REMOTE SENSING OF ALGAE IN INLAND SOUTHERN AFRICAN WATERS

Thesis submitted to Rhodes University in fulfilment of the requirements for the degree of Master of Science.

G QUIBELL
NOVEMBER 1991.

For my Father,
I wish he could have seen the final product.

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DECLARATION

This thesis is the result of my own independent research. However the advice and suggestions offered by my supervisor has been included. Parts of the thesis have been published in three internationally reviewed papers (listed below), the comments offered by the referees have also been incorporated in the final document.

The research was carried out as part of an assessment of the viability of using remote sensing for water quality surveys in South Africa and was done under the auspices of the Department of Water Affairs of the Republic of South Africa. This department was also responsible for funding the work.

The degree was read in absentia.

QUIBELL G. (1989) A comparison of multispectral photography and LANDSAT MSS for the detection of chlorophyll concentrations in inland waters. *S.Afr. J. Photogrammetry, Remote Sensing and Cartography,* 15(4), 160-168.

QUIBELL G. (1991) The effect of suspended sediment on reflectance from freshwater algae. *Int. J. Remote Sensing,* 12(1), 177-182.

QUIBELL G. (in press) Estimating chlorophyll concentrations using upwelling radiance from different freshwater algal genera. *Int. J. Remote Sensing,* (accepted December 1990)

Copies of the above are bound in Appendix C.

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ABSTRACT

Routine monitoring of algae in inland waters in southern Africa is a critical element in assessing the efficacy of eutrophication management options. Several authors have indicated that single point samples are not necessarily representative of conditions throughout the water body and some have suggested remote sensing as a means of overcoming this problem.

Remote sensing of algae normally involves deriving the empirical relationship between radiance detected at a sensor, and contact sensed chlorophyll concentrations. Quantification of, or compensation for, contributions to the upwelling radiance other than that light reflected by the algae is critical for this approach. In southern Africa these contributions arise primarily from atmospheric effects and from scattering by sediments in the water.

A review of the atmospheric correction models suggested that a cosine sun angle correction followed by dark pixel subtraction is the most feasible method to compensate for the former effects. Studies of the changes in upwelling radiance induced by addition of sediment to algal cultures indicated that subtraction of reflectance at ≈665nm from that at ≈700nm, may provide a means of compensating for the scattering by sediments. The disadvantage of this approach is that few sensor systems have narrow spectral bands centred at these wavelengths.

Investigations of the nature of the reflectance from 5 algal species indicated that all had similar reflectance spectra, but the blue-green genera had a smaller peak at ≈650nm. Chlorophyll absorption at ≈665nm was evident by lower reflectance at this point, but the alga *Microcystis sp.* did not conform to the conceptual model of reflectance, in that reflectance at 665nm was higher at increased cell density. Spectra of natural waters confirmed the results obtained in the laboratory. Reflectance at ≈700nm showed the largest changes with increasing chlorophyll concentration and also had the highest correlations to chlorophyll concentrations. However, due to the strong absorption of these wavelengths by water, this reflectance peak only occurred when sufficient cells were found in the upper layers of water. Use of these wavelengths in remote sensing models should therefore be restricted to highly eutrophied waters.

Although the reflectance spectra of different algae were similar, the amount of light scattered by each species (measured as turbidity) differed for any given chlorophyll concentration. This appeared to be due to the colonial nature of the cells and means that empirical models will be unique to the species on which they were developed.

Comparisons of multispectral photography (MSP) and LANDSAT MSS imagery indicated the MSP data had higher correlations with chlorophyll concentrations than did the MSS data. Chlorophyll simulations from a test set of data using ordinary multiple regression showed that the MSP imagery had mean errors of 7.3µg/l, while that for the MSS imagery was 7.4µg/l. Similar tests using the canonical procedure produced larger mean errors of 9µg/l and 12µg/l for the MSP and MSS data respectively. This was due to the fact that the canonical procedure is not suitable

for the spectral band widths of these sensors.
In spite of similar simulation accuracies, the MSS imagery produced very patchy synoptic views. This was due to the lower variance (radiometric resolution) in the LANDSAT MSS data. This appears to be the most important criterion for accurate chlorophyll mapping in inland waters.
Development of a single multidate algorithm for southern Africa is not yet feasible, and routine monitoring of chlorophyll using these techniques is impractical. However acceptable chlorophyll maps are possible if the model is recalibrated for each occasion and the sensor used has a high radiometric resolution.

CHAPTER ONE

WATER QUALITY PROBLEMS IN SOUTH AFRICA

1.1 Background

"Water, water everywhere nor any drop to drink"
(Rhyme of the Ancient Mariner- Coleridge)

This lament of the sailor is becoming increasingly poignant in many countries, and in southern Africa in particular. As some 71% of the earth's surface is covered by water, global availability of water is certainly not a problem, and parts of South Africa along the coastline have ready access to the sea. However, although it is technically feasible to treat the ocean to drinking water standards, the high costs of these processes make the sea an economically unavailable source of water. South Africa is therefore restricted to fresh water supplies which occur in lakes, rivers or as groundwater. These sources account for only 0.015% of the total amount of water on earth (Wetzel 1983).

In South Africa water availability is particularly important as some 65% of the country has a rainfall of 500mm or less, which is only 60% of the world average (DWA 1986). This situation is further exacerbated by the uneven distribution of this rainfall. The highest annual precipitation occurs in the eastern parts (800-1000mm) and this gradually drops off to the west coast which has less than 200mm of rain annually (DWA 1986). These shortages of water have required legislation by the South African government stipulating that all effluent should be returned to the river system from where it was originally abstracted (Water Act of 1956). These effluent unavoidably carry wastes generated by man's activity back to the river systems, and have led to the deterioration of the water quality of many South African rivers and impoundments. Higher concentrations of pollutants in turn result in increased costs of treatment of the raw water to potable standards, and Grabow (1986) reports that levels of total dissolved salts in the Vaal Barrage are approaching levels of $800mgl^{-1}$. This may require desalination at a cost of R140 million per year. To complicate the issue, a rapidly growing population not only places increasing demands on water supply, but also contributes to increased sewage and industrial runoff to our river systems.

The management of water resources to maintain equitable quality, as well as quantity, of water is therefore receiving more attention and forms part of the central mission of the Department of Water Affairs (DWA 1986). This emphasis on water quality management can be expected to grow as the demands for water outstrip the quantities available.

1.2 The problem of eutrophication

One of the more important consequences of the pollution of freshwater aquatic systems is the enhanced loading of plant nutrients, chiefly phosphorus and nitrogen species, to rivers and lakes. This process, known as eutrophication , often leads to excessive growth of floating planktonic algae (Wetzel 1983).

Blooms of planktonic algae have been noted in many South African impoundments (Toerien and Walmsley 1977 and Bruwer 1978) and Toerien, Hyman and Bruwer (1975) found 10% of South African water bodies to be eutrophic. These studies identified Hartbeespoort Dam, situated near the largest industrial areas in the country, as one of the worlds most eutrophic water bodies. However, Hutchinson, Pickford and Schuurman (1932) describe this impoundment as having deep clear waters with very little algae. The eutrophication, and consequent growth of algae, in Hartbeespoort Dam can be directly linked to the increased loading of nutrients to the water body which occurred with the expansion of Johannesburg in the catchment area.

Discharge of nutrients into water bodies due to man's activities (cultural eutrophication) is the cause of many serious water quality problems in South Africa (Bruwer 1978).
Blooms of planktonic algae, which often follow eutrophication, create a variety of problems for the authorities responsible for the treatment of water to potable standards, as well as for the recreational users of the water bodies. Water treatment organisations complain that filters rapidly clog with algae, shortening filter runs (Bruwer 1978). Taste and odour problems are imparted to the potable water by cytolysis of the algae (Eren 1972). Chlorination of some organic molecules associated with algae result in the production of tri-halomethanes (THMs) which are thought to be carcinogenic (Gehr 1989). Another important effect of the growth of algae in the surface waters is the production of anaerobic bottom waters due to the death, sinking and decay of algae. This can lead to the reduction of metal compounds in the bottom water and Bruwer (1978) reports a case in the Pietersburg government water scheme where more Aluminium sulphate, lime and chlorine dosages were required to reduce the iron content of the purified water to acceptable standards. Some of the problems of eutrophication are associated with the growth of certain species of algae, and Scott (1989) reports that death of livestock and game has been linked to the presence of toxic forms of *Microcystis spp*. in their drinking water. Bruwer (1978) reports that icthyotoxins produced by some species of algae can cause fish kills. The financial implications of these problems necessitates effective eutrophication management.

Growth of algae, like that for any plant, is associated with the availability of plant nutrients. In a study of 98 southern African impoundments Toerien *et al* (1975) found that in most impoundments phosphate was the major growth limiting nutrient for algae. If most of the phosphate comes from outside the system and is not rapidly recycled within the water body, control of the growth of algae should be possible by reducing the phosphate loading to the system. The Department of Water Affairs has consequently imposed a $1 mgl^{-1}$ phosphate standard for all point sources of pollution in seven sensitive catchments (DWA 1986). Other control measures such as the addition of Copper sulphate to kill the algae (Bruwer 1980), or aeration of the bottom waters (Chutter 1989) have, or will soon be, applied to South African waters. Gehr (1989) has also suggested that repositioning of offtake sites to areas with less algae may solve some of the problems within the treatment works.

These management methods are however expensive, and monitoring of the algal content of surface waters is important, not only to assess the efficacy of existing management options, but also to indicate when eutrophication management is necessary. Currently the Department of Water Affairs estimates the algal content of southern African impoundments is estimated by the analysis for the chlorophyll *a* concentration in samples taken from the water body.

1.3 Chlorophyll *a* analysis

Chlorophyll *a* is a constituent of all algal types (Bold and Wynne 1985) and the estimation of the algal population is normally done by analysis for the chlorophyll *a* concentration in a sample taken from the water body (Sartory 1982). This requires the filtering of the sample to trap the algae, boiling the trapped algae and filter paper in alcohol, and the measurement of the concentration of chlorophyll *a* in the extract (Sartory 1982). The latter technique involves the measurement of the absorbance of electromagnetic energy by the chlorophyll extract in a spectrophotometer. As it is impossible to separate the absorbance of phaeophytin and chlorophyll *a* from an extract of natural waters, the extract is normally acidified to determine the relative contribution of phaeophytin to the absorbance measured (Sartory 1982).

The above, or very similar methods for the analysis for chlorophyll *a* concentration have routinely been used as an indication of the algal density in South African dams. However, this method as a means of determining the average algal status of the whole water body is only as accurate as the method used to sample the water body. If the sample is not representative of the area in which it was taken, analysis for chlorophyll *a* will not provide an accurate estimate of the average algal status of the whole water body.

Samples are normally taken at a point near the dam wall, or more occasionally at a few selected points on the water body. A surface grab of the upper few centimeters of water, and/or an integration of the upper 5m of the water column is taken, and from this a given volume is filtered to extract the algae. As algal cells normally concentrate in the upper layers during the day, where there is sufficient light for photosynthesis, these methods should provide an accurate estimate of the algal population at that point. However, several authors have suggested that these single point samples are not necessarily representative of the average algal status of the water body (Howman, Grobler, Kempster and Seed 1989, Knowlton, Hoyer and Jones 1984, Stauffer 1988 and Thornton, Kennedy, Magoun and Saul 1982). This implies that in order to accurately estimate the average algal status of a water body, either many more samples should be taken, or some method of producing a synoptic view of the chlorophyll *a* distribution and concentration should be sought.

Synoptic views of algal concentrations and distribution will not only provide better indications of the efficacy of management options applied to the control of algal growth, but will also assist in the siting of abstraction points in parts of the water body less prone to algal blooms. Synoptic views of the distribution of algae can also provide valuable information on the lateral extent of in lake eutrophication management options such as aeration.

1.4 Remote sensing of water quality

Another commonly used water quality parameter is the measurement of the amount of light scattered by particles suspended in the water column. This is done in a turbidimeter which measures the amount of light scattered at right angles to a light source (Kirk 1988). These readings are expressed as nephelometric or fluorometeric turbidity units (NTU or FTU). The turbidity of the sample expressed as NTU provides an indication of the scattering coefficient of the water (Kirk 1988), which is a measure of the amount of light which is scattered out of the water body. Algae occur as particles suspended in the water column and also contribute to the turbidity of the water. Estimates of algal population density are therefore possible by measuring the amount of light scattered by the algae out of the water body.

Estimation of the amount of algae and/or other suspended solids by means of deriving the empirical relationship between surface samples and a measurement of the light received at a sensor placed above the water surface, has often been done (Adams, Scarpace, Scherz, and Woelkering 1977, Aranuvachapun and Walling, 1988, Boland 1976, Curran, Hansom, Plummer and Pedley 1987, Grimshaw, Torrans and Lera 1980, Grunwald, Mauser and Schneider 1988, Howman and Kempster 1986, Huang and Lulla 1986, Lathrop and Lillesand 1986, Mace 1983, Ritchie, Schiebe and Cooper 1986, Stumpf and Tyler 1988 and Verdin 1985). The remote sensors used in these studies have the advantage of producing synoptic views of a large area at any one time and as such can solve the problems associated with single point samples.

Quantification of algal populations using remote sensors placed some distance above the water surface has normally involved three steps. Firstly, the selection of the most suitable sensor to detect the reflectance from the water body. Secondly, the measurement of the changes in light scattered out of water bodies with increasing algal density. This is calculated as increased reflectance in some wavelengths and/or decreased reflectance in others. Lastly, compensation for the modifications and additions to this light by passage through the atmosphere.

However, the use of remote sensing techniques to quantify algal populations differs from contact sensing of chlorophyll *a* in several important aspects:

- remote sensing is based on reflectance from the whole algal cells, and not from the absorbance of one constituent of the cells (viz. chlorophyll *a*). The reflectance/absorbance characteristics of the whole cells may differ from that of pure chlorophyll *a*.
- light scattered out of the water by other particles in suspened in the water column is also detected. In turbid waters higher chlorophyll concentrations may be simulated due to reflectance from suspended sediments.
- in contact sensing, chlorophyll *a* in the extract is divided by the volume filtered to produce concentrations. Remote sensors however, detect light from an entire volume of water. Therefore at any given chlorophyll concentration, the number of cells which contribute to the radiance detected will differ with changes in the depth of remote sensing penetration.
- due to the wavelength dependent absorption of light by water, reflectance spectra of the algae will differ with their depth in the water column.
- The atmosphere between the water and sensor also affects the light detected.

Effective use of remote sensing technology rests upon the resolution of all of the above problems.

1.5 Objectives of this study

Several authors have demonstrated a significant relationship between chlorophyll *a* and upwelling radiance in one or more spectral bands or ratios of spectral bands (Adams *et al* 1977 Bukata, Jerome and Bruton 1988, Grimshaw *et al* 1980, Huang and

Lulla 1986, Lindell 1981, Shih and Gervin 1980 and Verdin 1985) and remote sensing technology has also already been used to monitor inland water quality in southern Africa (Howman and Kempster 1986). To prove that these techniques can still be applied to the South African situation would simply be reinventing the wheel. However, the real value of remote sensing lies in the use of the technology to monitor chlorophyll concentrations in our impoundments on a routine basis.

The objective of this study is therefore to assess the suitability of remote sensing techniques for the routine monitoring of algal concentrations in inland South African waters. This will be done by addressing the following issues:-

- Atmospheric correction. Compensation for the effects of the atmosphere on the remotely sensed signal are well documented (MacFarlane and Robinson 1984), and techniques for atmospheric correction only are addressed in the literature review (Chapter 2). The aim of this review is to identify the most suitable atmospheric correction for South African conditions.
- Reflectance from algae. The characteristics of the light scattered out of South African water bodies is poorly understood. An understanding of the light scattered out of eutrophic waters by the algae in suspension will indicate whether algorithms can be extrapolated to other impoundments, perhaps dominated by other algal species. This thesis addresses this problem by;
    i. examining the reflectance spectra of different species of algae isolated in pure culture. (Section 3.3)
    ii. correlating the radiance measured just above the water surface to the chlorophyll concentration. Total radiance is calculated as the geometric mean of radiance measured in 5nm steps for each of the spectral bands of several sensor systems. (Section 3.4)

iii. assessing the changes caused by the addition of suspended sediments to the upwelling radiance for pure cultures (Section 3.5).

iv. examining the depth of remote sensing penetration into the water body and the effect of cell depth on the reflectance spectra of algae. (Section 3.2).

• Sensor characteristics. In order to produce synoptic views, sensors must be placed some distance above the water surface. Such sensors normally do not measure radiance in discrete wavelengths, but integrate radiance over given spectral bands (Hilton 1984). The positioning of these bands with respect to the reflectance spectra from the target, as well as the ability of the sensors to detect small changes in radiance have been shown to be important for monitoring crop growth and development (Clevers 1988). In this thesis the importance of detecting small changes in algal density will be investigated by comparing rasterised multispectral aerial photography to LANDSAT MSS data as means of quantifying chlorophyll concentrations in inland waters. (Chapter 4)

1.6 Site description.

Roodeplaat Dam was chosen for the study due to it's proximity to the Hydrological Research Institute where the work was done. This impoundment is situated 30km north east of Pretoria. It is a eutrophic water body with high chlorophyll concentrations. The dam is situated at latitude 25° 37' South and the water surface covers an area of 398 hectares. The impoundment has two arms, a western and an eastern arm and is fed by three rivers (Fig 1.1). The Hartbeesspruit and the Pienaars River enter the water body in the western arm and introduce most of the sediment and nutrients to the system. The Edendalespruit flows into the eastern arm of Roodeplaat Dam and has lower nutrient concentrations.

The uneven distribution of nutrient loading to the system results in a chlorophyll concentration gradient with the highest concentrations normally occurring near the Pienaars and Hartbeesspruit inflows. The inflowing rivers also bring suspended sediments into the impoundment, these soon flocculate out of the water column and suspended sediment only occurs in the upper reaches of the inflows. High suspended sediment concentrations are therefore often associated high concentrations of chlorophyll. These gradients provide a wide range in water quality conditions and make Roodeplaat Dam an ideal site for this study.

1.7 Terminology

The following terms used in the study are defined here as;

Chlorophyll- This is chlorophyll *a* plus phaeophytin concentration measured using Sartory's (1982) method, and is expressed in microgrammes per liter ($\mu g.l^{-1}$).

Irradiance- The intensity of sunlight measured with a cosine receptor fitted to a LICOR LI-1800 spectroradiometer. Designated $L_{\delta d}$, and is expressed as milliWatts per centimeter squared per nanometer ($mW.cm^{-2}.nm^{-1}$) (LICOR instruction manual).

Specroradiometer Radiance- The intensity of upwelling light, measured with a telescopic receptor fitted to a LICOR LI-1800 spectroradiometer. Designated $L_{\delta u}$, and also is expressed as $mW.cm^{-2}.nm^{-1}$. (LICOR instruction manual).

Satellite Radiance- The intensity of upwelling light, measured at a satellite sensor. Expressed as $mW.cm^{-2}.nm^{-1}.ster^{-1}$. (LANDSAT data users notes).

Reflectance- This is radiance divided by irradiance and is expressed as a percentage.

Turbidity- A measurement of the scattering of light by a sample of water. Measured in a HACH turbidimeter as Nephelometric Turbidity Units NTU.

Rasterised- This refers to the process of determining the density of exposed aerial film over given small areas of the film, and the writing of these densities as integer digital values to computer compatible tapes (CCT's).

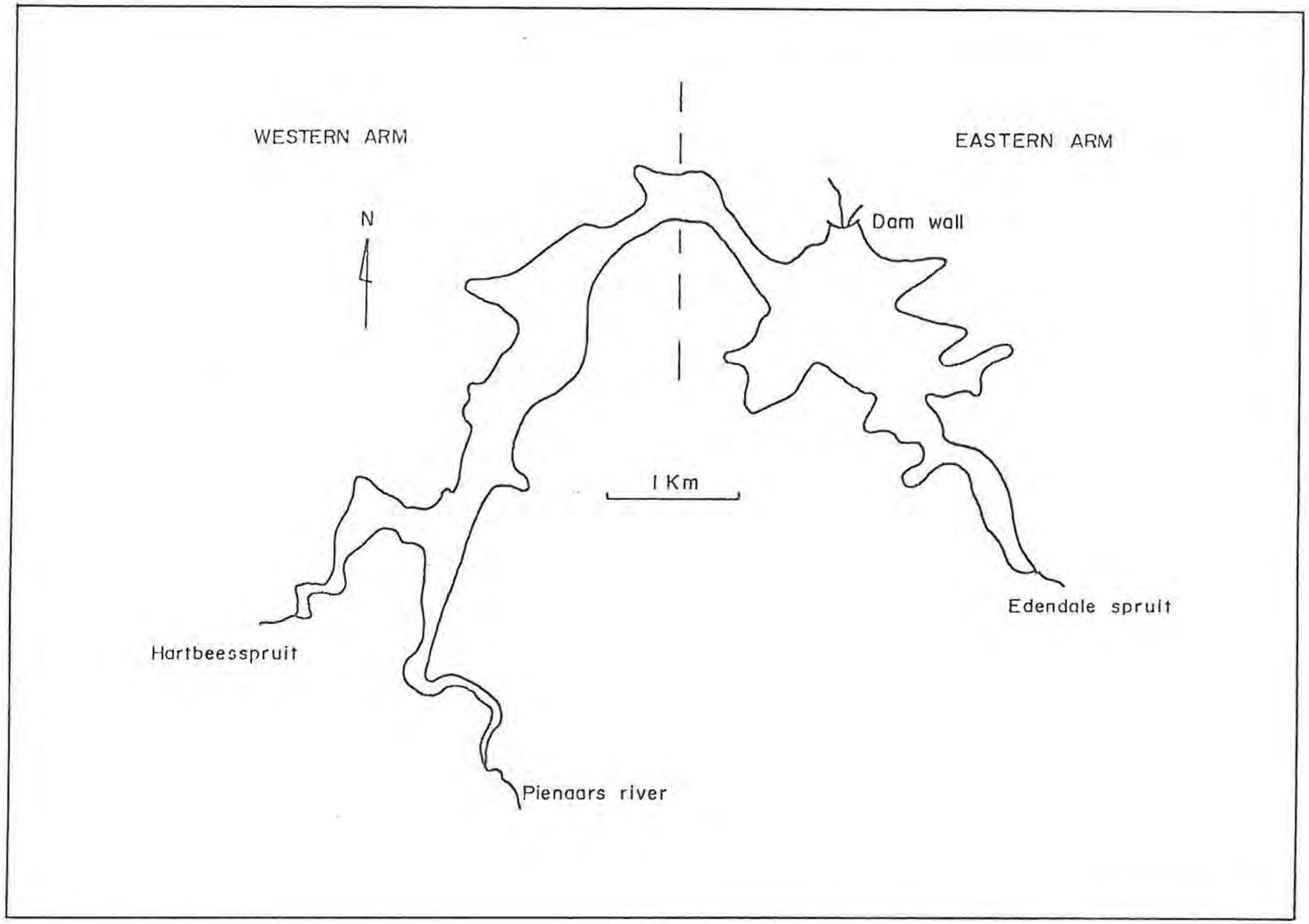


Figure 1.1. A map of study impoundment (Roodeplaat Dam) showing the two main arms of the impoundment and the inflowing rivers.

CHAPTER TWO

REMOTE SENSING IN THE AQUATIC ENVIRONMENT

2.1 Background.

Remote sensing has been described as:

> "the set of techniques used to obtain information about the earth's surface and atmosphere at some distance from them, usually by means of reflection from the electromagnetic spectrum." (Townshend 1981)

Remote sensing consists of sensors mounted onto platforms, an illumination source, and a target which reflects electromagnetic energy from the source back into the sensors. Remote sensors can be further divided into active and passive types (Hilton 1984). Active remote sensors use artificial radiation sources like radar or laser energy which is beamed at the target, while passive forms use the sun as a source of illumination. Most passive remote sensors use an array of sensors which detect different parts of the electromagnetic spectrum as several discrete spectral bands (Hilton 1984).

Sensors can be mounted on satellite or aircraft platforms, or may be placed just above the target (eg. hand held spectroradiometers). For satellite based sensors, upwelling radiance in each spectral band is usually converted to a digital value by an on board analog to digital converter. The digital values are sent as 6-bit (0-63), as 8-bit (0-255) or as 10-bit (0-1023) data to a ground receiving station. Here these digital values are written as integers onto computer compatible tapes (CCT's) (Boland, Shaeffer, Selfton, Clarke and Blackwell 1979). Scanning remote sensors use oscillating mirrors to divert upwelling light into the sensors, and the instantaneous field of view (IFOV) is that area on the target which is directed into the sensors at any instance.

The IFOV is the smallest unit of definition and is known as the pixel (Kirk 1983). A row of these pixels makes up one scan, and a series of scans makes up an image. Most remote sensors use a variety of spectral bands placed to detect different parts of the electromagnetic spectrum. Some systems have more than one sensor per spectral band, and several lines of the image are collected with each sweep of the mirror arm.

Although most of these systems are designed for terrestrial remote sensing, some eg. the Coastal Zone Color Scanner (CZCS) which was mounted on the Nimbus-7 satellite and the SeaWIFS scanner to be mounted on the LANDSAT 6 satellite, are/were designed specifically for ocean colour observations. Sensor systems designed for ocean colour observations have narrow spectral bands (20nm) placed to detect chlorophyll absorption peaks as well as bands which detect reflectance from algae (Table 2.1). The chlorophyll/radiance algorithms for these systems are therefore based on increased reflectance in some bands and/or decreased reflectance in others (Hilton 1984). In addition, these satellites are more sensitive to the small amount of radiance which is scattered out of water, and the CZCS has a radiometric sensitivity 60 times that of the LANDSAT MSS sensors (Kirk 1983). The combination of high spectral and radiometric resolution make ocean colour sensors capable of detecting small changes in chlorophyll concentrations.

These satellite systems should be the obvious choice for the remote sensing of water quality. However the pixel sizes of the CZCS and SeaWIFS sensors are too large to be practical for use on small water bodies (Table 2.1). The practical upshot of this is that in order to produce synoptic views of water quality for inland waters remote sensors designed for terrestrial applications must be used. In this study LANDSAT MSS imagery is compared to aerial photography as a means of quantifying chlorophyll concentrations in inland waters in South Africa.

Table 2.1. Spectral bands of the ocean colour satellites.

Coastal Zone Colour Scanner on the Nimbus 7 satellite. (pixel size = 1.1 km^2)

Band	Center	Width	Target object
1	443nm	20nm	chlorophyll absorbance
2	520nm	20nm	Reference
3	550nm	20nm	Gelbstoff & sediments
4	670nm	20nm	Chlorophyll absorbance
5	750nm	100nm	Vegetation
6	11.5µm	2.0µm	Temperature

SeaWiFS on LANDSAT 6* (pixel size = 1.1 km^2)

Band	Center	Width	Target object
1	443nm	20nm	Low chlorophyll
2	500nm	20nm	Other pigments
3	565nm	20nm	Baseline chlorophyll
4	665nm	20nm	Chlorophyll absorbance
5	765nm	40nm	Atmospheric effects
6	865nm	44nm	Atmospheric effects
7	11.0µm	1.0µm	Temperature
8	12µm	1.0µm	Temperature

* Still to be launched
(From NASA 1987.)

2.2 Remote sensing of algae in inland waters

Although active remote sensing using laser fluorescence of chlorophyll (lidar) has been used to detect chlorophyll concentrations in coastal waters (Diebel-Langor, Hengsterman and Reuter 1986), most applications in this field use passive forms of remote sensing. Early uses of terrestrial remote sensors for inland water quality observations involved the identification of "reflectance signatures" of test lakes with a known trophic status, and then the trophic classification of other lakes by the statistical comparison of their reflectance signatures to the test lakes (Adams, *et al* 1977, Boland 1976, Boland *et al* 1979, Bukata and Bruton 1974 and Raitala, Jantunen and Lampinen 1985). Some of these authors also saw the potential of developing regression models which can simulate contact sensed data using satellite detected radiance.

More recently, inland remote sensing studies have concentrated on the development of regression models between a variety of water quality parameters and remotely sensed radiance (Aranuvachapun and Walling 1988, Carpenter and Carpenter 1983, Grimshaw *et al* 1980, Grunwald *et al* 1988, Howman and Kempster, 1986, Huang and Lulla 1986, Lathrop and Lillesand 1986, Lindell 1981, Lyon, Bedford, Yen, Lee and Mark 1988, Mace 1983, Munday, Alfoldi and Amos 1979, Ritchie, Cooper and Yongoing 1987, Scarpace, Holmquist and Fisher 1979, Shih and Gervin 1980, Stumpf and Tyler 1988 and Verdin). Quantification of chlorophyll concentrations in most of these studies was based on increased reflectance with increasing algal density, and chlorophyll concentrations simulated from the remotely sensed radiance were usually within 20-40 % of the *in situ* concentrations.

Although these authors all develop a relationship between water quality and the remotely sensed signal, there is no consensus as to the exact nature of this relationship. This is particularly true of the relationship between chlorophyll and radiance. Most authors convert the digital value on the CCT to radiance and then use linear or multiple linear regression procedures to correlate logs or natural logs of the chlorophyll concentration to radiance (Grunwald *et al* 1988, Huang and Lulla 1986, Mace 1983 and Ritchie *et al* 1986). Some authors recommended exclusion of the infrared bands in these regressions due to the strong absorption of infrared light by water (Carpenter and Carpenter 1983, Lathrop and Lillesand 1986, Lindell 1981 and Verdin 1985). Other authors note the multicollinearity inherent in remotely sensed data and use sophisticated empirical procedures eg. ridge regression (Shih and Gervin 1980) or the canonical correlation analysis (Howman and Kempster 1986) to optimise the relationship. A few authors recognise that algae reflect light at some wavelengths and absorb in others. This means that some spectral bands should show increased reflectance with increasing chlorophyll concentration, while others should have a decreased reflectance. Ratios of these spectral bands are then used to optimise the relationship (Boland 1976, Grimshaw *et al* 1980 and Stumpf and Tyler 1988).

The lack of agreement on the nature of the relationship has been ascribed to factors (other than the constituent under study), which contribute to, or alter the upwelling signal (Curran and Novo 1988). Compensation for, or removal of these effects is essential for standardization, which is neccessary if routine use of remote sensing to monitor chlorophyll concentrations in inland waters in South Africa is to be practical.

A review of remote sensing in the aquatic environment, with respect to the correction for; The effects of the atmosphere, Variations in angle of illumination, and Sensor characteristics, is presented in the following section.

2.3 Remote sensing in the aquatic environment

2.3.1 Background

Water provides a unique medium for remote sensing as light is not only reflected off the surface, but is also scattered out of the water body from below the surface. It is this light scattered out of the water body by particles suspended or dissolved in the water, which is of interest to the remote sensor of water quality. More specifically, only that light which is reflected by the algae is necessary for the estimation of chlorophyll concentrations.

Radiation must pass through part of the water body before and after it is scattered by algae. The atmosphere between the water and sensors also contributes to the total signal detected. Signals received at a sensor over water, therefore, consist of a combination from several sources (Fig 2.1 and Eq 2.1). Sunlight ($L_{rs\delta}$) and diffuse skylight ($L_{rd\delta}$) can be reflected off the water surface back to the sensor. Absorption (T_a) and scattering ($L_{a\delta}$) of both the downwelling and upwelling light in the atmosphere can further alter the signal received at the sensors. This has been expressed mathematically by Millar, Jain, O'Neill, Thomson and Mc Neill (1977) who describe radiance received by a remote sensor as;

$$L_{z\delta} = T_a \, (L_{w\delta} + L_{rd\delta} + L_{rs\delta}) + L_{a\delta} \quad \text{........Eq 2.1}$$

Where: $L_{z\delta}$ = apparent upwelling radiance at altitude z and wavelength δ.
T_a = atmospheric transmittance
$L_{w\delta}$ = Inherent upwelling radiance at the water surface.
$L_{rd\delta}$= Upwelling radiance from specular reflection of diffuse skylight.
$L_{rs\delta}$= upwelling radiance from specular reflection from the water surface.
$L_{a\delta}$ = Upwelling radiance scattered by the atmosphere.

To complicate the issue several authors have highlighted the problem of angular anisotrophic (or bidirectional reflection distribution BRD) reflectance from terrestrial targets (Duggin 1985, Duggin and Philipson 1985 and Ott, Pfeiffer and Quiel 1984). Angular anisotrophic reflectance means that the angle at which the sensor views the water body as well as the angle of incident solar radiation can influence the signal detected at the remote sensor.

Water also demonstrates a wavelength dependent absorption of light, and reflectance from water bodies normally falls within the lower range of most sensor systems (Hilton 1984). The response of the sensor used to these low radiances will, therefore, also influence the ability of the sensor to detect smaller differences in chlorophyll concentration.

Routine use of remote sensing rests on either the quantification of all of these effects, or that the radiance be measured in such a way as to minimise or remove these effects (Curran and Novo 1988).

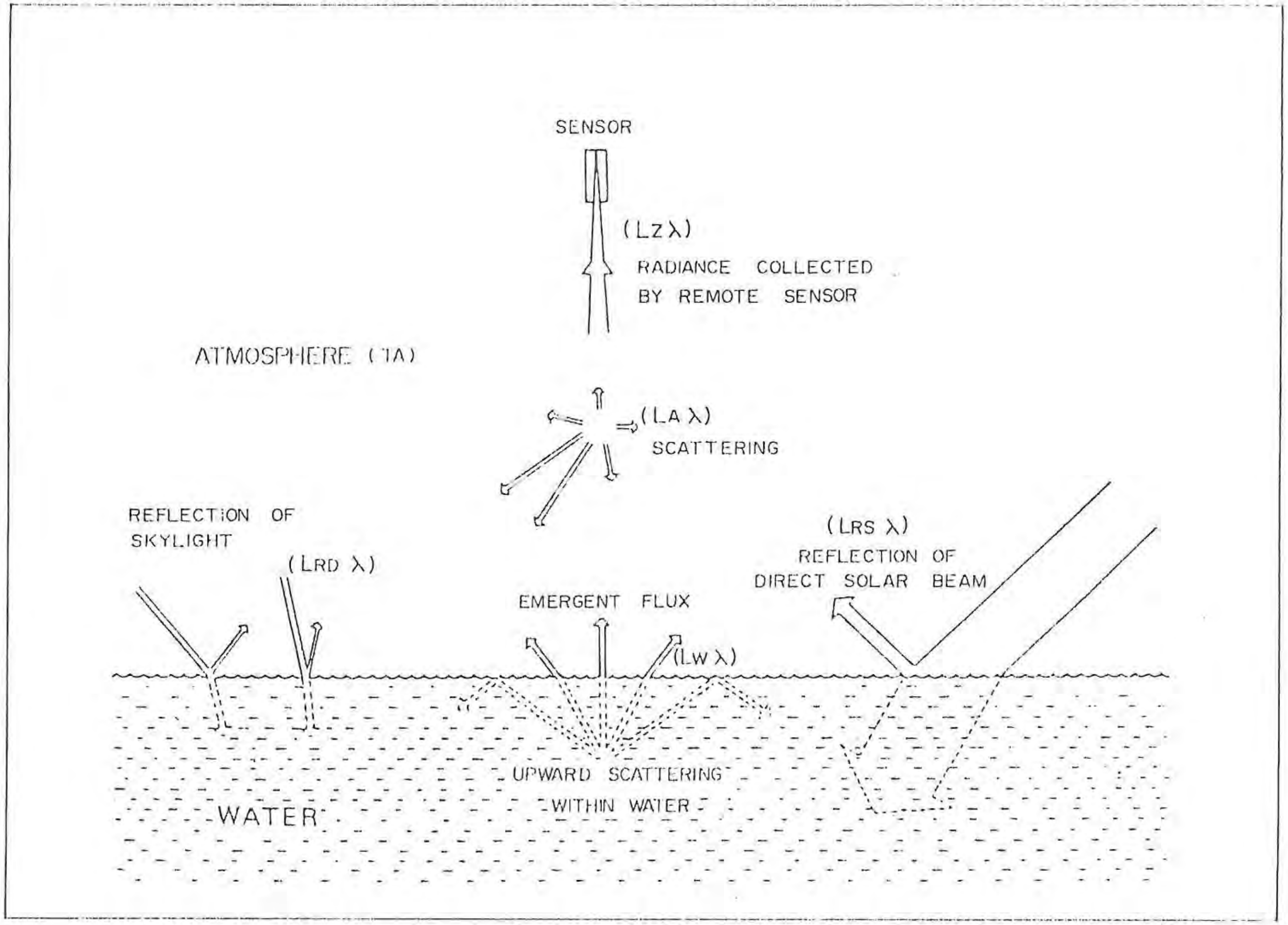


Figure 2.1. The different contributions to the total upwelling signal detected by a remote sensor over water. (The terms in brackets refer to Eq 2.1, Modified from Kirk 1983)

2.3.2 Atmospheric correction

Kirk (1983) suggested that 80 to 90% of the radiance received at a sensor over water is contributed by scattering in the atmosphere. Other authors, however, suggest that this can be as high as 95% (Curran and Novo 1988). Compensation for, or removal of, atmospheric effects is neccessary for standardization (MacFarlane and Robinson 1984) and atmospheric correction normally forms part of the modelling process (Curran and Novo 1988).

In order to produce synoptic views of chlorophyll distribution, the sensor platform must be placed some distance from the water surface and the effects of the atmosphere are, therefore, unavoidable. However, for aircraft platforms the atmospheric path is shorter and atmospheric correction is not as important. Some authors have nevertheless shown atmospheric correction is neccessary in aerial surveys (Ott, Pfeiffer and Quiel 1984 and Williams 1984).

The two best known atmospheric scattering models are the Rayleigh and Mie models (Chavez 1988). Rayleigh scattering is inversely proportional to the fourth power of the wavelength (δ^{-4}), while Mie scattering varies from δ^{-0} to δ^{-4} according to the scattering particle size (Chavez 1988). Generally, Rayleigh scattering accounts for dispersion by gas molecules, and Mie scattering is caused by smoke and dust particles in the atmosphere. As the distribution and concentration of gas molecules is generally known and constant in the atmosphere, the amount of Rayleigh scattering can be calculated with some degree of accuracy (Duggin 1985). Methods for this correction are presented by MacFarlane and Robinson (1984) and Walters (1985). The concentrations of smoke and dust particles in the atmosphere vary from place to place, and calculation of Mie scattering normally requires some form of *in situ* measurement. In water quality studies this is normally done by assuming zero radiance from water in the infrared wavelengths (MacFarlane and Robinson 1984). Chavez (1988) suggests that real atmospheric scattering is in the order of δ^{-1} to $\delta^{-0.5}$, and that Rayleigh scattering is only appropriate for very clear skies. As many southern African impoundments lie close to major industrial centres, which produce large amounts of smoke, correction for Mie scattering is essential if algorithms are to be extrapolated in time and space.

Several different techniques for atmospheric correction have been proposed and some are summarised below.

Verdin (1985) proposes a technique to compensate for atmospheric effects using data available from the remotely sensed scene. This technique is based on the premise that clear deep water should not reflect any light and a standard oligotrophic reflector is chosen on the lake. Ratioing of the radiance values in each band with the radiance values for the clear water should compensate for the effects of transmission through the atmosphere (Verdin 1985). This method presupposes that areas of deep clear water exist close to the area of interest, which is very unlikely in southern African water bodies.

Another similar technique is called dark pixel subtraction (Chavez 1988). This technique is based on the assumption that in every scene at least some pixels should have zero radiance (eg. cloud shadows) and that any reflection in these pixels is contributed by scattering within the atmosphere. Correction is then done by subtracting the darkest pixel digital values from each pixel in the scene. However, MacFarlane and Robinson (1984) suggest that dark pixel subtraction techniques are inadequate as the sole method of atmospheric correction.

Chavez (1988) proposed an improved dark pixel subtraction technique where the dark pixels in one of the spectral bands are used to correct for atmospheric effects at all wavelengths. The value of the dark pixel is determined from a histogram of any one band of an image covering a large area. This histogram should show a peak in the number of pixels at some non-zero digital value, which is assumed to be the haze contribution for the entire image (Chavez 1988). This digital value is used to indicate the type of scattering ($\delta^{-0.5}$ to δ^{-4}) which is then used in a relative scattering model to simulate the haze in other bands (Chavez 1988). The advantage of this method is that all the information required for the correction is contained within the image.

All the above techniques are based on the premise that effects of the atmosphere are dominantly additive and are spatially homogenous. That is component $L_{a\delta}$ of Eq 2.1 is responsible for most of the effects of the atmosphere.

More rigorous atmospheric correction techniques recognise that the effect of the atmosphere is both additive and multiplicative. This is summarised in equation 2.2 below (Scarpace *et al* 1979).

$$L_{z\delta} = T_a * L_{w\delta} + L_{a\delta} \qquad \text{..........Eq. 2.2}$$

The additive term, $L_{a\delta}$, means ratioing will not remove all the atmospheric effects and the multiplicative term, T_a, means that subtraction as the only method, will not be effective. The value of $L_{a\delta}$ can be calculated using dark pixel (normally deep clear water) subtraction, and the multiplicative term T_a, is estimated from ground areas of known high reflectance, which are assumed not to change over time eg. airport runways (Scarpace *et al* 1979). However, this model proved inadequate when used to correct for the effects of the atmosphere in LANDSAT water quality observations in the U.S.A. (Lillesand, Johnson, Deuell, Lindstrom and Meisner 1983). Although Caselles and Lopez-Garcia (1989) successfully used a similar technique to correct for atmospheric effects over a lagoon in the Mediterranean. This approach is also based on the assumption that the effects of the atmosphere are uniform over the scene of interest.

Munday, Alfoldi and Amos (1979) suggest chromaticity analysis as a means for removing spatial effects of the atmosphere, as well as any spatial noise in the data. This technique is based on the ratio transformations below;

$$X_i=N_i/\Sigma N_i \quad \text{.....................Eq. 2.3}$$

Where: X_i are the chromaticity coefficients, and N_i are the LANDSAT MSS band radiances in each band

Munday *et al* (1979) suggest that this ratio transformation will suppress noise and atmospheric effects when all the bands suffer radiance changes in the same proportion. This approach can be criticised as scattering in the atmosphere is wavelength dependent, but the method has the advantage of providing a pixel by pixel correction system. However this procedure, by the authors own admission, is inapplicable when high concentrations of algae occur together with high concentrations of suspended sediment.

MacFarlane and Robinson (1984) show that a simple atmospheric/surface correction algorithm, based on atmospheric optical transmission theory was the most satisfactory correction method when using LANDSAT MSS data to quantify offshore suspended sediment concentrations. This technique is based on the following premise; Radiance (L^i) received at the satellite in any band (i), is assumed to be made up of Rayleigh scattering ($L^i{}_{pr}$), aerosol (Mie) scattering ($L^i{}_{pa}$), sunglitter ($L^i{}_{sg}$), skyglitter ($L^i{}_{sh}$) and scattering by the sediment in suspension ($L^i{}_{s}$). The terms ($L^i{}_{pr}$), ($L^i{}_{sh}$) and ($L^i{}_{sg}$) are calculated from standard atmospheric scattering functions and values. The term

(L^{i}_{sh}), however, requires wind velocity data in it's calculation (MacFarlane and Robinson 1984). As the distribution of dust particles in the atmosphere is not constant, aerosol scattering cannot be calculated using standard functions. Initially MacFarlane and Robinson (1984) estimated aerosol scattering using visability data. However they suggest this did not provide accurate resulsts, and indicated that estimates of aerosol scattering were best achieved by assuming a zero water leaving radiance in the infrared band of the LANDSAT MSS data (band 4).

Use of ground visability as a calibration parameter for the LOWTRAN atmospheric correction model has been attempted under South African conditions (Meyer 1991). However, this model was not used in this study.

2.3.3 Sensing geometry.

Sensing geometry refers to the angle at which the target is viewed as well as the angle at which the target is illuminated. Sensing geometry has been shown to affect the relationship between suspended solid concentration and radiance (Curran and Novo 1988). This is due to the changes in the amount of sunglint and specular reflection of diffuse skylight ($L_{rs\delta}$ and $L_{rd\delta}$ Eq 2.1) as well as the amount of emergent flux which is detected at different illumination and view angles. This angular anisotrophy in reflectance can become important when pixels in the same scene are viewed at different angles. This is particularly true for aircraft borne systems, and are usually manifest as an east-west brightness change (Williams 1984).

At solar elevation angles of greater than 50°, specular reflection makes a significant contribution to the total radiance measured above the water (Kirk 1983), while at angles less than 40°, sunglint can be a problem (Curran and Novo 1988). Roughening of the surface of the water by wind also has little effect on the penetration of light into the water body at solar elevation angles of 40° to 50° (Kirk 1983). This makes illumination angles of between 40° and 50° ideal for remote sensing of algae.

Figure 2.2 shows the time of day when solar elevation angles are between 40° and 50° for southern African mid-latitude (28° S). Satellites in sun synchronous orbits (eg. LANDSAT) have fixed equatorial crossing times. The LANDSAT South African overpass time is approximately 09h30. Therefore, the periods of the year which have ideal solar elevation angles for South African water quality observation are limited to February to March and September and October.

The solar zenith angle also influences the amount of sunlight reaching the earth's surface. The higher the angle of the sun the more intense the downwelling light and consequently the greater the upwelling radiance. If empirical models are to be extrapolated over time, then correction for the different angles of the sun is essential. Turner (pers comm) has suggested that all LANDSAT MSS data be standardised to a 90° solar zenith angle using the following formula;

$$y' = (\cos\phi / \cos 90°) y'' \qquad \text{Eq. 2.4}$$

Where: y'' and y' are the MSS data before and after normalization.
and, ϕ is the zenith angle at the time of data acquisition.

This method changes overall scene brightness and hence compensates for lower sun angles. However, MacFarlane and Robinson (1984) indicate that similar sun angle corrections as the only radiometric transform, are also inadequate for water quality studies.

The angle at which the sensor views the water body can also influence the amount of specular reflection and sunglint detected. When the sensor view angle is towards the sun, a greater volume of light will be reflected specularly into the sensor. At view angles away from the sun, more radiance scattered by particles within the water column is detected (Curran and Novo 1988). Novo, Hansom and Curran (1989b) show that viewing geometry affected the relationship between suspended sediment and radiance measured just above the water surface, and the strength of the relationship decreased at off nadir view angles. This was especially noticeable at low suspended sediment concentrations, and was also wavelength dependent. Sub-surface scattering of light in water bodies is hence also subject to angular anisotrophy, and the amount of light detected above a water body is dependent on the angle at which the sensor views the target. This is important for airborne remote sensing systems where the sensors are closer to the target, and edges of the image are viewed at a significantly different angle to those in the center. When the sensors are placed far from the water surface (eg. satellites) the view angle differences are negligible over small water bodies.

Light reflected off a flat surface at 53° (Brewster's angle) is polarised (Kirk 1983). Polarizing filters can therefore be used to reduce specular reflection when upwelling radiance is measured close to Brewster's angle.

2.3.4 Sensor characteristics

In addition to factors which affect the signal received by the remote sensor, the response of the sensor to the upwelling signal is important. Most remote sensors convert radiance detected by photomultipliers into digital values, which are expressed as an integers. These integer values are stored on computer compatible tapes (CCT's), and are the basic source of data for all satellite studies.

However, the digital value to radiance conversion differs between sensor systems, and the calibration of any one system may also change over time. Conversion of the digital value to radiance (in mW. cm^{-2}. nm^{-1}. $ster^{-1}$) is therefore essential for standardization (Radiometric correction, sensu MacFarlane and Robinson 1984). This is done using linear calibration equations available for the sensor systems (Hilton 1984).

The absorption of electromagnetic energy by water means that only a small percentage of the downwelling light is scattered out of water bodies. Sensors designed for water quality observations must, therefore, be able to detect low radiances (referred to here as radiometric sensitivity) and should also be sensitive to small changes in radiance (referred to here as radiometric resolution).

Figure 2.3 shows two hypothetical plots of integer digital values (DN) to radiance. Sensor A detects a given range in radiance as many discrete DN steps, whereas sensor B detects the same range in fewer steps. Sensor A can therefore detect smaller changes in chlorophyll while sensor B will only be able to detect large changes in radiance.

Sensor A, in figure 2.3, will have a shallow slope to the digital value/radiance conversion, but sensor B will have a steep slope for this conversion. Slope of the digital value to radiance conversion can therefore be used as a measure of the radiometric resolution of the sensor (radiometric resolution is used in a different context in Prangsma and Roozekrans, 1989, who refer to the 6, 8 or 10 bit digital value output on the CCT). Table 2.2 gives the slope of the digital value to radiance conversion for several sensor systems. The CZCS, which was designed to detect small changes in chlorophyll concentration, has the shallowest slope and is capable of detecting very small differences in radiance. Of the LANDSAT MSS sensors, LANDSAT 4 appeared to be the best suited to water quality observations and LANDSAT 5 the least suited (Table 2.2). This may explain the poorer performance of the model CALMCAT developed by Howman and Kempster (1986) when calibrated with LANDSAT 5 MSS data (unpublished data).

Table 2.2 Slopes for the digital value to radiance conversion for several sensor systems. Slopes were calculated as the difference between the maximum & minimum radiances detected by the sensors over the number of digital value steps. Maximum and minimum radiances were available from the LANDSAT data users notes.

	LANDSAT							
Band	1	2	3	4	5	TM	Daed+	CZCS*
1	.39	.40	.40	.37	.42	.06	.35	.045
2	.32	.27	.28	.25	.27	.12	.23	.031
3	.28	.23	.23	.22	.23	.08	.29	.025
4	.25	.20	.20	.18	.19	.08	.54	.011
5						.01	.27	.094
6							.28	-.004

+ Daedalus Airborne Thematic Mapper
* Data from Walters (1987)

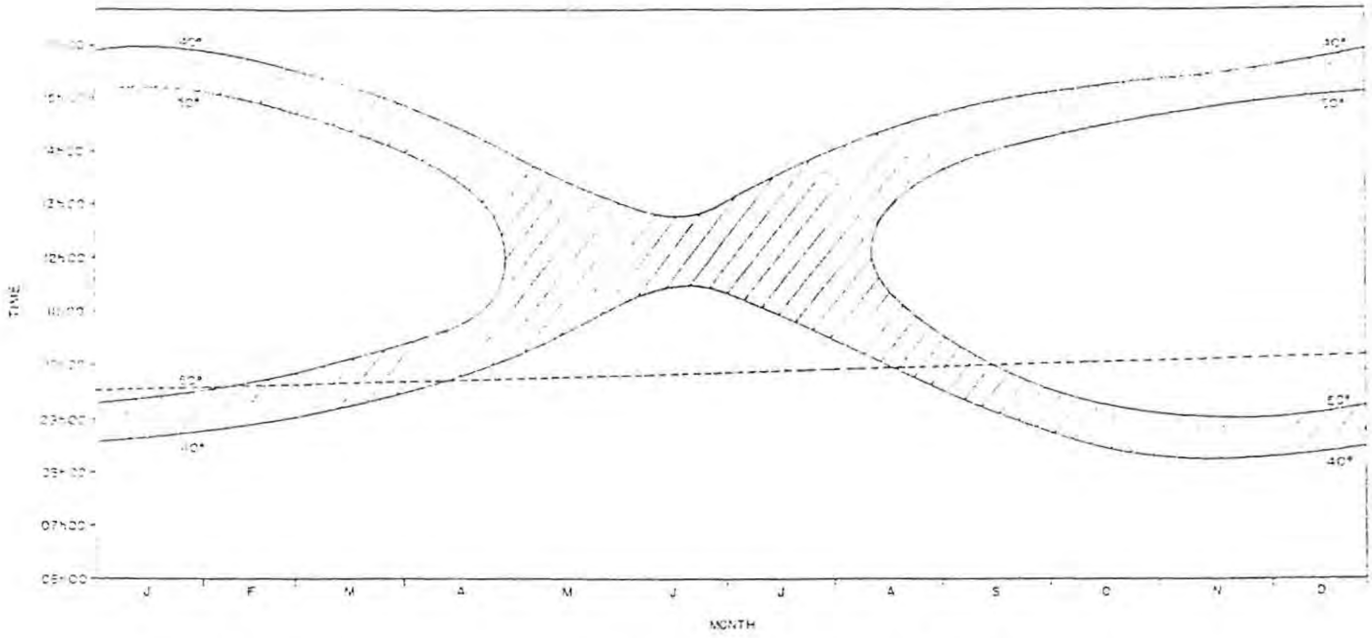


Figure 2.2. The time of day when the solar elevation angles are between 40° and 50°, for each month of the year (shaded area). Calculations were made for South African mid latitudes (28° S). The dotted line indicates the LANDSAT overpass time.

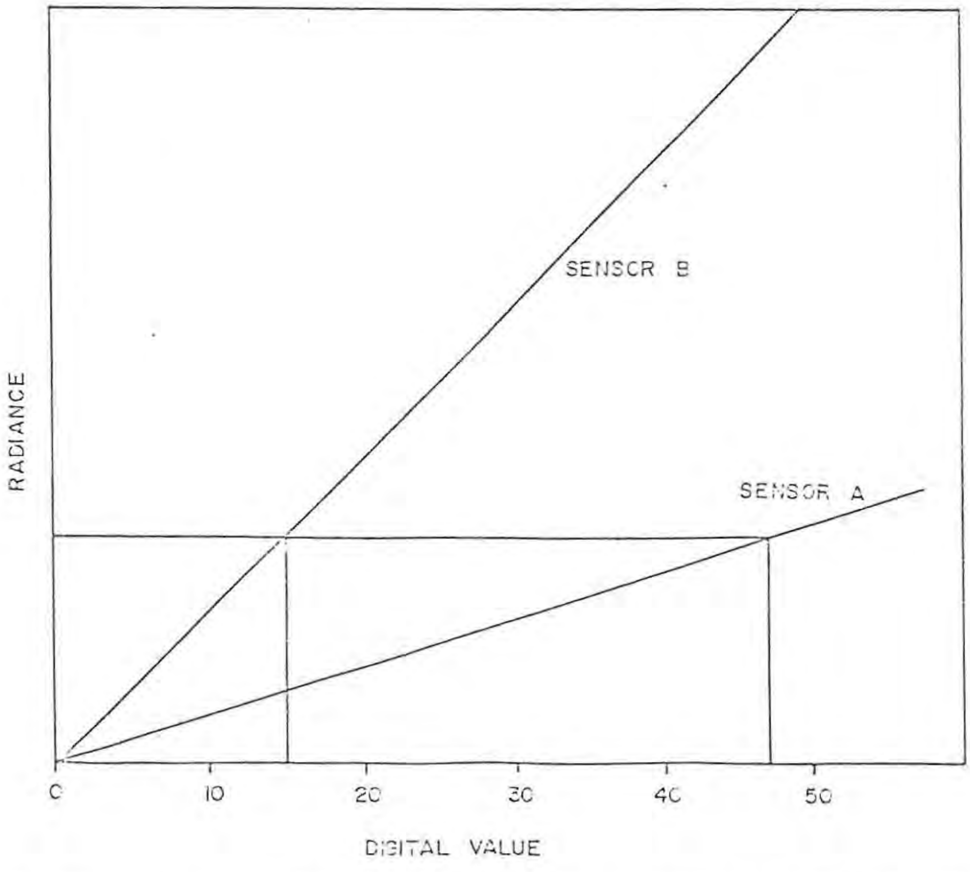


Figure 2.3. Plots of radiance against digital value for two hypothetical sensors. Sensor A detects a given range in radiance as more integer digital values i.e.has a greater radiometric resolution.

2.4 Conclusions

The potential use of remote sensing to routinely quantify chlorophyll concentrations in inland water lies in the ability of the techniques to produce synoptic views of chlorophyll distribution without the need for expensive recalibration. This necessities correction for other environmental factors which alter the upwelling signal from water. These factors are chiefly atmospheric and angular anisotrophic reflectance effects.

Examination of several atmospheric correction models available in the literature has shown that models based on radiative transfer theory provide the most accurate method of atmospheric correction for water quality studies. However, the estimate of aerosol (Mie) scattering proposed by MacFarlane and Robinson (1984) is based on the assumption of zero radiance in the infrared wavelengths. In oceanic waters, which generally have lower chlorophyll concentrations, this assumption is most likely valid. In inland waters in South Africa high concentrations of algae and/or sediment often occur in the surface layers, and in many cases the algae form scums on the surface (Bruwer 1978). In this case the assumption of zero water leaving radiance may not be valid. In this case aerosol (Mie) scattering will best be estimated from cloud and topographic shadows. A further disadvantage of the method proposed by MacFarlane and Robinson (1984) is the requirement of data other than that available from the remotely sensed scene.

The improved dark pixel subtraction method proposed by Chavez (1988) has the advantage of simplicity and may prove to be the most feasible method of atmospheric correction for the routine quantification of chlorophyll concentrations.

If an empirical radiance/chlorophyll model is recalibrated for each remotely sensed image, then temporal variations the atmosphere can be ignored. In this case radiometric correction is also unnecessary and raw digital values can be used in the equations. The assumption of an uniform atmosphere is also likely to be valid, particularly over small water bodies.

Sun angle corrections to a standard solar elevation are also necessary to ensure uniformity. The cosine correction (Eq. 2.4) adjusts for relative scene brightness and can be used to standardise images to a given solar elevation. However, the effect of angular anisotrophy in sub-surface scattering is difficult to quantify (Duggin 1985). For satellite borne sensors this should not be a problem, and for aircraft sensors the problem can be overcome by avoiding the edges of the images.

The digital value to radiance conversion differs between satellites and over time. Radiometric correction is therefore essential for standardization. However, the response of the sensor system to changes in radiance also influences the ability of the sensor to detect small changes in radiance (Radiometric resolution). Sensors designed for ocean colour observation have the highest radiometric resolution, but the low spatial resolution of these satellites makes them impractical for application to small water bodies. This means that satellite systems designed for terrestrial remote sensing (eg. LANDSAT MSS and TM) must be used for water quality observations in inland systems. This necessities a compromise in radiometric resolution with consequent loss in the ability to detect small changes in chlorophyll concentrations.

The implications of this are investigated in more detail in Chapter 4 of this thesis, by comparing simultaneously collected aerial photography and LANDSAT MSS imagery for the quantification of chlorophyll concentrations on Roodeplaat Dam.

MacFarlane and Robinson (1984) state that the greatest impediment to the development of a standard suspended sediment/radiance algorithm is the differing reflectance characteristics of the various types of sediment. The reflectance characteristics of different algae, and the effect of cell depth and the addition of sediment on this reflectance is investigated in the following chapter.

CHAPTER THREE

THE UPWELLING SIGNAL FROM EUTROPHIC WATERS

3.1 Introduction.

Passive remote sensing of algae, by virtue of its definition, does not entail the direct measurement of the algae, but rather relies on the empirical relationship between radiance in any pixel and some measure of the algal concentration in the same pixel. This normally involves the simultaneous measurement of that downwelling light which is scattered out of the water body by the algae, and chlorophyll concentrations. This approach presupposes that contributions to the upwelling signal, other than that light scattered by the algae, are either equal in all the pixels (or images), or that some radiometric preprocessing has been done to compensate for these effects. Solving equation 2.1 for the term $L_{w\delta}$ forms the crux of the atmospheric correction techniques reviewed in the previous chapter. These corrections can not however compensate for contributions to, or modification of, the total upwelling signal from algae before it leaves the water body.

In South Africa many rivers carry high sediment loads. These sediments are carried down to impoundments on the river where most of the particles settle out of suspension (Rooseboom 1978). The amount of sediment deposited in an impoundment is related to the size of the water body, and in impoundments greater than one times the mean annual runoff more than 96% of the sediment entering the reservoir is deposited within the water body (Rooseboom 1978). This means that many South African impoundments have a suspended sediment gradient from the river inflows to the dam wall, and in some parts of the water body upwelling radiance will be dominated by scattering by sediments, while in other parts algae may dominate the upwelling signal. This means that unless reflectance from sediments can be separated from that from the algae, chlorophyll disribution may be inaccurately simulated.

To complicate this issue, different species of algae vary in the type, proportions and concentration of pigments per cell (Sid'ko and Vasil'yev 1988). Different species may, therefore, show unique reflectance characteristics. This would require the development of a separate empirical relationship for each species. In this case the dominant algal species in the impoundment at the time of remote sensing would have to be known. If this cannot be determined from the remotely sensed data, ground truth data collection would have to be done. This would limit the value of remote sensing techniques for the routine monitoring of algae in inland waters.

Furthermore, as water shows a wavelength dependent absorption of light, the reflectance spectrum of any cell will also vary with its depth in the water column (Davies-Colley, Vant and Wilcock 1988). This may necessatate a different empirical approach in hypereutrophic lakes which often develope algal scums (eg. Hartbeespoort and Roodeplaat Dams). This problem is exacerbated by variations in the depth of remote sensing penetration. In clearer waters, light penetrates to a greater depth and more algal cells will contribute to the upwelling signal than in turbid waters with the same chlorophyll concentration.

Standardization of the chlorophyll/radiance relationship to cope with all possible limnological conditions is important if routine use of remote sensing is to be practicle in South Africa. The objective of this chapter is to generate an understanding of the components of the upwelling radiance from eutrophic waters. This is done by reviewing the absorption of light by water and the effect this has on remote sensing of algae. The depth of remote sensing penetration in natural water bodies is estimated, and is related to the Secchi disc penetration at that point.

The reflectance characteristics of different species of algae isolated in pure culture are compared, and reflectance from naturally occurring algal populations measured. The correlation of reflectance (integrated over different spectral bands) to chlorophyll concentration is examined to assess the value spectral resolution for the quantification of algae. The effects of the addition of sediment on reflectance from pure algal cultures is also explored. This will also generate a rationale for optimising the empirical approach for any given set of data.

3.2 Methods

3.2.1 Spectroradiometer

Radiance is measured with a LICOR LI-1800 scanning spectroradiometer. This instrument, when fitted with telescopic receptor, measures radiance from any target. The telescopic receptor can be adjusted to provide 4, 8 and 15 degree fields of view. In this study the 4 degree field of view was used to minimise the possibility of specular reflection from the water into the sensor. The LICOR LI-1800 can also be fitted with a cosine receptor, this was used to measure downwelling solar irradiance. This was done by placing the instrument in a large open area (or highest point on the boat. The cosine receptor therefore measured total downwelling irradiance, which includes solar irradiance and diffuse sky radiance. Reflectance was calculated as the percentage of the radiance/irradiance ratio.

The spectroradiometer is fitted with a grating monochromator, and is capable of measuring radiance in 2 or 5nm steps from 300-1100nm. The monochromator has 0.5mm slits, which produce a total bandwidth of 8nm (ie. when selecting 500nm, the instrument is measuring radiance from 496-504nm). This results in a series of overlapping spectral bands, which for the sake of simplicity were plotted as a single continueous line. Wavelength accuracy was factory tested six months prior to the study using lamps with known spectral emission lines. Radiometric calibration was achieved by measuring radiance from a known source (in this case a 1000W quartz tungsten lamp). This proceedure is used to set up calibration files for each of the receptors. These represent the spectroradiometer response (in mV) to the known source. Detector output in mV is divied by the calibration file for that detector to calculate radiance. Calibrations are stated as +-3% to 10% depending on wavelength.

In this study, radiance was measured in 5nm steps, and several scans of each target were taken. The instrument allows for these scans to be taken separately or several scans which are automatically averaged by the instrument, and a single mean scan stored on the internal memory bank. Obtaining several single scans of a target takes far longer than automatically averaging the scans. The latter was therefore chosen to minimise the scanning time, and hence to reduce the possibility of the algal density and solar elevation changing during the scanning period. A major disadvantage of this approach is that no indication of the variability in reflectance from any target was available. Consequently the statistical significance of the differences between scans was not addressed. The memory banks of the LICOR were interogated and the data dumped onto a personal computer for further analysis.

3.2.2 Limnological

<u>Chlorophyll analysis</u>

Samples were analysed for chlorophyll concentration using Sartory's (1982) technique. Water samples (1.5l) from Roodeplaat Dam were collected as a surface grab of the upper few centimeters of water, and as an integrated sample of the upper 5m of the water column using a hosepipe sampler. Samples of the pure algal cultures were also taken after scanning.

In all cases samples were immediately returned to the laboratory for analysis. Samples were well stirred before filtering through glass fibre filters. As much water as possible was filtered to increase the accuracy of the final chlorophyll esitmate. The filters and entrapped algae were boiled in 98% ethanol to extract the chlorophyll. The concentration of chlorophyll in the extract was measured in a spectrophotometer. The extract was then acidified to convert the chlorophyll *a* to phaeophytin, and the concentration measured again. As chlorophyll *a* and phaeophytin are spectrophotometrically indistinguishable, the two were added together and are reported here as chlorophyll concentration.

In each case only one sample was analysed and reported, but occasionally a dublicate sample was analysed to assess the accuracy of the analysis. A difference within 5µg/l for the duplicate samples was considered acceptable and was maintained throughout the study.

<u>Algal cultures</u>

Pure cultures of commonly occuring South African algae were produced by plating natural populations of algae on solid growth medium. After incubation a single colony was lifted and placed in a liquid growth medium. The algae were checked under the microscope to identify the species present. Cultures were also checked to ensure they contained only one genus.

Dilutions of the cultures were made by halfing the culture, and making up the volume with distilled water. This was done to get a range of chlorophyll concentrations. After scanning, a sample of the diluted culture was taken and analysed for the chlorophyll concentration using the above method. The light scattering properties of the samples were measured as turbidity in Nephelometric Turbidity Units (NTU) in a HACH turbidimeter.

Pure cultures of *Microcystis sp.* and *Anabeana sp.*, which are blue-green algae, as well as the green species *Chlorella sp., Ulothrix sp.* and *Selenastrum sp.* were produced.

Algal species were identified to genus level using the method proposed by Truter (1987). This entails preserving a sample in a Lugols solution, which also stains the algae. Lugols preserved samples were placed in a counting chamber and examined in an inverted microscope.

Suspended sediments

Suspended sediments carried by the rivers entering Roodeplaat Dam flocculate near the inflows producing a thick layer of bottom sediment. Samples of this sediment were collected with a bottom grab sampler and burnt in an oven at 400°C to remove organic matter. As particle size also influences reflectance from sediments (Novo *et al* 1989a), the dry sediment was then ground up and sieved through a 200µm sieve. The powdered sediment was then added to the algal cultures to produce suspended sediment concentrations (SSC) of 200, 400, and 600mg/l. A sub sample of the mixture was taken and the chlorophyll concentration determined using the above technique.

Turbidity of the samples was measured in a HACH turbidimeter and expressed in NTU.

3.3 The depth of remote sensing penetration

3.3.1 Background

As algae normally occur suspended within the water column, light must pass through at least some water both before and after it has been scattered by the algal cells. Water shows a wavelength dependent absorption of electromagnetic energy (List 1968) and not only the reflectance spectrum, but also the amount of light detected above the water surface, will change with the depth at which the cells occur. Cells deeper in the water column will contribute less reflectance than those near the surface and only reflectance from those cells above the maximum depth of remote sensing penetration can be detected above the water surface.

Many species of algae have either flotation mechanisms or motile organelles and adjust their depth within the water column (Bold and Wynne 1985). High concentrations of algae can therefore occur deeper into the water body and it is consequently essential to generate some understanding of the depth of remote sensing penetration for effective "ground truth" sampling. Furthermore, if two areas have the same density of cells, but different light penetration characteristics the radiance measured above these areas will differ. This effect can only be compensated for if the relationship between light penetration and remote sensing penetration is understood. Some comprehension of the depth of remote sensing penetration is also important to ensure that samples are not taken in places where bottom reflectance could effect the radiance detected (Whitlock, Witte, Usry, Gurganus 1978).

This section deals with the light penetration characteristics of natural waters and the influence of this on remote sensing of chlorophyll concentrations.

3.3.2 Methods

The transparency of water to light is commonly measured as Secchi disc depth (Wetzel 1983). This is a measure of the depth at which a black and white disc lowered into the water column, disappears from view. Remote sensing penetration in natural waters in this study was assessed in two ways. Firstly, by measuring the depth at which a large white board lowered into the water no longer influenced the radiance detected above the water surface and secondly, by measuring the contributions to the total upwelling signal from algae above a large black board lowered into the water column. The former method is similar to that described by Whitlock *et al* (1978) who measure the penetration depth of green light by lowering a green board into the water.

Upwelling radiance just above the water surface was measured with the LICOR LI 1800 spectroradiometer fitted with a telescopic receptor. The telescope receptor was mounted on a boom installed on a boat in a similar fashion to that described by Whitlock *et al* (1978). This ensured that no specular reflectance from the boat was detected. The field of view of the receptor was set at 4° to minimise the possibility of specular reflectance from the sun being detected. This also ensured that the board filled the entire field of view at all depths.

The depth of remote sensing penetration with the white board was estimated by expressing radiance measured when the board was lowered to different depths, as a percentage of the radiance from the board held above the water. This provided a measure of the attenuation of the contribution of the white board to the upwelling signal with water depth.

Percentage contributions from the particles suspended at different depths in the water column was measured by expressing radiance reflected by particles above the black board, as a percentage of the total radiance detected without the board. In this case, as the board was lowered more cells contributed to the upwelling signal, and more radiance was detected.

3.3.3 Results and Discussion

Whitlock *et al* (1978) describe the depth of remote sensing penetration as that depth above which 90% of the upwelling radiance originates. Kirk (1983) reports that this depth equates to that depth at which the light intensity is 37% of the surface intensity. The extinction of light in water is given by the equation;

$$L_{\delta x}=L_0 e^{-k\delta x} \quad \text{.............Eq 3.1}$$

(List 1968)

Where: $L_{\delta x}$ =intensity of light at wavelength δ and depth x.

L_0 =intensity of light at the surface

$k\delta$ =absorption coefficient of light at wavelength δ (includes both scattering and absorption coefficients).

Given the extinction coefficient, k, equation 3.1 can be used to calculate the depth of remote sensing. However, measurement of this coefficient is not yet feasible outside the laboratory (Dekker and Seyhan 1988). The extinction coeeficient at each wavelength for distilled water is known, and figure 3.1 describes a plot of that depth at which $L_{\delta x}/L_{\delta 0}$ is equal to 0.37 for pure water. This plot therefore indicates the theoretical maximum depth of remote sensing penetration. In pure water this occurs between 460-490nm, while wavelengths of over 700nm have a very shallow remote sensing penetration (Fig. 3.1). In natural waters the absorption coefficient is increased by scattering and absorption by particles suspended in the water column and by the intrinsic water colour (Kirk 1983). This means that the depth of remote sensing penetration is a lot less in natural waters than that shown in figure 3.1 and will also change with the nature of the suspended particles and water colour.

Measurements of the light scattered from the white board lowered to different depths, indicated that the least attenuation of light occurred at ≈550nm (Figs 3.2 and 3.3). This differs from the theoretical absorption characteristics of light. This effect has also been noted by Whitlock *et al* (1978) and is due to scattering of green light by the algal cells above the board.

In parts of the impoundment with low concentrations of chlorophyll, the attenuation of the upwelling signal from the white board was easily distinguishable (Fig 3.2). In these parts the strong absorption of infrared light by the water was evident and 50% attenuation of the green wavelengths was reached at ≈10% Secchi depth. However, measurements of the light from the white board taken in parts of the impoundment with shallower Secchi depths indicated that the attenuation of the signal was not as pronounced (Fig 3.3). This was due to the fact that more particles occurred in the water column above the board. These particles also scatter radiance out of the water, and the attenuation of reflectance from the white board is compensated by the increased reflectance from these particles. The white board method is therefore not a true measure of the attenuation of the remotely sensed signal. Similarly measurement of attenuation of green light by lowering a green board into the water (Whitlock *et al* 1978) will also not be a true measure of the attenuation of the green light.

In an attempt to overcome this problem a black board was used. As the black board will absorb all the downwelling light, the signal detected can only originate from the particles above the board and this method will be a more accurate measure of the depth above which 90% of the upwelling signal originates.

Experiments with the black board indicated that the largest contributions to the upwelling signal from cells at all depths was for wavelengths between 550 and 600nm. At wavelengths longer than 750nm most of the reflectance originated within the upper layers of the water column (Figs 3.4 and 3.5). Figure 3.4 shows that in water with a Secchi depth of 89cm, and for wavelengths between 550 and 600nm, 36% of the light originated above 10cm, 63% above 20cm and 70% above 30cm. At 700nm 90% of the upwelling light originated above 30cm (≈33% Secchi depth). However, at Secchi depths of 59cm, only 60% of the light originated above 20cm (≈33% Secchi depth).

This indicates that the relationship between Secchi depth and depth of remote sensing penetration is complex and no clear relationship between Secchi depth and remote sensing penetration was evident from the limited replication of this study. An estimation of the depth of remote sensing penetration was therefore not feasible using Secchi depth data collected on site. Furthermore, as the depth of remote sensing penetration is wavelength dependent, different spectral bands of a sensor system would have different penetration depths. However, the estimate of the remote sensing depth as 20-50% Secchi depth (Whitlock *et al* 1978) appears to be valid in the case of Roodeplaat Dam.

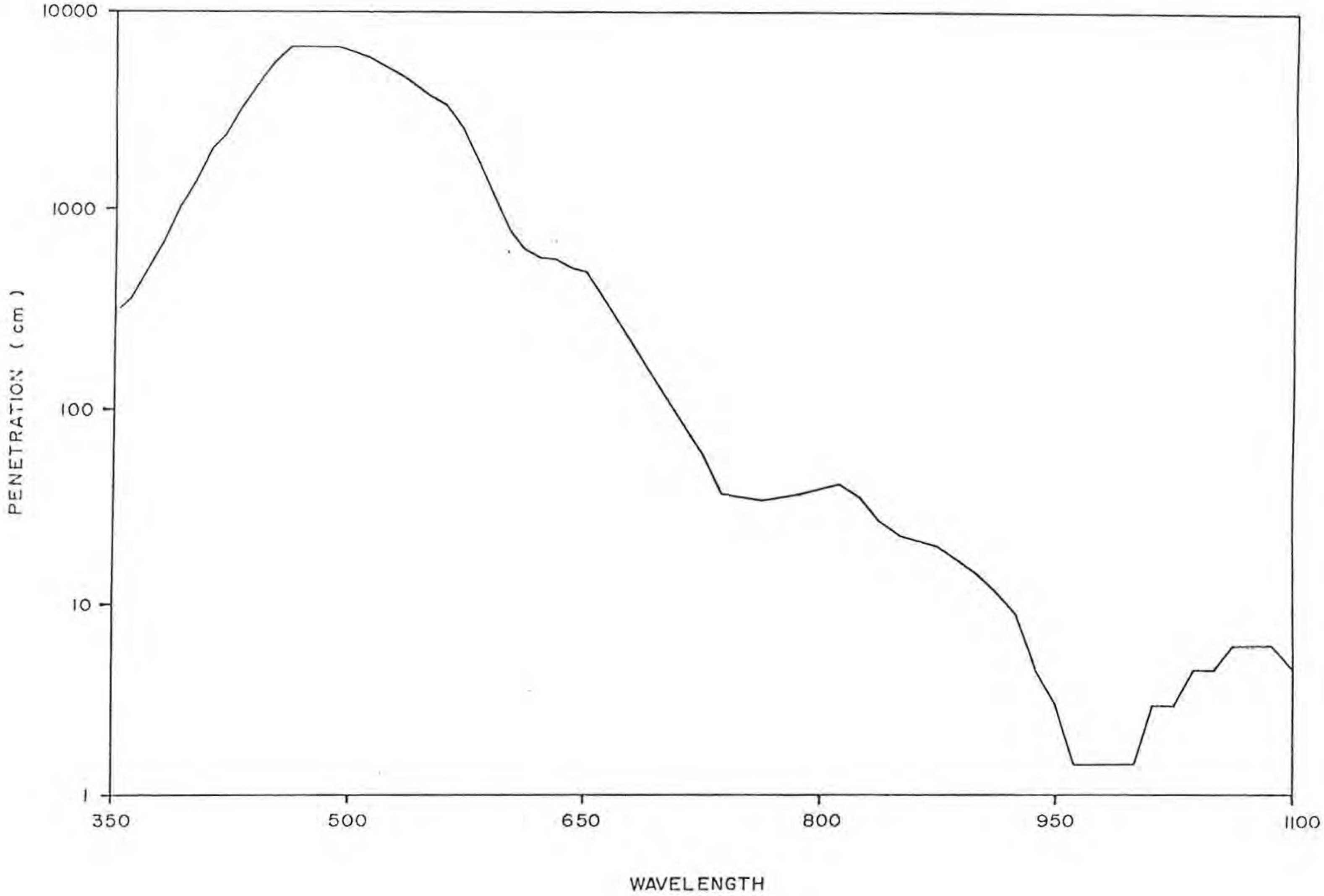


Figure 3.1. The depth of remote sensing penetration in pure water, calculated at 37% of the surface light intensity ($L_Z/L_0=0.37$). This approximates that depth above which 90% of the upwelling signal will originate in pure water.

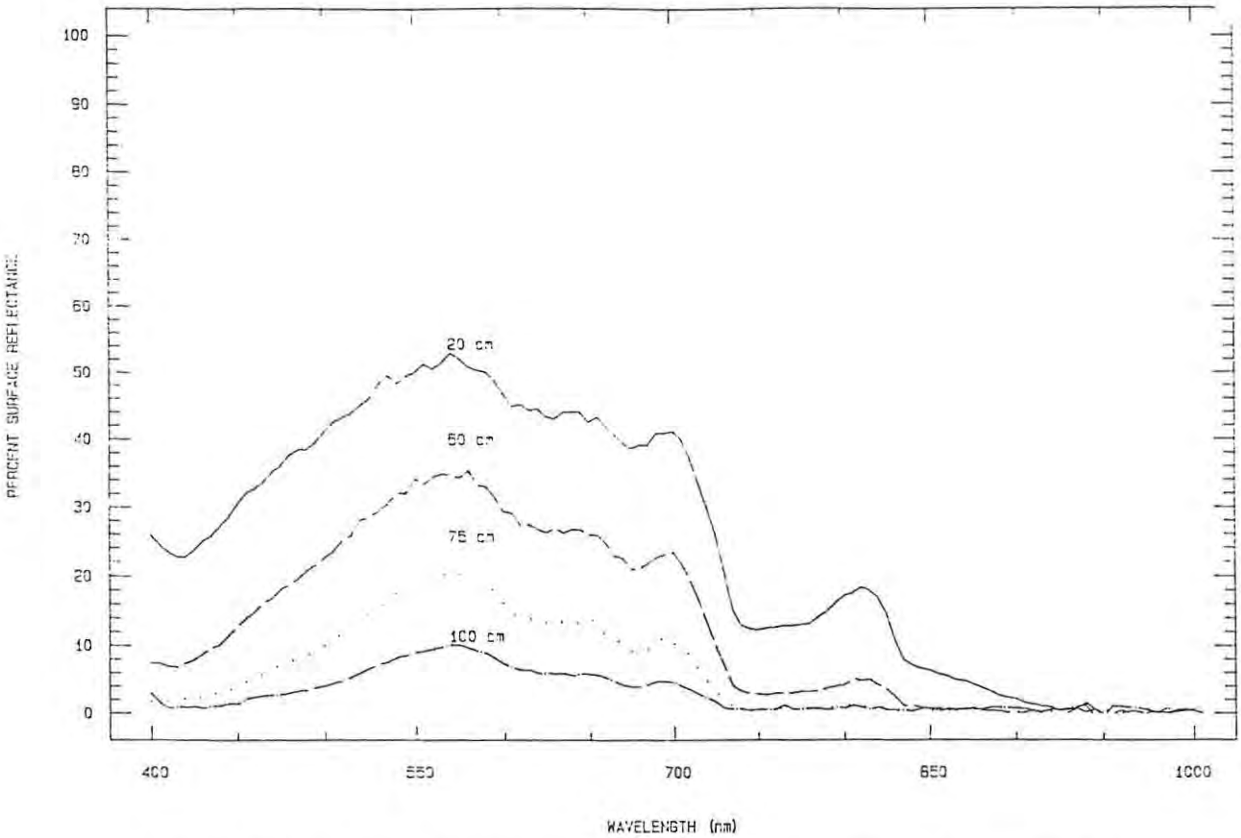


Figure 3.2. The attenuation of the upwelling signal from a white board lowered to different depths. Data was expressed as a percentage of the reflectance from the dry board.(Secchi= 200cm , Chl concentration= 20µg/l).

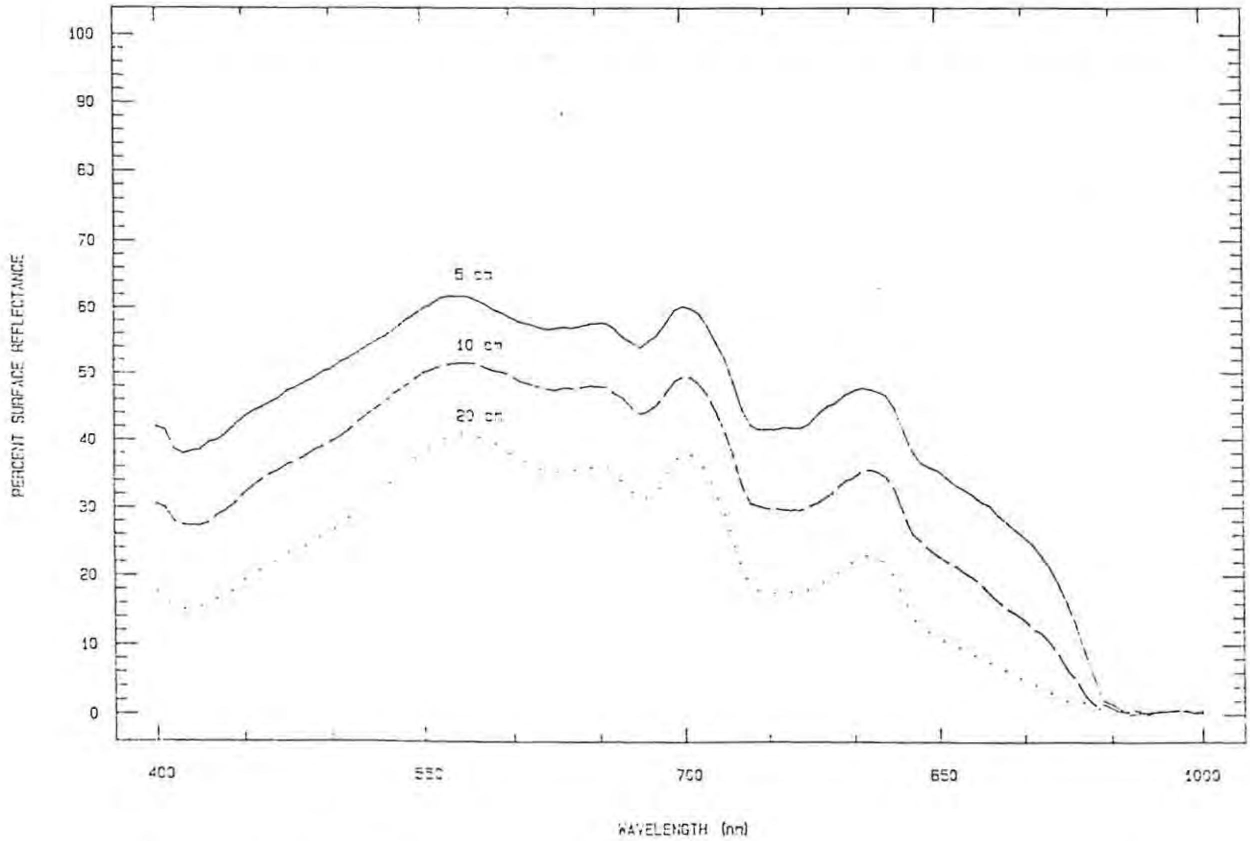


Figure 3.3. The attenuation of the upwelling signal from a white board lowered to different depths. Data was expressed as a percentage of the reflectance from the dry board. (Secchi= 45cm , Chl concentration= 42µg/l).

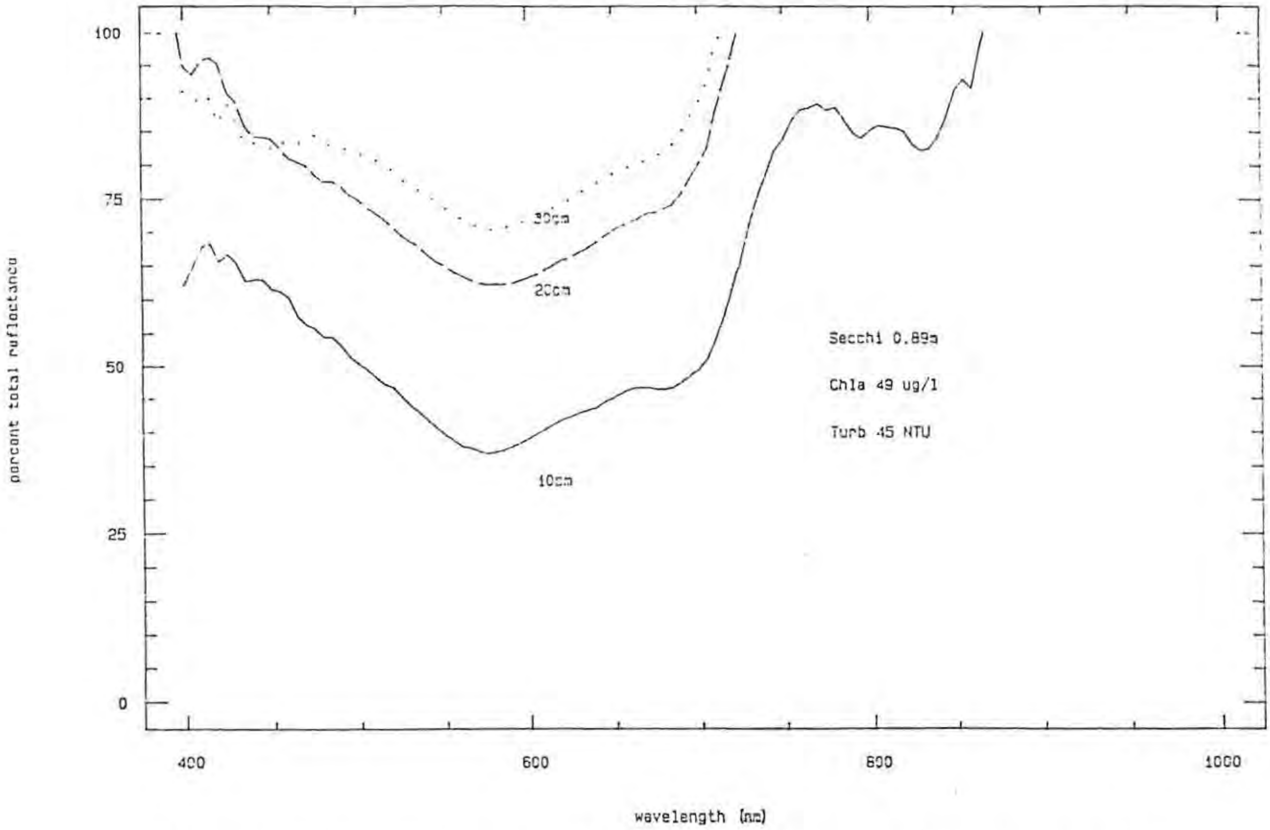


Figure 3.4. The contribution of particles suspended above a black board, lowered to different depths into the water column, as a percentage of the total upwelling signal without the board. (Secchi= 89cm, Chl concentration=49µg/l).

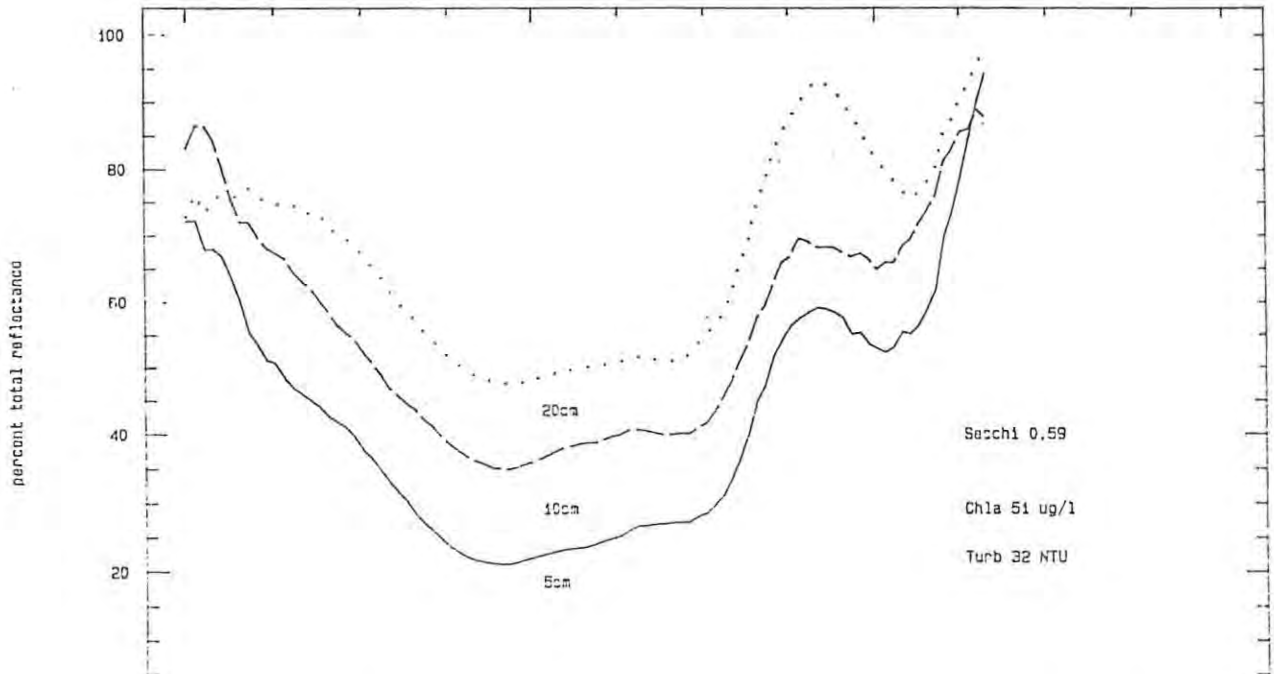


Figure 3.5. The contribution of particles suspended above a black board, lowered to different depths into the water column, as a percentage of the total upwelling signal without the board. (Secchi= 59cm, Chl concentration=51µg/l).

3.4 Reflectance from different algal species

3.4.1 Background

The primary classification of algae is partially based on the type of intracellular pigments present (Bold and Wynne 1985). All algae are classified into one of the following Phyla; the Phylum Cyanophyta or blue-green algae, the Phylum Chlorophyta or green algae, the Phylum Chyrysophyta or golden and yellow-green algae, the Phylum Euglenophyta, the Phylum Cryptophyta and the Phylum Pyrrophyta. In South Africa the most commonly occurring species belong to either the Cyanophyta or the Chlorophyta (Truter 1987). As these groups differ in the type of pigments present in the cells, it is conceivable that they will have distinctive reflectance spectra.

Lindell (1981) indicated that the signals received at the LANDSAT MSS sensors from parts of Lake Malaren, which were dominated by different species of algae, had different characteristics. Howman and Kempster (1986) show that the LANDSAT MSS band which has the best correlation with chlorophyll concentration differed on each overpass. These changes, they suggest, may result from changes in the dominant algal genera present at the time of each overpass. It is therefore feasible that different species may be detectable using satellite borne sensors.

If different species of algae have unique reflectance spectra, then each species would have to be treated separately in the empirical approach. This section addresses this problem by investigating the nature of light scattered by different species of commonly occurring South African algae.

3.4.2 Methods

Upwelling radiance from the pure algal cultures was measured by placing the telescopic receptor 0.5m above a sample container. The sample container was 0.3m deep and 0.1m in diameter. The container was painted absorbent black on the bottom, which prevented bottom reflectance influencing the radiance measured (Whitlock *et al* 1978), and white on the sides to allow lateral scattering of light (Novo *et al* 1989b). This sample container was thought to approximate the light conditions within a natural water body. However, as progressive shading of the white sides at higher cell densities could not be ruled out, and no measure of the variablity around the scans was available, results were only qualitatively analysed.

A nadir view angle has been shown to produce the strongest suspended sediment/radiance relationships (Novo *et al* 1989b), and the telescopic receptor was hence placed to detect light scattered at right angles out of the water. The view angle was also set at 4° to ensure none of the white sides of the container were visible and that specular reflectance from the water surface was not detected.

Scans of the upwelling radiance at each wavelength ($L_{\delta u}$) were alternated with scans of the downwelling irradiance ($L_{\delta u}$), and reflectance (R_δ) calculated according to Maracci and Ooms (1988) as;

$$R_\delta = L\delta_u / L\delta_d \times 100 \qquad \text{..........Eq 3.2}$$

Radiance was measured in 5nm steps from 400nm to 1000nm. Five replicate scans were taken of each sample and a single scan was calculated as a mean of the five. Scans were taken within two hours of midday on cloudless days and the experiment was done on two occasions, 19/05/89 and 13/07/89. The experiment was also repeated in the laboratory using two photoflood lamps to provide illumination at an angle of 45°.

3.4.3 Results and Discussion

A conceptual model of algal reflectance can be postulated using the known absorption spectrum of chlorophyll *a* and phaeophytin (Fig 3.6). Reflectance from pure chlorophyll would be highest where absorption and transmission is lowest. This occurs at wavelengths between 530 and 640nm and over 700nm. More importantly reflectance in wavelengths with a high absorbance should be lower at higher chlorophyll concentrations. This conceptual model of algal reflectance has been used in an attempt to isolate reflectance from sediments, from that from algae (Stumpf and Tyler 1988) and provides the rationale for ratioing spectral bands. If the conceptual model holds, ratios of absorption and reflection wavelengths will optimise the reflectance differences with increasing chlorophyll concentration.

However algae do not consist of only chlorophyll. Cells are normally made up of a cell wall or membrane structure which contains a variety of pigments as well as intracellular organelles, and reflectance from whole cells may differ from that of pure chlorophyll. Furthermore, reflectance spectra of natural populations of algae will be influenced by the absorption characteristics of the water itself. The attenuation of light in eutrophic waters has already been shown to be low in the green wavelengths. As chlorophyll does not absorb light at 550nm, reflectance of eutrophic waters should therefore peak at 550nm and will decrease towards the chlorophyll absorption peak at 665nm. Reflectance from algae in the infrared wavelengths (over 700nm) should also be high, but strong absorption in these wavelengths by water surrounding the cells should attenuate the radiance before it is detected above the water surface.

In this study all the algal genera demonstrated the expected peak in green reflectance at 550nm and the trough at 665nm (Figs. 3.7 to 3.11). The blue-green species however, had a smaller peak at 650nm noticeable at the higher concentrations (Fig 3.7 and 3.8). This peak is possibly associated with the presence of phycobiliproteins which can occur in this Phylum (Dekker, Malthus and Seyhan 1989). Percent reflectance in the near infrared (700-720nm) was high for all the species. This peak has been explained as a minimum in the combined absorption curves of algae and water (Dekker *et al* 1989). However the absorption minimum for pure water is closer to 800nm (Fig 3.1) and this peak is more likely due increased reflectance from algae in these wavelengths. Reflectance at ≈700nm showed the largest changes with successive dilution of the cultures. This is due to the fact in the near infrared wavelengths both attuenuation of light, as well as cell densities influence the total signal detected above the water.

Sid'ko and Vasil'yev (1988) show that for natural waters dominated by diatoms, the reflectance peak is shifted from 550nm to 580nm, but that the at peak ≈700nm was still present at higher concentrations.

Scans of the successive dilutions of the green algal species showed that reflectance of red light (660-670nm) was lower, and reflectance of green (525-575nm) was higher, at higher chlorophyll concentrations (Fig. 3.9 to 3.11). The green algae, therefore, fitted the conceptual model of chlorophyll reflectance. However, dilution of the *Microcystis sp.* cultures produced lower reflectance at all wavelengths (Fig. 3.7). Reflectance from *Microcystis sp.* did not therefore fit the conceptual model, and for this species, ratioing of spectral bands will not enhance the information content of the radiance data.

Turbidity as NTU is a function of the scattering coefficient of the sample (Kirk 1988). Lower turbidity means less light will be scattered out of the water column.

Turbidities of the algal cultures showed distinct characteristics (Fig. 3.12). Blue-green algae scattered less light for any given chlorophyll concentration than the green species (Fig. 3.12). The blue-green species used in the study, *Microcystis sp.* and *Anabaena sp.* are colonial algae, (Truter 1987). This means fewer particles are available for a given chlorophyll concentration, and this explains the lower scattering coefficients for these species. Changes in the chlorophyll/reflectance relationship will therefore occur with both variations in the chlorophyll/cell ratio, and the colonial status of the cells. Differences in species composition or colonial status will consequently require the development of new empirical relationships between radiance and chlorophyll concentration.

As most remote sensors do not measure radiance at discrete wavelengths, but integrate radiance over given spectral bands, the ability of a sensor system to detect different species is dependent on the width of the spectral bands. The algal species studied were spectrally very similar, and when spectral bands are broad, different algal species are unlikely to be detectable from the remotely sensed data. However, if the remote sensor has a narrow band centred at 650nm, shifts in species dominance from blue-green to green species may be detectable by relating reflectance in this band to another band.

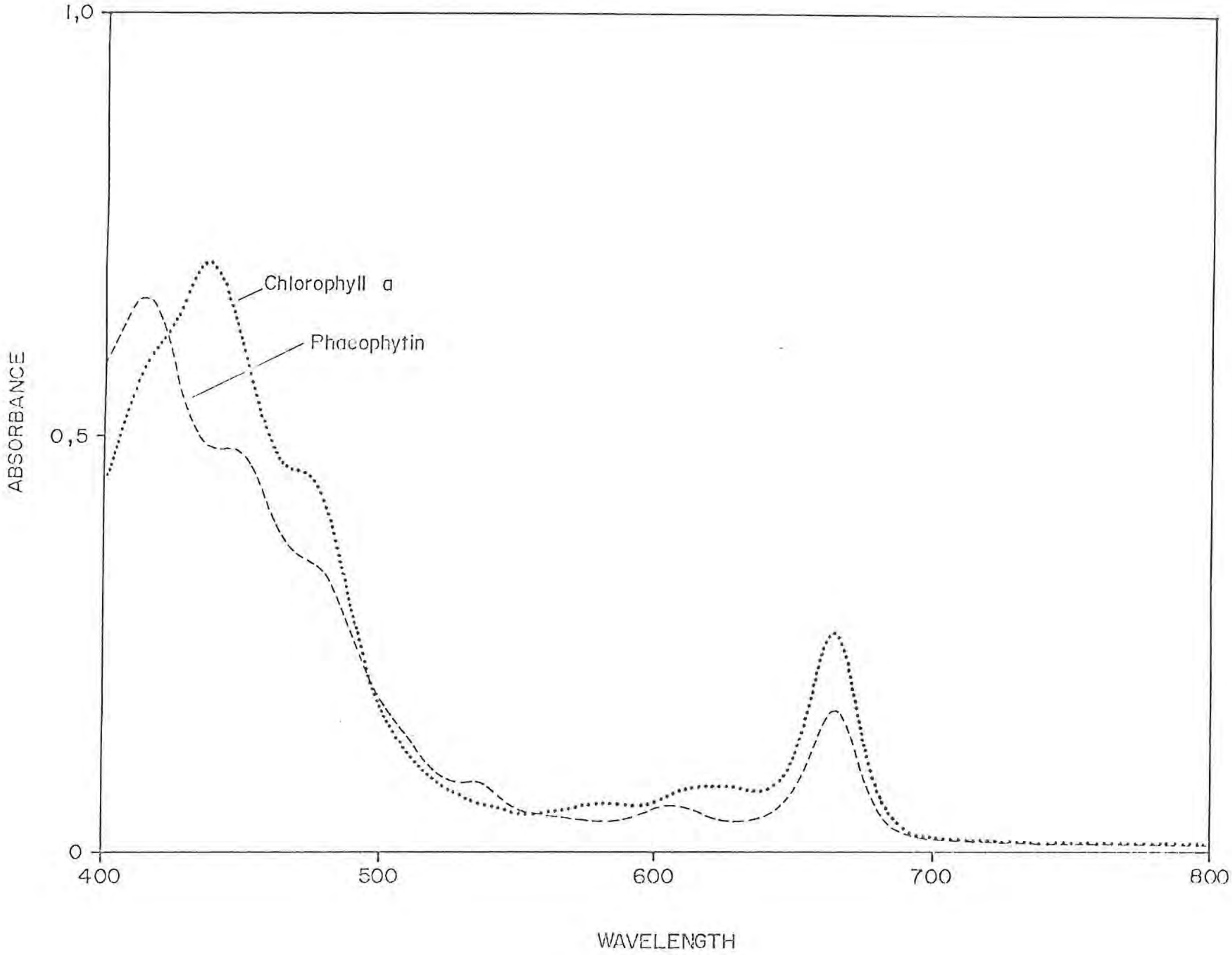


Figure 3.6. The in vitro absorbance spectra of chlorophyll _a_ and phaeophytin.

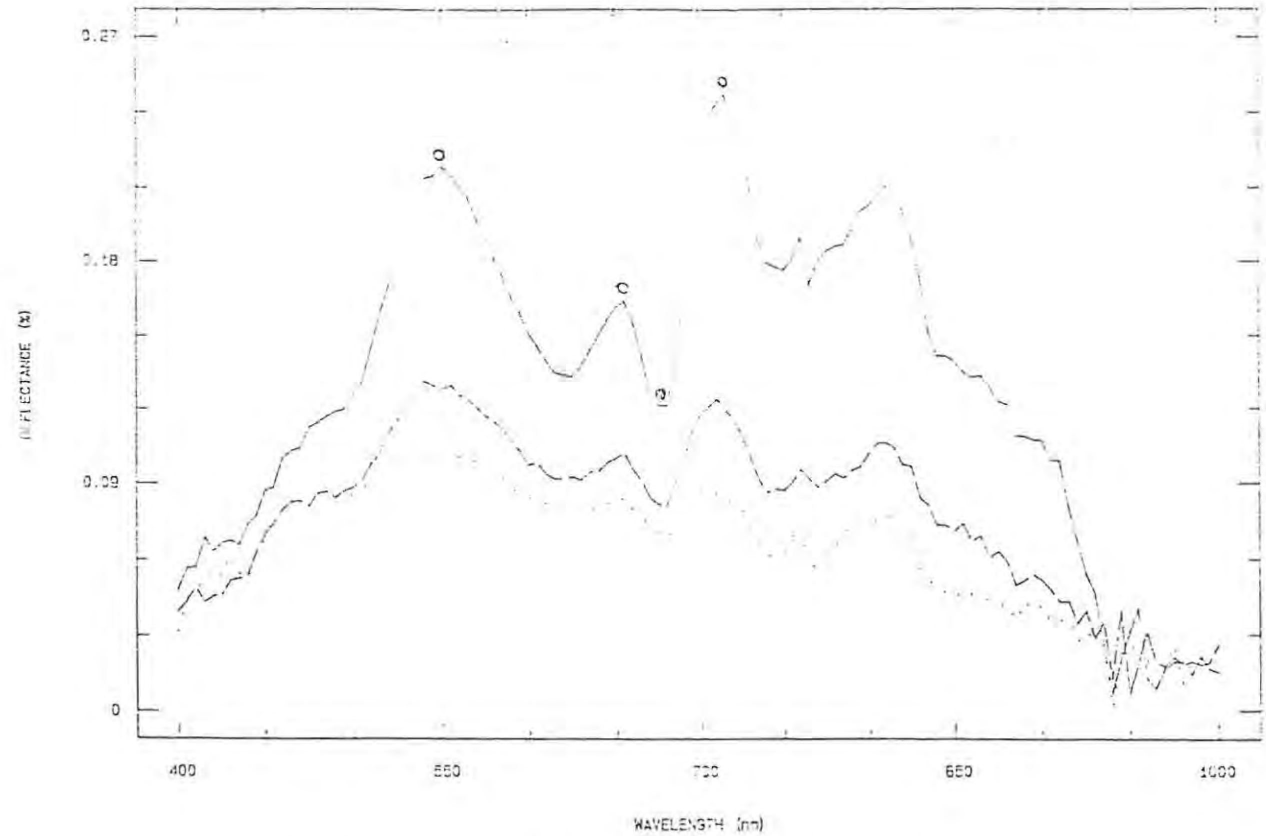


Figure 3.7. The reflectance spectra of successive dilutions of the algae, *Microcystis sp.* The green and infrared reflectance peaks as well as a peak in the red part of the spectrum are (O) shown. The chlorophyll absorbance wavelength is indicated by (O).

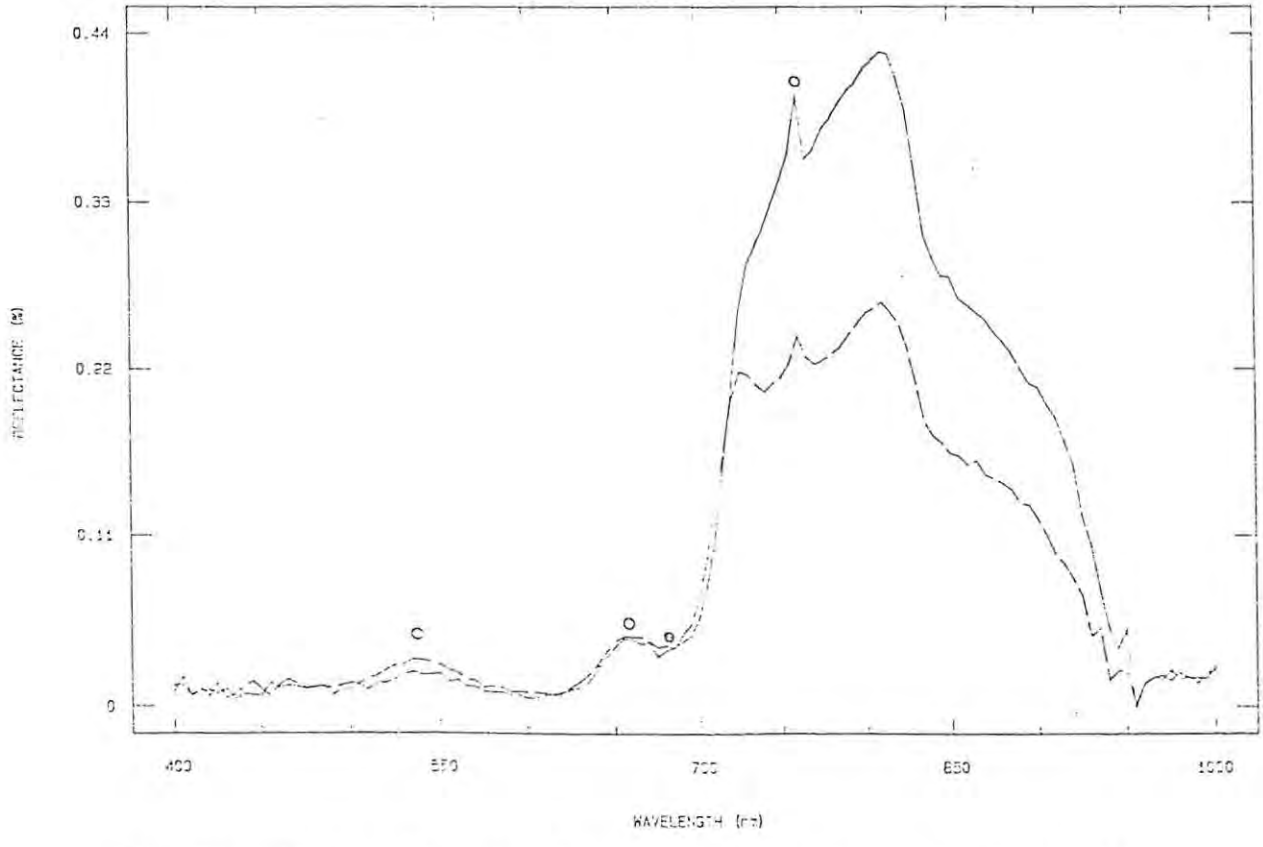


Figure 3.8. The reflectance spectra of successive dilutions of the algae, *Anebeana sp.* The green and infrared reflectance peaks as well as a peak in the red part of the spectrum are (O) shown. The chlorophyll absorbance wavelength is indicated by (⊙).

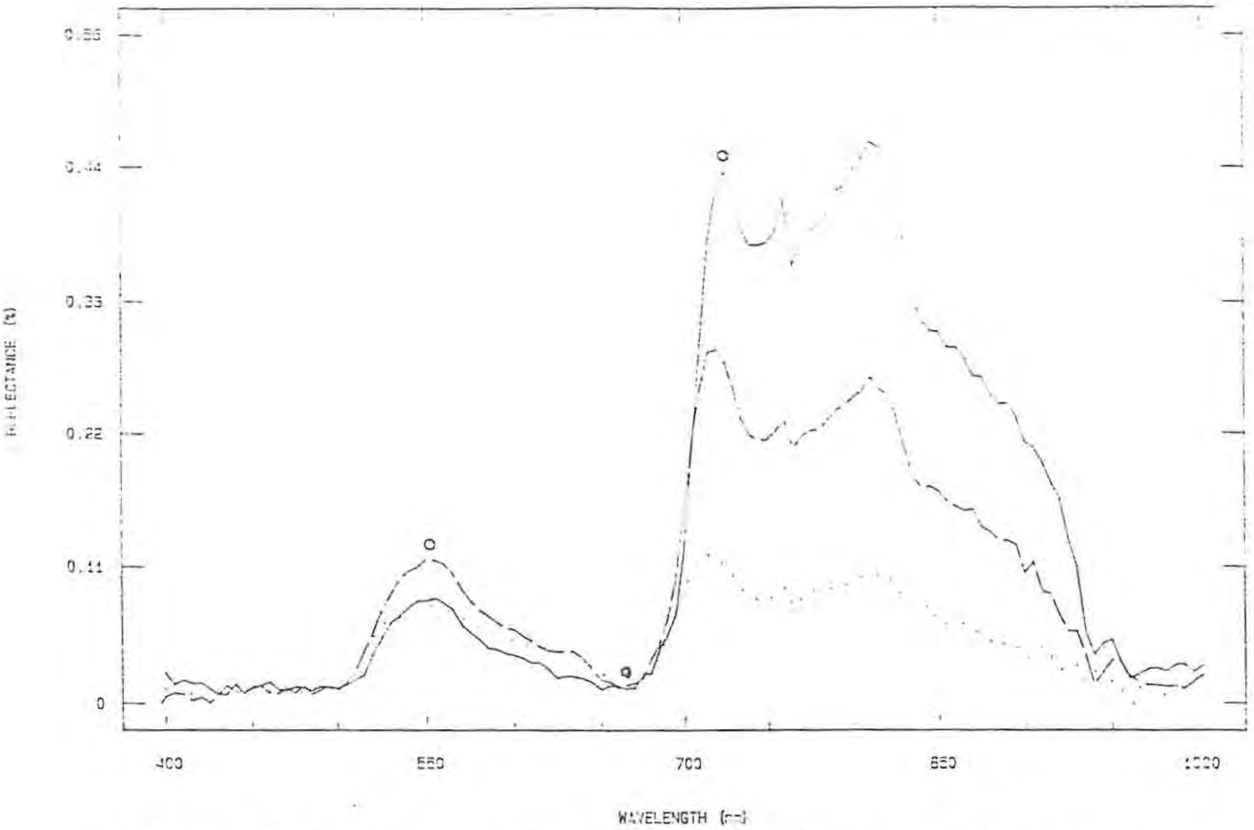


Figure 3.9. The reflectance spectra of successive dilutions of the algae, *Ulothrix sp.* The green and infrared reflectance peaks are (O) shown. The chlorophyll absorbance wavelength is indicated by (⊙).

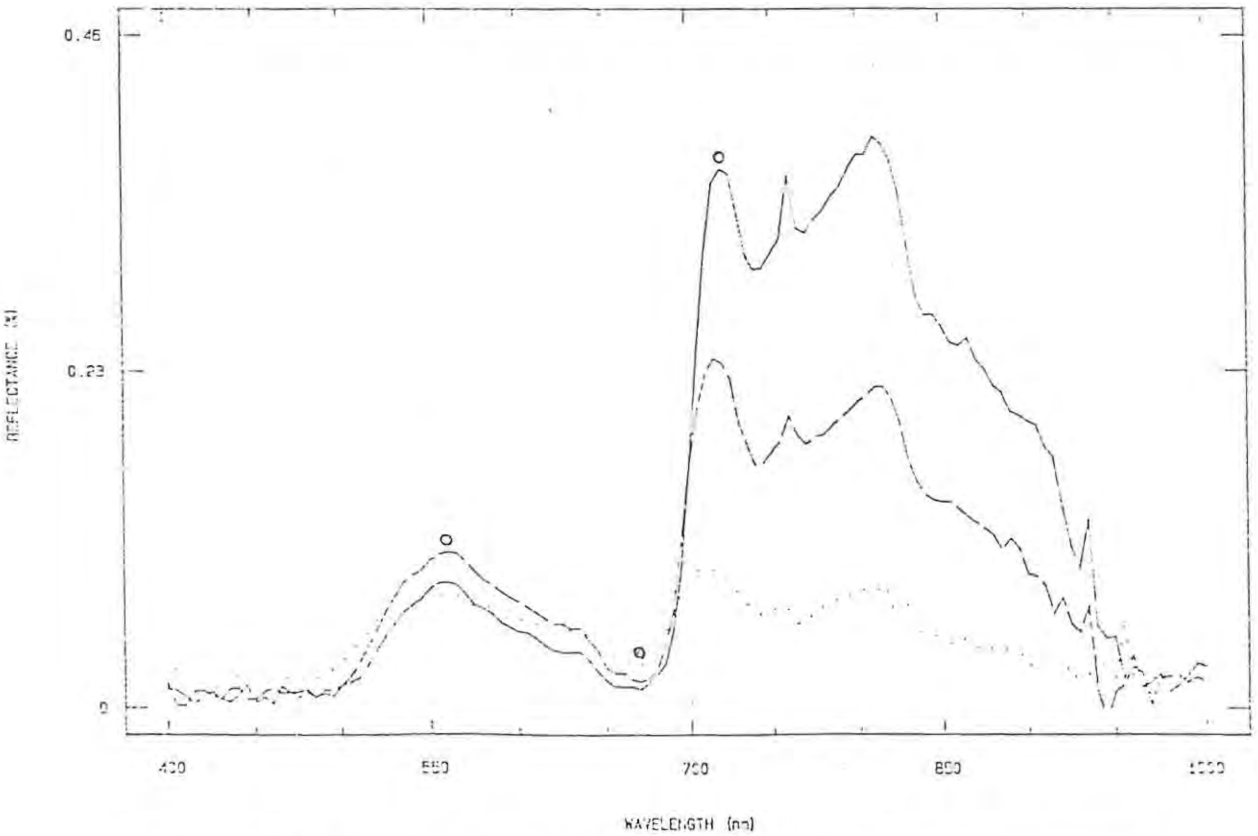


Figure 3.10. The reflectance spectra of successive dilutions of the algae, *Selenastrum sp.* The green and infrared reflectance peaks are (O) shown. The chlorophyll absorbance wavelength is indicated by (⊙).

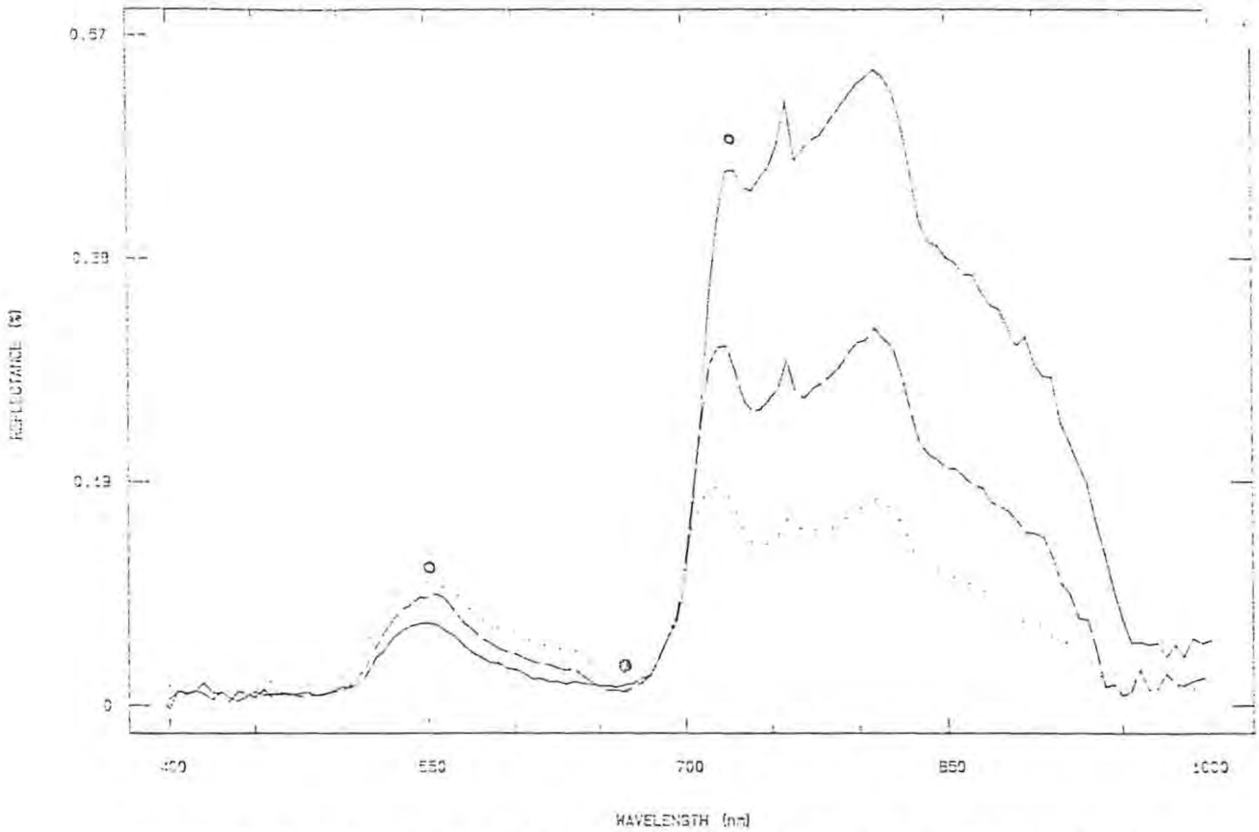


Figure 3.11. The reflectance spectra of successive dilutions of the algae, *Chlorella sp.* The green and infrared reflectance peaks are (O) shown. The chlorophyll absorbance wavelength is indicated by (O).

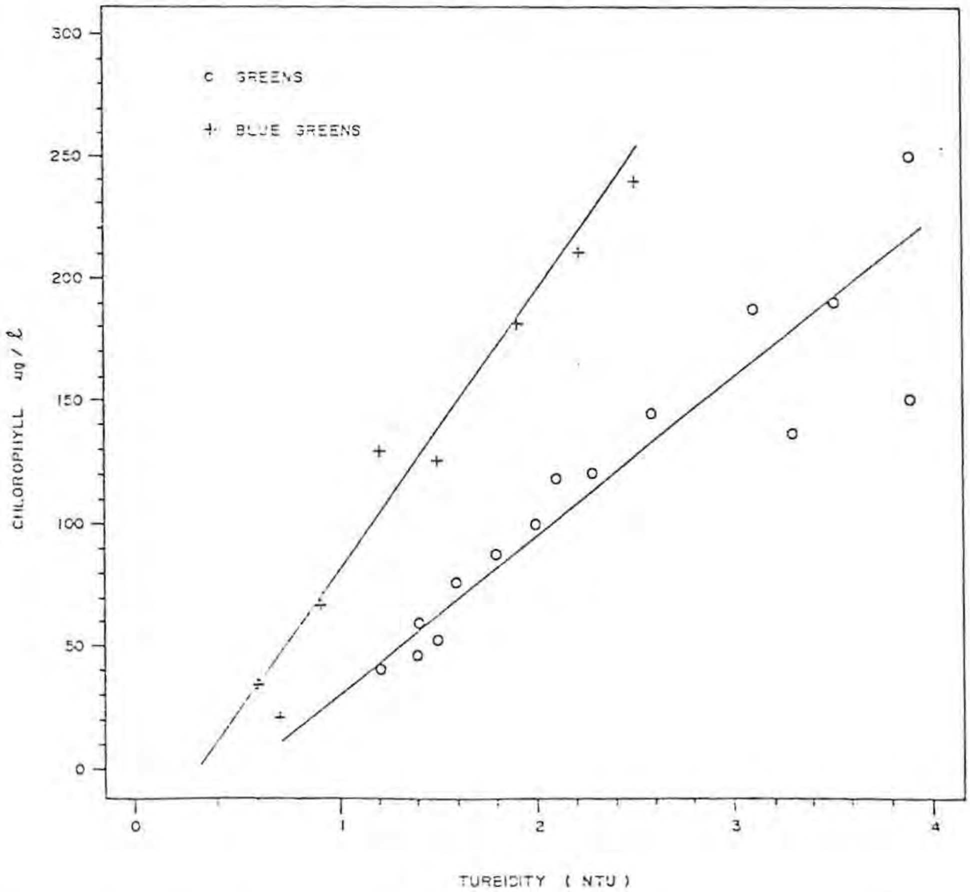


Figure 3.12. A plot of turbidity against chlorophyll concentration relationship of blue-green and green algal cultures. Turbidity is a measure of the total light which will be scattered by the sample.

3.5 Correlating reflectance to chlorophyll concentrations

3.5.1 Background

Reflectance from algae is not uniformly high across the whole spectrum and reflectance shows greater changes with increasing chlorophyll concentrations at some wavelengths (Figs 3.7 to 3.11). Wavelengths which show large changes in reflectance with increasing cell density will provide the best correlation between reflectance and chlorophyll concentration. The selection of the wavelengths used to develop the relationship between chlorophyll and radiance (or digital value) can therefore play an important role in the simulation accuracy of the empirical model. This is further complicated by the width of the spectral bands. If spectral bands are broad they may include algal reflectance peaks together with wavelengths which are absorbed by algae. This will smooth the differences which occur with increasing chlorophyll concentrations and will reduce the value of these spectral bands for the remote sensing of algae.

This section describes the correlation of reflectance measured at different points on a natural water body to the chlorophyll concentration at that same point. Reflectance is taken as integrals over the whole spectrum as well as over the spectral bands of several remote sensing systems. However, as it is difficult to relate ground based radiance to that detected at aircraft or satellite platforms (Duggin and Philipson 1985), this was done solely to indicate which spectral bands should prove to be the most suitable for algal studies.

3.5.2 Methods.

Upwelling radiance from natural populations of algae was measured at several points on Roodeplaat Dam. The telescopic sensor of the LICOR spectroradiometer was attached to a boom such that it was held away from the boat

to prevent reflectance from the boat being detected. The sensor was adjusted to give a nadir view using a spirit level. Sampling sites on the impoundment were chosen to provide a wide range in chlorophyll concentrations, but care was taken to avoid points near the inflows where suspended sediments could influence the reflectance. At each point three scans of the upwelling radiance were taken and a single scan was expressed as a mean of the three. Upwelling radiance ($L_{\delta u}$) was measured at 5nm intervals from 400-1000nm. At the time of scanning, the downwelling solar irradiance ($L_{\delta d}$) was measured with a cosine receptor. Reflectance (R_{δ}) was calculated using equation 3.2.
After scanning, a surface grab sample of the water under the telescope was taken and the water transparency measured by means of a Secchi disc reading. The water samples were returned to the laboratory for analysis for the chlorophyll concentration and turbidity. A sample of water was also preserved with Lugols solution (Truter 1987) and examined for dominant algal species.

Total reflectance over a given spectral band was calculated as the geometric mean of radiance at each 5nm step in the spectral window.

3.5.3 Results and Discussion

Microscopic examination of water samples from the impoundment showed that *Microcystis sp.* dominated the algal population at all the sampling points on Roodeplaat Dam on all sampling occasions. This was also evident from the shape of the reflectance spectra, which were typical of blue-green algae (Figs. 3.13 to 3.15). The similarity of the spectra to those from pure cultures suggests that other particles in suspension (eg. sediments) did not play a major role in the reflectance from the water. Reflectance spectra for Roodeplaat Dam were also similar to scans of upwelling subsurface radiance reported in Davies-Colley, *et al* (1988) for eutrophic lakes in New Zealand and for the eutrophic Loosdrecht lakes in the Netherlands (Dekker, *et al* 1989). Dekker, *et al* (1989) also report that Cyanophyta dominated the eutrophic Loosdrecht lakes.

At one point, reflectance from a thick scum of algae floating on the surface was measured. The shape of the reflectance scan for this point differed significantly from the other points (Fig. 3.13). When these scums occur, the absorption of infrared light by the water no longer influences reflectance, and the spectra of scums will be more typical of those for terrestrial plants. This supports the premise proposed in the previous section, that both reflectance characteristics of the algae as well as the absorbance of water are important in determining the upwelling flux in the infrared part of the spectrum. As none of the downwelling or upwelling light was absorbed by water above the algal scum, reflectance from the scum was much higher than that measured at other points on Roodeplaat Dam. Grubbs test for outliers indicated that reflectance from the scum occured as an outlier in the reflectance data, and was consequently excluded from further statistical analyses.

Reflectance from natural populations did not follow the conceptual model of algal reflectance, and higher chlorophyll concentrations lead to higher reflectance at all wavelengths (Fig. 3.14 and 3.15). This is consistent with the reflectance characteristics of *Microcystis sp* discussed in the previous section.

The largest changes in percent reflectance associated with increasing chlorophyll concentration occurred in the near infrared wavelengths (700-720nm). These wavelengths should therefore be included in empirical models. However, figure 3.15 shows that at low chlorophyll concentrations infrared reflectance disappears and larger changes occur in the green wavelengths. Algorithms which rely on reflectance from wavelengths longer than 700nm should therefore only be used when wide ranges in chlorophyll concentration occur. These algorithms will also only accurately simulate chlorophyll concentrations in the upper few centimeters of water. Care should therefore be taken in the interpretation of data from these models, as they may not indicate the total algal population in the impoundment.

If few cells occur in the upper layers of the water column, the infrared reflectance peak disappears (Fig 3.15) and the assumption of zero radiance in the infrared wavelengths, used in some atmospheric correction models (MacFarlane and Robinson 1984), is justified.

Regression of upwelling radiance ($L_{\delta u}$), integrated over the whole spectrum, with chlorophyll concentration indicated that there was no correlation between these variables. The upwelling radiance in $mW.cm^{-2}.nm^{-1}$ was directly related to the downwelling irradiance and higher $L_{\delta d}$ produced higher $L_{\delta u}$. Changes in the amount of irradiance are compensated in the calculation of reflectance (Eq 3.2), and reflectance (R_{δ}) was significantly correlated with the integral of the reflectance scan on both occasions (Table 3.1). When data from both the sampling occasions were included in a single analysis, correlation coefficients were lower, but because of the larger sample size, were still significant (Table 3.1).

When remote sensing from satellite or aircraft platforms, an entire water body is imaged virtually instantaneously and solar irradiance can be considered to be equal for all the 'water' pixels. Correction for irradiance by calculating reflectance is therefore not necessary. However, if an empirical model is being extrapolated from one date to another, some form of correction for changes in irradiance is essential. The amount of irradiance is primarily influenced by the angle of the sun above the horizon and most authors developing multidate algorithms have included sun angle corrections as part of the radiometric preprocessing. This can be done by using the sun angle correction outlined in equation 2.4.

Table 3.1 Regression analysis results for the integrated (400-1000nm) reflectance (R_5)/ chlorophyll relationship.

Date	n	R^2	SE	F-ratio	p-level
19/05/89	8	0.98	0.68	190.78	<0.05
13/07/89	12	0.93	1.83	79.35	<0.05
grouped	20	0.78	0.02	28.32	<0.05

SE= Standard error of estimate.
F-ratios are calculated between observed and predicted values for the full regression.

Equation 3.3 was used to integrate reflectance over the spectral bands of the LANDSAT Multispectral Scanner (MSS) and Thematic Mapper (TM) sensors as well as the Daedalus airborne themapic mapper (ATM). The Daedalus ATM has the highest spectral resolution of all these sensor systems with 8 spectral bands in the range 350-1100nm (Table 3.2). LANDSAT TM has better spectral resolution than LANDSAT MSS with narrower spectral bands.

Reflectance in each band was significantly correlated to chlorophyll concentrations in all but the blue spectral bands (<525nm, Table 3.2). The highest correlations were noted for the Daedalus channel 6, which detects the infrared peak at 700nm. Other spectral bands which show a high correlation with chlorophyll concentration are LANDSAT MSS band 3, and Daedalus channel 7 and TM band 4 (Table 3.2), which also detect the near infrared wavelengths. LANDSAT TM band 2 and Daedalus channel 3 are placed to distinguish the green reflectance peak from algae and also have high correlations with reflectance.

These analyses indicate that although most spectral bands are positively correlated to reflectance, narrow spectral bands centred over the green or infrared reflectance peaks will provide the most valuable data for the remote sensing of algal concentrations. Of these two, narrow bands in the near infrared wavelengths are the most promising.

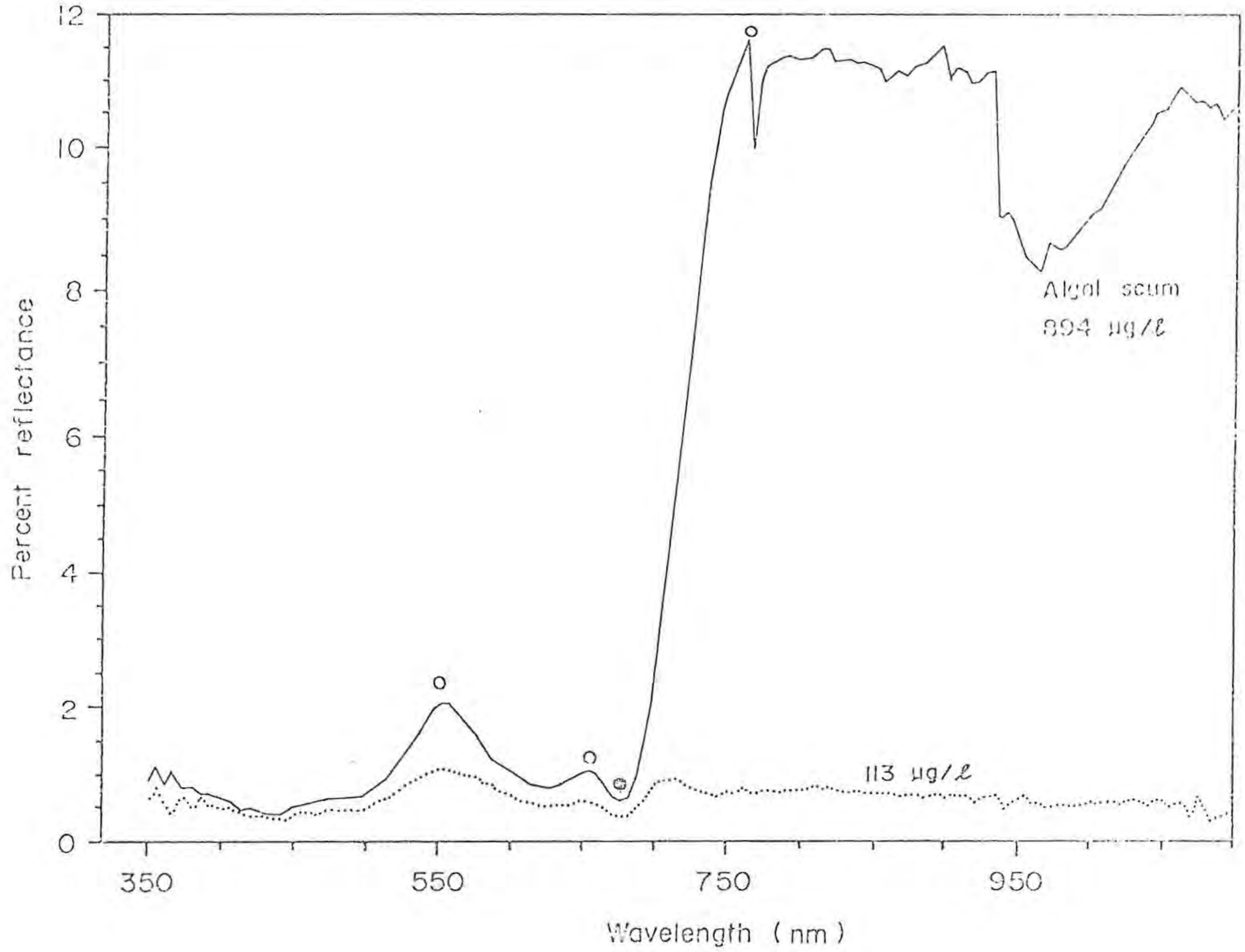


Figure 3.13. The reflectance spectrum of an algal scum together with the spectrum of algae within the water column.

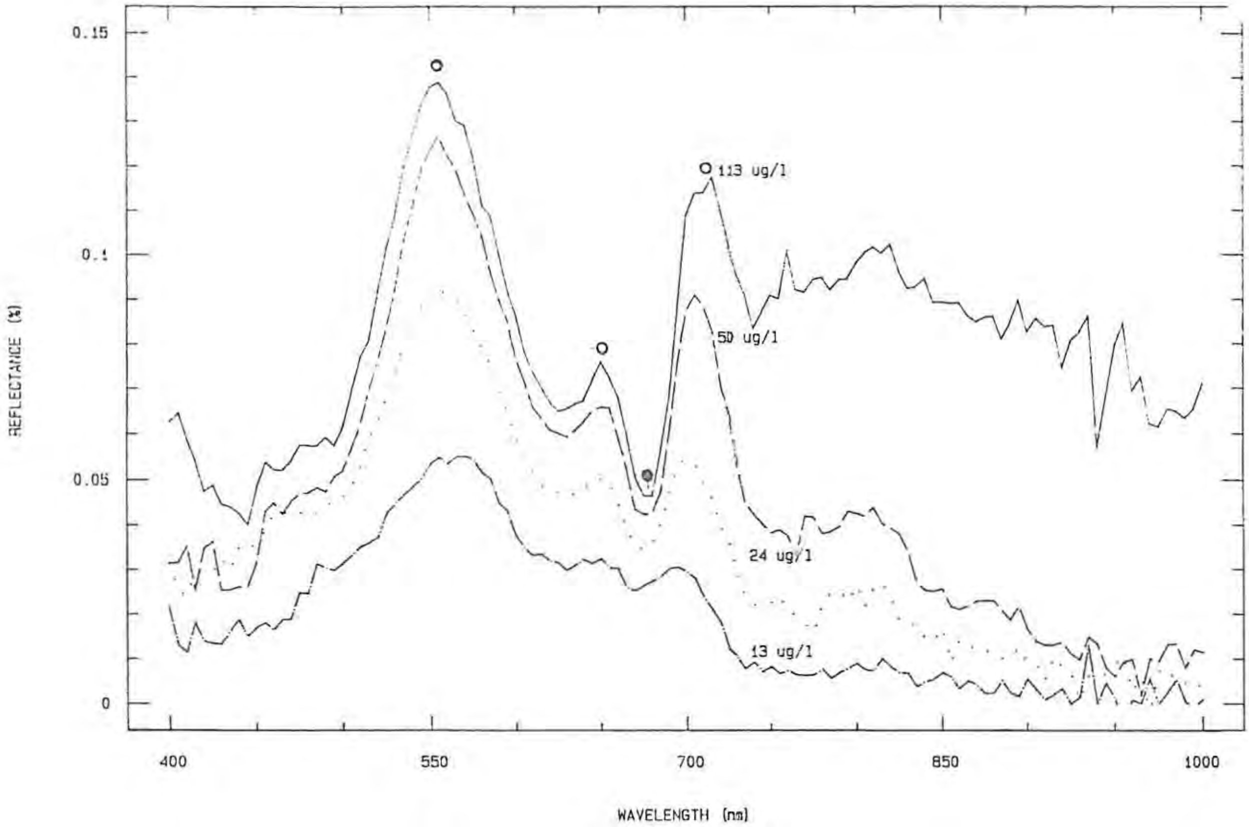


Figure 3.14. Reflectance spectra taken on parts of Roodeplaat Dam with high chlorophyll concentrations.

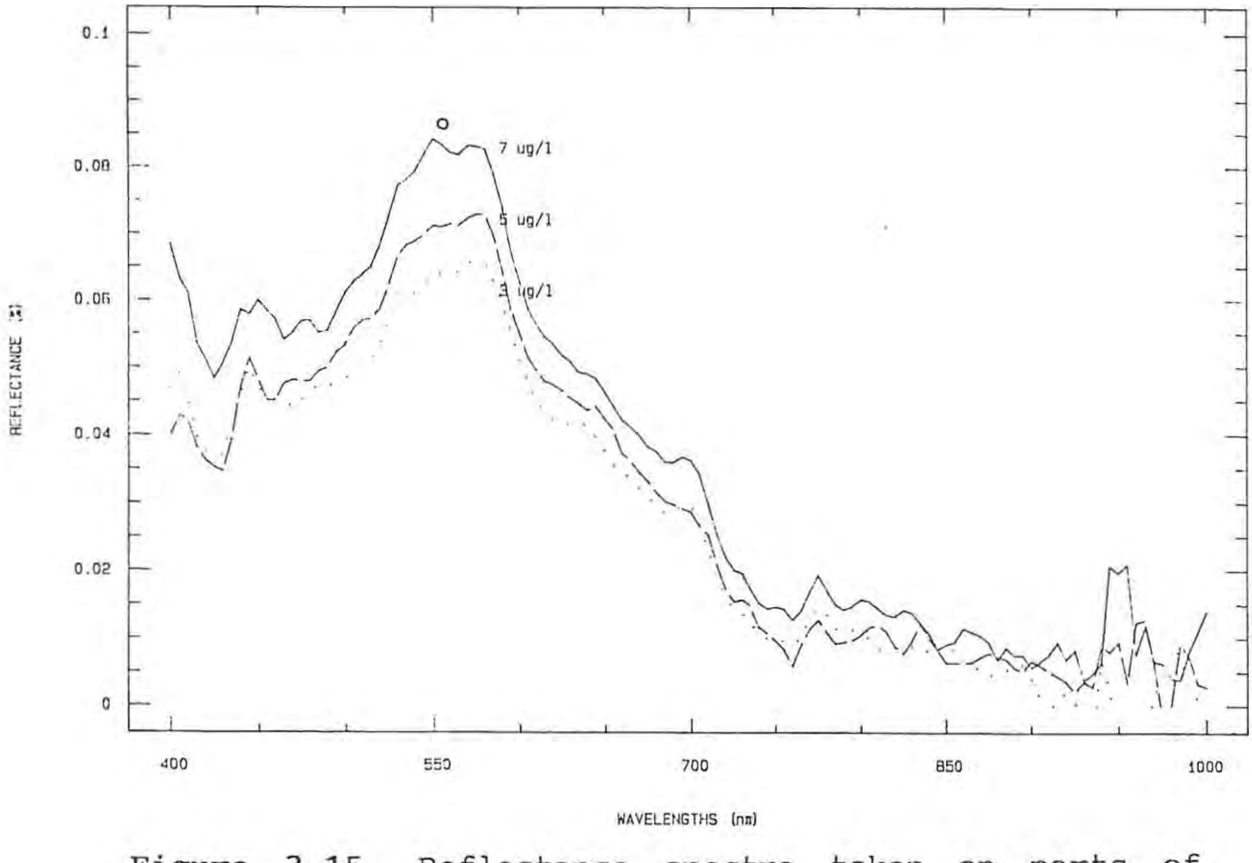


Figure 3.15. Reflectance spectra taken on parts of Roodeplaat Dam with lower chlorophyll concentrations.

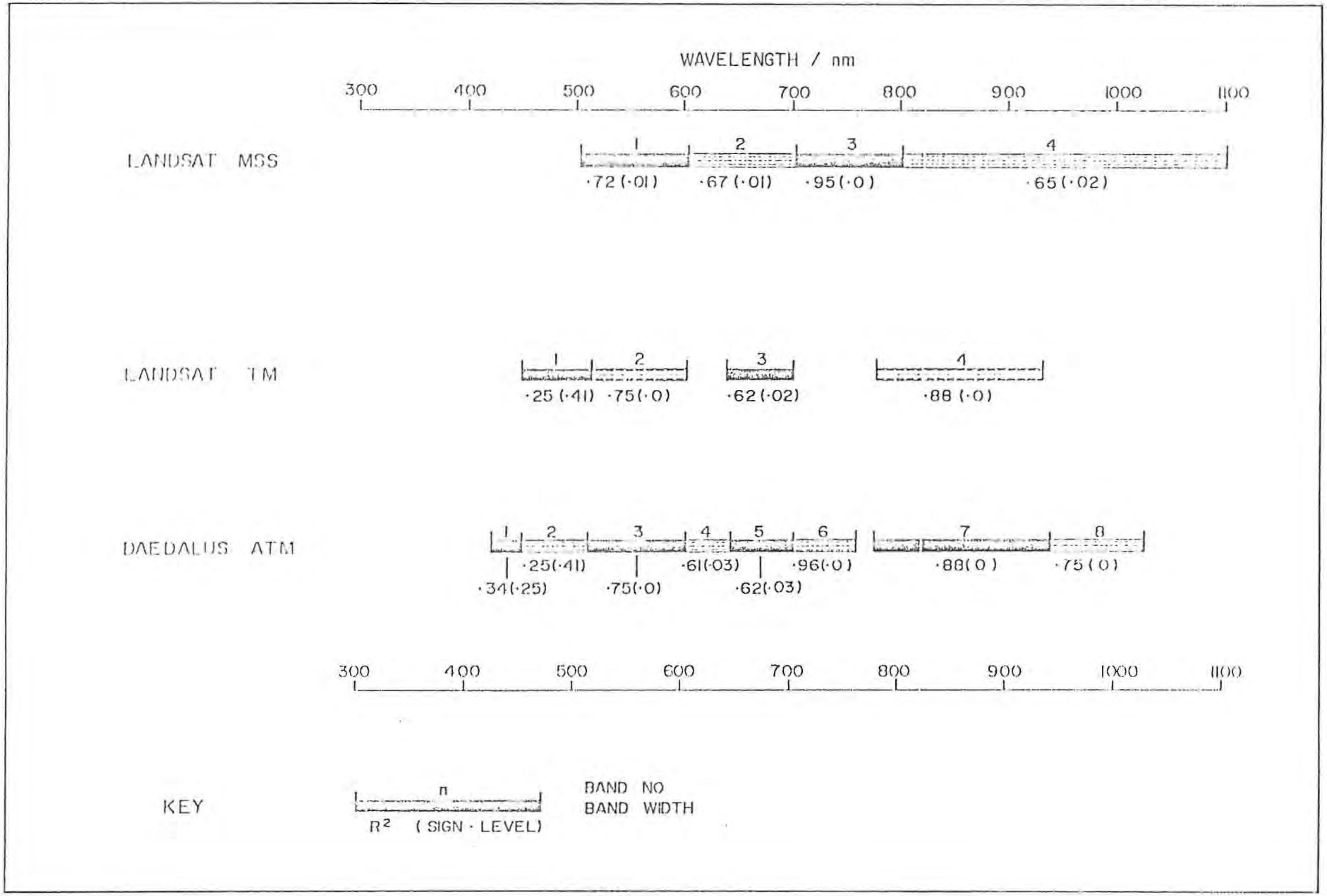


Table 3.2 Correlations of reflectance (integrated over the spectral bands of known sensor systems) with chlorophyll concentration. (n=20)

3.6 The effect of suspended sediments on reflectance

3.6.1 Background

The major drawback of an empirical approach is that light scattered out of water by algae may only form a small part of the total emergent flux. This is particularly important in the South African context where many rivers carry high sediment loads (Rooseboom 1978). Larger particles entering a water body rapidly settle out of suspension, and suspended sediment gradients often occur near the inflows to South African impoundments. As these sediments also contribute to the total upwelling radiance, chlorophyll concentrations can be over estimated near the inflows. Some method of compensating for the effect of reflectance from sediments is therefore essential.

Stumpf and Tyler (1988) have recognised the effects of suspended sediment on reflectance from algae and suggest ratios of the red and near infrared wavelengths as a means of compensating for these effects, based on a conceptual model of chlorophyll and sediment reflectance. However no rigorous investigation of the effect of suspended sediments on reflectance from algae has been done. This section describes the effect of the addition of suspended sediments to pure cultures of algae on the reflectance from these cultures.

3.6.2 Methods

Upwelling radiance from water samples was measured using the same apparatus described in section 3.4.2. In this case however, the study was conducted in a darkened laboratory using two photoflood lamps as a source of illumination. The lamps were positioned to provide illumination at 45° from the perpendicular. Downwelling radiance ($L_{\delta d}$) from the lamps was measured before and after the experiment. Reflectance (R_{δ}) was calculated using equation 3.2.

The alga *Selenastrum sp.* were isolated in pure culture and five 20*l* dilutions of the culture were made with distilled water. Powered sediments were added to these dilutions to produce suspended sediment concentrations of 200, 400 and 600 mg/l. Five scans of each sample were taken and a single scan expressed as a mean of the five. The sample was stirred between scans to ensure the sediments remained in suspension. A scan was also taken on Roodeplaat Dam near the inflows where sediments can influence the reflectance detected.

3.6.3 Results and Discussion

Upwelling radiance from Roodeplaat Dam sediments added to distilled water showed high reflectance in the 550-650nm range, and a smaller peak at 800-810nm (Fig. 3.16). The latter peak corresponds to an absorption minimum for pure water at this point (Fig 3.1) and is probably due to less attenuation of light both before and after it is scattered by the particles. Reflectance appeared to be asymptotic at SSC of over 400mg/l. The asymptotic nature of the SSC/reflectance relationship has also been demonstrated by Novo Hansom and Curran (1989a).

Reflectance from pure *Selenastrum sp.* cultures was the same as algal reflectance described in sections 3.3 and 3.4. Addition of sediment to the pure cultures produced a shift away from the reflectance peak at 550nm (Fig. 3.17 and 3.18), toward the sediment reflectance peak at 600-650nm. The magnitude of this shift appeared to be dependent on the amount of sediment added (Figs 3.17 and 3.18). However, the position of the algal reflectance peak at 700-750nm and the absorption peak at 665nm, remained unchanged and sediments increased the reflectance at these wavelengths. The difference between reflectance at ≈665nm and that at ≈700nm was constant, irrespective of the amount of sediment added (Figs. 3.17 and 3.18). Scans of the reflectance from points on Roodeplaat Dam near the inflows where high concentrations of suspended sediments occur, show that sediments in this impoundment have the same effect as that demonstrated in the laboratory (Fig 3.19). However, as different types of sediment have unique spectral characteristics (Novo *et al* 1989a), this effect may not be common to all water bodies.

As the difference between reflectance at ≈665nm and ≈700nm remained constant, subtraction may compensate for sediment reflection. This is similar to the method proposed by Stumpf and Tyler (1988), but relies on subtraction rather than ratios for the sediment correction. In this case subtraction is of greater value as reflectance from *Microcystis sp* does not fit the conceptual model of chlorophyll reflectance. Subtraction of spectral bands has also been proposed by Matsumura and Yokota (1989), who show that subtraction of reflectance between 450-500nm from that between 650-690nm provides the best correlation with chlorophyll extracted from red tide algae. However, for subtraction to be effective, the spectral bands would have to be narrow and placed to detect reflectance at ≈665nm and ≈700nm. As few sensor systems offer these spectral bands, subtraction is rather impractical as a means of correcting for suspended sediment. Furthermore as infrared reflectance only occurs at higher cell densities, this technique is only practical in some impoundments

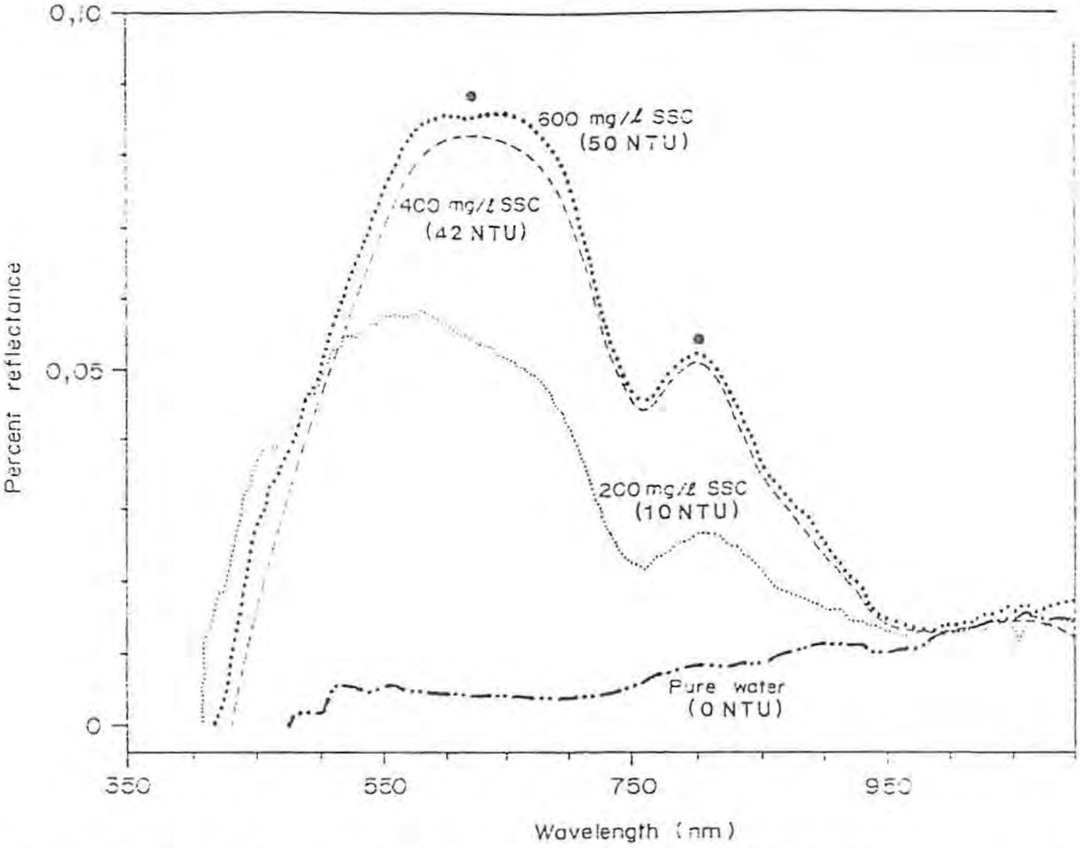


Figure 3.16. Reflectance spectra of different amounts of sediment added to distilled water. The spectrum of the pure water is also shown. (reflectance peaks are indicated by ●).

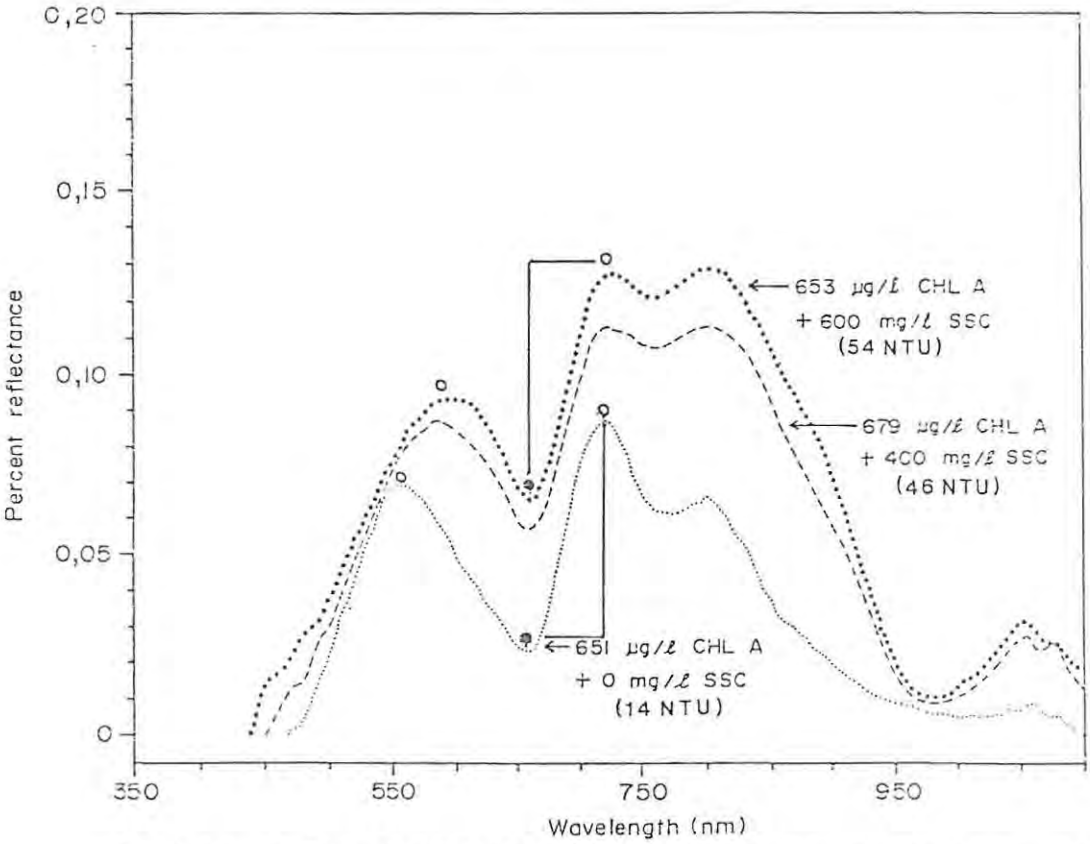


Figure 3.17. Reflectance spectra of a culture of the algae *Selenastrum sp.* without and after the addition of differing amounts of sediment. The constant difference in reflectance between reflectance at 665nm and 700nnm is indicated by the equallength of the bar.

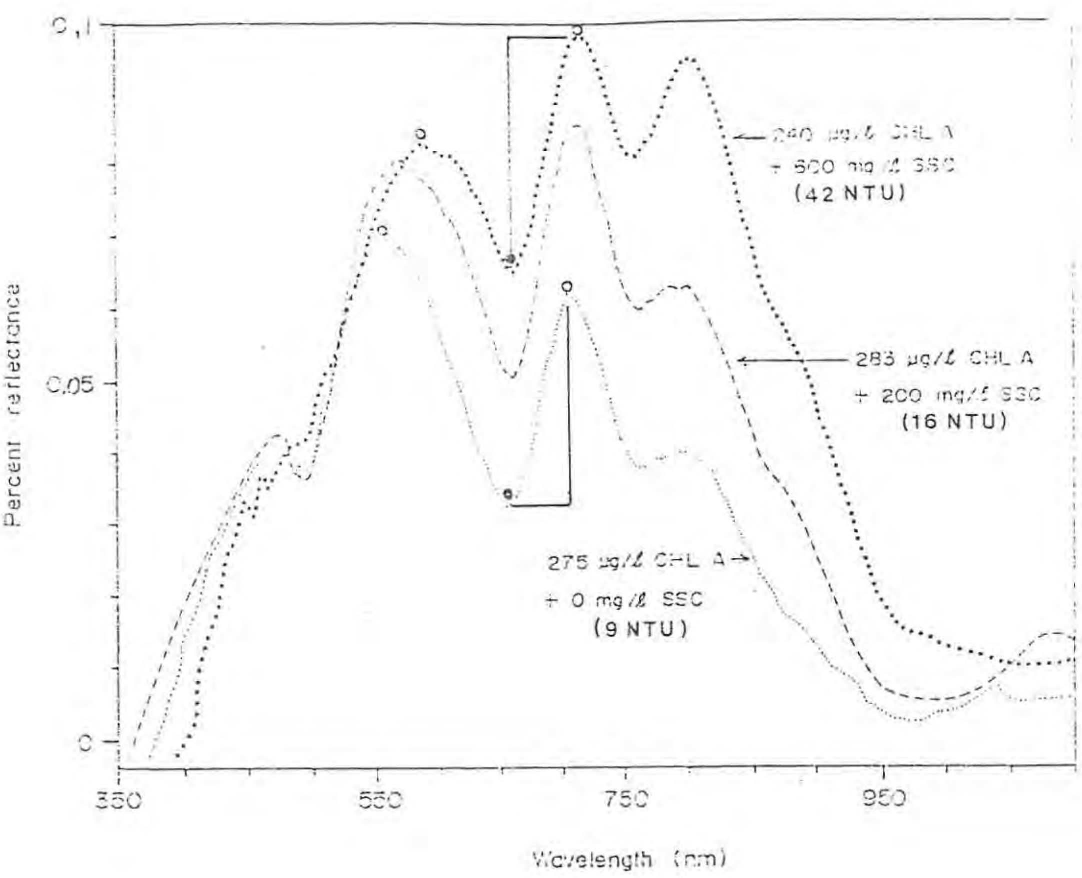


Figure 3.18. Reflectance spectra of a culture of the algae *Selenastrum sp.* without and after the addition of differing amounts of sediment. The constant difference in reflectance between reflectance at 665nm and 700nnm is indicated by the equallength of the bar.

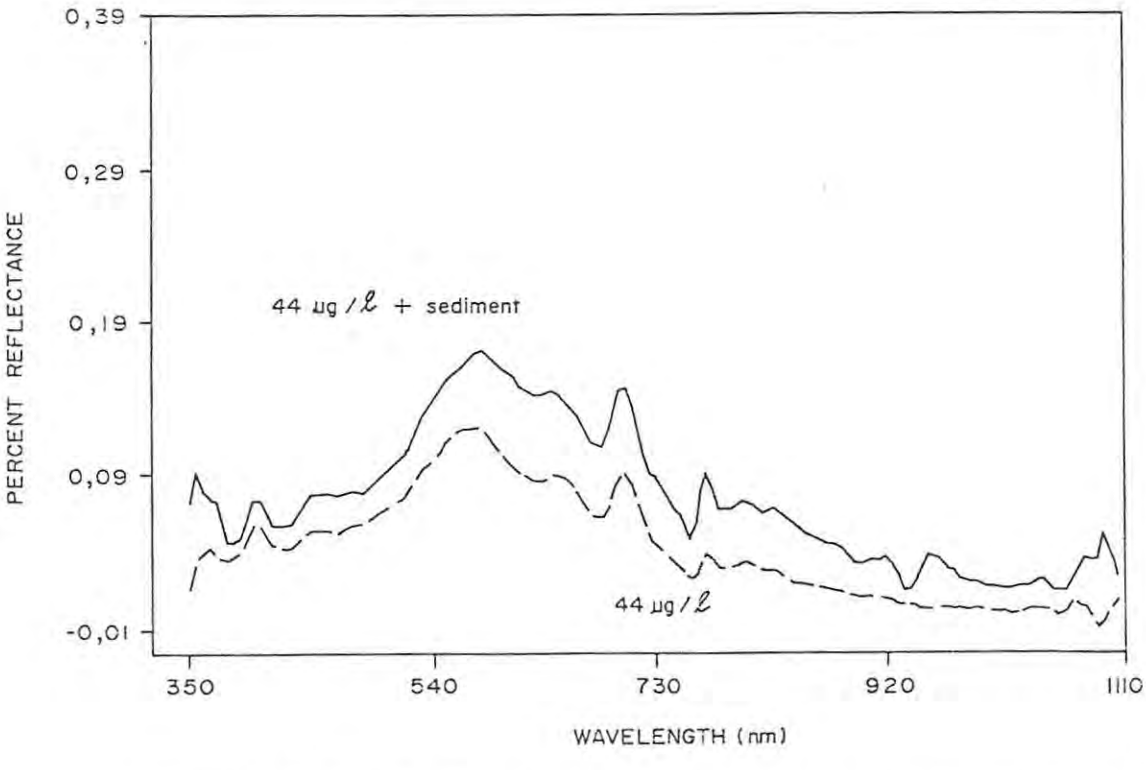


Figure 3.19. Reflectance spectra taken on Roodeplaat Dam, including a point near the Pienaars River inflow which had a high suspended sediment concentration (SSC), indicating the similar effect of sediment in natural waters.

3.7 Conclusions

An empirical approach to quantifying chlorophyll concentrations from radiance data relies on the premise that factors other than algae which contribute to the total signal are either constant at each point or have been compensated for by some means of radiometric preprocessing. This chapter dealt with the effects of changes in vertical distribution, changes in algal species and the presence of suspended sediments, on the nature of reflectance from algae measured just above the water surface. Unfortunately a major shortcoming of the approach used in this study was that the spectroradiometer automatically averages the replicate scans, and the variation in reflectance from any target could not be determined. Analysis of the scans was therefore predominantly qualititative.

The wavelength dependent absorption of electromagnetic energy by water played an important role in the reflectance from particles suspended in the water column. The absorption of light by pure water is altered in natural water bodies by the presence of these particles in the water. In eutrophic waters the algae increased the attentuation of blue light, and scattered green light deeper into the water. This appeared to shift the maximum depth of light penetration from the blue wavelengths (≈460nm), to the green (≈550nm). When the algae occurred as a scum on the surface, spectra were dominated by high reflectance in the infrared wavelengths. However, the high absorption coefficients for water of wavelengths over 700nm meant that when the cells occurred within the water this reflectance was attenuated. The combination of the absorption of infrared light by water, and the high reflectance by algae, meant that increases in the amount of upwelling radiance at higher algal densities are greatest in these wavelengths.

At higher algal densities, integrated reflectance over the 700-800nm range had the highest correlation with chlorophyll concentration. Spectral bands in these wavelengths will therefore be the most useful in empirical models, provided that the cells are evenly distributed within the upper layers of the water column. Correlations with spectral bands in the green part of the spectrum were not as good, but when low chlorophyll concentrations are expected, too few cells occur in the upper layers of water and the green wavelengths will be of greater value in empirical models. At wavelengths longer than 800nm, the extinction of light was high and only algal scums had significant reflectance in these wavelengths. Correlation of reflectance in these wavelengths to chlorophyll concentration was consequently the lowest and the exclusion of spectral bands in this part of the spectrum is justified.

Estimates of the depth of remote sensing penetration not only indicate where bottom reflectance plays a role in the signal measured, but will also contribute to more effective surface reference data collection. Only those algae above the depth of remote sensing penetration can contribute to the upwelling signature. Surface reference samples should therefore sample to this depth. This study indicated that the attenuation of reflectance from a white board was not a true reflection of the attenuation of the remotely sensed signal. However measurements of the contribution of cells above a black board indicated that the relationship between the depth of remote sensing penetration (as defined by Whitlock *et al* 1978) and Secchi depth was complex. A complete analysis of this relationship was considered beyond the scope of this study. Furthermore, depth of remote sensing penetration was wavelength dependant. Field estimation of the depth to which samples must be integrated is therefore impractical. However as most of the radiance originated above 50% Secchi depth, and Secchi depths in South African impoundments rarely go above 2m, a surface grab sample should be adequate when developing an empirical relationship between reflectance and chlorophyll.

Another important aspect of the depth of remote sensing penetration is that in clearer waters more cells can contribute to the reflectance. This means that smaller differences in algal density will produce greater changes in the number of cells which scatter light out of the water body. Remote sensing in clearer waters should therefore be more accurate. A simple method of compensating for clearer parts of a water body from knowledge of the depth of remote sensing penetration is also impractical.

The different species of algae studied were spectrally very similar. However a small peak in reflectance at 650nm consistently (27 scans) occurs in the reflectance spectrum of blue-green algae which is not present in the green algae. This peak is also evident in the spectra of natural waters dominated by blue-green algae, but is small in comparison to the peaks in reflectance at 550 and 700nm. This is unlikely to cause shifts in the spectral bands which show the best correlation with chlorophyll concentrations for different species. These shifts, noted by other authors (Howman and Kempster 1986 and Lindell 1981), are probably due to variations in the total chlorophyll concentrations or in the vertical distribution of algae.

However, the different species of algae had different light scattering properties (measured as turbidity). This appears to be due to the colonial nature of some algae. Colonial algae form clumps in the water, thereby reducing the number of particles which can scatter light for a given chlorophyll concentration. The amount of reflectance from colonial algae is therefore lower than that for non-colonial species at the same chlorophyll concentrations. The amount of light scattered by algae for a given chlorophyll concentration will also differ with changes in the chlorophyll to cell ratio. This means that empirical models would have to be species specific.

The presence of suspended sediments associated with the algae will influence the spectral signature of many Southn African waters. Addition of Roodeplaat Dam sediments to pure algal cultures had an additive effect on reflectance in wavelengths longer than 550nm. As this effect seems to be equal at all these wavelengths, subtraction of reflectance at ≈665nm from that at

≈700nm may provide a means of correcting for relection from suspended sediments. This will also correct for the additive effects of the atmosphere, assuming that these effects are also equal at these wavelengths. However, the value of this approach will be dependent on the inclusion of narrow spectral bands centred at these wavelengths. As no sensor systems readily available in South Africa have these bands this approach has limited value. Furthermore, as the method is dependent on the presence of a reflectance peak at 700nm, it can only be applied when chlorophyll concentrations are high. There is therefore no feasible method for compenstating for the effects of suspended sediment in the routine use of remote sensing to monitor chlorophyll concentrations in South African waters.

3.8 Optimising the empirical approach.

Multiple linear regression has been the most commonly used method of quantifying chlorophyll concentrations. However, some authors have attempted to take advantage of the conceptual reflectance characteristics of algae by means of reflectance ratios (Stumpf and Tyler 1988). Reflectance ratios have also been used as a means atmospheric correction (Munday *et al* 1979). This study has shown that the alga *Microcystis sp.* does not have lower reflectance in the chlorophyll absorption wavelengths with higher chlorophyll concentrations, and hence do not conform to the conceptual model chlorophyll reflectance. Reflectance ratios will not improve the performance of empirical methods for this species.

Some authors have proposed the canonical correlation procedure as a means of optimising the empirical approach (Carpenter and Carpenter 1983 and Howman and Kempster 1986). Howman and Kempster (1986) have used this procedure in the model CALMCAT. This model correlates linear combinations of surface and integrated (0-5m) chlorophyll concentrations and turbidities, with linear combinations of LANDSAT MSS spectral bands. The advantage of this method is that it will accommodate the changes in spectral signature caused by variations in the vertical distribution of algal cells and the presence of suspended sediments. As such, this approach is probably the most reliable method of coping with the complex nature of reflectance from natural water bodies.

However, a rationale for optimising the reflectance data should not be based on the measurement of reflectance at 5nm intervals, but rather on the integration of the reflectance over the spectral bands of the sensor system being used. Sensor systems with a high spectral resolution (many narrow spectral bands) will be more likely to discern the narrow reflectance and absorbance peaks of algae. The disadvantage of remote sensing of algae in inland waters is that the available sensor systems were designed for terrestrial remote sensing and have broad spectral bands. Broad bands can include both high and low reflectance wavelengths with consequent loss of information. This negates the advantages of subtraction and ratioing of wavebands, as well as the efficacy of the canonical procedure.

Another disadvantage of the application of satellites designed for terrestrial to water quality observations is the steep slopes of the digital value to radiance conversions (Radiometric resolution). This means that range in reflectance from water is contained in a few discrete digital values, which restricts the value of these systems to detect small changes in chlorophyll concentration. The following chapter addresses this issue by introducing rasterised aerial photography as an alternate source of data to LANDSAT MSS imagery. The two sensor systems as well as two empirical procedures are compared on the basis of accuracy in the simulation of chlorophyll concentrations in Roodeplaat Dam, from simultaneously collected radiance data.

CHAPTER FOUR.

A COMPARISON OF LANDSAT MSS AND MULTISPECTRAL AERIAL PHOTOGRAPHY

4.1 Introduction.

The aquatic environment provides unique challenges for the remote sensing of freshwater algae. The wavelength dependent absorption of electromagnetic energy by water (Fig 3.1) ensures that the radiance scattered out of a water body by algae is a fraction of that reflected by terrestrial plants. Accurate quantification of the amount of algae would, therefore, require remote sensors both sensitive to low radiances and capable of detecting small changes in radiance. The spectral resolution of a remote sensor has already been shown to be important for the accurate remote sensing of algae, and satellites designed specifically for water quality observation (eg. CZCS and SeaWiFS) typically have narrow spectral bands (20nm) (Table 2.1). These satellites are also capable of detecting low radiance (high radiometric sensitivity) and can detect small changes in radiance (high radiometric resolution) (Hilton 1984 and Table 2.2). Higher spectral and radiometric resolution is made possible by using larger pixels (Hilton 1984), and ocean colour satellites have pixels in the order of 1km x 1km. The pixels of these satellites are consequently too large to be practical for inland waters, and remote sensing of inland waters is reliant on systems designed for terrestrial remote sensing. This necessates a compromise in both radiometric and spectral sensitivity.

Another disadvantage of satellite systems is the fixed overpass dates. The LANDSAT satellites have a 16 day repeat cycle. This means that any one water body is imaged only occasionally, and these occasions may be cloudy. The fixed overpass time of the satellite also limits the periods of the year when images can be taken with a 40° to 50° solar elevation angle. Aircraft borne sensors would however provide the opportunity to adjust pixel size, spectral resolution and radiometric resolution to suit any particular requirement. These systems would also provide a partial solution to atmospheric correction since the atmospheric path is shorter. In addition aircraft borne systems are not tied to fixed overpass times and dates.

Airborne multispectral scanners have been used to quantify suspended sediment concentrations in the offshore environment (Collins and Pattiaratchi 1984, Curran 1987 and Curran, Hansom, Plummer and Pedley, 1987) and for bathiometric measurements of inland waters (Jain, Zwick, Weidmark and Neville, 1982). Airborne spectroradiometers have been used to monitor water quality in the U.S.A. (McKim, Merry and Layman, 1984) and the CAESAR MSS airborne scanning system has been used to quantify chlorophyll concentrations in the Loosdrecht Lakes (Dekker and Seyhan 1988). However, these instruments are expensive and are not readily obtainable in South Africa. Aerial photography, on the other hand, is available in South Africa, and has been suggested as an inexpensive remote sensing tool (Shafer and Degler 1986).

Visual interpretation of aerial photographs has been used for water pollution surveys (Bruins 1988 and Perchalski and Higgins 1988). Adams *et al* (1977) use multispectral aerial photography as a tool for remote sensing of aquatic macrophytes, but do not produce synoptic views of chlorophyll concentrations from the photography. Aerial photography has also been used for qualitative analysis of algal blooms (Dekker and Seyhan 1988 and Matsumura and Yokota 1989), but Hilton (1984) has suggested that quantitative information can be obtained from aerial photography by instrumentally obtaining the colour density of the film. Quantification of aerial photography in this manner has often been applied to terrestrial land cover studies (Dale, Hulsman and Chandica 1986,Frank and Isard 1986, Scarpace, Quirk, Kiefer and Wynn 1981 and Scogings and Piper 1985).

In this chapter a similar technique is applied to remotely sense algal concentrations in a eutrophic South African impoundment (Roodeplaat Dam). Rasterised multispectral aerial photography (MSP) from both small and large format camera systems is compared to simultaneously collected LANDSAT MSS imagery. Comparisons are made on the basis of radiometric resolution, correlation between remotely sensed radiance and chlorophyll concentrations, and accuracy in the simulation of chlorophyll concentrations from empirical models.

4.2 Methods.

4.2.1 Aerial photography.

In order to allow direct comparison of the LANDSAT MSS and aerial imagery, aerial photographs of Roodeplaat Dam were taken at the time of the LANDSAT overpass. Data were collected on two separate occasions and on both occasions the aerial photographs were taken by professional aerial survey companies.

On the first sampling occasion (5 October 1987) aerial photographs were taken from an altitude of 4700m with a small format camera. The camera system consisted of a 70mm format Hasselblad camera mounted on brackets outside the door of a Cessna 210 aircraft. Seventy millimeter format has also been used by Dale, Hulsman and Chandica (1986).

An open area of water was used to set the exposure and aperture settings to optimise the reflection from the water surface. These settings were then maintained throughout the flight. As land reflects more light, the areas of land in each photograph were overexposed. On this occasion, Roodeplaat Dam was photographed with colour and colour infrared (CIR) film. However, as a single camera system was used, the water body was first photographed in colour and immediately after in colour infrared, and the assumption is made that the distribution of the algae did not change in this time. However, due to the poor photographic results of the CIR (possibly because of the thermal sensitivity of the film), infrared was not included on the second occasion. Densities of the CIR film was also not correlated to chlorophyll concentrations or included in the linear regression proceedures. The photographs were taken with approximately 80% of overlap and near vertical photography was possible using a spirit level mounted on the camera.

Photographs for the second sampling occasion were taken with a large format aerial camera system mounted on gimbals below the aircraft. This system ensured that vertical photographs were taken irrespective of the attitude of the aircraft. On this occasion the camera system was pre-set to provide a 70% overlap, and the camera system automatically adjusted the exposure for each photograph. The altitude of photography was adjusted to ensure photographs at a scale of 1:14000.

4.2.2 Computer Compatible Tapes (CCT's).

Before the aerial data could be compared to the LANDSAT MSS data, the photographs had to be in a computer readable form. This was done by obtaining the optical density of the colour positive transparencies with an Optronix P1000 colorscan densitometer. This instrument measures the optical density of the transparency over 100µm x 100µm, or 50µm x 50µm, or 25µm x 25µm areas. In order to reduce the amount of data, the 100µm setting was used on both occasions. This produced pixels of 6m x 6m for the small format transparencies and 1.4m x 1.4m for the large format system.

The Optronix P1000 densitometer allows for filters to be placed between the film and the photomultiplier tube. These filters produce different spectral bands. The spectral bands produced by this technique are a combination of the spectral sensitivity of the film and the band pass characteristics of the Optronix filters. The spectral sensitivity of the films used is shown in figure 4.1 and the band pass characteristics of the standard filter options on the densitometer filters are presented in figure 4.2. The approximate spectral bands produced from this system are compared to the LANDSAT MSS bands in figure 4.3.

The optical density in each spectral band and each pixel is written onto the CCT as 8-bit (0-255 DN) data. It is possible to produce a density log exposure (dlogE) curve for the film types as described by Adams *et al* (1977) to assign a particular radiance to the digital number. However as this would have to be done for the particular exposure, aperture, and processing method used on each sampling occasion, it was considered beyond the scope of this study. Density of the exposed film was logarithmic with exposure, and the digital value data for aerial photography therefore logarithmic with radiance (Frank and Isard 1986).

4.2.3 Single images of the water surface.

Limitations on the altitude at which aerial photographs could be taken necessitated that several separate photographs of the water surface had to be taken. This required merging of the photographs to produce a single image of the whole water surface. As the photographs were taken with a high degree of overlap, only a small portion in the centre of each photograph was used to ensure near nadir viewing and consequently to avoid the problems associated with angular anisotrophy in reflectance (see section 2.3.3).

On each sampling occasion, the centre photograph was chosen as a standard. The adjacent photograph was then registered to the standard. The overlapping areas between the photographs was then subtracted on a band for band, pixel for pixel basis from one another. The statistics of the resulting image then gave the mean difference between the images in each spectral band and the intensity of the adjacent image was adjusted to the standard. The two photographs could then be merged. The above procedure and the assumptions inherent in the technique are explained in more detail in Appendix A.

Once a single image of the whole water body was produced, a region of interest routine was used to extract the water surface area.

4.2.4 LANDSAT MSS imagery.

The LANDSAT MSS sensors on board the satellite are arranged in an array of 6 sensors x 4 bands i.e. 24 sensors each with different radiometric properties. Six lines of MSS data are collected with each sweep of the mirror arm, and destripping is necessary to correct for the differences between the sensors (Ahern, *et al* 1987). The satellite is equipped with an analog to digital converter, and radiance measured by each sensor is converted to a 6-bit (0-63) digital value for transmission to earth. LANDSAT MSS data received at the Hartbeeshoek Satellite Applications Centre is converted from 6-bit data into 8-bit data via a lookup table. This is done to reduce the differences between the six sensors of each band, and consequently remove the striping on the image. These digital value data are linear with radiance (Hilton 1984).

LANDSAT 5 MSS images without any geometric correction were purchased from Hartbeeshoek on both occasions. Roodeplaat Dam lies within the world reference system (WRS) scene number 179/78. The scene numbers and sunangle characteristics of the images are presented in Table 4.1. A small sub image of the area around Roodeplaat Dam was extracted from the full MSS scene and this image was registered to fit the aerial image of the water body. The pixels in the aerial and LANDSAT images therefore corresponded to the same point on the water body.

Table 4.1 The scene number and solar elevation angle at the time of overpass of the images purchased.

Date	WRS No.	Scene No.	Sunangle
5/10/87	178/70	51313-07294	49.17
16/3/89	178/70	51841-07313	43.77

4.2.5 Surface reference data.

Surface reference data was collected as near as possible to the time of the satellite overpass. However, as it took at least one hour to collect all the samples, a time lag for some of the samples was unavoidable. Samples were returned to the laboratory and analysed for chlorophyll concentration, algal species present and turbidity using the techniques outlined in section 3.2.2. Secchi disk readings were also taken to provide an estimate of the depth of remote sensing penetration at that point. Samples were not taken in parts of the impoundment where water depth was less than the Secchi depth. This eliminated the possibility of bottom reflection contributing to the upwelling signal (see section 3.3). Samples were taken at 21 points on the impoundment on the first occasion (Fig. 4.4) and at 33 points on the second occasion (Fig. 4.5).

Several authors address the problem of the surface reference samples not being representative of the full range of water quality conditions in the water body (Boland *et al* 1979, Carpenter and Carpenter 1983, and Howman and Kempster 1986). These authors stress that the greater the range of surface reference data, the more successful are models which simulate chlorophyll concentrations from remotely sensed data. To ensure the full range of chlorophyll concentrations was sampled, sample sites were chosen from extensive prior knowledge of the algal distribution in the impoundment.

4.2.6 Pixel/sample site alignment.

The inaccurate placing of the pixel in which the surface reference sample was taken on the remotely sensed image can introduce substantial errors in the analysis of the relationship between chlorophyll concentration and reflectance (Carpenter and Carpenter 1983, Howman and Kempster 1986, Mace 1983 and Verdin 1985). The problem of inaccurate pixel/sample site alignment has been solved in various ways.

Grimshaw *et al* (1980) and Munday *et al* (1979) surveyed the sampling sites, while other workers have used a pixel averaging system to increase the likelihood of selecting the right pixel (Howman and Kempster 1986 and Shih and Gervin 1980). Pixel averaging normally involves the taking the mean reflectance in each band over a 3 x 3, or sometimes larger, pixel window. However, this increases the size of the resolution element and reduces the chance of the sample taken being representative of the whole pixel, and Johnson and Balm (1977) show how large errors can be introduced by averaging a 3 x 3 pixel window. Howman and Kempster (1986) compensate for this by weighting the centre pixel.

Accurate pixel/sample site alignment for this study was ensured by taking compass cross sightings on objects on the shoreline at the time of sampling. These objects were visible on the aerial image and could therefore be used to identify the pixel sampled. Sampling was done, wherever possible, at large buoys or rafts on the impoundment. As these sites, as well as the sampling boats were visible on the aerial image they could be used to confirm the accuracy of the cross sighting system. Cross sightings were accurate to within the 6m x 6m pixel of the small format system, but the smaller pixels of large format aerial data required that a 3 x 3 pixel window had to be averaged. As the LANDSAT MSS images were registered to the aerial images, the same pixel line and sample numbers for the sampling points on the aerial images could be used and pixel averaging was not necessary.

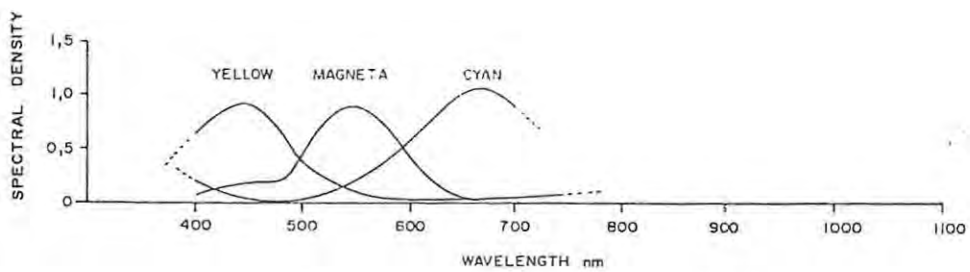


Figure 4.1. The spectral density characteristics of the aerial film used on 5 October 1989.

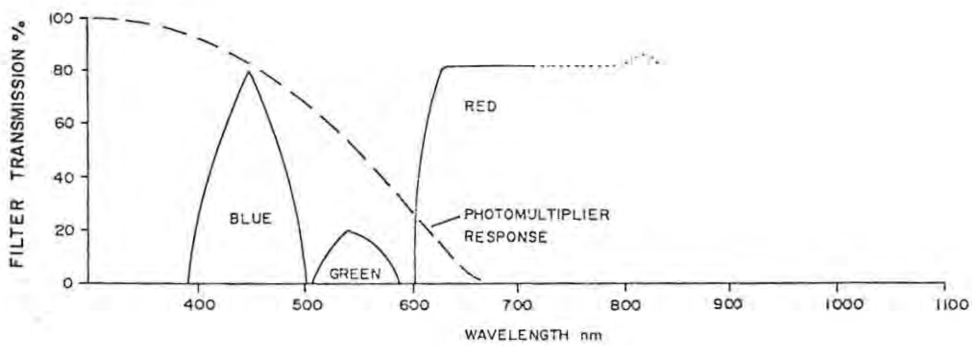


Figure 4.2. The filter transmission of the standard filters used in the Optronix P1000 colorscan, together with the photomultiplier response.

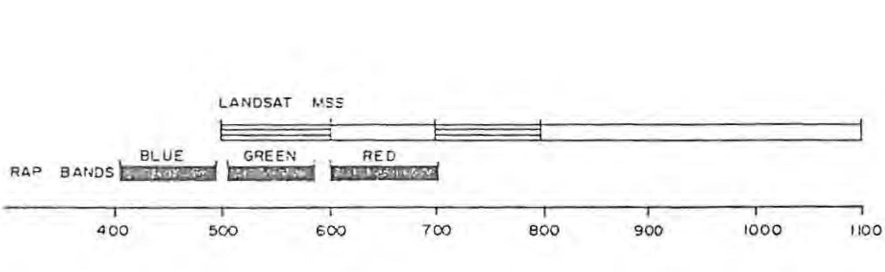


Figure 4.3. The spectral bands produced by rasterising the colour aerial photographs with the standard filter options on the Optronix colorscan. The spectral bands of the LANDSAT MSS sensors are also shown.

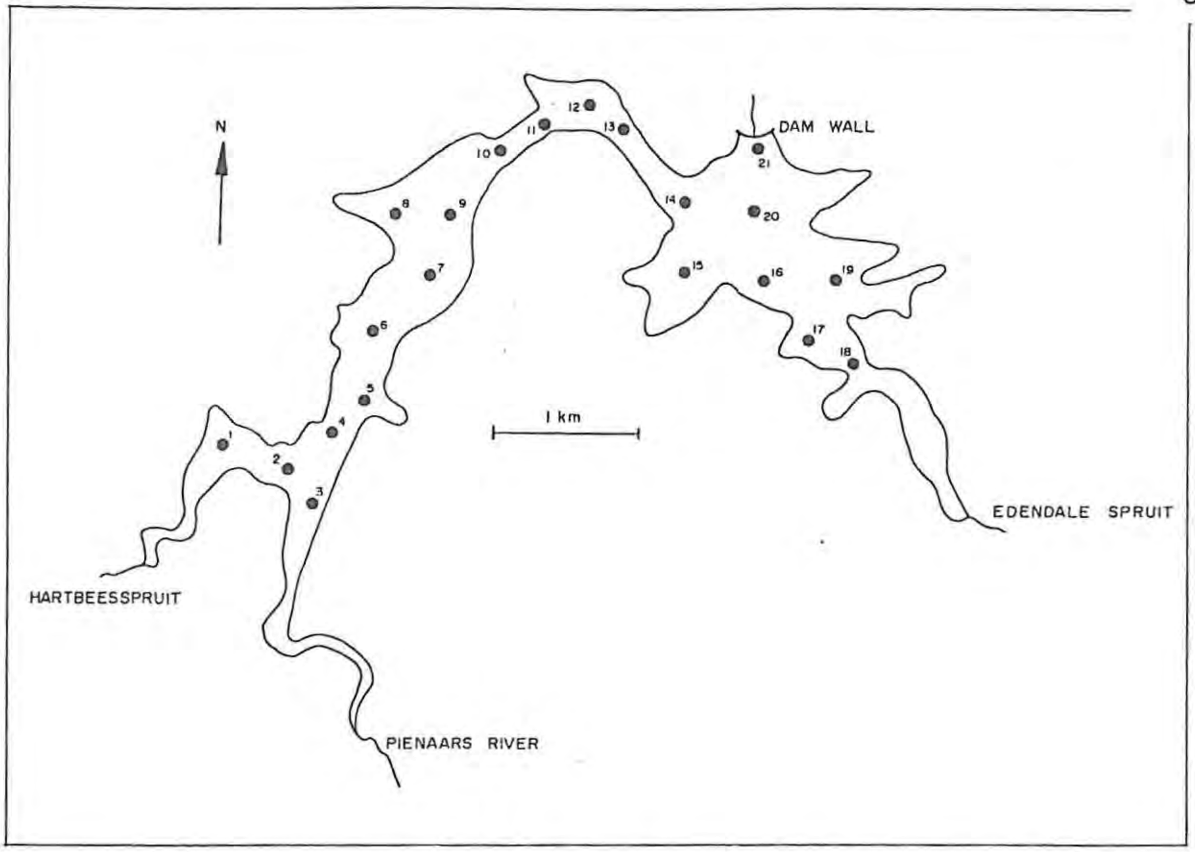


Figure 4.4. A map of Roodeplaat Dam showing the sampling points for the study of 5 October 1987.

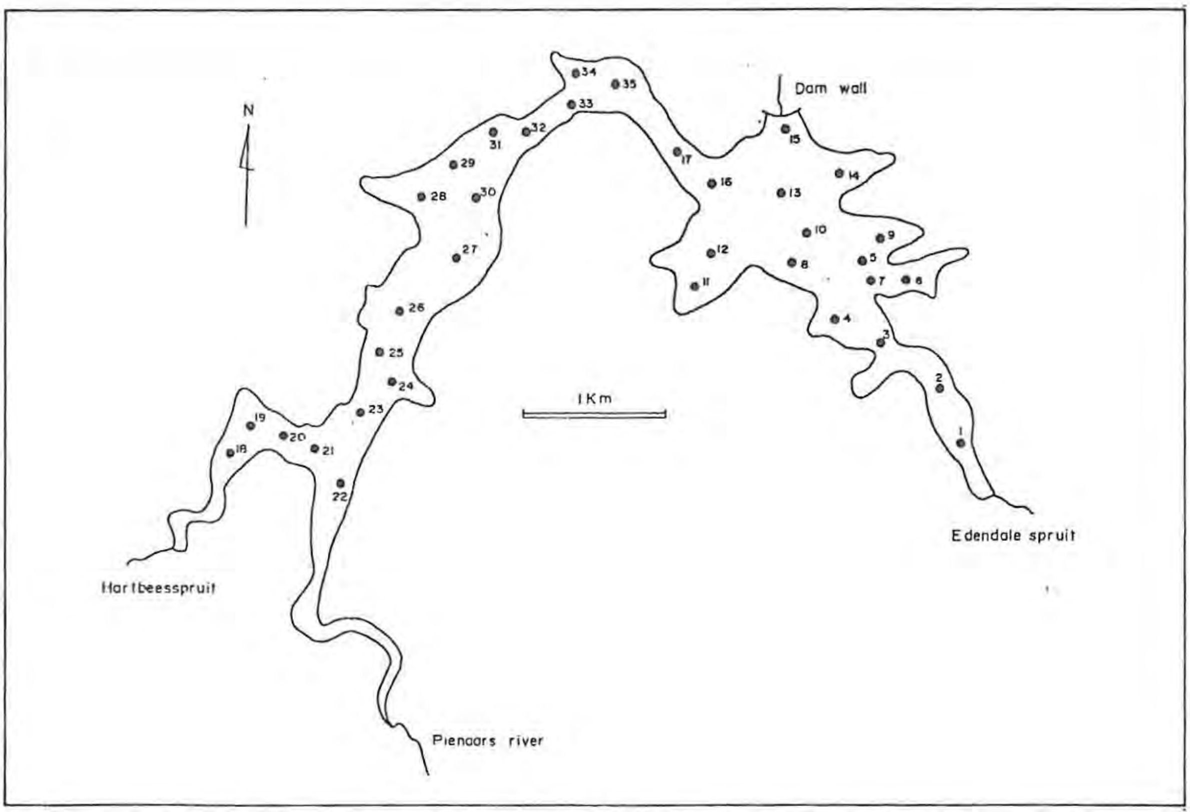


Figure 4.5. A map of Roodeplaat Dam showing the sampling points for the study of 16 March 1989.

4.3 Results and Discussion.

4.3.1 General.

Tables of the surface reference and the remotely sensed data are presented in Appendix B. On both sampling occasions *Microcystis sp.* dominated the algal composition of all the samples and the chlorophyll/radiance relationship could be considered to be uniform for the whole of Roodeplaat Dam (see section 3.4). On the first sampling run (5/10/87) surface chlorophyll concentrations were all within the 0 to 100 µg/l range, but on 16/3/89, surface chlorophyll concentrations were much higher and algal scums were noted in the western arm of Roodeplaat Dam. High suspended sediment loads were only noted at the river inflows. The highest measured chlorophyll concentrations occurred in the western arm of the impoundment near the confluence of the Pienaars river and Hartbeesspruit, on both sampling dates.

4.3.2 Colour coding.

Colour coding of each band of the imagery provides a visual impression of the distribution of the digital values over the water body. Colour coding for this study was done by dividing the 8-bit data range into 16 classes of 16 values each. Each class was then assigned a colour and all the pixels in each band were coloured according to their class. Colour coded images of the spectral bands of the LANDSAT and aerial data for the first sampling run are presented in Plates 4.1 and 4.2 respectively and for the second occasion in Plates 4.3 and 4.4.

On both occasions and in all the spectral bands, the rasterised multispectral aerial photography provided more information on the spatial distribution of reflectance. Using 16 digital values per colouronly divieded the LANDSAT spectral bands into two colours in most cases, but the aerial imagery was divided into 5 to 7 classes. The blue and green bands of the aerial imagery contained the most information of the distribution of reflectance over the water surface. The reflection peak of algae at 550nm (see Sections 3.3 and 3.4) lies within the green spectral band of the aerial imagery, and colour coding of this band should provide an approximate distribution of the algae. The blue spectral band shows a similar distribution of reflectance to the green band (Plates 4.2. and 4.4). This is due to that part of the green reflection peak which is detected in the blue spectral band. The red band produced by the standard filter option on the Optronix densitometer will detect part of the infrared reflectance peak which occurs at high chlorophyll concentrations. The range of radiance data contained in the red spectral band of the aerial image was therefore wider on the second occasion (Plates 4.2 and 4.3).

LANDSAT MSS imagery was also consistent with the known reflectance characteristics of algae in water. Colour coding of the image on the first occasion indicated that most of the information was contained in bands 1 and 2. However, on the second sampling occasion, bands 3 and 4 showed several distinct classes in the western arm of Roodeplaat Dam. This was likely due to the higher chlorophyll concentrations and scums, which result in higher reflectance in the near infrared wavelengths (see section 3.5).

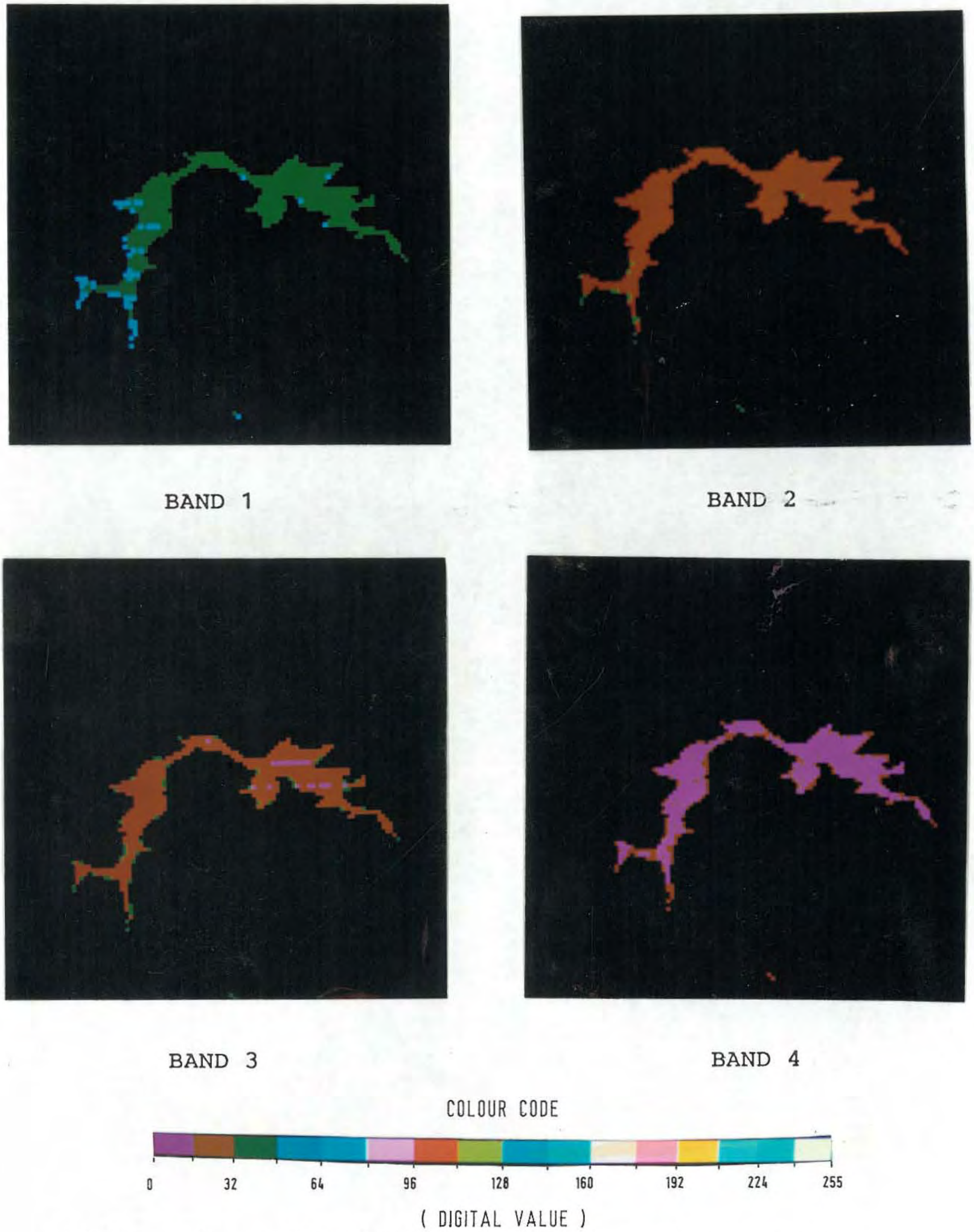


Plate 4.1. The distribution of reflectance (as digital values) for the LANDSAT imagery for the first sampling occasion.

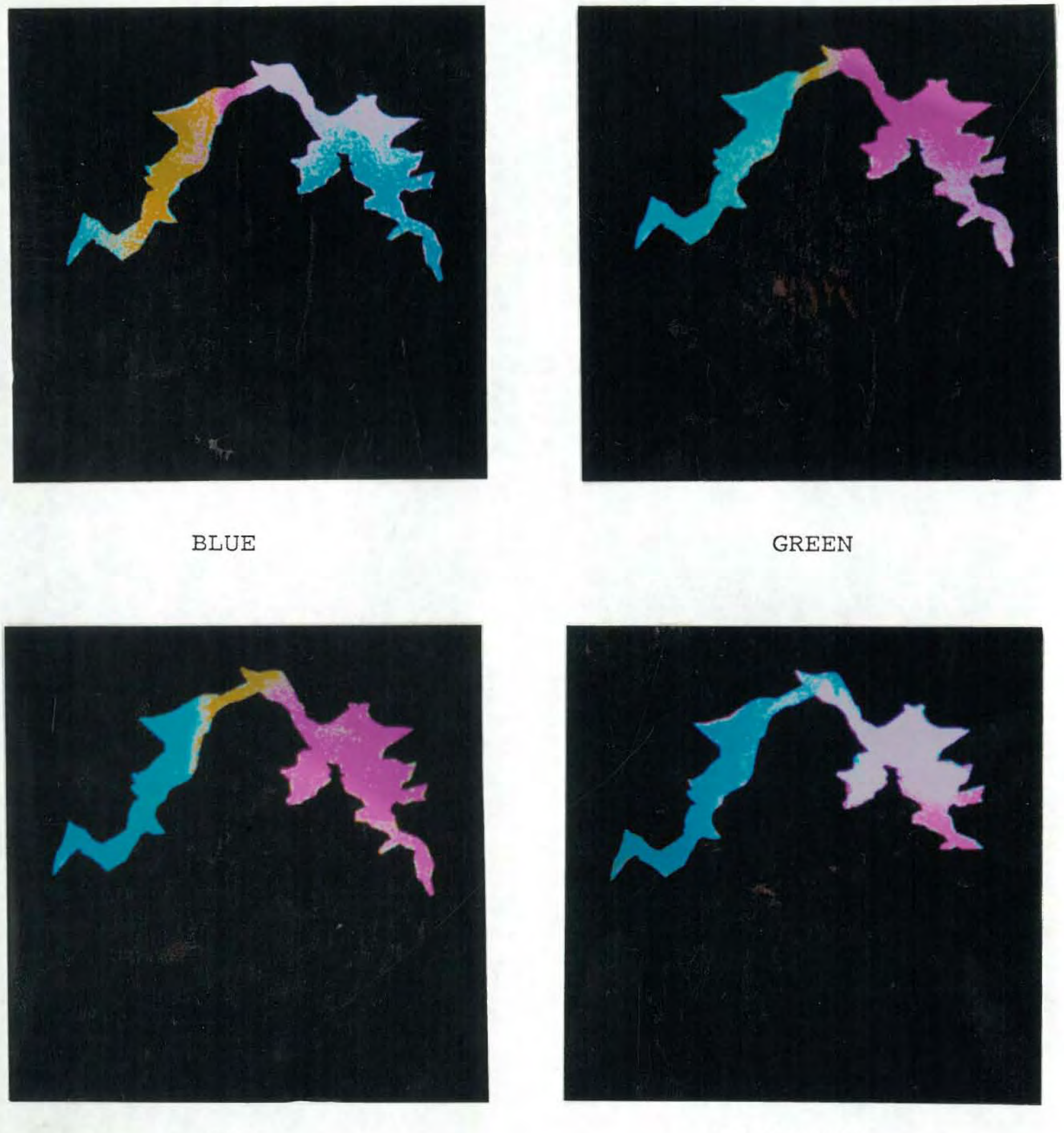


Plate 4.2. The distribution of reflectance (as digital values) for the aerial imagery for the first sampling occasion. (see Plate 4.1 for colour code)

BAND 1

BAND 2

BAND 3

BAND 4

Plate 4.3. The distribution of reflectance (as digital values) for the LANDSAT imagery for the second sampling occasion.

BLUE

GREEN

RED

Plate 4.4. The distribution of reflectance (as digital values) for the aerial imagery for the second sampling occasion. (see Plate 4.1 for colour code)

4.3.3 Radiometric resolutions.

Section 2.3.3 introduces the concept of radiometric resolution as the slope of the digital number to radiance conversion or, more simply, the number of discrete digital value steps for any change in radiance (Fig 2.3). It was not possible to assign a radiance to the digital values of the aerial imagery as a density/exposure curve (dLogE) was not produced for the exposure, aperture and processing method used for this study. However comparison of the range of digital values in each spectral band for each of the pixels sampled, with the range in chlorophyll concentrations, will provide some indication of the radiometric resolution of the sensors.

Boxplots of the digital values in each band for the pixels sampled show that the ranges in reflectance data are wider for the rasterised multispectral aerial photography (Figs 4.6 and 4.7). The aerial data therefore detects the range in chlorophyll in more discrete digital value steps and hence has a higher radiometric resolution. Although the ranges in chlorophyll are higher for the second sampling run, this had little effect on bands 1 and 2 of the LANDSAT imagery, but bands 3 and 4 do show increases in the range of reflectance data (Figs 4.6 and 4.7). This effect is also a result of the algal scums which shift the dominant reflectance wavelengths toward the infrared. As the aerial photographs were taken with different camera systems, the ranges in digital values for the first and second occasions could not be compared.

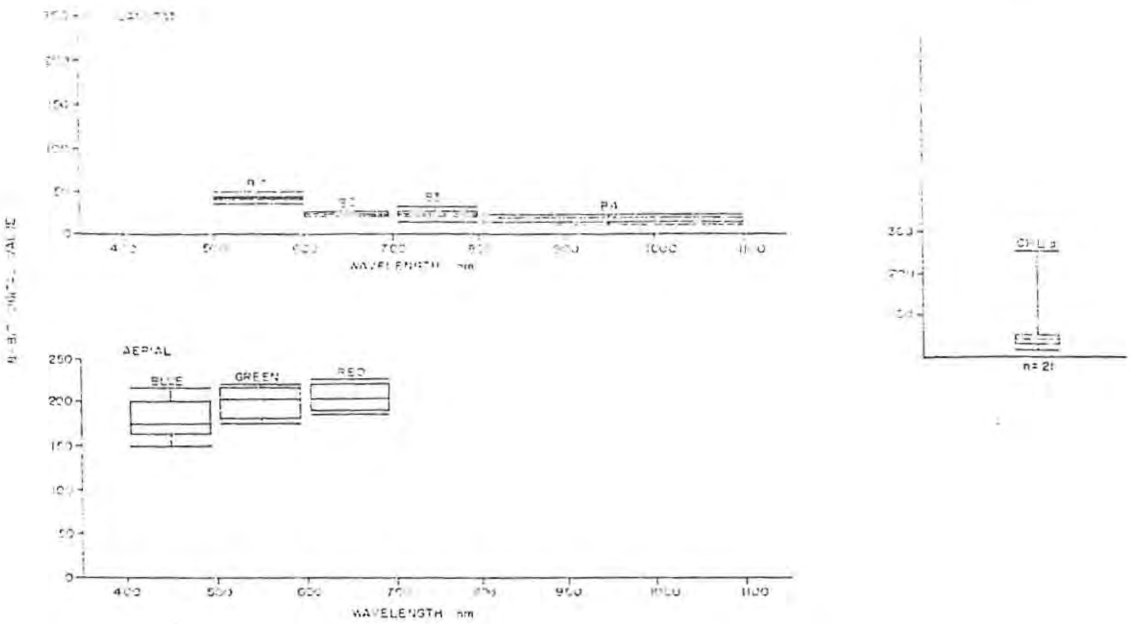


Figure 4.6. The range in digital value data for both the LANDSAT and aerial imagery, associated with the range in chlorophyll concentrations for the points sampled on the first sampling occasion.

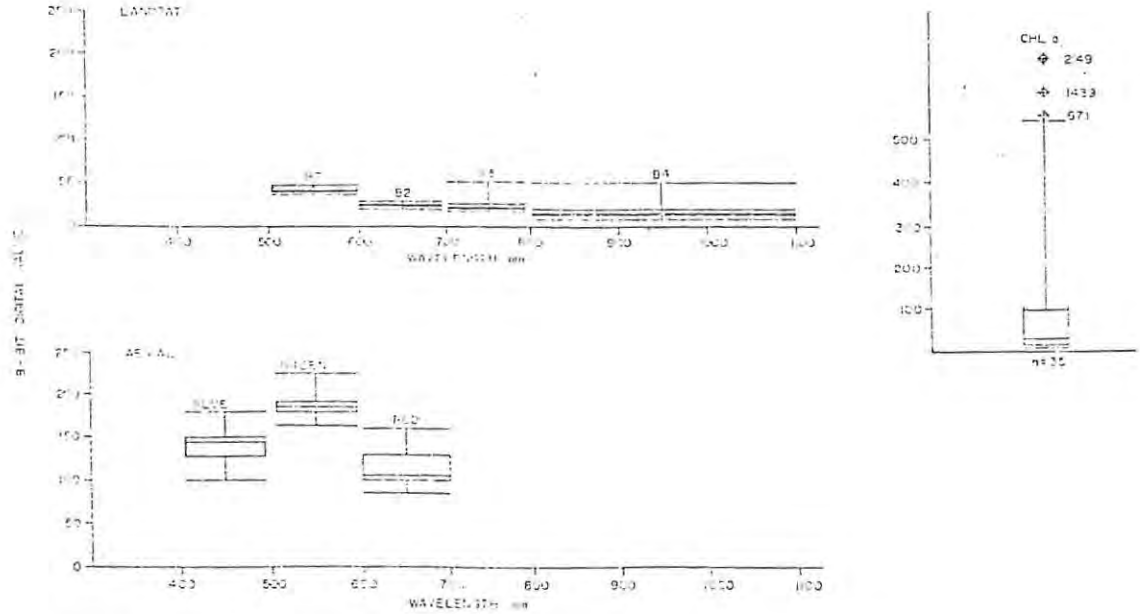


Figure 4.7. The range in digital value data for both the LANDSAT and aerial imagery, associated with the range in chlorophyll concentrations for the points sampled on the second sampling occasion.

4.3.4 Correlation of surface reference and remotely sensed data.

Quantification of the algal concentrations from remotely sensed data by empirical means rests on the strength of the relationship between the contact sensed chlorophyll concentrations, and radiance measured at the sensor (Curran and Novo 1988). In this case the empirical models were recalibrated for each image and atmospheric and sun angle corrections were not necessary. In addition radiometric correction (sensu MacFarlane and Robinson 1984) was not done and raw digital value data were used.

Comparison of the correlation between chlorophyll concentrations and the digital values from the LANDSAT and aerial imagery should therefore provide an indication of the value of the sensors for the quantification of chlorophyll concentrations.

Whitlock, Kuo and Le Croy (1982) stress that the relationship between dependent and independent data sets must be linear and most of the above authors have used logarithmic transforms of the ground truth data to ensure this linearity. In this study, log to the base 10 transforms of the chlorophyll data provided the best correlation with the remotely sensed data and were done as the first step in all the statistical analyses. Whitlock *et al* (1982) also stress that the ground truth data must be representative of the whole range of environmental combinations in the water body and that the dependent data set must be normally distributed. The full range of environmental conditions were sampled by placing the sampling points throughout the water body (Figs 4.4 and 4.5). Normality of the ground truth samples was tested by a combination of Fillibon's test for normality and Grubb's test for outliers as suggested in Howman and Kempster (1986). Normal probability plots were used to provide a visual impression of the distribution of the data (Fig 4.8 and 4.9).

On the first sampling occasion, log chlorophyll values were normally distributed after the exclusion of only one outlier (Fig 4.8), but normality of the second data set provided more of a problem. On this occasion Roodeplaat Dam could be divided into two areas. The western arm characterised by high chlorophyll concentrations and algal scums, and the eastern arm characterised by lower chlorophyll concentrations and no algal scums. Ground truth data also appeared to be binormally distributed (Fig 4.9) on these lines. This required that the samples be divided into two populations to ensure normality for statistical analysis. An unfortunate side effect of this was the reduction in the size of the sample for statistical analysis.

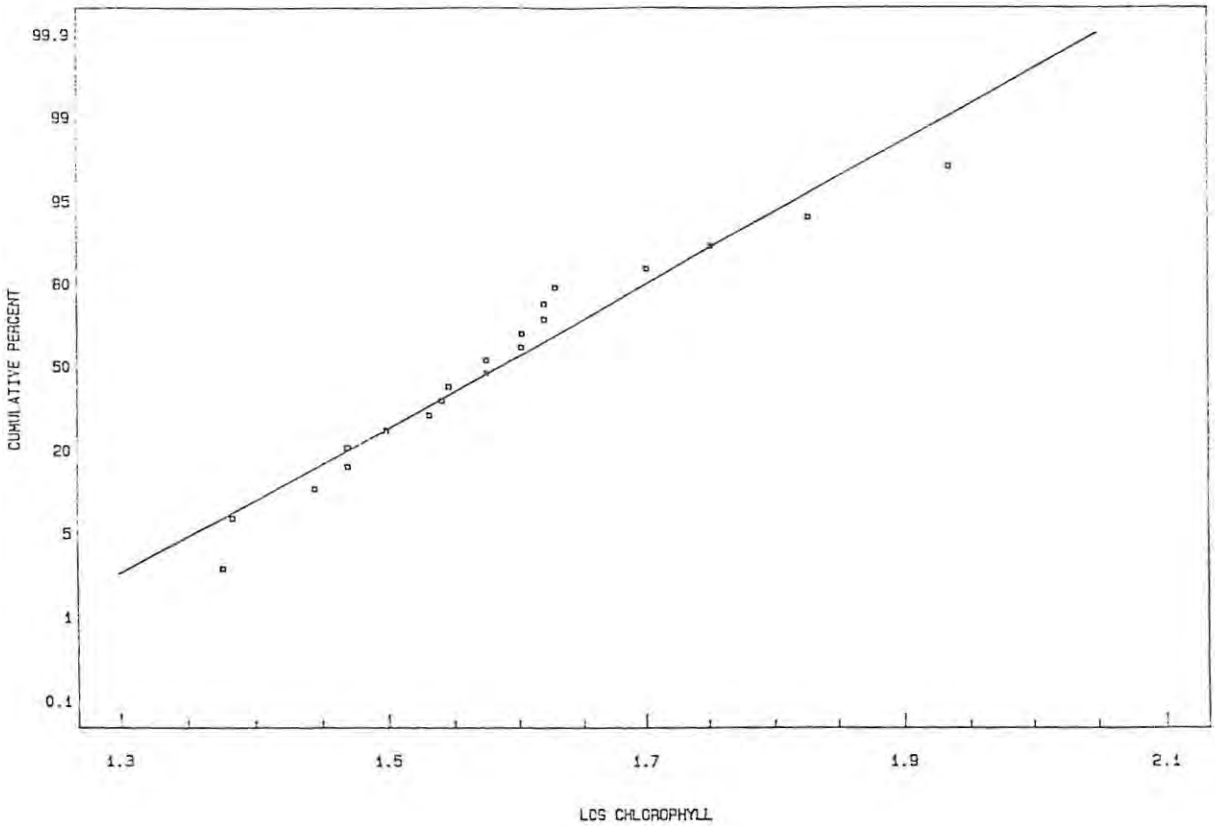


Figure 4.8. A normal distribution plot for the log chlorophyll concentrations on the first sampling occasion, indicating a single statistical population. (outlier excluded)

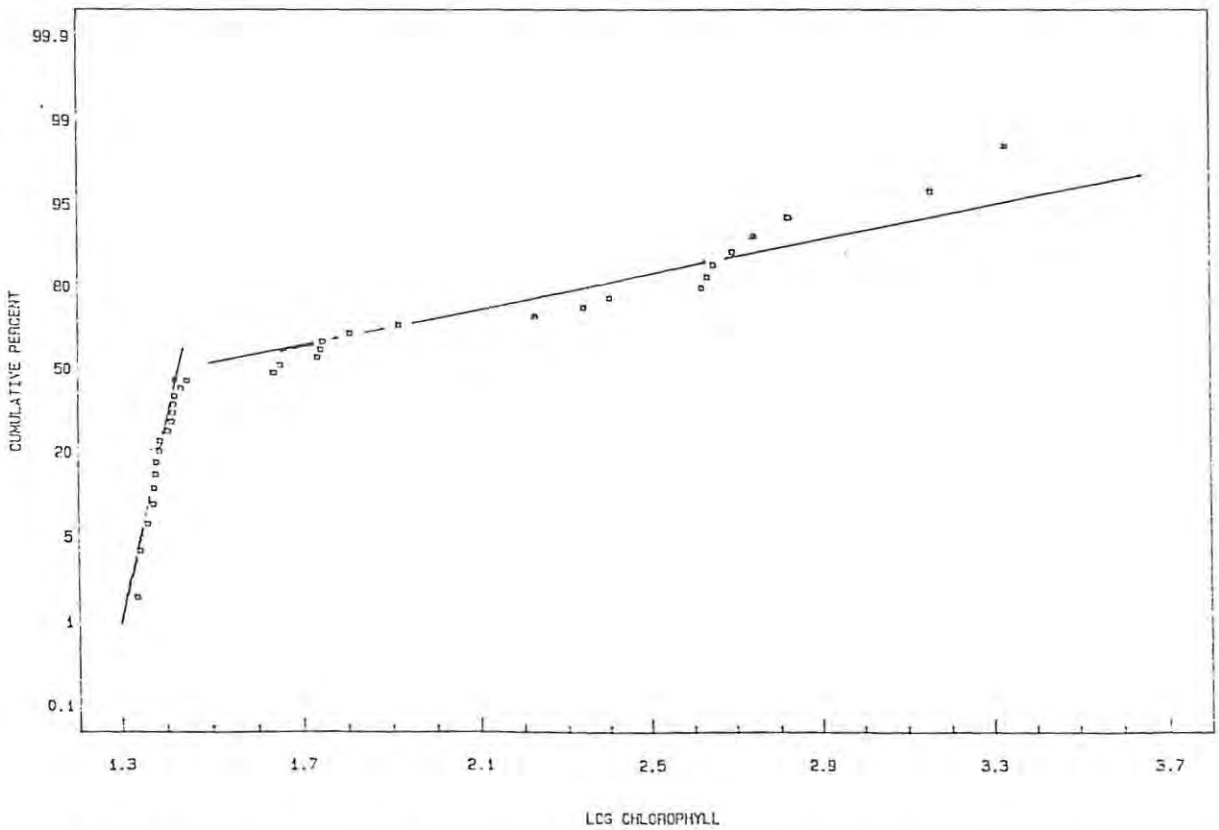


Figure 4.9. A normal distribution plot for the log chlorophyll concentrations on the second sampling occasion, indicating the binormal distribution.

Pearson's correlation matrices show that on the first occasion the LANDSAT MSS data only had significant correlations ($p<0.05$) in bands one and two (Table 4.2). The aerial data, however, showed significant correlations in all three bands. Correlation and significance levels were also much higher for the aerial data (Table 4.2).

Table 4.2 Pearson's correlation matrices for the data of the first flight (n=20). * = significant correlation.

LANDSAT MSS Log Chl	Band 1 0.58*	Band 2 0.54*	Band 3 0.38	Band 4 0.11
MSP Log Chl	Blue 0.78*	Green 0.75*	Red 0.80*	

MSP= Multispectral Photography

On 16/03/89 the sampling points with less than 30µg/l chlorophyll (=1.5 log chlorophyll) did not show significant correlation in any of the spectral bands (Table 4.3). The 16 points included in this group had a narrow range in chlorophyll concentration (22µg/l to 28µg/l). In this case radiance differences will be too small to be detected using terrestrial remote sensing tools, and poor correlations can be expected (see Section 3.4).

Table 4.3 Pearson's correlation matrices for the second flight for chlorophyll concentrations less than 30 µg/l (n=16). No significant correlations were noted.

LANDSAT MSS Log Chl < 1.5	Band 1 0.11	Band 2 0.07	Band 3 0.19	Band 4 0.02
MSP Log Chl < 1.5	Blue -0.05	Green -0.29	Red -0.39	

Ground truth samples with over 30µg/l chlorophyll on the second sampling occasion had significant correlation only in band 3 of the LANDSAT MSS data, but in all three bands of the aerial data. (Table 4.4). The LANDSAT bands with the best correlation to visible chlorophyll therefore shifted from bands 1 and 2 on the first occasion to band 3 on the second. In the previous chapter it was shown that at higher chlorophyll concentrations near infrared reflection shows the best correlation with chlorophyll. These wavelengths are detected by band 3 of the LANDSAT MSS imagery and the red band of the aerial imagery. Band correlations for both the aerial and LANDSAT data are therefore consistent with the scan data presented in the previous chapter.

Table 4.4 Pearson's correlation matrices for the data of the second flight for chlorophyll concentrations greater than 30 µg/l (n=18). * = significant correlation.

LANDSAT MSS Log Chl	Band 1 0.24	Band 2 0.14	Band 3 0.77*	Band 4 0.35
MSP Log Chl	Blue 0.67*	Green 0.72*	Red 0.74*	

Significance of correlation coefficients for the second occasion were lower than those for the first occasion. Galat and Verdin (1989) note that LANDSAT MSS band 3 radiance from algal scums is uniformly high. This they suggest is due to the fact that two scums of equal density, but different thickness will have the same reflectance but different concentrations of chlorophyll. This is possibly the cause of the poorer correlations seen on the second occasion. The asymptotic nature of the radiance to chlorophyll relationship descibed by Galat and Verdin (1989) will also make it difficult to quantify differences in algal density in algal scums.

4.3.5 Simulating chlorophyll concentrations.

Most authors who simulate chlorophyll concentrations from remotely sensed data have used linear multiple regression to develop empirical models (Aranuvachapun and Walling 1988, Carpenter and Carpenter 1983, Grimshaw *et al* 1980, Grunwald *et al* 1988, Huang and Lulla 1986, Lathrop and Lillesand 1986, Lindell 1981, Lyon *et al* 1988, Mace 1983, Munday *et al* 1980, Ritchie *et al* 1987, Scarpace *et al* 1979, Stumpf and Tyler 1988, and Verdin 1985). These linear multiple regressions normally take the form of;

$$\log Chl = k + a\, L_{\delta i} + b\, L_{\delta ii} + \ldots + n\, L_{\delta n} \qquad \text{Eq 4.1}$$

where Chl = chlorophyll concentration
k is a constant
$L_{\delta i-n}$ are the radiance or digital value outputs in each band.

Other authors have recognised the multicollinearity of the remotely sensed data and use more complex empirical procedures to compensate for this. Shih and Gervin (1980) use ridge regression techniques which reduced the mean square error of model simulations by 13-20 percent. Carpenter and Carpenter (1983) suggest the use of the canonical correlation procedure which was later applied by Howman and Kempster (1986) in the model CALMCAT. The canonical procedure is based on the covariance of linear combinations of dependent variables with a linear combinations of independent variables (Hotelling 1936). The model CALMCAT involves correlating linear combinations of water quality variables to linear combinations of the LANDSAT MSS spectral bands. In this study, the CALMCAT model was compared to linear multiple regression models which use the ordinary least squares approach.

In addition to the requirements of linearity and normality, Whitlock *et al* (1982) also emphasise the importance of Daniel and Wood's (1971) criteria for regression analysis. Daniel and Wood (1971) state that the variance in independent data used in the regression should be at least ten times the variance caused by data noise. In this case, variance in each spectral band should be ten times the data noise for that sensor. Noise in remotely sensed images can be esitmated by assessing the variation in digital values over a large area of known uniform reflectance. However, as no large area of uniform reflectance occurs in the Roodeplaat Dam area, it was difficult to estimate the data noise for this study. Therefore, no absolute measure of whether Daniel and Wood's (1971) criterion was met, was possible. Table 4.5 shows that the variance in the digital values for the aerial photography is larger than that for the LANDSAT data and aerial photography is therefore better able to tolerate noise. The total variance for the LANDSAT data is very low (Table 4.5) and is unlikely to satisfy Daniel and Wood's (1971) criterion. The variance in the remotely sensed data set is directly linked to the range in digital values and is hence also a function of the radiometric resolution of the sensors.

LANDSAT 4 has a higher radiometric resolution (Table 2.2). This explains the better performance of CALMCAT model reported by Howman and Kempster (1986) when calibrated on LANDSAT 4 data. Authors using LANDSAT thematic mapper imagery report more accurate simulation of chlorophyll concentrations (Lathrop and Lillesand 1986). This is most likely due to the improved radiometric resolution of this satellite.

Table 4.5 Variance in the digital value data in each band of the sensor systems. Variance is calculated as the square of standard deviation.

First flight				
LANDSAT	Band 1 9.1	Band 2 3.7	Band 3 16.6	Band 4 18.7
MSP	Blue 399.9	Green 307.4	Red 197.6	
Second fight				
LANDSAT	Band 1 5.5	Band 2 2.3	Band 3 50.9	Band 4 42.3
MSP	Blue 207.4	Green 299.2	Red 153.3	

Linear correlation of the digital value of each band to log chlorophyll in this case also makes several assumptions. As no pixel by pixel correction for the effects of the atmosphere was used, the first assumption is that the effect of the atmosphere was constant over the whole scene. In the case of Roodeplaat Dam the area of interest is small (5km x 5km) and this assumption is likely to hold. The second major assumption, is that algae played the dominant role in the radiance reflected out of the water. The majority of the sampling points were positioned away from the inflows to avoid the problems caused by suspended sediment reflection. Furthermore, as digital values and not radiance was used, the model calibrations are date and sensor specific.

In order to provide a means of testing the accuracy of the models, each data set was divided into a calibration and a validation set. The choice of the sampling points used in the calibration was made using the procedure recommended in Howman and Kempster (1986). This procedure, based on the normal distribution of the data, ensures a representative calibration set. The validation set was used to assess the accuracy of the model. In each case ten points were chosen to calibrate the model. The validation sets were therefore ten points for the first sampling occasion and eight for the second. Whitlock *et al* (1982) suggest the F-test as the most reliable way of assessinf model accuracy. In this study model performance was assessed by the F-test between the observed and simulated chlorophyll . Synoptic views of the simulated chlorophyll for the whole water body were produced by applying the model to each pixel in the images.

Mean differences between the observed and simulated data show that the aerial data produced only marginally better simulations than the LANDSAT data (Tables 4.6 and 4.7). On the first sampling occasion the least squares linear regression produced better results than the CALMCAT model. F-tests show that only the least squares method when applied to the aerial data produced significant ($p<0.05$) F-values. Model simulations for the second occasion were very inaccurate at some points (Table 4.7).

The greatest inaccuracies were noted for the high chlorophyll concentrations and are possibly due to the asymptotic nature of the radiance to chlorophyll relationship (Galat and Verdin 1989). These authors also show non-significant regressions for lakes with scum development.

Table 4.6 Model simulation accuracies for the multiple linear regression and canonical procedures for the first flight.

Multiple linear regression

			MSS			
	Max	Min	Mean	R^2	F-ratio	p-level
Errors	30	< 1	7.4	0.56	1.6	0.31
%	51	1	19.5			
			MSP			
	Max	Min	Mean	R^2	F-ratio	p-level
Errors	19	<1	7.3	0.85	11.1	0.01
%	45	1	17.3			

Canonical

			MSS			
	Max	Min	Mean	R^2	F-ratio	p-level
Errors	48	1	12.0	*	3.5	0.40
%	54	4	31			
			MSP			
	Max	Min	Mean	R^2	F-ratio	p-level
Errors	29	1	9.0	*	5.5	0.32
%	50	4	22			

* See Table 4.8

Table 4.7 Model simulation accuracies for the multiple linear regression for the second flight

Multiple linear regression

			MSS			
	Max	Min	Mean	R^2	F-ratio	p-level
Errors	30	< 1	7.4	0.56	1.6	0.31
%	51	1	19.5			
			MSP			
	Max	Min	Mean	R^2	F-ratio	p-level
Errors	19	<1	7.3	0.85	11.1	0.01
%	45	1	17.3			

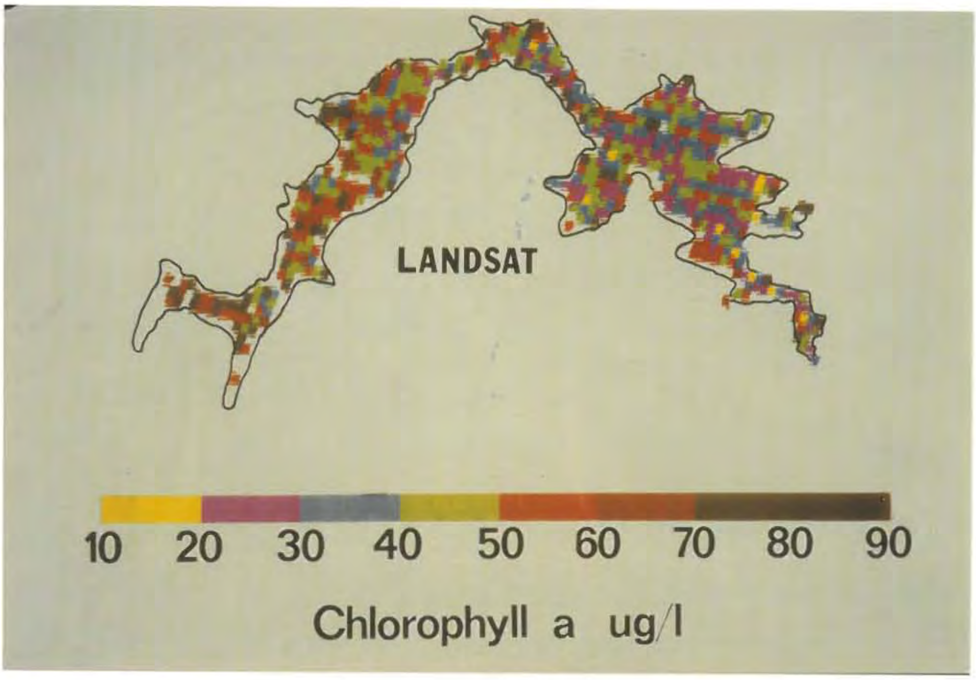
Table 4.8 Canonical correlations for paired combinations of the surface reference data.

Combination	LANDSAT	MSP
S.Chl-S.Turb	0.84	0.97
S.Chl-I.Chl	0.75	0.89
S.Turb-I.Turb	0.78	0.91
I.Chl-I.Turb	0.91	0.97

S. Chl= Surface chlorophyll
I. Chl= Integrated chlorophyll
S. Turb= Surface turbidity
I. Turb= Integrated turbidity

Although the model simulations for both the aerial and LANDSAT imagery are similar, the synoptic views produced by the image data are very different. Plates 4.5 and 4.6 show that the LANDSAT data produces very patchy distributions of simulated chlorophyll, whereas the aerial images give a more even distribution.
The patchiness of the LANDSAT produced chlorophyll distribution (Plate 4.5) suggests that the LANDSAT data was noisy when compared to the low variance in the radiance data, and that Daniel and Wood's (1971) criterion was not met.

Pixel averaging has often been used as a means of reducing data noise (Whitlock *et al* 1982). However, as the synoptic views are most affected by noise, pixel averaging would have to be done on the entire image and not just on those pixels in which ground truth samples were taken. In the case of small, spatially heterogenous impoundments, pixel averaging increases the risk of the radiance not being representative of the average chlorophyll conditions in that pixel.



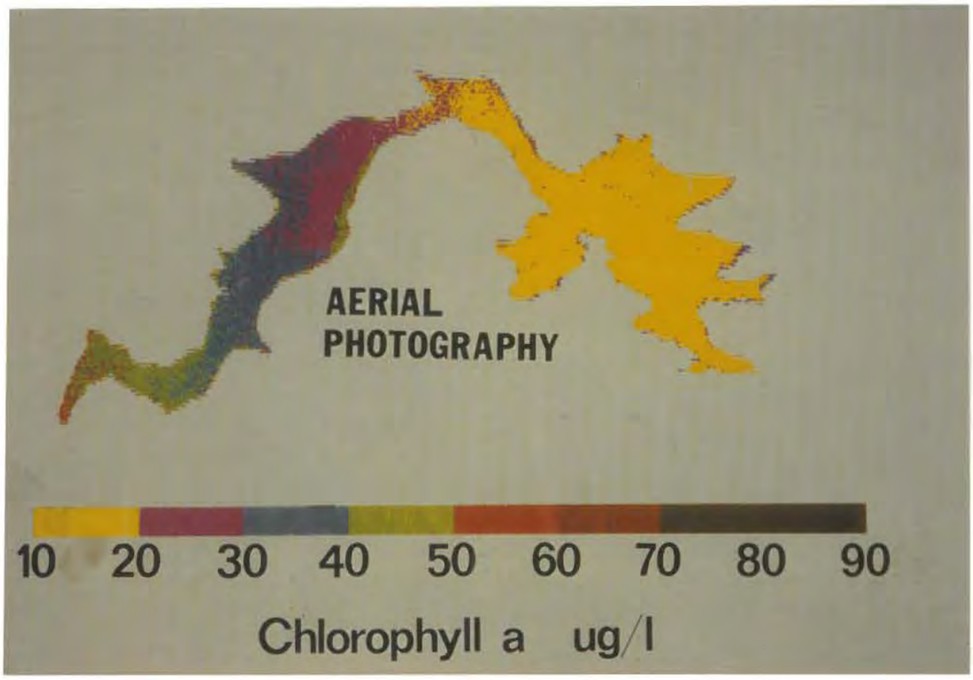


Plate 4.5. Synoptic views of simulated chlorophyll distributions for the LANDSAT and aerial imagery. Chlorophyll concentration was simulated using data from the first occasion and the CALMCAT model.

4.4 Conclusions

Although *Microcystis sp.* dominated the algal population on both occasions, the second sampling occasion differed in that the chlorophyll concentrations were much higher and algal scums occurred in the western arm of Roodeplaat Dam. The effect of these scums was to shift the wavelengths which would show the greatest range in data from blue and green wavelengths, to the red and infrared wavelengths. This also resulted in a shift in the bands which showed the highest correlation to chlorophyll values from the one overpass to the next. These shifts make it difficult to develop a single multidate algorithm which can be extrapolated from one date to the next.

The splitting of the dependent data set on the second occasion created one set with very little variance in chlorophyll concentrations. In this case correlation coefficients for the chlorophyll to digital value relationship was low for both the aerial and satellite data. This was most likely due to the fact that the radiometric resolution of both sensor systems was insufficient to detect small differences in radiance. This implies that a wide range in chlorophyll concentration is important to calibrate empirical models.

The spectral bands produced by the standard filter options on the Optronix colorscan, as well those of the LANDSAT MSS imagery, are too broad to separate the peaks and troughs in reflectance from algae. This means that part of the green reflectance from algae was detected in the blue spectral band, and part of the infrared peak is detected in the red band. Subtraction or ratios of spectral bands would not therefore have enhanced the information content of the remotely sensed data.

Correlation of digital values to chlorophyll concentrations are positive in all the spectral bands and empirical models have to be based only on increased reflectance with increasing chlorophyll concentration in all the bands. This was also to be expected as *Microcystis sp.* dominated the algal population throughout the impoundment on both occasions

Ranges in digital values for the LANDSAT MSS data were much lower than those for the aerial data for the same range in chlorophyll concentration. This means that the aerial imagery has a higher radiometric resolution than does the LANDSAT MSS imagery and should not only produce more accurate simulations of visible chlorophyll, but should also be more able to detect smaller changes in chlorophyll concentration. Furthermore, the poorer radiometric resolution of the LANDSAT MSS sensors resulted in a very small variance for the independent radiance data. This reduces the possibility of meeting Daniels and Wood's (1971) criterion.

Unfortunately, due to the small sample size, results of the statistical analysis of the data are necessarily tentative. However the aerial imagery shows better correlation with chlorophyll concentrations. Simulation of chlorophyll concentrations for the test set, also shows that the aerial data produces more accurate simulations. Inaccurate simulation of chlorophyll from the satellite data will be caused by one or more of the following;

- Non-homogenous atmospheric effects
- Suspended sediments in some samples.
- Samples not representative of the whole pixel.
- Daniel and Woods (1971) criterion not being met.
- Hysteresis of the scan data.

If the assumption of homogenous atmosphere over the 5km x 5km area holds, and sediments were present in only a few of the samples, then poor model performance for the LANDSAT data was either due to the larger pixels, the smaller variance, or the hysteresis in the LANDSAT bands. Hysteresis is caused by signal undershoot as the scan passes over the sharp interface between land and water (Tassan 1988). As Roodeplaat Dam is a narrow linear impoundment, hysteresis can affect a relatively large number of pixels.

In spite of the similar simulation accuracies of the aerial and satellite imagery, the synoptic views of chlorophyll distribution produced were very different. Chlorophyll maps produced from the LANDSAT imagery are very patchy. This suggests that, due to the low variance in the satellite data, Daniel and Wood's criterion was not met. If the aerial image of chlorophyll distribution is accepted as more accurate, then the differences between the images suggests that, in this case, the LANDSAT MSS data was inadequate to accurately quantify chlorophyll concentrations. Low variance is a direct result of the poor radiometric resolution of the LANDSAT MSS sensors. Radiometric resolution is therefore one of the most important criteria for the accurate use of remote sensing to monitor chlorophyll concentrations in inland waters.

This appears to contradict the extensive use of LANDSAT MSS imagery in the northern hemisphere. However, in the clearer waters typical of the northern hemishere, smaller differences in algal concentration produce larger changes in radiance due to the greater remote sensing depth (see section 3.3). Although LANDSAT thematic mapper imagery was not included in the comparison, its improved radiometric resolution would make it a better choice than LANDSAT MSS. LANDSAT TM imagery is currently being more extensively used by overseas workers. LANDSAT TM imagery is however as expensive as aerial photography of a single water body (unless it is very large) and is still restricted to fixed overpass dates.

The model CALMCAT produced poorer model simulations than did ordinary least squares multiple regression. This was possibly due to inadequate sampling of all the combinations of dependent data. If all the combinations of dependent data were to be sampled, the calibration data set would have to be much larger. If no atmospheric or sensor to sensor corrections are made, a model has to be recalibrated each time it is used and a large calibration set negates, to some extent, the need for a remotely sensed synoptic view. CALMCAT makes no provision for atmospheric or sensor differences, therefore, unless it produces much better results than the ordinary least squares approach, its value is limited.

CHAPTER FIVE

FEASIBILITY OF ROUTINE REMOTE SENSING OF ALGAE IN SOUTH AFRICA

5.1 Background

Eutrophication and consequent excessive growth of algae is one of the most important water quality problems in South Africa, and monitoring of chlorophyll concentrations in our inland waters is a essential part of national water quality surveillance. Routine monitoring of chlorophyll concentrations is also an essential part of appraising the efficacy of eutrophication management options.

Satellite remote sensing offers several advantages for the monitoring of chlorophyll in inland water bodies in South Africa;

- Satellite imagery can provide synoptic views of the chlorophyll distribution throughout the water body, and as such will eliminate the inaccuracies associated with single point samples.
- Chlorophyll concentrations can be simulated without the need of costly field surveys.
- Each satellite system covers a large area which may include several impoundments.
- The fixed orbit of the satellite allows repetitive imaging (albeit on a 16 day cycle).
- Satellite imagery purchased for a national land cover inventory could be used, thus spreading the cost of the imagery over several projects.

The real value of remote sensing therefore lies in the ability to accurately quantify chlorophyll concentrations in the water body without the need of costly ground truth sampling. This requires a single (or series of) multidate algorithms which can be applied to the satellite data without the need of recalibration. This study has highlighted some potential obstacles for the development of such multidate algorithms. These are discussed below.

5.2 Atmospheric correction

It has been suggested that 80-90% of the radiance detected at a sensor over water is contributed by scattering in the atmosphere. Correction for these effects is essential to produce a single multidate algorithm which can quantify algal populations without the need for recalibration.

The most suitable atmospheric correction models are those based on radiative transfer theory, and several examples are available in the literature. Calculation of Rayleigh scattering in these models is based on known optical thickness calculations which are generally constant. However, calculation of Mie scattering, essential in impoundments near urban and industrial centres (which includes most of the important water bodies), must be based on site specific data. This is normally done by assuming zero water leaving radiance in the infrared wavelengths. While this may be true for oceanic waters, it is not necessarily the case for inland waters with high sediment or algal concentrations.

Reflectance scans measured just above the water surface of the eutrophic Roodeplaat Dam (section 3.5) show that at high chlorophyll concentrations (over 50µg/l) some infrared reflectance is detectable above the water surface. This reflectance is positively to chlorophyll concentrations, and the assumption of zero radiance in these wavelengths in atmospheric correction will therefore remove some of the variability caused by the differences in algal density.

The improved dark pixel subtraction method (Chavez 1988), based on cloud and topographic shadows and not water pixels is therefore the most practical technique for South African waters. This requires that cloud or topographical shadows will be present in each scene, which will not necessarily be the case.

5.3 Sensing geometry

Changes in sensing geometry have been shown to influence strength of radiance/chlorophyll relationship. This is due to the angular anisotrophy in reflectance from subsurface scattering, and is also likely to be true of the chlorophyll/reflectance relationship.

This means that the chlorophyll/reflectance relationship will vary according to the angle at which the pixel is viewed, and the angle of illumination. This can be important when the viewing angle varies considerably across the scene, which is particularly true for aircraft borne sensors. Care to correct for this bidirectional distribution function would have to be taken. No literature was available describing the form this correction should take for algal studies.

Solar elevation angles of between 40° and 50° was shown to be the most suitable for remote sensing studies. Satellites are tied to fixed overpass times, and this limits the months of the year which will be ideally suited for algal studies (see Fig. 2.2).

5.4 The depth of remote sensing penetration

Knowledge of the depth of remote sensing penetration at any point is important to assess which particles contribute to the total signal measured above the water surface. Only those particles above the maximum depth of penetration can contribute significantly to the upwelling signal. In clearer waters with a greater remote sensing penetration, relatively more algae can contribute to the upwelling signal, and algorithms developed on clear water impoundments may not be applicable to turbid waters.

As yet, no field method of measuring this depth is feasible, and correction for the differing remote sensing penetration is therefore impractical.

5.5 Reflectance from different algal species

Studies of the reflectance from commonly occurring algal species have shown that spectral signatures of different species are very similar, differences in species dominance are unlikely to be detectable from the remotely sensed scene. However the scattering coefficients of the Phyla investigated differed. This appeared to be due to the colonial nature of the examples of the Phylum Cyanophyta used. This means that the chlorophyll radiance relationship can differ between the species, and within any species with changes in the colonial nature of the cells. Separate would therefore have to be developed for each species, and for each combination of species, for cases where no one alga dominates the population. The species composition of the impoundments at the time of remote sensing would therefore have to be known, which will necessitate ground truth sampling.

5.6 The effect of suspended sediments

Addition of sediments to pure cultures of algae altered and increased the reflectance spectrum from algae. These increases appeared to have an equal additive effect on wavelengths longer than 650nm. This suggests that subtraction of reflectance at ≈665nm from that at 700-720nm may provide a means of compensating for reflectance from sediments. However, no available sensor systems offer narrow spectral bands centred at these wavelengths, and correction for the effects of suspended sediments using available sensor systems is therefore unrealistic.

5.7 Comparison of different sensor systems

Rasterised multispectral aerial photography (MSP) was introduced as an alternative to LANDSAT MSS imagery for quantifying chlorophyll concentrations in inland waters. MSP had a higher radiometric sensitivity than the LANDSAT MSS sensors. The photography, therefore, provided more information on the spatial distribution of radiance over Roodeplaat Dam.

Correlation of the digital value output in each band with the chlorophyll concentrations was also higher for the aerial data. The correlations in each band were consistent with the reflectance scan data collected at ground level. At lower chlorophyll concentrations bands in the green region show the highest correlation, but when large numbers of cells occurred in the upper layer of water, the near infrared bands had the highest correlation.

The MSP spectral bands had a larger variance in digital values, and are, therefore, more likely to satisfy Daniel and Wood's (1971) criterion for regression analysis. In this study the variance in the LANDSAT MSS digital values was very low, and synoptic views of chlorophyll distribution were very patchy. This suggests that for the satellite data Daniel and Wood's (1971(criterion was not met. LANDSAT MSS imagery is currently the cheapest form of satellite imagery available, but in this case this imagery was not suitable for the production of accurate synoptic views of chlorophyll distribution.

The differences in the performance of the LANDSAT and aerial imagery are directly related to the poorer radiometric resolution of the LANDSAT MSS sensors. When radiometric resolution is low, the radiance scattered out of eutrophic water bodies is contained in a small number of discrete digital value steps and only gross differences in chlorophyll concentration can be detected. In turbid waters more light is scattered out of the water and LANDSAT MSS images can produce better distributions of suspended sediment concentrations.

High radiometric resolution appears to be the most important criterion for accurate remote sensing of chlorophyll concentration in inland waters. The choice of empirical procedure is of secondary importance and the principle of garbage in garbage out holds. High spectral resolution (many narrow spectral bands) will also improve the ability of a sensor system to resolve the reflectance peaks and troughs from algae, and will hence provide a better quality of data.

The most important advantage of rasterised aerial photography is the higher radiometric resolution, but several other benefits are offered by aerial photography :

- temporal flexibility, photographs can be taken whenever there are clear skies and are not dependent on fixed overpass dates.
- spatial flexibility, pixel sizes can be adjusted to suit the user's requirements.
- a shorter atmospheric path, which reduces the contributions of the atmosphere to the signal detected.
- improved spectral resolution. New filter options can be used in the rasterisation step to produce narrow, better placed spectral bands.

The disadvantage of aerial photography is the smaller area on the ground which is covered by each photograph. This increases the cost of photographing many impoundments which is necessary for routine monitoring. Aerial data also requires increased processing time to produce a single image of the water surface. The MSP digital values cannot be quantified in terms of radiance without a dLogE curve, which must be produced for each film type and exposure used. This means that temporal extrapolation of algorithms is only possible if these curves are produced. Aerial photography is therefore not suited to the routine monitoring of algae in inland systems.

5.8 Future work

As the real value of remote sensing of chlorophyll concentrations lies in the development of a (or several) multidate algorithms, further work should concentrate on the factors, mentioned above, which presently prevent this development.

This study indicated that no clear relationship was evident between Secchi depths and that depth above which 90% of the upwelling light originates. However this conclusion was based on relatively few scans (12) . More intensive studies may indicate that, in any given spectral band, the depth of remote sensing penetration can be estimated from the Secchi depth. This will allow correction for the differing depths of remote sensing penetration.

The work presented in section 3.3 and 3.5 was based primarily on spectral signatures of samples placed in a container. Although the container was painted black on the bottom and white on the sides to approximate the light conditions in a natural water body, container effects could not be ruled out. The spectra were therefore only qualitatively analysed. Unfortunately logistic considerations prevented the use of larger containers, but larger containers would have allowed the quantitative analysis of the results. This will provide a means of testing the viability of subtracting reflectance at 665nm from that at 700nm as a means of correcting for the suspended sediment present. This same method could have been tested by taking scans on Roodeplaat Dam where suspended sediment can influence the upwelling signal. A larger sample container would also have allowed the testing of ratios of wavelengths as a means of improving the reflectance/chlorophyll correlation for different species. Furthermore, some indication of the variation about the scan lines will allow a more quantitative approach to the problem.

The effect of intrinsic water colours (other than gelbstoff) was not addressed in this thesis. In inland systems where high organic loads can be expected, water colour may prove to contribute significantly to upwelling signal.

This study represented the first attempt at simulating chlorophyll concentrations from rasterised aerial photography. The value of this method was limited as no dLogE curves were produced to quantify the radiance detected by the aerial film. Production of dLogE curves should be included in future work. The possibility of standard reflectance pixels to correct for scene to scene differences should also be investigated.
Although attempts were made to approximate nadir viewing in the aerial images by only using the centre part of each photograph, some view angle differences must have occurred. This necessitated the assumption that subsurface scatter was equal in all directions. This is not consistent with some findings in the literature. The problem of the bidirectional reflectance distribution from algae needs to be investigated in more depth.

The technique used to produce a single image of the whole impoundment was simplistic. Subtraction of the digital values in adjacent photographs requires that the differences between corresponding pixels in the overlapping area were linear. This was never tested. This could have been done by deriving the statistical relationship between corresponding pixels in adjacent photographs.

5.9 Conclusions.

Routine monitoring of algal concentrations in inland waters in South Africa necessitates a single (or several) multidate algorithms which can be extrapolated to new dates without the need of recalibration. These multidate algorithms for algae do not seem to be attainable at the current state of our knowledge, and the problems mentioned above would have to be addressed.

Quantification of chlorophyll concentrations using remotely sensed data is certainly feasible (if sensors have acceptable radiometric resolution) provided that the algorithms are recalibrated for each study. However, recalibration of the model would require a large data set covering all conditions in the water body, and the value of the synoptic view would have to be weighed against the information that is available from the contact sensed data.

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APPENDIX A.

Production of a single raster image of Roodeplaat Dam.

One of the most important disadvantages of aerial photography is the small area covered by a single photograph. This is further exacerbated by the need to use only the area in the centre of the photograph to ensure near nadir viewing. This means that the water surface of most water bodies will have to be covered by several separate photographs.

As the relative amounts of land and water will differ between the photographs, the amount of light energy detected at the camera will be different for each image and the colour density of the transparencies will also change. This will be particularly evident in camera systems where the exposure setting is adjusted for each frame. This requires that some technique to standardise the colour densities of the transparencies, at least for any particular occasion, must be developed. This is possibly the greatest drawback in the use of rasterised multispectral aerial photography to quantify water quality conditions.

Standardisation of the colour densities of the transparencies for Roodeplaat Dam in this study was achieved by assuming that adjacent photographs were uniformly brighter or darker i.e. the relationship between corresponding pixels in adjacent images will be linear. This means that mean difference in density of the overlapping areas from adjacent photographs could be used to standardise the separate images.

This was done by choosing the centre photograph of the mosaic of the whole water, as a standard. The photographs were taken with a high degree of overlap and large areas were common to adjacent photographs. The first step was to write the center standard image to an output space large enough to contain an image of the whole water surface. The adjacent photograph was then registered to the standard such that the two could be merged. This was done by selecting objects common to both images (eg buildings, boats and rafts). The spatial relationship of these points could then be used to twist the adjacent image to fit the standard using the normal warping algorithms used to geocorrect satellite imagery to fit map projections. The two images would then have the same pixel line and sample numbers for any pixel in the area of overlap. As all the photographs were taken at the same height and as near to vertical as possible, this procedure was a simple rotation about an axis and warping accuracies were therefore very high (normally within $1m^2$).

Once the images had been registered to one another, the area of water common to both images was extracted from both images using a region of interest procedure. The water area from the adjacent photograph was then subtracted from that of the standard. A statistical analysis of the resultant "difference" image provided the mean difference in optical density (as a digital value) between the standard and the adjacent transparency. The mean difference was then added to all the pixels in the adjacent image and the images were then merged. The procedure was then repeated for the next image. A typical example of the difference statistics is presented in Table A.1. This table indicates that the standard deviation of the difference between adjacent images was small which suggests that the assumption of linearity, at least for the small range in digital values over the common areas, was valid.

Although this is a crude procedure the visual differences between the images were not noticeable after standardisation. This method could be improved by statistically finding the relationship between the common pixels in adjacent images.

Table A.1 An example of the differences in digital number of corresponding pixels of adjacent photographs. (n=262144)

Difference	Blue	Green	Red
Maximum	104	105	99
Minimum	59	29	50
Mean*	81	61	73
Stand. Dev	5.5	6.3	6.3

* mean difference was added to the adjacent image to eliminate differences in brightness.

APPENDIX B.

Surface reference and associated digital value data for the LANDSAT and aerial imagery.

Table B.1. Data for the first sampling occasion (5 October 1987).

						LANDSAT				AERIAL		
Pt	Chls	Chli	NTUs	NTUi	Secc	B1	B2	B3	B4	blue	green	red
1	71.6	54.4	13.0	9.4	50	46	26	24	16	214	216	227
2	60.6	50.3	9.0	7.5	57	43	25	21	11	199	217	219
3	169	49.8	7.8	5.6	53	45	27	30	12	207	217	220
4	96.1	121	6.5	8.0	60	43	25	21	11	199	217	219
5	58.1	57.7	5.4	5.9	80	49	26	20	10	201	217	220
6	44.1	48.7	5.1	5.0	65	40	27	32	26	200	210	218
7	45.1	53.3	4.8	5.4	70	43	25	21	22	200	216	210
8	44.4	51.8	5.0	5.0	60	42	25	18	10	192	212	211
9	46.0	50.1	4.5	5.4	80	45	26	18	10	194	217	210
10	37.4	45.6	3.6	4.2	90	45	26	20	15	186	203	204
11	39.8	45.7	4.0	4.0	105	44	24	19	10	174	199	196
12	38.3	42.4	6.0	4.2	95	42	25	15	15	166	189	189
13	26.1	43.9	3.0	4.0	100	40	24	19	10	164	183	190
14	45.0	42.2	3.1	3.5	115	42	22	18	10	166	183	189
15	34.1	46.0	2.5	3.2	120	42	22	18	10	158	181	191
16	26.2	44.5	2.6	3.5	125	39	22	17	12	159	181	189
17	30.1	49.1	2.6	2.9	120	37	21	19	10	158	174	190
18	32.5	46.0	2.5	3.0	160	38	22	18	15	150	175	189
19	41.5	43.0	2.5	2.8	150	42	23	20	15	159	174	188
20	31.5	42.2	3.1	3.1	130	42	23	18	10	167	180	188
21	38.3	46.6	4.0	3.6	120	37	21	17	10	167	183	191

Table B.2 . Data for the second sampling occasion (16 March 1989).

						LANDSAT				AERIAL		
Pt	Chls	Chli	NTUs	NTUi	Secc	B1	B2	B3	B4	blue	green	red
1	28.0		8.0		120	39	25	25	16	134	169	87
2	43.3		11.0		125	37	24	19	18	142	178	90
3	23.9		12.0		175	37	25	21	19	147	186	100
4	22.0		9.0		140	39	26	18	12	151	193	110
5	22.8		10.0		140	39	25	17	13	158	194	104
6	27.1		8.0		135	40	26	21	13	150	187	97
7	25.4		12.0		150	40	26	18	12	157	195	105
8	24.2		11.0		130	39	26	18	13	159	197	107
9	21.6		11.0		145	40	26	19	12	152	187	100
10	26.1		11.0		130	42	28	17	10	153	195	105
11	55.3	22.1	16.0	12.0	120	40	26	18	13	120	180	105
12	26.2	26.4	12.0	12.0	135	42	28	17	12	147	186	103
13	25.9	26.5	20.0	12.0	120	42	28	17	13	147	194	101
14	24.4	25.2	14.0	12.0	130	42	26	18	11	147	189	103
15	23.6	24.9	11.0	10.0	120	43	28	21	16	103	187	100
16	23.5	26.4	11.0	11.0	100	40	26	21	13	136	180	103
17	26.3	24.6	11.0	11.0	105	40	24	19	11	133	182	116
18	437	72.2	67.0	24.0	30	45	25	30	18	176	229	156
19	500	72.6	70.0	25.0	35	40	26	30	10	150	195	133
20	2149	87.1	62.0	20.0	10	44	28	53	47	173	228	144
21	671	53.3	62.0	18.0	40	40	26	27	18	134	194	159
22	451	44.3	62.0	15.0	55	40	26	27	7	150	194	126
23	423	47.3	57.0	14.0	60	39	25	25	16	149	186	128
24	1439	60.5	77.0	15.0	30	43	28	31	12	150	211	134
25	82.9		24.0		55	42	28	30	16	142	186	125
26	64.4	130	17.0	15.0	70	40	26	23	17	129	181	119
27	561		82.0		45	45	30	33	12	146	195	126
28	170		30.0		45	45	28	30	18	139	196	118
29	221		22.0		60	45	28	28	10	145	194	120
30	254		52.0		75	45	26	27	16	139	181	104
31	54.5		15.0		70	42	30	21	12	122	181	111
32	55.9		15.0		90	44	28	24	18	150	196	118
33	23.8		10.0		95	44	26	23	10	132	180	108
34	44.9		13.0		98	43	25	19	10	124	181	100

Chls= surface chlorophyll *a* plus pheophytin concentration (μg/l).
Chli= integrated chlorophyll *a* plus pheophytin concentration(μg/l).
NTUs= surface turbidity.
NTUi= integrated turbidity.
Secc= Secchi disc depth in centimeters.

APPENDIX C

Papers published from data collected for the thesis.

QUIBELL G. (1989) A comparison of multispectral photography and LANDSAT MSS for the detection of chlorophyll concentrations in inland waters. *S.Afr. J. Photogrammetry, Remote Sensing and Cartography,* 15(4), 160-168.

QUIBELL G. (1991) The effect of suspended sediment on reflectance from freshwater algae. *Int. J. Remote Sensing,* **12(1)**, 177-182.

QUIBELL G. (in press) Estimating chlorophyll concentrations using upwelling radiance from different freshwater algal genera. *Int. J. Remote Sensing,* (accepted December 1990)

Copies of these papers follow.

A COMPARISON OF MULTISPECTRAL PHOTOGRAPHY AND LANDSAT MSS FOR THE DETECTION OF CHLOROPHYLL CONCENTRATIONS IN INLAND WATERS

By

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[*MS received 16.6.89; accepted 23.10.89*]

ABSTRACT

Multispectral Aerial Photography (MSP) is investigated as an alternative to LANDSAT Multispectral Scanner (MSS) data for the remote sensing of chlorophyll concentrations in inland waters. The LANDSAT MSS satellite is designed for terrestrial remote sensing, and reflectance from water bodies falls within a narrow range of digital numbers on the 8-bit scale. However, when rasterized on a densitometer, MSP shows wider ranges in reflectance data. Empirical models calibrated on narrow ranges in reflectance data produce large changes in model output with small changes in input. Without effective pixel by pixel atmospheric correction techniques to remove the spatial noise, such models produce patchy synoptic views of chlorophyll a concentration.

The model CALMCAT was used to simulate chlorophyll a concentration from the reflectance data. This model gave mean errors in simulation of surface chlorophyll concentration of 12 $\mu g/\ell$ for the LANDSAT imagery and 8 $\mu g/\ell$ for the aerial imagery. In spite of these small errors, synoptic views of surface chlorophyll concentrations produced from the LANDSAT data differ from those produced from the aerial data. Small errors in simulation are therefore no guarantee of the accuracy of the synoptic view.

Multispectral aerial photography offers the following advantages over LANDSAT MSS data for the remote sensing of chlorophyll concentration:

- Wider ranges in reflectance data over water bodies and hence more robust empirical models.
- A smaller pixel, thereby reducing the chances of within pixel variation in cholorophyll concentration.
- Inclusion of a blue waveband, critical for the remote sensing in the aquatic environment.
- More flexible overflight times, photography can be timed for cloudless days or to observe short lived limnological phenomena.

As such it definitely provides a viable alternative to LANDSAT data.

1. INTRODUCTION

Excessive growth of floating planktonic algae in inland waters has severe economic implications for South Africa and other developing countries (Bruwer, 1979). It is therefore, essential to monitor changes in the trophic status, usually measured as chlorophyll concentration, in inland lakes and impoundments. However, the non-homogenous distribution of algae in water bodies makes the use of single point samples of chlorophyll a concentration inadequate as a means of estimating the overall trophic status of the whole water body (Knowlton, Hoyer and Jones; 1984 and Stauffer, 1988). One solution to this problem is to use remote sensing technology to produce synoptic views of chlorophyll distribution.

Estimation of chlorophyll a concentration from remotely sensed data normally involves the near simultaneous measurement of chlorophyll a concentration in the water and reflectance at the remote sensor, the derivation of the empirical relationship between these, and the testing of this relationship on a test set of data (Curren and Novo, 1988). The correlation of reflectance measured by the LANDSAT satellites and chlorophyll concentration has been well documented (Boland, 1976; Boland Shaeffer, Sefton, Clarke and Blackwell, 1979; Grimshaw, Torrans and Lera 1980; Howman and Kempster, 1986; Lathrop and Lillesand, 1986; Lindell, 1981; Ritchie, Schiebe and Cooper, 1986; Shih and Gervin, 1980 and Verdin, 1985). However, the LANDSAT satellites used in the above studies were calibrated to provide optimum terrestrial remote sensed data, and reflectance from water bodies forms only a small part of the total reflectance range available, hence the dark colour of water bodies on MSS imagery. Satellites designed specifically for water colour observations have, or will be, put into orbit (e.g. CZCS and SeaWIFS). These satellites have a radiometric sensitivity some sixty times that of the LANDSAT satellites (Kirk, 1983), which suggests greater radiometric sensitivity is required for water colour observations. However, these satellites have too large a pixel to be useful for application to small inland water bodies. Furthermore, the LANDSAT MSS satellites have already exceeded their expected lifespans and the future of these satellites is in doubt (NRSC, 1989). After this, only the more expensive data from LANDSAT Thematic Mapper and Spot satellites will be available. This requires that some alternative to LANDSAT MSS data be found. For this alternative to be used to detect chlorophyll in inland waters it must have a greater radiometric sensitivity than the LANDSAT satellites and be readily available. Scogings and Piper (1985) produced four band raster images by digitizing multispectral aerial photographs in the blue, green and red bands, and black and white infrared photographs as a single waveband. This system provided a viable alternative to LANDSAT data for the remote sensing of the terrestrial environment.

This paper reports on the results of a preliminary investigation into the use of rasterized aerial photography as an alternate source of data to LANDSAT MSS data to quantify chlorophyll a concentration in inland waters. This was done by taking multispectral aerial photographs at the same time as a LANDSAT 5 overpass. The empirical relationships between chlorophyll a concentration and remotely sensed data were derived using the model CALMCAT (Howman and Kempster, 1986). The accuracy in the simulation of surface chlorophyll concentrations for the photography and LANDSAT data were then compared.

2. METHODS

Roodeplaat Dam, situated north of Pretoria, was chosen as a suitably eutrophic water body for the study. Direct comparison of rasterized aerial photography and LANDSAT MSS data was possible as the impoundment was photographed at the same time as the LANDSAT overpass. LANDSAT 5 MSS data (Image ID 51233-07275, WRS 170-78) for the overpass on 5/10/87 was purchased. The image of Roodeplaat dam was extracted using 30 reflectance units in the infra-red band (band 4) as a land/water mask (Howman and Kempster, 1986). Aerial photographs of Roodeplaat Dam were taken with a Hasselblad 70 mm format camera mounted outside the door of a Cessna 210 aircraft. The time of photography was 09h48 on 5/10/87. Colour and colour infrared photographs were taken on alternate overflights. The shutter and aperture on the camera were set to optimize the reflectance from the water. Colour negatives were digitized on an Optronix P-1000 Colorscan in three wavebands, blue, green and red. The infrared negatives were digitized as a single band. The infrared band was registered with the colour bands to provide a single four band raster image comparable to the LANDSAT image.

As it was impossible to include the whole of Roodeplaat Dam in a single photograph, several separate images of the impoundment had to be joined. To compensate for any brightness change from one image to the next, photographs were taken with an 80% overlap and the overlapping areas used to compensate for between-image variations. A section of water in the middle of the centre image was chosen as a standard. The same area in the adjacent image was extracted and subtracted on a pixel by pixel, band for band basis from the standard. This allowed the calculation of the mean difference in brightness in each band from the standard area. These values could then be added to the adjacent image and two images joined. This process was then repeated for the next adjacent image. Although this is a crude process, most of the between-image variation could be removed. This process also removed areas of sunglint on the water surface and ensured that upwelling radiance was measured as close to the nadir as possible.

Twenty-one points on Roodeplaat Dam, as near as possible representative of the full range of chlorophyll a concentrations in the impoundment, were sampled concurrently with the collection of the remotely sensed data (Fig. 1). Surface and integrated (0–5 m) samples were taken and analysed for chlorophyll concentration using Sartory's (1982) method, and for turbidity in a HACH turbidimeter. At the time of sampling compass sightings were taken on objects on the shoreline. These were then used to identify the pixel sampled. The LANDSAT image was registered to fit the aerial image such that both images had the same number of pixels. The same pixel line and sample numbers were chosen for the sampling points in both images. This ensured accurate pixel/sample site alignment on both the aerial and the LANDSAT image.

Once analysed, surface reference data was logged and then subjected to Grubb's test for outliers and Fillibens test for normality as suggested by Howman and Kempster (1986). After the exclusion of one outlier the data were found to be normally distributed. Ten points, representative of the normal distribution, were chosen to calibrate the model CALMCAT* (Howman and Kempster 1986). The remaining ten were used to test the accuracy of the model.

The integrated sample was an average of the chlorophyll a concentration over the upper 5 m of water. Only those algae above the depth of remote sensing penetration will contribute to the reflected light. Ritchie *et al* (1986) estimate this to be 50% secchi depth, which was 1–2 m in this case. Therefore, although the model CALMCAT provides the opportunity to simulate both surface and integrated chlorophyll and turbidity, only surface chlorophyll was used to compare the two sources of data.

* CALMCAT = Canonical Analysis Landsat Model of Chlorophyll A and Turbidity.

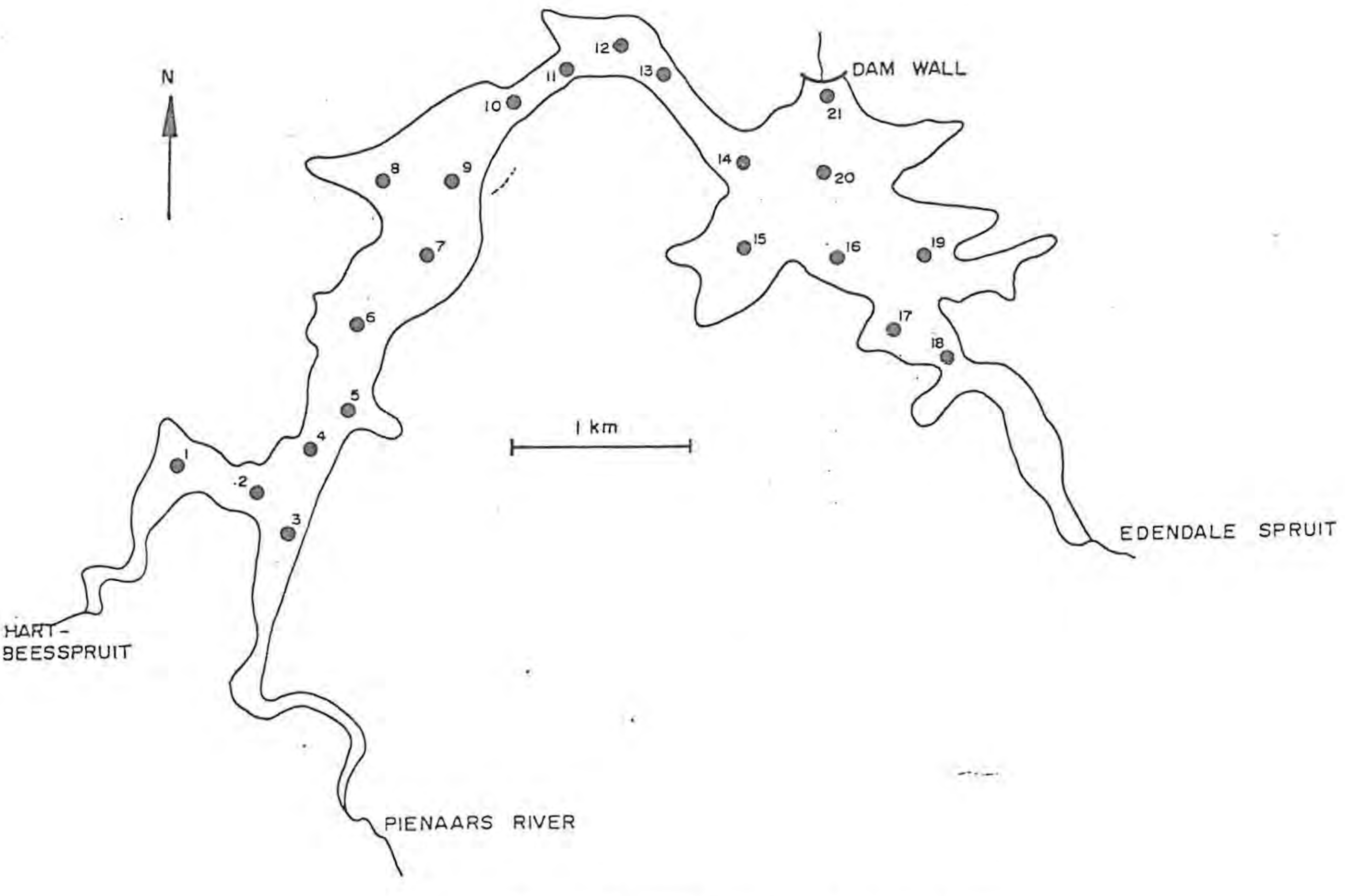

Fig. 1. A map of Roodeplaat Dam showing the points sampled.

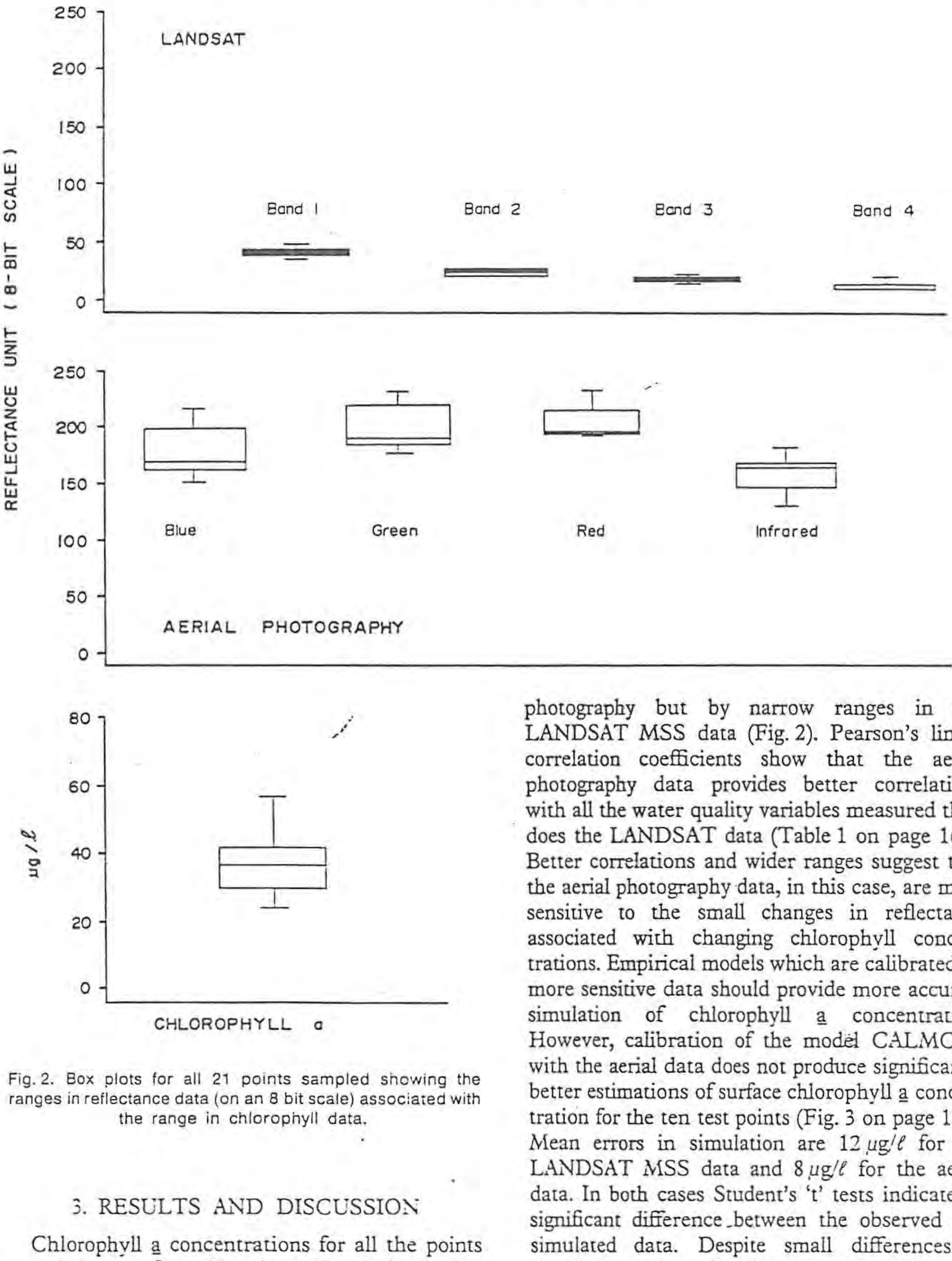

Fig. 2. Box plots for all 21 points sampled showing the ranges in reflectance data (on an 8 bit scale) associated with the range in chlorophyll data.

3. RESULTS AND DISCUSSION

Chlorophyll a concentrations for all the points sampled range from 23 µg/ℓ to 67 µg/ℓ (excluding the outlier). This is matched by wide ranges in reflectance data from the rasterized aerial photography but by narrow ranges in the LANDSAT MSS data (Fig. 2). Pearson's linear correlation coefficients show that the aerial photography data provides better correlations with all the water quality variables measured than does the LANDSAT data (Table 1 on page 164). Better correlations and wider ranges suggest that the aerial photography data, in this case, are more sensitive to the small changes in reflectance associated with changing chlorophyll concentrations. Empirical models which are calibrated on more sensitive data should provide more accurate simulation of chlorophyll a concentration. However, calibration of the model CALMCAT with the aerial data does not produce significantly better estimations of surface chlorophyll a concentration for the ten test points (Fig. 3 on page 165). Mean errors in simulation are 12 µg/ℓ for the LANDSAT MSS data and 8 µg/ℓ for the aerial data. In both cases Student's 't' tests indicate no significant difference between the observed and simulated data. Despite small differences in simulation errors for the test points, synoptic views of surface chlorophyll concentration produced from both sets of data are very different

TABLE 1

Pearson's correlation matrices for the LANDSAT and Aerial data.
All the water quality parameters measured are shown.
(n = 20, * = Significant correlation)

LANDSAT					
	S/Chl	I/Chl	S/Turb	I/Turb	
Band 1	0.616*	0.183	0.640*	0.699*	
Band 2	0.578*	0.528	0.632*	0.766*	
Band 3	0.564	0.713*	0.484	0.575*	
Band 4	0.431	0.597*	0.336	0.443	Mean = 0.549
AERIAL PHOTOGRAPHY					
	S/Chl	I/Chl	S/Turb	I/Turb	
Blue	0.880*	0.766*	0.916*	0.942*	
Green	0.811*	0.707*	0.840*	0.894*	
Red	0.861*	0.834*	0.912*	0.943*	
Infra Red	0.838*	0.729*	0.943*	0.962	Mean = 0.861*

S/Chl = Surface Chlorophyll concentration
I/Chl = Integrated Chlorophyll concentration
S/Turb = Surface Turbidity
I/Turb = Integrated Turbidity

(Plate 1). The patchy distribution of simulated chlorophyll concentration produced by the LANDSAT data and the model CALMCAT is typical of previous calibrations of this model on eutrophic South African impoundments (Howman and Kempster, 1986).

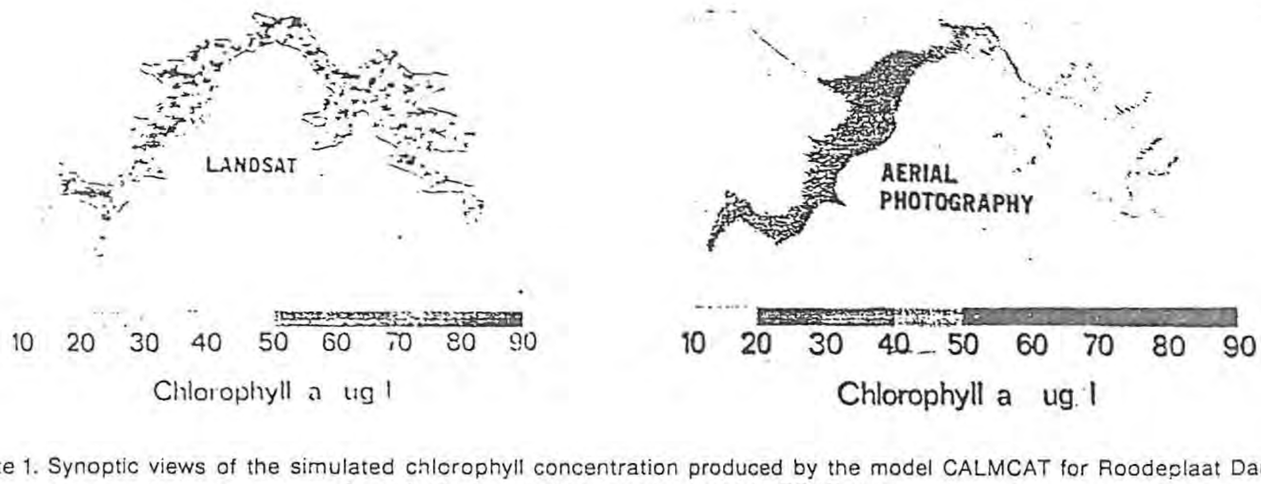

Plate 1. Synoptic views of the simulated chlorophyll concentration produced by the model CALMCAT for Roodeplaat Dam from both Aerial photography and LANDSAT data.

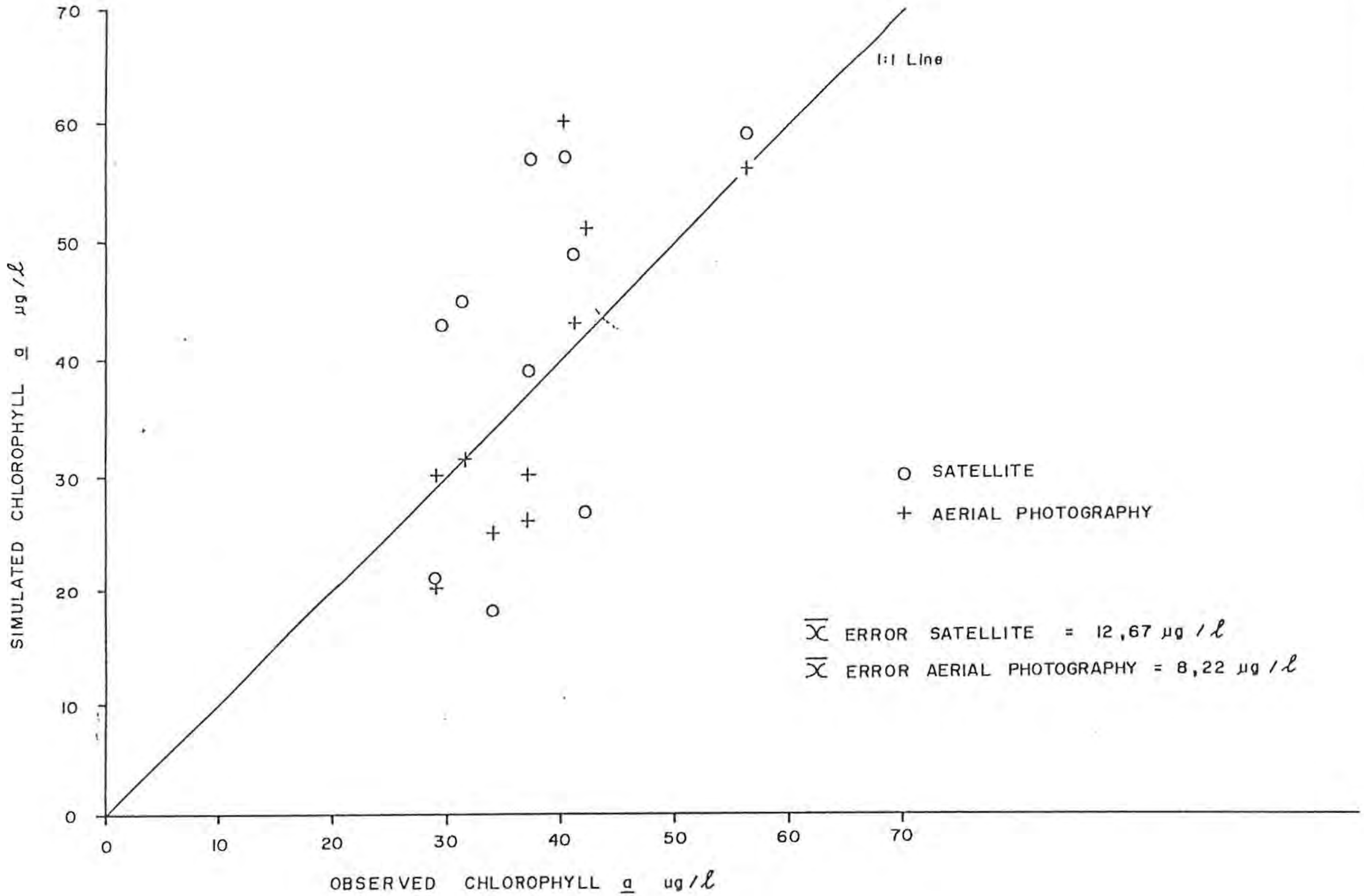

Fig. 3. Observed versus simulated chlorophyll concentrations for the aerial and satellite data.

Kirk (1983) suggested that only 10–20% of the reflectance measured at a satellite based sensor over water is reflected from particles in the water column. The 80–90% is contributed by a combination of scattering by the atmosphere, reflection of the solar beam at the water surface and reflection of skylight at the water surface. Changes in these will produce changes in reflectance at the sensor which are unrelated to changes in water quality. This suggests that either accurate removal of these effects is essential or the assumption must be made that these effects are constant over the area of interest. Several different techniques for the removal of the effects of the atmosphere have been proposed (Macfarlane and Robinson, 1984 and Verdin, 1985). However, most of these techniques assume that the effect of the atmosphere is constant over the water body and are only used for scene to scene correction. Munday, Alfoldi and Amos (1979) suggested a technique which will correct for the spatial patchiness caused by the non-homogenous distribution of the effects of the atmosphere, but this technique, by the authors own admission, is inapplicable in the presence of high chlorophyll concentrations. When calibrated on narrow ranges in reflectance data, empirical models show large changes in simulated chlorophyll concentration with small changes in reflectance. In such cases only a small amount of noise or non-homogenous distribution of the above mentioned effects is needed to produce a patchy image of chlorophyll concentration, hence the patchy image from the LANDSAT imagery. The wider ranges in reflectance data offered by the rasterized aerial photography are likely to produce more robust empirical models and hence more accurate synoptic views of chlorophyll concentration. The synoptic view available from LANDSAT data does, however, show that the average chlorophyll concentration of the western arm of the impoundment is higher than that for the main basin and is therefore useful to show gross differences in chlorophyll a concentration.

Limnologists who use remote sensing tools to examine chlorophyll concentration in impoundments may be interested , not only in the distribution of algae, but also in the average trophic status of the water body. The average trophic status of a water body, taken from a synoptic view of chlorophyll a concentration, could be estimated from histograms of the numbers of pixels at each chlorophyll concentration. Fig. 4 shows that the aerial photography data clearly indicates the average trophic status of the western arm of Roodeplaat Dam as 40 $\mu g/\ell$, but the LANDSAT data shows no clear indication of average trophic status. Overall impressions of the average trophic status for this arm of the impoundment from this type of histogram would depend on the remote sensing tool used. Obviously estimation of the average trophic status of a water body from the synoptic view produced from remote sensing tools will have to take cognisance of the limitations of the tool used. In this particular case, estimations of the trophic status of Roodeplaat Dam from the LANDSAT data may have been misleading.

Multispectral scanners which can be mounted on aircraft could be used for chlorophyll detection. Data from these devices may provide all or many of the advantages of aerial photography but, are expensive and are not readily available. Aerial photography on the other hand is readily available, even in third world countries, and is relatively inexpensive.

4. CONCLUSIONS

Assuming that the rasterized aerial photography, by providing wider ranges and better correlations, produces more accurate synoptic views of chlorophyll concentration, the patchy image produced by the LANDSAT 5 MSS imagery casts doubts as to its value as a tool for the remote sensing of chlorophyll distribution in inland waters. LANDSAT 5 MSS imagery did however allow the examination of gross differences in chlorophyll concentration in different parts of Roodeplaat Dam. Previously accurate simulation of chlorophyll concentration for the test points was accepted as an indication of the accuracy of the empirical model. However, reasonably accurate estimation of chlorophyll concentration for the ten test points using LANDSAT imagery in this case was no guarantee of the accuracy of the synoptic view.

Piper and Scogings (1987) discuss several advantages offered by aerial photography. These are:

- Low operating cost.
- Temporal flexibility.
- Spatial flexibility.
- Choice of pixel sizes.
- A shorter atmospheric path.

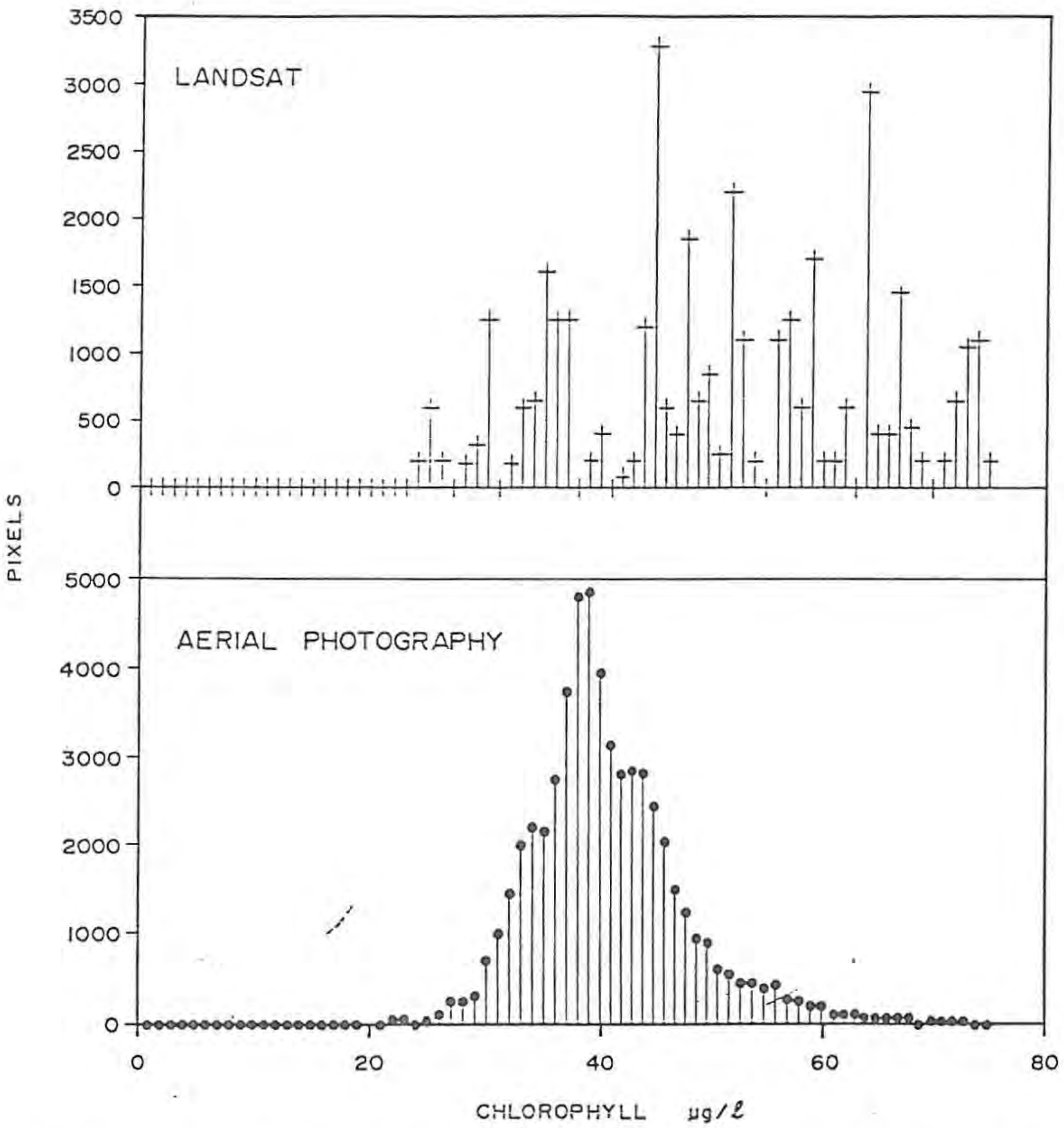

Fig. 4. Histograms of the simulated chlorophyll concentration for the western arm of Roodeplaat Dam.

When multispectral aerial photography is applied to detection of chlorophyll a, the major advantage gained is greater radiometric sensitivity and hence, more robust chlorophyll remote sensing models.

The main disadvantage of aerial photography for this study was the increased processing time required to produce a single image of the whole water body and the crude technique used to correct for between image variation.

Multispectral aerial photography data, therefore, does provide a viable alternative to LANDSAT MSS data for the remote sensing of chlorophyll concentrations in inland waters and as such definitely warrants further attention.

5. ACKNOWLEDGEMENTS

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The effect of suspended sediment on reflectance from freshwater algae

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Abstract. The effects of the addition of sediments on the upwelling radiance from pure algal cultures is examined. Upwelling reflectance signatures for both algae and suspended sediments are determined by the reflectance of the particles themselves, as well as absorbance by the water surrounding the particles. The addition of sediments to pure cultures of algae increased the reflectance at wavelengths longer than 550 nm. This effect was equal for wavelengths longer than 600 nm, and subtraction of reflectance at 660–720 nm is suggested as a means of compensating for these effects.

1. Introduction

The potential of remote sensing techniques to quantify planktonic algal populations has been recognised by several authors (Grunwald *et al.* 1988, Huang and Lulla 1986, Lathrop and Lillesand 1986, Stumpf and Tyler 1988). Quantification of algae in these studies involved the development of empirical relationships between chlorophyll concentrations and radiance measured at the sensors. The major drawback of this approach is that light scattered out of water forms only a small part of the total radiance measured by the sensors (Curran and Novo 1988, Kirk 1983). Therefore, either radiometric pre-processing is required to remove atmospheric effects on the radiance measured (MacFarlane and Robinson 1984), or the upwelling radiance must be measured in such a way as to minimize contributions from sources other than those from the constituent under study (Curran and Novo 1988). MacFarlane and Robinson (1984) have reviewed methods of correcting for atmospheric effects. Stumpf and Tyler (1988) have recognized the effects of suspended sediment on reflectance from algae, and suggest ratios of the red and near infrared wavelengths as a means of compensating for these effects. This suggestion was made on the basis of vector analysis of satellite sensor data and a conceptual model of chlorophyll and sediment reflectance. However, no rigorous analysis of the effect of suspended sediments on reflectance from algae has been done. This letter reports the results of a preliminary investigation into the changes in reflectance from pure algal cultures caused by the addition of suspended sediments.

2. Methods

Upwelling radiance from water samples was measured with a LICOR LI-1800 scanning spectroradiometer fitted with a telescopic sensor. This was placed 50 cm above a sample container, and was positioned to provide a nadir view of the water surface. The container was 30 cm deep and 10 cm in diameter, and was painted black on the bottom (Whitlock *et al.* 1982). This reduces the effect of bottom reflectance from the sample container on spectral signatures of the particles in suspension. The sensor view angle was set at 4°, which ensured that the black bottom of the container filled the entire field of view of the sensor. The sample container wqas also painted white on the sides to allow lateral scattering of light (Novo *et al.* 1986 b). This configuration was thought to approximate the light conditions in a natural water body. However, as a shading effect of the white sides of the container could not be ruled out, the reflectance spectra were only qualitatively analysed.

Downwelling irradiance was provided by two photoflood spot lamps, placed to provide illumination at an angle of 45°. The upwelling radiance $L_{\delta u}$ was measured at 5 nm intervals from 350 to 1100 nm, and the downwelling irradiance $L_{\delta d}$ from the lamps was measured with a cosine sensor. The per cent reflectance R_δ was expressed as

$$R_\delta = \frac{L_{\delta u}}{L_{\delta d}} \times 100$$

(Marracci and Ooms 1988). The algae *Selenastrum spp.* were isolated in pure culture and five 20 l dilutions of the culture were made with distilled water. Bottom sediments from Roodeplaat Dam, an impoundment situated some 30 km north-east of Pretoria, were used for the study. Suspended sediments carried by the rivers entering Roodeplaat Dam flocculate near the inflows, producing a thick layer of bottom sediment. This sediment was collected with a bottom grab sampler and burnt in an autoclave at 400°C to remove organic matter. As particle size plays a role in the reflectance from sediments (Novo *et al.* 1989 a), the dry sediment was ground up and sieved through a 200 μm sieve. The powdered sediment was then added to the samples to produce suspended sediment concentrations (SSC) of 200, 400 and 600 mg l.

Five separate scans of each of sample were taken and a single scan expressed was as a mean of the five. The samples were stirred before each scan to ensure even distribution of the particles and to prevent flocculation of the sediment in the container. After scanning, a subsample of the mixture was taken and the chlorophyll *a* concentration determined using Sartory's (1982) technique.

3. Results and discussion

Reflectance from pure water was low at all wavelengths, but increased marginally towards the infrared (figure 1). This was possibly owing to higher irradiance from the photoflood lamps in these wavelengths (figure 2). Roodeplaat Dam sediments added to distilled water showed high reflectance in the 550–650 nm range and a smaller peak at 800–810 nm (figure 1). The latter peak corresponds to an absorption minimum for pure water (List 1968) and is probably due to less attentuation of the radiance, both before and after it has been scattered by the particles in suspension. The absorption coefficients of infrared light are high (List 1968), and the low reflectance in these wavelengths is due to attenuation of this light by the water. Reflectance was asymptotic at SSC of over 400 mg/l. The asymptotic nature of the SSC and the reflectance relationship has also been demonstrated by Novo *et al.* (1989 a). Reflectance from the pure *Selenastrum spp.* cultures was high in the green (550 nm) and near infrared (700–750 nm) wavelengths. A trough in the spectral signature of the algae occurred at 665 nm, which corresponds to the absorption peak of chlorophyll (Sartory 1982, Stumpf and Tyler 1988). The algae also had the small reflectance peak at 800–810 nm, which results from the low absorption coefficients at these wavelengths. Reflectance scans of the algal cultures were similar to those reported by

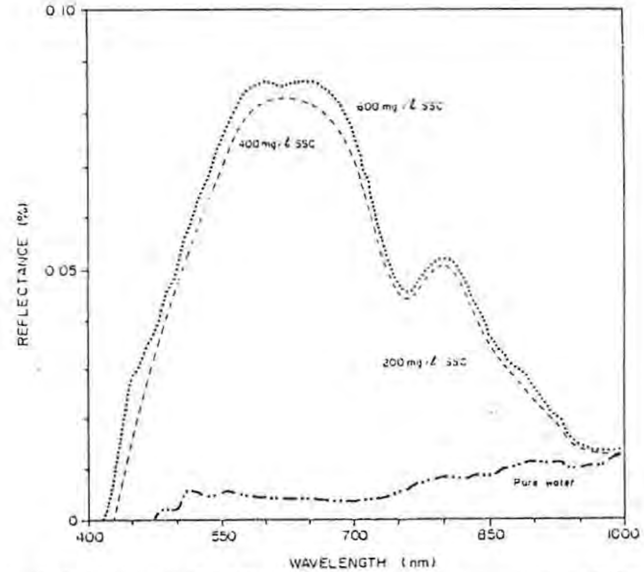

Figure 1. Reflectance spectra for different suspended sediment concentrations (SSC) added to distilled water, and reflectance of the pure water.

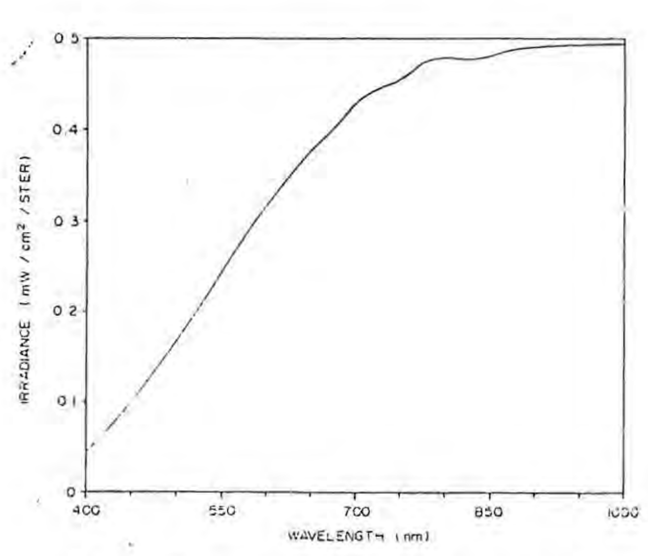

Figure 2. Downwelling irradiance from the photoflood lamps.

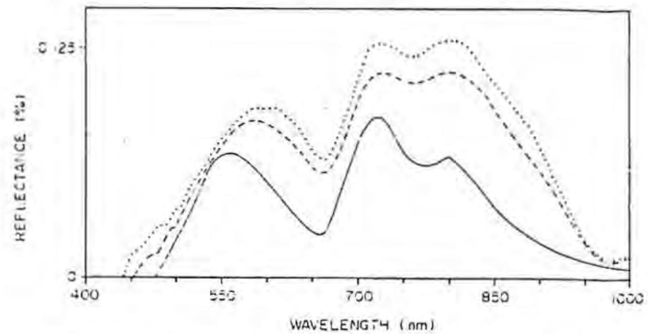

Figure 3. Reflectance spectra for different concentrations of sediments added the *Selenastrum spp.* culture. Chl = 650 μg/l; (——), pure culture; (– – –), +200 mg/l sediment; (· · · ·), +400 mg/l sediment.

Davies-Colley *et al.* (1988) for eutrophic New Zealand waters, and for measurements of the subsurface upwelling radiance of the eutrophic Loosdrecht lakes in The Netherlands (Dekker *et al.* 1989). This implies that the sample container and the irradiance from the photoflood lamps did not influence the shape of the reflectance signatures.

Addition of sediment to the pure cultures produced a shift away from the sharp reflectance peak at 550 nm to the sediment reflectance peak at 600–650 nm, and the magnitude of this shift was dependent on the amount of sediment added (figures 3 and 4). However, the positions of the algal reflectance peak at 700–720 nm and the absorption peak at 660–670 nm remained unchanged, and sediments increased the reflectance at these wavelengths. This effect was also proportional to the amount of sediments added.

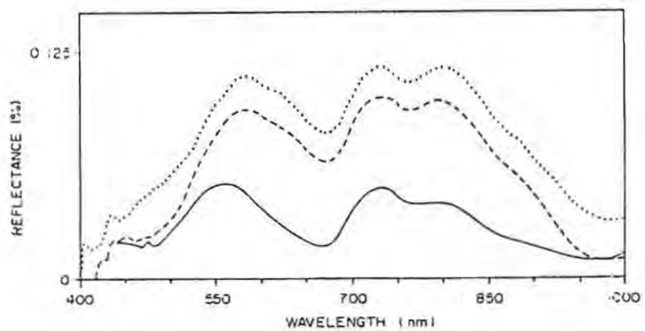

Figure 4. Reflectance spectra for different concentrations of sediments added the *Selenastrum spp.* culture. Chl = 250 μg/l; (——), pure culture; (– – –), +200 mg/l sediment; (· · · ·), +400 mg/l sediment.

Wavelength ratios are based on the premise that at higher chlorophyll concentrations more absorbance of red light occurs and reflectance of red light will be lower, while that in the green and infrared wavelengths will be higher. However, as sediments appeared to have an equal additive effect at both the red and infrared wavelengths, the ratios of these wavelengths will not have compensated for the suspended sediments. As the difference between reflectance at 700–720 nm and that at 660–670 nm appeared to be constant, irrespective of the amount of sediment added, subtraction of reflectance at ≈665 nm from that at ≈710 nm may provide a means of compensating for the effects of turbidity.

Most remote sensors do not detect radiance at discrete wavelengths, but integrate over given spectral bands (Hilton 1984). If the spectral bands are broad, they may include wavelengths with both high and low reflectance. This will negate the value of subtraction as a means of compensating for the effects of sediments. The merits of this technique must, therefore, be seen in the light of the availability of narrow spectral bands centred at 665 and 710 nm.

4. Conclusions

Reflectance spectra of both algae and sediments in water were influenced by the absorbance of light by the water before and after it is scattered by the particles. The addition of sediments to the algal suspensions produced spectra which were a combination of the sediment and algal reflectance. This is seen as a shift in the green reflectance peak of the *Selenastrum* cultures to the less defined peak at 600–650 nm for the sediments. The effects of the absorption of red light at 665 nm and reflectance at 700–750 nm by algae still influence the spectra of algae/sediment mixtures. Sediments increased the reflectance at wavelengths over 550 nm and this effect was equal for wavelengths over 600 nm. This suggests that subtraction of reflectance at ≈665 nm from that at ≈710 nm may provide a means of compensating for turbidity in radiance/chlorophyll models. A more intensive study of reflectance spectra taken at different parts of Roodeplaat Dam, is underway, to confirm the validity of this approach. However, as reflectance differs with sediment type and particle size (Novo *et al.* 1989 a) these findings must be seen as specific for the conditions of this study.

Acknowledgments

I would like to thank the Department of Water Affairs of the Republic of South Africa for the funding of this work and the South African Forestry Research Institute for the loan of the spectroradiometer. Thanks must also go to the the staff of the Remote sensing section of the Hydrological Research Institute for their comments on early drafts.

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ESTIMATING CHLOROPHYLL CONCENTRATIONS USING UPWELLING RADIANCE FROM DIFFERENT FRESHWATER ALGAL GENERA.

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Abstract. Upwelling radiance from pure cultures and natural populations of freshwater algae is examined. The effects of changes in the vertical distribution of the algae on the upwelling radiance are also explored. The different algae studied were spectrally very similar. The volume reflectance for any given chlorophyll concentration differed between the Phyla studied. This appeared to be due to the colonial nature of some species. Higher chlorophyll concentrations resulted in higher reflectance in all but the blue wavelengths, and correlations between reflectance in the near infrared and *Ln* chlorophyll were the highest. This suggests that remote sensing of algae in inland waters should be based on increased scattering by the cells and not increased absorbtion by chlorophyll.

1. INTRODUCTION

The enhanced loading of plant nutrients to inland water bodies (eutrophication) often leads to the excessive growth of floating planktonic algae (Wetzel 1983). These algae create a variety of problems for authorities treating water to potable standards, and the economic impact of eutrophication has made the estimation of algal concentrations an essential part of water quality monitoring. Algal populations have traditionally been quantified by extraction of the plant pigments from the cells and analysis of the chlorophyll *a* concentration in the extract (Nusch 1980). Chlorophyll *a* is a common constituent of most algal species and analysis for the chlorophyll *a* concentration allows different species to be directly compared. Recently the value of remote sensing techniques, as an alternative method of estimating algal populations, has been recognised. Remote sensing studies normally involve the mapping of chlorophyll concentrations in water bodies using radiance collected by sensors placed some distance above the water surface. Several sensor systems have been used including, LANDSAT MSS (Carpenter and Carpenter 1983, and Howman and Kempster 1988), LANDSAT TM (Grunwald, *et al* 1988, Huang and Lulla 1986, Lathrop and Lillesand 1986, and Stumpf and Tyler 1988) and the CZCS (Hovis 1981, Gordon *et al* 1983) imagery. Quantification of algal concentrations in these studies involved the development of the empirical models between radiance, measured at a remote sensor, and "ground truth" chlorophyll concentrations. Remote sensing has the advantage that synoptic views of algal distribution throughout the water body can be produced, which allow more accurate estimates of the overall trophic status of the water body. However, the real value of remote sensing for inland water quality monitoring lies in the production of synoptic views without the need of costly ground truth sampling to recalibrate the models. This requires the development of a universal algorithm which can be applied to the radiance data.

Estimation of chlorophyll concentrations from remotely sensed data differs from contact sensed methods in several aspects;

i. Light scattered by whole algal cells is detected. This includes measurement of the increased absorbtion of some wavelengths and increased scattering of others.

ii. All the cells above the depth of remote sensing penetration contribute to the upwelling radiance. This means that two areas with the same chlorophyll concentration, but differing light penetration will have different upwelling radiances.

iii. The water surrounding the cells absorbs, on a wavelength dependent basis, both the downwelling and upwelling light (List 1968).

iv. Particles other than algae suspended in the water column also contribute to the upwelling light.

v. The atmosphere between the water and sensor has an additive and multiplicative effect on the radiance detected (Curran and Novo 1988).

Furthermore, pigments other than chlorophyll present in the cells are one of the criteria used to classify algal species (Bold and Wynne 1985), and several authors have suggested that changes in dominant algal species or different growth stages of algae may alter the nature of the light detected at a remote sensor (Lindell 1981 and Stumpf and Tyler 1988). The reflectance spectra of algae will also differ with the depth at which they occur (Davies-Colley, *et al* 1988). The chlorophyll / radiance relationship can therefore differ with species and the depth at which the cells occur. To complicate the issue the presence of suspended sediments also influences the total upwelling radiance. Development of a universal remote sensing algorithm therefore requires that either the upwelling radiance be measured in such a way as to minimize the effect of other sources on the total radiance measured (Curran and Novo 1988) or that some radiometric preprocessing be done to compensate for these other effects (MacFarlane and Robinson 1984).

Macfarlane and Robinson (1984) have already reviewed atmospheric correction of the radiance data for the development of a universal suspended sediment/ radiance algorithm. Stumpf and Tyler (1988) have suggested methods of correcting for the effect of suspended sediments in chlorophyll / radiance models. Novo, *et al* (1989a) have examined the influence of sediment type on the upwelling radiance and show that different sediments have distinct reflectance spectra. This paper investigates the nature of light scattered out of water by pure cultures, as well as natural populations, of algae. The differences in reflectance between the different species and the changes induced by variations in the vertical distribution are highlighted. The implications of these changes for the remote sensing of inland algal concentrations are also discussed.

2. METHODS

Upwelling radiance was measured with a LICOR LI-1800 spectroradiometer fitted with a telescopic receptor. All measurements were taken outside using natural sunlight irradiance. Reflectance from pure algal cultures in suspension was measured by placing the telescopic receptor vertically above a sample container. This nadir view angle has been shown to provide the strongest reflectance/suspended sediment relationships (Novo *et al* 1989). The sample container was painted absorbant black on the bottom (Whitlock, *et al* 1982), but white on the sides to allow lateral scattering of the light. This configuration was thought to approximate the conditions in a natural water body. The angle of view of the telescope was set at 4° which ensured that none of the white sides were included in the field of view and reduced the possibility of specular reflectance from the water surface being detected by the sensor.

Upwelling radiance from natural populations of algae were measured on an eutrophic impoundment (Roodeplaat Dam) situated 30km north of Pretoria at 25°37' S, 28°22' E. These measurements were taken with the telescopic receptor mounted on a boom off a boat.

In both cases scans of the upwelling radiance at each wavelength ($L_{\delta u}$) were alternated with scans of the downwelling irradiance at the same wavelengths

($E_{\delta d}$) taken with a cosine receptor. Radiance detected by each sensor was corrected to $mW.cm^{-2}$ and reflectance (R_δ) was calculated according to Maracci and Ooms 1988) as;

$$R_\delta = \frac{L_{\delta u}}{E_{\delta d}} \times 100$$

Radiance was measured in 5nm intervals from 350nm to 1100nm. Five replicate scans were taken of each sample and a single scan was calculated as a mean of the five. The scans were taken within 2 hours of midday on cloudless days and the experiment was repeated on two separate occasions (19/05/89 and 13/07/89). The scans were not corrected for diffuse sky radiance or sunangle, as these were considered inherent in the measurement of downwelling irradiance.

Immediately after the scans were taken, a surface grab sample was taken from the scan site and these were later returned to the laboratory for analysis for the chlorophyll concentration. The turbidity of each sample was measured in a HACH turbidimeter as nephlometric turbidity units (NTU). Secchi disc water transparency readings were taken at each sample site on the impoundment. Sample sites were placed away from the inflows where suspended sediment, carrried by the rivers, could have influenced the radiance measured.
Radiance from different species of commonly occurring southern African algae (Truter 1987), was measured by isolating the algae in pure culture. The genera used were *Microcystis* sp. and *Anabaena* sp. which are blue-green algae, as well as the green species *Chlorella* sp, *Ulothrix* sp. and *Selenastrum* sp. Dilutions of these cultures were made with distilled water.

Samples were analysed for chlorophyll *a* and phaeophytin concentrations in the laboratory. As chlorophyll *a* and phaeophytin are spectrophotometrically indistinguishable, they were added together and are referred to here as total chlorophyll. Natural logs of the total chlorophyll concentration were used in the empirical procedures.

3. RESULTS AND DISCUSSION

<u>3.1 Reflectance from different algal genera.</u>

Lindell (1981) indicated that the signals received at the LANDSAT MSS sensors from parts of Lake Malaren, which were dominated by different algae, had different characteristics. Howman and Kempster (1986) show changes in the LANDSAT MSS bands which provide the best correlation to chlorophyll *a* concentration for separate overpasses. These changes, they suggest, result from changes in the dominant algal genera present at the time of each overpass. As pigments, other than chlorophyll, are one of the criteria used to classify algae (Bold and Wynne 1985), it is feasible that different algae will have different reflectance characteristics. Should this be the case, then empirical relationships developed to estimate chlorophyll concentrations from reflectance data would have to be species specific. Furthermore, single regression relationships between chlorophyll and radiance for any particular image could not be developed if different species dominate different parts of the water body.

The algal genera used in this study could be divided into two Phyla; the Cyanophyta or blue-green algae and the Chlorophyta or green algae. These Phyla also had typical reflectance spectra. Both groups demonstrated a peak in reflectance at 550nm and a troughs at 665nm, which corresponds to the in vitro absorption peak for chlorophyll (Stumpf and Tyler 1988) (Figs. 1 & 2). These scans also show the typical atmosheric absorbtion feature at ≈760nm, which suggests that division by the downwelling irradiance did not completely compensate for atmostheric effects.

The blue green species had a smaller peak at 650nm visible at the higher concentrations (Fig 1). This peak is possibly associated with the presence of phycobiliproteins which can occur in this Phylum (Dekker *et al* 1989). Percent reflectance in the near infrared (700-720nm) was high for all the species. This peak has been explained as a minimum in the combined absorption curves of algae and water (Vos, *et al* 1986, quoted in Dekker, et al 1989). Scans of the successive dilutions of the green species agreed with a conceptual model of algal reflectance in that absorption of red light was stronger at higher chlorophyll concentrations (Fig. 2), but the blue-green species did not show this same trend (Fig. 1). Therefore, for the blue-green species, increased scattering at higher algal concentrations has a greater influence on reflectance than increased absorbtion. This suggests that, for this

Phylum, increased absorbtion of light at ≈665nm cannot be used to quantify chlorophyll concentrations.

Turbidities of the algal cultures also indicated that the different Phyla had distinct scattering characteristics (Fig. 3). Turbidity as NTU is a function of the scattering coefficient of the sample (Kirk 1988). Measurement of the turbidity of algal cultures indicates the total light scattered by the sample and includes both scattering and absorbance wavelengths. Blue-green and Green algae therefore scattered different amounts of light for any given chlorophyll concentration (Fig. 3). Some algae tend to form clumps (Bold and Wynne 1985) in which case less light is scattered by the same amount of cells. The blue-green species used in the study, *Microcystis* spp. and *Anabaena* spp. are colonial algae, which explains the lower scattering coefficients for the blue-green algae (Fig. 3). The total volume reflectance for any given chlorophyll concentration can therefore differ between the algal species. Changes in species composition or colonial status will consequently require the development of new empirical relationships between radiance and chlorophyll concentration.

Most remote sensors do not measure radiance at discrete wavelengths, but integrate the radiance over given spectral bands (Hilton 1984). The small peak at 650nm for the blue-green algae will contribute negligible amounts to the volume reflectance if the spectral bands are wide. In this case the differences in reflectance spectra are unlikely to be detectable from the remotely sensed data, and changes in species composition will not influence the spectral bands which provide the best correlation with chlorophyll concentrations. However, if the remote sensor has a narrow band centred at 650nm, shifts in species dominance from blue-green to green species may be detectable by relating reflectance in this band to another band.

3.2 Reflectance from natural populations.

Microscopic examination of water samples from Roodeplaat Dam showed that *Microcystis* spp. dominated the algal population at all the sampling points on both occasions. This was also evident from the shape of the reflectance spectra, which were typical of blue-green algae (Figs 4 & 5). The similarity of the spectra to those from pure cultures suggests that other particles in suspension (eg. sediments) did not play a major role in the reflectance from the water and that the container used did approximate the conditions in a natural water body. Reflectance spectra for Roodeplaat Dam were also similar to scans of upwelling subsurface radiance reported in Davies-Colley, *et al* (1988) for eutrophic lakes in New Zealand and for the eutrophic Loosdrecht lakes in the Netherlands (Dekker, *et al* 1989). Dekker *et al* (1989) also report that Cyanophyta dominated the Loosdrecht lakes. At one point reflectance from a thick scum of algae floating on the surface was measured. The shape of the reflectance scan for this point differed significantly from the other points (Fig. 4). When these scums occur, the absorption of infrared light by the water no longer infuences reflectance, and the spectra of scums are more typical of those for terrestrial plants (Fig. 4). This indicates that reflectance and absorbance by the algae as well as the absorbance characteristics of the water itself, are important in determining the reflectance spectra of algae. When percent reflectance was integrated from 350-1100nm, the scum occurred as an outlier in the reflectance /chlorophyll relationship and was therefore excluded from further statistical analyses.

Reflectance from natural populations of *Microcystis* also did not follow the conceptual model of algal reflectance and higher concentrations of algae had a higher reflectance at all except the blue wavelengths (Fig. 5). The largest changes in reflectance associated with increasing chlorophyll concentration occured in the near infrared wavelengths (700-710nm). As the absorption coefficients of infrared light by water are high (List 1968), infrared reflectance must be related to the number of cells which occur in the upper few centimetres of water. In most cases the number of cells in the upper few centimetres of water will be representative of the overall algal concentration and near infrared reflectance will be useful in the simulation of average chlorophyll concentrations for that point. However many algal species have intracelluar gas vacuoles or other flotation mechanisms (Bold and Wynne 1985) and tend to float near the surface, particularly where high populations of the algae create competition for light. This means that infrared reflection plays a more important role at the higher concentrations. Under different light conditions the algae may move down into the water column. In such a case the infrared reflectance would virtually disappear, but the overall algal population at that point would still be high. Remote sensing algorithms which rely on reflectance from wavelengths longer than 700nm are therefore dependent on the even vertical distribution of the algae or will only accurately simulate chlorophyll concentrations in the upper few centimetres of water.

At low chlorophyll concentrations (under 10μg/l) the distinction of the green reflectance peak was less clear and the near infrared reflectance peak disappeared (Fig. 5). This justifies the asumption of zero radiance in the infrared spectral bands used in some atmospheric correction models (MacFarlane and Robinson 1984), if the chlorophyll concentrations are low but not if the concentrations are higher.
Regression analysis of the integral between 350nm and 1100nm of each scan produced significant correlations with *Ln* chlorophyll for both the sampling occasions (Table 1). When data from both the sampling occasions were included in a single analysis, correlation coefficients were lower but were still significant at the 95% confidence limit (Table 1). This suggests that in this case, scattering of light in all the wavelengths was the dominant influence on the total reflectance measured.
Integration of the reflectance over the spectral bands of the LANDSAT MSS and TM sensors as well as the Daedalus airborne MSS indicated that positive correlations were noted in all bands (Fig. 6). The bands which had the highest correlation with *Ln* chlorophyll concentrations were those situated to detect the reflectance peak at 700-710nm, while those bands positioned in the blue region of the spectrum had the lowest correlations. This indicates that, as with the pure cultures, scattering by chlorophyllus sediment plays a more important role than increased absorbtion by the cells. Therefore chlorophyll concentrations could be more accurately detected by measuring the increased reflectance in the green or, more suitably, the near infrared wavelengths.

4. CONCLUSIONS

The different algae studied were spectrally very similar and changes in algal species dominance is unlikely to cause shifts in correlations between spectral bands of most remote sensors. However, different algae show distinct light scattering properties, probably due to the tendency of some species to form colonies. This implies that algorithms based on increased reflectance should be specific for the species composition used in the calibration of the model.

Changes in the position of the algae within the water column will produce changes in the reflectance spectra. These changes will be more pronounced for wavelengths longer than 700nm where the absorption characteristics of the water have a greater influence on reflectance measured just above the water surface. As algae can adjust their vertical distribution within the water column, algorithms using these wavelengths are dependent on the even distribution of algae in the water column throughout the water body.
In inland waters chlorophyll concentrations are typically much higher than those in marine waters. Higher concentrations of *Microcystis* in Roodeplaat Dam waters produced higher reflectance at all wavelengths (except the blue wavelengths) and integration of reflectance over given spectral bands produced significant positive correlations in most bands. This study indicated that, at least in the case of remotely sensing *Microcystis* populations, increased reflectance rather than increased absorbtion would prove more valuable in chlorophyll/ reflectance models. This differs from the measurement of increased absorbtion of light used for remote sensing of marine algae, and highlights the differences between inland and marine systems. For inland waters with high concentrations of algae, measurement of increased reflectance at 700-710nm should provide the best radiance / chlorophyll models, but such models will be subject to the even distribution of the cells in the upper layers of the water column.

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I wish to thank the Department of Water Affairs of the Republic of South Africa for funding the project as well as the South African Forestry Research Institute for the loan of the spectroradiometer. Thanks must also go to the staff of the remote sensing section of the Hydrological Research Institute for their comments of drafts of the paper.

Table 1. Regression analysis results for integrated percentage reflectance / *Ln* chlorophyll concentration relationship.

	n	R^2	R-squared	SE	F-Ratio	p-level
19/05/89	8	0.87	76.95%	0.67	19.7	<0.05
13/07/89	12	0.90	85.83%	2.33	69.45	<0.05
Grouped	20	0.74	59.41%	0.05	25.2	<0.05

SE= Standard error of estimate

Running title: Upwelling radiance from different algal genera.

Figure ledgends:

Figure 1. Percent reflectance, measured just above the water surface, for dilutions of the blue-green algae *Microcysis* sp.

Figure 2. Percent reflectance, measured just above the water surface, for dilutions of the green algae *Selenastrum* sp.

Figure 3. Turbidities of pure cultures of algae at different concentrations.

Figure 4. Percent reflectance, measured just above the water surface, of an algal scum on Roodeplaat Dam and for algae with in the water column.

Figure 5. Percent reflectance, measured just above the water surface, at selected sites on Roodeplaat Dam with different chlorophyll concentrations.

Figure 6. Correlations between reflectance integrated over the specral bands of several sensors systems, and *Ln* chlorophyll concentrations.

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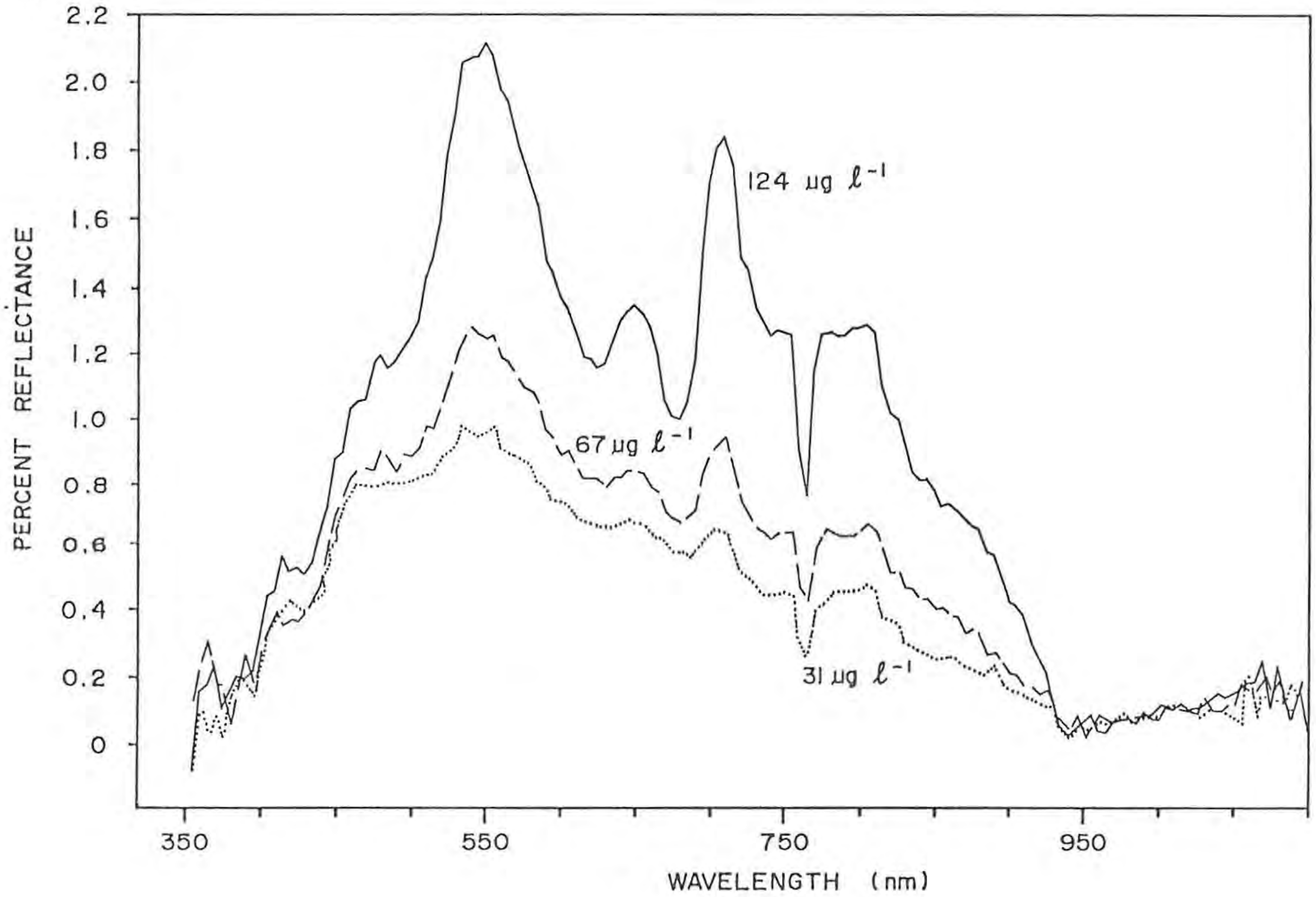
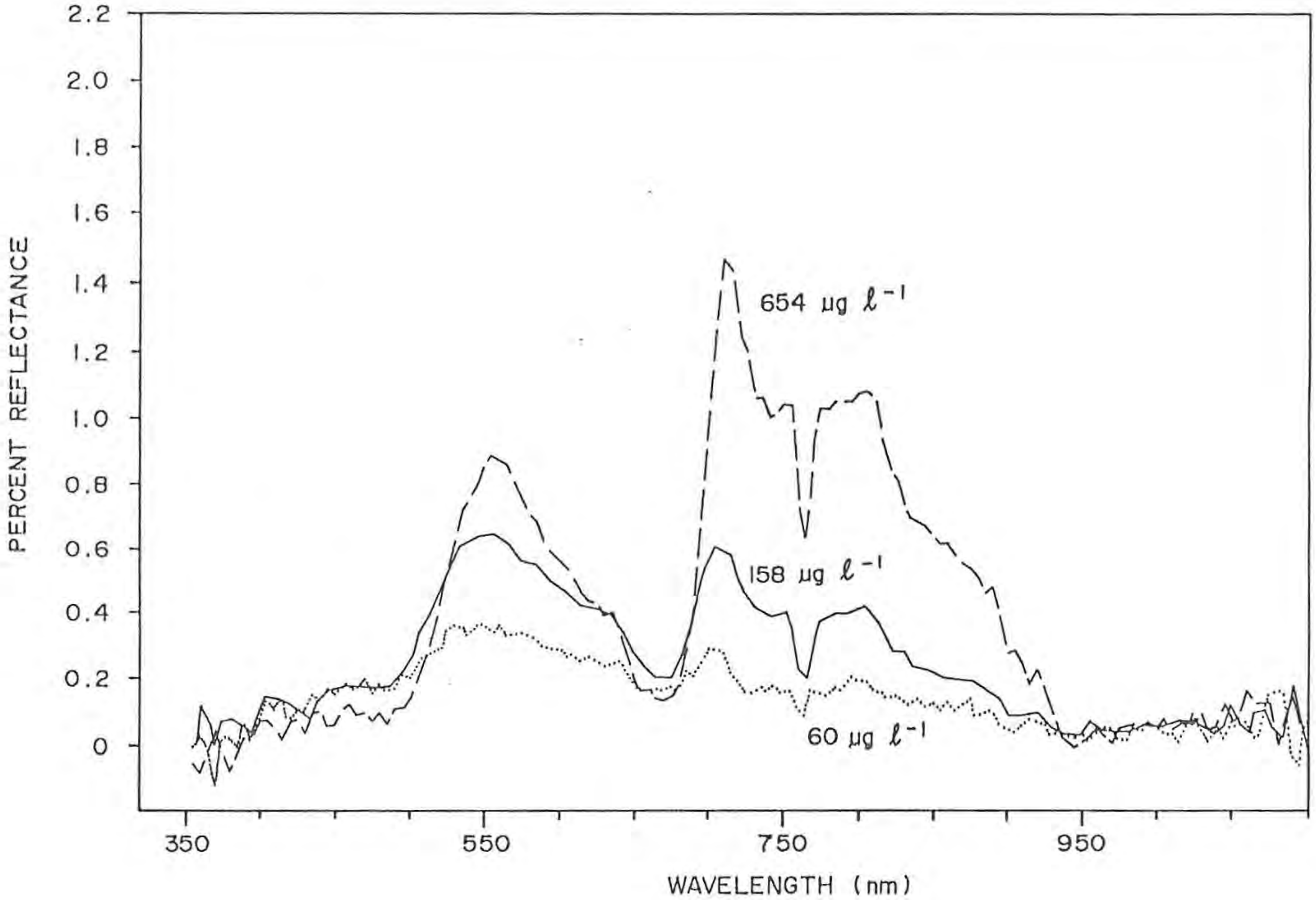
Fig 1

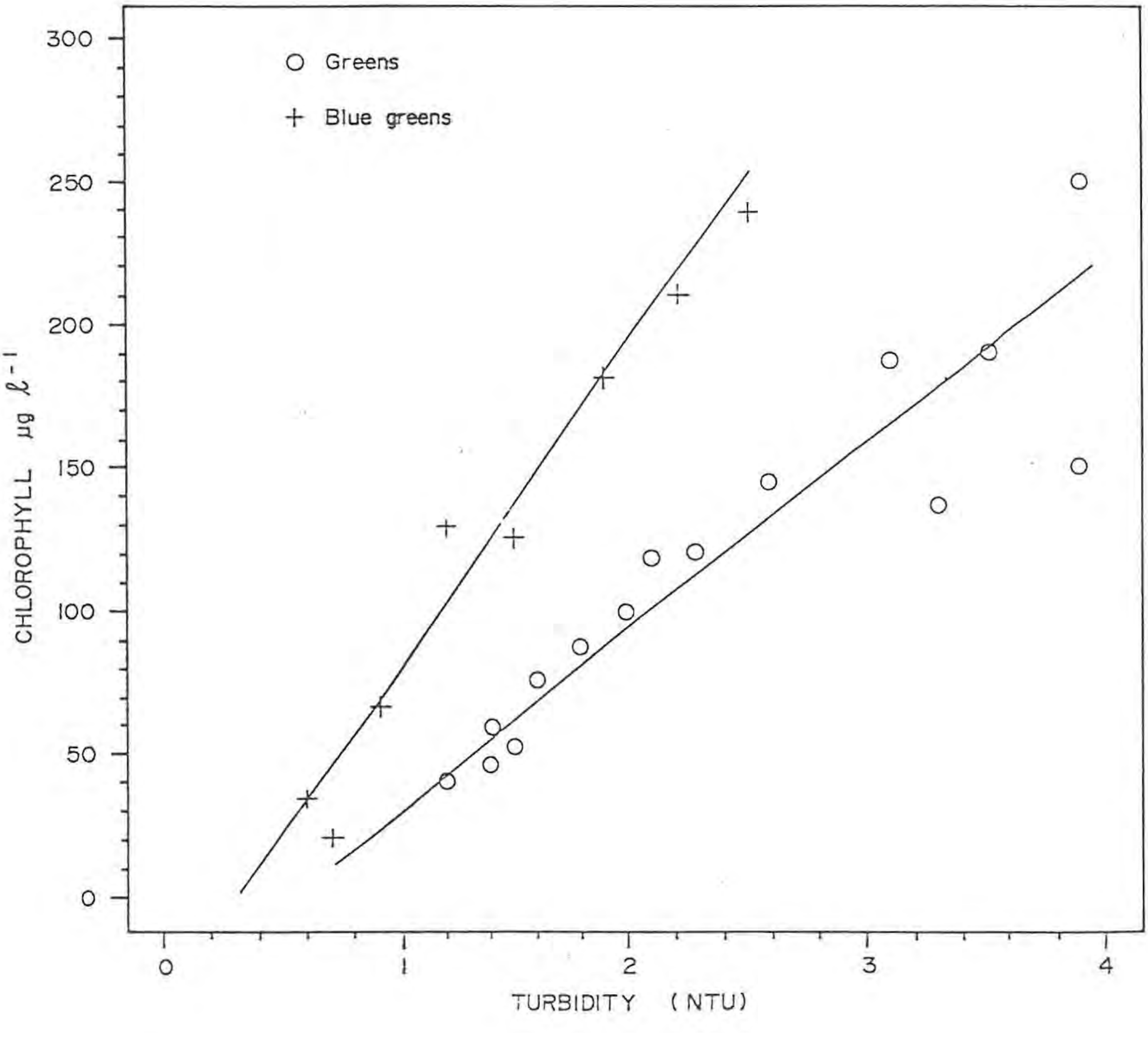

2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
PERCENT REFLECTANCE
124 µg ℓ^{-1}
67 µg ℓ^{-1}
31 µg ℓ^{-1}
350
550
750
950
WAVELENGTH (nm)

Fig, 2



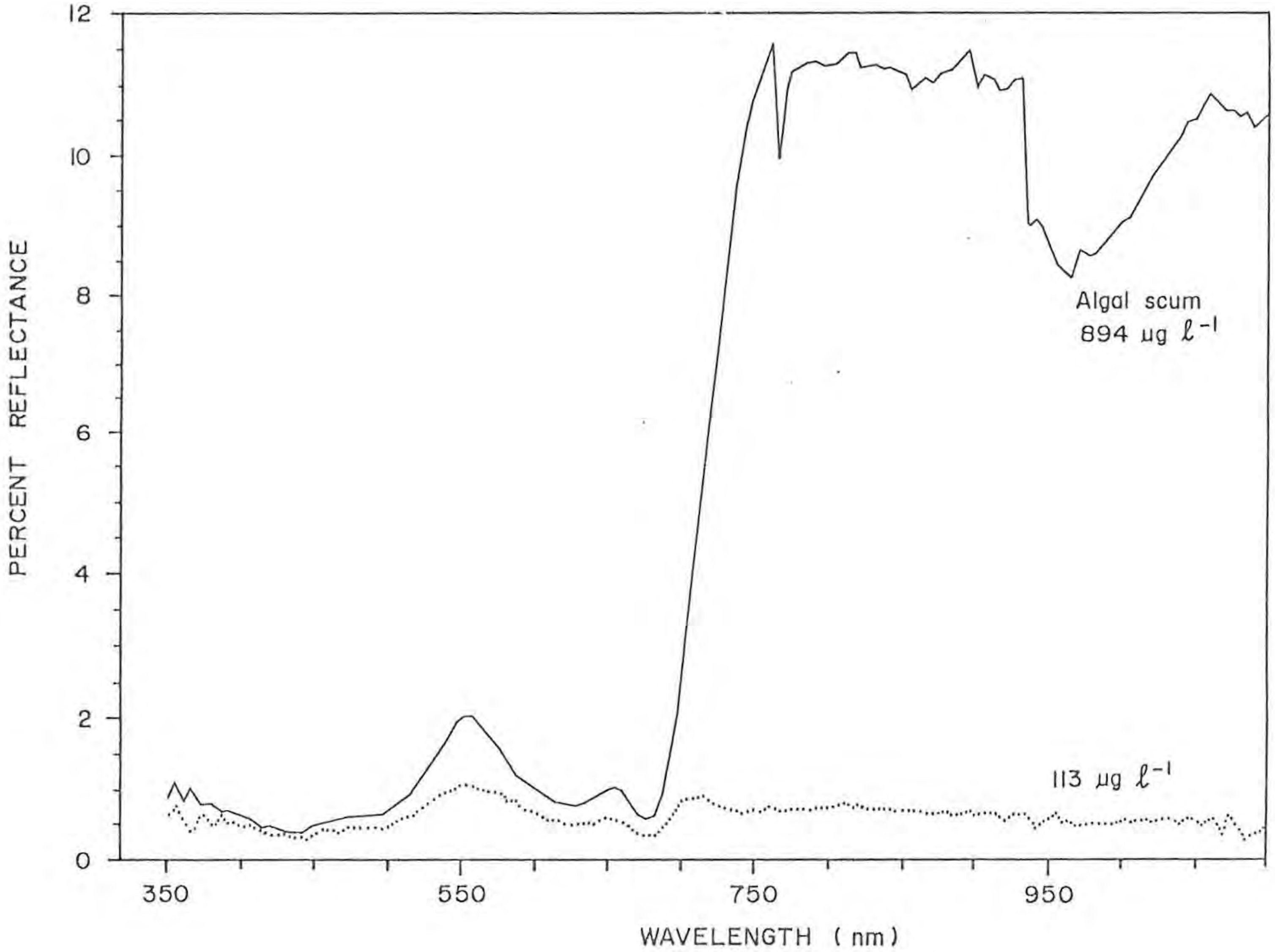
PERCENT REFLECTANCE
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
654 µg ℓ⁻¹
158 µg ℓ⁻¹
60 µg ℓ⁻¹
350
550
750
950
WAVELENGTH (nm)

Fig 3



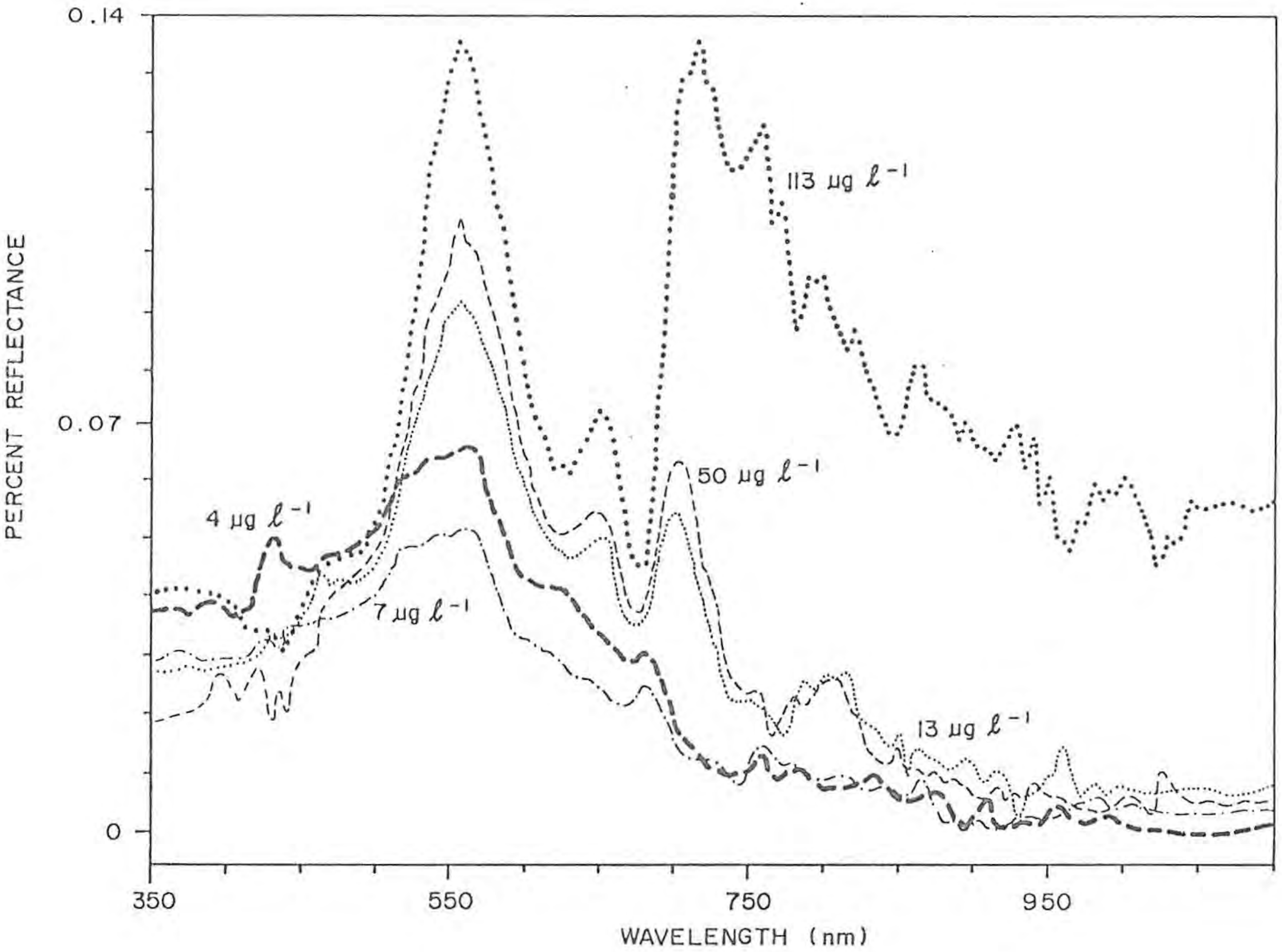
Greens
Blue greens
CHLOROPHYLL µg ℓ-1
TURBIDITY (NTU)
300
250
200
150
100
50
0
0
1
2
3
4

Fig4



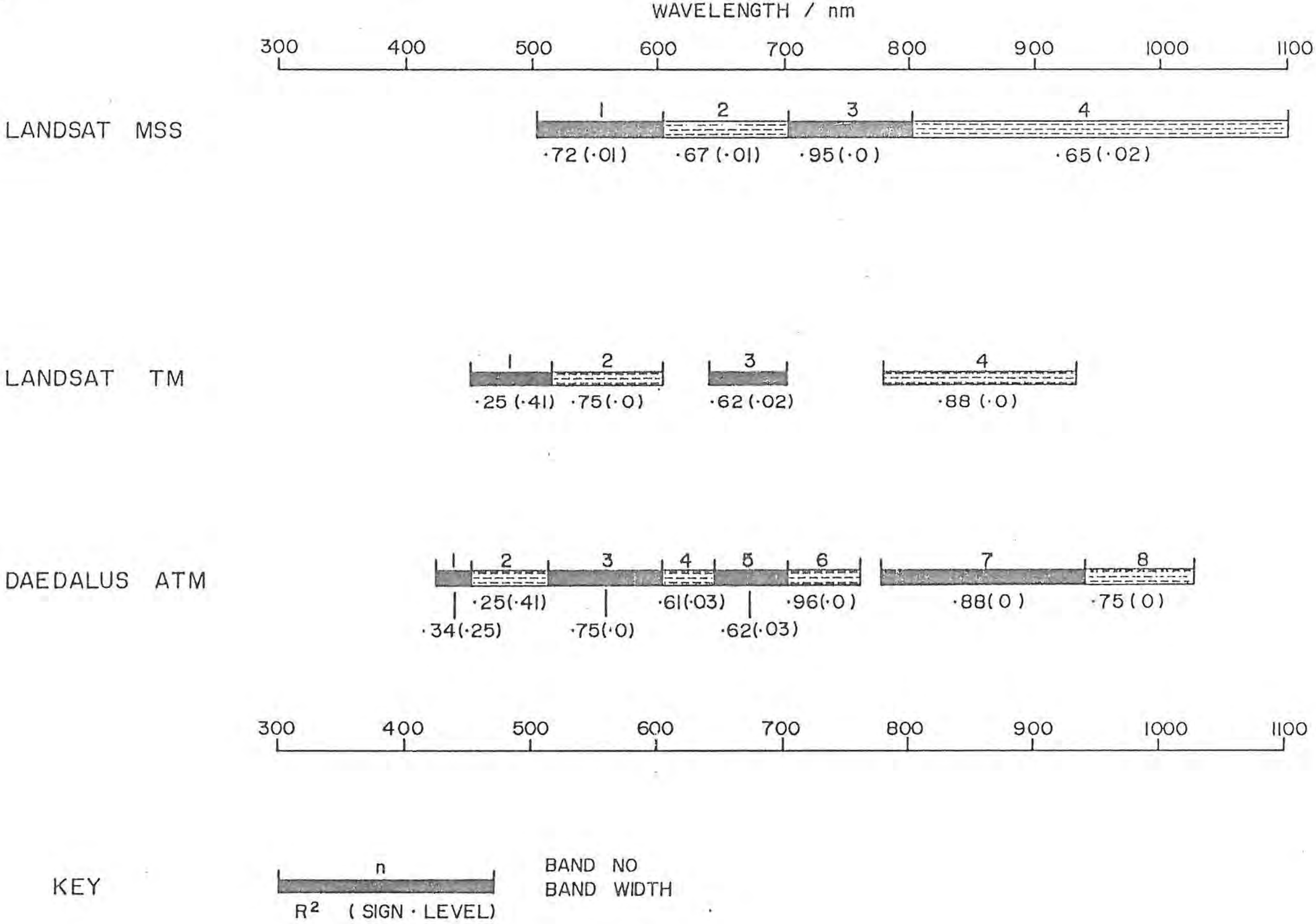
12
10
8
6
4
2
0
PERCENT REFLECTANCE
350
550
750
950
WAVELENGTH (nm)
Algal scum
894 µg ℓ⁻¹
113 µg ℓ⁻¹

Fig 5



0.14
0.07
0
PERCENT REFLECTANCE
350
550
750
950
WAVELENGTH (nm)
113 µg ℓ⁻¹
50 µg ℓ⁻¹
4 µg ℓ⁻¹
7 µg ℓ⁻¹
13 µg ℓ⁻¹

Fig 6


WAVELENGTH / nm
300 400 500 600 700 800 900 1000 1100
LANDSAT MSS
1 2 3 4
·72 (·01) ·67 (·01) ·95 (·0) ·65 (·02)
LANDSAT TM
1 2 3 4
·25 (·41) ·75 (·0) ·62 (·02) ·88 (·0)
DAEDALUS ATM
1 2 3 4 5 6 7 8
·25(·41) ·61(·03) ·96(·0) ·88(0) ·75(0)
·34(·25) ·75(·0) ·62(·03)
300 400 500 600 700 800 900 1000 1100
KEY
n
R² (SIGN · LEVEL)
BAND NO
BAND WIDTH