LANDSAT - WATER QUALITY

SURVEILLANCE OF ROODEPLAAT DAM

by

ALISON M. HOWMAN

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ABSTRACT

The need for accurate, synoptic, up to date information, concerning the quality of South African impoundments, prompted a study into the relationship between Landsat reflectance data and chlorophyll a and turbidity in Roodeplaat Dam.

Surface and integrated chlorophyll a as well as surface and integrated turbidity were collected simultaneously with the satellite's overpass, from 32 sampling sites on the impoundment. Six days, between 81.10.14 and 82.11.16, were cloud free and the data were analysed in order to establish the relationship between the specific water quality conditions and the satellite reflectance data.

Prior to the analysis certain factors required attention. Firstly, it was important to accurately align the sampling sites with their corresponding Landsat pixels. Secondly, the satellite reflectance data were corrected for influences of haze and the angle of the sun. Thirdly, the requirement that the water quality surface reference data be representaive of the range of conditions in the impoundment was recognised. Lastly, the interrelationship between chlorophyll a and turbidity and the multi-collinearity evident between the four reflectance bands, demanded that a multi-variate statistical technique be implemented, in order to adequately analyse the available data.

The Canonical Correlation multi-variate regression analysis was chosen to investigate the relationship between the surface reference data and the four Landsat wavebands. Canonical Correlations (r) ranged from 0,95 to 0,79, and the Canonical Coefficients enabled characteristics of the relationship between the variables to be established. As a general trend, surface chlorophyll a showed correlation with all of the wavebands, whereas integrated chlorophyll a corresponded with bands 6 and 7. Surface turbidity mainly related to bands 4 and 5, but also at times to bands 6 and 7, while integrated turbidity related to bands 4 and 5. The trends varied between overpasses however, indicating that the relationship was complex and unique to each specific overpass.

In addition to the use of the Canonical Correlation Analysis, the unsupervised classification technique and colour coding assisted in the interpretation of the conditions within the impoundment.

The Canonical Correlation Analysis has shown its potential for assessing chlorophyll a and turbidity in impoundments. It is recommended that the technique be pursued in an attempt to establish a model with which to acquire explicit information of the water quality conditions in impoundments using Landsat data.

CHAPTER 1

1. BACKGROUND INFORMATION

1.1 INTRODUCTION

The space race and the decision to get a man on the moon by the end of the 1960's started a trend in technology which has since proved to be an invaluable source of data of the Earth's resources. The space race stimulated the science of remote sensing defined as "the science and/or technique used in gaining information about material objects by means of measurements made over a distance without physical contact" (Liebenberg, 1977). The first space images showed how solar energy reflected by objects on the earth's surface could be measured and registered by remotely placed sensors, namely satellites. Together with the revolutionary progress in the field of spectroscopy and electronics, the sensors were not confined to capturing data in the visible spectrum and extended further into the infra-red range of the electro-magnetic spectrum. The value of satellite imagery was recognised and rapid growth took place in the field of remote sensing.

In 1972, Landsat 1, the first of the more important Earth resources satellite series, was launched (Curran, 1984). Subsequently, Landsats 2, 3, 4 and 5 were put into operation, providing near world wide coverage of the earth and its resources. Investigations have indicated a wide range of applications for which Landsat imagery can be used (Ackermann, 1974; House of Lords Select Committee on Science and Technology, 1983).

The critical nature of South Africa's water resources, Landsat's unique monitoring ability and the direct reception of Landsat data in South Africa, provided the impetus for the study.

1.2 SCOPE OF THE THESIS

This thesis examines the relationship between Landsat satellite reflectance data and surface reference data. The surface reference data were collected from a single impoundment on six occasions, concurrently with the satellites overflights. The problem of correlating four wavebands with four mutually interdependent water quality conditions has been acknowledged in the literature but has not been successfully achieved. In an attempt to overcome the problem this Remote Sensing thesis uses an impoundment to test the statistical technique of Canonical Correlation Analysis for investigating the correlation of the satellite reflectance data with two specific limnological criteria, i.e. chlorophyll a and turbidity. An investigation of the limnology of the impoundment *per se* is outside the scope of this thesis, and consequently no attempt is made to address the limnology of the impoundment.

1.3 SOUTH AFRICA'S WATER PROBLEM - A BRIEF REVIEW

South African water resource managers and planners face the problem of a severe shortfall of water by the year 2 000 (Department of Water Affairs, 1985). The concern is directly related to South Africa's position in the drought belt of the globe and it socio-economic standing as a fast developing country.

The high population growth rate, increasing urbanization and industrialization, rising expectations and standards of living, present a grave picture when combined with the scarcity and variability of the rainfall, which is the major source of water in South Africa (Whitmore, 1978).

It is therefore of major importance that the water resources of South Africa be managed and developed with maximum efficiency and speed. This entails maintaining the quality of established and new water supplies, developing new sources of water, and being able to quantify the water resources available at any one time. It is at this point that the lack of accurate, up to date data impedes efficient management. Researchers have suggested that an answer to the problem lies in the use of satellite imagery with its regularly recorded, accurate, synoptic data, available at low cost and in quantifiable terms (Kendrick, 1976; Malan, 1976; Skibitzke, 1976; Reed, 1978; Croteau, 1979).

Research in America and Europe has indicated that Landsat has been successful in water quality surveillance, particularly in detecting chlorophyll a (algal pigment) and turbidity (suspended solids) in water bodies (Bukata and Bruton, 1974; Moore, 1980; Lindell, 1981). An image received of an impoundment in South Africa, Bloemhof Dam, showed evidence of above-mentioned water quality conditions. Plate 1.1 shows firstly, an algal bloom in the southern arm of the impoundment indicated by red patches visible on the surface of the water, and secondly, suspended solids are visible in the northern arm of the impoundment, identified by a bluish-white colour.

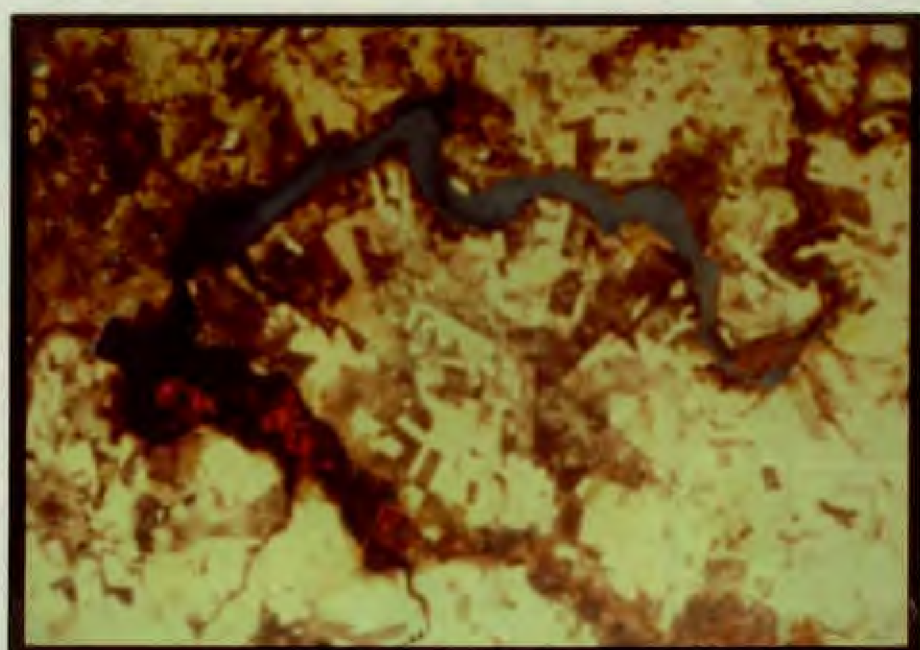

Plate 1.1: Bloemhof Dam showing an algal bloom in the southern arm and suspended solids in the northern arm of the impoundment

The fact that the two conditions are visible on the image raises the question; to what extent can quantitative information of water quality conditions be gained from satellite imagery? In an attempt to throw further light on the subject, it was decided to investigate Landsat's potential for monitoring the possible deterioration of a South African impoundment by pollution in the form of sediment and nutrient containing effluent from urban, industrial and farming sources.

In 1981, the Satellite Remote Sensing Centre (SRSC), South Africa's tracking and receiving station, began receiving data direct from Landsat. The water quality project on Roodeplaat Dam was initiated and this thesis presents the methodology and results obtained from the study.

1.4 LANDSAT

The Landsat series of satellites have a number of characteristics which have made them invaluable data captors (Lillesand and Kiefer, 1979). Positioned in a sun synchronous, polar orbit, and flying at a fixed altitude, varying between 920 kilometre (km) and 700 (km) depending on the specific Landsat concerned, Landsat has been equipped with a Multi-Spectral Scanner (MSS) which records energy returns of radiance from the earth in four spectral bands. These bands correspond to wavelengths in the visible, green and red and two bands in the near infra-red spectral regions : Band 4 = 0,5 to 0,6 µm*; Band 5 = 0,6 to 0,7 µm; Band 6 = 0,7 to 0,8 µm and Band 7 = 0,8 to 1,1 µm. The multiwaveband data are recorded in digital format of integer values, 0 to 255 inclusive.

The satellites provide synoptic views of the earth's surface. Each image covers an area of 180 km by 180 km and the same area can be imaged every 18 days. Regular monitoring can be carried out and the resolution of each picture element (pixel) on the earth's surface is 80 metres(m) by 80 m. Thus for the first time rapid, regular, synoptic, quantifiable data can be obtained of the everchanging features of the earth's surface. This means that objective spatial comparisons can be made, inaccessible areas reached, and manpower, time and money saved. The major disadvantages are:

(i) the 18 day delay period between coverage,

(ii) the fact that cloud cover obstructs Landsat images and

(iii) that the imagery needs specific image processing equipment and expertise to take full advantage of the images' potential.

* µm = micrometer.

In the field of water quality Landsat has been used in a number of different applications (Rodda, 1976; Munday et al, 1979; Hill and Graham, 1980; Moore, 1980; Muralikrishna and Rao, 1982; Thiruvengadachari et al, 1983). A summary of some of the major applications are presented in Table 1.1.

TABLE 1.1: APPLICATIONS OF LANDSAT-DERIVED INFORMATION IN THE FIELD OF WATER QUALITY

1. The measuring and delineation in impoundments of:
1.1 Particulate contaminants
1.2 Chlorophyll concentration levels
1.3 Turbidity concentration levels/suspended solids
1.4 Circulation features
2. Assessing discharge plumes
3. Constructing and calibrating water quality models
4. Seasonal monitoring of impoundments
5. Regulatory permit monitoring

1.5 SPECIFIC WATER QUALITY CONDITIONS: CHLOROPHYLL a AND TURBIDITY

The two water quality conditions chosen for examination using Landsat data were chlorophyll a (algal pigment) and turbidity (suspended solids).

1.5.1 Chlorophyll a

Chlorophyll a is "generally considered the most reliable measure of "an impoundment's" response to eutrophication" (Lambou et al, 1982). It is the primary green photosynthetic pigment present in algae and in all oxygen-evolving photosynthetic organisms (Wetzel, 1983). It is the algal plant pigment, chlorophyll a that the satellite detects and not algal biomass per se. The presence of chlorophyll elicits the red pseudo colouring seen on satellite images.

For the purposes of this thesis the occurrence of chlorophyll a is considered to be synonymous with the presence of algae.

Algae are microscopic aquatic organisms that grow extremely fast in the presence of plant nutrients such as phosphorus and nitrogen. Excessive algal growth is considered to be a major water quality problem (Toerien, 1975, 1977). For example, the clogging of filters, flow meters, valves and irrigation canals may occur. Tastes and odours can be unpleasant and foul smelling scums on water surfaces are not conducive to recreational activities. Certain algae, under specific conditions, release toxins that can poison livestock (Powling, 1977).

It is therefore important to try and assess chlorophyll a concentrations in an impoundment. Previously, estimations of chlorophyll a concentrations were carried out using point source measurements. However, it has been recognised that satellite-derived data, with synoptic and quantifiable advantages, can be of aid in determining the distribution of chlorophyll a concentrations with greater efficiency (Bukata and Bruton, 1974; Sydor et al, 1978; Welby et al, 1980; Canfield, 1983).

1.5.2 Turbidity

The level of turbidity is determined by the concentration, size, shape and refractive index of suspended particles (suspensoids), which increase the amount of energy backscattered in water bodies (Moore, 1980; Kirk, 1985). The presence of suspensoids is evidenced in the turbidity of the water, which is recognised as bluish-white on satellite images. "Suspensoids include both an inorganic fraction (suspended sediments) and an organic fraction (suspended living zooplankton, suspended living phytoplankton - algae, containing chlorophyll a - and dead fragments of both). Turbidity is a measure of all suspended particles" (Dr. J. Day* - pers. comm.).

A number of effects may be associated with turbidity. For instance, decreased light penetration can occur, resulting in decreased light in the euphotic zone which may inhibit rooted plant growth and algal production. On the other hand

* Dr. J. Day - Department of Zoology, University of Cape Town.

suspended sediments are associated with nutrients which, depending on the availability can serve as a stimulus for algal productivity (Lambou et al, 1982).

Sediment laden waters also affect the treatability of water, sometimes blocking filters, pipelines and tunnels, and attempts to flocculate certain types of sediment can be expensive and difficult.

Investigations into sediment transport are important in understanding the hydro-dynamics of a water body and for the purposes of modelling the system (Hill and Graham, 1980).

Satellite imagery's synoptic and quantifiable data could be advantageous in assessing the turbidity in an impoundment.

1.6 OBJECTIVE OF THE PROJECT

The major objective of the study was to study the relationship between Landsat reflectance data and turbidity and chlorophyll a in a specific water body. The aim being to assess the possibility of obtaining reasonable estimates of chlorophyll a and turbidity using satellite-derived data. The remote sensing technique provides a potential method for obtaining synoptic data on chlorophyll a and turbidity in impoundments not readily obtainable by other methods.

1.7 OVERVIEW OF THE THESIS

Attempts to present and evaluate information and literature relevant to the topic are presented in Chapter 2. Chapter 3 presents the method of analysis used to obtain accurate surface reference and satellite reflectance data, and the statistical technique used to analyse the data. The results of the statistical analyses, utilizing the Canonical Correlation Analysis are presented, and an interpretation of the results is attempted in Chapter 4. Chapter 5 concludes the thesis, emphasising the most important aspects revealed in the study.

CHAPTER 2

2. LITERATURE REVIEW

2.1 INTRODUCTION

Investigations into the spatial and temporal nature of satellite data have shown that satellite imagery can be a valuable monitoring tool for assessing and evaluating water resources (McGinnis et al, 1980). Table 2.1 presents a few of the fields of study in which satellite imagery has been applied. The potential applications would be greatly increased if the data detected by the satellite could be accurately quantified.

This review presents some of the factors that remote sensing researchers, working in the field of water quality, have recognised as requiring attention if the quantification of water quality conditions using satellite imagery is to be successfully achieved.

TABLE 2.1: SOME EXAMPLES OF WATER RESOURCES INVESTIGATIONS CARRIED OUT USING SATELLITE-DERIVED DATA

INVESTIGATIONS INTO WATER BODY DYNAMICS

Reservoir monitoring
Seasonal changes
Circulation patterns
Establish current conditions of lake
Monitor nature, extent and source of possible changes
Set up, calibrate and verify real time estuarine water quality models
Mixing between fresh and sea water

HAVE BEEN RESEARCHED BY:
Gupta and Bodechtel, (1982)
Burgy, (1973)
Moore, (1980)
Shih and Gervin, (1980)
Bukata et al, (1975)
Hill and Graham, (1980).

INVESTIGATIONS INTO ENVIRONMENTAL PROBLEMS

Siltation/sedimentation
Distribution and transport of sediment
Trophic status/eutrophication
Biomass energy balance
Reliable alarm facility
Contaminants due to erosion, run-off and industrial discharge

HAVE BEEN RESEARCHED BY:
Muralikrishna and Rao, (1982)
Moore, (1980)
Thiruvengadachari et al, (1980)
Munday et al, (1979)
Gupta and Bodechtel, (1982)
Herschy, (1980)
Welby et al, (1980)
Sydor et al, (1978)
Witzig and Whitehurst, (1981)
Verdin, (1985).

INVESTIGATIONS INTO RESOURCE MANAGEMENT

Tourism/Recreation
Commercial
Agriculture
Irrigation
Water quality
Simultaneous view of other water bodies
Comprehensive data base
Planning and evaluating the results of water management activities

HAVE BEEN RESEARCHED BY
Scarpace et al, (1979)
Khorram, (1981)
Thiruvengadachari et al, (1980)
Carpenter, (1982).

OTHER INVESTIGATIONS

Cheaper alternatives for limnological surveys
Flood control
Ground water recharge
Drainage networks
Establishment and enforcement of regulations
Understanding the system
Environmental impact of land use practices within surrounding environment

HAVE BEEN RESEARCHED BY:
Lindell, (1981)
Thiruvengadachari et al, (1983)
Jarman, (1973)
Khorram, (1981).

2.2 SURFACE REFERENCE DATA CONSIDERATIONS

Landsat's ability to detect water quality conditions in an impoundment can only be accurately assessed when used in conjunction and calibrated with, water quality data obtained simultaneously with the satellite's overpass (Anderson, 1979; Schaeffer et al, 1979; LeCroy, 1982; Whitlock et al, 1982; Khorram and Cheshire, 1983; Thiruvengadachari et al, 1983). Without accurate surface reference data, the relationship between water quality conditions and satellite reflectance data cannot be adequately calibrated and any inaccuracies in the data collection or analysis will result in erroneous conclusions.

2.2.1 Concurrent Collection of Surface and Satellite Data

The collection of water quality data carried out simultaneously with the satellite overflight is essential to avoid distortions due to significant atmospheric, hydraulic and solar influences (LeCroy, 1982; Whitlock et al, 1982). Some researchers have found this requirement to be physically and economically unachievable and yet procedures to correct for the time lapse between overflights and sampling have not been discussed in the available literature (Kuo and Blair, 1976). As short a time lapse as possible between the overpass and data sampling has been recommended by many investigators.

2.2.2 Sampling Depth

The problem of depth is considered to be very important where bottom depth in shallow waters can influence relationships and reflectance values (McCluney, 1974; Whitlock et al, 1978; Khorram, 1981; Lillesand et al, 1983). Alternatively sampling to secchi disc depth (m) has been considered appropriate (Thiruvengadachari et al, 1983). Secchi disc measurements give an indication of water clarity but are criticised because of their crudity and the fact the measurement is dependent on cloud cover and an individual's acuity of vision (Scarpace et al, 1979; Lillesand et al, 1983).

2.2.3 Identification of Sampling Sites

The identification of sampling sites is a problem faced by many researchers, particularly when repetitive coverage from the same sampling point is required. Vandalism often prevents the use of marker buoys and determining sampling positions from landmarks can be difficult, especially when sampling is carried out on large water bodies.

The importance of accurately locating sampling sites in order to relate to specific satellite pixels cannot be overemphasised and is discussed in Section 2.4.4.

2.2.4 Sampling Design

Daniel and Wood (1971), Harris et al (1976), Boland et al (1979), Carpenter (1982) and Mace (1983), all point out that the design of the sampling program is crucial. A major source of error can be introduced into data if the surface reference data obtained is not representative of the whole range of water quality conditions present in the impoundment at that time. Prior knowledge of the idiosyncrasies of the impoundment is highly advantageous. Mace (1983), suggested that sampling points should be located "to minimise the number of points necessary to characterise lake water quality and to ensure that their distribution matches both the variability inherent in the water and the resolution of the remote sensing system" Thornton et al (1982), point out that the "sample design should allow the characterization of the system as well as permit comparative evaluation through time and/or across systems"

2.2.5 Preservation, Storage and Analysis of Surface Reference Data

Thiruvengadachari et al (1983), point out that fundamental to the collection of water quality samples is the preservation, storage and analysis of the data. Analyses should be consistently accurate and should be performed as soon as possible after data collection (Whitlock et al, 1978). Turbidity and chlorophyll a samples, in particular, change irreversibly due to inadequate preservation and storage (Sartory, 1982).

2.3 WATER QUALITY PARAMETERS

In an attempt to determine the range of variables that can be detected by remote sensing satellites, a number of water quality parameters have been investigated for possible correlation with reflectance data. Chlorophyll a and turbidity are two water quality conditions that can be directly sensed by Landsat (Harris et al, 1976; Carpenter and Carpenter, 1983; Ulbricht, 1983), refer to Section 1.5. Parameters which directly affect reflectance values in one or all of the four wavebands can be directly measured when calibrated with surface reference data. For the purpose of this thesis these parameters will be called 'direct' parameters. The parameters which do not themselves affect reflectance values, but instead do so via one of the direct parameters will be called 'indirect' parameters (Iwanski et al, 1980). Table 2.2 presents a list of parameters that have been investigated.

TABLE 2.2: EXAMPLES OF WATER QUALITY PARAMETERS SO FAR INVESTIGATED

(a) Parameters with direct correlation with reflectance intensity

Chlorophyll a/algae
Suspended sediments
Temperature (sensor dependent)
Secchi disc depth
Light transmission
Colour
Sediment transport and circulation patterns
Particulate organic carbon
Phaeopigments
Chlorophyll c and b
Iron
Tannin and lignin

(b) Parameters with indirect correlation with reflectance intensity

Conductivity
Salinity
Dissolved oxygen
Alkalinity
Calcium
Nitrite
Nitrate
Magnesium
Total organic carbon
Dissolved organic carbon
Total phosphorus
Total nitrogen
Ammonia
Kjeldahl nitrogen
Dissolved and total orthophosphate
Wind speed
Filtered and unfiltered water

2.3.1 Water Quality Conditions as Sensed via Indirect Parameters

Of all of the parameters investigated there are few that can be directly sensed. Most of the parameters do not reflect light in the range measured by the satellite. Indirect relationships between some of the variables, e.g. the presence of chlorophyll a (direct parameter) and the presence of phosphorus and nitrogen (indirect parameters) can indicate correlations with the reflectance bands, but correlations can also be spurious. For instance, Khorram and Cheshire (1983), in their work on the Neuse River Estuary in North Carolina, U.S.A., indicated that reflectance data was significantly correlated with salinity. It is unlikely, however, that salinity can be detected by the satellite, instead, it may be a variation of chlorophyll a associated with variations in salinity that the satellite is measuring. In addition, an indirect relationship such as this can really only be applied in a steady state condition where the situation is localised.

Grimshaw et al (1980), report that variables such as log total orthosphosphate and log total alkalinity did not contribute to the multiple regression in a highly significant manner. Similarly Shimoda et al (1984), found that there was no correlation between the indirect variables of oxygen saturation, acid soluble calcium concentrations or acid soluble magnesium concentrations and satellite reflectance data.

2.3.2 Direct Water Quality Conditions: Chlorophyll a and Turbidity

The presence of chlorophyll a and turbidity in impoundments has long been recognised on satellite imagery and attempts have been made to quantify these conditions (Yarger et al, 1973; Bukata and Bruton, 1974; Bukata et al, 1975; Rogers et al, 1975; Harris et al, 1976; McHenry et al, 1976; Ritchie et al, 1976; Stortz et al, 1976; Chagarlamudi et al, 1979; Munday et al, 1979; Scarpace et al, 1979; Schaeffer et al, 1979; Sheng and Lick, 1979; Hill and Graham, 1980; Iwanski et al, 1980; Moore, 1980; Welby et al, 1980; Lindell, 1981; Carpenter, 1982; Ulbricht, 1983; Hilton, 1984). The results of the investigations have all shown that Landsat does indeed detect chlorophyll a and turbidity.

Bukata et al (1974), determined that band 4 clearly delineated the bottom contours of the impoundment, if surface turbidity was relatively low and the maximum optical penetration was over 14 metres. Band 5 was found to have a linear correlation with turbidity while bands 6 and 7 measured surface chlorophyll a for concentrations of 4 mg/m^3 or more. Muraliskrishna and Rao (1982), indicated that bands 6 and 7 correspond to surface features whereas bands 4 and 5 offer information on subsurface features. Further research has confirmed these claims (Harris et al, 1976; Bartolucci et al, 1977; Scarpace et al, 1979; LeCroy, 1982).

2.3.3 Algae

Algae vary greatly in size, shape and colour. Green algae can consist of individual cells, small colonies of free floating cells or chains of cells forming filaments, and can be found in all waters. Blue-green algae occur in clumps or as filaments and can on occasion appear as a thick green scum on the water surface. Diatoms are usually brown or yellow and can be suspended in the water column or attached to other plants. Flagellates are all shapes and colours and are capable of independent movement (Powling, 1977). All algae contain chlorophyll a but the different colours of the various algal taxa are due to the presence of a variety of other pigments, which will presumably result in different reflectance signatures. For example Lindell (1981), analysed reflectance signals with respect to different algal species dominating different parts of a lake and indicated that the different types of algae may emit different reflectances. Hilton (1984), reports that limited work has been done on obtaining equivalent multispectral scanner spectral intensities of the major algal groups and the research that has been carried out is usually under laboratory conditions or from aircraft remote sensing (Lekan and Coney, 1982). Hilton (1984), suggests that "the use of sensors with more channels could allow spectral signatures of different groups of algae to be typed and mapped. It is unlikely that remote sensing will ever get down to genus level let alone species level but it could be useful in improving sampling strategy".

Yentsch and Phinney (1982) and Carpenter (1982), make the point that in the chemical analysis of chlorophyll _a_ a combination of degradation products including phaeopigments, detrital material and dissolved fluorescent material are measured and that the variability in accessory pigmentation can be a major source of error in any analysis. The variations in chlorophyll that occur from lake to lake and within lakes may provide a key to the assessment of satellite data (Carpenter, 1982). On this issue little research has been carried out (Witzig and Whitehurst, 1981; Carpenter, 1982; Hilton, 1984).

2.3.4. Vertical Migration of Algae

Algae migrate vertically in the water column in a light orientated response (Wetzel, 1983). This vertical migration contributes significantly to the changing conditions in an impoundment and can cause a distinct error in the surface reference data collected hours or days after the satellite overpass (Klemas, 1976). Harris _et al_ (1976), report that "it is possible that surface values of chlorophyll may be nowhere similar to the samples taken due to the microstratification of phytoplankton". Ulbricht (1983), expresses the view that algae can only be detected by satellites due to their presence near or on the surface of the water by bands 6 and 7, and just under the surface by bands 4 and 5.

2.3.5 Horizontal Movement of Algae

Mainly as a result of wind and water movement, horizontal variations in algae are fairly significant, particularly in close proximity to the littorial zone (Wetzel, 1983). Wind has a great impact on algal movement and on the resuspension of algae. For example, diatoms are particularly heavy and therefore usually mix and move in response to wind or current action (Mrs. S. Young* - pers. comm.). Some lack of correlation could therefore occur between the detection and the quantification of chlorophyll a, as a result of these horizontal variations.

2.3.6 Activity Stages of Algae

Algal cells increase or decrease in numbers, sink, rest, metabolize and decay, and depending on the proportion of cells in the various physiological stages, the rate of growth and size of the population will differ (Wetzel, 1983). Scarpace et al (1979), report that a eutrophic lake could be classified as being oligotrophic if it were sampled the day after a large algal bloom had died off.

Phaeopigments are the products of chlorophyll breakdown, in other words, of decaying algae. The relative proportions of phaeopigment to the total chlorophyll a pigment is an

* Mrs S. Young - Hydrological Research Institute, Department of Water Affairs.

indication of the health of the algae in an impoundment. The detection of phaeopigments using satellite data is something that has not been pursued in any great detail but it is possible that differences in reflectance may exist between healthy and decaying algae.

2.3.7 The Relationship between Algae and Turbidity

The remote sensing researcher should be aware of the fact that sunlight as well as nutrients such as nitrogen and phosphorus, are required for algae to grow. The presence therefore, of suspended sediments can have two conflicting effects on algal growth. Firstly, the prevention of light penetration by sediments in suspension inhibits algal production. Secondly, "phosphate adsorbed onto sediments can make up a large proportion of the total phosphate available for algal growth in an impoundment" (Grobler and Davies, 1981). Harris et al (1976), report that the presence of suspended solids undoubtedly interferes with the reflectance values of low chlorophyll levels and may overwhelm small to moderate values of surface chlorophyll. These researchers indicate that if there is low radiance*, surface algae will show up in bands 4 and 5 whereas if there is high radiance they will show up in bands 6 and 7.

* The terms radiance and reflectance are used interchangeably in the literature.

In addition, turbidity is a measure of light penetration and absorbance and therefore inorganic as well as organic suspended solids will be included in the turbidity measured by nephelometry. A problem can arise therefore in situations when there is a low turbidity and high chlorophyll a (Holmquist, 1977; Hilton, 1984; Verdin, 1985).

It becomes apparent that the relationship between turbidity and algae is complex and highly interrelated. This problem has been recognised by scientists and the consequences of this interrelatedness will be discussed in Section 2.4.7 and Section 2.5.2.

2.4 SATELLITE REFLECTANCE DATA CONSIDERATIONS

Landsat's sensors (refer to Section 1.4) were specifically designed and optimised for observations of land cover and terrestrial resources rather than for water resources. Therefore the data received from the satellite have not been considered to be well suited to aquatic applications (Carpenter, 1982; Hilton, 1984). Nevertheless, the potential offered by such a data source could not be overlooked and, despite the difficulties, a lot of research has been undertaken in the water resources field (Ackermann, 1974; Skibitzke, 1976).

The major factors to be considered when using satellite reflectance data in the field of water quality determination are discussed below.

2.4.1 Corrections

In the process of capturing and transmitting data from and to earth, Landsat MSS data can be distorted, mainly due to satellite or terrestrial effects or limitations in the sensor systems. "Radiometrically, the digital numbers do not always accurately relate to scene energy levels; geometrically, image positions of features do not accurately relate to map positions" (Lillesand and Kiefer, 1979).

2.4.2 Geometric corrections

In order to obtain quantitative results and to enable precise registration of an image with reference points, the correction of major distortions inherent in Landsat MSS data are considered to be necessary by most researchers (Schaeffer et al, 1979). The distortions are mainly a result of, firstly, the satellites variation in altitude, attitude and velocity. Secondly, of the sensors detectors, optics and scan mechanism and lastly, variations in terrain, perspective and map projection (Palmer, 1981). Standard geometric transformations are usually applied to correct the data.

2.4.3 Radiometric Corrections

The radiance values obtained from MSS data are not always equivalent to ground reflectance values due to atmospheric attenuation, haze and the angle of the sun. These three factors are a major source of error and many algorithms have been suggested in order to correct images (Bukata et al, 1974; Holmquist, 1977; Welby et al, 1980; Aranuvachapun and LeBlond, 1981; MacFarlane and Robinson, 1984).

Atmospheric effects and haze have been estimated by researchers using radiation values obtained from airports and clear lakes (Holmquist, 1977; Scarpace et al, 1979; Lillesand et al, 1983; Verdin, 1985). Problems occur though, where features of this nature are not present or are too small to recognise.

The position of the sun at the time of image capture has a strong influence on reflectance values (Ritchie et al, 1976). Carpenter (1982), proposes that the sun's elevation is an important predictor in models of turbidity and chlorophyll pigments. Oppositely Munday et al (1979), report that the solar angle has a negligible effect on their regression analysis and instead use a method of data reduction known as chromaticity analysis, which permits the adjustment of atmospheric variation between dates. The Munday et al noise correction technique "suppresses noise when all bands suffer radiance changes in the same proportion while leaving spectral properties of the data unaffected". These researchers claim that their technique can be applied to new data that lack surface calibration for standardizing the data. LeCroy (1982), recommends that "variations in solar zenith angle should be normalized or accounted for in the data reduction process as well as atmospheric effects".

Verdin (1985) proposes that "Failure to account for atmospheric effects when working with multidate imagery can potentially lead to erroneous assessments of reservoir trophic state".

Sometimes a malfunctioning detector may cause image lines to be defective thereby resulting in a striping or banding effect on the image. Striping in the reflectance data can have a big influence on water quality monitoring due to the low reflectances of water (Shimoda et al, 1984). In order to establish a greater degree of uniformity, researchers have recalibrated the data to improve homogeneity as in the case of Carpenter (1982), or have used statistical techniques such as mean and standard deviations matching, histogram equalization and random noise additions as proposed by Shimoda et al, (1984).

2.4.4 Sampling Site/Pixel Registration

Substantial errors can be introduced into an analysis of the relationship between water quality conditions and satellite reflectance data if sampling positions are inaccurately located and registered with the satellites pixels values (Carpenter, 1982; Lillesand et al, 1983; Mace, 1983; Verdin, 1985). Attempts to overcome this problem of misregistration have been tackled in various ways. Munday et al (1979), and Grimshaw et al (1980), undertook surveys of all the sampling positions. Khorram and Cheshire (1983), located sites on a nautical chart. Many other researchers have used a pixel averaging system so that the effect of possible inaccuracies of locating a sampling site would be minimised (Shih and Gervin, 1980). Pixel averaging is a widely recognised technique used to smooth data. Averaging effectively increases the size of the resolution element and supposedly removes random errors and noise without substantially degrading the imagery (Whitlock et al, 1982; Mace, 1983). Variations between 36 pixel averages (Bukata et al, 1975) and 3 x 3 pixel windows have been used (LeCroy, 1982; Lillesand et al, 1983; Shimoda et al, 1984).

In most cases research has shown that the use of more than one pixel value is necessary and averaging of the values helps minimise the uncertainty and possible spurious variations due to the inexact location of sites.

2.4.5 Water/Land Delineation

Although water bodies are usually easily recognisable on a Landsat image, delineation of the water/land boundary is sometimes not clear. This indistinction can be due to reed beds growing along the edges of the impoundment, the presence of algae or turbidity or the 80 m resolution of the satellite which picks up mixels. Mixels, in this instance, are a mixed land and water pixels.

In order to classify a water pixel band 7, which shows up the greatest difference between land and water, is often used to delimit the boundary. Schaeffer et al (1979), Thiruvengadachari et al (1980), Lindell (1981), Hilton (1984), Khorram and Cheshire (1983), Lillesand et al (1983) and Mace (1983) are a few of the researchers who have used band 7 as a means of separating land from water.

Supervised classification is a technique whereby a researcher identifies surface cover categories visible on the image, either by the chromatic signature or by surface reference data, and uses a computer based routine to convert reflectance data into sets of specific, discrete classes (Lillesand and Kiefer, 1979). Supervised classification has also been used to determine the land/water boundary (Bukata and Bruton, 1974; Muraliskrishna and Rao, 1982; Graham and Hill, 1983).

2.4.6 Colour Coding

The interpretation of relative differences of water quality conditions in an impoundment can be improved by certain image enhancement techniques. A technique frequently used is colour coding which represents reflectance values as colours with a colour code representing a concentration scale. Therefore different colours correspond to designated reflectance values and in turn, interpretations can be made on the basis of relative amounts of each colour present (Iwanski et al, 1980; Khorram and Cheshire, 1983; Shimoda et al, 1984). Experience is required to classify subtle differences in colour (Holmquist, 1977; Lindell, 1981), but often colour coding can give an immediately discernable picture of distribution patterns of reflectances in an impoundment.

2.4.7 Multicollinearity

A very important feature of Landsat's MSS, with respect to examining water quality conditions, is the multi-collinearity of the reflectance data (Shih and Gervin, 1980). An inspection of colour coded images indicates that water quality conditions are usually visible in at least three of the four bands depending on the concentrations. Bands 4, 5 and 6 are often correlated to turbidity while band 7 usually correlates with high concentrations of chlorophyll a (Bukata et al, 1975; Harris et al, 1976; Holmquist, 1977; Boland et al, 1979; Munday et al, 1979; Le Croy, 1982; Muraliskrishna and Rao, 1982).

It has been established that information from more than one band width is required to predict water quality conditions with any reasonable degree of accuracy (Grimshaw et al, 1980).

2.4.8 General

Finally, on a general note, many researchers mention difficulties associated with unpredictable circumstances such as satellite failure, uncoordinated overflight/ sampling operations and the inability to read computer compatible tapes.

2.5 STATISTICAL CONSIDERATIONS

Statistical analyses in the form of multi-variate statistical techniques are necessary to determine the relationship between surface reference data and satellite reflectance data (Boland et al, 1979; Scarpace et al, 1979; Shih and Gervin, 1980; Lindell, 1981; Whitlock et al, 1982; Khorram and Cheshire, 1983; Lillesand et al, 1983; Mace, 1983; Shimoda et al, 1984) Two important issues which need discussing are representativeness and interdependence of the data.

2.5.1 Representativeness

The poor fit sometimes achieved between water quality variables and reflectance data in regression equations has been of vital concern to many researchers. This problem has been attributed to an inadequate range of water quality data used to obtain the regression equations (Boland et al, 1979; Carpenter, 1982). A requirement of regression analysis if it is to provide useful predictive models, is that the parameters cover a representative range of values (Carpenter, 1982). Over a restricted range of values, a statistical relationship can only be valid if the conditions are constant. The greater the range of data obtained covering the full complement of conditions, the more successful the regression equation will be. In an effort to space data evenly along the full range of values, sampling sites have been chosen specifically to include a representative range of problem areas (LeCroy, 1982). Lillesand et al (1983), have gone to the other extreme and avoid any apparent extraneous scene element such as algal blooms that could cause anomalies in the relationship. This approach can be criticised in that deliberate exclusion of high concentrations of algae will cause inaccurate calibration of water quality conditions.

In addition, a standard practice is to transform to logarithm, turbidity and chlorophyll, in an attempt to reduce the variance of the larger values. Log transformations have been used by numerous researchers

(Munday et al, 1979; Grimshaw et al, 1980; Aranuvachapun and LeBlond, 1981; Carpenter, 1982).

It is, therefore, imperative that information on the full range of values present in the water body at the time of sampling, be included in the statistical analysis in order to ensure statistical representativeness of the relevant conditions (Boland et al, 1979; LeCroy, 1982).

2.5.2 Interdependence

The interdependence between each of the four reflectance bands and between each of the surface reference variables amounts to dealing with a high level of multicollinearity (Grimshaw et al, 1980; Whitlock et al, 1982; Khorram and Cheshire, 1983). Some researchers have ignored this factor and have excluded reflectance bands with the idea in mind that the band excluded does not contain satisfactory information (Carpenter, 1982; Mace, 1983; Verdin, 1985).

Carpenter decided that band 7 data contributed very little to the relationship between satellite reflectance data and surface reference data and therefore excluded band 7 from his models. Boland et al (1979), determined that although band 7 had "the poorest discrimination and the lowest information content of any of the bands, it weighed heavily and consistently in all models. When this band was excluded, the resulting models were statistically unsatisfactory".

Other researchers have employed linear regression techniques that regress one Y variable with multiple X variables (Holmquist, 1977; Aranuvachapun et LeBlond, 1981; LeCroy, 1982). Shih and Gervin (1980), used ridge regression analysis to eliminate the multicollinearity.

Some researchers have recognised the importance of the multicollinearity evident between water quality variables and reflectance bands and attempts have been made to examine all of the statistical parameters involved (Witzig and Whitehurst, 1981; Whitlock et al, 1982; Khorram and Cheshire, 1983). Carpenter (1982), suggested that canonical variate analysis could be undertaken to establish quantitative relationships.

2.5.3 Statistical Techniques

A variety of statistical techniques have been used in attempts to calibrate reflectance values with surface reference data. The variety and number of methods illustrates the difficulties experienced in determining the relationship and emphasises the point that more than one approach can be used to analyse the data. The types of analyses used by researchers vary from simple linear regression and principle components analysis to stepwise multiple linear regression and ridge regression analysis. Classification procedures, enhancement techniques and pattern recognition have been used by many other researchers in conjunction with other statistical techniques (Jarman, 1973; Bartolucci et al, 1977; Holmquist, 1977; Gupta and Bodechtel, 1982; Lekan and Coney, 1982; Muralikrishna and Rao, 1982; Ulbricht, 1983).

2.5.4 The Modelling of Water Quality Conditions using Satellite Reflectance Data

Multiple linear regression equations have been produced illustrating the relationships that have been established between water quality conditions and satellite reflectance values.

Boland et al (1979), undertook an extensive comprehensive study of selected Illinois water bodies. The equations that were developed provided relative estimates of chlorophyll and secchi disc depth (as well as other factors) and were used to develop generalised rankings of trophic classification of lakes.

Carpenter (1982), investigated lakes in Australia and attempted to model one reservoir using six days of data. In order to generate regression equation models that were not date specific, two significant predictions were included; the trigonometric sine of the sun's elevation angle, in an attempt to account for variation in scene brightness between different dates; and the time of sampling, as a predictor for pigment (Carpenter and Carpenter, 1983).

In summary, in the search for reasonably accurate equations to predict water quality conditions using satellite data it becomes apparent that the following factors need to be considered:

(1) Multi-variate linear regression statistical techniques are required which include all the reflectance bands and water quality parameters.

(2) The accurate alignment of sampling position with the corresponding Landsat pixel is essential.

(3) The data used has to be representative of the conditions within the impoundment.

(4) Corrections for sun's angle effects and dehazing are advisable.

CHAPTER 3

3. METHOD OF ANALYSIS

3.1 SURFACE REFERENCE DATA

In order to achieve the objective of the project, accurate information of the conditions in the water body were required. The collection of surface reference data was therefore of prime importance.

It is necessary to point out differences in terminology here. Many studies have been undertaken in which the term "ground truth data" appears. This term was unsuitable for our purposes considering firstly that we were dealing with a water surface and not with the ground. Secondly, one cannot expect a single measurement to represent the 'truth' of a whole 80 m x 80 m pixel. The term 'surface reference data' was preferred because it acknowledges the limitations of a single reference point in time and space.

3.1.1 The Sampling Network

In order to assess Landsat as an aid to water quality surveillance, Roodeplaat Dam, situated 30 km north east of Pretoria and covering an area of 398 hectares, was chosen as

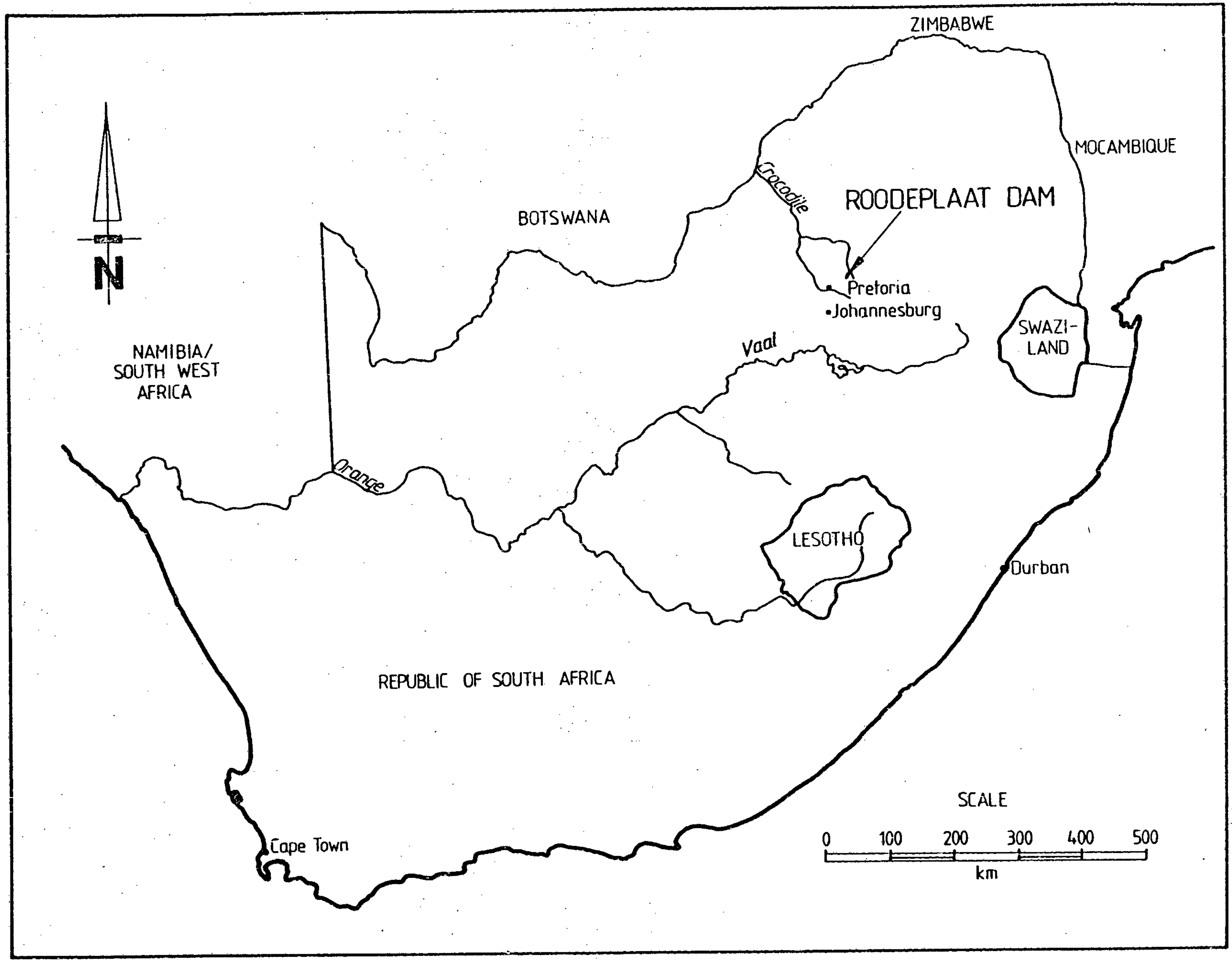

FIGURE 3.1 : LOCATION OF ROODEPLAAT DAM

the site for an extensive sampling program (Figure 3.1). Tables 3.1 and 3.2 present the characteristics of Roodeplaat Dam and its catchment.

Roodeplaat Dam has two arms, the western arm is long and fairly narrow, while the eastern arm is fairly broad and open. The major rivers flowing into the impoundment are the Hartbeesspruit and the Pienaars River, which enter the impoundment at the southern end of the western arm and the Edendalespruit which enters at the eastern side of the impoundment. Most pollution enters the impoundment from the Hartbeesspruit and Pienaars rivers, which flow through Pretoria's eastern suburbs. Therefore it is in the western arm of the impoundment where concentrations of sediment and chlorophyll a are highest. The water in the eastern main body of the impoundment generally has lower chlorophyll a and turbidity values.

3.1.2 Sampling Undertaken Concurrently with the Satellites Overflight

Landsat passes over the Johannesburg/Pretoria area at approximately 09h25 and records the whole scene in approximately 27 seconds. Weather conditions in the area fluctuate, with cloudy conditions around noon being apparent in summer, and hazy conditions due to dust etc., being manifest in winter. It is therefore fortunate that the satellite overflights are early in the day. It was

TABLE 3.1: CHARACTERISTICS OF ROODEPLAAT DAM AND ITS CATCHMENT +

Geographical location	25° 37'S; 28° 22'E
Magisterial district	Pretoria
Catchment type	Urban/industrial, farmland, mines
Usage of dam	Recreation, potable water
Catchment area	668 km^2
Inflowing rivers	Pienaars River, Hartbeesspruit, Edendalespruit.
Dam wall completed	1959
*F.S.L. volume	41,907 x 10^6 m^3
F.S.L. area	3,96 km^2
F.S.L. maximum depth	43 m
F.S.L mean depth	10,6 m

*F.S.L = full supply level

\+ Modified from: Pieterse and Bruwer, 1980.

TABLE 3.2: AVERAGE TERM ANNUAL HYDROLOGICAL CHARACTERISTICS OF ROODEPLAAT DAM +

	*Average mean	*C.V. %
Volume x 10^6 m^3	41,425	3,3
Area km^2	3,898	2,6
Mean depth (m)	10,57	0,7
Annual inflow x 10^6 m^3	59,01	
Annual outflow x 10^6 m^3	55,68	
Retention time a (years)	0,70	

*Average mean is based on monthly values and an annual cycle;
Period: January to December (1970-1978);
C.V. = coefficient of variation

\+ Modified from: Pieterse and Bruwer, 1980.

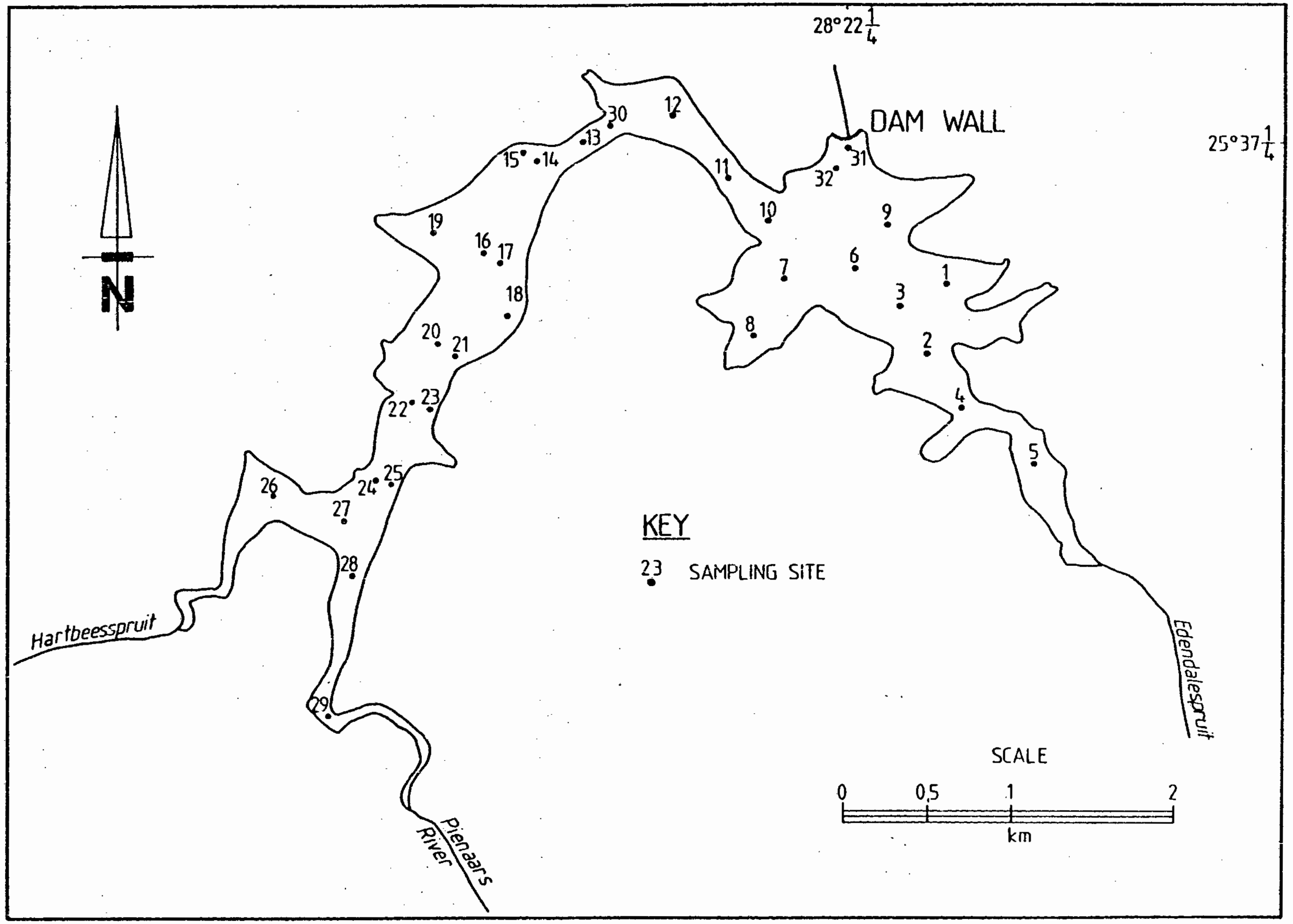

FIGURE 3.2 : ROODEPLAAT DAM SHOWING SAMPLING SITES: 32 POINTS

imperative that the surface reference data were obtained as near as possible to the time of overflight and a routine became established in which, one hour before each overflight, two HRI boats and well instructed personnel would be on the water collecting their first water samples. Generally all of the samples were collected within two hours. It also became apparent that the sampling team had to be prepared to sample at every opportunity as the chances of completely cloud free weather were low.

Roodeplaat Dam had a previously existing network of seven sampling sites and it was decided in September 1981 to increase the number of sites to 32, including the existing sampling sites. The sampling network was established on a randomly distributed basis giving good coverage to all areas within the impoundment (Figure 3.2). Where available, existing stabilised platforms or buoys were used to mark the sampling positions.

For the first four months of this project, two separate sets of samples were taken, 50 metres apart, at each of the 32 sampling sites in order to examine how representative were the sampled data. In the following analysis, data collected from the 32 sampling sites were examined.

3.1.3 Water Quality Variables

The water quality data collected for analysis during each overflight were as follows:

(i) Surface chlorophyll a (μg/ℓ)

(ii) Integrated chlorophyll a (μg/ℓ)

(iii) Secchi disc depth (m)

(iv) Surface turbidity (NTU)

(v) Integrated turbidity (NTU)

3.1.4 Sampling Techniques and Equipment

Hydrological Research Institute (HRI) personnel used standard sampling techniques to collect the water quality samples. Surface samples of chlorophyll and turbidity were taken directly from the surface of the water using buckets and transferred to 1 litre plastic bottles.

Integrated samples were obtained using hosepipe sampling. A 1.9 cm diameter hosepipe with a weighted end was lowered into the water as far as the secchi disc visibility depth. The weighted end was then raised to the surface capturing the water column in the pipe.

Secchi disc depths were determined using standard black and white, 30 cm diameter secchi discs, suspended from the shaded side of the boat. The secchi depth was used to indicate the depth to which water had to be sampled when taking the integrated samples.

3.1.5 Analysis of Water Samples

The water quality samples were analysed by the staff of the Chemical and Biological Analytical Service (HRI) on the same day immediately after the sampling operation. The chlorophyll a samples were analysed by the method described in Appendix A (Truter, 1981; Sartory, 1982). Turbidity analyses were carried out using a Hach Turbidimeter and measured in nephelometric turbidity units (NTU).

3.1.6 Storage of data

The data were then recorded on data coding forms, punched onto computer cards and stored on data files in the format given in Appendix B. The surface reference data for each of the six days under analysis are presented in Appendix C.

3.2 SATELLITE REFLECTANCE DATA

The 14th October, 1981 saw the first simultaneous Landsat overflight/water quality sampling operation take place on Roodeplaat Dam. It was the first of many attempts to obtain data but the efforts of the research team were continually thwarted by cloud and rain and by the breakdown of Landsat 2 in February 1982. Eventually a total of six attempts proved to be successful throughout the period October 1981 to November 1982 and these are discussed in detail. Although it would have been preferred to have obtained data for each season of the year this was not possible.

3.2.1 The Computer Compatible Tapes

The Computer Compatible Tapes (CCT's), were obtained from the Satellite Remote Sensing Centre (SRSC) at Hartbeesthoek. All of the tapes were corrected for sun's angle and were dehazed in a standard manner at Hartbeesthoek in order to maintain uniformity. There was one problem. Landsat 2 broke down in February 1982. Landsat 3 quickly took over but there were difficulties in data capture and eventually by the end of the project Landsat 4 was in operation. This meant that data were collected by three different satellites and therefore were subject to different data processing. Without adequate image processing facilities or expertise, it was considered to be impossible for the researcher to take into consideration these differences, be they large or small, and therefore this problem was not investigated.

Information concerning the CCT's obtained for the Landsat Water Quality Project for Roodeplaat Dam is given in Table 3.3

TABLE 3.3: INFORMATION ON THE COMPUTER COMPATIBLE TAPES USED IN THE LANDSAT WATER QUALITY PROJECT

WRS*	DATE	SUN'S ANGLE	IDENTITY NO.+
182/78	81.10.14	48° 36'	22457-07143
182/78	81.11.01	51° 80'	22475-07150
182/78	81.12.07	52° 71'	22511-07162
170/78	82.09.13	42° 34'	40058-07293
182/78	82.09.30	46° 48'	31670-07231
170/78	82.11.16	50° 40'	40122-07302

* World Reference System
\+ The individual Landsats are identified by the first digit of the identity number.

The digital data from the tapes were stored on the mainframe departmental computer system and any further manipulations and statistical analyses were carried out using the digital data.

The data were accessed by an image processing system originally called CATNIPS (Cape Town Image Processing Suite) and modified for use on the departmental system (Maaren, 1981).

3.2.2 Colour Coding of the Reflectance Data

The initial analysis of the satellite reflectance data was carried out on the image processing system at the SRSC. Roodeplaat Dam was located and the surrounding land areas

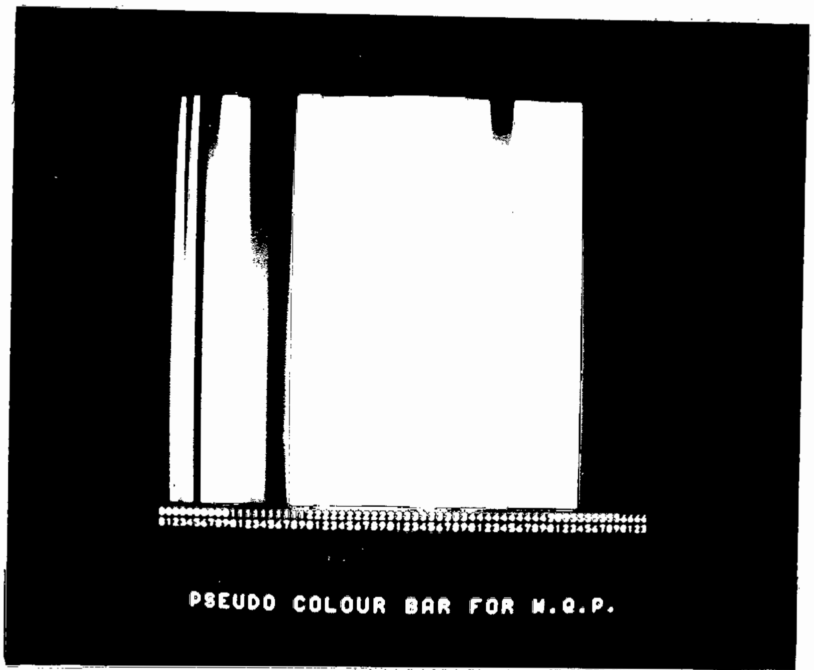

Plate 3.1: Colour Coded Bar showing the full range of 0-255 reflectance values divided into 25 colour classes

were masked out using band 7 values as the land/water delimiter (refer to Section 2.4.5). The reflectance values within the impoundment in each reflectance band were then colour coded (refer to Section 2.4.6) using a predetermined coded pseudo colour key bar (Plate 3.1). The satellite reflectance values are indicated on the horizontal axis of the bar. The full range of 0-255 reflectance values was divided into 25 classes. Each colour on the bar represented an actual reflectance interval of 4 x n reflectance units where n = 1 to 5. For example, from left to right, the darkest blue colour labelled 0 represented reflectance values of 0 to 3, therefore the lowest values recorded by the satellite. The light blue colour labelled 2 represented reflectance values of 8 to 11, and the yellow

(4) represented 16 to 19 digital reflectance values. The green shade, labelled 6 and 7 (with n=2) represented digital reflectance values 24 to 31.

The colour coded images in each spectral band for three of the days analysed, presented on Plates 4.1 to 4.12, provided a visual impression of reflectance conditions in the impoundment at a glance (refer to Section 4.2).

3.2.3 Unsupervised Classification of the Reflectance Data

The visual data, although helpful, were considered to provide insufficient quantifiable information and the image processing system CATNIPS was used to undertake any further classification and analysis.

Unsupervised classification, or "numerical taxonomy", splits pixels into groups or clusters in feature space "such that the distances between points within a cluster are a miniumum while the distances between clusters are a maximum" (Piper, 1981). Unsupervised classification using all four reflectance bands was undertaken and results are discussed in Section 4.3.

3.2.4 The Alignment of Reflectance Data with Surface Reference Data

A problem arose with the digital data when trying to accurately align pixel values with their corresponding surface reference sampling points. This matter of cartographic registration could greatly affect results and therefore a mathematical method for estimating pixel position was investigated (refer to Section 2.4.4).

The most accurate means of achieving this alignment obviously would be by obtaining the geometric latitude and longitude of both sampling position and pixel position. Unfortunately geometric positioning was not included with the satellite data and manually assessing latitudes and longitudes for both the satellite data and the sampling sites was time consuming. Therefore alternative methods had to be investigated. Sampling sites were identified on the impoundment using suitable landmarks, which in turn, could be recognised on the satellite image. In order to identify the pixel corresponding to the sampling position three methods were used. The first method named 'Chance a Pixel' simply meant pinpointing the sampling point on a map of the impoundment (the blocked "9" in Figure 3.3). This technique required a good knowledge of the research area. Although fairly accurate it was decided to improve on the reliability by using Method 2.

Method 2, or 'Average Pixel', involved using the pinpointed pixel of Method 1 and averaging its value together with those of the surrounding pixels (Figure 3.3). Method 3 or 'Weighted Pixel' used the 'Chance a Pixel' (Method 1) and weighted it and the surrounding eight values in the following manner. The 'Chance a Pixel' was given a weighting of 4, all crosswise pixels were weighted by 2 and

Method 1

'Chance A Pixel'

38	35	9	8	14
37	14	9	14	15
35	34	9	14	12
9	6	10	10	9
5	3	7	7	5

Value = 9

Method 2

'Average Pixel'

38	35	9	8	14
37	14	9	14	15
35	34	9	14	12
9	6	10	10	8
5	3	7	7	5

Value = 86 ÷ 8 = 11

Method 3

'Weighted Pixel'

Weightings

1	2	1
2	4	2
1	2	1

Value = 146 ÷ 14 = 10

FIGURE 3.3: THREE DIFFERENT METHODS USED TO DETERMINE PIXEL REFLECTANCE VALUES FOR THE SAMPLING SITES

diagonal pixels by 1. The sum of the pixel values was divided by the sum of all the weights of the pixel values used in the summation.

It is important to note here that due to the fact that pixel reflectance values vary with individual wave bands, and because of the possibility that some sampling points may be positioned near land areas, band 7 values were used to determine the water/land value limit. The computer program was written in such a way that the water/land boundary as determined by band 7 would set the limits for the remaining 3 bands. Any values falling outside the limit would not be included in the estimation and the weightings would be affected accordingly.

In order to determine which of the three methods was best, 'Chance a Pixel', 'Average Pixel' and 'Weighted Pixel' values for two different data sets (81.10.14 and 81.12.07) were examined using the Canonical Correlation Analysis (see Section 3.3.2.). The results are shown in Table 3.4.

Table 3.4 indicated that the 'Weighted Pixel' method produced the best overall results and the decision was made to use the 'Weighted Pixel' method only for subsequent analyses.

TABLE 3.4: CANONICAL CORRELATIONS (r) OBTAINED FOR ROODEPLAAT DAM, USING THREE DIFFERENT PIXEL ALIGNMENT METHODS

Variables	'Chance a Pixel'	'Average Pixel'	'Weighted Pixel'	Date
Surface chlorophyll a	0,76	0,82	0,84	81.10.14 n = 32
and Surface turbidity	0,95	0,93	0,93	81.12.07 n = 28
Integrated chlorophyll a	0,77	0,83	0,86	81.10.14 n = 32
and Integrated turbidity	0,95	0,95	0,95	81.12.07 n = 28

3.3 STATISTICAL ANALYSIS

At the outset it must be stressed that, judging by the literature and the visual satellite imagery, it was assumed that a relationship between specific water quality parameters and satellite reflectance data does exist.

3.3.1 To Establish the Representativeness and Accuracy of the Surface Reference Data

At each sampling site two sets of surface reference data were collected, 50 metres apart from each other. The reason for this was to give an indication of the representativeness and accuracy of the bucket samples collected within a 6400 m^2 area. Simple linear correlation analysis was carried out on all of the 32 duplicate data sets. The statistics for the individual data sets for one day's data (81.12.07) are given in Table 3.5. Table 3.6 shows the results of the linear correlation analysis between the duplicate samples at each point for surface chlorophyll a (r* = 0,94), surface turbidity (r = 0,99), integrated chlorophyll a (r = 0,78) and integrated turbidity (r = 0,97). The results provide evidence that

* r = Correlation coefficient where r = 1 indicates a perfect correlation and r = 0 indicates no correlation at all.

TABLE 3.5: SUMMARY OF STATISTICS FOR SURFACE REFERENCE DATA SETS, ROODEPLAAT DAM 81.12.07

Variable (1) n = 28	Mean	Standard deviation	Coefficient of variation	Smallest value	Largest value	Smallest standard score	Largest standard score	Skewness	Kurtosis
SUCOB	20,7	14,3	0,69	4,60	44,20	-1,13	1,64	0,29	-1,68
SUCOA	21,0	15,1	0,72	2,00	45,80	-1,26	1,64	0,32	-1,67
INCOB	16,6	13,7	0,82	4,30	42,70	-0,90	1,90	0,85	-1,05
INCOA	21,4	16,6	0,8	2,30	43,30	-1,15	1,35	0,04	-2,00
SUTURA	5,6	4,3	0,77	1,10	13,00	-1,04	1,73	0,45	-1,47
SUTURB	5,7	4,5	0,78	1,00	14,00	-1,06	1,85	0,47	-1,32
INTURA	5,8	4,4	0,79	0,90	14,00	-1,07	1,80	0,47	-1,36
INTURB	5,3	3,9	0,74	1,30	13,00	-1,02	1,95	0,68	-1,13

(1) Code: SU = Surface; IN = Integrated; CO = Chlorophyll a (µg/ℓ); TUR = Turbidity (NTU);
A = 1st data set; B = Duplicate data set (2nd)

TABLE 3.6: LINEAR CORRELATIONS (r) OF TWO SETS OF SURFACE REFERENCE DATA FOR 81.12.07

n = 28	SUCOB	SUCOA	INCOB	INCOA	SUTURB	INTURA	INTURB	SUTURA
SUCOB	1,00							
SUCOA	0,94	1,00						
INCOB	0,83	0,76	1,00					
INCOA	0,83	0,90	0,78	1,00				
SUTURB	0,95	0,96	0,83	0,85	1,00			
INTURA	0,94	0,96	0,83	0,83	0,99	1,00		
INTURB	0,94	0,94	0,91	0,88	0,97	0,97	1,00	
SUTURA	0,95	0,98	0,83	0,89	0,99	0,99	0,97	1,00

Code: SU = Surface; IN = Integrated; CO = Chlorophyll a(μg/ℓ); TUR = Turbidity (NTU);
A = 1st data set; B = Duplicate data set (2nd)

the surface reference data are representative of the pixel and of the situation within their respective 6400m^2 pixel area. In addition, the efficiency of the analytical methods used in the water quality analysis was illustrated by the agreement achieved between the duplicate sampling points. Appendix C shows the surface reference data collected concurrently with each satellite overflight. The mean of the two sets of data are given for the first three overflights. Duplicate samples were not taken for the remaining three overflights.

To deal with any possible lack of linearity, log transformation of the surface reference data was used. As seen in Table 3.5 the data in this instance proved to be positively skewed with a negative kurtosis, thereby requiring a transform.

The means of the duplicate samples were then established and a linear correlation analysis of the logs of the four prime independent variables showed some important relationships. Table 3.7 gives the statistical characteristics of the log transformed data sets and shows that the variables are highly correlated with one another. The correlation r = 0,82 between surface chlorophyll a and surface turbidity and r = 0,83 between integrated chlorophyll a and integrated turbidity, indicates that chlorophyll a and turbidity are virtually indistinguishable from one another.

TABLE 3.7: LINEAR CORRELATIONS (r) OF LOG TRANSFORMED DATA (81.12.07)

n = 28	SUCOL	INCOL	INTUL	SUTUL
SUCOL	1,00			
INCOL	0,73	1,00		
INTUL	0,77	0,83	1,00	
SUTUL	0,82	0,88	0,94	1,00

3.3.2 The Canonical Correlation Analysis

The interdependency of both the water quality conditions (chlorophyll a and turbidity) and between the four reflectance bands, meant that a statistical test was required that would take into account the interrelatedness. A multi-variate multiple regression analysis technique was required and the use of Canonical Correlation Analysis was recommended.

Howard Hotelling, the motivator behind the Canonical Correlation Analysis in 1936, described the concept behind his work as follows:

"Marksmen side by side firing simultaneous shots at targets so that the deviations are in part due to independent individual errors and in part to common causes such as wind, provide a familiar introduction to the theory of correlation; but only the correlation of the horizontal components is ordinarily discussed, whereas the complex consisting of horizontal and vertical deviations may be even more interesting. The wind at two places may be compared, using both components of the velocity in each place. A fluctuating vector is thus matched at each moment with another fluctuating vector." (Hotelling, 1936).

Hotelling developed the technique to extract suitable descriptive functions from a multiplicity of correlations in psychological testing. Since then the Canonical

Correlation Analysis has been used to study the correlation structure between two sets of variables (Haan, 1977) and "can be viewed as extension of multiple regression analysis" (Dixon and Brown, 1979). There are usually sets of dependent Y variables (in this instance reflectance bands 4, 5, 6 and 7) as well as sets of independent X variables (surface chlorophyll a and turbidity, integrated chlorophyll a and turbidity). "The problem is to find a linear combination of the X variables that has maximum correlation with a linear combination of the Y variables" (Dixon and Brown, 1979).

The computerised Canonical Correlation Analysis used is part of the BMDP Biomedical Computer Program P-series (Dixon and Brown, 1979).

Canonical Correlation Analysis was carried out between the following sets of data:

(1) Log surface chlorophyll a (SUCOL) and log surface turbidity (SUTUL) with reflectance bands 4, 5, 6 and 7.

(2) Log integrated chlorophyll a (INCOL) and log integrated turbidity (INTUL) with reflectance bands 4, 5, 6 and 7.

In the statistical analysis, the independent data sets were split up owing to the fact that the presence of too many mutual correlations within the independent data set resulted in singularity (Gittins, 1979). The splitting up of the data set also simplified the interpretation of results.

The Canonical Correlation produced two correlations: the maximum and the second highest correlation possible between the variates. Analysis indicated that the second coefficient was of little value for the requirements of this research and therefore the analysis was confined to the first and highest correlation coefficient.

The Canonical Coefficients can be presented as such or in a standardised manner. It was decided not to use the standardised form as this involves standard deviation units, which could vary between overpasses.

Concerning the Canonical Coefficients the following is important: if the logs of the surface reference data values are similar and in the same order of magnitude, then a comparison of coefficients provides a direct indication of the relative contribution of each variable to the Y variates. If the numerical values are not the same order of magnitude then the coefficients cannot be directly compared. The comparison in the latter case was done between the absolute value of the product of a Canonical Coefficient and the mean value of the variables concerned. In this case the data were within the same order of magnitude and therefore the coefficients did indicate relative magnitudes of importance. It was therefore possible to ascertain the relationships between the individual water quality variables and the separate reflectance bands.

Canonical Correlations and Coefficients for the variables were obtained for each day's data. Each variable's percentage contribution to the relationship was obtained using the Canonical Coefficient and the mean of the data set. The negative sign of the coefficient was not included in the calculation. The following formula was used:

To determine the percentage contribution of surface chlorophyll a, SUCOL:

$$\frac{\text{(SUCOL (Coeff) x SUCOL (Mean))}}{\text{(SUCOL(Coeff) x SUCOL(Mean)) + (SUTUL(Coeff) x (SUTUL(Mean))}} \times 100 = \%$$

To determine the percentage contribution of BAND 4:

$$\frac{\text{(BAND4 (Coeff) x BAND4 (Mean))}}{\text{(B4(Coeff) x B4(Mean)) + (B5(Coeff) x B5(Mean)) + (B6(Coeff) x B6(Mean)) + (B7(Coeff) x B7(Mean))}} \times 100 = \%$$

.... Equation 1

CHAPTER 4

4. RESULTS AND DISCUSSION OF ANALYSIS

Using the Canonical Correlation multivariate regression analysis (refer to Section 3.3.2.), the relationship between the surface reference data and satellite reflectance data for six days of data were investigated.

In addition, unsupervised classification of the satellite reflectance data was computed and the colour coded imagery discussed (refer to Section 3.2.3 and Section 3.2.2).

4.1. CANONICAL CORRELATION ANALYSIS

A Canonical Correlation Analysis was carried out between the following data:

(1) Log surface chlorophyll a (SUCOL) and log surface turbidity (SUTUL) with reflectance bands 4, 5, 6 and 7, (BAND 4, BAND 5, BAND 6, BAND 7).

(2) Log integrated chlorophyll a (INCOL) and log integrated turbidity (INTUL) with reflectance bands 4, 5, 6, and 7, (BAND 4, BAND 5, BAND 6, BAND 7).

TABLE 4.1: CANONICAL CORRELATIONS r

DATE	SUCOL/ SUTUL	INCOL/ INTUL
81.10.14	0,88	0,89
81.11.01	0,79	0,93
81.12.07	0,94	0,95
82.09.13	0,87	0,86
82.09.30	0,90	0,92
82.11.16	0,95	0,95

The Canonical Correlations for the data collected on each of the six days, as shown in Table 4.1, indicate that the r values are relatively high in each instance. The Canonical Correlation finding is, by definition, the best possible linear polynomial correlation between variables. The r correlations are however a function of the data set, which may or may not be representative of the real underlying correlation for the parent population. Therefore the high r values are not sufficient evidence of stable correlation. Examination of the Canonical Coefficients and the percentage contribution of each variable to the relationship (refer to Section 3.3.2, Equation 1) brought to light more information (Tables 4.2 to 4.7).

It is important to note that Canonical Coefficients are difficult to interpret. An attempt at interpreting the Canonical Correlation Analysis follows (Howman and Kempster, 1983). The standard linear regression equation $Y = MX + K$ can aid in understanding the results of the Canonical Correlation Analysis.

If Y represents the dependent variables, in this instance reflectance bands 4, 5, 6 and 7,

X represents the independent variables, surface and integrated chlorophyll a and surface and integrated turbidity,

M is the slope of the regression line and

K is the intercept on the Y axis.

As an example the polynomial function, obtained for the 81.10.14 overpass for surface chlorophyll a and turbidity shown in Table 4.2, may be written as follows:

BAND 4 (0,39) + BAND 5 (0,08) + BAND 6 (0,03) + BAND 7 (0,06) = M (SUCOL (0,91) + SUTUL (6,43)) + K.

The major points to be noted are:

(1) Surface chlorophyll a with a coefficient of 0,91 contributes 23% of the relationship to the independent variable.

(2) Surface turbidity is the major independent variable representing 77% of the relationship.

(3) Band 4 with a coefficient of 0,39 is seen to be the most important dependent variable (64%).

(4) Bands 6 + 7 jointly represent 21% of the relationship contributed by the dependent variables.

(5) The highest independent coefficient may be directly related to the highest dependent coefficient, thereby connecting surface turbidity with band 4. The Canonical Correlation mainly represents a relationship between surface turbidity and band 4 since the contribution of surface chlorophyll a to the relationship is only 23%.

TABLE 4.2: RESULTS OF THE CANONICAL CORRELATION ANALYSIS FOR 81.10.14

DATE: 81.10.14	n 32	CC	Mean	%	n 32	CC	Mean	%
INDEPENDENT	SUCOL	0,91	1,46	23	INCOL	-0,99	1,46	21
X VARIABLES	SUTUL	6,43	0,7	77	INTUL	7,15	0,74	79
DEPENDENT	BAND 4	0,39	5,59	64	BAND 4	0,32	5,59	56
Y	BAND 5	0,08	6,41	15	BAND 5	0,18	6,41	36
VARIABLES	BAND 6	0,03	8,81	8	BAND 6	0,02	8,81	6
	BAND 7	0,06	7,25	13	BAND 7	0,01	7,25	2
CANONICAL CORRELATION	r	0,88				0,89		
TAIL PROBABILITY		0,0000				0,0000		

CC = CANONICAL COEFFICIENT
MEAN = MEAN OF DATA SET
SUCOL = SURFACE CHLOROPHYLL a
INCOL = INTEGRATED CHLOROPHYLL a
n = NUMBER OF SAMPLING POINTS
% = PERCENTAGE CONTRIBUTION
SUTUL = SURFACE TURBIDITY
INTUL = INTEGRATED TURBIDITY

The polynomial function for integrated chlorophyll a and integrated turbidity data (Table 4.2) could be:

BAND 4 (0,32) + BAND 5 (0,18) + BAND 6 (0,02) + BAND 7 (0,01)
= M (INCOL (-0,99) + INTUL (7,15)) + K

This equation suggests the following:

(1) Integrated turbidity is the prime independent variable contributing 79% of the relationship.

(2) Band 4 is the prime dependent variable (56%).

(3) Band 4 is linked to integrated turbidity.

(4) Bands 6 and 7 have less significance (8%)

The results for 81.10.14 indicate that Landsat detects suspended solids (turbidity) in Roodeplaat Dam. Both surface and integrated turbidity results are highly correlated with band 4 and to a lesser extent with band 5: this supports the established theory that bands 4 and 5 show up suspended solids (Bukata and Bruton, 1974; Moore, 1980; Lindell, 1981). A low band 7 contribution suggests that there are no high concentrations of algae.

Only for one other day's data, 82.09.13 (Table 4.5) does the abovementioned trend follow. On two occasions, 81.12.07

TABLE 4.3: RESULTS OF THE CANONICAL CORRELATION ANALYSIS FOR 81.11.01

DATE: 81.11.01		n 32	CC	Mean	%		n 32	CC	Mean	%
INDEPENDENT	SUCOL		-4,23	1,51	50	INCOL		1,29	1,53	31
X VARIABLES	SUTUL		7,87	0,8	50	INTUL		5,57	0,80	69
DEPENDENT	BAND 4		0,2	6,19	23	BAND 4		0,15	6,19	21
Y	BAND 5		0,08	7,25	11	BAND 5		0,27	7,27	43
VARIABLES	BAND 6		0,28	8,56	44	BAND 6		0,07	8,56	13
	BAND 7		-0,2	6,0	22	BAND 7		-0,17	6,0	23
CANONICAL CORRELATION	r		0,79					0,93		
TAIL PROBABILITY			0,0001					0,0000		

CC = CANONICAL COEFFICIENT
MEAN = MEAN OF DATA SET
SUCOL = SURFACE CHLOROPHYLL a
INCOL = INTEGRATED CHLOROPHYLL a
n = NUMBER OF SAMPLING POINTS
% = PERCENTAGE CONTRIBUTION
SUTUL = SURFACE TURBIDITY
INTUL = INTEGRATED TURBIDITY

TABLE 4.4: RESULTS OF THE CANONICAL CORRELATION ANALYSIS FOR 81.12.07

DATE: 81.12.07		n 32	CC	Mean	%		n 32	CC	Mean	%
INDEPENDENT	SUCOL		0,02	1,14	2	INCOL		0,63	1,13	35
X VARIABLES	SUTUL		2,62	0,54	98	INTUL		2,38	0,56	65
DEPENDENT	BAND 4		0,15	11,93	21	BAND 4		0,06	11,93	41
Y	BAND 5		0,06	10,93	23	BAND 5		0,05	10,93	31
VARIABLES	BAND 6		0,1	8,46	30	BAND 6		0,05	8,46	24
	BAND 7		-0,12	6,25	26	BAND 7		-0,01	6,25	4
CANONICAL CORRELATION	r		0,94					0,95		
TAIL PROBABILITY			0,0000					0,0000		

CC = CANONICAL COEFFICIENT
MEAN = MEAN OF DATA SET
SUCOL = SURFACE CHLOROPHYLL *a*
INCOL = INTEGRATED CHLOROPHYLL *a*
n = NUMBER OF SAMPLING POINTS
% = PERCENTAGE CONTRIBUTION
SUTUL = SURFACE TURBIDITY
INTUL = INTEGRATED TURBIDITY

TABLE 4.5: RESULTS OF THE CANONICAL CORRELATION ANALYSIS FOR 82.09.13

DATE: 82.09.13		n 32	CC	Mean	%		n 32	CC	Mean	%
INDEPENDENT	SUCOL		0,43	1,25	11	INCOL		-0,64	1,23	13
X VARIABLES	SUTUL		6,73	0,70	59	INTUL		7,23	0,74	87
DEPENDENT	BAND 4		0,05	14,52	11	BAND 4		0,03	14,52	8
Y	BAND 5		0,35	9,16	59	BAND 5		0,34	9,20	59
VARIABLES	BAND 6		0,10	7,81	14	BAND 6		0,14	7,81	20
	BAND 7		-0, 1	7,77	14	BAND 7		-0, 1	7,77	14
CANONICAL CORRELATION	r		0,87					0,67		
TAIL PROBABILITY			0,0000					0,0000		

CC = CANONICAL COEFFICIENT
MEAN = MEAN OF DATA SET
SUCOL = SURFACE CHLOROPHYLL *a*
INCOL = INTEGRATED CHLOROPHYLL *a*
n = NUMBER OF SAMPLING POINTS
% = PERCENTAGE CONTRIBUTION
SUTUL = SURFACE TURBIDITY
INTUL = INTEGRATED TURBIDITY

TABLE 4.6: RESULTS OF THE CANONICAL CORRELATION ANALYSIS FOR 82.09.30

DATE: 82.09.30	n 32	CC	Mean	%	n 32	CC	Mean	%
INDEPENDENT	SUCOL	3,62	1, 3	97	INCOL	-0,66	1,35	17
X VARIABLES	SUTUL	0,24	0,71	3	INTUL	6,26	0,71	83
DEPENDENT	BAND 4	0,31	21, 3	79	BAND 4	0,14	21,31	41
Y	BAND 5	0,06	14,13	10	BAND 5	0,11	14,13	22
VARIABLES	BAND 6	0,05	12,78	8	BAND 6	0,14	12,78	25
	BAND 7	-0,02	10,78	3	BAND 7	-0,08	10,78	12
CANONICAL CORRELATION	r	0,90				0,92		
TAIL PROBABILITY		0,0000				0,0000		

CC = CANONICAL COEFFICIENT
MEAN = MEAN OF DATA SET
SUCOL = SURFACE CHLOROPHYLL a
INCOL = INTEGRATED CHLOROPHYLL a
n = NUMBER OF SAMPLING POINTS
% = PERCENTAGE CONTRIBUTION
SUTUL = SURFACE TURBIDITY
INTUL = INTEGRATED TURBIDITY

TABLE 4.7: RESULTS OF THE CANONICAL CORRELATION ANALYSIS FOR 82.11.16

DATE: 82.11.16	n 28	CC	Mean	%	n 28	CC	Mean	%
INDEPENDENT	SUCOL	2,67	1,4	89	INCOL	2,65	1,39	87
X VARIABLES	SUTUL	0,58	0,78	11	INTUL	0,68	0,82	13
DEPENDENT	BAND 4	0, 3	21, 5	42	BAND 4	0,29	21, 5	41
Y	BAND 5	-0,05	22,39	8	BAND 5	-0,05	22,39	7
VARIABLES	BAND 6	0,24	20,79	32	BAND 6	0,24	20,79	32
	BAND 7	-0,13	21,79	18	BAND 7	-0,14	21,79	20
CANONICAL CORRELATION	r	0,95				0,95		
TAIL PROBABILITY		0,0000				0,0000		

CC = CANONICAL COEFFICIENT
MEAN = MEAN OF DATA SET
SUCOL = SURFACE CHLOROPHYLL *a*
INCOL = INTEGRATED CHLOROPHYLL *a*
n = NUMBER OF SAMPLING POINTS
% = PERCENTAGE CONTRIBUTION
SUTUL = SURFACE TURBIDITY
INTUL = INTEGRATED TURBIDITY

(Table 4.4) and 82.09.30 (Table 4.6), integrated turbidity is related to bands 4 and 5. Conversely though, on 81.12.07 (Table 4.4) surface turbidity appears to be related to band 6. On 82.09.30 (Table 4.6) surface chlorophyll a is connected with band 4. Further discrepancies are found on 82.11.16 (Table 4.7) where both surface and integrated chlorophyll a appear to be related to band 4. The existence of the abovementioned discrepancies is not unexpected as discussed in Section 2.4.7. There are many factors that affect the relationship between water quality conditions and satellite reflectance values.

A major reason for the inconsistencies could be the presence of different algal species in different regions of the impoundment at the time of the overflight (refer to Section 2.3.3). Figure 4.1 gives the results of a brief taxonomic analysis of the distribution of the main algal genera present at specific points in the impoundment during each overflight (refer to Figure 3.2). It is apparent that the proportion of the genera is fairly constant at each site. Equally relevant is the fact that the genera change from month to month. The green algae (*Oöcystis* sp, *Cryptomonas* sp and *Pediastrum* sp) are largely evident in October 1981 and September 1982. The blue-greens (*Microcystis* sp, *Anabaena* sp and *Chroococcus* sp) appear in December 1981 and November 1982. The Diatoms (*Melosira* sp) appear in November and December 1981.

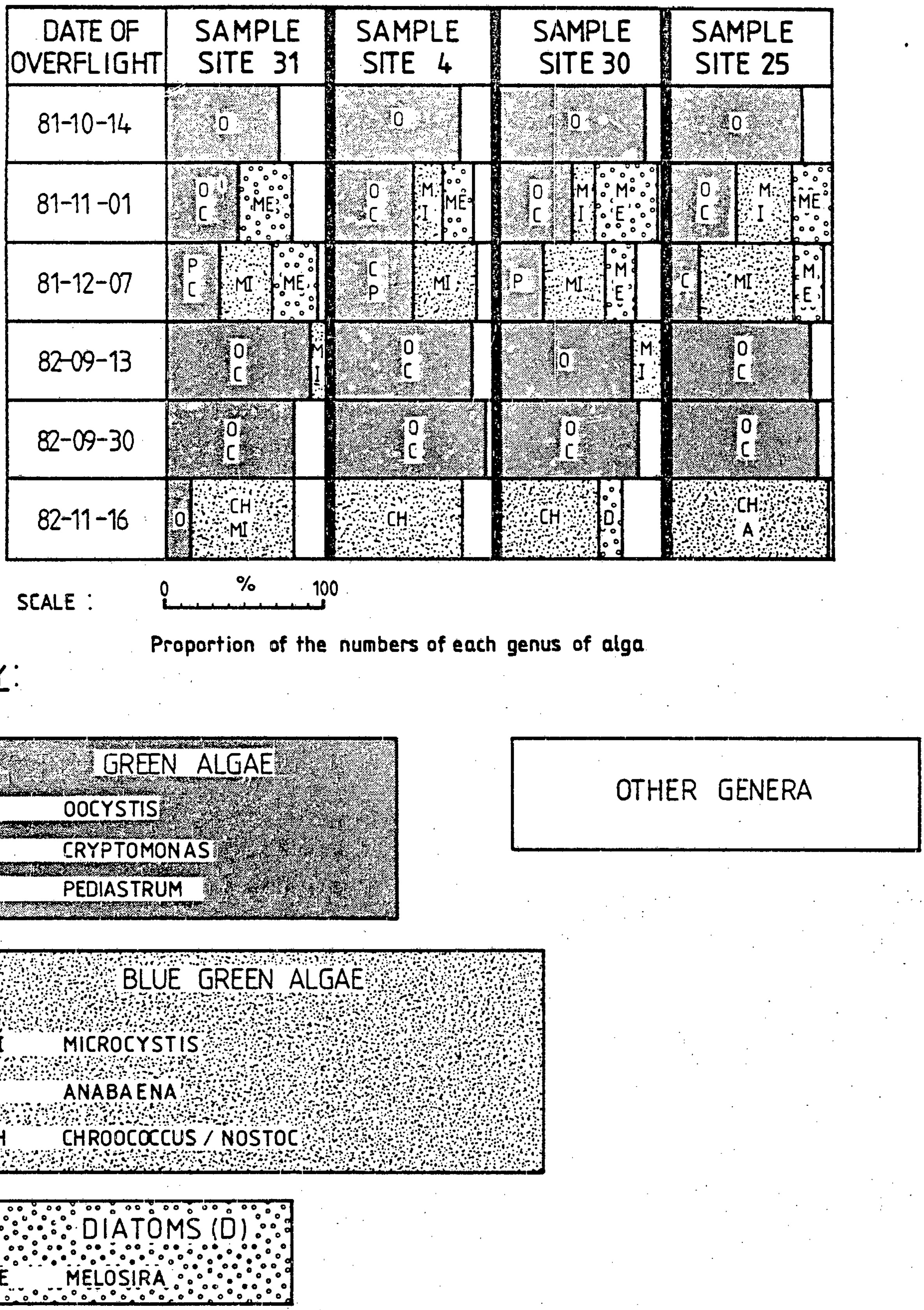

FIGURE 4.1: MAJOR ALGAL GENERA PRESENT AT FOUR SAMPLING SITES ON ROODEPLAAT DAM AT THE TIME OF THE SATELLITE OVERFLIGHTS

Overall the green algal species appear to be the most prevalent. The possiblity that blue-green algae reflect light differently from green algae is a question beyond the scope of this study.

The relative stages in the life cycles of the algae might also be important in understanding the inconsistencies in the results. The presence of phaeopigments was examined to determine a possible influence, if any, on the data (see Section 2.3.6). Canonical Correlation Analysis using phaeopigment data was attempted but the complexity of the results and the obvious intercorrelations made it difficult to come to a definite conclusion. In an attempt to assess the influence of phaeopigment on the Canonical Correlation Analysis of chlorophyll a, a simple linear regression analysis was carried out. All six day's data were analysed. Table 4.8 lists the results.

TABLE 4.8: LINEAR REGRESSION ANALYSIS OF PHAEOPIGMENT WITH THE CANONICAL COEFICIENTS OF THE REFLECTANCE BANDS

DATE	RATIO OF PHAEOPIGMENT/ TOTAL PIGMENT	CANONICAL COEFFICIENTS BAND 7	BAND 6	BAND 5	BAND 4
81.10.14	0,129	0,06	0,025	0,084	0,387
81.11.01	0,219	-0,198	0,28	0,082	0,195
81.12.07	0,264	-0,121	0,096	0,055	0,048
82.09.13	0,164	-0,1	0,102	0,364	0,052
82.09.30	0,164	-0,024	0,05	0,062	0,313
82.11.16	0,110	-0,131	0,238	-0,053	0,301
r		-0,47	0,082	0,089	-0,70
Y intercept		0,045	0,106	0,614	0,52
Slope		-0,007	0,001	0,002	-0,017

The results of this brief analysis indicated very low correlation between ratio phaeopigment/total pigment ratio. The Canonical Correlation for the reflectance bands 5 and 6 were r = 0,089 and r = 0,082 respectively, and negative correlations between the Canonical Correlation for band 7 (r = -0,47) and band 4 (r = -0,70). This suggests that the state of health of the algae, as reflected in the amount of phaeopigment present, has a noticeable effect on the Canonical calibration, particularly for the Canonical Correlation of band 4. The influence of phaeopigments on the calibration of surface reference data relative to satellite reflectance data, is something that would be worth pursuing but is beyond the scope of this study.

4.2 AN INTERPRETATION OF THE COLOUR CODING

The digital reflectance data in colour coded format provided visual impressions of conditions in the impoundments at different times (refer to Section 3.2.2).

Data for the 82.09.30, illustrated on Plates 4.1 to 4.4, indicate relatively high reflectance values all over the impoundment in bands 4 and 5. Band 6 shows a heterogeneous range of values while band 7 has fairly low reflectances. This could indicate the presence of more turbid than chlorophyll laden water due to the high values recognisable in bands 4 and 5.

Plate 4.1: Colour Coded Reflectance Band 4 - 82.09.30

Plate 4.2: Colour Coded Reflectance Band 5 - 82.09.30

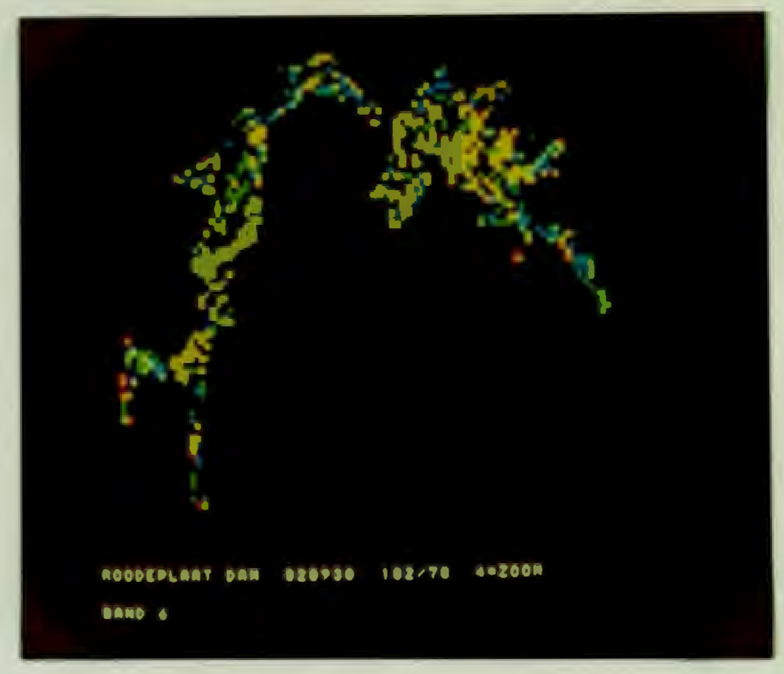

Plate 4.3: Colour Coded Reflectance Band 6 - 82.09.30

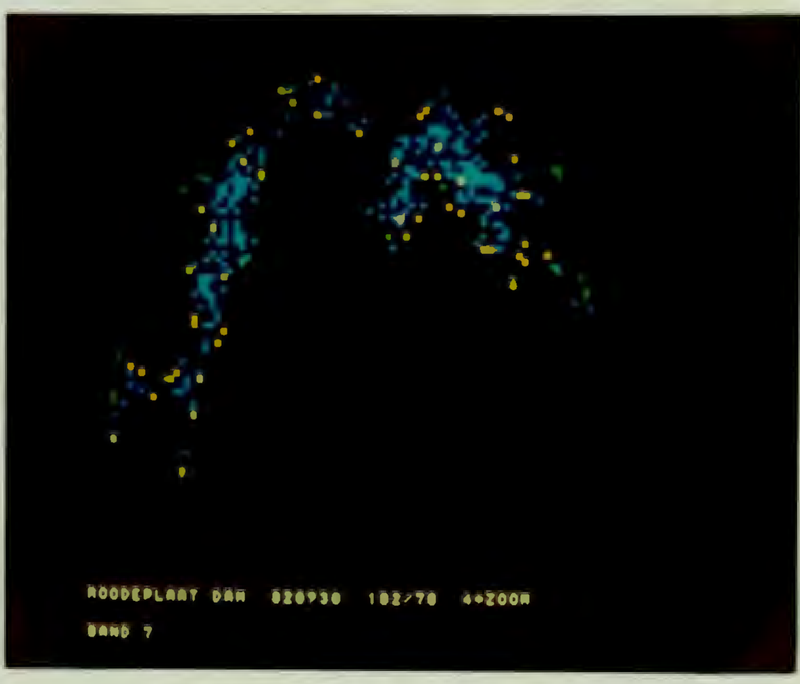

Plate 4.4: Colour Coded Reflectance Band 7 - 82.09.30

Plate 4.5: Colour Coded Reflectance Band 4 - 82.11.16

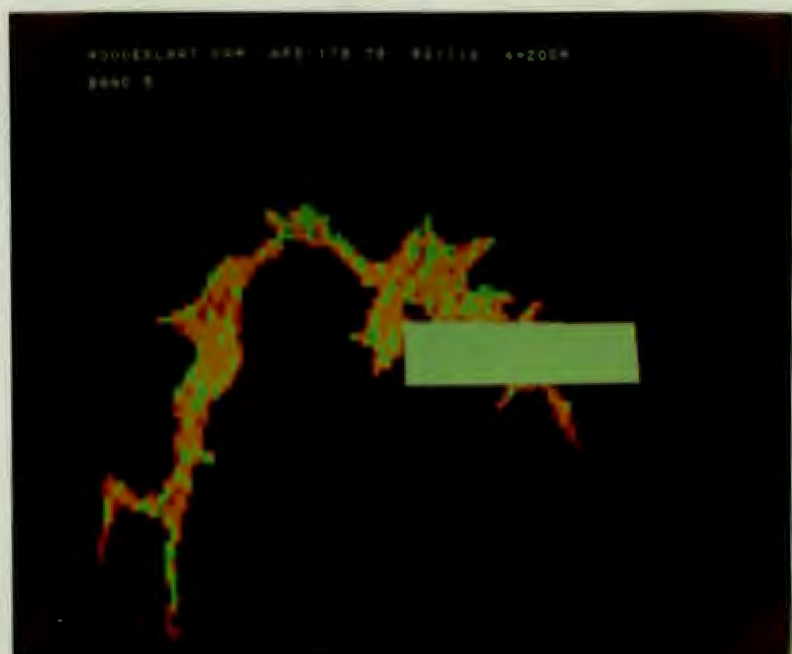

Plate 4.6: Colour Coded Reflectance Band 5 - 82.11.16

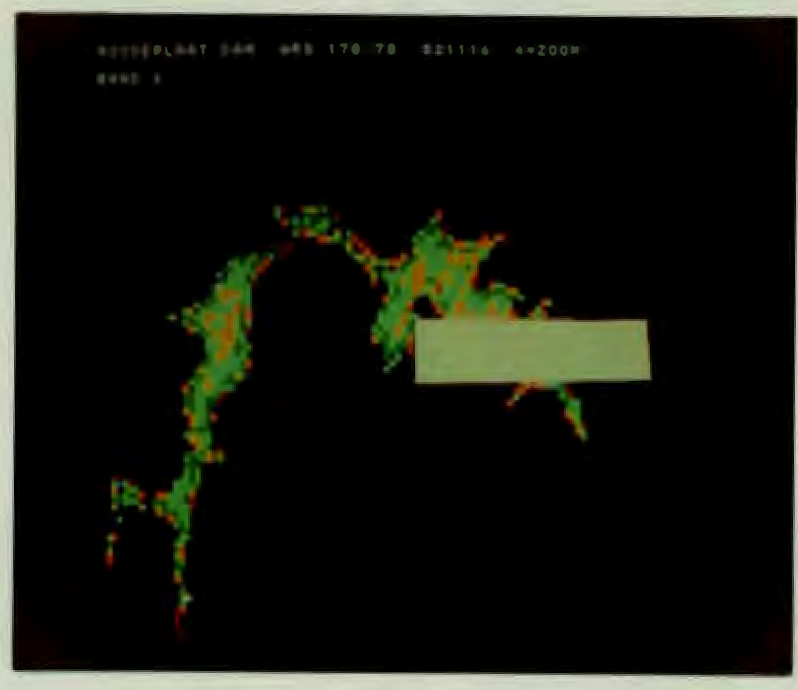

Plate 4.7: Colour Coded Reflectance Band 6 - 82.11.16

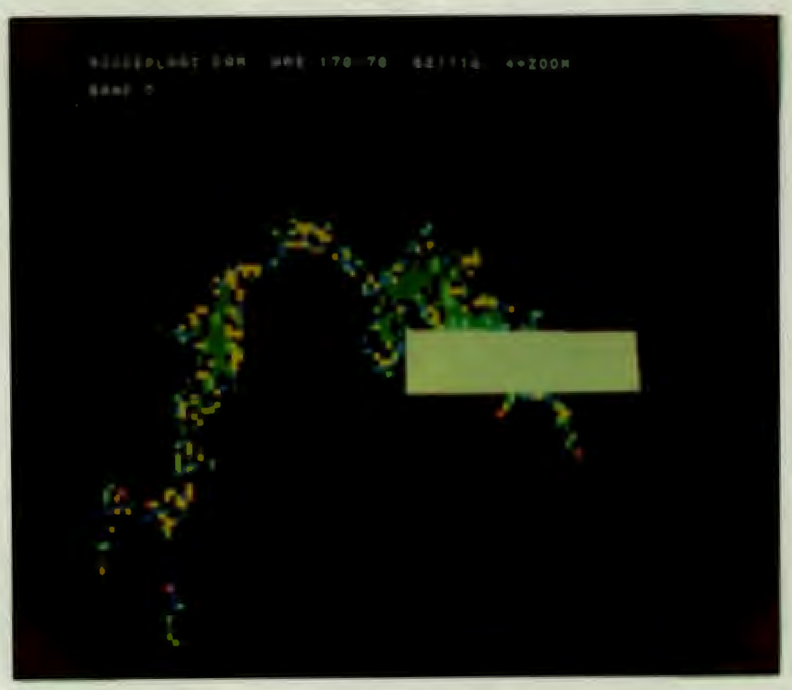

Plate 4.8: Colour Coded Reflectance Band 7 - 82.11.16

Table 4.6, which presents the Canonical Coefficients and the percentage contribution of each variable to the relationship on the 82.09.30, indicates that surface chlorophyll a and integrated turbidity are both related to band 4, a contradictory picture.

Plates 4.5 to 4.8 of the day 82.11.16, illustrate an error that can occur with satellite data. A radiometric error has caused some data to be lost. Plates 4.5 and 4.6 show band 4 and 5 to have high reflectance values all over the impoundment. Bands 6 and 7 also have relatively high values indicating the possible presence of chlorophyll. Table 4.7 supports this observation with surface and integrated chlorophyll a relating to band 4 on 82.11.16.

Colour coding therefore enables qualitative and comparative observations to be made. The degree of heterogeneity can be assessed, but the distinction between chlorophyll a and turbidity distributions is not always obvious, particularly when low concentrations of both chlorophyll and turbidity are present. Finally, a problem associated with colour coding is the photographic process involved, which can cause variation between the colour distributions.

4.3 UNSUPERVISED CLASSIFICATION

Using a modified image processing program (Modified CATNIPS) an unsupervised classification of 4 wave bands for each day's data produced classified digital images of Roodeplaat Dam. The different signatures on the classified image were represented by symbols to enhance the visual effect. One image for 81.12.07 showed outstanding differences in the classification (Figure 4.2). The statistics performed on the data (Table 4.9) indicate that bands 4 and 5 mainly account for 3 of the 4 reflectance classes. The two more significant classes ($,M) evident along the western arm of the impoundment indicate different water quality conditions. The relationship to bands 4 and 5 suggests the presence of suspended sediments (mean reflectance units of 15,621 and 20,979 for band 4 and 12,807 and 22,643 for band 5).

The 4th class (-), registering a relatively high value in band 7 (16,669) and found only along the shoreline can be considered to be mixels (mixed water and vegetation pixels).

FIGURE 4.2: UNSUPERVISED CLASSIFICATION OF ROODEPLAAT DAM 81-12-07

TABLE 4.9: STATISTICS OF THE UNSUPERVISED CLASSIFICATION FOR 81.12.07

CLUSTER SYMBOL	NUMBER OF PIXELS	R MEAN*	R SIGMA*
M	140	12,93	1,16
$	140	14,90	3,26
.	568	7,34	2,93
-	133	10,16	3,80

MEANS* for 4 by 20 clusters

BANDS	M	$	.	-
4	15,621	20,979	6,845	8,414
5	12,807	22,643	4,607	8,902
6	8,221	17,086	3,968	16,218
7	4,871	9,693	3,928	16,669

* Reflectance units

4.4 OVERVIEW OF ONE DAY'S DATA 81.12.07

The data for 81.12.07 contained the most widely distributed water quality conditions and therefore this day was chosen to provide an example of the issues involved.

To reconstruct a picture of the data already presented:

Plates 4.9 to 4.12 illustrate the colour coded reflectance data for 81.12.07.

Plate 4.9: Colour Coded Reflectance Band 4 - 81.12.07

Plate 4.10: Colour Coded Reflectance Band 5 - 81.12.07

Plate 4.11: Colour Coded Reflectance Band 6 - 81.12.07

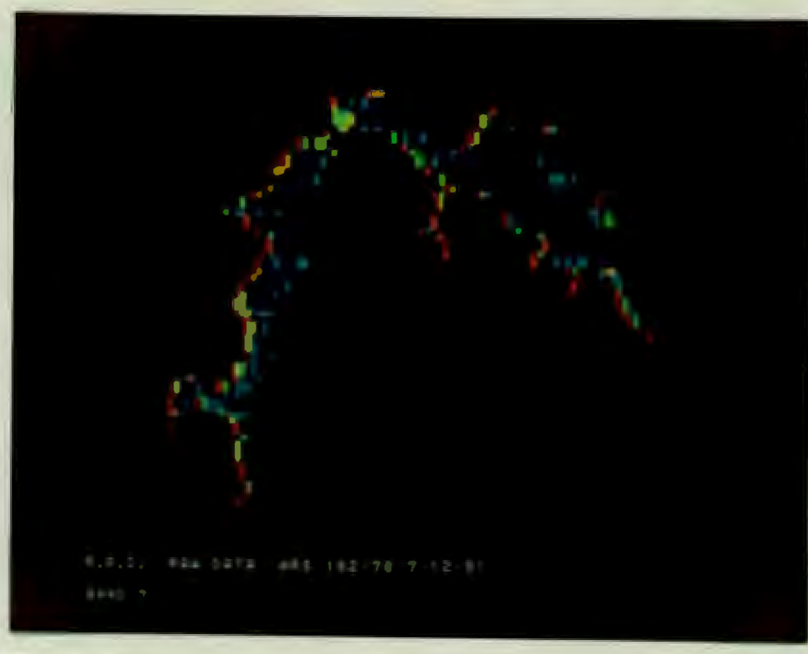

Plate 4.12: Colour Coded Reflectance Band 7 - 81.12.07

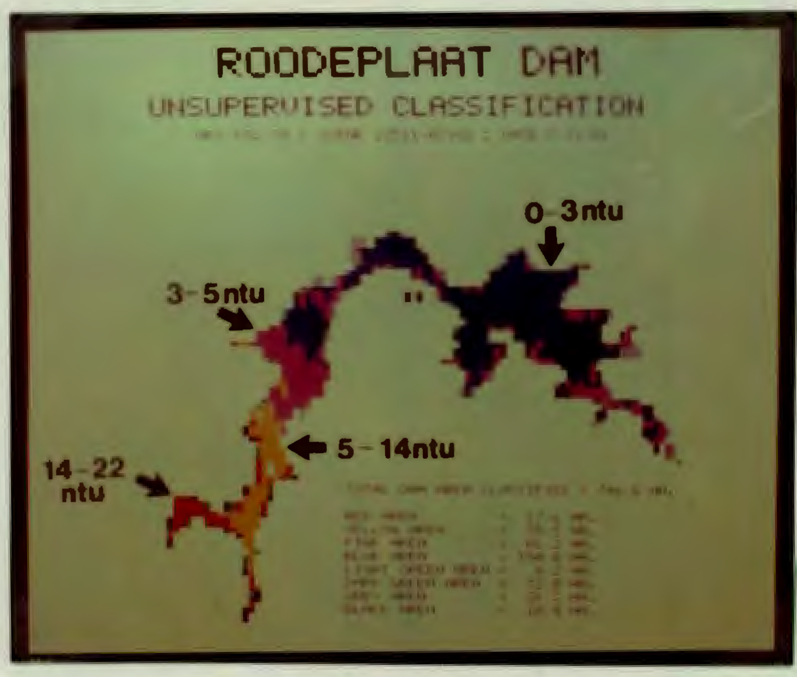

Plate 4.13: **Unsupervised Classification of Roodeplaat Dam - 81.12.07**

Table 4.4 discloses the Canonical Correlation, Canonical Coefficients and each variables percentage contribution to the relationship for 81.12.07.

Figure 4.2, Table 4.9 and Plate 4.13 present information concerning the unsupervised classification of the day's data.

Plates 4.9 and 4.10, the colour coded images for bands 4 and 5 clearly indicate the presence of water quality conditions along the southern part of the left arm of Roodeplaat Dam. Bands 6 and 7 (Plates 4.11 and 4.12) also indicate differing conditions but to a lesser extent. The remainder of the impoundment appears to be relatively homogeneous.

Table 4.4 reveals that for this overpass surface turbidity is by far the dominant variable (98%) and that all of the bands contribute fairly equally to the relationship. Band 6 shows a slight head (30%). The Canonical Correlation of 0,94 is high. The integrated turbidity contribution of 65% in relation to band 4 (41%) and a high Canonical Correlation of 0,95, affirms the strong presence of turbidity.

The unsupervised classification and colour coded images were further reinforced by a classification of the 81.12.07 image being produced by an image processing system at

Hartbeesthoek, Plate 4.13. The classification identified 8 classes, 4 of which could be considered to be border classes indicating mixed areas of vegetation and water. The remaining 4 classes distinguished different water quality conditions that have been attributed turbidity categories of 0-3, 3-5, 5-14 and 14+ NTU.

From the abovementioned results, due to the obvious weight in favour of turbidity, the image classes were compared with the surface reference data for surface and integrated turbidity (Figure 4.3). Five turbidity categories became apparent (Figure 4.4).

A query arose as to the importance of bands 6 and 7 which had fairly high percentage contributions in the relationship (30 and 26% respectively). The surface reference data for surface and integrated chlorophyll a are presented in Figure 4.5. Figure 4.6 illustrates the chlorophyll a classes that can be distinguished from the data in concentrations of approximately 1-10 μg/ℓ, 10-20 μg/ℓ, 20-30 μg/ℓ, 30-40 μg/ℓ and + 40 μg/ℓ.

The interrelatedness of the data illustrates the complexity of distinguishing different water quality conditions and reinforces the necessity of applying multi-variate analysis to the data.

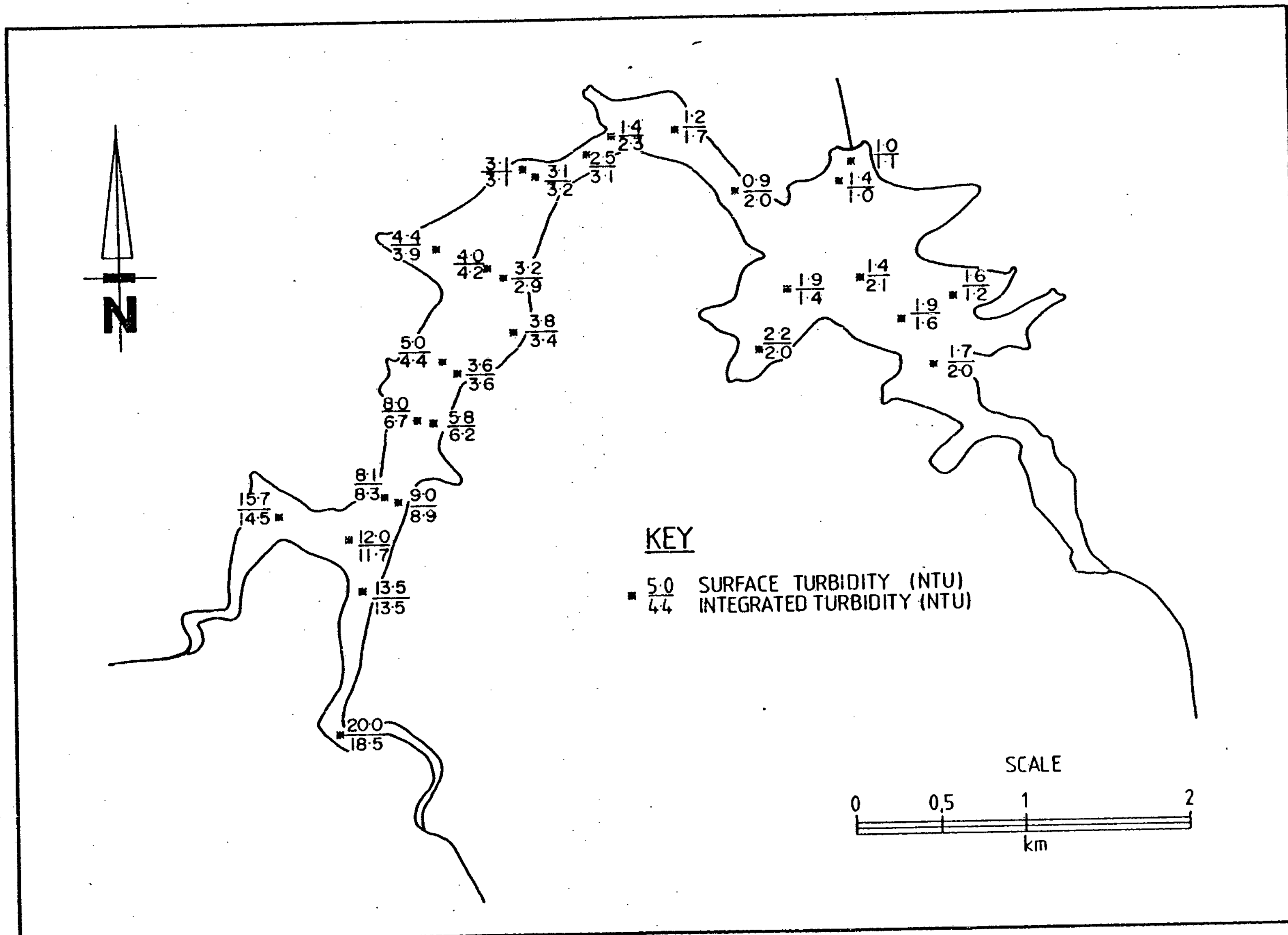

FIGURE 4.3: SURFACE AND INTEGRATED TURBIDITY SURFACE REFERENCE DATA FOR 81·12·07

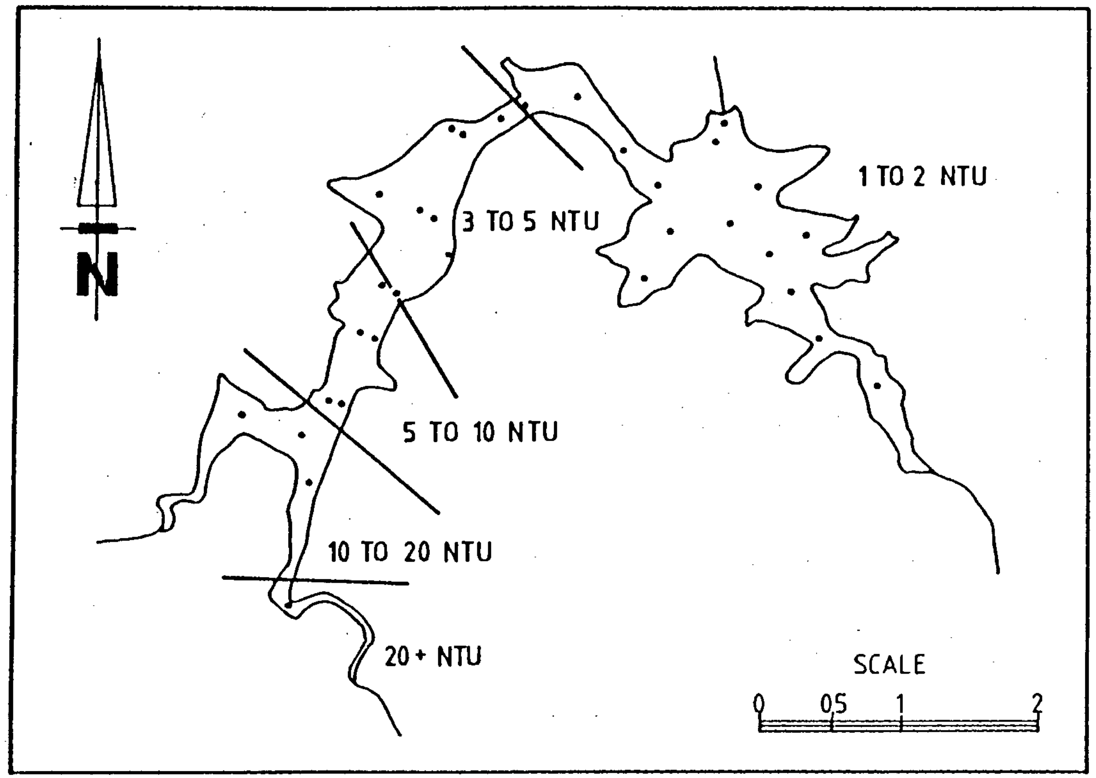

FIGURE 4.4: SURFACE AND INTEGRATED TURBIDITY CLASSES FOR ROODEPLAAT DAM - 81·12·07

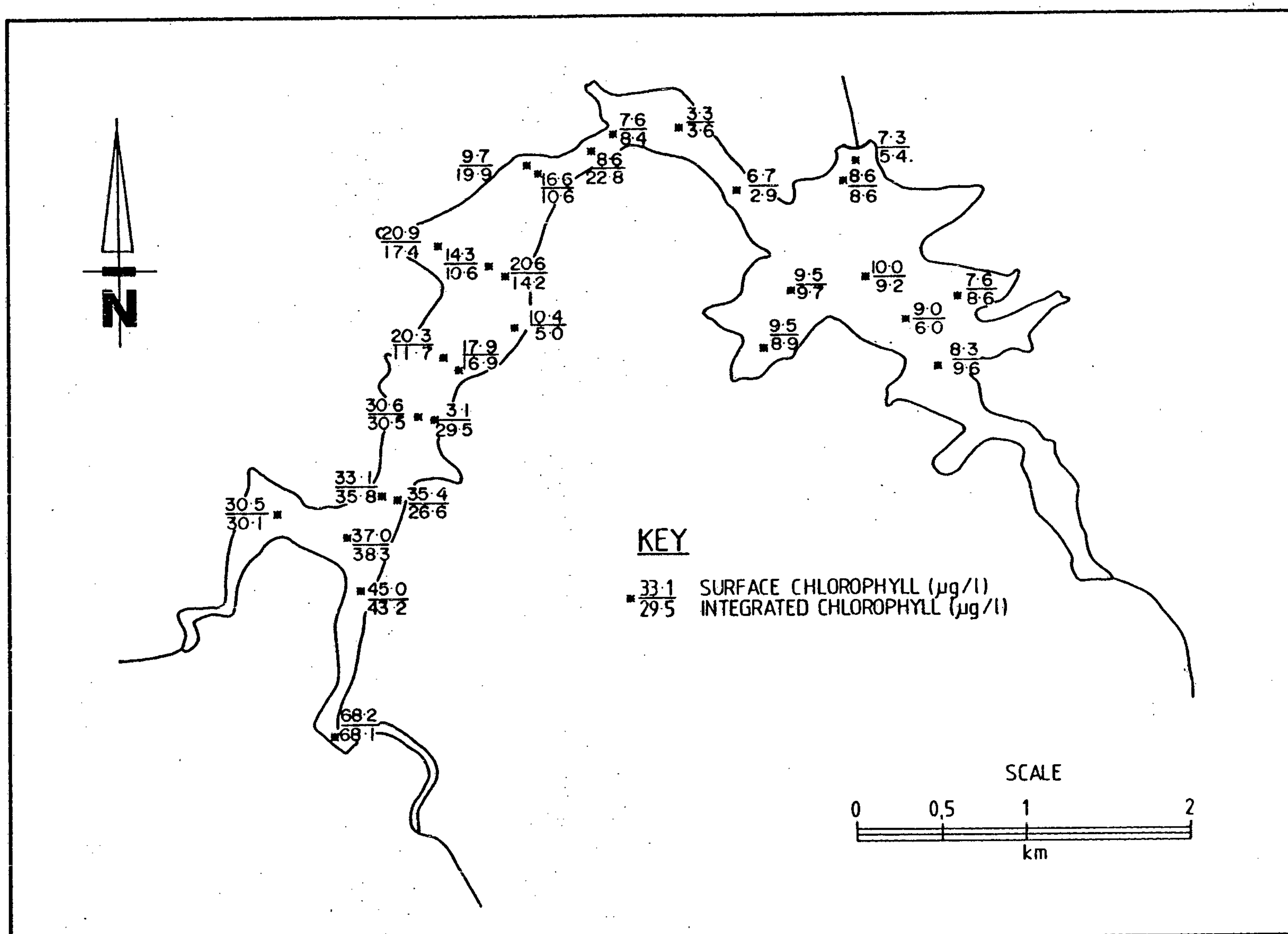

FIGURE 4.5 : SURFACE AND INTEGRATED CHLOROPHYLL SURFACE REFERENCE DATA FOR 81·12·07

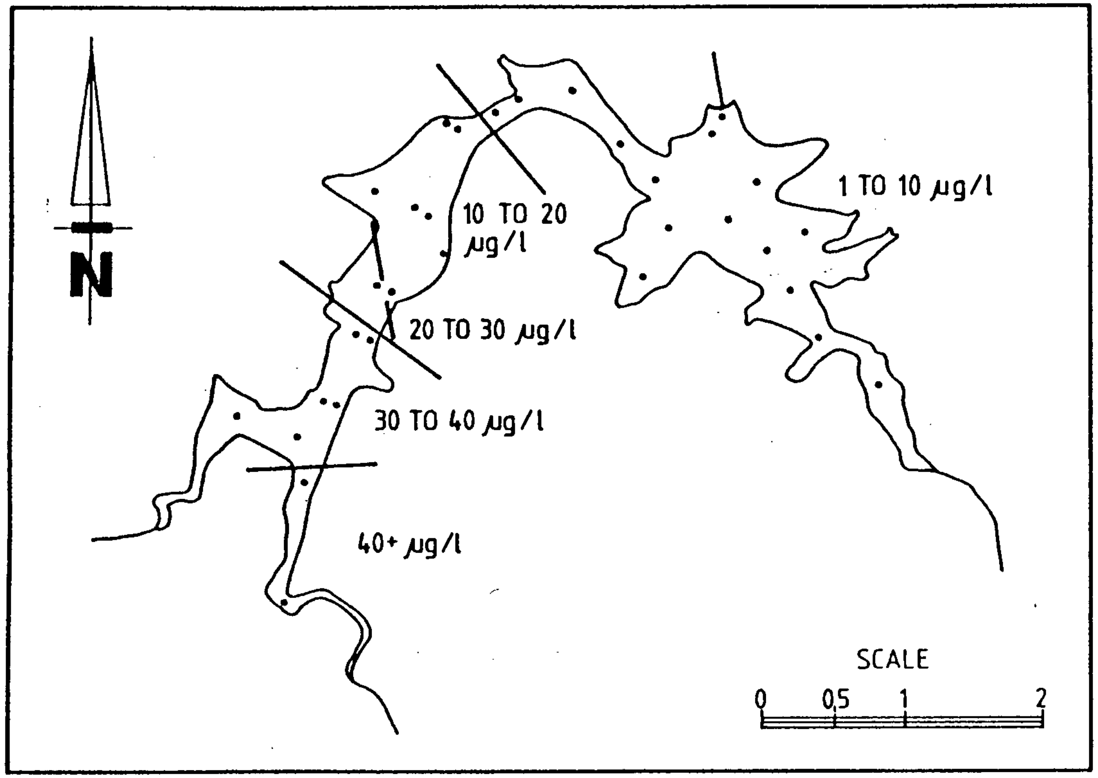

FIGURE 4.6 : SURFACE AND INTEGRATED CHLOROPHYLL CLASSES FOR ROODEPLAAT DAM - 81·12·07

4.5 SUMMARY

The results of the investigation have highlighted some important points. Firstly, there is a distinct correlation between specific water quality conditions and satellite reflectance data. Secondly, the relationship between the dependent and independent data sets is a complex one and it is not easy to isolate individual relationships. Thirdly, chlorophyll a and turbidity, particularly at low concentrations, are highly interrelated. In order to gain quantitative results it is therefore essential to build on the basis of multi-variate analysis, incorporating the problem of multicollinearity of the data set.

CHAPTER 5

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The objective of the project was to investigate the relationship between Landsat reflectance data and chlorophyll a and turbidity. Six scenes of satellite reflectance data and concurrently collected water quality data were analysed using the Canonical Correlation multi-variate statistical technique.

The Canonical Correlation Analysis enabled the multicollinearity and the interrelatedness of the reflectance data and the water quality conditions to be taken into account and the complex relationship between the variables to be examined.

The Canonical Correlations (r) for the data collected for the six days studied, ranged from 0,79 to 0,95, and indicated a strong relationship between the satellite reflectance data and the chlorophyll a and turbidity surface reference data. The Canonical Coefficients themselves were difficult to interpret and varied greatly between overpasses. The percentage contribution of each variable to the relationship aided in the interpretation of the results. As a general trend integrated turbidity related to bands 4 and 5 whereas surface turbidity mainly related to the same bands and on other occasions to bands 6 and 7. Integrated chlorophyll a generally corresponded to bands 6 and 7 whereas surface chlorophyll a evidently related to all of the wavebands. These trends were in line with the generally accepted relationship of turbidity with bands 4 and 5 and chlorophyll a with bands 6 and 7. The finding, from the Canonical Correlation Analysis, that surface turbidity related on occasions to band 6 and 7 as well as bands 4 and 5, however, indicated the interrelatedness of the chlorophyll a and turbidity reference data, and explained why other workers have had difficulties in achieving predictive equations using simple linear regression.

Colour coding of the digital data proved to be a quick, visual and qualitative method of interpreting chlorophyll a and turbidity data. Patterns of reflectance distributions in each waveband further illustrated the interrelationship between the water quality variables.

The influence of phaeopigments i.e. chlorophyll breakdown products, on the calibration of the surface reference data and the satellite reflectance data was investigated using a linear regression, and indicated a relationship with band 4 that may be worthwhile pursuing.

The brief analysis of the taxonomic composition of the algae (refer to Section 4.1) shows that different algae may dominate the impoundment at different times. Since these differences may influence the spectral characteristics of the impoundment this may be one reason for the difficulties in extrapolating from one overflight to another.

It was evident from this information that firstly, each day had different calibration equations, indicating that the nature of the relationship between the surface reference data and satellite reflectance data was unique to each specific overpass. Secondly, each band contributed to the relationship and therefore all of the bands should be included in analysis. Thirdly, there are difficulties in distinguishing between chlorophyll a and turbidity if multivariate statistical techniques had not been used. Fourthly, it became apparent that simpler analysis will not be able to establish the relationship between surface reference data and satellite reflectance data. Lastly, it is suggested that if a method could be found to mathematically use the Canonical Correlation Coefficients in predictive fashion and enable the multi-variate calibration equations to be extrapolated to incorporate the entire surface area of the impoundment, then calculation of water quality conditions on a synoptic scale might be feasible. I feel that the results presented in this thesis show that it is a useful tool and that it is worthwhile to pursue this statistical technique in an attempt to provide a model to determine water quality conditions. This falls beyond the scope of this thesis.

5.2 RECOMMENDATIONS

In order for accurate assessment to be carried out it is recommended that the following practical rules be observed:

(1) The sampling of a water body should be undertaken concurrently with the satellite overflight.

(2) The sampling network should be set out to ensure that the entire range of different water quality conditions within the water body are represented in the analysis. The representativeness of the surface reference data of conditions in the impoundment is an essential requirement.

(3) The analysis of the water quality samples should be undertaken as soon as possible after the sampling operation to avoid degradation of chlorophyll a.

(4) The alignment of the sampling position with its corresponding Landsat pixel should be as accurate as possible.

(5) The water quality conditions that are being investigated should be visible to the satellite. This implies that water quality conditions without reflectance in the spectral region 0,5 µm to 1,1 µm cannot be directly monitored.

(6) As an aid to the assessment of the digital reflectance data it is suggested that colour coding and unsupervised classifications of the images be carried out. Colour coding provides quick impressions of the heterogeneity of an impoundment and enables qualitative, comparative observations to be made. Unsupervised classification separates the digital data into characteristically similar classes.

(7) The interrelatedness of the water quality conditions and their corresponding reflectances should be recognised and a suitable multivariate statistical analysis technique should be used.

(8) The Canonical Correlation Analysis has indicated that it is feasible to semi-quantitatively assess the relationship between the dependent and independent variables. It is therefore recommended that the Canonical Correlation Analysis technique be pursued in an attempt to acquire quantifiable synoptic information of conditions in impoundments.

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APPENDIX A

ANALYSIS OF CHLOROPHYLL a

IN FRESHWATER PHYTOPLANKTON

TRUTER, E.; 1981 MANUAL FOR BIOLOGICAL ANALYSIS OF FRESHWATER SAMPLES
PROJECT N3/0501 TASK 1 CHEMICAL/BIOLOGICAL ANALYTICAL SERVICES

ANALYSIS OF CHLOROPHYLL a IN FRESHWATER PHYTOPLANKTON

1. Apparatus

(a) Filter Apparatus: e.g. Millipore vacuum/pressure pump 115 v 50 Hz (xx60 110 50) with a 6 place filter holder manifold (xx25 047 00)

(b) Spectrophotometer: e.g. Varian Techtron UV-Vis Model 635.

(c) Water bath with contact thermometer.

(d) Centrifuge.

(e) Test tubes with screw caps.

(f) Centrifuge tubes with caps.

(g) Glass-fibre filter membranes: e.g. Sartorius SM 134000 or Whatman GF/C.

2. Method

(i) Filter a known volume of sample through a glass-fibre filter, allow to suck dry.

(ii) Roll up filter with the entrapped algae and place in a screw capped test tube.

(iii) Add 9.8 ml 91.8% ethanol. As the glass-fibre filters retain on average 0.2 ml of water, this gives a final concentration of 10 ml 90% ethanol. Mark the final volume level.

(iv) Place in water bath at 78°C and allow to boil for 5 min. Make sure that the screw caps are not too loose as the ethanol will evaporate off. If any loss is noted after boiling, make up to volume mark with 90% ethanol.

(v) Allow to stand in the dark at room temperature for 1 h to 24 hours. If room temperature is high (> 30°C) place in a refrigerator.

(vi) After extraction decant extract into a centrifuge tube and cap. The tube must be capped as ethanol will evaporate from an open tube during centrifugation.

(vii) Centrifuge at 4 000 rpm for 5 min.

(viii) Decant 4 mℓ of sample into a 1 cm pathlength spectrophotometer cuvette.

(ix) Read the absorbance at 665 nm and 750 nm, using 90% ethanol as the reference blank.

(x) Add 100 µℓ of a 0.3 moles/ℓ HCL solution, shake well and allow to stand for 2 min.

(xi) Reread the "665 nm" absorbance, scanning for the Absorbance peak between 665 nm and 666.5 nm. Reread the absorbance at 750 nm.

3. <u>Calculation</u>

(i) Values from step 9 are $D_{665}b$ and $D_{750}b$

Values from step 11 are $D_{665}a$ and $D_{750}a$

(ii) Subtract the 750 nm readings from the 665 nm readings.

e.g. $D_{665}b - D_{750}b = E_{665}b$

$D_{665}a - D_{750}a = E_{665}a$.

(iii) Insert values into the formula:

$$\text{chlorohyll } \underline{a} \text{ (mg/}\ell \text{ extract)} = \frac{(E_{665}\,b - E_{665}\,a)\,(R/R-1)\,K}{L}$$

where (R/R-1) = 2.39 (R = the "acid factor" 1.72)

K = 11.99 (specific absorption coefficient of chlorophyll a in 90% ethanol = 83.4)

L = Pathlength of cuvette in centimeters (= 1 cm).

The Equation is thus:

$$\text{Chlorophyll } \underline{a} \text{ (mg/}\ell \text{ extract)} = E_{665}b - E_{665}a)\ 28.66$$

(iv) To convert above to $\mu g/\ell$ sample multiply by the factor appropiate to the volume of sample filtered (see attached table).

For 800 ml sample multiply the mg/ℓ extract by 12.5 to give the final value in $\mu g/\ell$ sample.

If 10 cm^3 extract is used, then for the final answer multiply the mg/ℓ by the following amounts depending on the original volume filtered. The final answer is in $\mu g/\ell$.

Formula: $$\frac{C_a \times V}{V_1}$$

C_a = Concentration of chlorophyll a in mg/ℓ in the extract.

V = Volume of extract in mℓ.

V_1 = Volume of sample filtered in litres.

Vol. filtered	Multiply mg/ℓ by
1 000 mℓ	10,0
900 mℓ	11,1
850 mℓ	11,8
800 mℓ	12,5
750 mℓ	13,3
700 mℓ	14,3
650 mℓ	15,4
600 mℓ	16,7
550 mℓ	18,2
500 mℓ	20,0
450 mℓ	22,2
400 mℓ	25,0
350 mℓ	28,6
300 mℓ	33,3
250 mℓ	40,0
200 mℓ	50,0
150 mℓ	66,7
100 mℓ	100,0

APPENDIX B

LANDSAT/WATER QUALITY

SURFACE REFERENCE DATA

SAMPLING FORM

LANDSAT/WATER QUALITY DATA SAMPLING FORM

SITE 1 [: : : : : : : : :] 10

DATE 11 [: : : : :] 16

SUNSHINE CONDITIONS 17

1	CLEAR
2	MEDIUM
3	OVERCAST

TIME 18 [: : : :] 22

SAMPLE POINT 23 [:] 24

SAMPLE A

SURFACE CHLOROPHYLL µg/ℓ	25 [: : : :] 29	
INTEGRATED CHLOROPHYLL µg/ℓ	30 [: : : :] 34	
SECCHI DISC m	35 [: : :] 38	
SURFACE TURBIDITY NTU	39 [: : :] 42	
INTEGRATED TURBIDITY NTU	43 [: : :] 46	

WIND SPEED m/sec 47 [: : :] 50

WIND DIRECTION 51 [:] 52

AIR TEMPERATURE °C 53 [: : :] 56

CARD NUMBER 80 [ ]

APPENDIX C

SURFACE REFERENCE DATA COLLECTED FOR ROODEPLAAT DAM CONCURRENTLY WITH THE SATELLITE OVERFLIGHTS

81.10.14
81.11.01
81.12.07
82.09.13
82.09.30
82.11.16.

SURFACE REFERENCE DATA, MEAN OF DUPLICATES
81.10.14

SAMPLING POINT NO.	SURFACE CHLOROPHYLL a µg/ℓ	INTEGRATED CHLOROPHYLL a µg/ℓ	SURFACE TURBIDITY NTU	INTEGRATED TURBIDITY NTU
1	25,3	33,0	3,0	3,6
2	28,0	34,1	3,4	3,9
3	22,8	29,3	3,1	3,5
4	33,3	39,0	3,9	3,9
5	32,2	34,7	4,2	4,6
6	32,8	39,3	3,2	3,5
7	26,1	26,7	3,3	4,0
8	29,3	28,8	3,6	3,6
9	21,2	27,5	3,3	3,8
10	24,9	32,1	3,7	5,8
11	30,4	30,7	3,7	4,0
12	29,9	30,4	5,9	5,2
13	29,3	33,9	5,6	6,8
14	26,9	20,5	5,4	5,3
15	27,2	32,7	5,4	5,9
16	22,8	25,3	5,9	6,2
17	22,6	24,7	5,5	6,1
18	42,0	18,3	7,3	6,0
19	29,0	22,4	8,0	5,8
20	27,7	19,6	6,7	7,8
21	23,0	20,6	7,0	6,4
22	27,4	24,0	6,3	6,9
23	24,8	24,9	6,6	6,8
24	33,4	25,2	6,3	7,2
25	28,0	27,9	6,6	7,5
26	25,3	27,7	7,8	8,8
27	33,4	23,4	6,0	6,6
28	33,7	30,9	6,8	7,3
29	107,6	82,0	10,9	13,5
30	23,1	31,0	5,5	6,1
31	30,2	31,3	3,8	4,4
32	26,1	30,4	3,8	3,8

SURFACE REFERENCE DATA, MEAN OF DUPLICATES
81.11.01

SAMPLING POINT NO.	SURFACE CHLOROPHYLL *a* µg/ℓ	INTEGRATED CHLOROPHYLL *a* µg/ℓ	SURFACE TURBIDITY NTU	INTEGRATED TURBIDITY NTU
1	16,8	32,70	3,3	4,2
2	39,4	35,5	4,5	4,5
3	29,7	32,0	4,0	4,2
4	33,8	32,0	4,6	4,4
5	34,7	30,6	4,9	5,4
6	21,9	35,3	4,0	4,9
7	84,2	26,9	17,2	4,1
8	18,7	25,7	4,0	4,8
9	18,3	18,9	3,8	4,3
10	22,8	23,8	4,1	4,7
11	26,1	25,4	4,1	4,2
12	24,4	28,9	4,3	4,2
13	62,2	40,7	10,4	6,1
14	37,7	41,0	6,3	7,7
15	36,3	40,4	7,4	7,0
16	37,5	35,0	6,7	7,8
17	45,7	42,2	7,9	7,5
18	29,8	39,6	6,3	6,8
19	47,4	37,1	8,2	7,1
20	44,5	45,9	7,8	8,3
21	52,5	41,0	10,2	7,5
22	29,1	40,0	7,7	10,0
23	32 8	46,7	7,8	8,8
24	27,9	29,9	7,4	11,2
25	22,8	38,1	6,8	9,1
26	29,3	42,4	8,9	10,4
27	33,6	35,5	8,5	9,7
28	31,4	40,8	9,8	12,5
29	33,5	31,8	10,5	12,5
30	107,8	46,7	18,0	6,7
31	18,2	27,7	3,1	3,5
32	20,1	26,7	3,6	3,9

SURFACE REFERENCE DATA, MEAN OF DUPLICATES
81.12.07

SAMPLING POINT NO.	SURFACE CHLOROPHYLL a µg/ℓ	INTEGRATED CHLOROPHYLL a µg/ℓ	SURFACE TURBIDITY NTU	INTEGRATED TURBIDITY NTU
1	7,6	8,6	1,6	1,2
2	8,3	9,6	1,7	2,0
3	9,0	6,0	1,9	1,6
6	10,0	9,2	1,4	2,1
7	9,5	9,7	1,9	1,4
8	9,5	8,9	2,2	2,0
11	6,7	2,9	0,9	2,0
12	3,3	3,6	1,2	1,7
13	8,6	22,8	2,5	3,1
14	16,6	10,6	3,1	3,2
15	9,7	19,9	3,1	3,1
16	14,3	10,6	4,0	4,2
17	20,6	14,2	3,2	2,9
18	10,4	5,0	3,8	3,4
19	20,9	17,4	4,4	3,9
20	20,3	11,7	5,0	4,4
21	17,9	16,9	3,6	3,6
22	30,6	30,5	8,0	6,7
23	3,1	29,5	5,8	6,2
24	33,1	35,8	8,1	8,3
25	35,4	26,6	9,0	8,9
26	30,5	30,1	15,7	14,5
27	37,0	38,3	12,0	11,7
28	45,0	43,2	13,5	13,5
29	68,2	68,1	20,0	18,5
30	7,6	8,4	1,4	2,3
31	7,3	5,4	1,0	1,1
32	8,6	8,6	1,4	1,0

SURFACE REFERENCE DATA
82.09.13

SAMPLING POINT NO.	SURFACE CHLOROPHYLL a µg/ℓ	INTEGRATED CHLOROPHYLL a µg/ℓ	SURFACE TURBIDITY NTU	INTEGRATED TURBIDITY NTU
1	15,2	17,5	4,3	4,9
2	18,1	17,9	4,2	4,9
3	15,0	16,1	4,0	4,7
4	21,8	22,6	4,4	5,2
5	25,4	29,7	5,4	6,2
6	16,5	13,6	4,3	4,1
7	14,0	12,9	3,7	4,1
8	13,9	10,7	4,3	3,7
9	12,3	12,7	3,6	3,8
10	11,9	12,7	3,7	3,7
11	11,5	10,7	3,6	4,4
12	13,1	14,3	3,9	4,5
13	16,4	14,3	4,1	4,4
15	22,9	18,8	4,9	5,4
16	20,9	24,2	5,0	5,5
17	21,3	18,8	4,4	4,6
18	18,8	17,2	4,5	5,3
19	16,8	22,5	5,3	5,5
20	20,1	22,9	5,5	6,2
21	22,9	21,7	5,0	5,8
22	24,2	12,3	6,1	6,7
23	22,5	20,1	6,7	6,8
24	27,0	23,4	6,7	7,4
25	27,0	27,5	6,8	6,9
26	29,5	29,5	7,2	7,7
27	35,7	26,6	7,1	7,4
28	32,8	45,5	7,7	8,0
29	55,3	50,4	17,0	21,0
30	11,5	11,9	4,2	4,2
31	13,1	12,7	3,9	4,5
32	12,7	9,8	3,6	4,0

SURFACE REFERENCE DATA
82.09.30

SAMPLING POINT NO.	SURFACE CHLOROPHYLL a µg/ℓ	INTEGRATED CHLOROPHYLL a µg/ℓ	SURFACE TURBIDITY NTU	INTEGRATED TURBIDITY NTU
1	10,7	13,3	4,0	3,4
2	11,5	12,9	3,7	4,0
3	11,5	12,2	3,3	3,5
4	11,1	11,5	3,2	3,5
5	14,0	17,9	3,6	4,5
6	10,7	12,9	3,6	3,7
7	10,7	13,3	3,1	3,3
8	10,7	12,5	3,2	3,3
9	9,3	14,0	3,2	3,4
10	12,9	14,0	3,8	3,9
11	12,5	14,3	3,6	3,5
12	17,2	17,9	4,2	4,6
13	15,8	17,9	4,2	4,5
14	17,5	20,1	4,1	4,2
15	17,2	20,1	4,0	4,3
16	22,9	23,3	4,7	4,7
17	18,3	25,8	4,2	4,9
18	25,1	27,2	4,7	5,0
19	17,2	22,6	4,3	4,7
20	33,7	39,4	5,3	5,8
21	29,7	30,8	5,1	5,5
22	39,8	41,9	6,4	7,4
23	40,5	43,0	7,8	7,3
24	42,6	41,2	6,7	7,5
25	45.9	44,1	8,2	8,5
26	51,6	49,3	8,7	9,2
27	50,4	57,3	12,0	12,0
28	42,4	40,1	8,0	8,7
29	82,0	111,2	18,0	20,0
30	16,8	18,9	4,0	4,5
31	15,0	14,0	3,4	3,5
32	9,3	12,5	3,4	4,1

SURFACE REFERENCE DATA
82.11.16

SAMPLING POINT NO.	SURFACE CHLOROPHYLL a µg/ℓ	INTEGRATED CHLOROPHYLL a µg/ℓ	SURFACE TURBIDITY NTU	INTEGRATED TURBIDITY NTU
1	9,7	11,8	3,0	3,1
2	12,6	14,3	3,4	3,9
3	13,2	13,2	3,6	3,6
4	11,8	11,2	3,4	3,6
5	13,2	12,6	3,1	4,0
6	13,8	14,6	4,1	4,6
7	14,9	13,5	3,6	4,1
8	16,6	18,1	4,2	4,4
9	13,2	10,9	3,1	3,4
10	14,0	14,0	3,8	3,9
11	12,9	11,8	4,2	4,4
12	14,0	13,2	4,4	4,5
13	19,5	18,9	4,6	4,7
14	20,1	19,2	5,2	5,5
15	21,5	22,1	5,0	5,5
16	24,1	21,2	6,0	6,1
17	23,5	24,7	5,5	6,4
18	21,3	20,7	6,0	6,2
19	22,1	21,8	5,0	5,6
20	27,4	26,1	6,4	6,5
21	32,1	30,1	5,5	6,5
22	33,0	32,2	8,3	8,0
23	33,7	33,7	7,3	7,4
24	48,3	45,5	9,8	13,0
25	42 2	40,6	7,5	7,8
26	34 8	38,1	13,0	13,5
27	57,4	56,0	8,4	9,5
28	121,0	114,6	15,5	17,0
29	369,7	325,3	28,0	31,0
30	17,2	16,8	4,0	4,5
31	13,0	13,5	3,9	4,0
32	14,0	12,6	17,0	18,0