	0.04	-.09*
%DO	.37*	.15*	-.10*	-0.07	.10*	0.04	0.08	-.33*	.19*	-0.07	.18*	.25*	-.19*	-.12*	-.16*	-.13*	-.20*	-.17*	-.23*	-.13*	-.14*	-.28*	-.44*	-.19*	-.32*	0.03	-.19*
TKN	0	-0.05	0.04	-0.01	0.05	0.02	0.04	.13*	-0.02	.28*	-.13*	0.06	.14*	.26*	0.03	.22*	.15*	.14*	.15*	.30*	.29*	.11*	.22*	.14*	.09*	0	.16*
PR FLUSH	0.05	0.06	0.1	0	-0.02	-0.01	-0.04	-0.08	0	.22*	-0.03	.18*	0	.43*	-0.05	.38*	.22*	.21*	.22*	.42*	.31*	-0.05	0.02	-0.03	-0.07	-0.01	0.01

	CL	F	SO4	TP	SRP	TN:TP	TN:SRP	TN:SI	TP:SI	SRP:SI	TDS	SS	CU	ZN	PB	CD	CR	HG	SE	NI	TOC	BOD	DO	%DO	TKN	PR FLUSH
CL	1																									
F	.13*	1																								
SO4	.84*	0.07	1																							
TP	.58*	-0.02	.83*	1																						
SRP	.66*	0.05	.86*	.83*	1																					
TN:TP	-.20*	0.02	-.24*	-.34*	-.21*	1																				
TN:SRP	-.30*	-0.03	-.30*	-.27*	-.37*	.61*	1																			
TN:SI	.18*	.10*	.18*	0.06	.12*	.25*	.27*	1																		
TP:SI	.68*	-0.08	.60*	.91*	.78*	-.39*	-.32*	.16*	1																	
SRP:SI	.61*	-0.02	.81*	.73*	.82*	-.28*	-.38*	.20*	.83*	1																
TDS	.98*	0.07	.94*	.83*	.87*	-.25*	-.32*	.13*	.68*	.82*	1															
SS	.29*	.10*	.31*	.51*	.27*	-.19*	-0.03	0.03	.33*	.14*	.33*	1														
CU	-0.06	-0.07	-0.02	-0.01	-0.04	-0.05	-0.04	0.05	0.02	-0.02	-0.05	-0.03	1													
ZN	0.07	.16*	0.09	0.08	.12*	0.08	0.03	.11*	0.01	0.03	0.08	0.06	0.07	1												
PB	.28*	0.03	.27*	.20*	.22*	-0.07	0.03	0.06	.10*	.13*	.24*	.23*	0.02	.17*	1											
CD	-0.04	-0.04	0.02	-0.03	-0.01	0.01	0.02	-0.04	-0.03	-0.01	-0.01	-0.02	.12*	0.07	.10*	1										
CR	-0.08	.17*	-0.05	0.03	-0.02	-0.05	0.02	-0.06	-0.06	-.10*	-0.02	.27*	0	.10*	0.08	.21*	1									
HG	0	0.01	0.08	0.07	0.05	0.07	.16*	0.05	-0.03	-0.04	0.04	.20*	0.01	.17*	.19*	-0.03	.12*	1								
SE	-.34*	.10*	-0.07	-0.01	-0.04	0.02	0.03	-.14*	-0.07	-.11*	-.11*	0.03	0.03	-0.03	0	.12*	0.09	.32*	1							
NI	.53*	.31*	.60*	.47*	.37*	-.25*	-.21*	0.09	.38*	.29*	.57*	.64*	0.01	.11*	.24*	-0.05	.25*	.20*	0.04	1						
TOC	.69*	.05*	.85*	.60*	.60*	-.29*	-.32*	0.07	.53*	.54*	.89*	.37*	-0.06	0.05	.22*	-0.05	-0.03	0.04	-.12*	.55*	1					
BOD	.35*	.39*	.27*	.16*	.24*	-0.06	-.09*	.20*	0.09	.13*	.22*	.11*	-0.02	.35*	.14*	0.01	0.05	0.09	-0.01	.19*	.25*	1				
DO	-.10*	-.16*	-.10*	-.10*	-.13*	0.01	-0.04	-0.06	0	-0.03	-.13*	-.23*	0.01	-.33*	-0.08	-0.03	-.20*	-.15*	-0.01	-.11*	-.10*	-.17*	1			
%DO	-.18*	-.17*	-.14*	-.11*	-.38*	-.09*	-0.05	-.17*	-0.02	-0.07	-.17*	-.18*	-0.05	-.25*	-.10*	-0.06	-.18*	-.16*	0.02	-.11*	-.11*	-.19*	.87*	1		
TKN	.25*	0	.28*	.27*	.32*	0	0.01	0.02	.19*	.15*	.29*	.17*	-0.06	0.06	0.03	-0.06	.25*	.13*	-0.03	.23*	.25*	0.02	-0.07	-0.05	1	
PR FLUSH	.35*	-0.03	.39*	.20*	.32*	-0.08	-.11*	-0.05	.21*	.32*	.38*	0.01	-0.07	-0.03	.23*	.24*	-0.05	0.04	-0.01	.15*	.39*	.33*	.16*	.15*	0.09	1

A2.2 Water quality and environmental conditions in all lakes studied

Initial analyses included all eight lakes identified in the study. Of the 52 potential PC's only the first 13 were worthy of interpretation (i.e. having eigen-values greater than unity (Manly 1994)). They accounted for some 77% of the variation in the environmental data with the first 5 accounting for more than half of the total variability (Table A2.2).

An examination of the variable loadings on these PCs (Table A2.3) revealed that PC_1 could be described as a "conductivity" axis with many of the "salts" which contribute to high conductivities in natural waters having high loadings on this axis. The other key PCs could be similarly described by the types of environmental variables which had high loadings on the respective axes (Table A2.3) and were respectively PC_2 - "turbidity," PC_3 - "N:P ratio," PC_4 - "nutrient loads" and PC_5 - "stability."

Table A2.2 Key results from a standardised Principal Components Analysis (performed on the full (all lakes) environmental correlation matrix) for the first 13 axes. The first 5 axes are named

AXIS	EIGENVALUE	PERCENT OF TOTAL	CUMULATIVE PERCENT	Axis name
1	14.285	27.47	27.47	'Conductivity'
2	5.798	11.15	38.62	'Turbidity'
3	3.624	6.97	45.59	'N:P ratio'
4	3.186	6.13	51.72	'Nutrient loads'
5	2.309	4.44	56.16	'Stability'
6	1.917	3.69	59.85	
7	1.572	3.02	62.87	
8	1.526	2.94	65.80	
9	1.339	2.58	68.38	
10	1.291	2.48	70.86	
11	1.174	2.26	73.12	
12	1.107	2.13	75.25	
13	1.049	2.02	77.26	

To illustrate the multicollinearity effect mentioned, and how variables with high loadings on a particular PC axis have high correlations with each other, the correlation matrix for all environmental variables in all the lakes studied (Table A2.1) was considered. As an example the PC_1 axis was defined as a 'Conductivity' axis on the basis of the following variables having high correlations with it; Alkalinity (0.96), Hardness (0.86), Calcium (0.84), Magnesium (0.85), Sodium (0.97), Potassium (0.94), Sulphate (0.97), Chloride (0.98), Total Dissolved Solids (0.96) and Total Organic Carbon (0.88). Interestingly, although Total Organic Carbon is not typically recognised as affecting Conductivity, its variability appears to be co-varying with this variable. Clearly such high correlations indicate close relationships among these variables, and how a single variable (in this instance Conductivity), could usefully capture this aspect of the variation, or trend, in the data. Successive PC axes capture different and unique aspects of variation in the data set.

Table A2.3 Ranked environmental variable loadings on the first five PCs/axes from PCA analysis of data from all lakes. Variables with the highest loadings on (and therefore association with) respective axes are *highlighted*. See Table 2.2 for an explanation of codes used for environmental variables

Variable	PC_1	Variable	PC_2	Variable	PC_3	Variable	PC_4	Variable	PC_5
TN/SRP	-0.09	*Fe*	*-0.31*	*temp*	*-0.31*	Se	-0.17	*WnSp*	*-0.42*
TN/TP	-0.08	*NO3*	*-0.30*	*turb*	*-0.27*	TP/Si	-0.14	*stabE4*	*-0.34*
secc	-0.07	*TNE3*	*-0.30*	*TAl*	*-0.27*	TP	-0.14	*%DO*	*-0.30*
%DO	-0.06	*Si*	*-0.30*	*SS*	*-0.24*	DO	-0.12	*DO*	*-0.26*
DO	-0.04	*TAl*	*-0.27*	*stabE4*	*-0.23*	SRP	-0.10	*WnDir*	*-0.24*
Se	-0.04	*turb*	*-0.26*	TPLDE-1	-0.18	Hg	-0.10	*Si*	*-0.21*
TNLDE-3	-0.03	*SS*	*-0.21*	Fe	-0.16	SRP/Si	-0.09	*TN/TP*	*-0.20*
SHrs	-0.02	Hg	-0.19	Cr	-0.15	Cu	-0.08	TN/SRP	-0.17
Cu	-0.01	Cr	-0.19	TNLDE-3	-0.14	%DO	-0.08	Temp	-0.16
Cd	-0.01	TN/SRP	-0.16	%DO	-0.14	SHrs	-0.06	PH	-0.13
TPLDE-1	-0.01	NH4	-0.13	SRPLD	-0.14	Ni	-0.05	NO3	-0.09
NO2	-0.01	Mn	-0.13	Ni	-0.11	chl	-0.04	Mg	-0.09
Cr	0.00	TN/TP	-0.13	pH	-0.10	Cd	-0.04	TNE3	-0.09
Si	0.01	Zn	-0.11	Si	-0.08	Pb	-0.03	Cl	-0.09
Hg	0.02	Ni	-0.11	WnSp	-0.08	SO4	-0.03	TOC	-0.08
SRPLD	0.02	BOD	-0.10	TP	-0.07	Fe	-0.03	Fe	-0.07
temp	0.02	Pb	-0.10	chl	-0.06	SS	-0.03	cond	-0.05
stabE4	0.02	Se	-0.09	F	-0.06	TOC	-0.03	NO2	-0.05
TAl	0.03	TN/Si	-0.08	Se	-0.04	TAl	-0.03	Pb	-0.04
Zn	0.03	F	-0.08	TOC	-0.04	Na	-0.02	NH4	-0.04
F	0.04	TKN	-0.06	TP/Si	-0.03	K	-0.02	hardness	-0.04
NO3	0.05	NO2	-0.03	TKN	-0.01	turb	-0.02	TAl	-0.04
TN/Si	0.06	TP	-0.02	DO	-0.01	cond	-0.01	Na	-0.04
Fe	0.06	SHrs	-0.01	TDS	0.01	TDS	-0.01	TDS	-0.04
TNE3	0.07	chl	-0.01	Pb	0.01	Si	-0.01	alkal	-0.04
NH4	0.07	Cd	-0.01	Cd	0.02	TKN	0.00	TN/Si	-0.03
BOD	0.07	stabE4	0.00	Mg	0.02	stabE4	0.00	K	0.00
TKN	0.08	SRP	0.00	hardness	0.03	alkal	0.01	SO4	0.00
Pb	0.08	Cu	0.01	Ca	0.03	Cl	0.02	secc	0.00
WnSp	0.08	WnDir	0.01	alkal	0.03	Cr	0.02	turb	0.02
turb	0.09	TOC	0.02	K	0.04	pH	0.04	Ca	0.02
WnDir	0.10	K	0.03	SRP	0.04	NO2	0.04	Mn	0.05
SS	0.12	TDS	0.03	Hg	0.04	Mn	0.04	SS	0.06
pH	0.12	SO4	0.03	cond	0.04	NH4	0.05	F	0.06
Mn	0.16	Cl	0.04	Cl	0.04	secc	0.06	Se	0.07
Ni	0.17	temp	0.04	Na	0.05	WnSp	0.06	BOD	0.07
chl	0.18	Na	0.04	NO2	0.05	WnDir	0.09	Ni	0.08
TP/Si	0.18	Mg	0.04	Cu	0.05	BOD	0.09	chl	0.08
SRP/Si	0.18	WnSp	0.05	WnDir	0.05	Zn	0.09	Hg	0.08
TP	0.20	TNLDE-3	0.05	SRP/Si	0.05	Mg	0.11	TKN	0.08
SRP	0.20	cond	0.06	SO4	0.06	hardness	0.12	SHrs	0.08
Ca	*0.23*	hardness	0.09	BOD	0.07	Ca	0.13	Zn	0.10
Mg	*0.23*	TP/Si	0.09	Zn	0.08	TN/SRP	0.13	SRP	0.12
hardness	*0.23*	alkal	0.10	Mn	0.15	TN/TP	0.14	SRP/Si	0.12
TOC	*0.23*	TPLDE-1	0.10	SHrs	0.15	temp	0.15	TNLDE-3	0.13
alkal	*0.25*	SRP/Si	0.10	TN/SRP	0.17	TNE3	0.15	Cd	0.14
SO4	*0.25*	Ca	0.12	NO3	0.18	NO3	0.16	Cu	0.14
Na	*0.25*	SRPLD	0.13	*secc*	*0.22*	TN/Si	0.18	TP	0.15
K	*0.25*	pH	0.17	*TNE3*	*0.23*	*F*	*0.26*	SRPLD	0.15
TDS	*0.25*	DO	0.17	*NH4*	*0.24*	*TPLDE-1*	*0.43*	TPLDE-1	0.16
cond	*0.25*	%DO	0.19	*TN/TP*	*0.26*	*TNLDE-3*	*0.43*	TP/Si	0.17
Cl	*0.25*	*secc*	*0.22*	*TN/Si*	*0.29*	*SRPLD*	*0.45*	Cr	0.18

As noted by numerous authors (e.g. Gauch *et. al.* 1977; Moral & Watson 1978; Reyment 1980) if there are outliers in the data set then it is best to remove these prior to data analysis, this especially so where ordination is used as an analytical technique (Gauch 1982). Outliers probably represent extreme environmental conditions. To check for the presence of outliers, firstly the physico-chemical and then the biological (algal) similarities between lakes were considered. The more dissimilar sites were, the more likely they were to be outliers and hence likely to cloud the central focus of this study i.e. in establishing the key environmental variables influencing problematic algae.

To determine the physico-chemical similarity between the various lakes a plot of lake sites along the first two PCA axes (Fig. A2.1) reveals how different Shongweni is from all other lakes (Shongweni located apart from the other clustered lake sites).

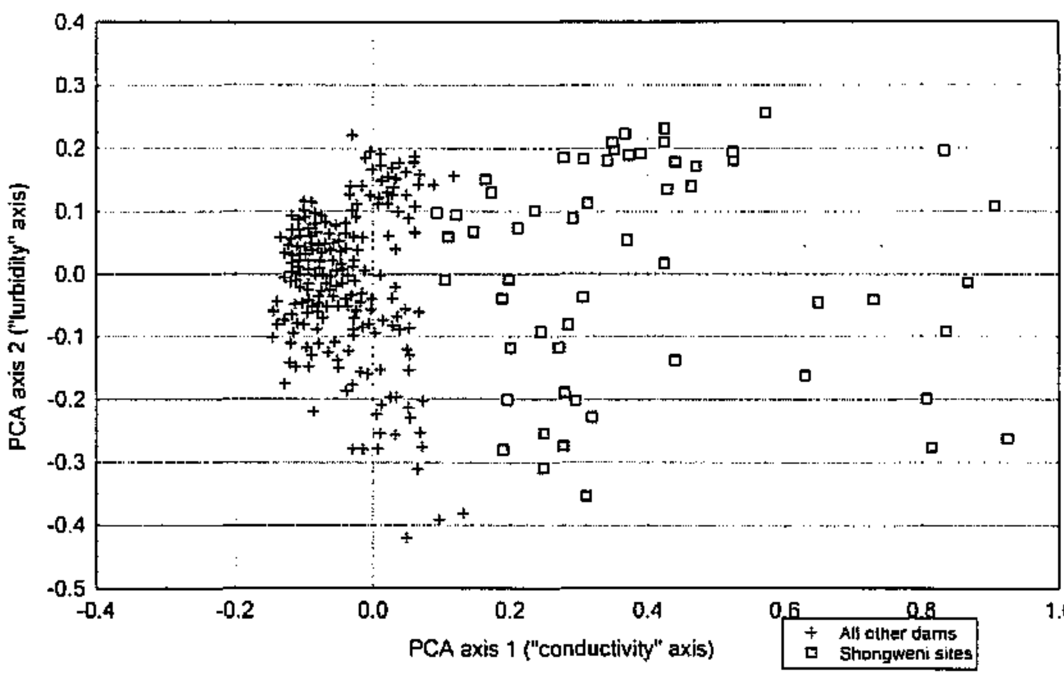

Figure A2.1 PCA ordination plot of Shongweni and all other lakes. Note: lake sites closely clustered on the ordination diagram have more similar physico-chemical conditions compared to sites further apart on the ordination diagram.

Some of the explanation of this difference between Shongweni and all other lakes was provided by examining Figure A2.2 where the former appeared to be characterised by variables ('salts') contributing to high conductivities.

An examination of the algal (or biological) pattern of differences between Shongweni and the other lakes further emphasised the difference between this lake and all others in the study. Ordination of sites using Correspondence Analysis (CA) produced an indication of the separation of lake sites on the basis of their algal composition (Fig. A2.3).

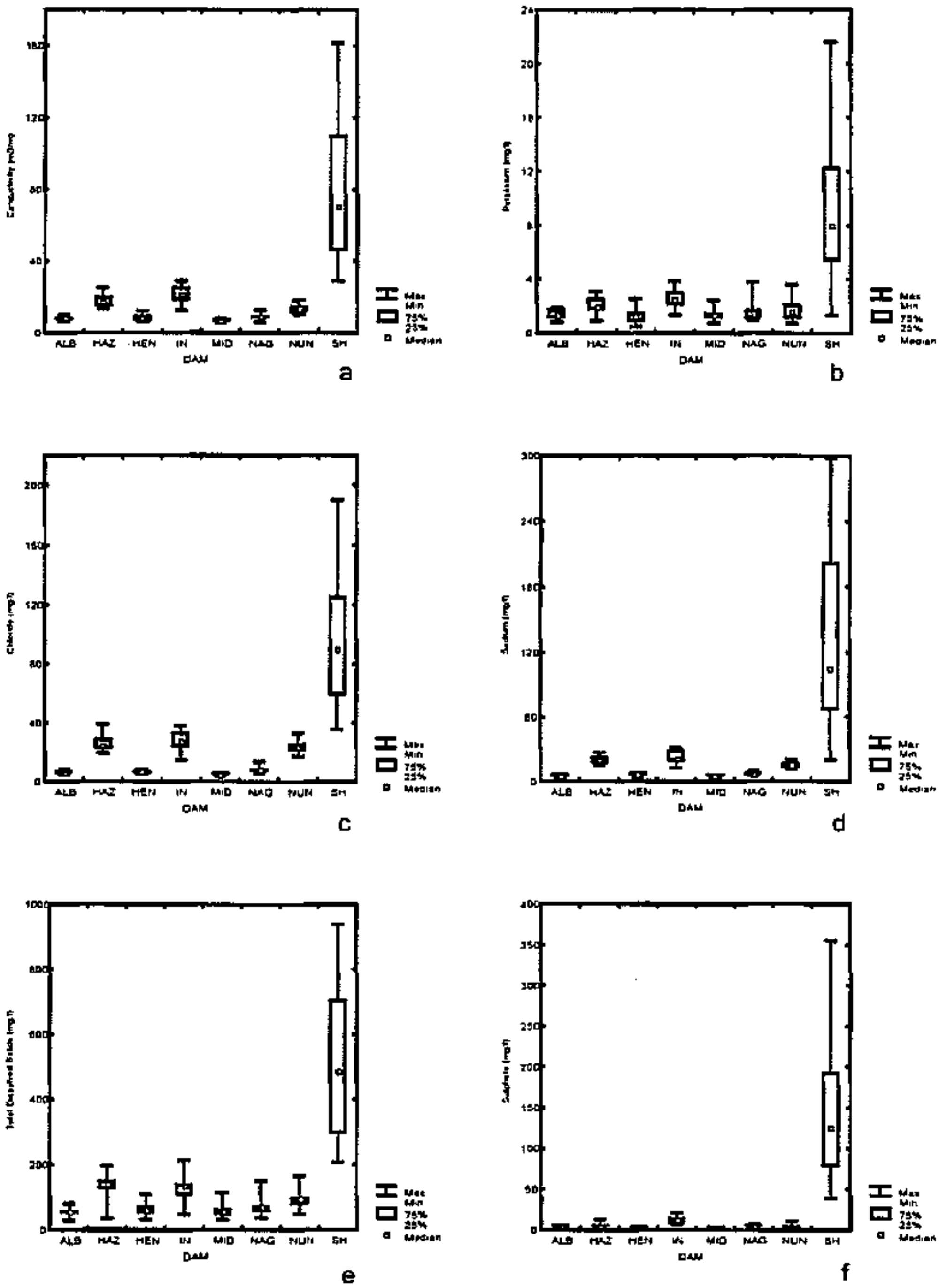

Figure A2.2 Variation of environmental variables with high loading on the first PC axis separating Shongweni sites from other lakes[3] respectively conductivity (a), potassium (b), chloride (c), sodium (d), total dissolved solids (e) and sulphate (f).

[3] Note the exceptionally high values of these parameters in Shongweni compared to all other lakes.

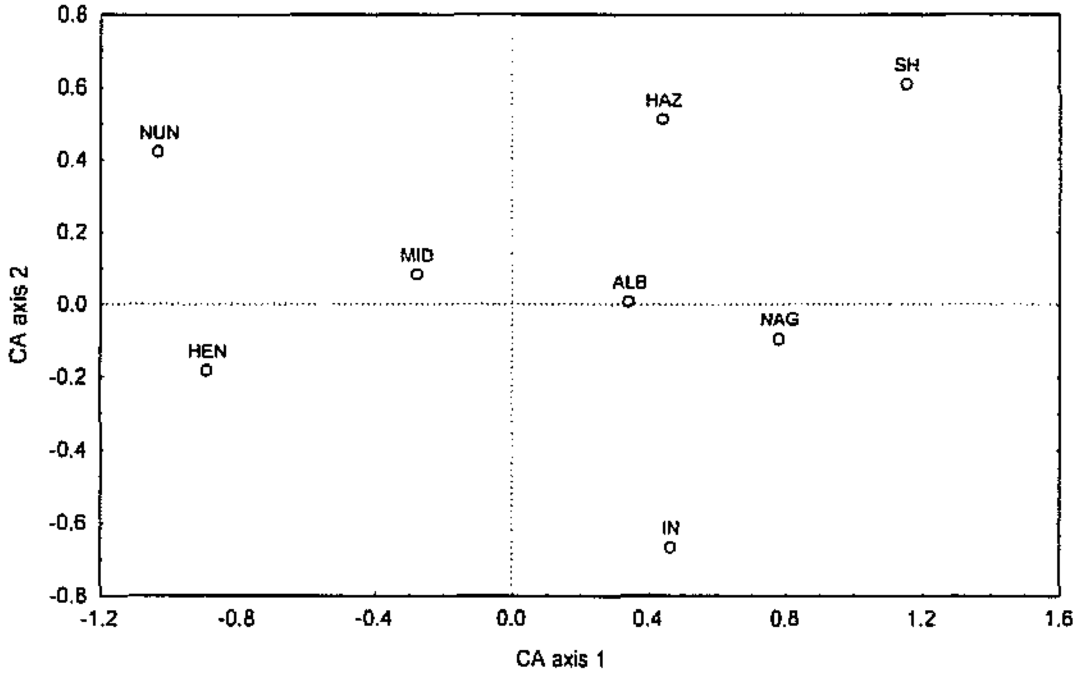

Figure A2.3 Correspondence analysis ordination of biological (algal) data from all lake sites (average site scores (centroids) for lakes have been used as points as individual sites were omitted for clarity).

Again (as in all ordination diagrams) sites which are closer together on an ordination diagram are more similar in terms of their underlying algal composition and abundance compared to sites which are further apart. For example then, Nagle and Hazelmere have a greater similarity in their algal community to Shongweni than do Henley and Nungwane.

It was of interest to note the specific algal genera accounting for the difference, or separation, between Shongweni and all other lakes noted in the Correspondence Analysis ordination of lakes seen in Figure A2.3. This was investigated by examining an ordination of genera over all the sites ordinated in the CA (Fig. A2.4) (i.e. which algal genera dominate the respective areas of the ordination of lake sites in Fig. A2.3). The actual abundance of genera, which distinguish between Shongweni and other lake sites, was then investigated, firstly by ordination diagrams (Figs. A2.6 to A2.8) and then graphically (Figs. A2.8 & A2.9 - algal abundance and proportional composition in respective lakes).

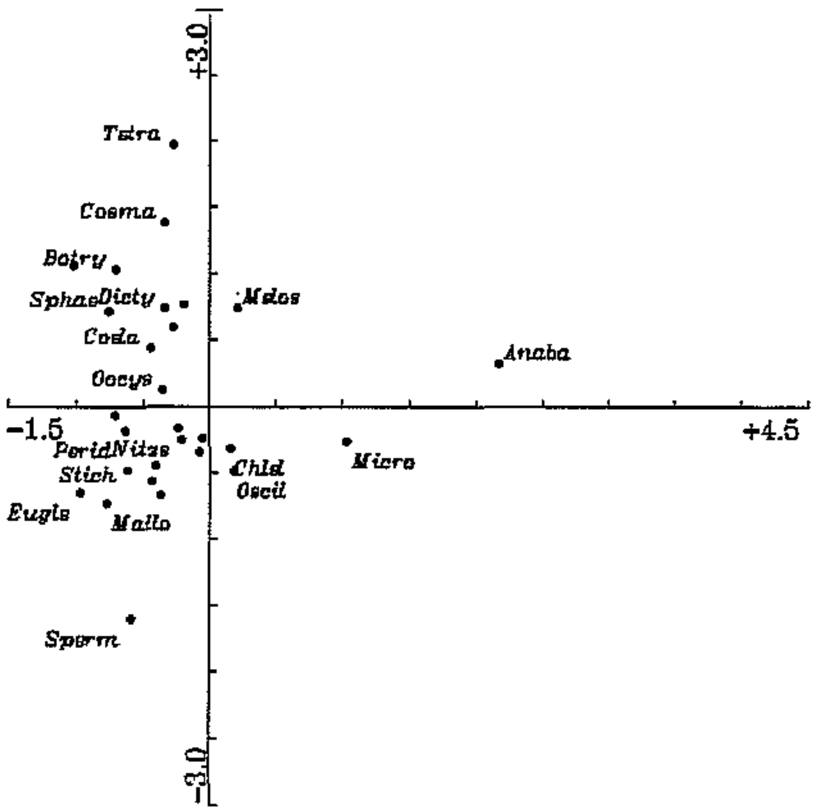

Figure A2.4 Correspondence Analysis ordination of algae over all lakes studied (to be read with site ordinations Fig. A2.3). Algal genera as per Table 2.4.

Genera that are closer together on an ordination diagram are more similar in terms of their occurrence and abundance compared to genera that are further apart. For example then, *Anabaena* and *Microcystis* are more likely to occur together than either of them would with for example *Spermatozopsis* (further apart on the ordination diagram Fig. A2.4)). It is this variability and association amongst the algae, which dictates the ordination of sites as in Figure A2.3.

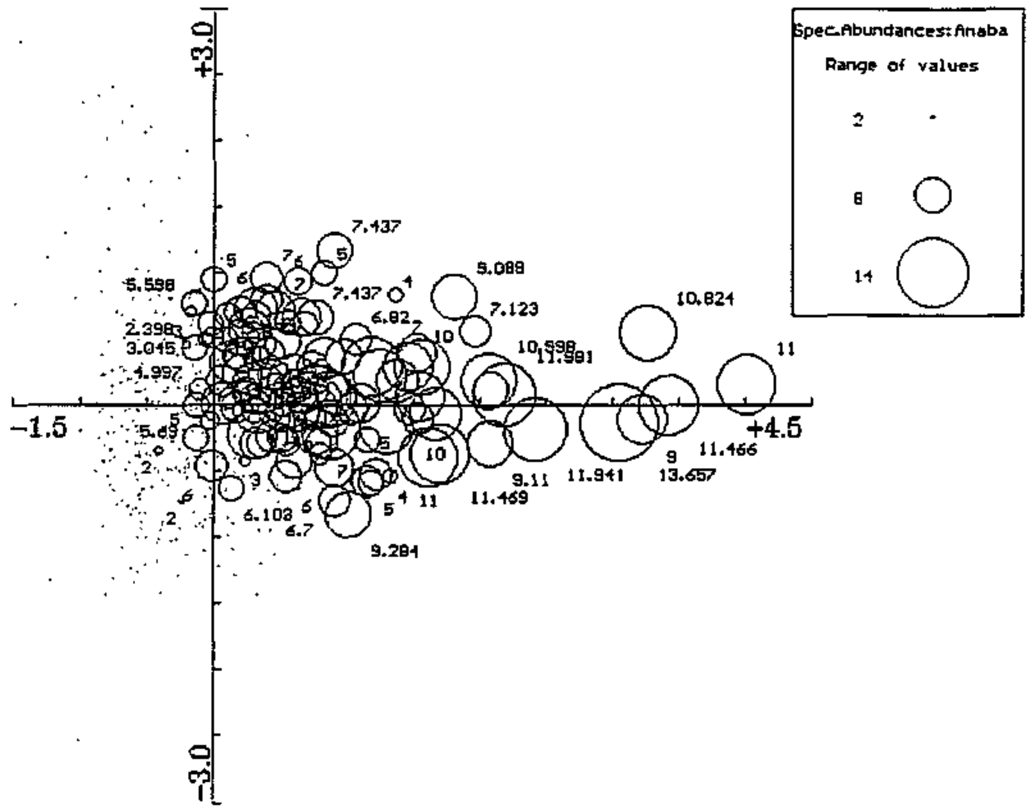

Figure A2.5 Ordination showing the natural log abundance values of *Anabaena* at respective lake sites after Correspondence Analysis (CA).

The CA ordination of all algae (Fig. A2.4), and then the ordination of the abundance of *Anabaena* over all lake sites (Fig. A2.5), shows this alga as dominating sites at the extreme right hand end of the first CA axis which corresponds to the 'eutrophic' grouping of lake sites. The detail of this figure is not as important as the indication that this genus is most dominant at 'eutrophic' sites. Noteworthy are the number of sites on the extreme left of the first ordination axis which have no *Anabaena* in them at all (represented by dots on Figs. A2.5 & A2.6).

A similar, although not as marked, situation exists for another blue-green alga, *Microcystis*, which Figure A2.6 shows as also being dominant at the eutrophic (right-hand-side) end of the first CA axis.

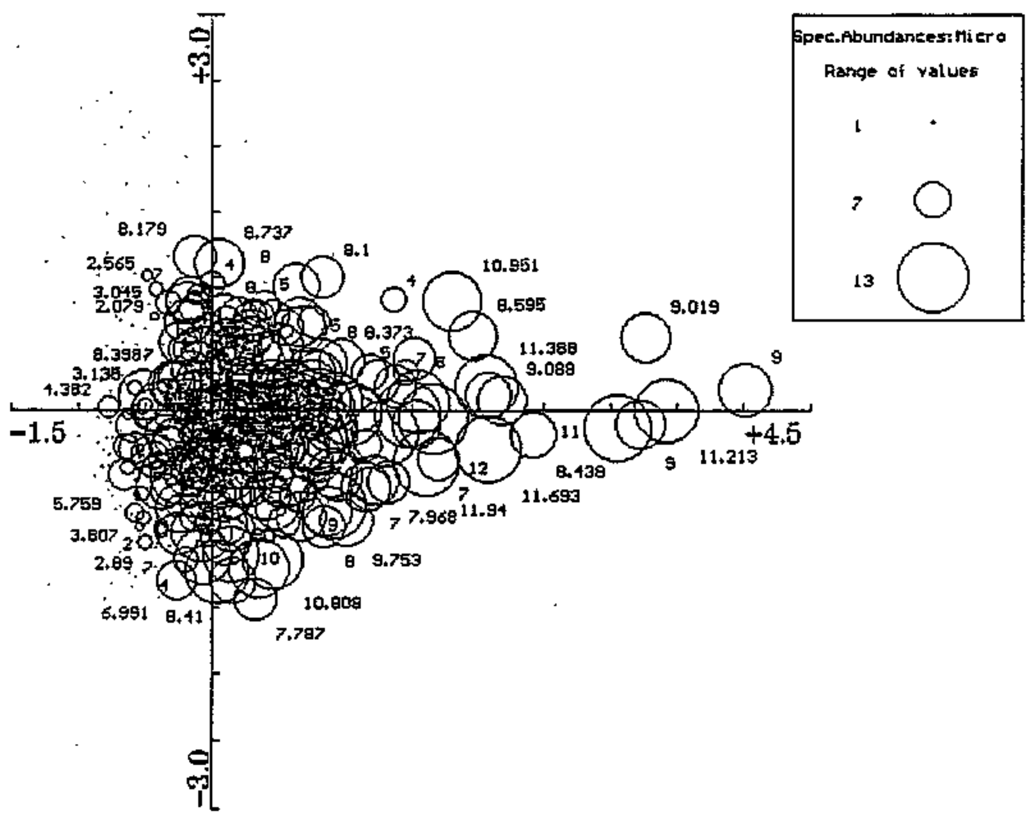

Figure A2.6 Ordination of natural log transformed *Microcystis* abundance data at respective lake sites after CA.

These trends are further illustrated with the plots of algal abundance (Fig. A2.7) and proportional composition (Fig. A2.8).

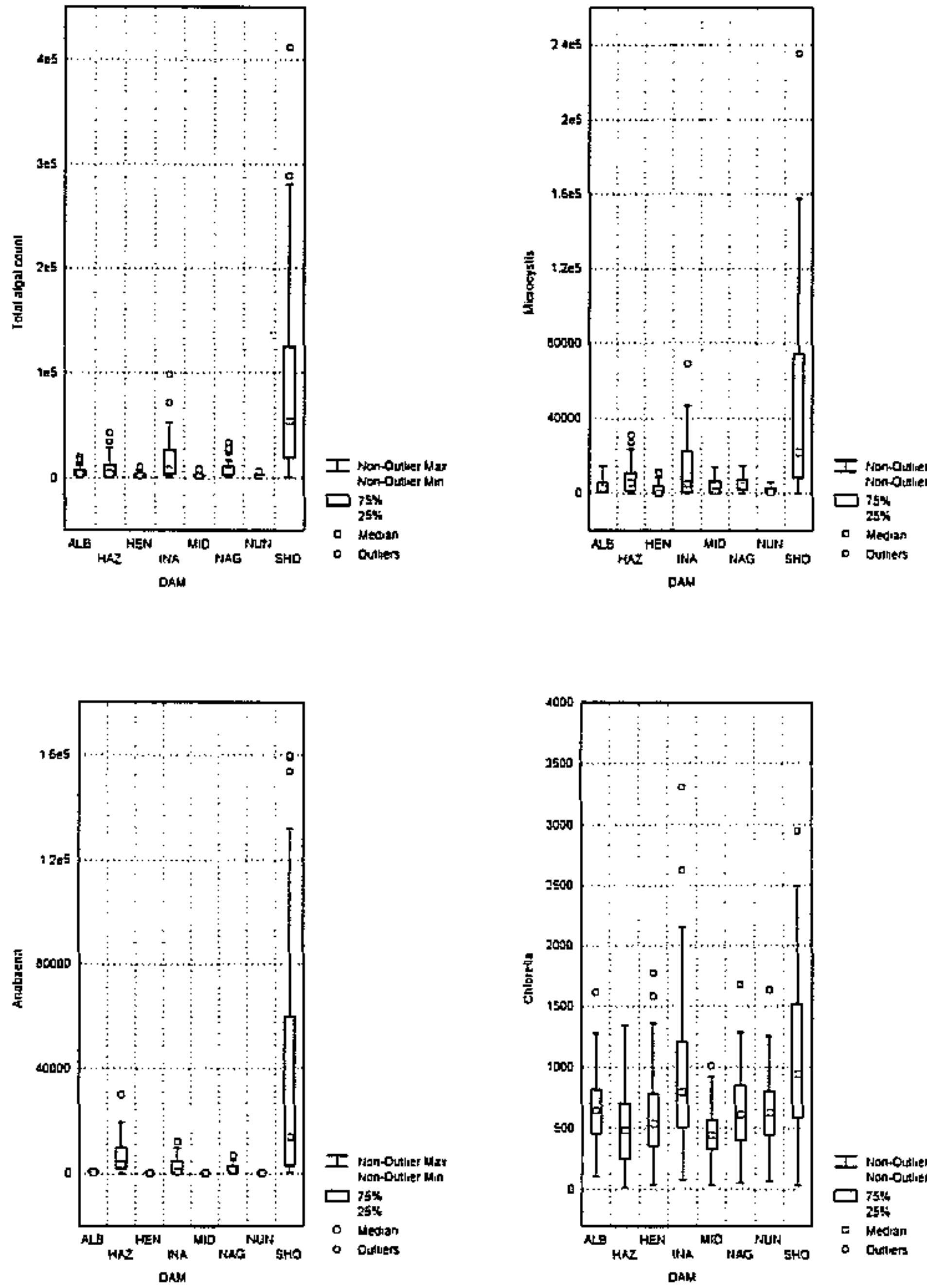

Figure A2.7 Abundance of algal populations, and some dominant algal genera recorded from all lakes studied (including Shongweni) during the study period.

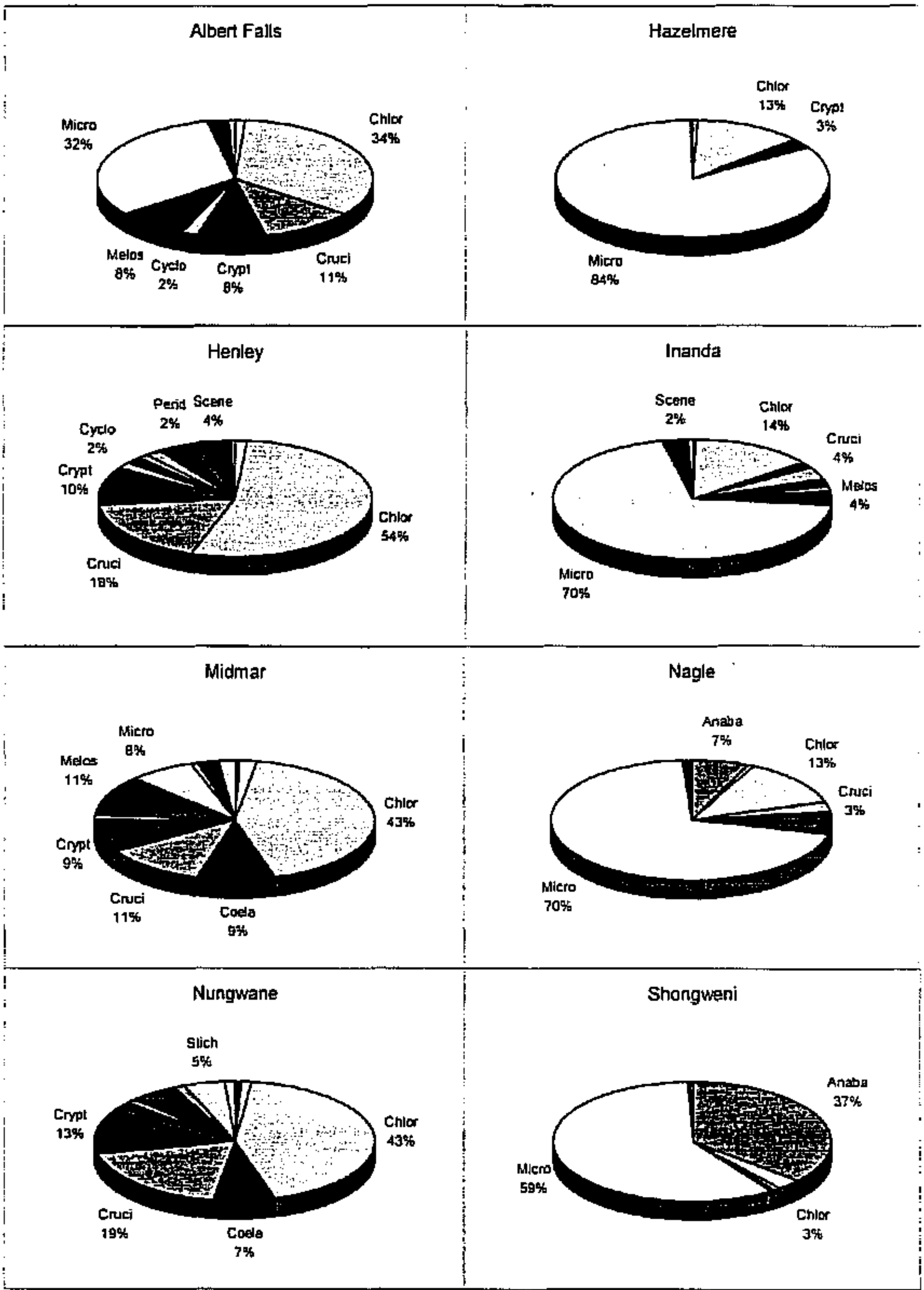

Figure A2.8 Proportional composition (as a percentage of the total median) for respective lakes for the duration of the study period (Chlor=*Chlorella*; Crypt=*Cryptomonas*; Cruci=*Crucigena*; Melos=*Melosira*; Anab=*Anabaena*; Micro=*Microcystis*; Coel=*Coelastrum*; Stich=*Stichococcus*; Perid=*Peridinum*; Scene=*Scenedesmus*; Cyclo=*Cyclotella*).

These figures clearly show Lake Shongweni as numerically and proportionally dominated by the blue-green algae (*Microcystis* and *Anabaena*). The algal counts for *Chlorella*, another dominant to sub-dominant algae, are more evenly spread over the other lakes in the study.

Indications from these analyses were that Shongweni was particularly different from all the other lakes in the study - from both a physico-chemical as well as biological point of view. It was therefore eliminated from further analyses. It was reasoned that its inclusion, with very high values for certain environmental and algal variables, would dominate analyses and mask potentially important relationships in other potable water supply lakes. The high counts of *Anabaena* and *Microcystis* in this lake are the key algae that, although not restricted to this lake, are apparently separating it from all other lakes in the study.

The causes of physico-chemical and algal difference between Shongweni and other lakes in the study are probably related to inputs of industrial effluents and agricultural runoff emanating from large textile industries and intensively farmed agricultural lands located in the catchment. Many of the processes in the textile industry produce high 'salt' effluents. This contributed to the lake being decommissioned as a regular supplier of potable waters (Wilson 1992).

A2.3 Water quality and environmental conditions in all lakes excluding Shongweni

The environmental data in the remaining seven lakes was again analysed using standardised Principal Components Analysis (PCA) on the correlation matrix to produce a few key Principal Components (PCs) which describe a substantial portion of the variation in the environmental data. The rationale for the use of this method was as for the previous analysis, i.e. to reduce the complexity (and dimensionality) of the environmental data to a manageable number of biologically meaningful variables, whilst removing the multicollinearity problem often found with such environmental data sets.

Of the 52 potential PCs only the first 14 were worthy of interpretation. They accounted for 77% of the variation in the environmental data with the first five accounting for over half of the total variation (Table A2.4). As with the previous analyses (§ A2.2 - PCA with all lakes), an examination of the loadings of environmental variables on these axes (Table A2.5 - loading table) revealed that the first few key PCs (in terms of the proportion of environmental data variability explained) could be described as follows: PC_1 - "conductivity", PC_2 - "turbidity", PC_3 - "N & P", PC_4 – "nutrient loads or inflow volumes" and PC_5 - "stability" (Table A2.4). This indicated that even after the removal of the Shongweni data (dominated by highly mineralised waters with high conductivity) from the analyses there was *still* a similar pattern of variation (or structure) in the environmental data in the remaining seven lakes.

All the nutrient loadings (i.e. total phosphorus, soluble reactive phosphorus and total inorganic nitrogen) came out strongly together at the one end of PC_4 (Table A2.5). This indicates that some common environmental parameter is underlying the variability of the nutrient loads. This was obviously 'inflow' volume into the lakes as it was used in conjunction with a discrete sample in the calculation of all nutrient loads (§ A1.4.2 - calculation of nutrient loads). Section A1.4.2.3 discusses the relationship between inflow, nutrient concentration and nutrient loads in greater detail.

Table A2.4 Key results from a standardised Principal Components Analysis for the first 14 axes (performed on the environmental correlation matrix with the exclusion of all Shongweni sites from the data set). The first 5 axes are named

AXIS	EIGENVALUE	PERCENT OF TOTAL	CUMULATIVE PERCENT	Axis name
1	10.199	19.61	19.61	'Conductivity'
2	6.701	12.89	32.50	'Turbidity'
3	4.408	8.48	40.98	'N&P'
4	3.132	6.02	47.00	'Nutrient loads' or 'Inflow'
5	2.400	4.62	51.61	'Stability'
6	2.252	4.33	55.94	
7	1.687	3.24	59.19	
8	1.574	3.03	62.22	
9	1.523	2.93	65.14	
10	1.396	2.68	67.83	
11	1.308	2.52	70.34	
12	1.201	2.31	72.65	
13	1.100	2.12	74.77	
14	1.024	1.97	76.74	

Table A2.5 Ranked environmental variable loadings on the first five PCs/axes from PCA analysis of all lakes excluding Shongweni. Variables with the highest loadings on (and therefore association with) respective axes *highlighted*. See Table 2.2 for an explanation of codes used for environmental variables

Variable	PC$_1$	Variable	PC$_2$	Variable	PC$_3$	Variable	PC$_4$	Variable	PC$_5$
Se	-0.13	*secc*	*-0.24*	*TP*	*-0.30*	*TNLDE-3*	*-0.47*	*stabE4*	*-0.33*
Hg	-0.11	Ca	-0.13	*TP/Si*	*-0.26*	*TPLDE-1*	*-0.45*	*WnSp*	*-0.33*
Cd	-0.05	DO	-0.12	Ni	-0.19	*SRPLD*	*-0.41*	*%DO*	*-0.32*
TKN	-0.04	%DO	-0.12	SS	-0.18	temp	-0.24	*DO*	*-0.23*
TN/SRP	-0.04	SRPLD	-0.11	TAl	-0.18	F	-0.20	*Si*	*-0.21*
SHrs	-0.04	SRP/Si	-0.11	turb	-0.18	chl	-0.19	*WnDir*	*-0.20*
NH4	-0.04	TP/Si	-0.09	temp	-0.13	TKN	-0.14	temp	-0.19
Zn	-0.04	TPLDE-1	-0.08	SRP/Si	-0.13	Cr	-0.13	Cl	-0.14
Cu	-0.03	pH	-0.08	SRP	-0.12	stabE4	-0.11	TOC	-0.14
%DO	-0.03	alkal	-0.07	Cr	-0.11	TN/SRP	-0.10	Zn	-0.11
TNE3	-0.03	SO4	-0.06	%DO	-0.11	turb	-0.06	pH	-0.09
Cr	-0.03	hardness	-0.06	BOD	-0.11	SS	-0.06	Na	-0.09
TN/TP	-0.02	Cu	-0.05	chl	-0.10	%DO	-0.05	chl	-0.09
Si	-0.02	TNLDE-3	-0.05	pH	-0.10	NO3	-0.04	TDS	-0.08
NO3	-0.02	TN/Si	-0.02	stabE4	-0.09	Zn	-0.04	SRP	-0.06
NO2	-0.01	Cd	-0.02	Fe	-0.09	TN/TP	-0.03	cond	-0.04
Pb	-0.01	SHrs	-0.01	TOC	-0.08	Cd	-0.03	Fe	-0.03
DO	-0.01	K	0.00	TPLDE-1	-0.05	TNE3	-0.03	Pb	-0.01
secc	-0.01	chl	0.01	Se	-0.04	Si	-0.02	TN/TP	-0.01
BOD	-0.01	NO2	0.02	Cu	-0.02	pH	-0.02	Mg	0.00
TP	-0.01	Zn	0.03	K	-0.02	TAl	-0.01	BOD	0.01
stabE4	0.00	cond	0.03	DO	-0.02	Ni	-0.01	Se	0.02
Ni	0.02	BOD	0.03	SRPLD	-0.02	NO2	-0.01	TKN	0.03
Fe	0.03	Mg	0.03	TNLDE-3	0.00	Ca	-0.01	NO2	0.04
SRP	0.03	WnDir	0.04	F	0.00	SO4	-0.01	K	0.04
Mn	0.03	F	0.05	Ca	0.01	TDS	0.00	secc	0.05
chl	0.03	temp	0.06	Pb	0.01	Se	0.00	NO3	0.06
SS	0.03	Se	0.06	TDS	0.02	secc	0.01	alkal	0.07
TAl	0.04	TKN	0.06	Cd	0.02	hardness	0.02	Cd	0.07
turb	0.04	WnSp	0.07	hardness	0.03	Fe	0.02	NH4	0.07
TNLDE-3	0.06	Na	0.07	TKN	0.03	Pb	0.03	Cu	0.07
TP/Si	0.07	TN/TP	0.08	alkal	0.03	Hg	0.03	Hg	0.08
temp	0.09	Cl	0.09	SO4	0.03	Na	0.04	TNE3	0.08
TPLDE-1	0.09	NH4	0.11	Hg	0.04	WnDir	0.05	TPLDE-1	0.08
TN/Si	0.11	Pb	0.11	WnSp	0.04	Mg	0.05	SRPLD	0.09
F	0.11	stabE4	0.11	Mg	0.05	cond	0.05	hardness	0.09
SRP/Si	0.11	SRP	0.11	cond	0.07	NH4	0.05	Mn	0.09
WnDir	0.13	Hg	0.12	NO2	0.07	TOC	0.05	TNLDE-3	0.10
pH	0.13	TN/SRP	0.12	SHrs	0.08	Cl	0.06	TAl	0.10
SRPLD	0.14	TDS	0.13	Si	0.09	WnSp	0.06	TN/SRP	0.10
WnSp	0.16	TOC	0.13	Na	0.09	Cu	0.07	F	0.11
TOC	0.16	Ni	0.14	Cl	0.09	K	0.07	TP	0.11
TDS	*0.25*	TP	0.15	WnDir	0.09	alkal	0.08	SO4	0.11
K	*0.27*	Mn	0.16	Zn	0.12	DO	0.09	turb	0.12
Ca	*0.27*	Cr	0.16	Mn	0.15	BOD	0.09	Ni	0.13
Cl	*0.27*	*NO3*	*0.26*	secc	0.16	SHrs	0.09	Cr	0.14
alkal	*0.27*	*TNE3*	*0.26*	TN/Si	0.18	Mn	0.09	SRP/Si	0.15
SO4	*0.28*	*SS*	*0.27*	*NH4*	*0.22*	TP	0.09	SS	0.15
Na	*0.29*	*TAl*	*0.30*	*NO3*	*0.22*	TN/Si	0.09	Ca	0.16
hardness	*0.30*	*turb*	*0.31*	*TNE3*	*0.26*	TP/Si	0.17	*SHrs*	*0.20*
Mg	*0.30*	*Si*	*0.31*	*TN/SRP*	*0.31*	SRP	0.18	*TP/Si*	*0.23*
cond	*0.30*	*Fe*	*0.32*	*TN/TP*	*0.40*	*SRP/Si*	*0.22*	*TN/Si*	*0.27*

An examination of the distribution of lakes, in the absence of Shongweni data, by means of a PCA ordination diagram (Fig. A2.10), reveals how Inanda sites now tended to dominate the high end of the first PC axis which represented a conductivity gradient (Tables A2.4 & A2.5) whilst the other lakes were arranged further back along this axis. This followed the expected pattern for these lakes, i.e. along an increasing pollution gradient of conductivity (and hence salts). 'Cleaner' inland lakes (Henley, Midmar, Albert Falls and Nagle) were all at the low end of the conductivity gradient with coastal lakes (Nungwane, Hazelmere and Inanda) coming out at the 'high' conductivity end of PC_1.

Interestingly, all the Mgeni River lakes were closely grouped at the low end of PC_1 with Inanda, a distinct outlier, at the high end of the 'conductivity' gradient. With few other major tributaries, other than the polluted Msunduzi River, coming into the Mgeni system between Nagle and Inanda (Fig. 1.1 - Study area), the relative impact of this tributary on the water chemistry of Inanda is demonstrated by this analysis. The Msunduzi is acknowledged to be a polluted river system, passing as it does through the urbanised Pietermaritzburg area with its associated inputs from industry, sewage effluent and storm-water runoff (MCMP 1996).

The second PC axis, identified in this analysis as a turbidity gradient (Tables A2.4 & A2.5), had all the Mgeni River lakes grouped at its lower end (PC_2, Fig. A2.10). On the other hand, Hazelmere on the Mdloti River is clearly separated out at the upper end of this axis. This lake is acknowledged to be a highly turbid system (e.g. Walmsley & Butty 1980). Nungwane (and to a lesser extent Henley) is also separated from the Mgeni system lakes by this turbidity feature on the second axis.

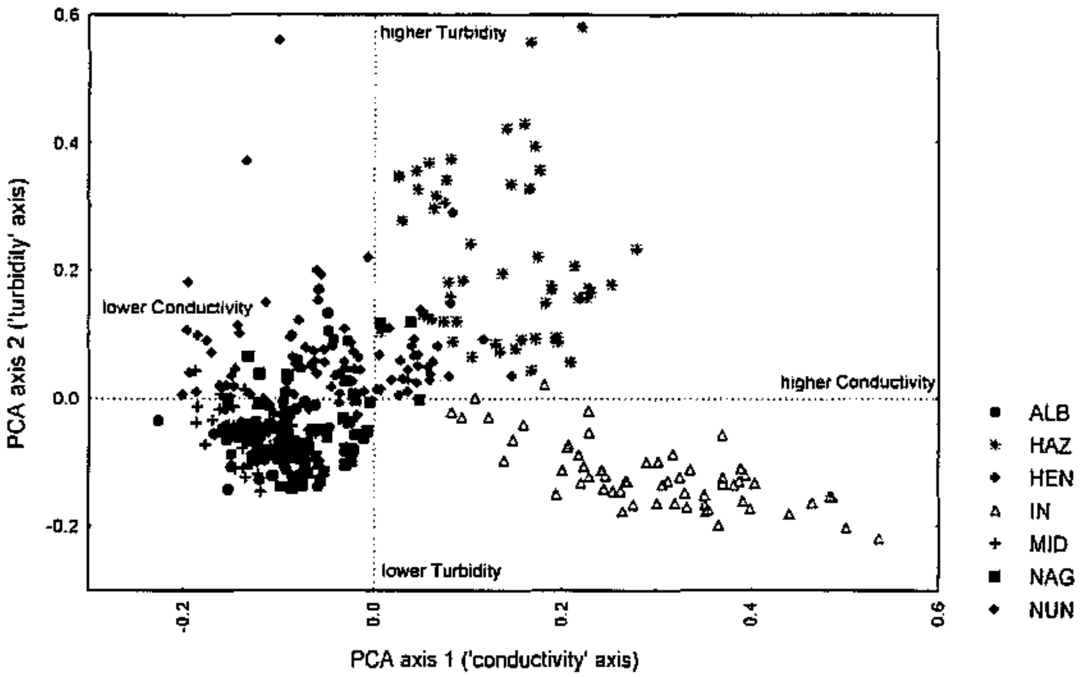

Figure A2.9 Principal Components Analysis ordination of lake sites on the first two PC axes ('conductivity' and 'turbidity').

The other interesting feature of Figure A2.9 is the close proximity and progression, from Midmar through to Albert Falls and then on to Nagle, which respectively lie downstream from one another on the Mgeni system. This analysis indicates that their general water quality is more similar as a group of lakes compared to all the other lakes studied. Henley (fairly similar to this group), although in a different sub-catchment (the Msunduzi River), is a physico-chemically similar system originating in the kwaZulu-Natal Midlands. The coastal lakes (Nungwane on the Nungwane River and Hazelmere on the Mdloti River) are increasingly different in their overall water chemistry from the Mgeni system lakes and are hence further apart on Figure A2.9.

Ordination of lake sites on the third and fourth PCA axes (respectively identified as gradients in 'N & P' and 'inflow volumes' (Fig. A2.10 - PCA ordination with 3rd and 4th axes) did not give as good a separation of sites in relation to these gradients as was obtained with the first two ordination axes. This was not surprising given that successive axes in PCA account for progressively less variation in the underlying environmental data set (Table A2.4). Table A2.4 indicates that the third and fourth axes only account for 8% and 6% of the variability in the environmental data respectively whilst the first two axes accounted for 20% and 13% respectively.

Although there was relatively poor separation of sites there did appear to be a few interesting trends. The majority of Midmar, Nagle and Albert Falls sites appeared to be tending towards the higher Total Phosphorus end of PC_3 axis, whilst Nungwane, and to a lesser extent Henley, were at the end with higher Total Nitrogen. Walmsley & Butty (1980) have also noted that Henley is influenced by high nitrogen values. Inanda sites were widely spread over both ends of all axes indicating it experiences a range of environmental conditions. No clear trends existed for the separation of lakes along the 'inflow' gradient (PC_4).

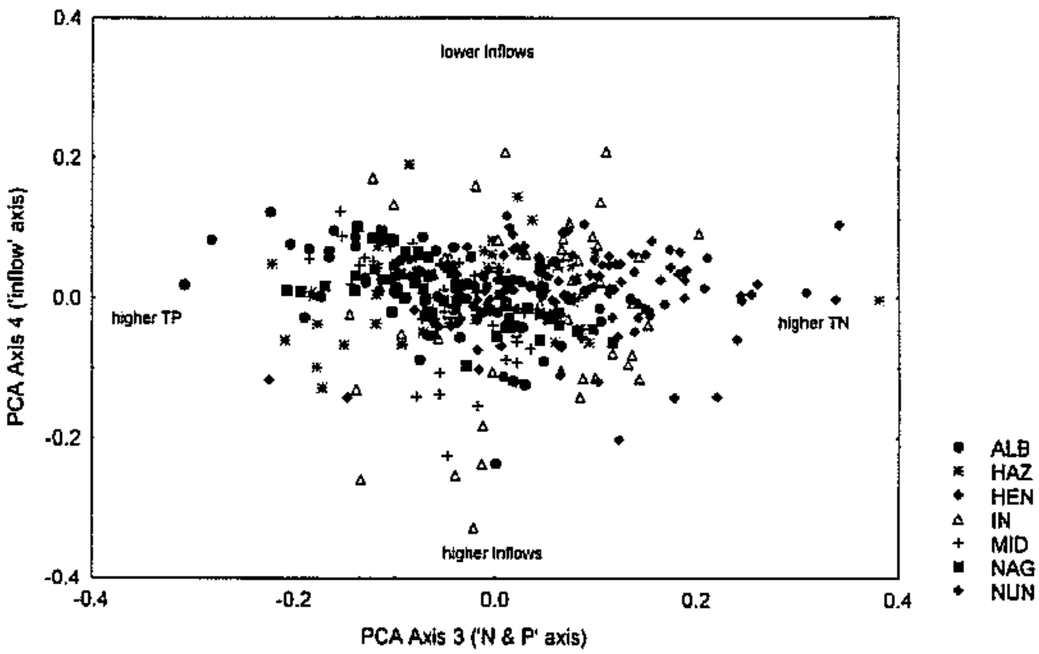

Figure A2.10 Principal Components Analysis ordination of lake sites on the third and fourth PCA axes ('N & P' and 'inflow volumes').

APPENDIX 3
ENVIRONMENTAL EFFECTS ON ALGAL POPULATIONS

A3.1 Introduction

A broad summary of the results presented here (but with little of the statistical detail) is provided in Chapter 4 of this report.

One of the primary aims of this study was *"establishing the key environmental variables influencing the distribution and abundance of problematic algae in lakes within the Umgeni Water operational area"*. This clearly had a number of aspects. Firstly in establishing the *"key environmental variables influencing algae"* (Appendix 2 & 3), secondly the *"problematic algae"* (§ 2.3, Table 2.4) and then finally the relationship between these two (this appendix). To address this a series of analyses were undertaken to determine which facets of the environment (measured environmental variables (§ A3.3), effects unique to respective lakes (§ A3.4) and seasonality (months § A3.5)) were playing the most significant part in explaining the observed variability in the algal populations. Each of these analyses revealed a different aspect of how environmental variables were influencing algal populations in the study lakes.

A3.2 Outline as to how algae/environmental relationships were studied

A detailed set of analyses (summarised in Appendix 2 - Water Quality and Environmental Conditions of the Lakes Studied within the Umgeni Water Operational Area) revealed how different Shongweni was from all other lakes in the study – this from both a water physico-chemical as well as biological (algal) point of view. There appeared to be reasonable grounds in that analysis to separate this lake from all further analyses addressing the relationships between algae and the environment. This was because this lake was generally dominated by blue-green algae and represented the extreme end of a mineralisation, or eutrophication, gradient. Its retention would have clouded further analyses that planned to establish possible key environmental variables influencing algal populations in the lakes (§ 1.2 – Project Aims). The blue-green algae dominating Shongweni were not exclusively restricted to that lake and hence, the relationship of this important group of algae to the environment was still able to be determined.

A summary of trends identified in the environmental data is presented here prior to the inclusion of environmental variables in analyses with algae (§ A3.3).

A3.2.1 Summary discussion of trends identified in the environmental data for all lakes investigated (excluding Shongweni)

Analyses restricted to examining the environmental data in the seven lakes remaining after Shongweni had been excluded (Appendix 2, § A2.3) identified a reduced number of environmental variables that appeared to describe the key elements of variability in the environmental data set almost as well as the complete set (Table A3.1). This reduced set of environmental parameters covered the major physico-chemical processes known to affect algae and were taken forward in analyses investigating the environmental effect on algal populations. Prior to this however certain noteworthy features about trends in the environmental data are presented here.

In conjunction with its statistical ability to summarise the correlation structure underlying the environmental data (§ Ch. 3), Principal Components Analysis (PCA) provided a useful graphical summary of the general water quality (physico-chemistry) observed in lakes and how, from a management perspective, they could be grouped. Those lakes that are grouped closer together on PCA ordinations (e.g. Fig. A2.10) have a similar water physico-chemistry, and therefore could be expected to have a similar response to a change in management or natural perturbation. The differences and similarities are also reflected in later analyses where their algal composition and abundance are considered (§ A2.2 and Figs. A2.8 & A2.9). Geology, soil types, catchment land-use as well as physical processes operating and interacting with these factors may account for the differences between lakes distinguished by this set of analyses.

The Principal Components Analysis identified a number of axes of major variation in the environmental data set that represented the co-variation of a suite of closely related environmental variables. In further analyses these PC axes, or major gradients in the environmental data, were represented by a handful of key environmental variables that had high loadings (and hence association) with their respective PC axes (Tables A2.4 & A2.5). This reduced set of nine environmental variables (Table A3.1) effectively acted as representatives of groups of closely associated variables that had been identified by PCA. There was also greater intuitive appeal in using 'real' environmental variables, over statistically defined PC axes (composite environmental gradients), for use in establishing algae/environment relationships.

Table A3.1[4] Reduced key environmental data set representing axes of major variation in the environmental data set (also reflecting major physico-chemical limnological processes occurring in lakes)

Principal Component axis	PC_1	PC_2	PC_3	PC_4	PC_5
Environmental variables	conductivity	secchi	total inorganic N	Inflow	% DO
		Silicon	total Phosphorus	Temperature	Stability

Most of the major physico-chemical limnological processes known to affect algae (nutrients, energy, water column stability and light regime (e.g. Sommer 1989; Tilman et. al. 1986; Viner 1985) were represented in some measure by the selected variables. The assumption was that the selection of this reduced

[4] Data derived from Appendix 2 – Water quality and environmental conditions of the lakes studied within the Umgeni Water operational area.

set of 'key' environmental variables would in fact effectively represent the major *limnological* processes as they *influenced* algae in the lakes in this study. It should be emphasised that these few 'key' environmental variables are closely associated (co-vary) with other groups of variables (see Table A2.5 - loadings of variables on axes, § A2.2) so that their effects are not unique in terms of describing observed variability in the algae (Chapter 4). Because of the strong association between the 'key' environmental variables and their associated variables both were usefully employed in interpretations of algae and environment relationships (Chapter 4 - algae/environment analyses).

The reduced data set of key environmental variables, representing axes of major variation in the environment, (Table A3.1), was used in further analyses to determine which aspects, and to what degree, the environment may be influencing the distribution and abundance of problematic algae in the lakes within the Umgeni Water operational area (first objective of the study).

Analyses relying principally on ordination techniques (Ch. 3 – Methods of Data Analysis) were used due to the multivariate nature of this study i.e. different types of algae and numerous measures of the environment. Essentially algae are not independent, i.e. do not exist alone in aquatic systems, as there are always a range of biological interactions taking place in these communities - be it competitive exclusion, luxury nutrient uptake, predation, etc. (e.g. Hart 1992; Shapiro 1997). Therefore attempts to model individual algal genera, as independent factors, against a range of environmental parameters will always be fraught with problems if interactions among algae are ignored. Soudant *et al.* (1997) note that due to the inherent complexity of this type of algal data, and the high variability often associated with algae over time, (generated by processes occurring at different spatial and temporal scales), static regression models are not suitable for this type of analysis. Multiple regression ordination techniques elegantly surmount this problem and consider the response of algae to the environment at the community level i.e. how are all the algae responding to the environment as a whole?

Due to the nature of the data (i.e. the relatively short environmental axes, likely to represent linear relationships between algae and the environment, see Chapter 3 - Statistical Methods) Redundancy Analysis (RDA) was the technique chosen to perform the multivariate ordinations on log transformed algal data.

A3.2.2 The Interpretation of ordination figures and kriged data

A brief summary provided to the reader as an aid in the interpretation of all further ordination figures and kriged data is presented here. More detail on the analytical methods used is provided in Chapter 3.

The aim of ordinations, as presented here, is to arrange lake sites or samples (represented by points) such that points that are close together correspond with sites that are similar in algal composition. Obviously sites that are further apart correspond with sites that are dissimilar in algal composition. The ordination of algae, by contrast, produces arrows (in RDA methods) on an ordination diagram where the arrows corresponds with the rate of change in abundance of respective algae over these ordinated lake sites. At each ordinated lake site there is corresponding environmental information available on environmental variables.

In an effort to develop predictive models relating algae to the environment kriging was employed. This essentially takes the values for environmental variables of interest at respectively ordinated lake sites and creates contours of similarity over the ordination diagram. In other words as the values for an environmental variable change at respective sites over an ordination diagram, *contours are created to represent this trend surface (in rate, value and direction) over the ordination. Kriging therefore provided semi-quantitative models relating algae to key environmental elements. Results for this are summarised in Table 4.1 (summary by genera of algae/environment relations). In the same way, as kriging was used to fit* ***environmental*** *trend surfaces across the ordination diagrams, an* ***algal*** *abundance trend surface could be fitted. This provides a more general indication than the algae/environment biplot (Fig. 4.2) as to where algal abundances could be expected to be highest (and expected algal counts) and under what environmental conditions.*

In the interpretation of RDA ordination figures, algal genera should strictly be represented as arrows as the rationale underlying the technique assumes that there is a linear change of algae across the ordination diagram. However, for clarity genera in some ordination figures were represented by dots. Environmental (and algal) variables are positively correlated if their arrows subtend a small angle, uncorrelated (independent) if their arrows are at 90°, and negatively correlated if their arrows are in opposite directions. Environmental variables with the longest arrows relative to an axis have the greatest influence on that axis. Algae with long arrows (distance from the origin of ordinations) have a greater proportion of their variability explained by the ordination than do algae closer to the origin. They are consequently responding more strongly (rate of change) to the measured environmental variables. The order of genera along any environmental gradient is obtained by dropping a perpendicular bisector from the end of the arrows (points), representing algal genera, to the extended line of an environmental arrow.

A3.3 Effects of 'key' environmental variables on algal populations

A3.3.1 Introduction

Key environmental variables (identified from previous analyses of PCA on environmental data, Appendix 2, §A2.3) were fitted to the algal data with the spatial effects of respective lakes and the temporal effects of months overlain as passive variables. The 'fitting' of environmental data was to determine which elements of the environment appeared to be significantly related to the pattern of variability observed in the algal data. 'Passive' plotting of variables was to examine the relationship of these variables to the algae and the key environmental variables of interest but without restricting the derivation of the ordination axes with their inclusion. Redundancy Analysis (RDA §3.2.2) was used for this aspect of the analysis with the objective of investigating the unique contribution key environmental variables were providing to the explanation of observed variability in the algal data. This would provide some information on possible cause/effect relationships between water quality and the various algal genera. If there appeared to be any relationship then this could be Monte Carlo permutation tested to establish the probability that the relationship was due not just to chance. Though not specifically reported for each analysis it should be noted that all algae and 'general' environment relationships were found to be significant ($P < 0.01$, ter Braak 1987-1992).

A3.3.2 Results and Discussion

Results from these analyses are summarised in Table A3.2 and Figure A3.1. It should be emphasised that all further results presented in this report pertain to analyses performed on the reduced lake data set i.e. after the removal of Lake Shongweni data.

Table A3.2 Results from analyses where 'key' environmental variables were related to algae in all lakes except for Shongweni

Axes	1	2	3	4	Total variance
Eigenvalues	0.08	0.03	0.02	0.01	1.00
Algae-environment correlations	0.69	0.52	0.51	0.42	
Cumulative % variance					
of algal data.	8.0	11.0	12.8	14.0	
of algae-env. relation	51.2	69.6	81.3	88.9	
Sum of all unconstrained eigen values					1.00
Sum of all canonical eigenvalues					0.16
Algal variability explained by analysis					15.7%

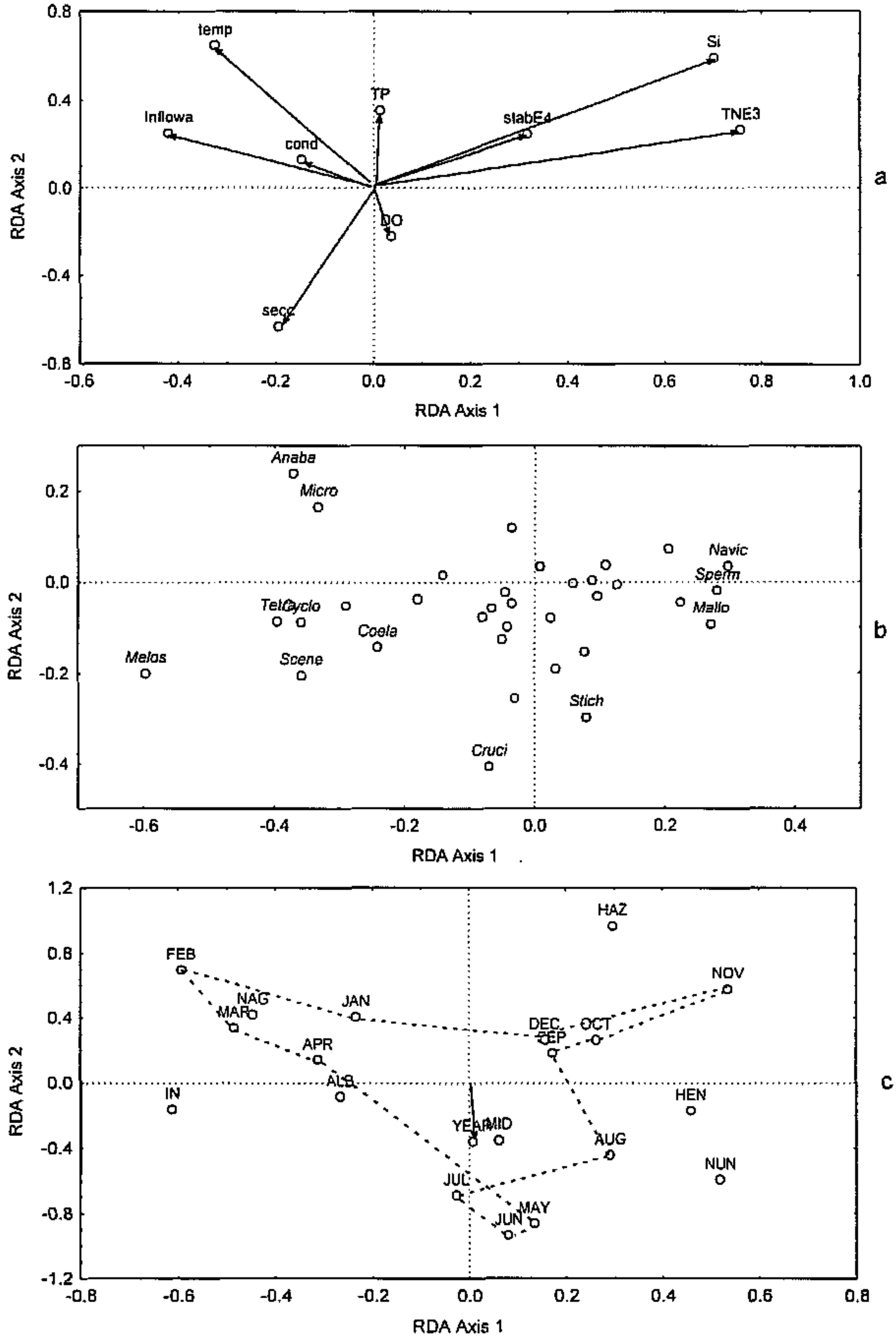

Figure A3.1 Ordinations where key environmental variables influencing algae were examined (a). Lakes and months (seasons) were plotted as passives (c). Algal genera with >10% of their variation explained by the analysis are plotted and labelled. Abbreviations as per Tables 2.1 & 2.4 and interpretations of the figures as detailed in § A3.2.2.

Key findings and observations were that the first 2 axes accounted for only 11% of species data variation and 70% of the species/environment relationship (Table A3.2). It should be noted that this low proportion of the variance accounted for is not atypical of multi-species data sets, particularly when there are many zero values (e.g. Stevenson *et al.* 1991; Agbieti 1992) and that it can still provide a useful description of observed pattern (ter Braak 1987-1992). Gauch (1982) notes that ordination diagrams that explain only a low percentage of species variability may still be quite informative with ter Braak (1990) indicating that the low explained variance is not as important as the significance testing. The most important environmental parameters identified as explaining the variability in the species data were total inorganic nitrogen, silicon, temperature and inflow on the first axis with total phosphorus and secchi important on the second axis (Fig. 4.1a).

Algal genera which had a significant proportion (>10%) of their variance explained by the environmental variables in this analysis are labelled on the ordination (Fig. 4.1) and summarised in Table A3.3. These results show the ranked response of genera (in terms of variance explained) to the supplied environmental variables. Clearly *Melosira* has more of its variability explainable by the supplied environmental variables than does *Euglena*. The higher this variance, the greater the confidence that the supplied environmental variables are important in explaining observed variability in the algae.

Table A3.3 Ranked response of genera (in terms of variance explained) to the supplied key environmental variables (only genera with >10% variance explained indicated)

Genus	Cumulative % variance explained
Melosira	49.42
Anabaena	22.39
Tetraedron	22.26
Cyclotella	21.94
Crucigenia	20.26
Scenedesmus	19.48
Peridinium	18.81
Spermatozopsis	16.98
Microcysits	16.68
Stichococcus	16.09
Mallomonas	15.83
Cosmarium	14.10
Coelastrum	13.28
Navicula	12.72
Cryptomonas	12.24
Botryococcus	11.26
Euglena	10.87

Trend surface plots for key environmental variables (Figs. 4.3 to 4.9) and responsive algae (Figs. 4.10 to 4.16) over all sites in the ordinations were fitted using kriging (see Ch 3 - Methods). This resulted in semi-quantitative models relating algae to the environment. The kriging approach provided best fit 'contours' for environmental variables across the ordination diagram. When read in conjunction with the algae/environment biplot (Fig. 4.2) they provide some indication of the levels of key environmental variables when respective algae are abundant.

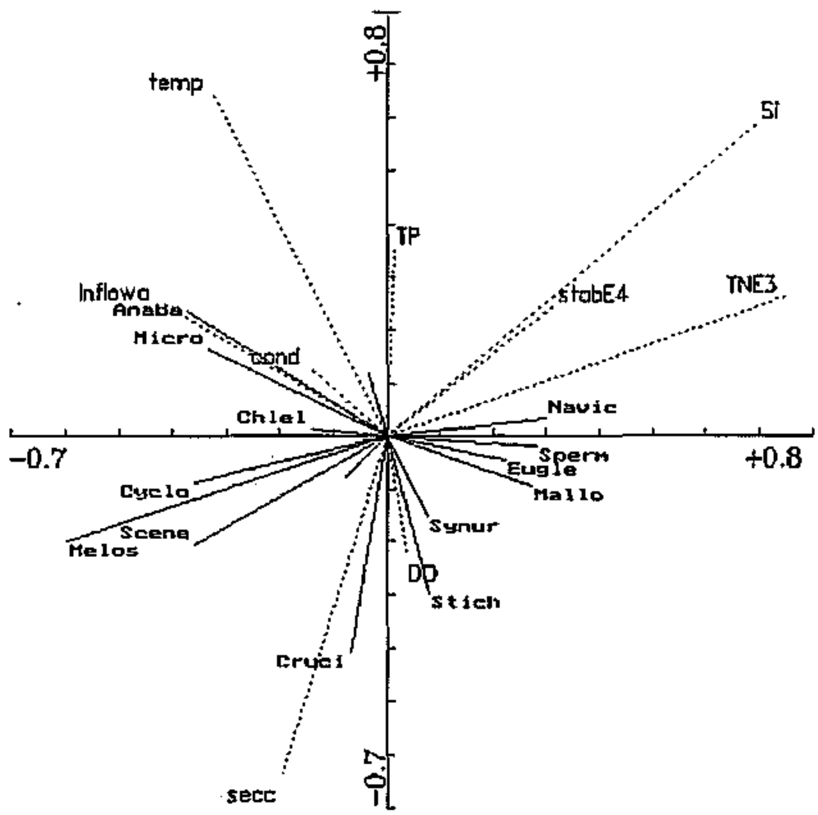

Figure A3.2 Biplot ordination of algae and key environmental variables (summary of Fig. A3.1a & b). Algal genera are: Anaba=*Anabaena*, Micro=*Microcystis*, Navic=*Navicula*, Sperm=*Spermatozopsis*, Eugle=*Euglena*, Mallo=*Mallomonas*, Synur=*Synura*, Stich=*Stichococcus*, Cruci=*Crucigena*, Scene=*Scenedesmus*, Melos=*Melosira*, Cyclo=*Cyclotella* and Chlel=*Chlorella*. Environmental variables are: TP=Total Phosphorus, Si=Silicon, stabE4=stability, TNE3=Total Inorganic Nitrogen, DO=%Dissolved Oxygen, cond=conductivity, Inflowa=inflow and temp=temperature.

INTERPRETATION OF FIGURE A3.2

This figure illustrates the joint variation of key environmental variables along with algae which had a reasonable proportion of their variability explained by the supplied environmental variables. Note the length of the environmental arrows indicating their importance, rate and direction of change in explaining observed algal variability. Of these variables silica, total nitrogen, temperature, inflow and secchi are important (relatively long arrows). The angle subtended by arrows indicates the degree of correlation between variables e.g. temp and inflow are positively correlated, TP and secchi negatively correlated (on different sides of the origin) whilst temp and silicon (or total inorganic nitrogen) are not correlated. Higher temperature and inflow favour the blue-green algae *Anabaena* and *Microcystis* whilst the opposite set of conditions favour *Stichococcus*, *Mallomonas*, *Euglena* and *Spermatozopsis*. High total inorganic nitrogen and silicon tends to favour *Navicula*, *Stichococcus*, *Mallomonas*, *Euglena* and *Spermatozopsis*, whilst low readings for these variables favours *Cyclotella*, *Melosira* and *Scenedesmus*. Clear water with a high secchi and generally low TP favours *Crucigena*.

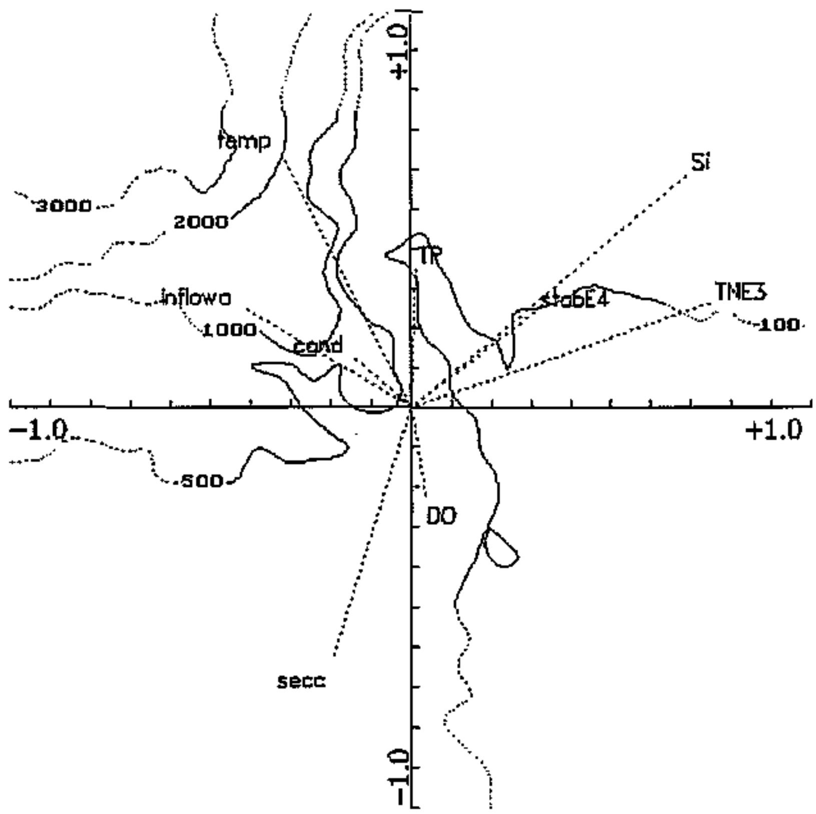

Figure A3.3 Inflow (Mℓ/day) trend data fitted to the ordination of sites from all seven lakes.

Interpretation of Figure A3.3 (to be read in conjunction with Fig. A3.2)

This figure illustrates the trend of inflow data over all the sites underlying this ordination. Clearly inflow is highest in the top left quadrant of the ordination diagram. This corresponds with that grouping of lake sites sites having a large proportional abundance of the blue-green algae *Anabaena* and *Microcystis*. Optimal inflow conditions favouring these algae appear to be >1000Mℓ/day. Lowest flows (<500Mℓ/day) are in the bottom right quadrant of the ordination figure.

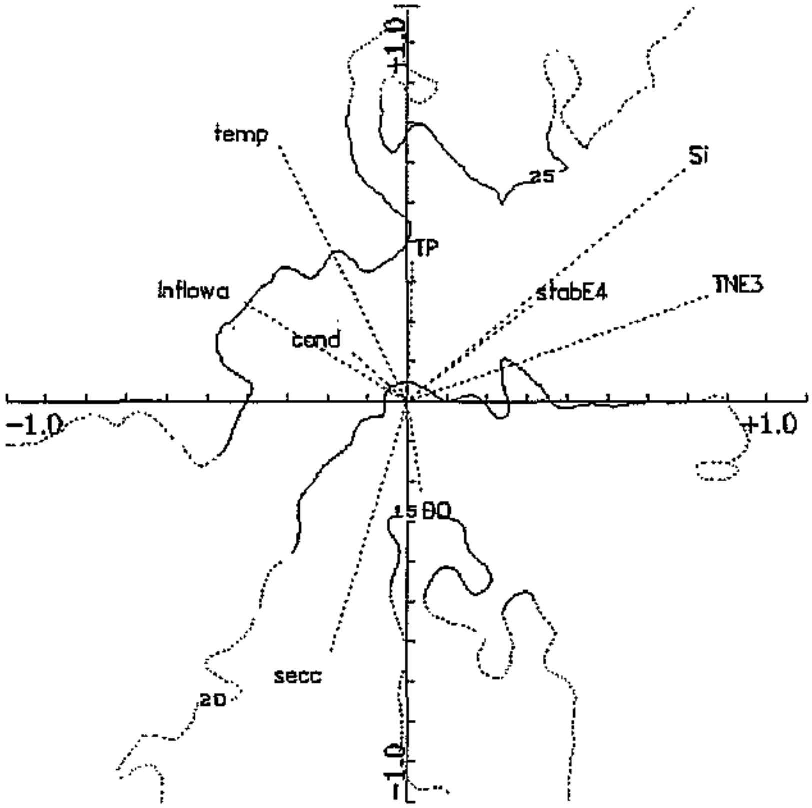

Figure A3.4 Temperature (°C) trend data fitted to the ordination of sites from all seven lakes.

Interpretation of Figure A3.4 (to be interpreted in conjunction with Fig. A3.2)

This figure illustrates the trend of temperature data over all the sites underlying this ordination. Clearly temperature is highest in the top left quadrant of the ordination diagram. This corresponds with that grouping of lake sites having a large proportional abundance of the blue-green algae *Anabaena* and *Microcystis*. Optimal temperature conditions favouring these algae appear to be >20°C. *Melosira, Cyclotella* and *Scenedesmus* appear to favour temperatures between 20° and 25°C whilst *Spermatozopsis, Euglena, Synura, Stichococcus* and *Mallomonas* favour temperatures <20°C.

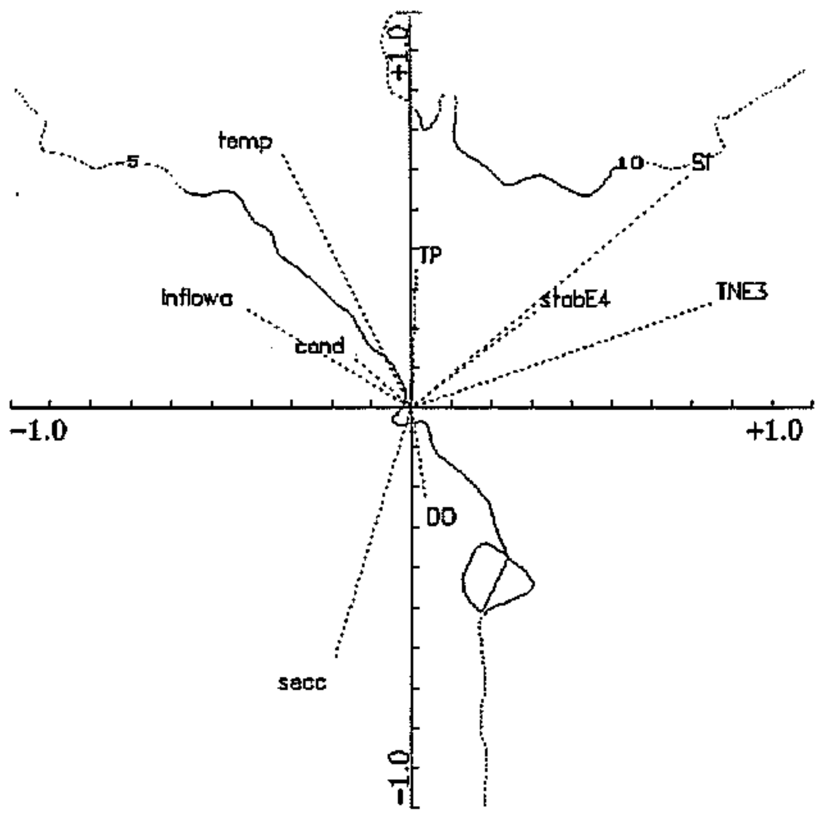

Figure A3.5 Silicon (mg/ℓ) trend data fitted to the ordination of sites from all seven lakes.

Interpretation of Figure A3.5 (to be read in conjunction with Fig. A3.2)

This figure illustrates the trend of silica data over all the sites underlying this ordination. Clearly silicon concentration is highest in the top right quadrant of the ordination diagram whilst lowest in the bottom left quadrant. *Melosira, Cyclotella, Crucigena, Microcystis, Anabaena* and *Scenedesmus* appear to favour silicon concentrations <5mg/ℓ.

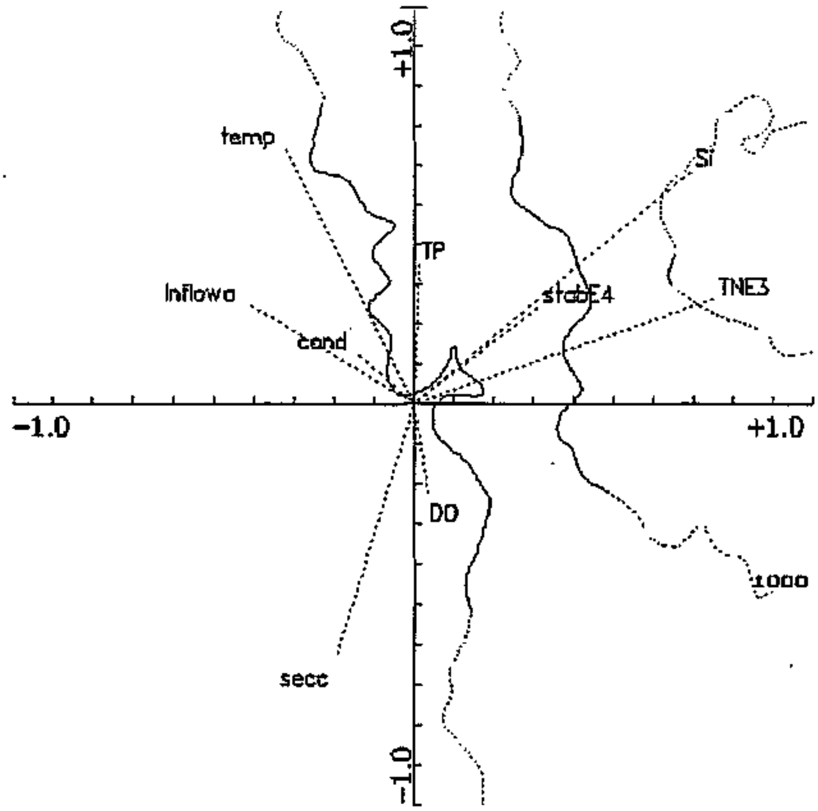

Figure A3.6 Total inorganic nitrogen (TNE3 mg/ℓ) trend data fitted to the ordination of sites from all seven lakes. Note contours (at 500, 1000 & 1500) on this ordination multiplied by a factor of 1000 i.e. 1000 contour = 1mg/ℓ N.

Interpretation of Figure A3.6 (to be read in conjunction with Fig. A3.2)

This figure illustrates the trend of total nitrogen data over all the sites underlying this ordination. Clearly total inorganic nitrogen concentration is highest in the top right quadrant of the ordination diagram whilst lowest in the bottom left quadrant. *Melosira, Cyclotella, Crucigena, Microcystis, Anabaena* and *Scenedesmus* appear to favour total inorganic nitrogen concentrations <0.5mg/ℓ.

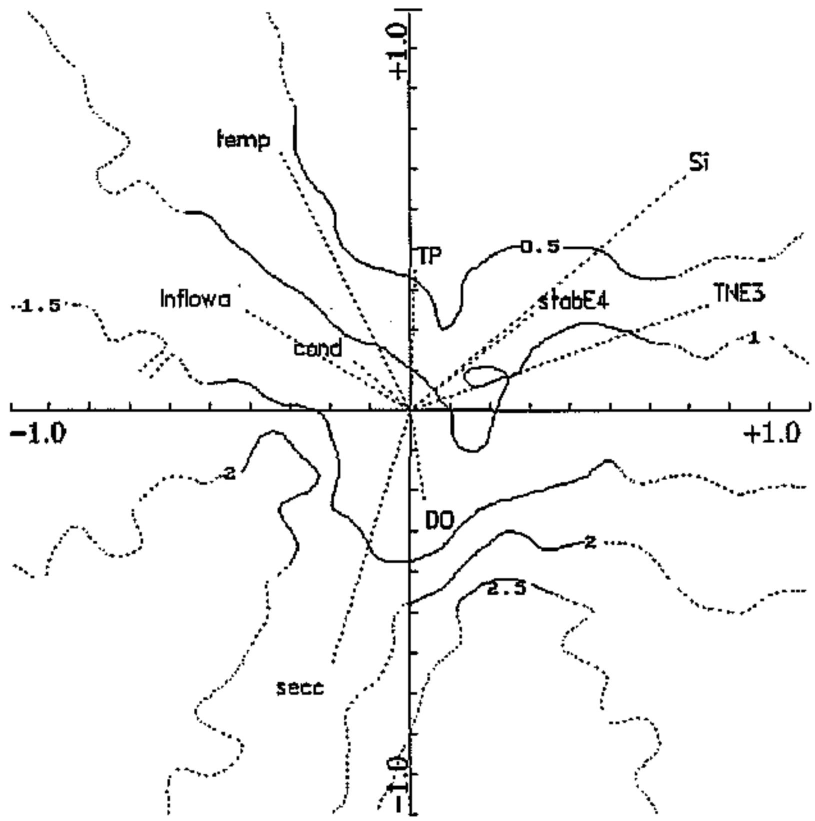

Figure A3.7 Secchi depth (metres) trend data fitted to the ordination of sites from all seven lakes.

Interpretation of Figure A3.7 (to be read in conjunction with Fig. A3.2)

This figure illustrates the trend of secchi depth data over all the sites underlying this ordination. Clearly sites in the lower half of the ordination diagram have clearer water (high secchi i.e. >1.5m). Clearer water appears to favour *Melosira*, *Cyclotella*, *Scenedesmus*, *Stichococcus* and particularly *Crucigena*. Moderately turbid water (secchi 1 to 1.5m) appears to favour the important blue-green algae.

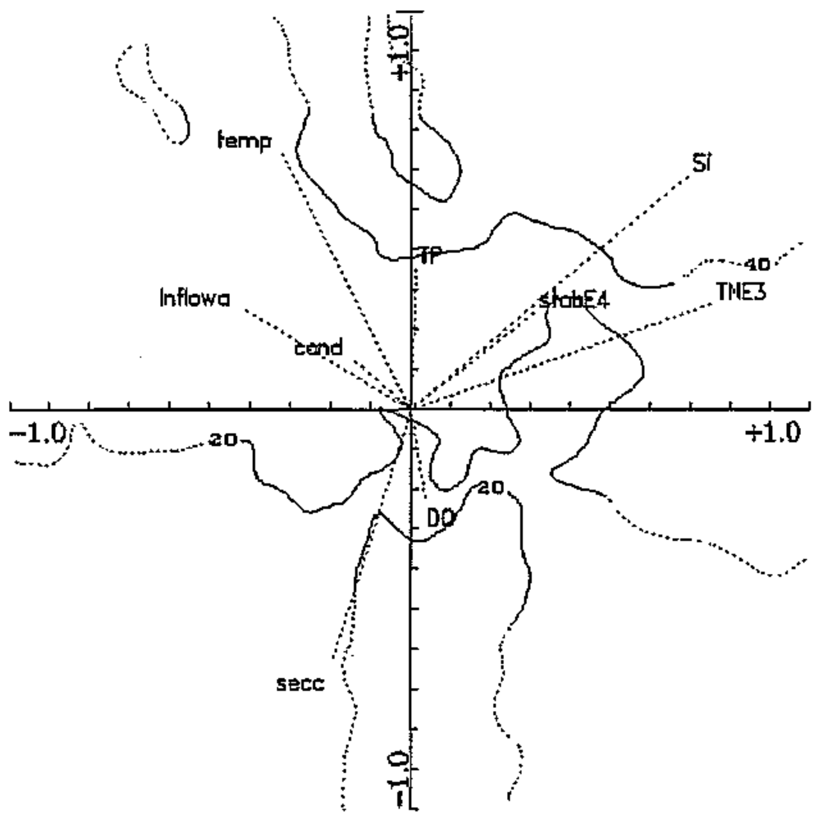

Figure A3.8 Total phosphorus (ug/ℓ) trend data fitted to the ordination of sites from all seven lakes.

Interpretation of Figure A3.8 (to be read in conjunction with Fig. A3.2)

This figure illustrates the trend of total phosphorus data over all the sites underlying this ordination. Clearly TP concentration is highest in the top half of the ordination diagram whilst lowest in the bottom half. An increase in TP (i.e. between 20 to 40 ug/ℓ) favours the blue-green algae whilst most other algae appear to prefer TP concentrations <20 ug/ℓ.

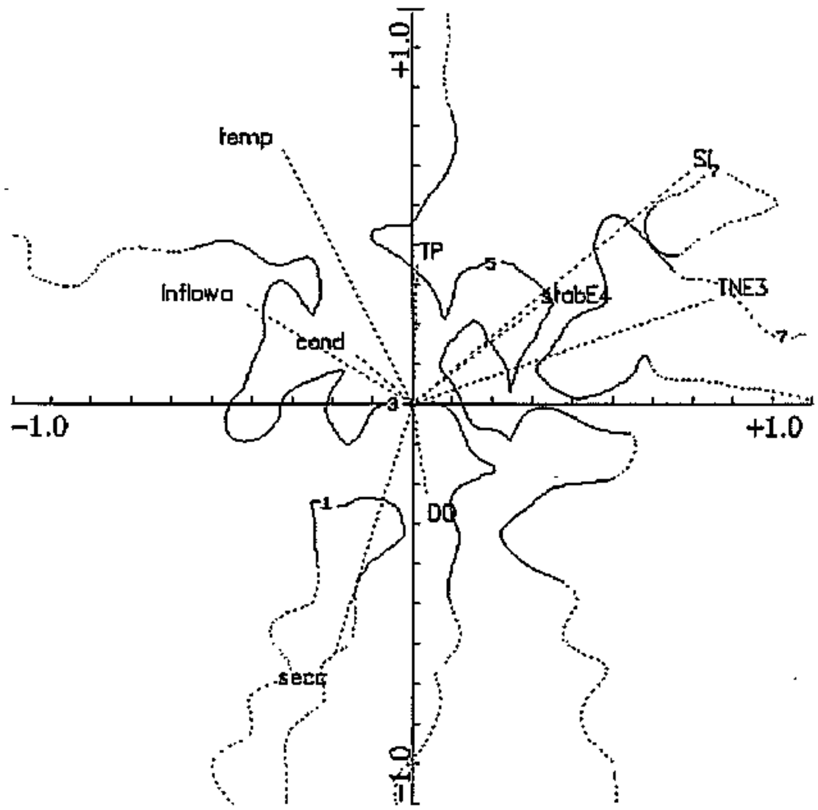

Figure A3.9 Stability (s^{-2}) trend data fitted to the ordination of sites from all seven lakes.

Interpretation of Figure A3.9 (to be read in conjunction with Fig. A3.2)

This figure illustrates the water column stability trend over all the sites underlying this ordination. Sites in the upper right quadrant generally have more stable water column conditions whilst those sites in the lower left quadrant are more unstable. Low column stability appears to particularly favour *Crucigena* and to a lesser extent *Cyclotella*, *Melosira* and *Scenedesmus*. Moderate stability favours most other algal genera.

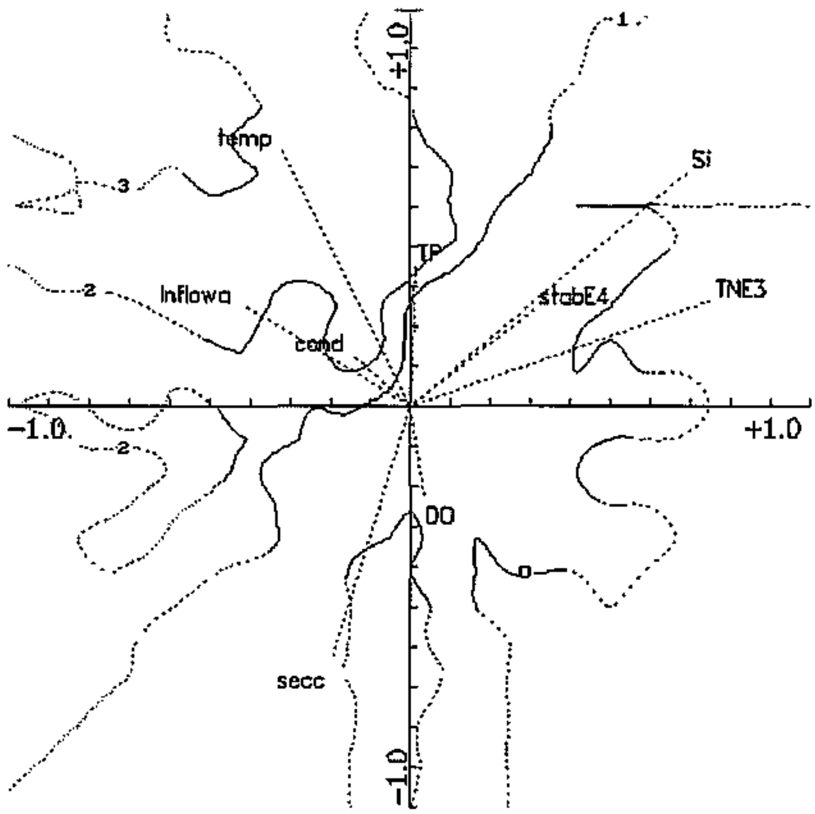

Figure A3.10 Trends of *Anabaena* counts (log data) fitted to the ordination of sites from all seven lakes.

Interpretation of Figure A3.10 (to be read in conjunction with Fig. A3.2)

This figure illustrates the change in log abundance data of *Anabaena* over all the sites underlying this ordination. Sites in the upper left quadrant generally have high counts (100 to 1000 cells/mℓ) for this genus whilst those sites in the lower right quadrant have low counts (<1 cell/mℓ).

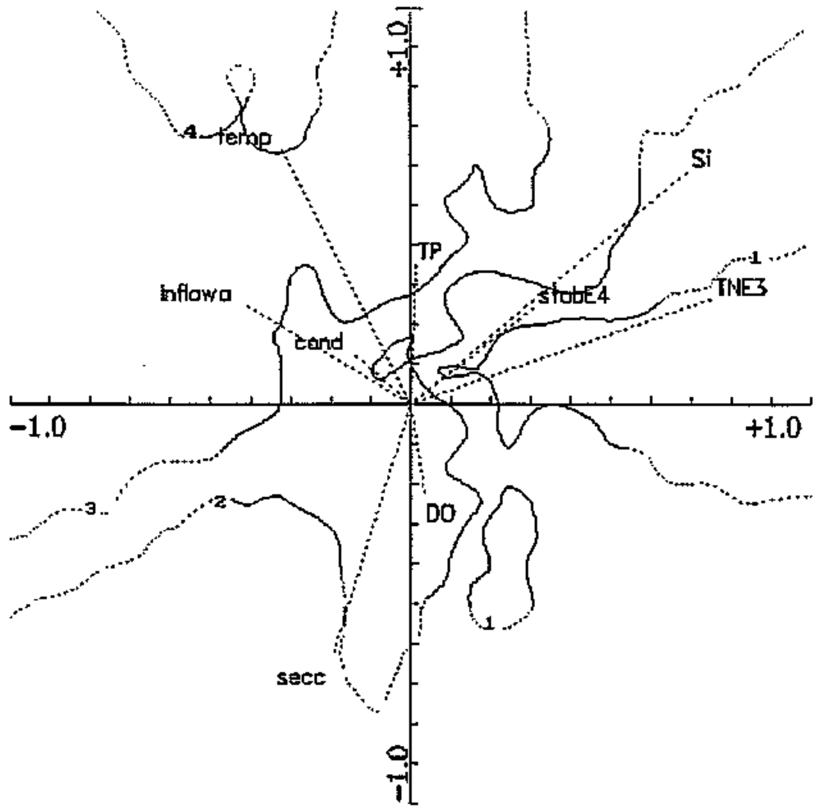

Figure A3.11 Trends of *Microcystis* counts (log data) fitted to the ordination of sites from all seven lakes.

Interpretation of Figure A3.11 (to be read in conjunction with Fig. A3.2)

This figure illustrates the change in log abundance data of *Microcystis* over all the sites underlying this ordination. Sites in the upper left quadrant generally have high counts (1000 to 10 000 cells/mℓ) for this genus whilst those sites in the lower right quadrant have low counts (<10 cells/mℓ).

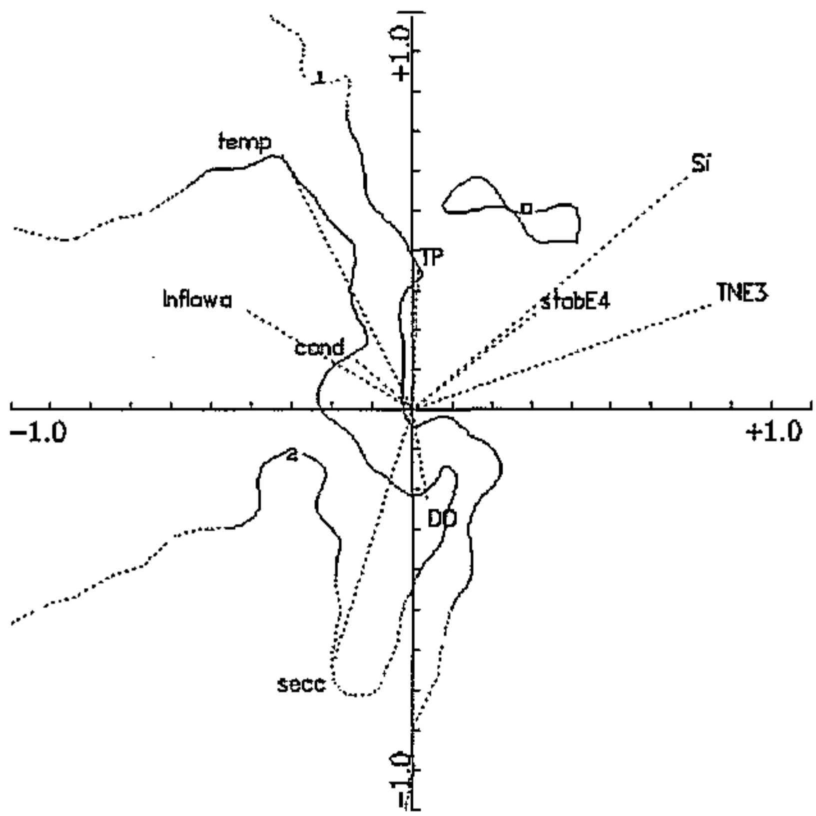

Figure A3.12 Trends of *Melosira* counts (log data) fitted to the ordination of sites from all seven lakes.

Interpretation of Figure A3.12 (to be read in conjunction with Fig. A3.2)

This figure illustrates the change in log abundance data of *Melosira* over all the sites underlying this ordination. Sites in the lower left quadrant generally have relatively high counts (>100 cells/mℓ) for this genus whilst those sites in the upper right quadrant have low counts (<1 cells/mℓ).

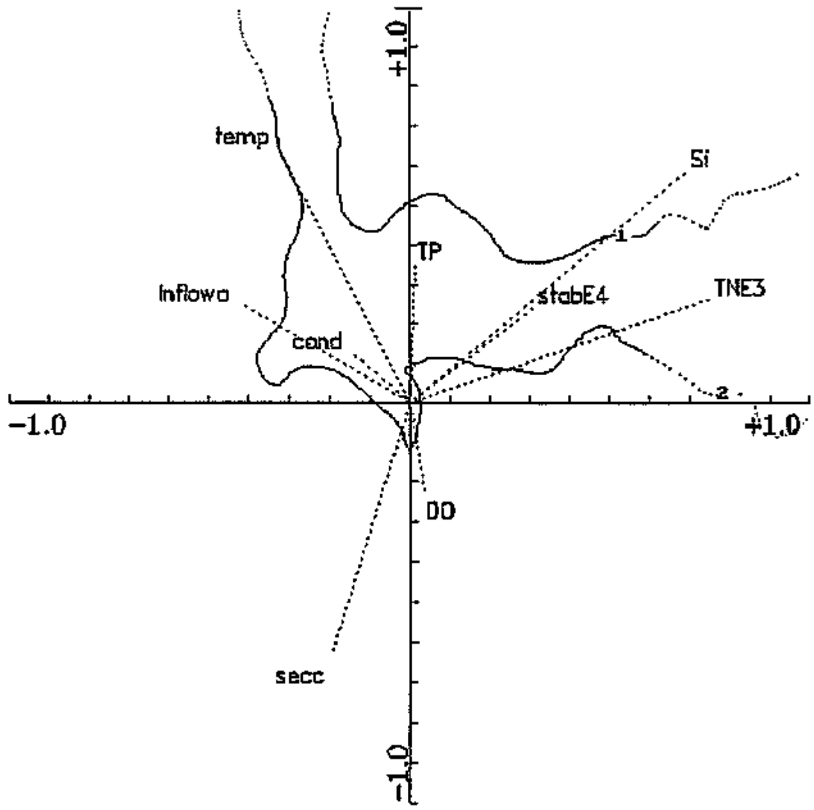

Figure A3.13 Trends of *Crucigena* counts (log data) fitted to the ordination of sites from all seven lakes.

Interpretation of Figure A3.13 (to be read in conjunction with Fig. A3.2)

This figure illustrates the change in log abundance data of *Crucigena* over all the sites underlying this ordination. Sites in the lower left quadrant generally have relatively high counts (>100 cells/mℓ) for this genus whilst those sites in the upper right quadrant have low counts (<1 cells/mℓ).

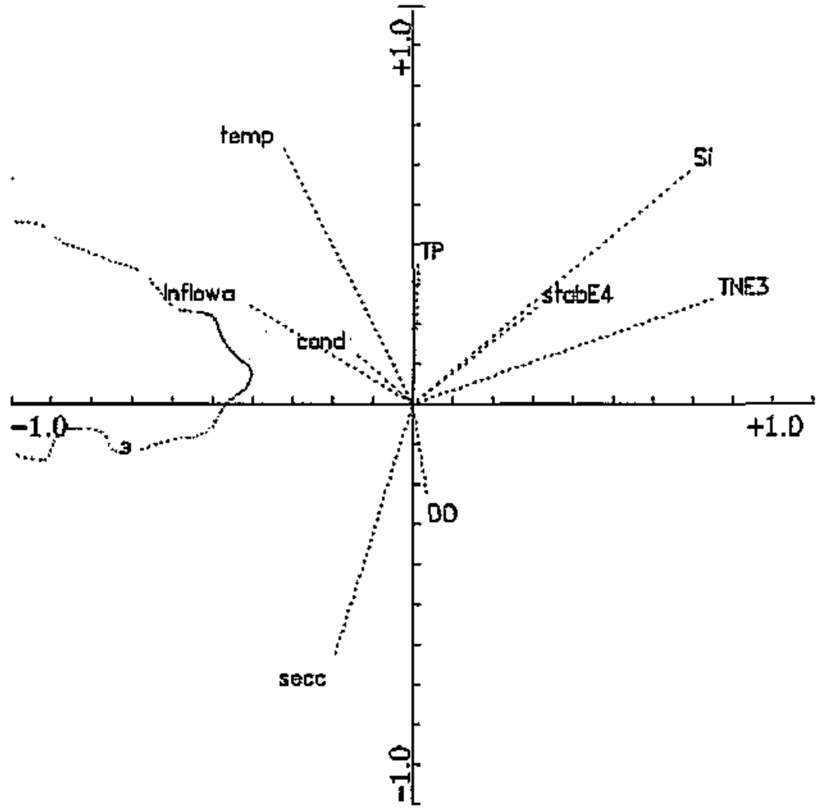

Figure A3.14 Trends of *Chlorella* counts (log data) fitted to the ordination of sites from all seven lakes.

Interpretation of Figure A3.14 (to be read in conjunction with Fig. A3.2)

This figure illustrates the change in log abundance data of *Chlorella* over all the sites underlying this ordination. As noted in the analyses this genus did not vary much across the sites and if anything tended to most dominant in sites on the extreme left of the ordination diagram.

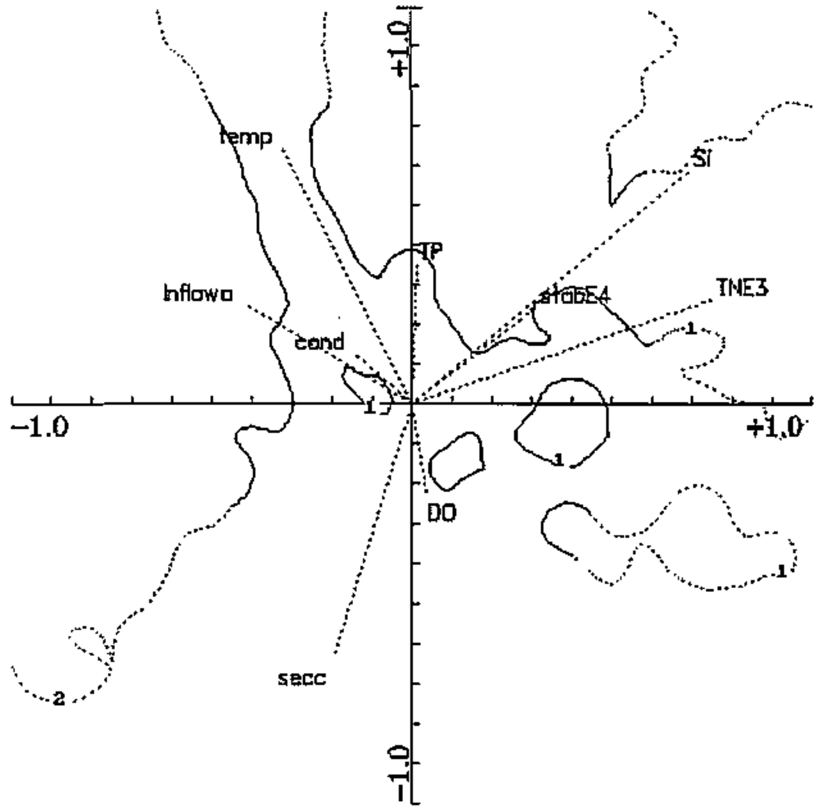

Figure A3.15 Trends of *Scenedesmus* counts (log data) fitted to the ordination of sites from all seven lakes.

Interpretation of Figure A3.15 (to be read in conjunction with Fig. A3.2)

This figure illustrates the change in log abundance data of *Scenedesmus* over all the sites underlying this ordination. Sites in the extreme left of the ordination have relatively high counts (>100 cells/mℓ) for this genus whilst those sites in the right have low counts (<1 cells/mℓ).

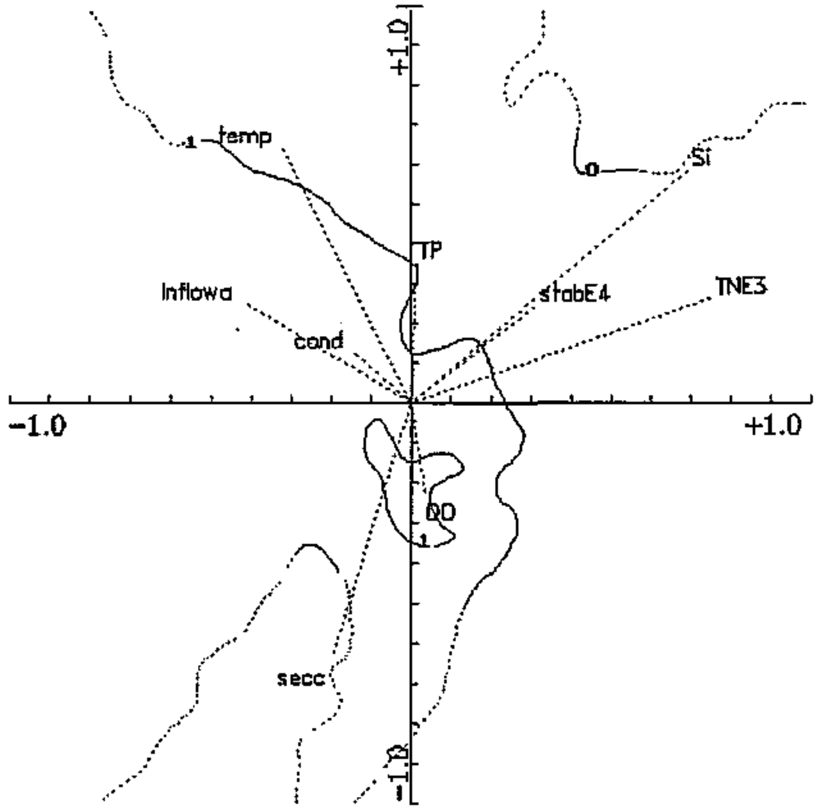

Figure A3.16 Trends of *Cyclotella* counts (log data) fitted to the ordination of sites from all seven lakes.

Interpretation of Figure A3.16 (to be read in conjunction with Fig. A3.2)

This figure illustrates the change in log abundance data of *Cyclotella* over all the sites underlying this ordination. Generally if this genus occurred it was only in low abundance. Sites in the extreme left of the ordination have relatively high counts (>10 cells/mℓ) for this genus whilst those sites in the right have low counts (<1 cells/mℓ).

A3.3.2.1 Discussion of results from the kriging of key environmental variables and algae.

Of the algal genera apparently responding to these environmental gradients (Fig 3.1a&b and Fig. 3.2) *Anabaena* and *Microcystis* (blue-green algae) were most abundant (100-1000 and 1000-10 000 cells/mℓ respectively) at the higher temperatures (20-25°C), inflows (>1000Mℓ/day) and conductivities that one would expect with summer conditions whilst favouring lower silicon (Si <5mg/ℓ) and total inorganic nitrogen (TN <1mgN/ℓ) values. Conversely *Navicula, Spermatozopsis* and *Mallomonas* were responding to relatively higher Si (>5mg/ℓ) and TN (>1mgN/ℓ). Cooler (<20°C), clear waters (secchi >1.5m) with low total phosphorus (<20μg/ℓ) favour *Crucigena* whilst waters generally low in TN (<0.5mgN/ℓ) and Si (<5mg/ℓ) have *Melosira, Scenedesmus, Cyclotella* and *Tetraedron* predominating. These waters are also generally clear (higher secchi) and have lower water column stability. Reynolds & Walsby (1975) note that conditions of stable stratification selects against diatoms and non-motile green algae. In this study it was found that low water column stability favoured the potentially important filter clogging diatoms *Melosira* and *Cyclotella* and non-motile green algae *Scenedesmus* and *Tetraedron* (Belcher & Swale 1979). These latter two genera are not particularly important from a filter clogging point of view although *Scenedesmus* has been implicated in taste and odour formation in some waters (Palmer 1959).

Unfortunately not much may said about *Chlorella*, a dominant or sub-dominant species in many lakes (Fig. 2.1 proportional composition figures for lakes), as its variability is not well explained by the measured environmental variables.

Although discussed earlier in this report the relevance and interpretation of 'inflow' probably bears some consideration here as it appeared to be such an important variable explaining algal variability. During the analysis of purely environmental data (on the seven lakes excluding Shongweni) all the nutrient loadings (i.e. total phosphorus, soluble reactive phosphorus and total nitrogen) came out strongly together at the one end the fourth principal component or environmental axis (Table A2.5 - PC axes loadings). This indicates that some common environmental parameter was underlying the variability of the nutrient loads. This was obviously 'inflow' volumes into the lakes, discussed in more detail in (§A1.4.2.3).

In the same way as nutrient loads were identified as being strongly correlated with each other at the end of the 4th PC axis (Appendix 2, Table A2.5, - PC axes loadings), total inorganic nitrogen (TN) was identified as being strongly and positively correlated with the TN:TP ratio at the end of the 3rd PC axis (Table A2.5 - PC axes loadings). The implications of this are that they represent similar aspects of variation in the environmental data set identified by the third PC axis. Because of this relationship the low end of the total inorganic nitrogen axis corresponds with a generally low TN:TP ratio. The blue-green algae *Microcystis* and *Anabaena* appear to favour this low end of the TN/TN:TP gradient. Figure A3.17 provides some descriptive statistics for this ratio over the respective lakes. Clearly some lakes had generally higher TN:TP ratios than others. The observed ranking of the lakes according to these ratios (from high to low median values) was as follows: Nungwane, Henley, Inanda, Hazelmere, Midmar, Albert Falls, Nagle and Shongweni. Shongweni was included in this figure to represent the extreme end of the eutrophication gradient with its associated blue-green dominated algal communities (identified in Appendix 2).

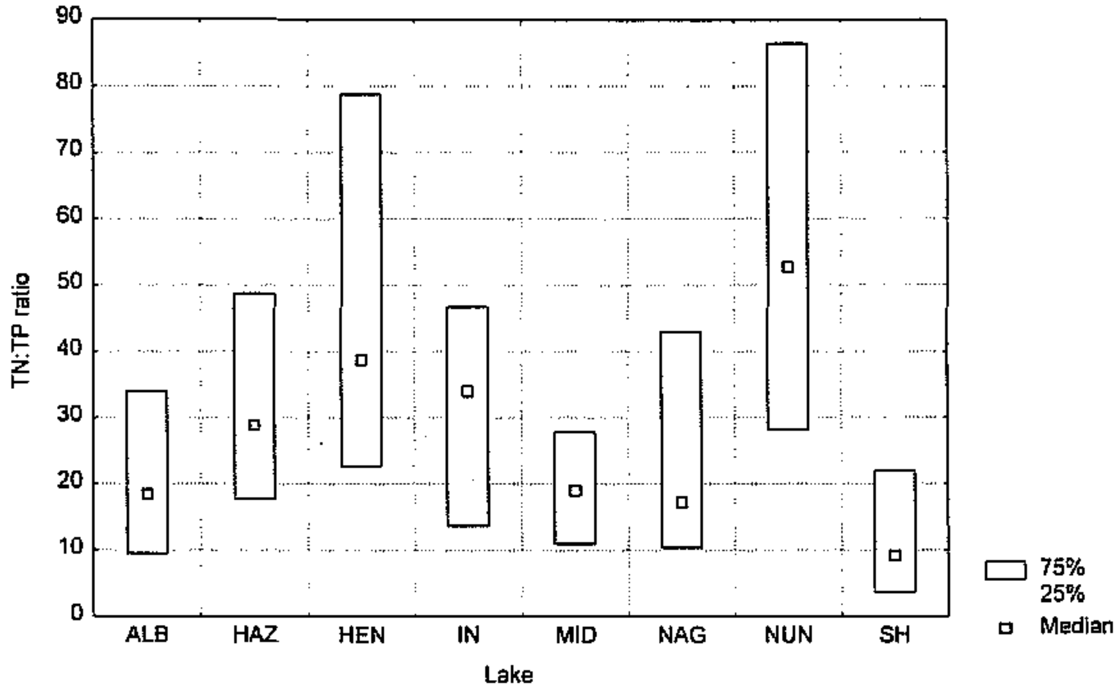

Figure A3.17 Summary statistics for the Total Inorganic Nitrogen/Total Phosphorus (TN:TP) ratios in all lakes studied. Note Shongweni (as an example of high eutrophication (§ A2.2)) is included in this figure for comparative purposes.

The passively plotted lakes, discussed below (§ 4.3.2.2), also reflected how Nagle and to a lessor degree Midmar and Albert Falls were at the low end of the total inorganic nitrogen (TN:TP) gradient (median values < 20). The figure indicating the proportional composition of the different types of algae in the respective lakes (Fig. 2.1 - proportional composition) shows the importance this TN:TP ratio appears to have with occurrence of the blue-green algae *Anabaena* and particularly *Microcystis*. All the lakes with a low TN:TP ratio had a composition proportionally high in these algae. Midmar was an apparent anomaly and hence interesting in this respect as its TN:TP ratio indicates its potential to have blue-green algae problems. Its ambient water temperatures (another important variable explaining the variability of the blue-greens) probably prevent these algae from becoming too dominant and hence problematic however. The literature supports this finding i.e. that blue-green algae favour low TN:TP ratios (e.g. Smith 1983; Jensen *et al.* 1994).

Lakes Henley and Nungwane, with low proportions and abundance of blue-green algae (Figs. 2.1 & 2.2) were at the high TN:TP ratio end of the axis. Their algal composition was dominated by green algae with the literature generally supporting this observation i.e. green algae favouring higher TN:TP ratios compared to blue-green algae (e.g. Jensen *et al.* 1994).

A3.3.2.2 Discussion of results from passively ordinated spatial (lakes) and temporal (months) effects in the analysis of 'key' environmental variables and algae.

To reiterate, 'passive' plotting of variables was to examine the relationship of these variables (passives) to the algae and the environmental variables that had been 'actively' used in deriving 'restricted' ordinations or relationships of interest - be they algae/environmental (§ A3.3), algae/spatial (§ A3.4) or algal/temporal (§ A3.5) effects which were respectively under focus. This provided information about the possible relationship that passive variables may have with a particular relationship being examined, but without restricting that particular analysis with their inclusion. The following discussion of results from the analysis of key environmental variables and algae illustrates the utility of plotting passive variables.

Plotting lakes (spatial effects) and season (temporal effects) as 'passives' (Fig. 4.1c) reveals that the variability among species, as described by the key environmental variables, is more closely related to variation among lakes than seasonal or yearly differences (distance respective centroids are away from the origin). Hazelmere (Fig.A3.1c), in the early part of the summer rainy season (September to December), is dominated by high silica and total nitrogen and low secchi (high turbidity). The algal variability observed in Henley and Nungwane appears to be related to relatively high silicon and total inorganic nitrogen and correspondingly low temperatures and inflow volumes associated with spring (August to September). Having just come through the winter, where water temperatures and inflows are at their lowest (the area having a summer rainfall pattern), this would be a reasonable explanation for this observed pattern. Lakes Inanda and Nagle on the other hand appear to have higher temperatures and inflows and lower silicon and total inorganic nitrogen dominating their algal distribution and hence ordination, particularly during late summer period from January through to April.

Further interpretation and a summary of these algal results is presented in Chapter 6.

A3.4 Lake unique effects and their effect on algal populations

A3.4.1 Introduction

The unique difference between lakes, and how these may be influencing the different types and abundance of algae present there were then examined. This was to determine if there were significant effects uniquely associated with the different lakes in the study. It would also determine if there were processes occurring in these lakes which had not been accounted for in the environmental parameters measured for this project (§A3.3 – 'key' environmental analysis).

The mean seasonal (month) effects/trends were removed as co-variables with environmental variables overlain as passive variables (Ch. 3 - Analytical methods). The rationale for the plotting of passive variables was as described earlier. This time, with passive plotting of environmental parameters, the key focus was on the spatial differences between lakes and how, in an unrestricted manner, environmental effects may be related to these spatial differences.

A3.4.2 Results and Discussion

Results are reported in Table A3.4 and Figure A3.18.

Table A3.4 Key results from analyses where the lake unique effects of lakes were related to algae in all lakes except for Shongweni

Axes	1	2	3	4	Total variance
Eigenvalues	0.09	0.05	0.02	0.01	1.00
Algae-environment correlations	0.77	0.67	0.61	0.43	
Cumulative % variance					
of algal data.	10.1	15.3	17.1	18.0	
of algae-env. relation	53.1	79.9	89.5	94.5	
Sum of all unconstrained eigen values					0.92
(after fitting covariables)					
Sum of all canonical eigenvalues					0.18
(after fitting covariables)					
Algal variability explained by analysis					17.6%

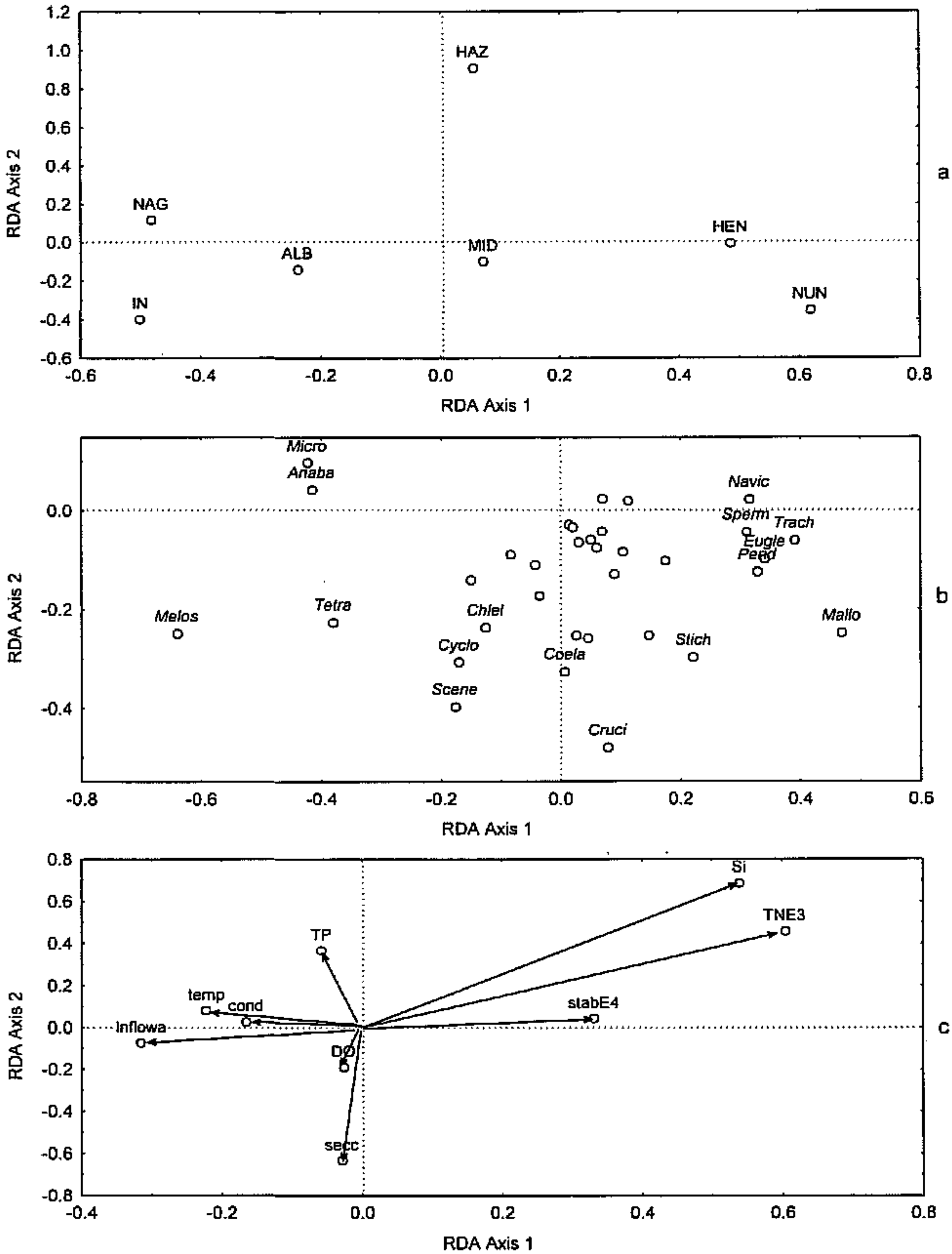

Figure A3.18 Ordinations where the effects unique to lakes, and how these were influencing algae, were the focus of interest (a). Environmental variables plotted as passives (c). Genera with >10% of their variation explained by the analysis plotted and labelled (b). Abbreviations as per Tables 2.1 & 2.4 and interpretations of the figures as detailed in § A3.2.2.

Key findings here were that eigen-values and algae/environment correlations were marginally greater in this analysis than in the previous one where only key environmental variables were related to algal variability (Table A3.3 vs. Table A3.1). The implication of this is that effects unique to different lakes are slightly better able to describe the variability observed in the algal populations than the key environmental variables alone. Therefore some other factors or effects, which vary amongst lakes and which were either not included in the reduced 'key' environmental data set or are unmonitored, must be affecting algal composition. Further interpretation of the data (§4.4.5 - passive plotting of PCA axes) indicates that this un-quantified effect is probably due to unmonitored environmental variables. The analysis with the key environmental data at least goes part of the way in providing explanation for some of the observed algal variability.

On the basis of its algal composition, and how this is related to spatial differences between lakes, Hazelmere again appears distinctly different from all other lakes (Fig A3.18a), ordinated as it is at the extreme end of the second axis. This difference appears primarily associated with higher turbidities (low secchi Fig. 4.18c). Lakes Hazelmere, Nungwane and Inanda (and to a lesser extent Nagle) are all at the extreme edges of the ordination (Fig. A3.18a) illustrating their relative differences. Given that they are all on entirely different river systems (except Nagle and Inanda on the Mgeni River) with different water physico-chemistry this is not surprising.

There is an interesting trend in lakes from generally upper catchment (Henley), down the Mgeni system sequentially to the coastal lakes (Inanda, Fig. A3.18a). Nungwane is an apparent anomaly in this trend as it is generally classifed as a 'coastal' lake but is positioned at the upper end of ***its*** catchment. From its relative positioning on the ordination diagram (Fig. A3.18a) it appears to have a greater affinity to the upper catchment.

Catchment position would, therefore, appear to play a more important role on observed algae in the lakes than does proximity to the coast.

A3.4.3 Discussion of results from passively ordinated key environmental variables

Passive plotting of environmental variables over this data indicates that the observed trend/difference between lakes with progression down the catchment may be associated with factors associated with increasing inflow, temperature and conductivity approaching the lower catchment on the Mgeni system with parallel decreases in stability and lowered silicon and total nitrogen values. This response of lakes was similar to that noted where environmental variables were the key variables of interest and lakes had been plotted as passive variables. Again Henley and Nungwane are characterised by higher stabilities, silicon and total inorganic nitrogen and lower inflows and temperatures whilst the lower Mgeni River lakes (Nagle and Inanda) are characterised by the opposite set of conditions. It should be noted however that the analysis does point to there being some 'unmonitored' factors that also account for differences between lakes.

Silicon and total nitrogen concentrations (long arrows on the first axis of Fig A3.18c) appear to be the most important variables associated with the observed spatial differences among the lakes (Fig. A3.18a) - particularly Henley and Nungwane compared to all the other Mgeni system lakes. This implies that these two environmental variables are important in distinguishing between these two groups (Henley and Nungwane and all others). They also appear to have more stable water column conditions compared to the other lakes. This may be affected by local wind conditions and certainly Henley is acknowledged to be a sheltered lake situated as it is in hills above Pietermaritzburg (Walmsley & Butty 1980).

The warmer conditions in lakes at the lower end of the Mgeni River system (Inanda and Nagle) appear to produce less stable water column conditions. Prevailing and strong winds may be a possible explanation for the reduced stability in these lakes. Unfortunately no measure combining duration, direction and speed of wind was available or could be derived to verify this hypothesis.

The algal distribution on the ordination (Fig A3.18b) (and relation to passively plotted environmental variables) is not markedly different from that observed in the previous analysis examining algae and restricted environmental effects (§ A3.3).

Algal genera with a significant proportion (>10%) of their variance explained by the spatial effects associated with the different lakes are indicated in Table A3.5. As with the previous analysis, *Melosira* again has a significant proportion of its variance explained by the spatial effects associated with different lakes. Figures 2.1 (proportional composition) and 2.3 (abundance) indicate that this genus is only really in appreciable numbers and proportionally abundant in Lakes Midmar, Albert Falls, Nagle and Inanda. This genus is potentially problematic to the water industry, where it can reduce filter runs, and therefore appears to be most significant on the Mgeni system lakes. *Navicula, Euglena, Spermatozopsis, Trachelomonas, Peridinium* and *Mallomonas* appear to be restricted to Henley and Nungwane. Their abundance (Tables 2.3 & 2.4) and relative proportion (Fig. 2.1) in these lakes is never significantly high from a water treatment point of view however.

Table A3.5 Ranked algal responses (in terms of variance explained) to lake unique effects (only genera with >10% variance explained shown)

Genera	Cumultive % variance explained
Melosira	54.42
Mallomonas	32.58
Peridinium	26.46
Tetraedron	26.13
Crucigenia	25.72
Scenedesmus	23.66
Anabaena	22.92
Stichococcus	22.22
Microcysits	19.48
Spermatozopsis	18.57
Trachelomonas	18.12
Coelastrum	15.17
Euglena	15.12
Cyclotella	14.86
Navicula	10.67
Chlorella	10.65

A3.4.4 Passive plotting of PCA axes

It was identified that some other factors or effects (other than measured key environmental variables), which vary amongst lakes, must be affecting algal composition. Indications from Table A3.6 (correlations of passively plotted PCA axes) are that including further key environmental variables from the original data set, or using the original PCAs will not help identify these unknown factors. The first five PCs (with associated key environmental variables with high loadings on respective axes, Appendix 2, Table A2.5), when passively overlain onto the algal data in RDA, are the only axes to show a reasonably strong co-relation with observed algal variability. The implication of this is that further axes (with associated environmental variables with high loadings on these axes) will not add significantly to the explanation of algal variability.

Table A3.6 Correlation of passively plotted PCA axes with species axes in analyses where lake differences and seasonal trends were removed. Note only the first 5 PCA's have a reasonable association with lake differences (especially PC_2 and PC_3 - turbidity/secchi and N&P gradients respectively).

	SPEC AX1	SPEC AX2	SPEC AX3	SPEC AX4
PC_1	**-.2238**	-.0176	-.1049	.2001
PC_2	**.3280**	**.5775**	.0235	-.0083
PC_3	**-.3417**	.0722	.2061	.0065
PC_4	**-.2253**	.0873	-.1791	-.0301
PC_5	**-.2200**	.1580	-.0040	.0453
PC_6	-.1448	.0487	.0833	-.0075
PC_7	-.0462	.1378	.1254	-.0743
PC_8	-.0751	-.0172	-.0354	-.0478
PC_9	.0895	-.1954	-.0806	-.0859
PC_{10}	-.0184	-.1512	-.1064	-.0257
PC_{11}	.0826	-.0531	.1351	.0306
PC_{12}	.1699	-.0912	.2028	-.0098
PC_{13}	-.0416	.0169	-.0143	-.1543
PC_{14}	-.0662	.0748	.0911	-.0527
PC_{15}	.0991	-.1044	-.0327	-.1059

A3.5 Seasonal effects on algal populations

A3.5.1 Introduction

Seasonal trends (both within the year, i.e. on a monthly basis, and annually i.e. over the duration of the study) were then examined to determine if these were significantly affecting algal populations in the study lakes. Again RDA was used to establish this relationship. The mean spatial effects/trends of individual lakes were removed as co-variables with environmental variables overlain as passive variables (see § A3.3.2.2 - Discussion of results from passively ordinated spatial (lakes) and temporal (months) effects in the analysis of 'key' environmental variables and algae).

A3.5.2 Results and discussion

Results are reported in Table A3.7 and Figures A3.19

Table A3.7 Key results from analyses where the temporal effects of months were related to algae in all lakes except for Shongweni

Axes	1	2	3	4	Total variance
Eigenvalues	0.03	0.02	0.01	0.01	1.00
Algae-environment correlations	0.56	0.55	0.55	0.41	
Cumulative % variance					
of algal data.	3.3	5.7	7.0	7.6	
of algae-env. relation	35.7	61.7	76.1	83.4	
Sum of all unconstrained eigen values (after fitting covariables)					0.82
Sum of all canonical eigenvalues (after fitting covariables)					0.08
Algal variability explained by analysis					7.5%

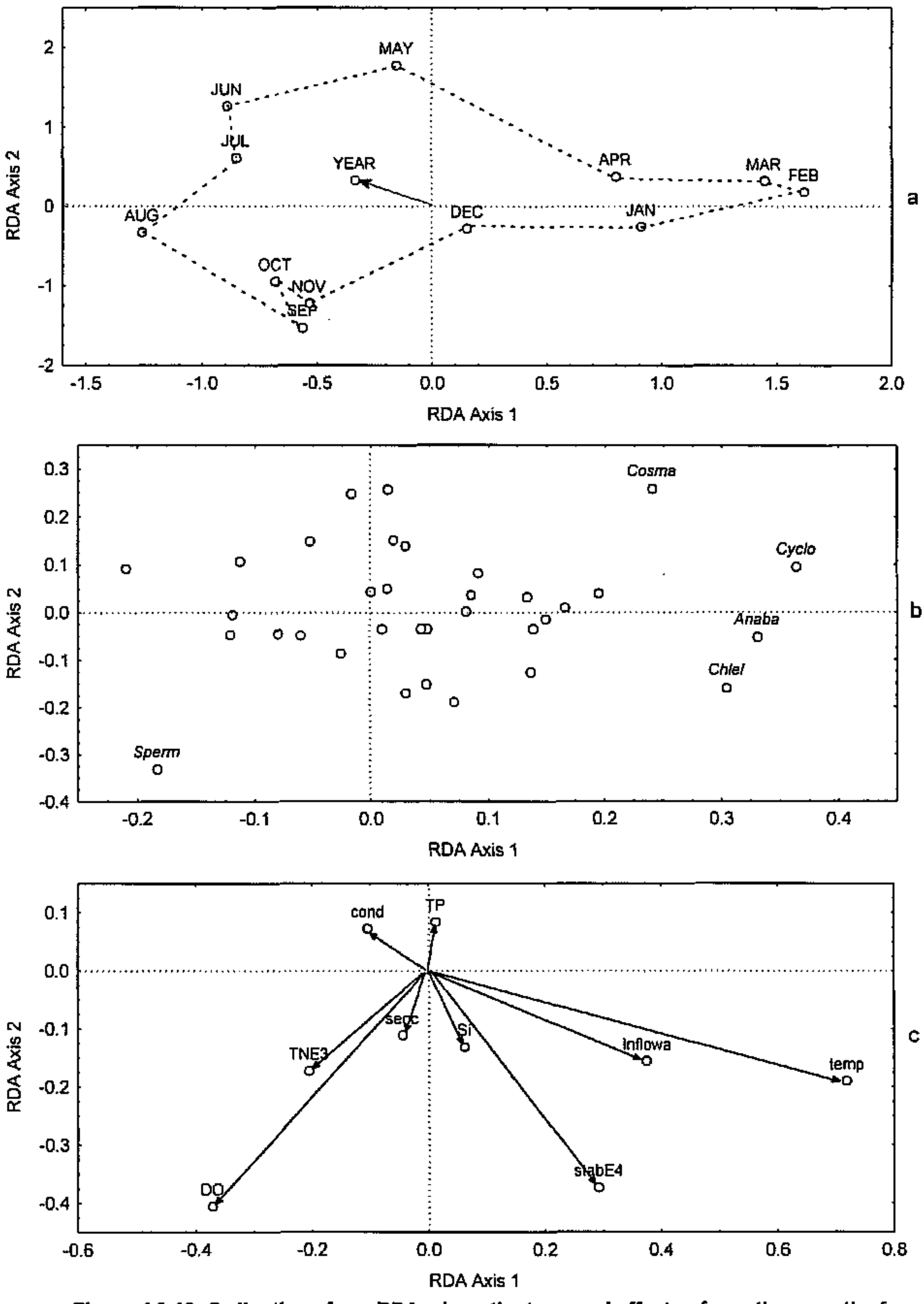

Figure A3.19 Ordinations from RDA where the temporal effects of months were the focus of interest (a). Environmental variables plotted as passives (c). Genera with >10% of their variation explained by the analysis plotted and labelled (b). Abbreviations as per Tables 2.1 & 2.4 and interpretations of the figures as detailed in § A3.2.2.

Key findings here were that the first two axes of Figure A3.19a had eigen values, species/environment correlations and cumulative percentage variance of species/environment relations (Table A3.7) lower than all other effects investigated (key environmental and lake unique effects - Tables A3.1 & A3.3 respectively). The implication of this is that when seasonal effects are compared to all other effects (key environmental and lake unique effects), seasonality accounts for a relatively small amount of algal variability. There is nevertheless still a clear and statistically significant seasonal pattern in the algal data.

For the duration of the study any longer term directional changes (succession) which may have been happening within the algal communities in the lakes (represented by YEAR on Fig. A3.19a) are less significant than monthly changes (shorter term successional patterns). This is indicated by the relatively short length of the YEAR axis (longer-term succession) compared to the distance monthly centroids are apart (shorter term succession) on Figure A3.19a. This implies that there is no overall successional trend in the algal populations in the lakes under study. In other words, the systems are relatively stable within the annual seasonal changes represented by months and are not showing some directional movement toward a particular type or community of algae dominating the systems. Had the annual successional change been larger than seasonal successional change, and in a particular direction of algal community, then this may have been some cause for concern – particularly it the algal community structure was dominated by problematic genera.

Algal genera which appear to have a significant proportion of their variability (>10%) explained by seasonal effects are shown in Table A3.8. This amounted to fewer genera with significant portions of their variability explained compared to either of the previous two analyses (key environmental and spatial (lake) variables). Again this emphasises the lower significance seasonal (monthly) effects have on algal populations compared to pure environmental and spatial effects (associated with different lakes).

Table A3.8 Ranked algal responses (in terms of variance explained) to the effects of season (months) (only genera with >10% variance explained shown)

Genera	Cumulative % variance explained
Chlorella	20.52
Spermatozopsis	20.13
Cyclotella	17.23
Cosmarium	15.37
Cryptomonas	13.43
Anabaena	12.71

Where *Chlorella* previously had a low proportion of its variability explained by key environmental (7.42%) and lake unique effects (10.65%), this analysis of seasonal effects accounted for a greater proportion of its variability (20.52%). This was significant when it was considered that this genus was a dominant to subdominant genus in many lakes Figs. 2.1 (proportional composition) and 2.4 (abundance). This implies that there is some unmeasured seasonal factor(s) in the environment, of either biotic or abiotic origin, which is explaining some of this genus' variability.

As a generalisation in terms of the successional pattern observed within the year (i.e. from month to month), the sequence of abundance is from *Chlorella* and *Anabaena* (in the height of the summer in the early part of the calendar year when inflows and temperatures are greatest) through to *Cyclotella* and *Cosmarium* in autumn (March/April). *Spermatozopsis* is likely to be more abundant in spring (August to October) when factors associated with dissolved oxygen concentrations in the water appear to be higher.

Reference to Figures 2.1 - 2.4 (proportional abundance figures and abundances) indicate that it is only really *Chlorella* and *Anabaena* which are ever really numerically and proportionally abundant. Of these two it is the latter that is the most significant affecting water treatment processes due its potential to form taste and odour forming compounds (see Chapter 5 - Water treatment models). The analysis indicates that January through to April are the months where this genus may be expected to become abundant and therefore cause treatment problems.

The passive plotting of environmental variables onto this analysis indicates that factors associated with elevated temperatures and inflows are closely associated with this summer bloom of *Anabaena* and *Chlorella*.

Another noteworthy feature of this analysis of seasonal effects is the apparently relatively large shift in composition (or succession) occurring at certain times of the year associated with changes in season. This is particularly evident during autumn (March/April to May/June) and then again in early summer (September to November) through to late summer (January/February) when conditions appear to change quite dramatically from the earlier period. This is seen in Figure A3.19a in the distance centroids (representing months) are apart from one another (the greater this distance the greater the degree of successional change in the algal communities in lakes).

This shift in seasonal pattern is most probably associated with changes in the water column physical stability (establishment and breakdown of stratification within the water column). This supposition is supported by the extent to which environmental variables, which may traditionally be associated with physical conditions in the water column (temperature, inflow, stability and DO), are related to algal variability uniquely associated with this analysis of seasonal effects. Classically stratification of the water column occurs in early summer with de-stratification in autumn. These are periods of major physico-chemical change in the water column that could be expected to have a significant impact on algae resident there.

In previous analyses (environmental and spatial effects) dissolved oxygen appears to make a limited contribution to the explanation of variability underlying the algal populations (Figs. A3.19a & A3.19c – relatively short arrows on ordination diagrams). Examination of environmental variables in the analysis probing seasonal effects however indicate that DO is closely related to the seasonality in the algal variability (Fig. A3.19c – long arrow). This observation is in accordance with the understanding that the water columns oxygen profile changes significantly during stratification. For similar reasons 'stability' also appears to be more strongly related to the seasonal aspects of algal variability than had been noted in previous analyses.

A3.6 Direct gradient analysis

As a supplement to the interpretation of the multivariate analyses, classical direct gradient analysis (DGA) was performed to graph individual algal responses to important environmental variables. This information was used in both confirming and supplementing the summary of key algal responses shown in Table 4.1 (Chapter 4 – discussion of relationships between environmental variables and how they relate to algae).

Multivariate analyses (Redundancy Analysis) identified a number of 'responsive' algae and a number of environmental variables that appeared to be accounting for the bulk of the variability in the observed algal data. The identified environmental variables were also shown to represent major axes of variation in the environmental data set itself as well as often being highly correlated with a range of other environmental variables (Appendix 2). These 'other' environmental variables were also used in the DGA figures. Only algae which showed a reasonable response to identified environmental variables in DGA were plotted (Figures A3.20 – A3.24). A polynomial best-fit line (with 95% confidence bands) was applied to the data. The formula for the best-fit line is given above each figure.

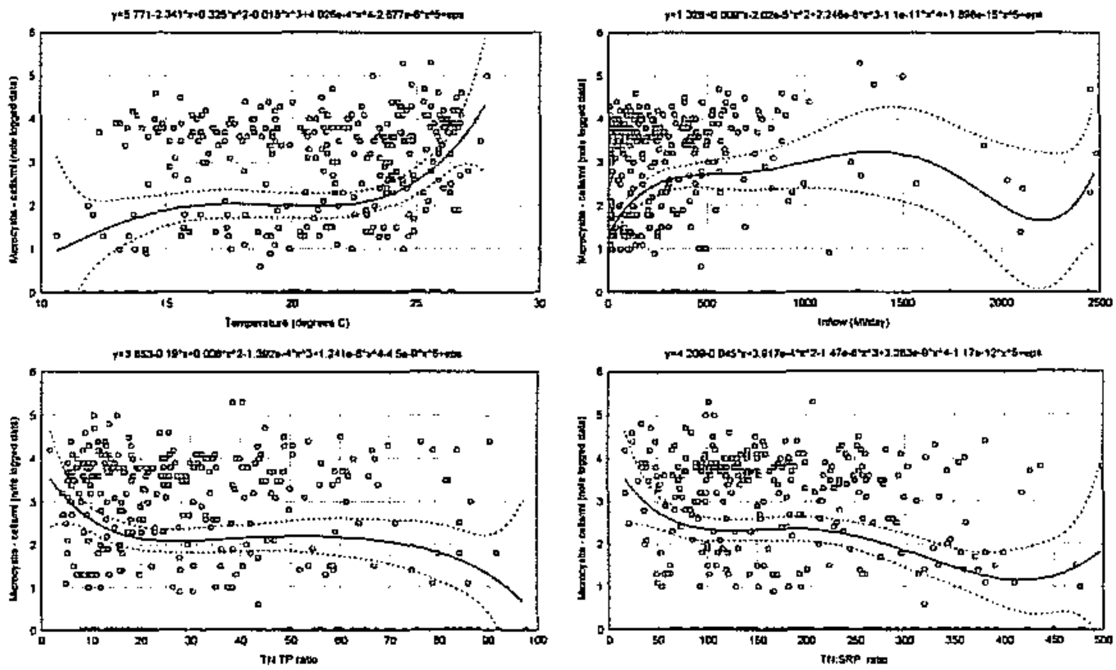

Figure A3.20. Direct gradient analysis plots (with 95% confidence bands) of *Microcystis* against various important environmental variables. Formula for the polynomial best-fit line given above respective graphs.

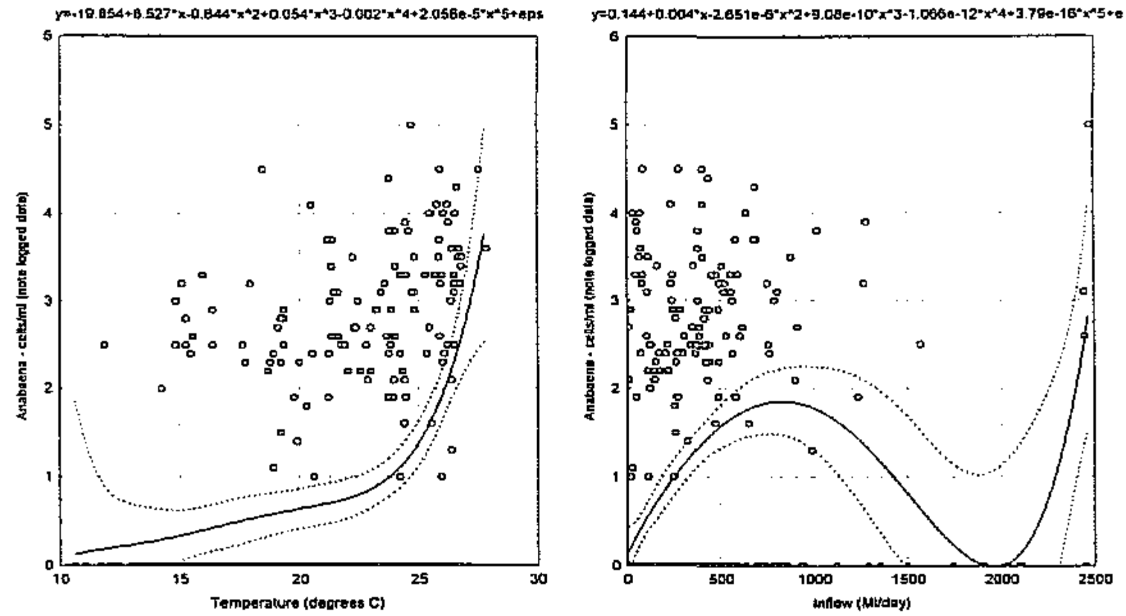

Figure A3.21. Direct gradient analysis plots (with 95% confidence bands) of *Anabaena* against various important environmental variables. Formula for the polynomial best-fit line given above respective graphs.

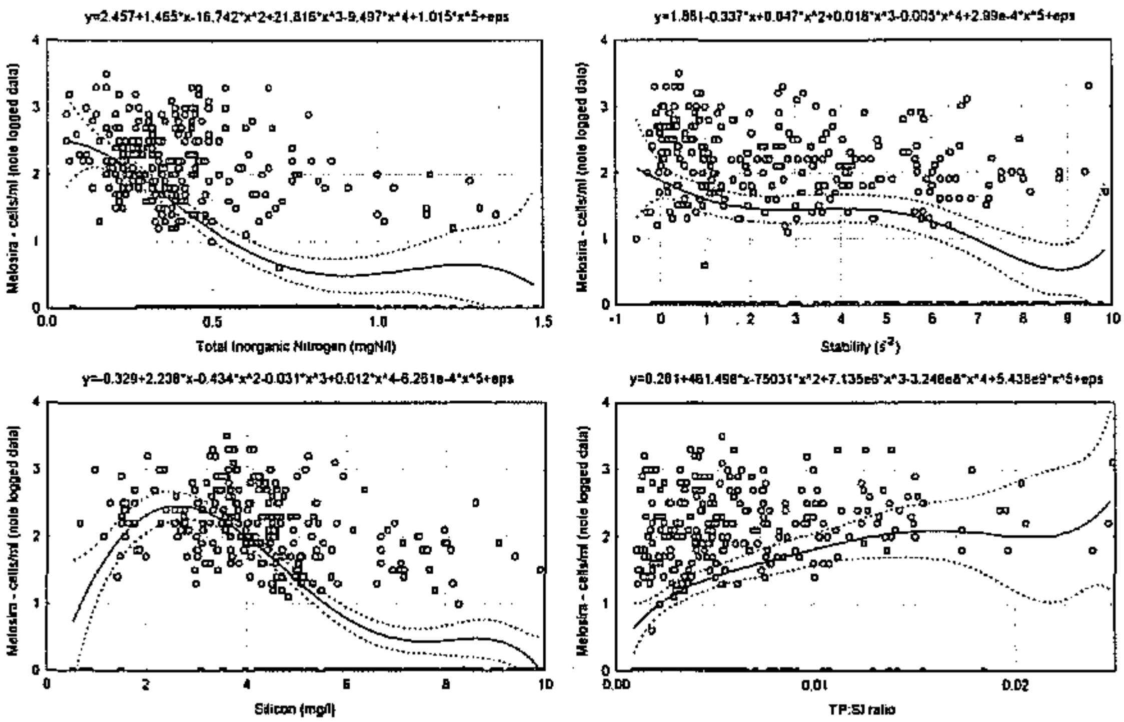

Figure A3.22. Direct gradient analysis plots (with 95% confidence bands) of *Melosira* against various important environmental variables. Formula for the polynomial best-fit line given above respective graphs.

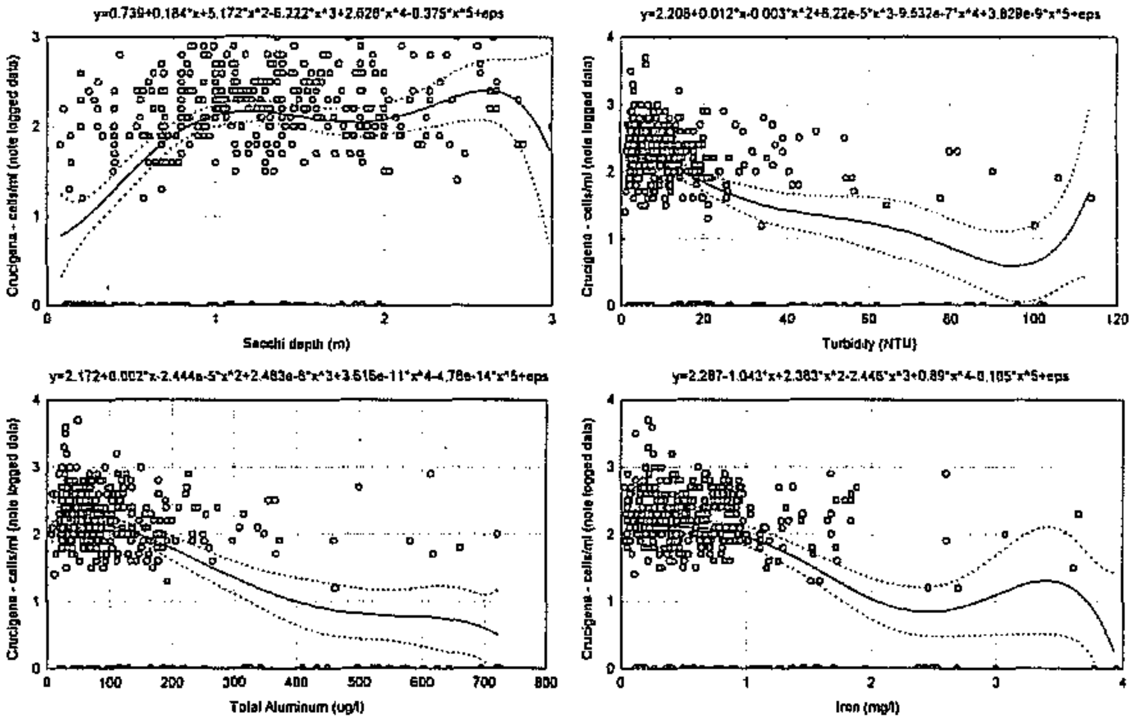

Figure A3.23. Direct gradient analysis plots (with 95% confidence bands) of *Crucigena* against various important environmental variables. Formula for the polynomial best-fit line given above respective graphs.

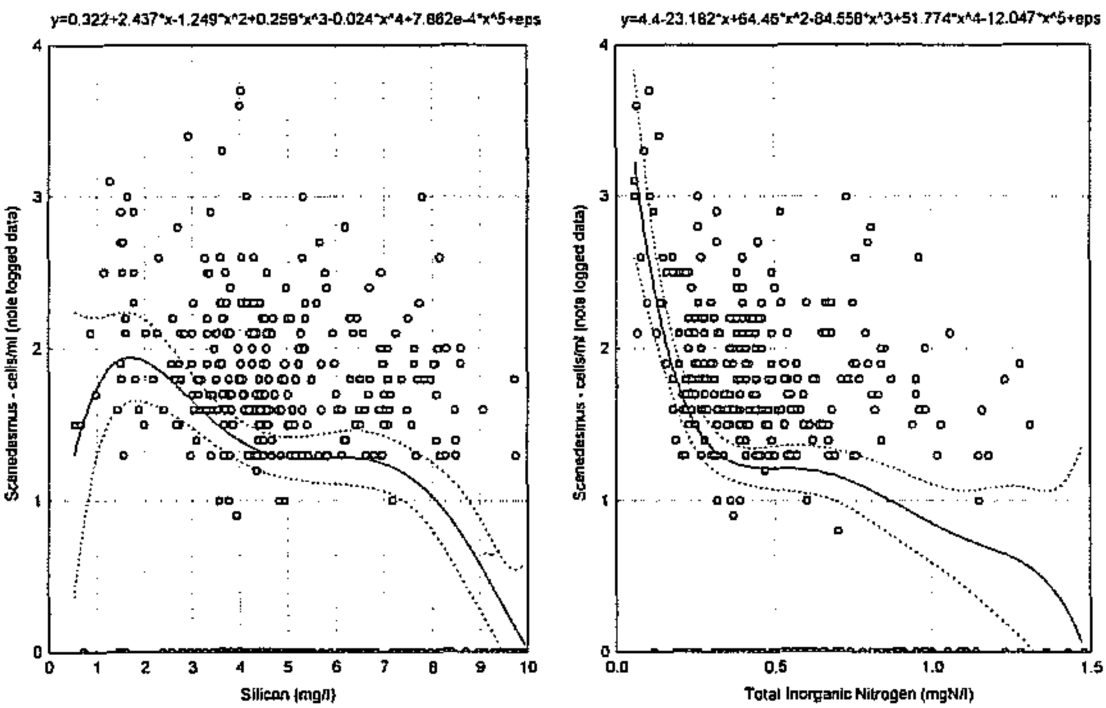

Figure A3.24. Direct gradient analysis plots (with 95% confidence bands) of *Crucigena* against various important environmental variables. Formula for the polynomial best-fit line given above respective graphs.

A3.7 Regression modelling

Attempts at rigorous multiple regression modelling of total algal counts, and some of the individual algal genera, were not particularly successful for a number of reasons elucidated as follows. All of the algal genera and total algal counts are skewed in some way. This is to be expected. Therefore, if the actual data is modelled then one of the main assumptions of the regression model, namely constant error variance, is violated. The standard procedure is to then transform the response variate, in this case the algal count. The Box-Cox procedure was used to identify the best transformation. When this was applied then the problem of non-constant errors disappears, but strangely, the predictive ability (i.e. the variance accounted for by the model) drops drastically. A University of Natal statistician (Dicks 1997, pers. com.) is not sure why this is so as a transformation suggested by the Box-Cox algorithm usually leads to an improvement (or at least no change) in model fit as well as variance stability. A check on the collinearity that may exist among some of the predictor (x) variables (environmental variables) indicates that this is not causing the problem nor are the instances of few very high algal counts. Attempts to formulate the model within a Generalized Linear Model framework, where one specifies a particular distribution for the errors (not normal), rather than transforming the y variable, did not solve the problem of the skewed y variate. It appears that temporal autocorrelation and differences between lakes, where counts are high in only certain lakes at rare intervals, may be contributing to the problem.

At this stage to pursue the multiple regression modelling approach would require each lake to be modelled separately, accounting for both the temporal cycle (through fitting appropriately shaped harmonic functions) and the effects of variables which are not related to the seasonal cycle. Daily, or weekly data, may be useful for this. This exhaustive approach to the modelling exercise would have to be balanced against how such models could be used. More importantly, as others have suggested (e.g. van Tongeren 1992), it may be an impossible goal to try and predict the individual contribution to algal abundance of a number of factors which are intrinsically related (e.g. temperature and stability). Multivariate analyses, where the joint contribution of variables can be examined are perhaps more useful for understanding the pattern (again noted by others in the literature e.g. van Tongeren *et al.* 1992) of algae community variation in the lakes under consideration.

Chapter 4 provides a more general (non-statistical) summary of algal results as they relate to the first aim of this study viz. establishing the key environmental variables influencing problematic algae.

APPENDIX 4

THE DEVELOPMENT OF WATER TREATMENT COST MODELS

A4.1 Introduction

The following appendix provides detailed analyses used in the derivation of the water treatment cost models. The key findings of this appendix are summarised in Chapter 5.

The December 1996 water treatment chemical prices used in analyses (based on information supplied by the UW Finance and Administration Division) are presented in Table A4.1. Prices are expressed as South African Rands/kg.

Table A4.1 Water treatment chemical prices (expressed in December 1996 Rands/kg)

	Chemicals (R/kg)								
Water Works	Chlorine	Granular Chlorine (HTH)	Ammonia	Polymeric coagulant	Lime	Bentonite	Activated Carbon	Ferric Chloride	Sodium Chlorite
Hazelmere	2.82	8.57		3.06	0.53				3.62
Durban Heights	2.82	8.57		3.34	0.78	0.68	3.25		
DV Harris	2.82	8.60	5.66	4.07	0.53	0.69		0.59	
Wiggins	2.82	8.57		3.34	0.53	0.65	3.25		2.20

A4.2 Variables selected for analysis in the estimation of water treatment costs in selected waterworks

Selection of variables for inclusion in economic models to estimate the water treatment costs at respective WW was based on correlation analysis. The selected variables (with their correlations with treatment costs) are presented in the following tables.

Table A4.2 Correlation coefficients for important algae & environmental variables at the Hazelmere WW

VARIABLE	UNITS	Correlations with treatment costs
ENVIRONMENTAL VARIABLES		
Turbidity	NTU	0.7619**
Total Organic Carbon	mg/l	0.6857**
Suspended Solids	mg/l	0.6741**
Total Aluminium	ug/l	0.6552**
Alkalinity	mg/l	-0.5686**
Boron[1]	ug/l	0.5665**
Nitrate	mgN/l	0.5577**
Sulphate	mg/l	0.5151**
Potassium	mg/l	0.4937**
Inflow	Mℓ/day	0.4170**
Chrome	ug/l	0.3060*
Total Dissolved Solids	mg/l	0.2899*
Iron	mg/l	0.2735*
Manganese	mg/l	0.2360*
pH		-0.2591*
ALGAL GENERA		
Chlorella	cells/ml	-0.4749**
Cryptomonas	cells/ml	-0.3216**
Microcystis	cells/ml	-0.2705*
Nitzschia	cells/ml	-0.2637*
Scenedesmus	cells/ml	-0.2495*

* Significant at 5%, ** Significant at 1%

[5] Although cost was significantly correlated with Boron (r^2 = 0.567), this variable was omitted owing to a large number of missing values. Boron had only 21 valid cases as opposed to 71 cases recorded for other variables

Table A4.3 Correlation coefficients for important algae & environmental variables at the Durban Heights WW

VARIABLE	UNITS	Correlations with treatment costs
ENVIRONMENTAL VARIABLES		
Turbidity	NTU	0.7345**
Suspended Solids	mg/l	0.6135**
Conductivity	mS/m	0.5655**
Total Organic Carbon	mg/l	0.5540**
Iron	mg/l	0.5442**
Secchi	m	-0.5244**
Total Hardness	mg/l CaCO3	0.5200**
Nitrate	mgN/l	0.5177**
Silicon	mg/l	0.5044**
Potassium	mg/l	0.4937**
Total Aluminium	ug/l	0.4563**
Soluble Reactive Phosphorus	ugP/l	0.4271**
Total Phosphorus	ugP/l	0.4126**
Coliforms	colony counts/100ml	0.4068**
pH		-0.3873**
E. coli	colony counts/100ml	0.3757**
Temperature	°C	0.3662**
Manganese	mg/l	0.3449**
Dissolved oxygen	mg/l 02	-0.3394**
Total Kjel Nitrogen	mgN/l	0.2484*
ALGAL GENERA		
Microcystis	cells/ml	0.4092**
Anabaena	cells/ml	0.3234**
Chlorella	cells/ml	-0.2589*

* Significant at 5%, ** Significant at 1%

Table A4.4 Correlation coefficients for important algae & environmental variables at the DV Harris WW

VARIABLE	UNITS	Correlations with treatment costs
ENVIRONMENTAL VARIABLES		
Alkalinity	mg/l	-0.615**
Coliforms	colony counts/100ml	0.604**
E.coli	colony counts/100ml	0.562**
Total Hardness	mg/l $CaCo_3$	-0.528**
Potassium	mg/l	0.456**
Trend Variable	Month	0.437**
Nitrate	mgN/l	0.436**
Manganese	mg/l	-0.359**
Conductivity	mS/m	-0.323**
Silicon	mg/l	0.329**
Dissolved Oxygen	mg/l O_2	-0.310*
Temperature	^oC	0.267*
Total Organic Carbon	mg/l	0.225
Suspended Solids	mg/l	-0.205
Turbidity	NTU	-0.189
ALGAL GENERA		
Chlorella	cells/ml	-0.479*

*Significant at 5%, ** Significant at 1%

Table A4.5 Correlation coefficients for important algae & environmental variables at the Wiggins WW

VARIABLE	UNITS	Correlations with treatment costs
ENVIRONMENTAL VARIABLES		
Turbidity	NTU	0.871**
Total aluminium	ug/l	0.702**
Iron	mg/l	0.613**
Suspended Solids	mg/l	0.577**
Nitrate	mgN/l	0.534**
Total Organic Carbon	mg/l	0.481**
Total Dissolved Solids	mg/l	0.422**
pH		-0.402**
Secchi	m	-0.377**
Silicon	mg/l	0.335**
Potassium	mg/l	0.321**
Trend	Months	0.318**
Coliforms	colony counts/100ml	0.279*
Sulphate	mg/l	0.245*
Temperature	°C	0.245*
ALGAL GENERA		
Trachelomonas	cells/ml	0.574**
Chlorella	cells/ml	-0.365**
Cryptomonas	cells/ml	-0.254*
Crucigenia	cells/ml	-0.218*
Anabaena	cells/ml	0.089

* Significant at 5%, ** Significant at 1%

A4.3 Principal Components Analysis (PCA) as applied to the economic models of water treatment costs.

The *t*-values of the original model estimates (before removing the multicollinearity problem) are often extremely low for certain variables (e.g. suspended solids, total organic carbon and total aluminium in the Hazelmere system) which may have been anticipated to have been higher (more significant). Likewise the signs of the coefficients of these variables do not conform to *a priori* relationships understood to exist with treatment costs. For example in the Hazlemere system, suspended solids would be expected to positively influence treatment costs – indicating that as they increased in the raw water so too would polymeric coagulant demand and hence costs. This lack of adherence to *a priori* expectations is a classic symptom of the multicollinearity anticipated in these types of models (Gujurati, 1988). It was therefore clear that the original models were all severely affected by multicolinearity and this had to be analytically catered for. Principal Components Analysis was employed for this purpose.

Principal Components Analysis (PCA) was employed to overcome the problem of multicollinearity (Chattterjee & Price, 1977). This technique converts the original variables into uncorrelated variables called principal components, PCs. PCs are linear combinations of the original variables:

$PC_i = \alpha_{i1}X_1 + \alpha_{i2}X_2 + \ldots + \alpha_{ik}X_k$

where PC_i = *i*th principal component

α_{ij} = component loadings

X_j = original variables

The principal components must satisfy two conditions; they must be orthogonal and the first component (PC_1) should account for the maximum proportion of variation in the original variables. Each subsequent PC should account for the maximum remaining variation in the original variables. Successive principal components were dropped until the sign and magnitude of each estimated coefficient stabilised. For example, following this approach, a total of five principal components were retained, accounting for almost 76 percent of the variation in the original variables for the DV Harris model. The loadings estimated for the retained PC's for the three selected WW are given in Tables A4.6 to A4.8.

Table A4.6 Component loadings estimated for the eight principal components retained in the Hazelmere WW model

Variable	PC_1	PC_2	PC_3	PC_4	PC_5	PC_6	PC_7	PC_8
pH	0.1503	-0.4508	0.2493	0.3310	0.6893	-0.1933	-0.0582	-0.0669
Turbidity	-0.4149	-0.2162	-0.0884	-0.1427	0.0178	-0.0075	-0.0764	0.0679
Total Aluminium	-0.3903	-0.2293	-0.1259	-0.0493	0.2110	-0.0939	-0.0855	-0.1178
Alkalinity	0.3290	-0.2367	0.3816	-0.1000	-0.1280	0.0344	-0.1524	0.7318
Potassium	-0.2718	-0.0978	0.5706	-0.0307	-0.0793	0.1577	0.7399	-0.0923
Manganese	0.0301	-0.4432	-0.1464	0.6755	-0.5557	0.0407	0.0123	-0.1043
Nitrate	-0.2474	0.3758	0.0411	0.3235	-0.0409	-0.7577	0.1368	0.3108
Sulphates	-0.2094	0.2753	0.6141	0.2034	-0.0960	0.1081	-0.5816	-0.2886
Suspended Solids	-0.3918	-0.3030	-0.0898	-0.0846	0.0330	-0.0185	-0.1220	0.1788
Total Organic Carbon	-0.3889	-0.1616	0.0718	-0.1986	-0.2084	0.0245	-0.1915	0.2191
Chlorella	0.2453	-0.3170	0.1718	-0.4558	-0.3051	-0.5826	-0.0638	-0.4029
Eigen Value	4.87	1.63	1.20	0.93	0.72	0.59	0.39	0.29
% Variation	44.30	14.80	10.90	8.40	6.50	5.30	3.50	2.7
Cum. %	44.30	59.00	70.10	78.40	84.90	90.30	93.70	96.4

Table A4.7 Component loadings estimated for the eight principal components retained in the Durban Heights WW model

Variable	PC1	PC2	PC3	PC4	PC5
Temperature	0.1122	0.4498	-0.1943	-0.4236	0.3299
Coliform	0.2310	0.2022	-0.1840	0.2578	-0.2085
pH	-0.2135	0.2843	-0.2431	0.3935	0.0302
Turbidity	0.3539	0.0689	0.0207	-0.0752	-0.1807
Iron	0.2896	0.2329	0.1724	0.2560	-0.0628
Suspended Solids	0.3136	0.1774	-0.1760	0.2187	-0.0681
Secchi	-0.2834	-0.0986	0.1013	-0.3429	0.1566
Conductivity	0.3122	-0.2468	-0.1014	-0.0098	0.2322
Total Hardness	0.2697	-0.2081	-0.3152	0.0522	0.0387
Potassium	0.2678	-0.2839	-0.0179	-0.0236	0.2008
Silicon	0.2271	0.1066	0.4625	-0.1335	-0.0029
Nitrate	0.2772	0.0545	0.4539	-0.0880	0.0441
Total Organic Carbon	0.2994	-0.3025	-0.0958	0.0259	0.1927
Dissolved Oxygen	-0.1578	-0.5305	-0.0752	0.1953	-0.1422
Microcystis	0.1052	-0.0578	-0.2083	-0.4649	-0.7545
Anabaena	0.0690	0.0170	-0.4580	-0.2807	0.2380
Eigen Value	6.78	1.89	1.76	1.16	0.95
% of Variation	42.39	11.81	10.97	7.25	5.90
Cum. %	42.39	54.20	65.17	72.42	78.32

Table A4.8 Component loadings estimated for the five principal components retained in the DV Harris WW model

VARIABLE	PC1	PC2	PC3	PC4	PC5
Alkalinity	-0.3926	-0.1500	0.0233	0.1735	-0.2815
Coliforms	0.2494	-0.3615	-0.1151	-0.1930	-0.0932
E.coli	0.2878	-0.2351	-0.1263	-0.2764	-0.1120
Total Hardness	-0.3686	-0.2627	0.0875	0.0421	-0.0255
Potassium	0.2364	-0.1979	0.0912	-0.2990	-0.3385
Trend Variable	0.2050	-0.0525	0.4657	0.2899	0.0354
Nitrate	0.2111	0.0839	-0.0527	-0.1783	0.6906
Manganese	-0.1878	0.1503	-0.5032	-0.0236	-0.2240
Conductivity	-0.2914	-0.3797	-0.0289	0.1267	0.1613
Silica	0.3017	0.2904	-0.1675	-0.0629	-0.3082
Dissolved Oxygen	-0.1570	0.2833	0.3782	-0.1977	0.0312
Temperature	0.1073	-0.4644	-0.2747	0.1458	0.1067
Total Organic Carbon	0.1859	-0.0784	0.3877	0.1453	-0.3329
Suspended Solids	-0.1421	-0.0928	0.1032	-0.5202	-0.0245
Turbidity	-0.2094	-0.1999	0.2458	-0.4693	0.0579
Chlorella	-0.2768	0.2682	-0.1126	-0.2377	-0.0883
Eigen Value	4.30	2.70	2.17	1.91	1.16
% of Variation	26.87	16.68	13.59	11.93	7.26
Cum. %	26.87	43.55	57.14	69.07	76.33

The regression models were then re-estimated using the principal components as explanatory variables and standardised COST (ZCOST) as the dependent variable. Results are presented in Tables A4.9, A4.10, A4.11 and A4.12 for Hazelmere, Durban Heights, DV Harris and Wiggins WW respectively.

Table A4.9 Regression coefficients for principal components retained in the Hazelmere WW model

Explanatory Variable	Coefficients	t-values
PC_1	-0.373	-15.45*
PC_2	-0.038	-0.92
PC_3	0.051	1.05
PC_4	0.273	4.94*
PC_5	-0.236	-3.77*
PC_6	-0.007	-0.10
PC_7	0.074	0.86
PC_8	-0.021	-0.21
R^2 79%		
Adj. R^2: 76%		

*Sig. at 1%

Table A4.10 Regression coefficients estimated for principal components retained in the Durban Heights WW model

Explanatory Variable	Coefficients	t-values
PC_1	0.291	11.42*
PC_2	0.056	1.16
PC_3	-0.073	-1.46
PC_4	-0.206	-3.35*
PC_5	-0.075	-1.10
R^2	64%	
Adj. R^2	62%	

*Sig. At 1%

Table A4.11 Regression coefficients estimated for principal components retained in the DV Harris WW model

Explanatory Variable	Coefficients	t-values
PC_1	0.376	10.93*
PC_2	0.124	2.84*
PC_3	-0.017	-0.36
PC_4	-0.053	1.02
PC_5	-0.119	-1.79
R^2	67%	
Adj. R^2	64%	

*Sig. at 1%

Table A4.12 Regression coefficients estimated for principal components retained in the Wiggins WW model

Explanatory Variable	Coefficients	t-values
PC_1	-0.811	-15.22***
PC_2	-0.100	-1.88*
PC_3	0.312	5.85***
PC_4	0.032	0.60
PC5	-0.119	-1.98*
PC6	-0.043	-0.81
PC7	-0.100	-1.88*
R^2	79%	
Adj. R^2	77%	

**Sig. at 10%, **Sig. at 5%, ***Sig. at 1%

No attempt was made to interpret the principal components because they were employed only to combat multicollinearity and not for predictive or policy purposes. To accomplish these goals, the models presented in Tables A4.9 to A4.12, were expressed in terms of the original variables following the procedure described by Nieuwoudt (1972), and Chatterjee and Price (1977). This procedure uses the component loadings to transform the regression coefficients estimated for the principal components into standardised estimates for the original variables. For example, the standardised coefficients of ALKALINITY (β_1) and COLIFORMS (β_2) for the DV Harris were computed as follows:

$\beta_1 = -0.3926\alpha_1 \; -0.1500\alpha_2 +0.0233\alpha_3 +0.1735\alpha_4 -0.2815\alpha_5$

$\beta_2 = 0.2494\alpha_1 \; -0.3615\alpha_2 -0.1151\alpha_3 -0.1930\alpha_4 -0.0932\alpha_5$

where; $\alpha_1=0.376$, $\alpha_2 = -0.124$, $\alpha_3 = -0.017$, $\alpha_4 = -0.053$, $\alpha_5 = -0.119$,

Tables A4.13 to A4.16 present the standardised regression coefficients for the original explanatory variables estimated for the respective systems. The *t*-values were computed as $\frac{b_i}{\sqrt{Var(b_i)}}$ where $Var(b_j) = \sum_{i=1}^{k}((PC\ loading_i)^2 * Var(\alpha_i))$ with k = the number of principal components retained.

Table A4.13 Standardised regression coefficients estimated for contaminants after removing multicollinearity for the Hazelmere WW model

VARIABLE	Coefficients	t-values
pH	-0.1002	-1.84
Turbidity	0.1082	5.78**
Total Aluminium	0.0813	3.24*
Alkalinity	-0.1177	-1.53
Potassium	0.2000	2.80*
Manganese	0.3168	5.67**
Nitrate	0.1871	1.01
Sulphate	0.1388	2.26*
Suspended Solids	0.1096	4.10**
Total Organic Carbon	0.1309	3.82*
Chlorella	-0.1150	-1.71
R^2	79%	
Adjusted R^2	76%	
Number of cases	71	

*Sig. at 5% and ** Sig. at 1%.

According to the standardised coefficients in Table A4.13, contaminants that have the greatest impact on treatment costs, in descending order, are manganese, potassium, nitrate, sulphate, total organic carbon, alkalinity, *Chlorella*, suspended solids, turbidity, pH, and total aluminium at Hazelmere WW.

Table A4.14 Standardised regression coefficients estimated for contaminants after removing multicollinearity for the Durban Heights WW model

VARIABLE	Coefficients	t-values
Temperature	0.134	3.20*
Coliforms	0.054	2.10*
pH	-0.112	-3.62*
Turbidity	0.134	8.33**
Iron	0.037	1.60
Suspended Solids	0.074	3.62*
Secchi	-0.036	-1.42
Conductivity	0.069	3.14*
Total Hardness	0.076	3.74**
Potassium	0.053	2.58*
Silicon	0.066	2.56*
Nitrate	0.059	2.40*
Total Organic Carbon	0.057	2.65*
Dissolved Oxygen	-0.099	-3.30*
Microcystis	0.195	3.25*
Anabaena	0.094	2.86*
R^2	64%	
Adjusted R^2	62%	
Number of cases	84	

*Sig. at 5% and ** Sig. at 1%.

According to the standardised coefficients in Table A4.14, *Microcystis*, turbidity, temperature, and pH are the contaminants that have the largest impact on treatment costs at Durban Heights.

Table A4.15 Standardised regression coefficients estimated for contaminants after removing multicollinearity for the DV Harris WW model

VARIABLE		Coefficients	t-values
Alkalinity		-0.171	-6.70**
Coliforms		0.136	6.13**
E.coli		0.136	6.12**
Total Hardness		-0.110	-6.16**
Potassium		0.091	3.02*
Trend Variable		0.081	3.09*
Nitrate		0.160	3.37*
Manganese		-0.123	-4.11**
Conductivity		-0.051	-2.19
Silicon		0.041	1.50
Dissolved Oxygen		-0.078	-2.94*
Temperature		0.098	3.69*
Total Organic Carbon		0.039	1.27
Suspended Solids		-0.016	-0.55
Turbidity		-0.018	0.61
Chlorella		-0.137	-6.53**
R^2	67%		
Adj. R^2	64%		
Number of cases	64		

"Sig. at 5%, "Sig. at 1%

For the DV Harris system standardised coefficients in Table A4.15 show that alkalinity, nitrates, coliforms, E.coli, and *Chlorella* are the most important variables affecting cost.

Table A4.16 Standardised regression coefficients estimated for contaminants after removing multicollinearity for the Wiggins WW model

VARIABLE	Coefficients	t-values
Constant	34.288	1.96*
Turbidity	0.193	13.88***
Total aluminium	0.136	6.95***
Iron	0.140	4.67***
Suspended Solids	0.124	3.76***
Nitrate	0.096	4.33***
Total Organic Carbon	0.108	5.15***
Total Dissolved Solids	0.101	3.90***
pH	-0.072	-2.32**
Silica	0.078	3.23***
Trend	0.072	2.25**
Coliforms	0.220	3.79***
Sulphates	0.047	1.78*
Temperature	0.134	2.42**
Anabaena	0.101	2.01**
R^2: 79%		
Adj. R^2: 77%		
Number of cases 82		

*Sig. at 10%, **Sig. at 5%, ***Sig. at 1%

For the Wiggins WW system standardised coefficients in Table A4.16 show that coliforms, turbidity, iron and total aluminium are the most important variables affecting cost.

These standardised coefficients (b_i) are useful for policy purposes because they are independent of the original units of measurement and therefore show the relative importance of each explanatory variable to changes in cost (Nieuwoudt, 1972)

However, for predictive purposes the standardised variables were converted to original scale using the method proposed by Kendall (1957). The b_i's were multiplied by Sy/Sx_i (the standard deviation of the dependent variable divided by the standard deviation of the independent variable) and the constant term was calculated as the difference between the mean values of the observed and predicted costs.

A4.4 Linear relationships between Suspended Solids, Total Aluminium and Turbidity in respective WW.

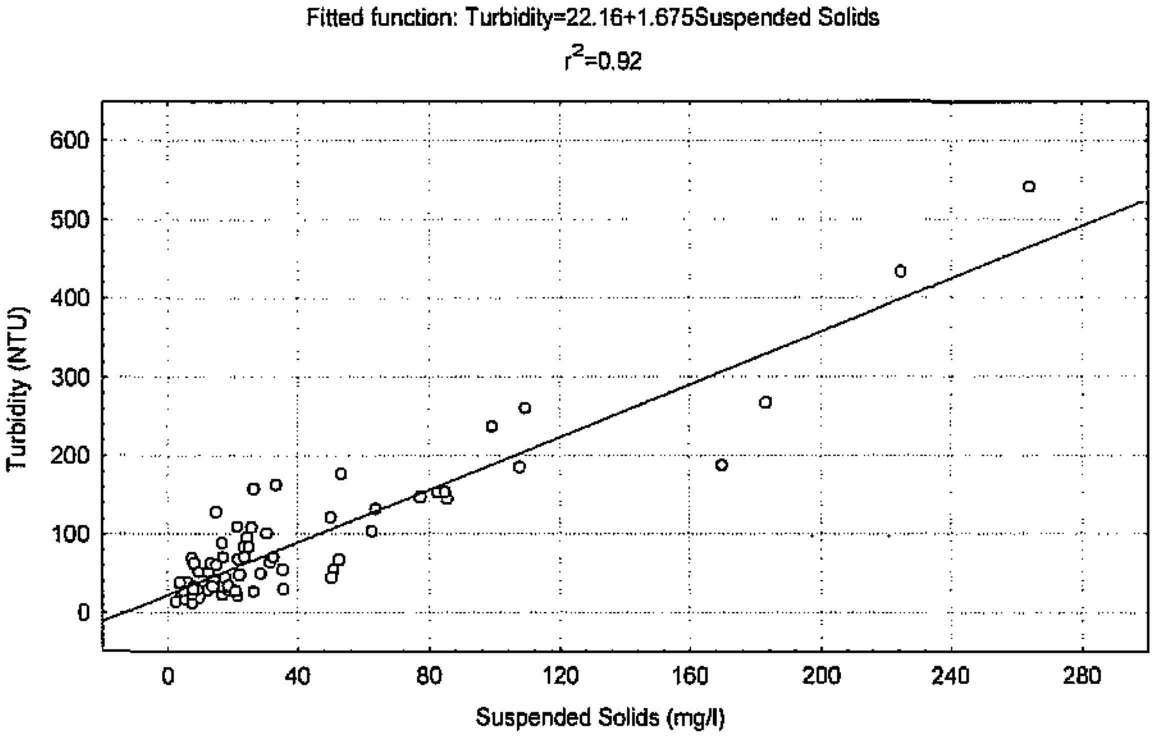

Figure A4.1 Linear relationship between Turbidity and Suspended Solids: Hazelmere WW raw water.

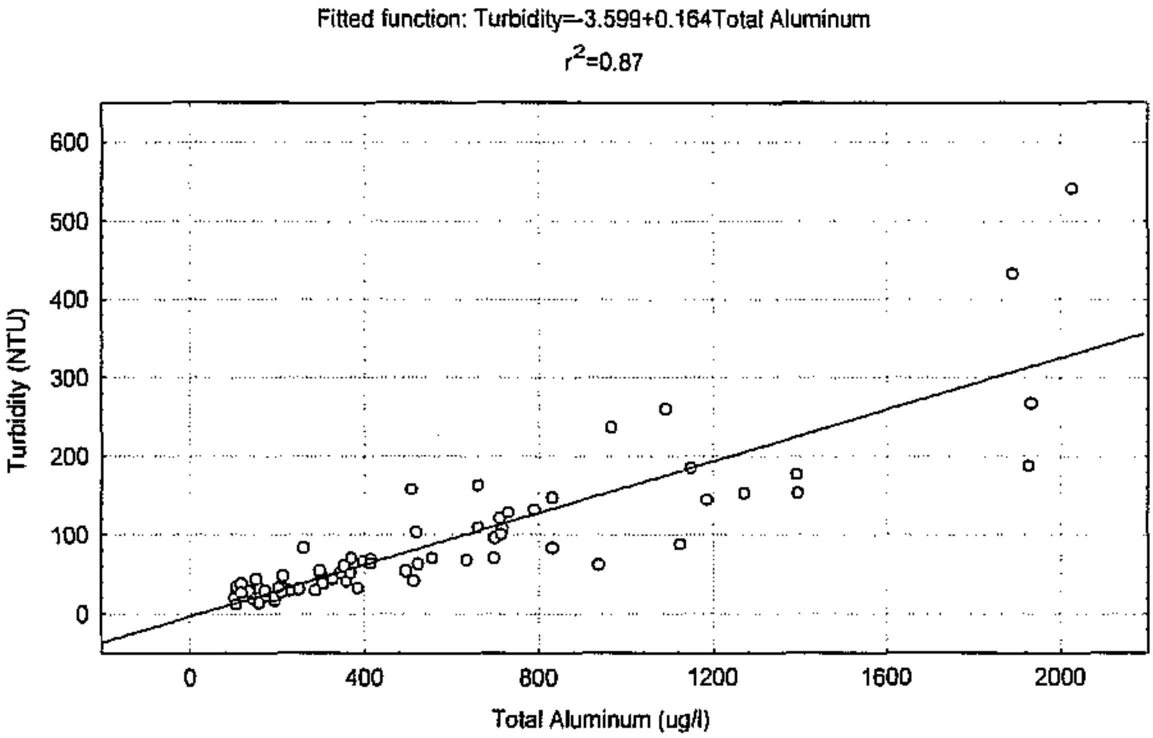

Figure A4.2 Linear relationship between Turbidity and Total Aluminium: Hazelmere WW raw water.

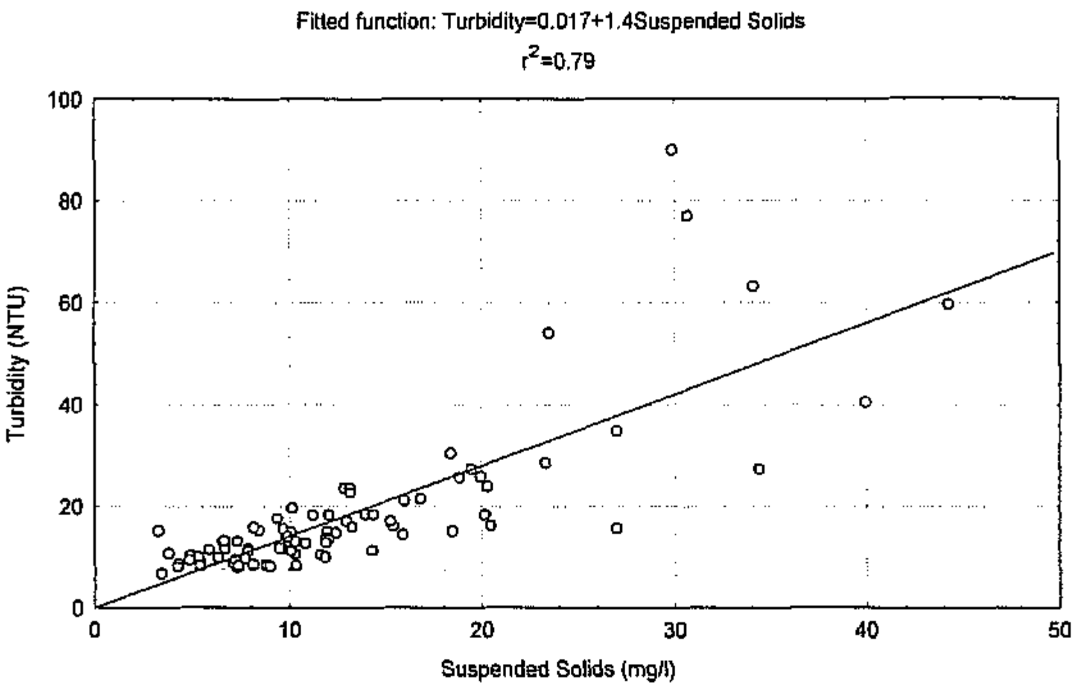

Figure A4.3 Linear relationship between Turbidity and Suspended Solids: Durban Heights WW raw water.

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