APPLICATION OF SATELLITE REMOTE SENSING TO NORTH CAROLINA– DEVELOPMENT OF A MONITORING METHODOLOGY FOR TROPHIC STATES OF LAKES IN NORTH CAROLINA

(NASA-CR-150419) APPLICATION OF SATELLITE REMOTE SENSING TO NORTH CAROLINA. DEVELOPMENT OF A MONITORING METHODOLOGY FOR TROPHIC STATES OF LAKES IN NORTH CAROLINA Final Report (North Carolina State Univ.) N77-33590
A/C A06/MF A01
Unclas
G3/43 50765

FINAL REPORT

Contract No. NAS8-31984

1 August 1977

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TABLE OF CONTENTS

LIST OF FIGURES

TABLES

ABSTRACT

Conjunctive study of four shallow coastal plain lakes in northeastern North Carolina and their Landsat-2 images demonstrates that it is possible to differentiate between the lakes and their respective trophic states on the basis of the multispectral scanner imagery. The year-long investigation has established that monitoring of the trophic states of the lakes on a seasonal basis through application of color additive imagery enhancement techniques is possible. Utilizing a standard setting of the color additive viewer, an investigator can normalize the imagery to an internal standard of constant reflectance characteristics. By comparison of the false color renditions with a standard interference color chart combined with brightness measurements made on the viewer screen, one can relate the lake reflectances to their trophic states. Two or more bands of the imagery are required, and the present study has established that for the lakes studied Band 5 and Band 6 form a good combination.

One problem which arises through use of density measurements alone for monitoring trophic states of the lakes through time is the necessity of establishing an internal gray scale within the imagery scene and of using it for comparison between images. Band 5 imagery proved the most useful for mapping underwater vegetation by density slicing techniques when the water column had less than 30mg/1 suspended material. Bottom configuration can be mapped by means of density slicing in those cases where the water depth is less than 3 meters, with Band 4 proving most effective for this use of the imagery. However, the technique is dependent upon the suspended material load, and it cannot be used when wind action stirs the bottomsof the lakes.

Spectroradiometric measurements of the lakes, potential internal standards, and a swimming pool established the efficacy of the normalization procedures used in this study.

For the satellite monitoring system to function effectively and properly, the person doing the monitoring must have a good knowledge of the probable seasonal cycle of the lake and of the lake environment.

1.0 INTRODUCTION

Water quality monitoring and measurement of the trophic states of coastal lakes of North Carolina through use of satellite imagery has certain attractiveness. When the methodology is developed so that the cycles of individual lakes can be monitored relatively simply through use of satellite imagery, then resource managers can identify those lakes which need concentrated attention and can apply limited resources available for intensive ground level monitoring to those lakes in greatest need of attention.

By systematic monitoring of the lakes through use of satellite imagery resource managers should be able to detect long-term changes which water samples occasionally collected cannot pinpoint. Thus intelligent use of the imagery in conjunction with an understanding of the natural history of the lakes should increase the effectiveness of the resource management team.

Use of the Landsat imagery for trophic level monitoring depends upon the nature of the reflections from the water bodies, both the intensity of the reflections and their spectral distribution. It is inherent in the method that there be demonstrated some systematic relationship between the reflected energy received by the satellite from the lakes and the trophic state and/or water quality of the lake. Thus development of the relationship depends upon intensive groundtruth measurements combined with study and interpretation of the imagery in terms of the groundtruth. As with interpretation of most remotely sensed imagery the interaction of the interpreter with the imagery is important.

Early in the investigation both the imagery and the groundtruth showed that four types of lakes were represented in the test site area. Moreover, it became apparent that among the important distinctions to be made were those showing changes in the individual lakes from one time period to another as well as the differences among the several lakes.

One image is probably adequate to demonstrate that the lakes are different from one another; it requires a considerable amount of groundtruth to determine the average trophic state of each individual lake at a given moment. However, the changes that each individual lake undergoes during the course of a year is seemingly of greater importance than the actual trophic state on a given date. In other words, the seasonal cycle tells more about the condition of the lake and its long-term trophic state than does the condition on a particular date. It was with the seasonal requirement in mind that the investigation was undertaken. Attempts have been made to relate the groundtruth data to the reflections from the lakes on particular days and to define thereby the changes that each lake passes through during the course of a year.

From a review of several classifications of trophic states of lakes (Sheldon, 1972) the investigators concluded that it would be difficult to classify meaningfully from satellite imagery the trophic states as defined in the general terms oligotrophic, mesotrophic, eutrophic. Rather, it became apparent that it should be possible to use the satellite imagery to study the suspended materials in the water of the shallow lakes and to derive from this information either directly or indirectly some indication of the conditions in the water mass comprising the lakes. Since the intermediate trophic levels are dependent upon the nutrient levels in the water, it is possible to determine the trophic levels only if there is demonstrated a direct and continuing relationship between suspended material loads and the nutrient levels.

Experience has shown that for individual images it is possible to work out such a direct relationship in some instances, but it appears that the same relationship does not carry from one image to another of the same lake nor from lake to lake in the same scene (Boland, 1976). Thus the approach developed in this investigation is to evaluate the imagery and the groundtruth in terms of the individual lake and in terms of the condition of the water mass expressed as an index or combination of indices. Then seasonal changes and/or short-term changes can be monitored without the investigator's becoming enmeshed in the question of in which particular trophic state the lake may be.

1.1 Acknowledgements

Many people assisted in a variety of ways in the investigation. Our sincere appreciation for this help and guidance is acknowledged here.

Dr. A. M. Witherspoon, Department of Botany, North Carolina State University, provided laboratory space and equipment during the entire course of the investigation as well as insight into appropriate analytical methods. James Overton, Frank Matago, John Bullock, Grover Nicholson, and Paul Schlirf aided in the field and laboratory. Dr. L. A. Whitford and Dr. P. H. Campbell assisted with algal species identification. Mr. James Robert, Manager, Mattamuskeet National Wildlife Refuge, and his staff assisted with logistics.

Dr. M. R. Overcash and his technical staff assisted with the nutrient analyses.

Equipment and miscellaneous materials were made available by Dr. E. D. Seneca, Dr. B. K. Huang, Dr. A. F. Schreiner, Dr. J. H. Kerby, Dr. G. Goldfinger, Dr. C. E. Knowles, and Dr. W. L. Switzer. Funds for purchase of the Spectra Lumicon light meter came from the University Environmental Studies Program, Dr. A. C. Barefoot, Director. Dr. T. E. Maki and the North Carolina Fisheries and Wildlife Commission made available aircraft time for two multispectral camera flights over the lakes. Personnel of the North Carolina Office of Environmental Management were consulted as particular needs arose.

1.2 Objectives

The overall objectives of the investigation were to demonstrate the utilitarian aspect of space-acquired imagery for trophic level and water quality monitoring of coastal plain lakes in North Carolina. A special objective was to refine available techniques so that relatively simple optical enhancement procedures might be used by state agency personnel to monitor the lakes systematically and in a cost-effective manner.

An important component of the investigation was to make appropriate state agency personnel aware of the investigation and to keep them advised of its progress so that at an appropriate time it would be possible to transfer the technology developed during the investigation to these people for more or less routine use. The investigation as originally proposed to NASA was based upon concerns expressed by various state agency personnel over the trophic state of Lake Phelps and a general concern of many individuals over the effects that large-scale agricultural activities around Lake Phelps and Lake Mattamuskeet would have upon the trophic levels of these lakes. Cooperation from the U. S. Fish and Wildlife Service and from the North Carolina Division of State Parks was obtained. Informal contact with personnel of these agencies kept them abreast of the investigation, and the personnel contributed information helpful to the investigation. The analytical work undertaken to establish the groundtruth for the interpretation of the satellite imagery represents the most intensive study of the water quality of these lakes ever undertaken.

Representatives of the North Carolian Division of Environmental Management were kept abreast of the progress of the investigation as conditions warranted. Advice and assistance was sought informally. One presentation of preliminary results was made to Environmental Management personnel in February 1977 to elucidate their comments and ideas. During the time period covered by the investigation the Division was undergoing organizational and attendant personnel changes. Thus it was not possible to maintain the level of coordination originally conceived.

Other agency personnel who saw the investigation as of potential benefit to North Carolina water quality monitoring programs are to be found in the University of North Carolina Water Resources Research Institute and the North Carolina Division of Earth Resources - Resource Inventory Group, and Raleigh Office of the U. S. Geological Survey, Water Resources Division.

Although every reasonable opportunity was taken to assure that state agency personnel at various management levels were kept abreast of the investigation, it appears that appropriate distribution of copies of the final report will alert appropriate resource planners and managers to the probable utilitarian aspects of satellite remote sensing for lake trophic state monitoring.

1.3 Test Site

The test site used in the investigation was chosen because of the proximity of the four lakes eventually used in the study and in particular because of the proximity of Lake Mattamuskeet and Lake Phelps. All of the lakes appear on the same Landsat image, and Landsat-1 images showed that the lakes exhibited different patterns of reflectance. Figure 1 shows the location of the lakes in Washington, Tyrrell, and Hyde Counties on the Albemarle-Pamlico Peninsula of northeastern North Carolina.

Two of the lakes, Lake Phelps and Lake Mattamuskeet, were studied more intensively than were the other two, Pungo Lake and New (Alligator) Lake. Weiss and Kuenzler (1976) indicate that Lake Phelps is mesotrophic and Lake Mattamuskeet is α-eutrophic. According to their evaluations of water suitability for various recreational uses, Lake Phelps is good for body contact activity and fair for fishing potential. In contrast, Lake Mattamuskeet is considered to be only fair for body contact water sports and good for fishing. Information on Pungo and New are not available in the Weiss and Kuenzler publication, but work accomplished during this investigation indicates that they can be considered α-eutrophic at least,

TEST SITE LOCATIONS

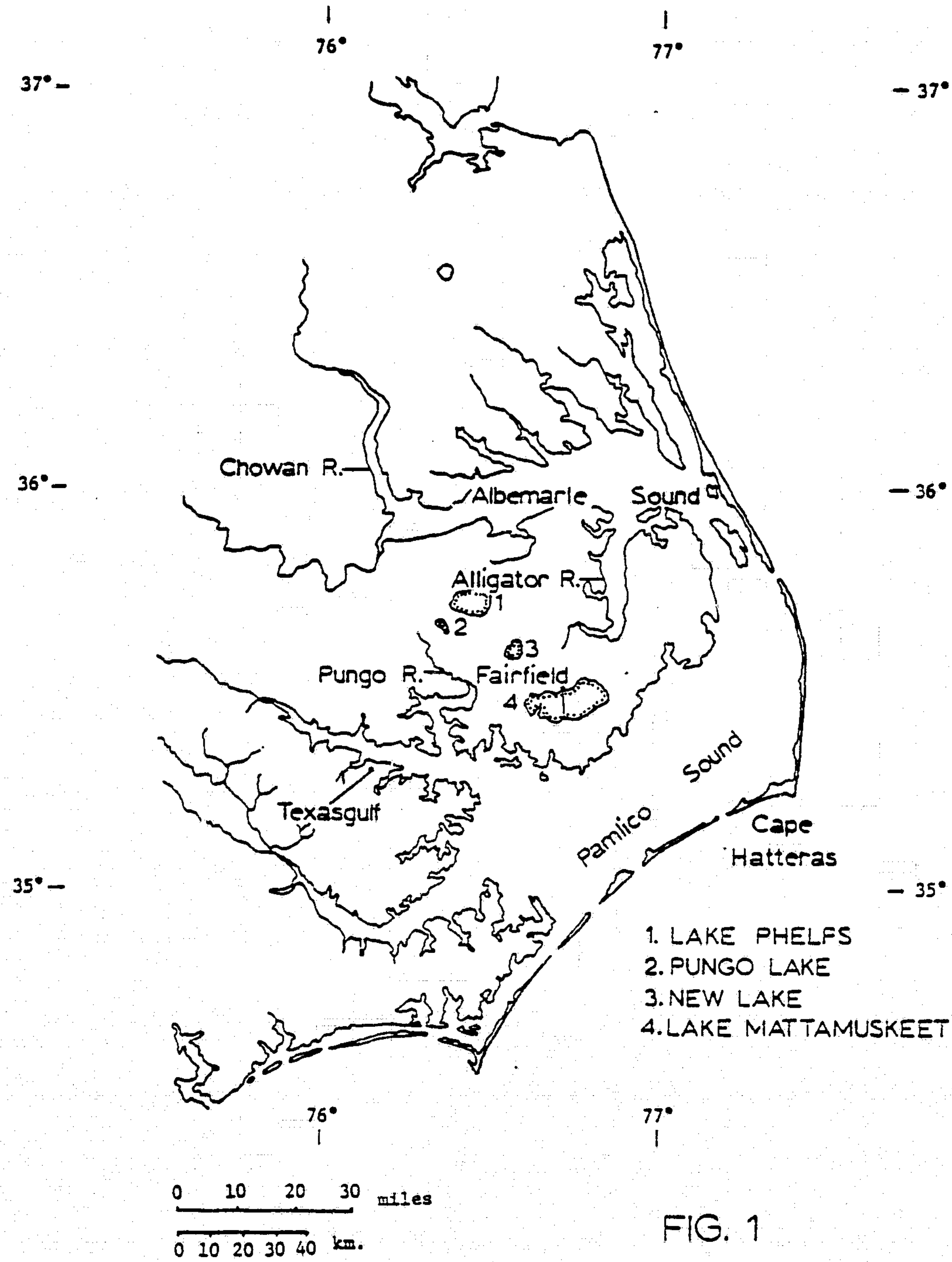


FIG. 1

and that probably Pungo is at least β-eutrophic. Table 1 summarizes the seasonal characteristics of the lakes.

Most of the area within which the lakes are set is 1.5 meters or less above sea level; the highest elevations are along the Suffolk Scarp which lies to the west of the test site area. The lakes themselves lie on the Pamlico surface. Soils are predominantly organic (histosols) with some mineral soils (Lee, 1955). Large-scale agricultural activity has developed adjacent to the lakes (Carter, 1975), and logging activity is dominated by the Weyerhaeuser Company.

The climate of the area is subhumid temperate with precipitation averaging 1275 mm/yr based upon data covering a 56-year span (Heath, 1975). During 1976 rainfall totaled 1111 mm. Winds blew largely from the south-southwest during seven months of 1976 (J. Roberts, personal communication, 1976). Air temperature on the lakes ranged from -11°C in January to 35°C in July (J. Roberts, personal communication, 1976).

Three rivers drain the area, the Alligator, the Pungo, and the Scuppernong. They derive their water from overland flow from the surrounding swampland (Heath, 1975).

The four lakes in the region were originally landlocked, but canals constructed at various times in the past connect them to the natural drainage. The first of the drainage operations was undertaken in 1787 (Heath, 1975).

1.3.1 Lake Phelps

A part of the Pettigrew State Park, this lake covers approximately 6,500 hectares (Heath, 1975) and has an average depth of 1.85 m. The rim of the lake basin, which is marked by a low sand ridge, is at a general elevation of about 5 m and its bottom at about 3 m. Normal overflow occurs through a low area in the rim in the northwestern quadrant of the lake (Heath, 1975).

A canal was dug from the lake to the Scuppernong River in 1787 in an attempt to use a portion of the area for rice culture. The lake is now surrounded by a series of agricultural drainage canals designed to lower the high water table around it.

A thin strip of pond pine (*Pinus serotina*), blackgum (*Nyssa sylvatica*) and bald cypress (*Taxodium distichum*) trees border the lake; beyond this strip about 85 percent of the land is under cultivation. The remaining 15 percent has been left with pocosin vegetation. Macrophytes such as species of rushes (*Juncus* spp.), parrot feather (*Myriophyllum*

Table 1

Lake Seasonal Characteristics

Lakes		Phelps		Pungo		New		Mattamuskeet	
Dates		12 Jun 76	9 Dec 76	12 Jun 76	8 Dec 76	12 Jun 76	8 Dec 76	12 Jun 76	9 Dec 76
I.	Temp. (°C)	22	6	NO DATA	10.3	NO DATA	8.4	28	4
	Transparency (cm.)	189	146		3		8	48	15
	light meter (f8, ASA 100)	250	+250		15		- -	250	+250
	suspended mat. (mg/1)	- -	2.36		769.9		338.4	- -	173.1
	Total solids (mg/1)	- -	48		576		156	- -	2414
	weather	clear	clear		cloudy		cloudy	overcast	clear
	wind speed (mph)	2-5	0		8-15		15-20	2-5	8-10
	wind dir.	N.E.	- -		N.W.		N.W.	N.E.	N.W.
	color (Plat.Cobl.)	- -	5		500		100	- -	25
II.	oxygen (ppm)	9.4	13		11.5		12.0	8.4	12.3
	% saturation	108	97		102		101	108	94
	conductivity (microwatts/cm^2)	- -	90		120		78	- -	3445
	pH	7.5	4.8		5.2		4.8	7.4	6.3
	sulfate (mg/1)	26	- -		- -		- -	104	- -
	chloride (mg/1)	10	7.5		11.1		7.6	1096	1260
	chlorophyll-a (μg/1)	2.18	4.26		14.94		5.48	6.78	5.22
	total K Nitrogen	0.73	0.91		11.39		6.57	1.53	2.69
	NH_3 (mg/1)	0.05	0.025		0.025		0.03	0.01	0.010
	NO_3 (mg/1)	0.195	0.019		0.239		0.059	0.00	0.015
	NO_2 (mg/1)	0.00	0.10		0.018		0.011	0.00	0.010
	Total Phosphorus	0.06	0.09		0.94		0.49	0.08	0.26
	Ortho-phos. (mg/1)	0.02	0.01		0.02		0.02	0.01	0.02
III.	No. cells/ml.	8,559	6,282		19,090		9,696	1,020,241	1,158,912
	Biomass $10^3\mu^3$/ml.	20,172	9,397		10,735		5,172	14,172	9,115

exalbescens), pickerelweed (Pontederia cordata), and eelgrass (Vallesneria americana) grow in the shallow water and shoreline areas (Wilson, 1975).

A sand ridge extends southerly across the lake from near the midpoint of the northwestern shore. The ridge is composed of well-packed sand, and the average depth of its crest is between 1 and 1.3 m. Space-acquired imagery records the presence of this ridge consistently. Another shallow area exists along the southwestern shore and extends eastward. Juncus sp. grows on this shoal, becoming increasingly dense to the east.

Predominant south-southwesterly winds blow across the area (J. Roberts, personal communication, 1976). The winds cause suspended material to be carried toward the northeastern shore, creating new shoal areas where macrophytes and cypress trees can establish themselves. Much of the suspended material appears to originate from the lake shores and surrounding fields, apparently carried to the lake in dust storms. The public boat launching ramp of the state park is located in the midst of the sediment buildup.

Data collected during the present investigation support earlier casual observations about this area as well as those of Growell (1966), namely that the water over the developing shoals usually has a greater suspended load, a greater nutrient content, and a greater biomass level than any other part of the lake. The higher levels are particularly evident when there has been just prior to sampling or there is at the time of sampling a wind from the south-southwest blowing across the lake.

Drainage activities in the surrounding area combined with the infilling of the basin is apparently decreasing the depth of the water and aiding in the extension of transitional plants into the lake. The migration of transitional plants into a lake indicates the trend from an aquatic to terrestrial environment. This initial rise in natural eutrophication to eutrophic conditions later drops off when the water body becomes senescent (Lindeman, 1942).

The deeper waters on either side of the ridge have a layer of organic matter (pulpy peat) lying over the sand, and blue-green algae forms a mat over this part of the bottom. Existence and approximate extent of the mat was confirmed by diving, and the blue-green algal mat was found to be absent in areas of sandy bottom.

Low turbidity levels characterize the water of Lake Phelps, and except for winter months when suspended material is present in relatively large quantities in the water mass, all four colors of the modified Secchi disc can be seen when the disc is on the bottom. During the winter months the turbidity increased along the bottom, obscuring the disc at an average distance of 59 cm off the bottom. Comparison of the water samples with the ISSC-NBC color chips (Smith and Anson, 1968) demonstrated that the lake could be considered white (no color), Color No. 263.

1.3.2. Pungo Lake

Pungo Lake is part of the Pungo National Wildlife Refuge and has approximately 1,140 hectares of surface area (Heath, 1975). The lake, lying between elevations of 3 and 5 m has an average depth of 0.85 m. Canals were dug from Pungo and New Lakes to the Pungo River in 1843 to drain the surrounding area for cultivation (Heath, 1975). Migrating waterfowl use the lake during the winter months.

Vegetation typical of pocosins ("swamp on a hill") surrounds Pungo Lake, and macrophytes such as bulrush (Scripus sp.) are located along portions of the perimeter of the lake. A flat sandy shore extends into the lake to a water depth of 0.32 m on the southwestern side of the lake. The eastern part of the lake is its deepest portion; stumps and a layer of peat are present on the bottom here. The peat and the associated stumpy character of the bottom extends onto the eastern shoreline.

Pungo Lake maintains a high turbidity level. The extinction depth for a Secchi disc is typically of the order of 3 cm. Comparison of the water of Pungo Lake with ISCC-NBC color chips (Smith and Anson, 1968) established the lake water color as black (Color No.65). Water from which the suspended matter has been filtered is essentially clear or white (ISCC-NBC Color No. 263).

1.3.3 New (Alligator) Lake

New Lake, privately owned, covers 1,990 hectares (Heath, 1975). The lake has an average depth of 1.33 m and lies between elevations of 1.5 and 3 m.

Bald cypress, pond pine and blackgum trees grow along the edge of the lake. Macrophytes, including pondweed (Potamogeton sp.) and bulrush (Scripus sp.), occupy portions of the lake's edge (Smith and Baker, 1965).

Cultivation accounts for about 40 percent of the land use surrounding the lake; the other 60 percent of the land is occupied by typical pocosin vegetation. Stumps are exposed along the perimeter of the lake, and logs are found on the hard black clay and detritus bottom (Smith and Baker, 1965).

New Lake is always turbid with a typical Secchi disc depth of 12 cm. As indicated by this typical Secchi disc depth, New Lake is less turbid than Pungo, and the water color of New Lake can best be described in the ISCC-NBC color system as Color No. 59, Dark Brown. Filtered water samples showed a clear color (ISCC-NBC Color No. 263).

1.3.4 Lake Mattamuskeet

Lake Mattamuskeet, covering 17,245 hectares, and part of Mattamuskeet National Wildlife Refuge, is the largest natural lake in North Carolina (Heath, 1975). The average water depth is 0.73 m, and the bottom lies below the 1.5 m contour.

Two canals were dug between 1838 and 1849 to drain the northeastern region around the lake for agricultural purposes (Heath, 1975). A large-scale farming operation attempted to drain the lake and farm the bottom in 1915. This project finally failed, and the federal government purchased the lake and surrounding land for the wildlife refuge in 1934 (Ward, 1949).

A causeway constructed in the period 1941-1942 (Cahoon, 1953), cuts the lake essentially into two separate lakes which are connected by five culverts beneath the causeway. The portion of Lake Mattamuskeet east of the causeway with a sandy bottom was once cultivated; the portion west of the causeway has a peaty bottom and was never under cultivation.

Lake Mattamuskeet is surrounded by a thin strip of bald cypress, loblolly pine (*Pinus taeda*) and black gum trees. Outside of this strip the main land use is for agriculture; dwellings are concentrated along the northern shoreline in the vicinity of Fairfield (Fig. 1). Some of the marshy areas adjacent to the lake have been impounded to increase macrophyte production as feed for migrating wildfowl (Bond, 1975). The macrophytes include cattails (*Typha* spp.), cordgrass (*Spartina patens*), spikerushes (*Eleocharis* spp.), millets (*Panicum* spp.), bulrush (*Scirpus americanus*), and smartweed (*Polygonum* spp.) (Yelverton and Quay, 1959).

Lake Mattamuskeet is almost completely surrounded by a system of interconnecting canals. Five main canals drain the lake; four of them carry water directly into Pamlico Sound. Tide gate structures control the flow of water between the lake and the sound, permitting undirectional flow from the lake to the sound.

Waterfowl provide an important nutrient source for the lake; however, in recent years the total number using the lake have declined. One factor believed to be contributing to this decline is the increased cultivation in the mid-Atlantic region (Delaware, Maryland) along the Atlantic Flyway. This cultivation keeps the birds farther north in the many unplowed fields. Another reason for the decline is believed to be the poor waterfowl habitat that now exists within the refuge (Bond, 1975). Waterfowl utilize the lake mainly during the winter months of each year.

The lake is shallow, and muskgrasses (Charceae family) cover large areas of its bottom. Chief areas in which these submerged plants are located are found along the eastern part of the causeway, extreme western end, and in a band running along the southern to the eastern shore of the lake (Florscehutz, 1975). The dominant species found in the Charceae family are *Nitella hyalina*, *Nitella tenuissima* and *Cara zeylanica* (Wood, 1954).

Other submerged aquatic plants found are naiad (*Najas* sp.), wild celery (*Vallisneria americana*, milfoil (*Myrophyllum spicatum*), and redhead grass (*Potamogeton perfoliatus*) (Bond, 1975). Milfoil is isolated in an impoundment located in the southwestern part of the refuge (L. Fulton, personal communication, 1976).

The turbidity level of the water is dependent on the wind conditions because of the shallow depth of the lake. Water transparency can change from clear so that the bottom can be seen to Secchi disc depths of less than 13 cm in a matter of minutes as local breezes arise. Comparison of water samples with the ISCC-NBC color chips (Smith and Anson, 1968) show the lake to be gray-yellow-brown (Color No. 80). The color of the filtered water is slightly yellowish and is believed attributable to the presence of dissolved solids. Aside from the slight yellowish tint the color of the filtered Lake Mattamuskeet water is similar to that of the filtered water from the other three lakes used in this study.

Bars have formed at either end of all five culverts beneath the causeway. Rosebay Canal, located in the extreme western part of the lake, seems to be the main outlet for the western portion of the lake. Salinity in the western portion of the lake is generally lower than that of the eastern part.

Data collected during this investigation show the existence of differences in the physical, chemical, and biological parameters on either side of the causeway (Appendix). The predominant wind direction during the year is from the south-southwest (J. Roberts, personal communication, 1976). Sediment transport as a result of the wind activity has caused the northeastern part of the lake to become very shallow.

The seasonal characteristics of Lake Mattamuskeet, as well as of the other lakes, are found in Table 1, and Table 2 from Heath (1975) summarizes the physical characteristics of the lakes.

Table 2

Physical Characteristics of Lakes
(from Heath, 1975) *

Lake name	Surface area (square miles)	hectares	"Average" depth (feet)	meters	"Average" level above sea level (feet)	meters	Bottom relative to sea level (feet)	meters	Altitude of land surface above sea level (feet)	meters	Storage (Millions of gallons)	millions of liters
Matta-muskeet	66.7	(17,245)	2.5	(0.76)	0.5	(0.15)	-2	(-0.61)	3-5	(0.91-1.52)	34,772	(131,626)
Phelps	25.0	(6,500)	5	(1.52)	10	(3.05)	5	(1.52)	11-14	(3.35-4.27)	26,066	(98,671)
New	7.7	(1,990)	3	(0.91)	9	(2.74)	6	(1.83)	10-13	(3.05-3.96)	4,817	(18,234)
Pungo	4.4	(1,140)	3	(0.91)	10	(3.05)	7	(2.13)	11-14	(3.35-4.27)	2.753	(10,421)

* English units were used in original table; approximate S.I.U. units are shown in parentheses.

2.0 SUMMARY OF EARLIER WORK

2.1 Test Site Lakes

A considerable amount of work has been done recently in the Albemarle-Pamlico peninsula of North Carolina, yet information about the lakes in this region is scarce except in the case of Lake Mattamuskeet National Wildlife Regue. Cahoon (1953) gives a brief history of the lake and describes the removal of carp (*Cyprinus carpio*) from the lake. Wood (1954) describes the species from the Characeae family (muskgrass) that have invaded the lake bottom since the carp removal. Yelverton and Quay (1959) define the vegetation communities within the refuge and their relationship to Canada geese. Finally Florscehutz (1975) has produced maps of the aquatic and terrestrial vegetation found within the refuge boundaries.

Other, more recent studies have been conducted on Lake Phelps. Growell (1966) surveyed the lake and included values for some physical, chemical and biological parameters. Wilson (1975) described the vegetation found within Pettigrew State Park, which is located along the northern shore of the lake.

General studies of the Albemarle-Pamlico region have included data concerning the lakes and the land immediately surrounding them. Dolman and Buol (1967) describe a typical organic (histosol) soil of the tidewater region located near Pungo Lake. Carter (1975) presents the background of the largescale farming operation that now exists in this region. Heath (1975) discusses the hydrology of this peninsula and includes some physical characteristics of the four lakes. Finally, Weiss and Kuenzler (1976) summarize the trophic state of Lake Phelps and Lake Mattamuskeet.

2.2 Eutrophication

The term eutrophication has evolved so that its meaning now encompasses more than was meant when the term was first coined. Weber in 1907, cited in Boland (1976), first used the term to describe the high nutrient levels in German peat bogs. Vollenweider in 1968, cited in Boland (1976), concluded that eutrophication had come to mean the "enrichment in nutrients and the ensuing deterioration of quality" of water body.

Eutrophication can be considered a natural aging process of a water body. The water body changes from an aquatic ecosystem to a terrestrial one. The process can be accelerated by the influence of man, and the hastening of the process by man is known as "cultural eutrophication" (Liken, 1972). The lakes that have been studied during this investigation lie in an environment that is conducive to cultural eutrophication.

2.3 Trophic State

Because of the need for demonstrating the distance along the path of eutrophism taken by a given water body, there has developed the concept of trophic state. This concept identifies a body of water by its "relative level of nutrient richness and nutrient utilization in organic production" (Weiss and Kunzler, 1976). Many parameters have been tested as indicators of the trophic state of a given body of water. These have been biological, chemical, and physical in nature, singly or in combination.

Fruh, et al (1966) and Hooper (1969) concluded that the most of the parameters used in the past to define various trophic states and eutrophic conditions have had some measure of success. Most of the relationships seem to be indirect, and there does not seem to be a universally applicable combination of parameters which when taken in a standard fashion define unequivocally the trophic levels. Definitions of trophic state and the data to be used in indicating a given trophic state are not yet systematized. Some of the methods that have been used in the past include transparency, algal cell counts, algal biomass, chlorophyll-a, suspended solids, total solids, pH, oxygen, rooted aquatic plants, fish species, carbon-14, zooplankton changes, bottom fauna, mean depth and nutrients (Fruh, et al, 1966).

Evaluation of the literature and of the nature of the lakes under study indicated to the authors that the Trophic State Index (Carlson, 1977) seemed most meaningful. This index represents an approach that takes into account the fact that several factors controlled the trophic state of the shallow coastal plain lakes. Similarly, it was recognized that the Landsat imagery contained within each of its several bands a composite record of what was reflected from the lakes.

2.4 Remote Sensing Studies of Lake Trophic States

Use of remote sensing techniques and methodology for water quality parameter detection has been of considerable interest for the past decade. Leeman (1972) studied the spectral responses of many earth resources, and he found that the spectral reflectance from each body of water is dependent upon many factors. The study indicated that in a large number of cases, if not most, this reflectance is unique to the particular water body.

Two separate groups of remote sensors have been studied for application to water quality parameter detection and monitoring. One of these groups, which has been used only experimentally thus far, includes radar and laser methodology. These are the active sensors. The second group comprises the passive sensors such as multispectral scanners and photography. It is to the second group that the data obtained from Landsat belongs.

Many investigators have attempted to correlate water quality parameters and trophic states of lakes with Landsat data. Scherz et al (1974) defined a relationship between light reflectance from the water and turbidity. A brightness change was correlated with the presence of living plant material. Horne (1976) demonstrated a linear correlation of algae concentration with reflectance in the near-infrared region of the spectrum. Blackwell and Boland (1975) defined a correlation between Landsat data and EPA water quality information of many northern lakes from Landsat data using computer techniques. These lakes differ in their depth and surroundings from the lakes studied in this investigation. Werzernak et al (1976) used multivariate analysis techniques to study the applicability of low level multispectral scanner data to the determination of the trophic states of lakes. They found a good correlation between the trophic states as defined by the water sampling and the scanner data which indicated various differences in reflectances from the water. The bands of the spectrum used in this study were much narrower than the Landsat bands.

McKeon and Rogers (1976) used computer processing techniques to develop a water quality map of Saginaw Bay, Michigan. They used linear regression techniques to develop a map showing distribution and concentration of nine water quality parameters in the bay.

Polycn and Lyzenga (1973) using narrow bands on a multispectral scanner were able to differentiate between water masses with different amounts of chlorophyll. Their approach was one of ratioing various bands and of taking differences between different bands and then ratioing the difference to a third band. Blanchard and Leamer (1973) developed a series of curves showing the relationships between reflectance and suspended sediment and algae. Curves for reflectance from water containing selected algae were developed by Gramms and Boyle (1971). Both of these laboratory-oriented studies showed decreasing peak intensities with increasing algae and sediment concentrations.

Photographic enhancement techniques are described by Yost (1974), and Welby (1976) has described one approach to the use of photographic materials in monitoring the trophic conditions of the Chowan River. Scarpace, et al (1974) used densitometric measurements of Landsat Band 5 imagery of 37 lakes in Wisconsin to establish an algorithm relating groundtruth and the satellite data to trophic states of the lakes. They worked primarily with Band 4 and Band 5, finding an exponential relationship between the Secchi disc depth and the density of the lakes.

3.0 PROCEDURES

The procedures used during the investigation can be conveniently divided into two broad groups: those concerned with groundtruth collection and analysis and those concerned with the study of the satellite imagery. Systematic collection of groundtruth began on 12 June 1976 and extended through 20 May 1977.

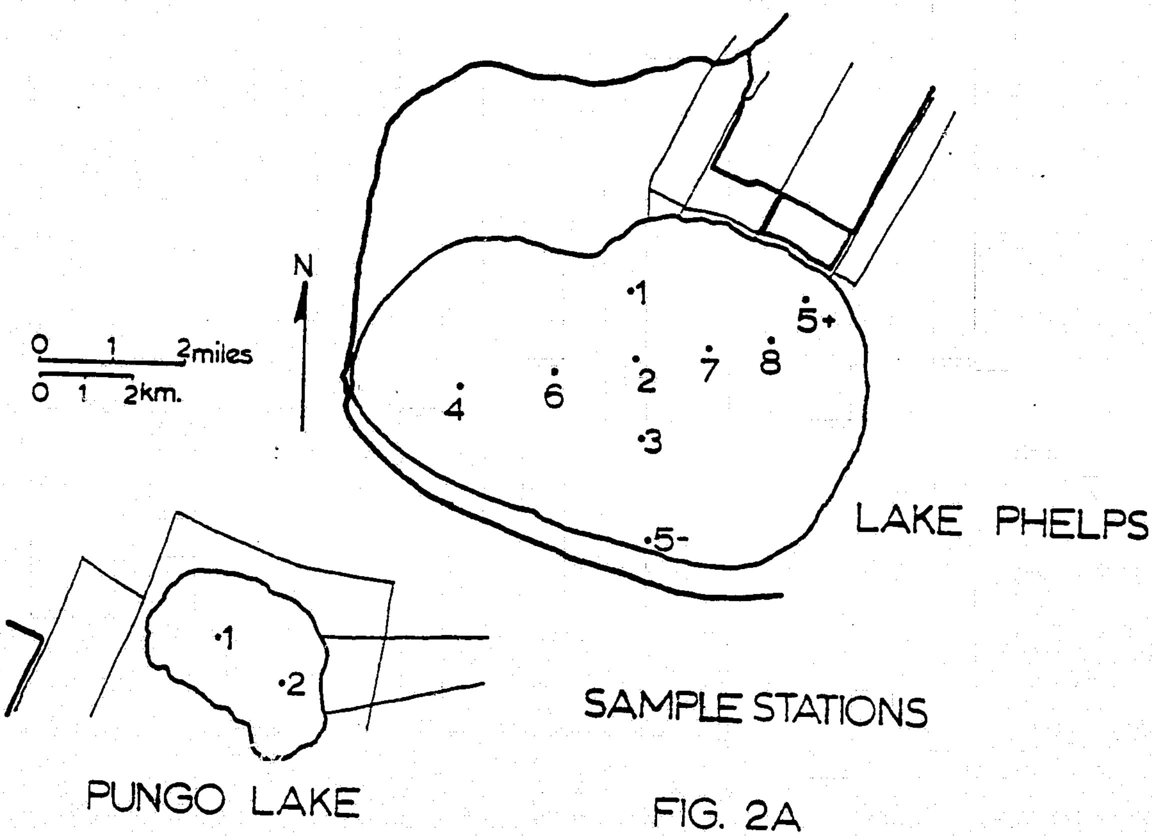
3.1 Groundtruth

Sampling, and thus study efforts, concentrated upon Lake Phelps and Lake Mattamuskeet because of their recreational value and because of their importance in the management of the wildlife resource of the northeastern part of the North Carolina coastal plain. Also, because of the cooperation of the state and federal agencies responsible for the management of the two lakes access was relatively easy. Pungo and New Lake were sampled only seasonally because of financial constraints and because it appeared that the comparison between Phelps and Mattamuskeet would be most meaningful in terms of the proposed study.

Eight stations were initially established on Lake Phelps, but a ninth, a shoreline station, was added. Twelve stations were established for Lake Mattamuskeet, one being moved during the investigation so that samples from it would reflect more representatively the water mass around it. Each station, marked by a white plastic bottle attached to the lake bottom, was occupied at the time of each sampling (Fig. 2). The sample stations were established by compass bearings to prominent shoreline features so that the stations could be reoccupied in the event the buoys were lost.

Two stations were established on Pungo Lake and three on New Lake. None of these was marked with buoys because of the relatively small size of the lakes and because sampling was done only on a seasonal basis. Precise relocation of sample stations did not seem necessary for the study of these lakes.

Sampling was scheduled to coincide with the overpass of Landsat-2 at approximately 10:00 A.M. EST during the months of June, July, August, September, and October 1976 and February, March, April, and May 1977. In November, December, and January only one sampling run per month was made because of the minimal amount of biological activity in the lakes during the winter months, and more frequent sampling was thought not to be required. Pungo and New Lakes were sampled in October and December of 1976 and again in March and June 1977.

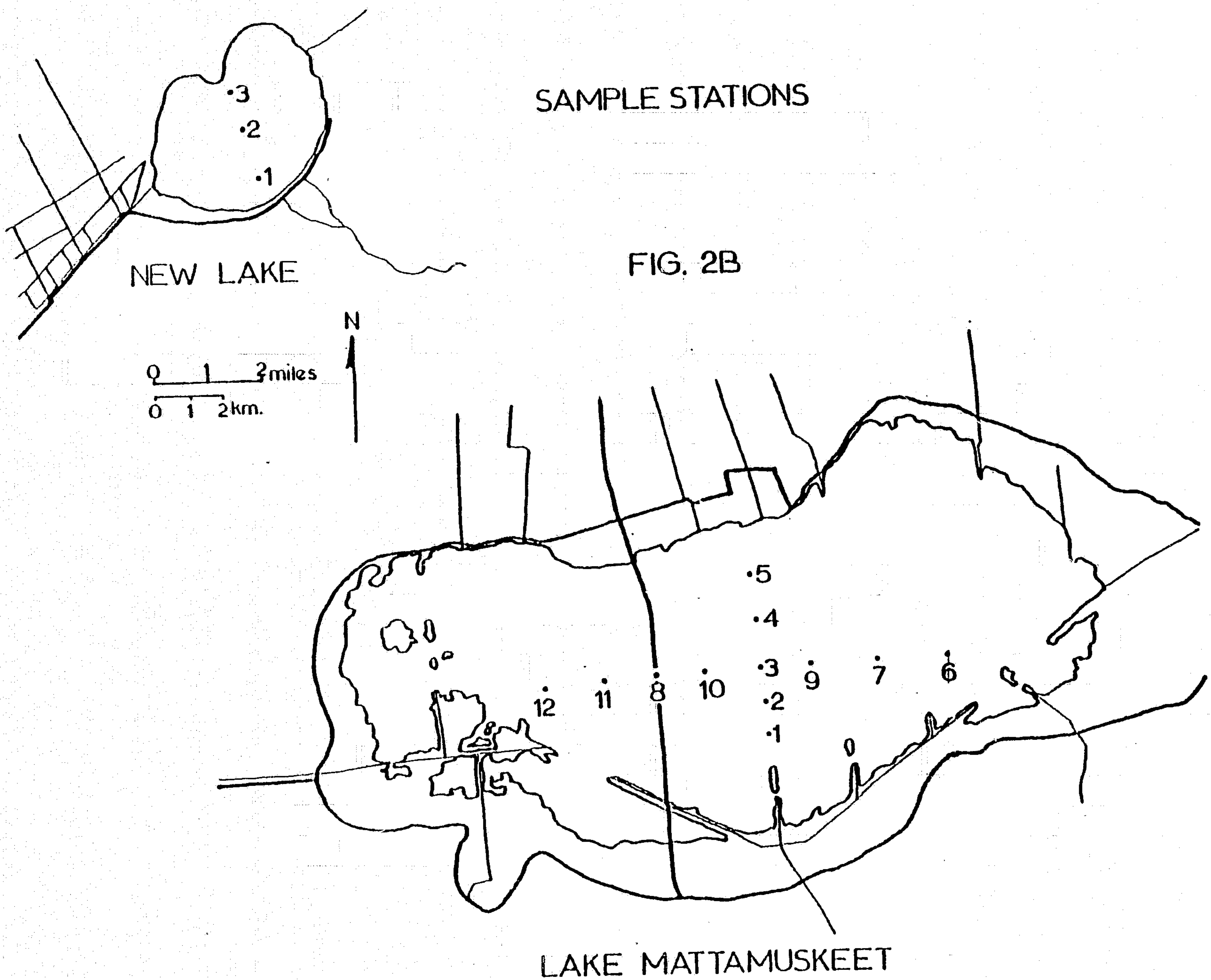


SAMPLE STATIONS

FIG. 2A

SAMPLE STATIONS

FIG. 2B



Shallow draft boats were used to collect samples in all four lakes. The water samples were collected in 500 ml polyethylene bottles and taken directly from the water mass within 15 cm of the surface. Four 500 ml samples were collected at each station. One was collected for nutrient analysis; one for chlorophyll-a analysis; one for phytoplankton study; and one was collected for determination of suspended matter and total solids.

The sample collected for the nutrient analysis was placed immediately after collection into an ice-filled chest. A 20 to 250 ml aliquot of the chlorophyll-a sample was filtered in the field, and the filter stored in an aluminum-covered vial for later analysis. The size of the aliquot was dependent upon the suspended load and its filter-clogging characteristics. Filtering continued until the filter became clogged. The sample taken for phytoplankton determinations was preserved by placing in it 1 to 2 ml of Lugol's solution. On occasion a fifth sample was collected for living phytoplankton identification.

The sample collected for determination of suspended matter was also used for conductivity and color determinations in the laboratory. Temperature, transparency, reflected light, weather conditions, oxygen, and pH were determined in the field together with the spectroradiometric measurements.

Because both Lake Phelps and Lake Mattamuskeet could not both be sampled simultaneously with the Landsat-2 overpass, the two lakes were sampled alternately with the overpasses. Thus if on one date Lake Mattamuskeet was sampled coincident with the satellite overpass, Lake Phelps was sampled in the afternoon; on the next overpass date Lake Phelps was sampled coincident with the passage of Landsat, and Lake Mattamuskeet was sampled in the afternoon. Pongo and New Lakes were sampled as near to the satellite overpass as practicable, but no more than 24 hours before or after the satellite pass. Table 3 lists the various types of groundtruth obtained.

3.2 Groundtruth Analysis

3.2.1 Physical parameters

Temperature was determined using an IBC thermister probe graduated in Celsius units.

Table 3

Groundtruth

Physical

- Temperature
- Transparency
  - Reflected light measured by Zeiss Light meter at ASA100,f8.
  - Secchi disc
- Suspended matter
- Total solids
- Color
  - Munsell color
  - Platinum - cobalt disc
- Weather conditions
- Spectral reflectance characteristics
  - (ISCO Model SR Spectroradiometer with a 1.9 m fiberoptics probe)

Chemical

- Oxygen
- pH
- Conductivity
- Chlorophyll-a
- Sulfate
- Chloride
- Nitrogen
  - total nitrogen
  - ammonia
  - nitrate
  - nitrite
- Phosphorus
  - total phosphorus
  - ortho-phosphorus

Biological-Phytoplankton

- Species identification
- Cell counts
- Biovolume

Transparency (turbidity) was measured with a colored 18 inch diameter Secchi disc divided and painted so that there was a white quadrant, a red quadrant, a green quadrant, and a blue quadrant (Welby, 1976; Eister and Stepnak, 1967). The reflectance characteristics of the four quadrants were measured with a General Electric GE-Hardy reflecting spectrophotometer.* The curves are shown as Fig. 3. Extinction depths for a standard white Secchi disc were determined and found to be the same as the depths obtained from the white quadrant of the modified Secchi disc.

Depth to the extinction of each color was recorded together with the amount of reflected light as measured by a Zeiss light meter. The extinction depths, measured in inches from a scale on the wooden handle of the Secchi disc, were determined by the same observer at all stations during a given sampling period.

The light meter reading was made at the same angle as that used by the observer in establishing the extinction depths. A standard meter setting of f8 and an ASA film speed of 100 was used when the light was being measured. This particular setting lies in the midrange of the light meter sensitivity.

Use of the modified Secchi disc was an attempt to determine the extinction depth for the different parts of the spectrum. The light meter readings were to be used to adjust for different light conditions (Welby, 1976).

Suspended matter was determined through use of a modified Strickland and Parson (1972) procedure. GF/A glass fiber filters were used, and the filters were dried in covered petri dishes for two days. The results were recorded in mg/l.

Total solids were determined by evaporating 200 ml of the sample in an evaporating dish at 70°C for approximately two days. The method is modified from that described in Standard Methods (American Public Health Assoc., 1971).

Color of the unfiltered water was determined from a standard platinum-cobalt disc (American Public Health Assoc., 1971). In addition, the average water color was determined by comparison with a Munsell color chart (Smith and Anson, 1968).

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* Citation of a manufacturer's name does not imply endorsement of the equipment but is given for descriptive purposes only.

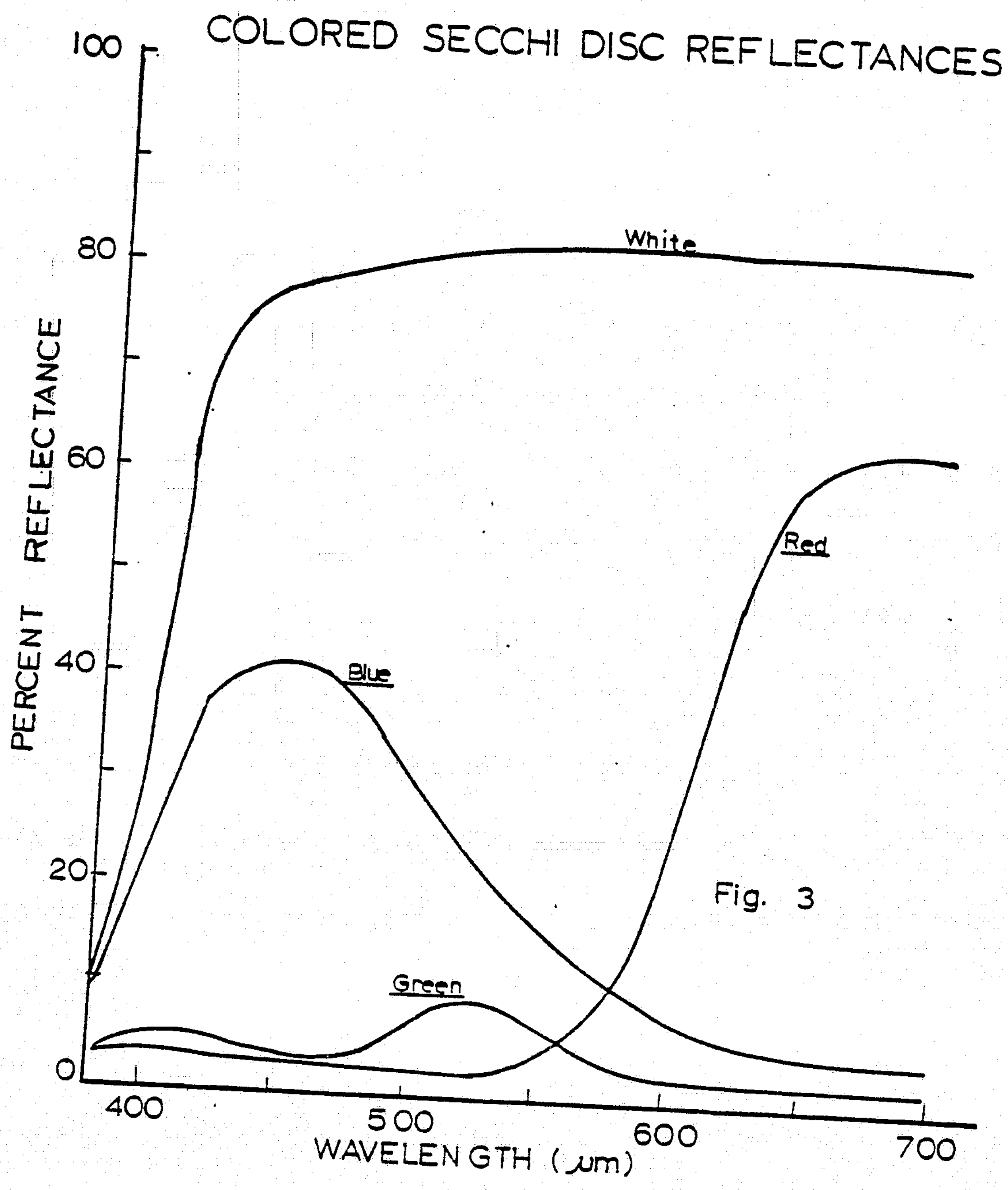

COLORED SECCHI DISC REFLECTANCES
100
80
60
40
20
0
PERCENT REFLECTANCE
White
Red
Blue
Green
400
500
600
700
WAVELENGTH (μm)

Fig. 3

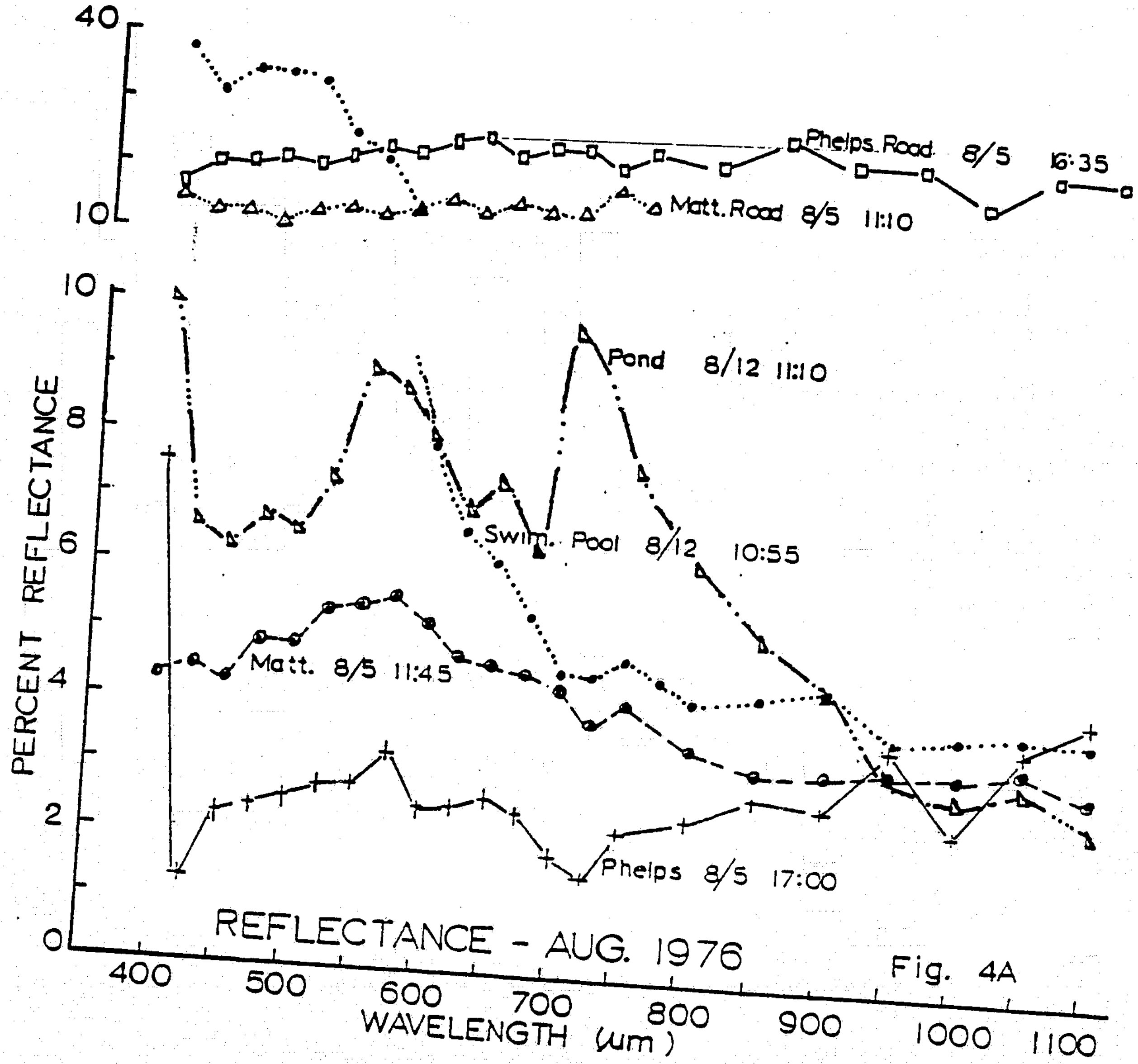
Weather conditions were determined at each station during the sampling period. Wind direction was determined by compass bearings and wind speed by a handheld wind gage. Records from the meteorological station at Lake Mattamuskeet were also used.

Spectral reflectance characteristics were measured as close to the satellite overpass as possible at times when there was little or no cloud cover. Spectroradiometer measurements of several standard features as well as the reflectances (400 um - 1100 um) from the waters of the lakes were measured with an ISCO Model SR Spectroradiometer.

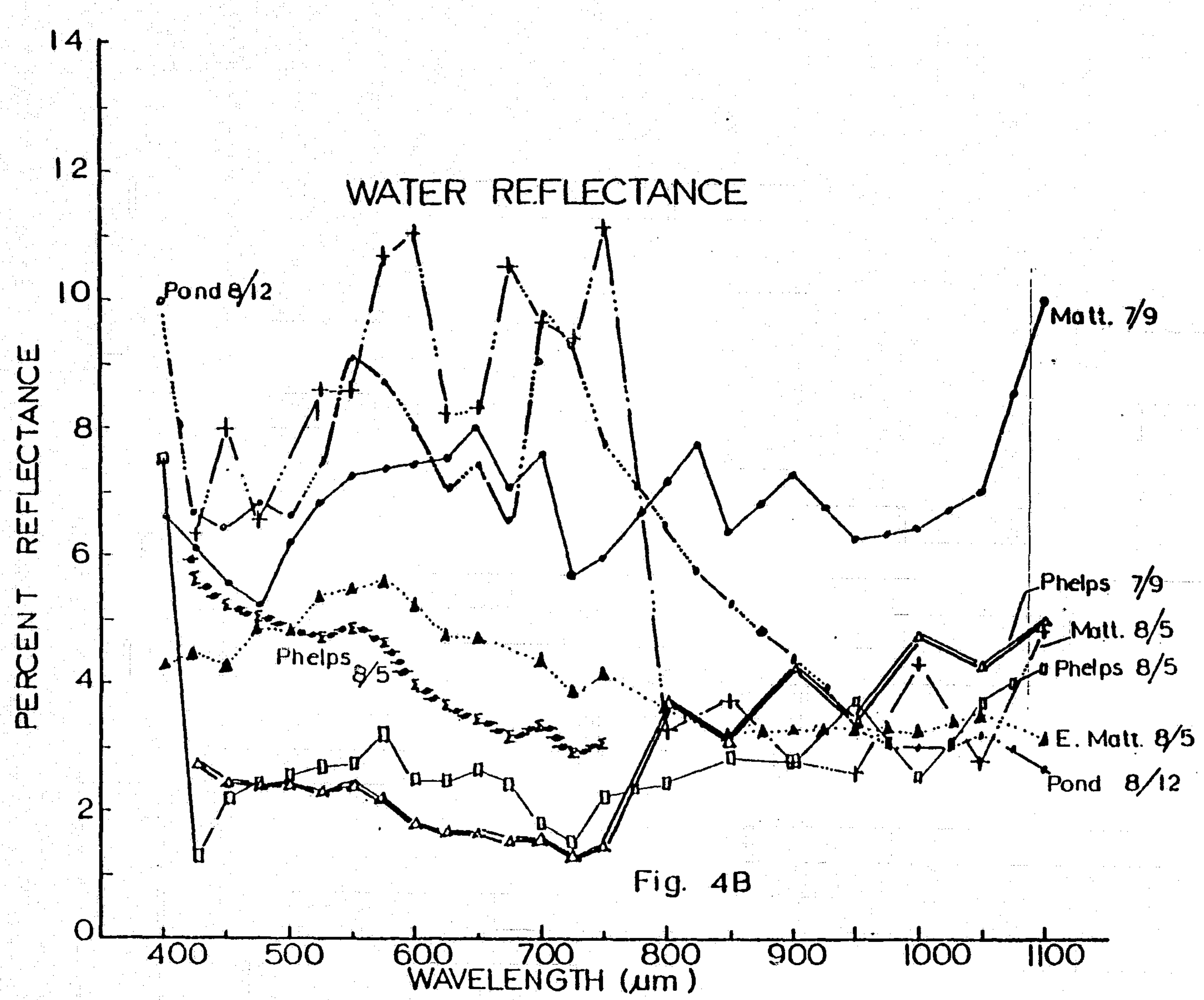
Station 5+ in Lake Phelps and Station 8 in Lake Mattamuskeet were set as standard locations for spectroradiometer measurements for the two lakes. The reference areas for reflectance were the dock road on the northeast side of Lake Phelps and the roadway on the causeway across Lake Mattamuskeet adjacent to Station 8. Also a standard photographic 18% reflectance gray scale was measured.

The measurements were taken with a 1.9 m fiber optics probe attached to the spectroradiometer. The field of view is 180 degrees. The head of the probe was held approximately 30 cm above the surface whose reflectance was being measured, and incoming radiation was measured at 1.9 m above the reflecting surface.

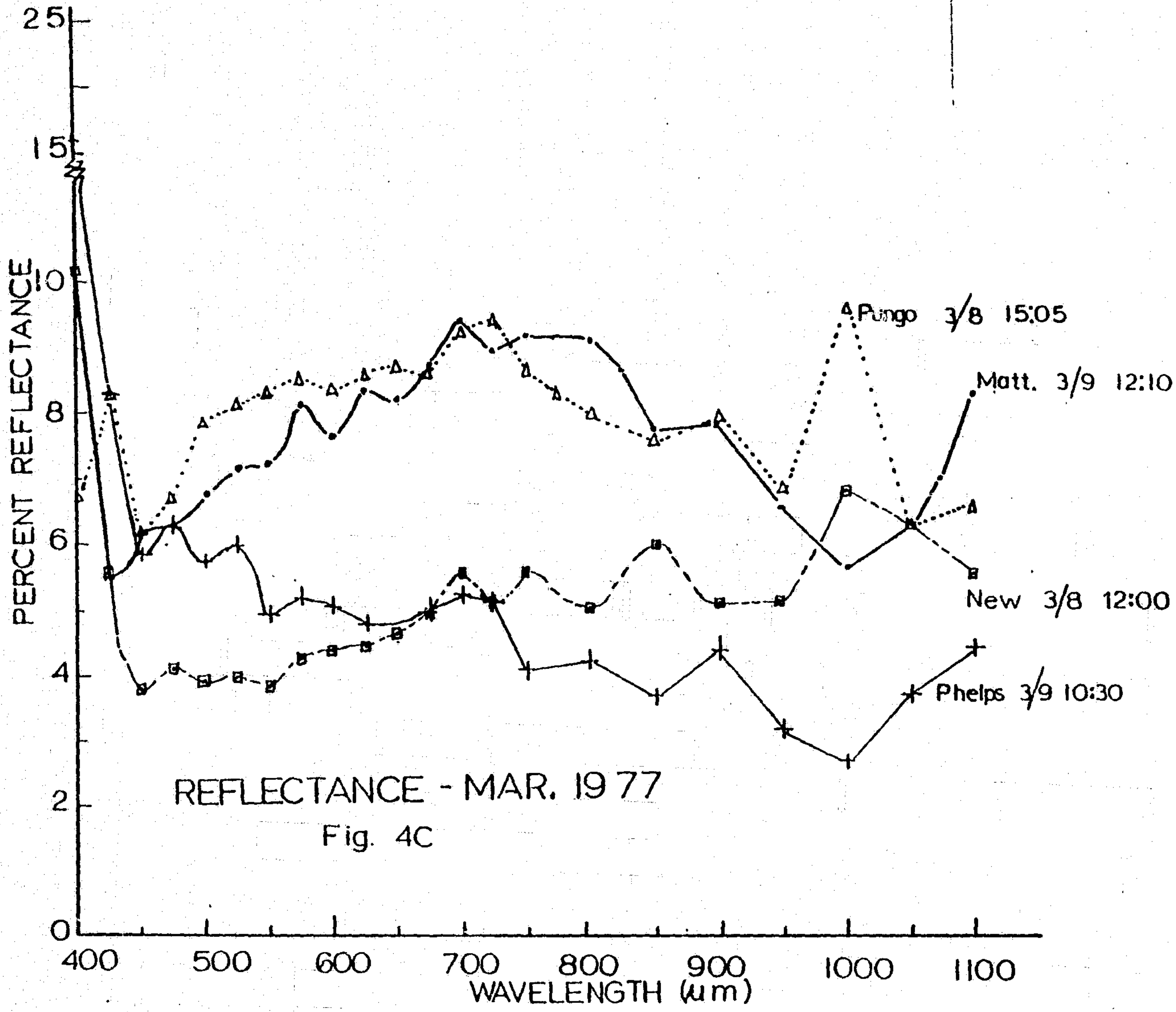
For comparison purposes the reflectance from the white-bottomed swimming pool of the North Carolina State University Faculty Club was measured on 12 August 1976. Water depth at the point of measurement was approximately 3 m, and the measurement was made from the end of a 1 m diving board. The day was bright and clear, and the measurement was made at approximately 10:30 A.M. EST. Spectroradiometric measurements of a nearby algae-enriched dairy farm pond were also made shortly after the measurements on the swimming pool. Dominant algal species was Anacystic cyanca (blue-green) with a biomass of about 1.2×10^7/ml. Typical spectroradiometric curves for both lake sites and for the sites on North Carolina State University property are illustrated in Fig. 4 as are curves for incident light for general comparative purposes.



40
10
Phelps Road 8/5 16:35
Matt. Road 8/5 11:10
10
8
6
4
2
0
PERCENT REFLECTANCE
Pond 8/12 11:10
Swim. Pool 8/12 10:55
Matt. 8/5 11:45
Phelps 8/5 17:00
REFLECTANCE - AUG. 1976
Fig. 4A
400
500
600
700
800
900
1000
1100
WAVELENGTH (μm)

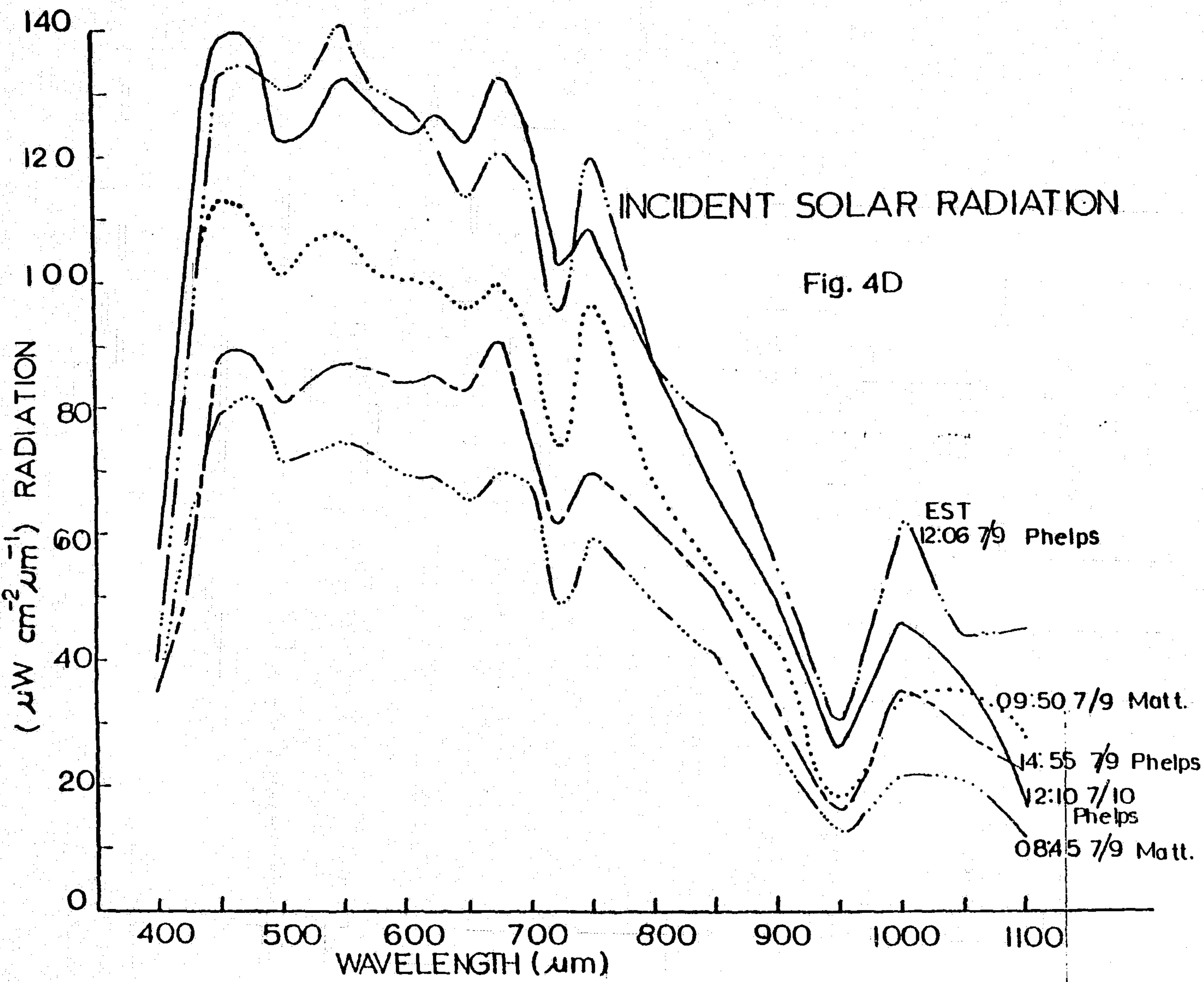


WATER REFLECTANCE
PERCENT REFLECTANCE
WAVELENGTH (μm)
0
2
4
6
8
10
12
14
400
500
600
700
800
900
1000
1100
Pond 8/12
Matt. 7/9
Phelps 7/9
Matt. 8/5
Phelps 8/5
E. Matt. 8/5
Pond 8/12
Phelps 8/5
Fig. 4B



REFLECTANCE - MAR. 1977

Fig. 4C



INCIDENT SOLAR RADIATION
Fig. 4D
(µW cm⁻² µm⁻¹) RADIATION
WAVELENGTH (µm)
140
120
100
80
60
40
20
0
400
500
600
700
800
900
1000
1100
EST
12:06 7/9 Phelps
09:50 7/9 Matt.
14:55 7/9 Phelps
12:10 7/10
Phelps
08:45 7/9 Matt.

3.2.2 Chemical parameters

Oxygen content of the water at each station was determined in the field with an IBC polarographic probe. Calibration was accomplished in both the laboratory and the field according to the manufacturer's specifications. Percent oxygen saturation was also determined.

Conductivity measurements were made in the laboratory with a Beckman conductivity meter. The results were recorded in micromhos/cm (American Public Health Assoc., 1971).

pH was determined in the field with an Instrumentation Corporation portable glass electrode field pH meter. Calibration was done in the field with standard pH 7 and pH 3 solutions.

Chlorophyll-a determinations utilized a Turner III Fluorometer and followed the method of Strickland and Parsons (1972). In the case of the present analyses however, a standard door of relatively low sensitivity was used. Such a door was required for the analyses because the chlorophyll values are much higher in the fresh water systems than in the sea water systems studied by Strickland and Parsons (1972).

The GF/A glass fiber filter was substituted for the GF/C filter in the analsis. A pheophyin correction was also applied to the values according to the equation given by Strickland and Parsons (1972). Calibration was achieved through use of a pure chlorophyll-a extract run on a Cary-14 spectrophotometer and by application of the UNESCO equation (Strickland and Parsons, 1972).

Sulfate determinations were made following slightly modified Standard Methods (American Public Health Assoc., 1971) procedures. A 25 ml sample was alternately stirred and settled for periods of one minute for a total elapsed time of 5 minutes. The analysis was run on a Bausch and Lomb Spectronic 20 Spectrophotometer ar 440 µm. The procedure used is described by Rhus (1971).

Chloride content of the samples was established by a modified method for autoanalysis (Technicon, 1970) and reported as mg/l.

Nitrogen is reported in the form of total nitrogen, ammonia-nitrogen, nitrate-nitrogen, and nitrate-nitrogen. Determinations were made by standard methods modified slightly from those described for autoanalyzers (Technicon, 1970, 1974). The results were recorded in mg/l.

Phosophorus is reported as total phosphorus and ortho-phophorus, and the analyses were done following methods described for autoanalyzers (Technicon, 1974), but modified slightly for the particular system used. The results are reported in mg/l.

3.2.3 Biological - Phytoplankton Parameters

Species determination: Phytoplankton species were identified through use of a Leitz compound microscope and a Zeiss inverted microscope. Most identification was done on samples to which Lugol's solution had been added as a preservative, although some identification was undertaken on samples containing living specimens. Hyrex mounts were used for diatom identification. The Utermohl technique described by Lund (1958) was used to estimate the proportions of various species present in individual samples. Species identification was accomplished through use of standard classifications (e.g., Prescott, 1962; Whitford and Schumacher, 1973).

Biovolume values were calculated for each species. Each individual species was related to a simple geometrical solid of known dimensions, and average cell volumes for each species was determined from the cell coun made using the Utermohl technique (Findenegg, 1969). The total biomass of a particular species was then expressed as cubic microns x 10^3/ml. Also utilized were the determinations of biovolume compiled by Dr. P. H. Campbell (personal communication, 1977).

3.3 Satellite Imagery Interpretation

The data base for the imagery studies is the standard 70 mm negatives and positives purchased directly from the EROS Data Center. Table 4 lists the imagery used in this investigation and the respective dates. Discussion of the imagery will refer to it by the dates as this seems most useful for a season-related study. Density slicing and color additive viewing ~~were the enhancement~~ techniques utilized during the course of this study. and various techniques for making quantitative measurements of the reflection information from the viewer screen were attempted.

3.3.1 Color additive approaches

The imagery was studied in a color additive viewer (Spectral Data Model 66) soon after receipt, and attempts were made to determine if there were any significant differences between images that could be measured in some manner, either by describing the color differences between scenes or by measuring brightnesses along with the color

Table 4

LANDSAT-2 Imagery Available

Date	Condition	Image Number
25 May 1976	(cloud cover)	2489-14571
12 June 1976	(extremely hazy)	2507-14564
5 August 1976	(scattered clouds)	2561-14551
23 August 1976	(cloud cover except over lakes)	2579-14544
16 October 1976	(scattered clouds)	2633-14530
21 November 1976	(clouds over two lakes)	2669-14514
9 December 1976	(clear)	2687-14505
27 December 1976	No ground data (clear)	2705-14051
1 February 1977	No ground data (clear)	2741-14485
9 March 1977	(scattered clouds)	2777-14472
27 March 1977	(scattered clouds)	2795-14463

differences.

To derive a better understanding of the meaning of any color differences found on the screen, the spectral pattern of the several filters and lights used in the viewer were measured with an ISCO Model SR Spectroradiometer. Figure 5 illustrates typical curves. Further detailed discussion is left to Section 4.8.

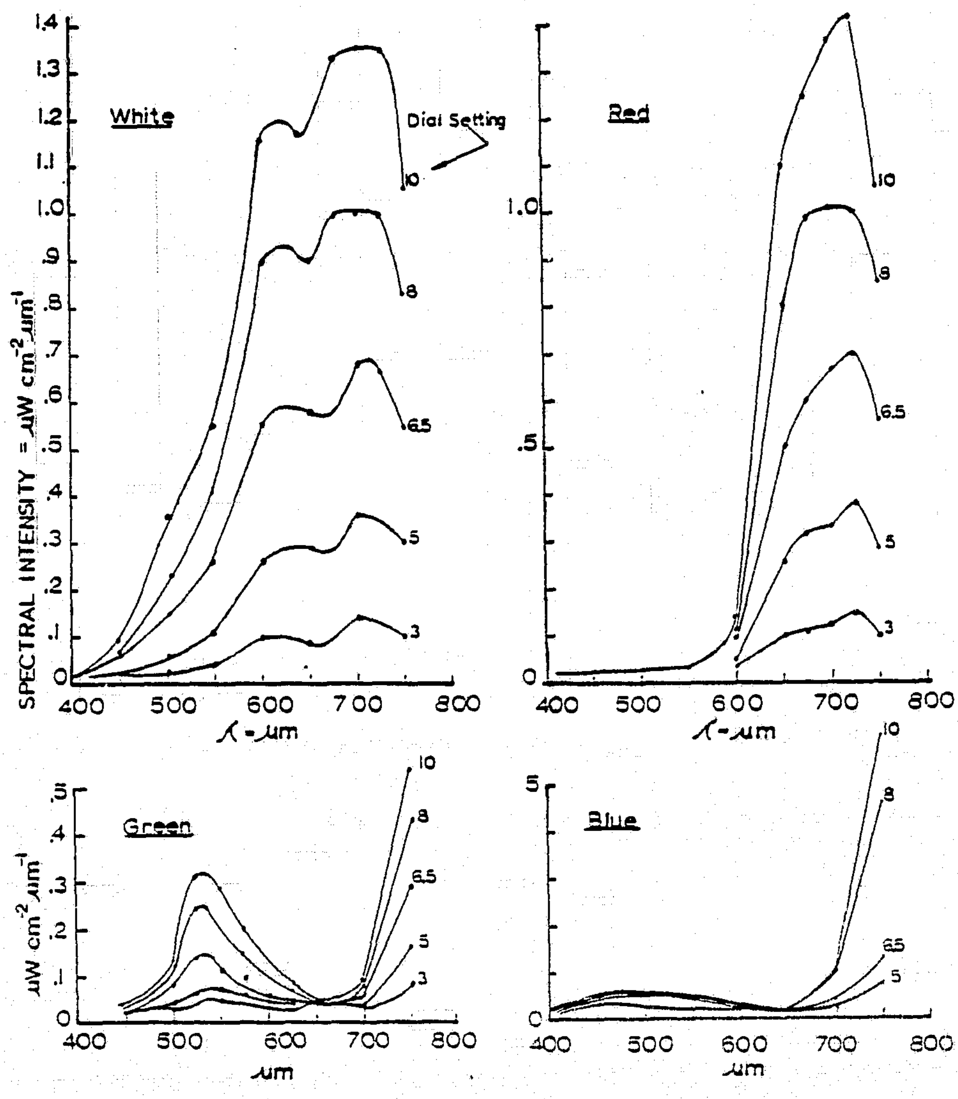
Investigations were made into the possibility of utilizing the spectroradiometric measurements and the brightness measurements as data to compute the tristimulus values of the colors seen on the color additive viewer screen.

Light intensity fall-off across the screen of the color additive viewer was determined with a Spectra Lumicon light meter. Within the central portion of the color additive viewer screen the fall-off seemed to be inconsequential for the purposes of the investigation and within the limits of accuracy of the instruments used.

The brightness measurements were made with a 3 mm fiber optics probe over which a cap had been placed and into which a 0.5 mm diameter hole had been drilled at the center of the cap. The light meter used reads in ft-candles, and these are the units used to express the brightness measurements. At the approximate 1:840,000 scale on the viewer screen the area covered by the 0.5 mm diameter hole is approximately 14 hectares, or approximately 35 acres.

Even though it was possible to measure the brightness values using a fiber optics probe attached to a Spectra Lumicon Series II light meter, measurement of the spectral ranges of the color combinations seen on the viewer screen proved impractical with the equipment at hand. Thus for the color designations reliance was placed upon the Munsell colors found in the Manual of Color Aerial Photography (Smith and Anson), Munsell Soil Color Chart (Soil Conservation Service, 1954) and upon a chart of interference colors found in Kerr (1959). For most of the color descriptions the chart of interference colors proved most useful.

One of the problems faced in using the satellite imagery of the same scene taken at different times for monitoring the changes in the lake water is that the atmospheric conditions and sun angle are different for successive imagery. Thus apparent differences in reflections from the water may be more related to the differences in physical setting of the images than to biological or other activity associated with the water mass. Spectroradiometric measurements of the roadways were utilized



SPECTRAL CHARACTERISTICS C.A.V. FILTERS

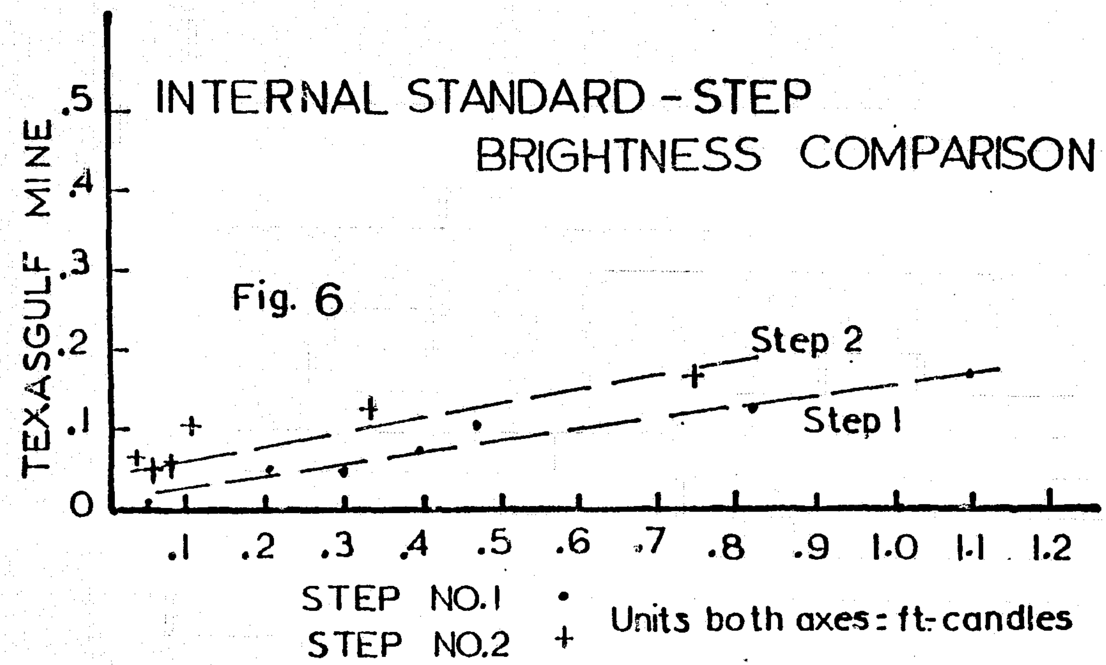
Fig. 5

as a guide to these possible differences (Fig. 4). When the imagery was studied in the color additive viewer the Texasgulf phosphate mine at Aurora, N. C. (Fig. 1) was utilized as an internal standard, although no spectroradiometric measurements were made of the site. Exposed in the mined area are light-colored sediments similar in general appearance to the eye to the appearance of the crushed Castle Hayne limestone found at the dock on Lake Phelps (Fig. 4). In the positive images much of the mine area appears white with a high level of brightness. It was believed that by utilizing the reflectance from the mine it would be possible to develop a standard reflectance level which would for all practical purposes remove the effects of atmospheric and/or sun angle differences between images, thus making measurements on the waters truly record the water quality differences. The technique was most successfully applied to the study of the negatives.

Work with the 70 mm chips in the density slicer (Spatial Data Systems Eyecom Image Scanner, Model 700SV) showed that the standard step wedge placed on the bottom of each 70 mm chip was not constant from chip to chip. These differences showed up also in the color additive viewer studies.

When the chips (either positive or negative) were combined in the color additive viewer, brightness measurements were made on the several steps of the gray scale at the standard setting used to compare the images made at different times of the year. It was found that there was a straight line relationship between the brightness of a given step and the brightness of the Texasgulf complex as measured under the same conditions (Fig. 6). It was also found that for each of the scenes used there exists for each combination of two or more bands a characteristic curve, based upon the step wedges, peculiar to that particular image. The central part of the curve is a straight line when drawn as a log-log plot of transmittance (in ft-candles) vs film step number. These curves combined with the Texasgulf brightness curve comparing the brightness of a given step on the gray scale with the brightness of the mine site (Fig. 6) give a method of converting the overall scene brightness for one pass to that for another time.

The brightness values can then be used as one piece of data to aid in determining whether there has been a significant change in the water

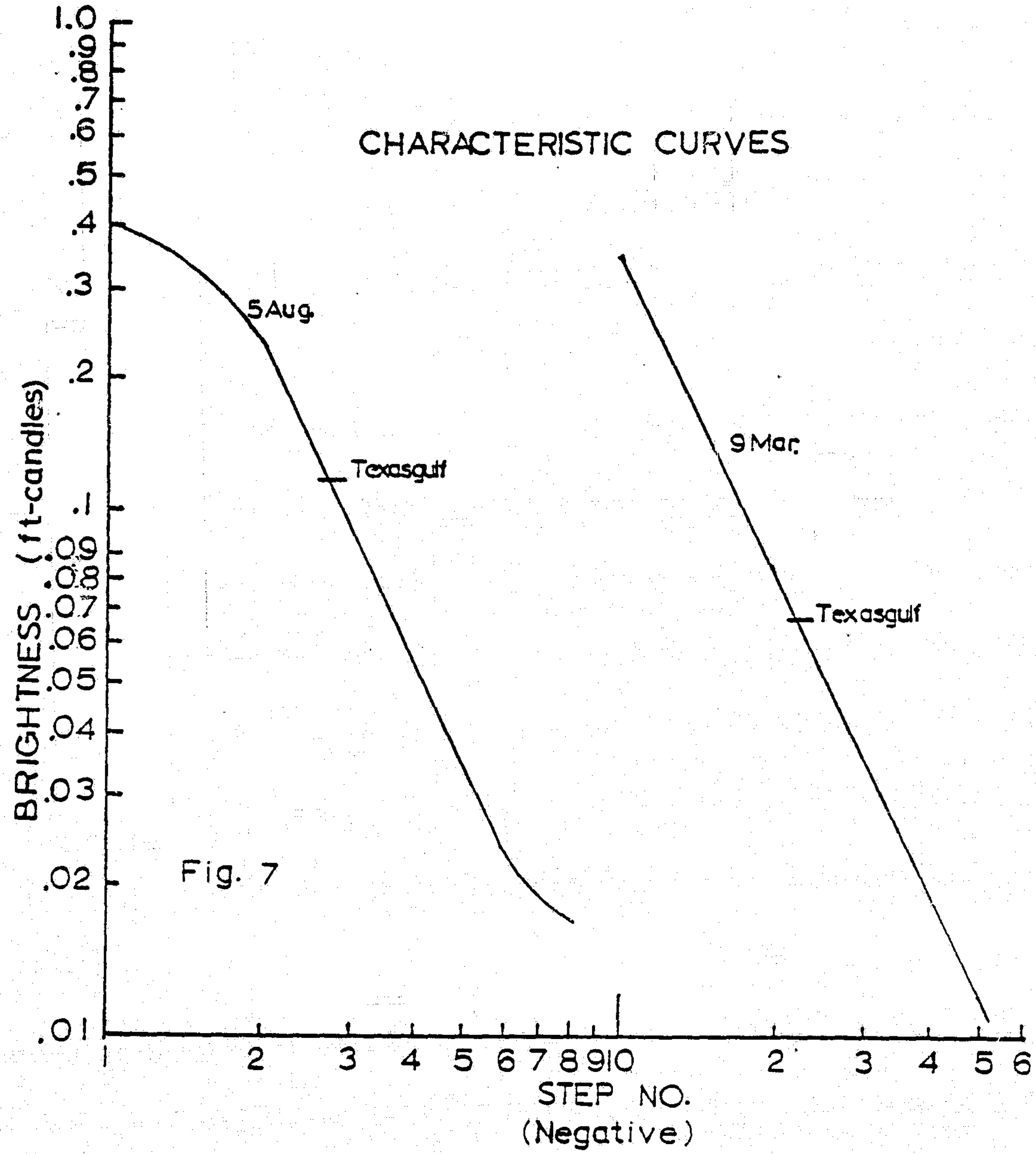

INTERNAL STANDARD - STEP
BRIGHTNESS COMPARISON
Fig. 6
TEXASGULF MINE
.5
.4
.3
.2
.1
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
1.1
1.2
Step 2
Step 1
STEP NO.1 •
STEP NO.2 +
Units both axes: ft-candles

quality parameters of the individual lakes. By plotting the brightness of the steps vs the step number (characteristic curve; Fig. 7) one can apparently correct for atmospheric and sun angle differences between overpasses.

Ideally, of course, one should have at least two "internal standards," such as the Texasgulf facility, which would provide a range of reflectance values for standardization of the imagery. However, there are no other appropriate large features within the scene utilized in this study. The spectroradiometric measurements of the causeway were designed to aid in setting up an internal standard, but the causeway is too narrow to be used for this purpose.

Analysis of the imagery with respect to the groundtruth data must address the fact that the quantity of energy reaching the satellite from the lake is determined by the sum of the energy returned from the water mass as well as any returned from the bottom of the lake. If the water mass contains sufficient suspended material, no energy reaches the bottom, or that which does is absorbed before it leaves the water mass after being reflected from the bottom. Any interpretation of the imagery must take this relationship into account, and it is necessary to view the energy received by the satellite in each band as the algebraic sum of the energy reflected back from the lake within the spectral range covered by that particular band of Landsat imagery. From the spectroradiometer curves it appears that Band 5 and Band 6 of the imagery should contain the most information about the suspended solids within the water column, and it is theoretically possible, at least, for the information contained in the Band 6 imagery to provide adequate information about the biomass concentrations and the chlorophyll concentrations, important clues to the water quality and trophic levels of the shallow coastal lakes. Bartolucci, et al (1977) found that for turbid river water (99 mg/l) bottom reflectances were unimportant when the water was deeper than 30 cm. They also found that the turbid river water had a higher spectral response in the 600 - 700 μm and 700 - 900 μm range than did the clear (10 mg/l) water.

In addition to the use of the standard 70 mm Landsat chips, both positive and negatives, some effort was devoted to photographically stretching the imagery. Also for those images in which the Band 6 and Band 7 step wedges were different from those for Band 4 and Band 5 attempts were made to bring the step wedges of the four bands to the



CHARACTERISTIC CURVES
BRIGHTNESS (ft-candles)
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
.09
.08
.07
.06
.05
.04
.03
.02
.01
5 Aug.
Texasgulf
9 Mar.
Texasgulf
Fig. 7
1
2
3
4
5
6
7
8
9
10
2
3
4
5
6
STEP NO.
(Negative)

same density distribution by controlling development and exposure times. Time and resources did not permit completion of this part of the investigation. Therefore, the greatest reliance was placed upon the standard data products as they represented a product with good quality control, a standard format, and ready availability.

3.3.2 Density slicing

Density slicing techniques were employed on the individual bands. A calibrated step wedge was used as a means for standardizing the settings between the different bands of the same scene and between images made at different times. However, no technique was developed which allowed for a normalization of the imagery to some standard sun angle and atmospheric effect.

4.0 RESULTS

4.1 Previous Work on Northeastern North Carolina Lakes

Heath (1975) provides the most recent description of the four test site lakes. In a major survey of the trophic states of North Carolina lakes Weiss and Kuenzler (1976) provide chemical analyses of the lake waters. The data found in their report are based upon just two samples collected from the lakes during a one-year period.

Although the values of most of the parameters given in the earlier reports and those obtained during the current investigation compare favorably, there are two notable exceptions. The nutrient parameter values of ammonia-nitrogen and ortho-phosphorus are lower by an order of magnitude for the earlier work. This relationship can only be explained by the different analytical procedures followed in the two studies.

A second difference is found in the phytoplankton data. Generally Weiss and Kuenzler report a lower phytoplankton number and biomass. They used a centrifuge method to concentrate the phytoplankton; in comparison, the phytoplankton data for this study were obtained by the Utermohl method which is considered to give more consistent results and a greater accuracy than other methods (Lund, 1958).

4.2 Seasonal Cycles of the Lakes

Groundtruth indicates the cyclic nature of the trophic state of the lakes. Figure 8A shows the yearly pattern of chlorophyll-a which tends to reflect the biomass content of the water (Fig. 8C). Figure 8B probably indicates the major nutrient pattern. Comparison of these figures shows that typically as the phytoplankton concentration increases the nutrients once again increase. During the winter period and the spring runoff the nutrient levels increase in the lakes. Any indication of nutrient buildup must come from a relationship between the suspended matter in the lakes and the nutrient levels, for the nutrients themselves do not appear to have a significant spectral response.

4.3 Trophic State Index (TSI)

A variety of trophic state indices has been formulated (Sheldon, 1972). Their purpose is to provide a means for describing numerically the trophic state of a water body. Because of the dynamic nature of water bodies the use of many parameters for determination of the trophic state of a given body is required, making the problem multivariate in

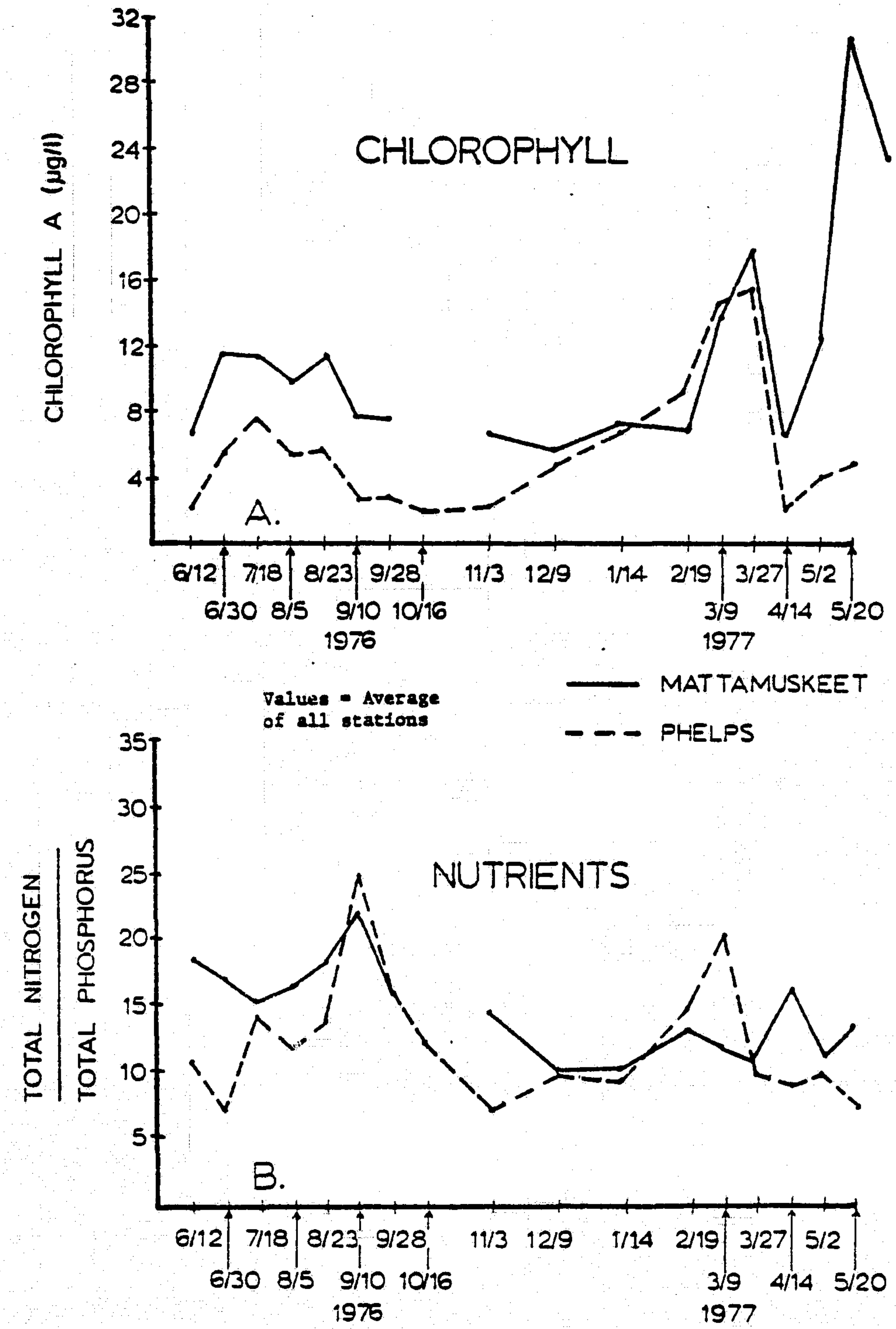

CHLOROPHYLL
CHLOROPHYLL A (μg/l)
32
28
24
20
16
12
8
4
A.
6/12 7/18 8/23 9/28 11/3 12/9 1/14 2/19 3/27 5/2
6/30 8/5 9/10 10/16 3/9 4/14 5/20
1976
1977
MATTAMUSKEET
PHELPS
Values = Average of all stations
NUTRIENTS
TOTAL NITROGEN / TOTAL PHOSPHORUS
35
30
25
20
15
10
5
B.
6/12 7/18 8/23 9/28 11/3 12/9 1/14 2/19 3/27 5/2
6/30 8/5 9/10 10/16 3/9 4/14 5/20
1976
1977

FIG. 8

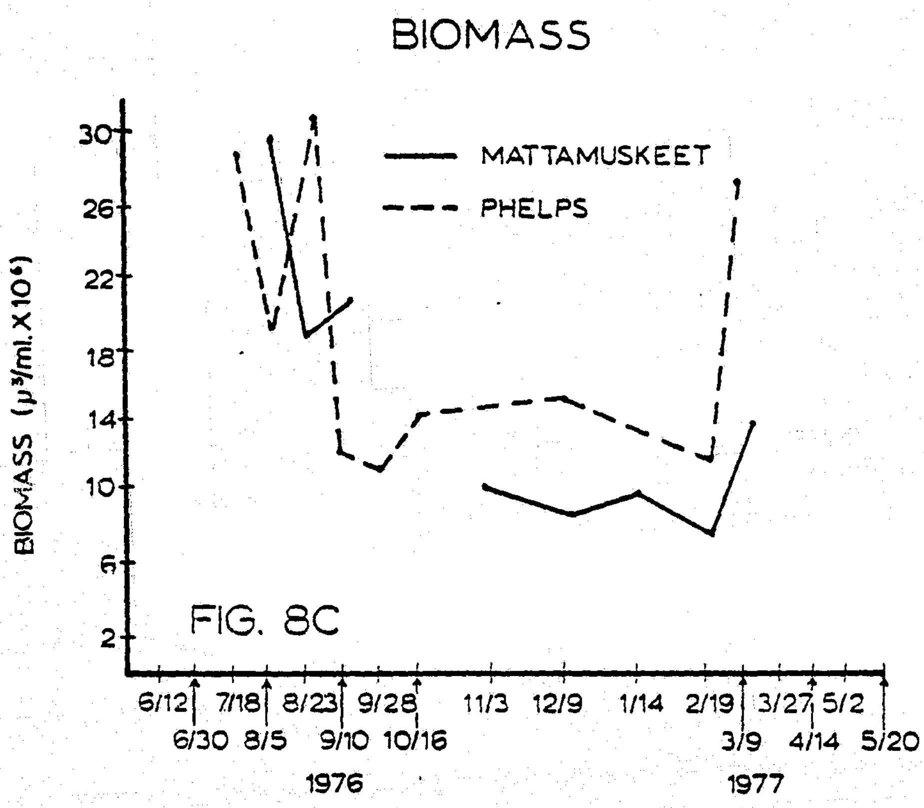

BIOMASS
MATTAMUSKEET
PHELPS
BIOMASS (μ³/ml. X 10⁶)
30
26
22
18
14
10
6
2
6/12
6/30
7/18
8/5
8/23
9/10
9/28
10/16
11/3
12/9
1/14
2/19
3/9
3/27
4/14
5/2
5/20
1976
1977

FIG. 8C

nature (Sheldon, 1972).

Many investigators have recognized the multidimensional character of the problem and have applied complex multivariance mathematical techniques to determine trophic state. The mathematical approach is time-consuming, computer-oriented, and costly. In the long run, it appears that the trophic state indicated in a particular situation is left to the investigator's judgment because no universal trophic state index (TSI) has been accepted.

Carlson (1977) has developed a simple trophic index based upon three water quality characteristics of parameters: Secchi disc depth, total phosphorus, and chlorophyll-a. The values for this index range from 1 through 100, and included in this range of values are the most extreme values encountered to date for the three parameters used (Carlson, 1977).

The rationale for the approach is that the biological and chemical parameters affect in some way the physical parameter, transparency as measured by Secchi disc depth, of a water body. The equations used in determining the index are derived from a log-log linear regression calculation based upon data from six published and unpublished studies (Carlson, 1977).

According to Carlson (1977) the average TSI value for the three parameters cannot be used when chlorophyll-a and the total phosphorus TSI values are not the same. This view is taken because it is felt that the biological and chemical conditions would not be properly represented in the average (Carlson, 1977). Trophic State Index ranges are given in Table 5.

Consideration of the nature of the shallow coastal lakes of North Carolina suggests that the Trophic State Index obtained by averaging all three parameters is a better indicator of the state of the individual lake than is just one parameter. This relationship develops because of the fluctuating nature of the parameters in the shallow lakes. For example, when the biomass is high, the nutrient content is low and conversely for low biomass values. The Total Nitrogen/Total Phosphorus ratio is directly proportional to the biomass values (Fig. 8). Secchi disc depth is related not only to the biomass content of the watermass but also to the materials stirred from the bottom by wind activity.

Table 5

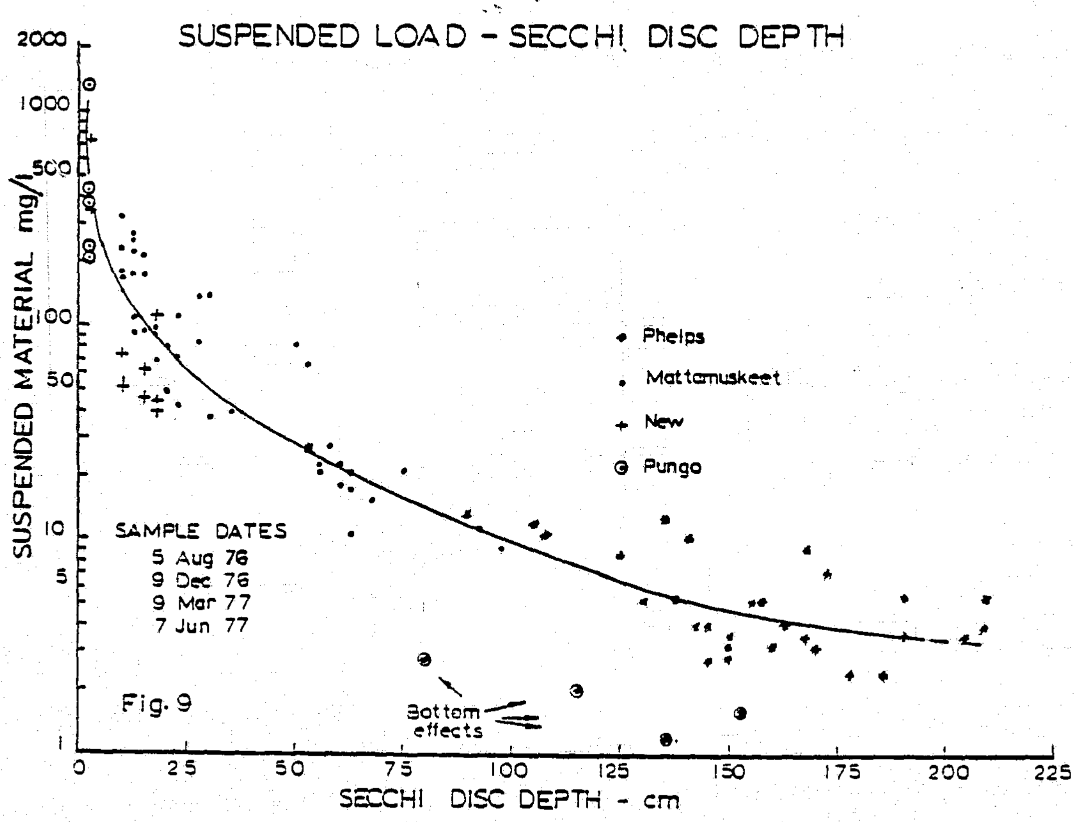
TSI	Secchi disk (meters)	Surface Total Phosphorus (mg/m^3)	Surface Chlorophyll-a (mg/m^3)
0	64	0.75	0.04
10	32	1.5	0.12
20	16	3	0.34
30	8	6	0.94
40	4	12	2.6
50	2	24	6.4
60	1	48	20
70	0.5	96	56
80	0.25	192	154
90	0.12	384	427
100	0.062	768	1,183

Table 5. Trophic State Index (From Carlson, 1977).

Wind activity has a great influence on the trophic state of the coastal lakes. Their shallow nature makes it possible for complete mixing of the water column in response to the wind-generated forces. Bottom materials, usually including nutrients, are mixed upward into the water column. When this increased suspended load is combined with the warm temperatures during the spring and fall, the trophic state usually increases in response to a rise in phytoplankton activity. Thus the TSI value obtained by averaging the separate TSI values for Total Phosphorus, chlorophyll-a, and Secchi disc depth should usually provide a better understanding of the average trophic state of a shallow coastal lake than can be obtained from just one TSI value computed from one of the three water quality parameters. Also computation of the TSI value of the lake made by first averaging the water quality parameter values from the several stations and then computing for the TSI value for each parameter should give a more accurate indication of the general trophic state of the lake than a TSI value based upon one parameter alone. It is to be expected that because of inherent variations within the lake that analyses of one sample and computation of the TSI from the data can be misleading.

In their study of North Carolina lakes Weiss and Kuenzler (1976, Table 61) give the trophic state for Lake Mattamuskeet as α-eutrophic and for Lake Phelps as mesotrophic. These classifications fit the numerical values derived using the modified Carlson technique for computation of the Trophic State Index. Eutrophic lakes appear to have TSI values of greater than 60 and mesotrophic lakes have values between 45 and 60. The Trophic State Index (TSI) appears to be compatible in its use with remotely sensed data obtained from space.

Interpretation of the data received by the four multispectral scanners on Landsat-2 cannot be based upon a straight-line relationship between suspended material and reflectances. Figure 9 shows that the Secchi disc-suspended material relationship is not a straight-line one. Of interest here is the fact that the Secchi disc depth-suspended material relation is slightly different for each lake. Scarpace, et al (1974) in their study of Wisconsin Lakes did not attempt to correlate suspended load with Secchi disc depth as they apparently had only the Secchi disc depth data. They found that the Band 4 and Band 5 densities had an exponential relationship with the Secchi disc depth data. Also they state that there was no correlation between the Band 6 imagery and


SUSPENDED LOAD - SECCHI DISC DEPTH
SUSPENDED MATERIAL mg/l
2000
1000
500
100
50
10
5
1
Phelps
Mattamuskeet
New
Pungo
SAMPLE DATES
5 Aug 76
9 Dec 76
9 Mar 77
7 Jun 77
Fig. 9
Bottom effects
0
25
50
75
100
125
150
175
200
225
SECCHI DISC DEPTH - cm

the Secchi disc depth. However, if one places their plot of the Secchi disc - Band 5 exposure relationship over their figure for the Secchi disc - Band 6 exposure plot, the regression curve for the Band 5 data fits well on the Band 6 data. The implication here is that the Band 6 and Band 5 densities are both useful, and because Band 6 reflectances do not have the hazard of bottom reflections, they appear more useful for shallow lakes.

The biological and chemical parameters of the lakes are less directly measured, but as will be demonstrated later, the Trophic State Index shows a correlation with various imagery features.

In the present study the trophic state of each lake was determined by calculating the average value of each parameter for each date of a satellite overpass. The eastern portion of Lake Mattamuskeet was treated separately from the portion west of the causeway. The groundtruth values were then substituted into the Carlson (1977) equations for Trophic State Index (Table 6). Figure 10 gives the seasonal trophic ranges for the four lakes.

Averaging of the samples from each lake probably gives an overall representation of the trophic state of the lake. However, it is to be expected that within each of the lakes differences in the several parameters exist and that the samples collected do not necessarily sample the entire range of each parameter. Study of the individual images in the color additive viewer indicates some areas in Mattamuskeet, in particular, where the reflectances are somewhat higher than in the part of the lake sampled, suggesting for the given image that local areas of higher concentrations of suspended material and/or biomass are present than in the areas sampled. However, since the Trophic State Index is a composite calculation, it would appear that the averaging of the sample data as well as the averaging of the three trophic state indices (chemical, biological, and physical) provides as accurate a method for determining the trophic conditions of the lake as is possible at the present time.

4.4 Density - Suspended Material Relationships

Review of the relationships between the various parameters along with the spectral characteristics of the absolute reflections as well as the reflectances indicates that in general as the suspended load increases the chlorophyll-a content increases and so does the level of reflection. In the four lakes the suspended matter plays the dominant role in the energy return from the water mass, and the chlorophyll-a response comprises a small proportion of the reflectance (e.g., Fig.4).

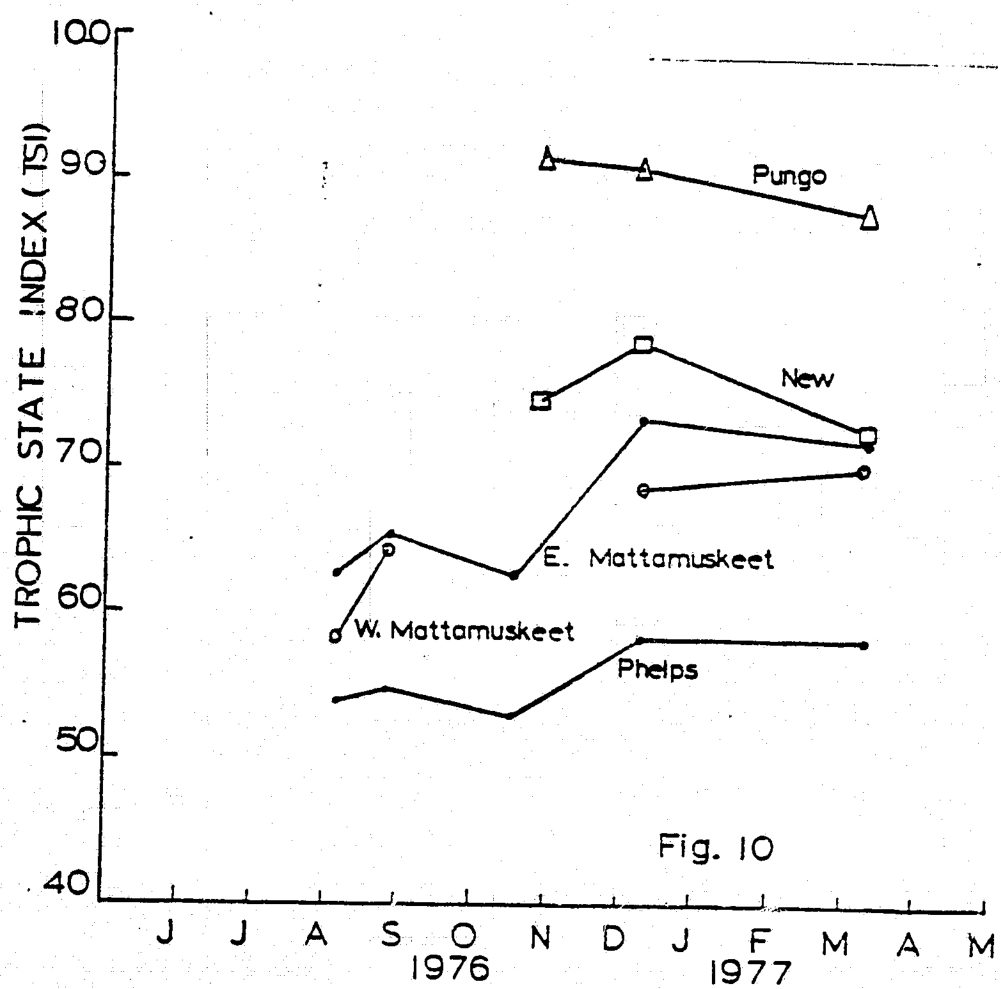
<u>Table 6</u>

[Secchi Disc] $\quad TSI(SD) = 10\ (6 - \frac{\ln SD}{\ln 2})$

[Chlorophyll-a] $\quad TSI(Chl) = 10\ (6 - \frac{2.04 - 0.68\ \ln Chl}{\ln 2})$

[Total Phosphorus] $\quad TSI(TP) = 10\ (6 - \frac{\ln \frac{48}{TP}}{\ln 2})$

Table 6. Trophic state index equations for the three parameters used. (From Carlson, 1977)



SEASONAL TROPHIC STATES

The reflective response as shown by field spectroradiometric measurements of Lake Phelps on 9 March 1977 and Lake Mattamuskeet on 2 May 1977 were similar. Groundtruth measurements indicate that the suspended load at each station was between 27 and 50 mg/l on these dates. Density slices of the 9 December and 9 March images (Band 5) showed a correlation between the suspended material load and the density distribution on the image. Figure 11 and 12 show these relationships.

Because of the suspended load in the water masses of the two lakes for these two dates (Appendix) it is unlikely that there was any reflectance from the bottom, and it appears that the density distributions record the suspended load distributions within Mattamuskeet and in the case of Lake Phelps in the upper 1.5 to 2.0 m.

For Mattamuskeet the 5 August imagery (Fig. 13) shows a correlation between the density distributions and the concentration of suspended materials. For this date there appears to be a correlation between the suspended load and the chlorophyll-a. Therefore, density measurements of Band 5 can be used for this date to estimate the chlorophyll-a content of the water and indirectly the biomass. However, this was the only image for which this correlation could be found. Preliminary results from 12 June 1976 indicate that there should also be a good correlation between suspended material and chlorophyll-a concentration. Cloud cover obscured enough of the imagery of each lake so that appropriate optical measurements on the imagery cannot be made to establish conclusively the imagery-suspended material-chlorophyll relationship.

Apparently the explanation for this non-constant nature of the chlorophyll-suspended material relationship lies in the fact that the chlorophyll concentration depends upon more than just the suspended material load. Chlorophyll levels reflect the seasonal stages in the biological cycle of the lakes, and the suspended material may be both biological and inorganic in origin. Phytoplankton are most active during the warmer months of the year while at the same time the inorganic and dead vegetation portions of the suspended load are relatively low. Thus much of the suspended load is comprised of the phytoplankton, and the horizontal distribution pattern of suspended material correlates well with the distribution pattern of the chlorophyll. At times of the year when the suspended load is largely inorganic material and/or "yellow stuff," the total biomass and associated chlorophyll content of the

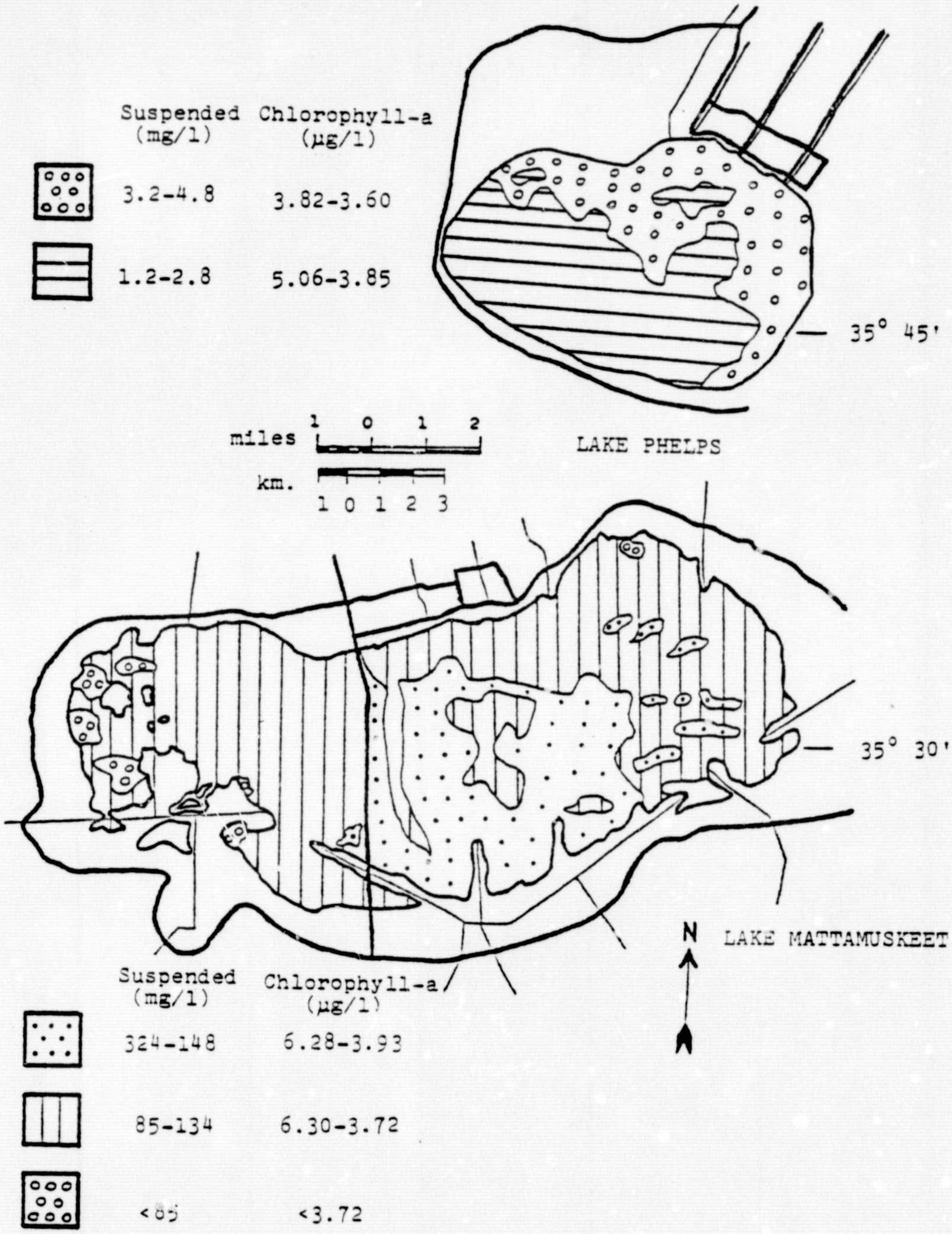


Fig. 11 Density Slice December 9, 1976 (2687-14505-5)

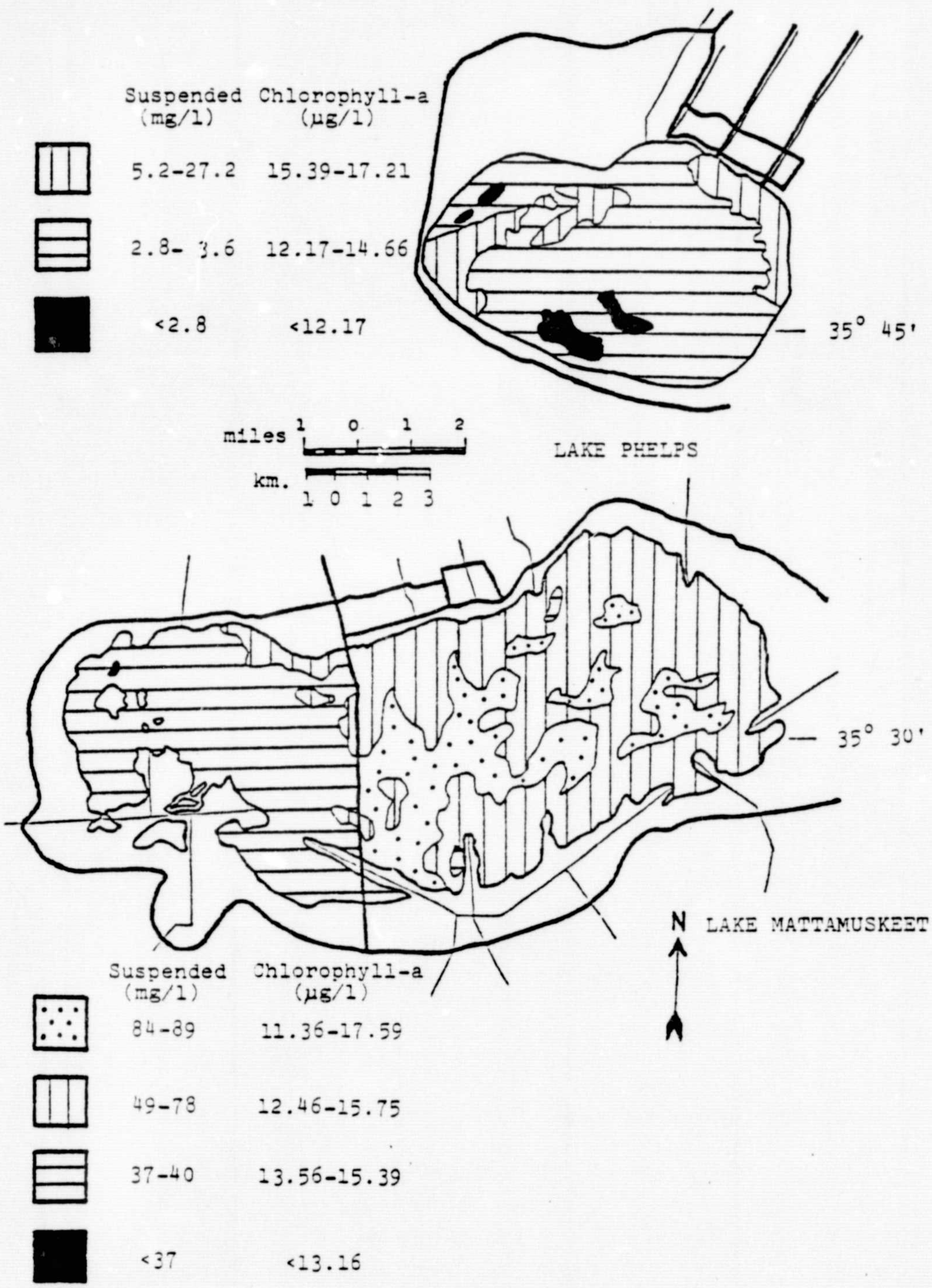


Fig. 12 Density Slice March 9, 1977 (2777-14472-5)

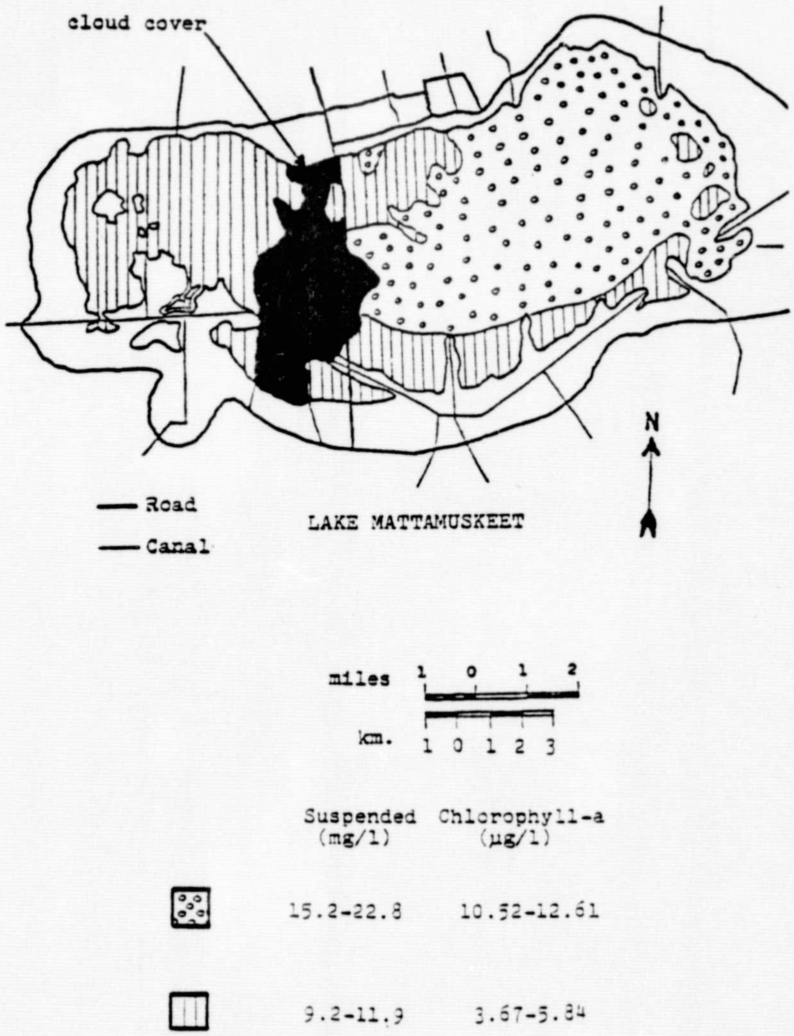


Fig. 13 Density Slice August 5, 1976 (2561-14551-4)

water is low. At these times the biomass distribution may or may not correspond to the total suspended load distribution pattern. Thus the chlorophyll distribution pattern may or may not be directly related to the suspended load pattern in the winter and early spring. Additionally, the composition of the phytoplankton population at a given time controls the chlorophyll content of the water. If the population is characterized by species with relatively large percentages of chlorophyll, then a low phytoplankton population may give relatively high chlorophyll values; conversely, if the phytoplankton population is characterized by species with relatively low chlorophyll contents, high biomass, and apparently a high suspended load may be associated with relatively lower chlorophyll contents.

4.5 Suspended Load - Nutrients

Plots of suspended load and nutrients, suspended load and chlorophyll-a, and suspended load and biomass indicate no discernible,consistent, meaningful relationship between the suspended load and the other parameters. The biomass determinations were made for three stations in Lake Phelps and Lake Mattamuskeet and for one station sampled in Pungo and New Lakes. Chlorophyll-a seems to serve as a reasonable indicator of biomass, except that when phytoplankton with relatively low chlorophyll-a content dominate the biomass, the chlorophyll-biomass relationship is different from that which exists when the green species are ascendent.

When there is a low suspended load in the lakes, there seems to be a general positive correlation between the suspended load and the chlorophyll-a content of the water. Both Blanchard and Leamer (1973) and Gramms and Boyle (1971) show that as the concentrations of chlorophyll-bearing organisms increase, the chlorophyll peaks decline in intensity; also Blanchard and Leamer (1973) show that for red-colored suspended sediment the same relationship holds for the reflectances across the whole spectrum. For black sediment they found that the reflectances increased with an increase in the suspended load. On the other hand, Tabor (1975, Fig. 6.2) indicates that with dilution of a standard algae mixture the reflectance decreases. Hence, there seems to be no consistent experimental evidence on which to base an interpretation of the reflectances recorded by the satellite in terms of the suspended material concentrations and the concentrations of chlorophyll-bearing phytoplankton. Likewise, from the evidence obtained during this study of the coastal plain lakes it appears that a consistently good correlation between nutrient levels and suspended material will be difficult to establish. In dealing with the problem one has to consider the nature of the lake's seasonal cycle and to evaluate whether any seeming correlation between the Landsat data and groundtruth is real or whether it is an artifact of the mathematical treatment of the data.

Details of the density slicing experiment may be found in Section 4.9 and Table 10.

4.6 Depth Contouring and Bottom Vegetation

Density slicing of Lake Phelps images of 5 August and 23 August indicated existence of a correlation between the water depth and the density pattern on the images. Thus it became possible, using Band 4, to draw bottom contours of Lake Phelps. Figure 14 illustrates the results of this experiment.

As work progressed on Lake Phelps it became apparent that the mat of blue-green algae (Chroococcus sp.) conformed to the part of the bottom exceeding a depth of 198 cm. The algae grows on a thin black organic layer. Band 5 proved best for depicting the distribution of the algae apparently because of the absorption peak for chlorophyll in this part of the spectrum. The area underlain by the algae appeared more dense on the positives than the surrounding areas.

In the case of Lake Mattamuskeet the same density represented members of the Characeae family (especially, Chara sp. and Nitella sp.). Chara was first found in the lake in 1949 (Wood, 1954). The distribution of the Chara and associated species as shown by the density slicing Fig. 15 corresponds closely with a vegetation map of the lake prepared by Florscehutz (1975).

4.7 Spectroradiometric Measurements

The limited number of spectroradiometric measurements were made chiefly to learn the general pattern of reflectance from the lakes. However, examination of the several curves suggested that it might be possible to establish the existence of a relationship between them and the groundtruth collected more or less at the same time. It was anticipated that the comparison of the data would provide information about the relationship between the trophic states of the lakes and the corresponding reflectances recorded on the satellite imagery.

Since Band 5 and Band 6 were recognized as the two bands which sould provide the most information about the lakes, those parts of the spectroradimeter reflectance curves corresponding to Band 5 (600 - 700 μm)

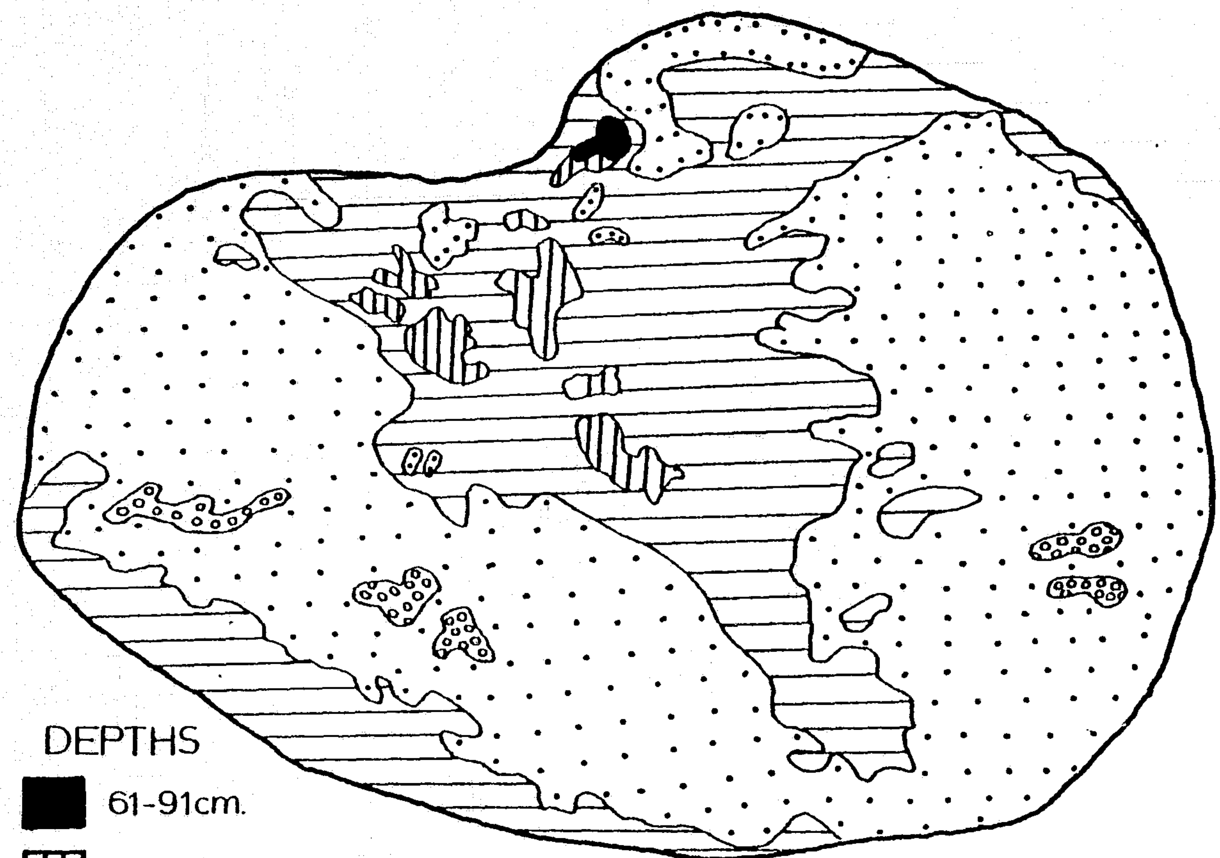


FIG.14

DEPTH CONTOURS FROM DENSITY SLICE OF LAKE PHELPS 23 AUGUST 1976 (2979-14544-4)

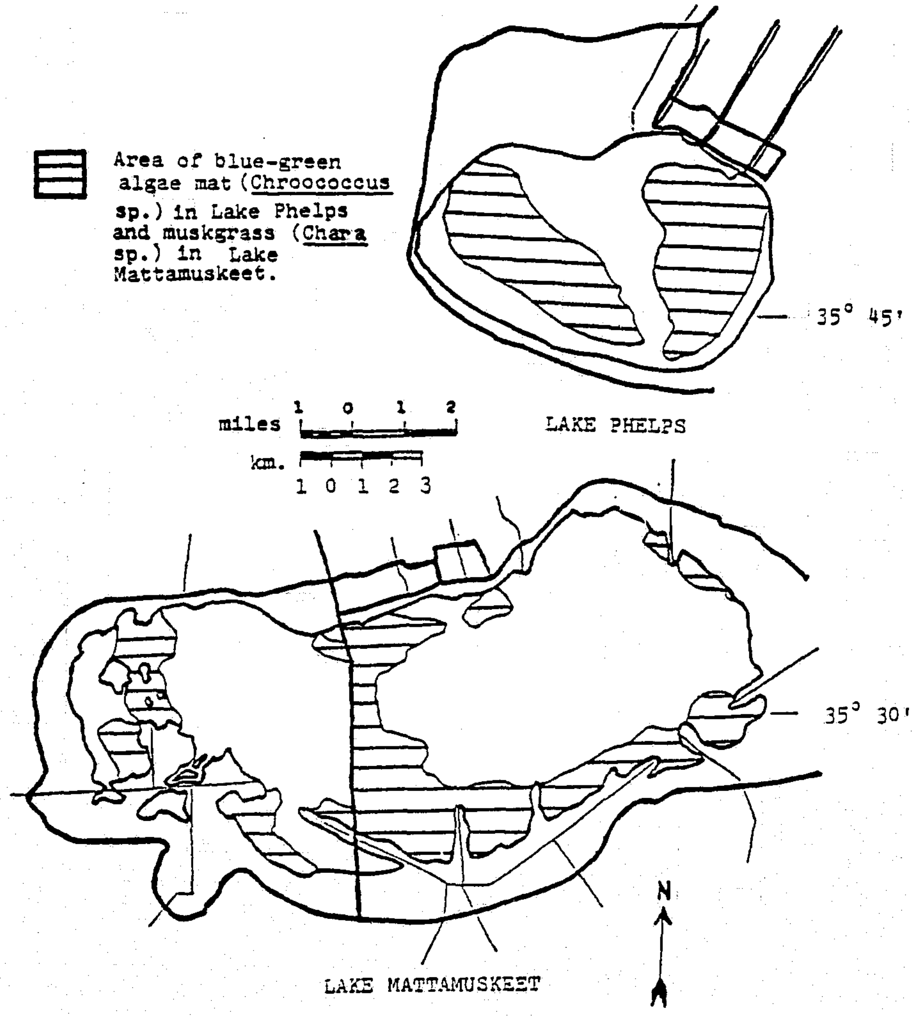


Fig. 15 Bottom vegetation-Density Slices
Aug. 5 and Aug. 23, 1976.

Table 7

Curve Area Ratios

	Band 5 / Band 6	Lake / Pool	Ratio Lake / Ratio Pool
5 August 1976			
East Mattamuskeet			
Band 5	1.15	.828	.935
Band 6		.884	
Phelps			
Band 5	1.11	.493	.902
Band 6		.548	
12 August 1976			
Swimming Pool			
Band 5	1.23	1.0	1.0
Band 6		1.0	
Farm Pond			
Band 5	.992	1.11	.806
Band 6		1.38	
23 August 1976			
Phelps			
Band 5	1.00	.506	.813
Band 6		.620	
9 March 1977			
East Mattamuskeet			
Band 5	.920	1.23	.748
Band 6		1.65	
Phelps			
Band 5	1.21	.793	.983
Band 6		.804	
Pungo			
Band 5	.983	1.21	.799
Band 6		1.52	
New			
Band 5	.628	.693	.510
Band 6		1.36	

and Band 6 (700 - 800 μm) were used. The area under the curves within these spectral bands was taken to be a measure of the energy returning to the satellite from the lakes and was determined by graphical means. For comparative purposes the reflectance curve of the Faculty Club swimming pool (Fig. 4) was chosen as a standard reference curve, and various ratios between the lake reflectances and the swimming pool reflectances were calculated (Table 7). Figures 16, 17, and 18 are curves drawn from these ratios.

Presumably the swimming pool had no phytoplankton in it, and thus the indication of the trophic state depends upon the Secchi depth and the phosphorus content. No chemical analyses are available for the water, but in general it can be assumed that this chemical parameter is low so that the factor in the TSI equation for phosphorus which accounts for the phosphorus content approaches zero. Calculation of the TSI based upon water transparency and the phosphorus indicates a TSI of 15 to 20. The TSI scale starts at one (Carlson, 1977), and in reality it may be better to assume that the swimming pool has this TSI.

Both Fig. 16 and Fig. 17 show a scatter of points which is not readily amenable to curve fitting. However, when the swimming pool values are placed in the plots whether at a TSI of 20 or at a TSI of one, the curve pattern that seems to emerge is curvilinear. Dashed lines were placed by eye in the figures to suggest the pattern.

The spectroradiometric measurements made on the small pond on the North Carolina State University dairy farm were intended solely as an experiment to determine the reflectance pattern of the phytoplankton enriched water compared with that of the swimming pool. A biological analysis of the water indicated a blue-green algae (Anacystic cyanca) was dominant with a biomass of about $1.2 \times 10^7 \mu^3$/ml. The pond obviously possessed on 12 August 1976 a moderately high TSI. If the several ratios for this pond (Table 7) are used with graphs, the TSI values fall in the lower end of the eutrophic range. The Secchi disc depth for the pond was of the order of 30 to 50 cm which would provide a TSI based upon a Secchi disc depth alone of between 70 and 89 (Table 5).

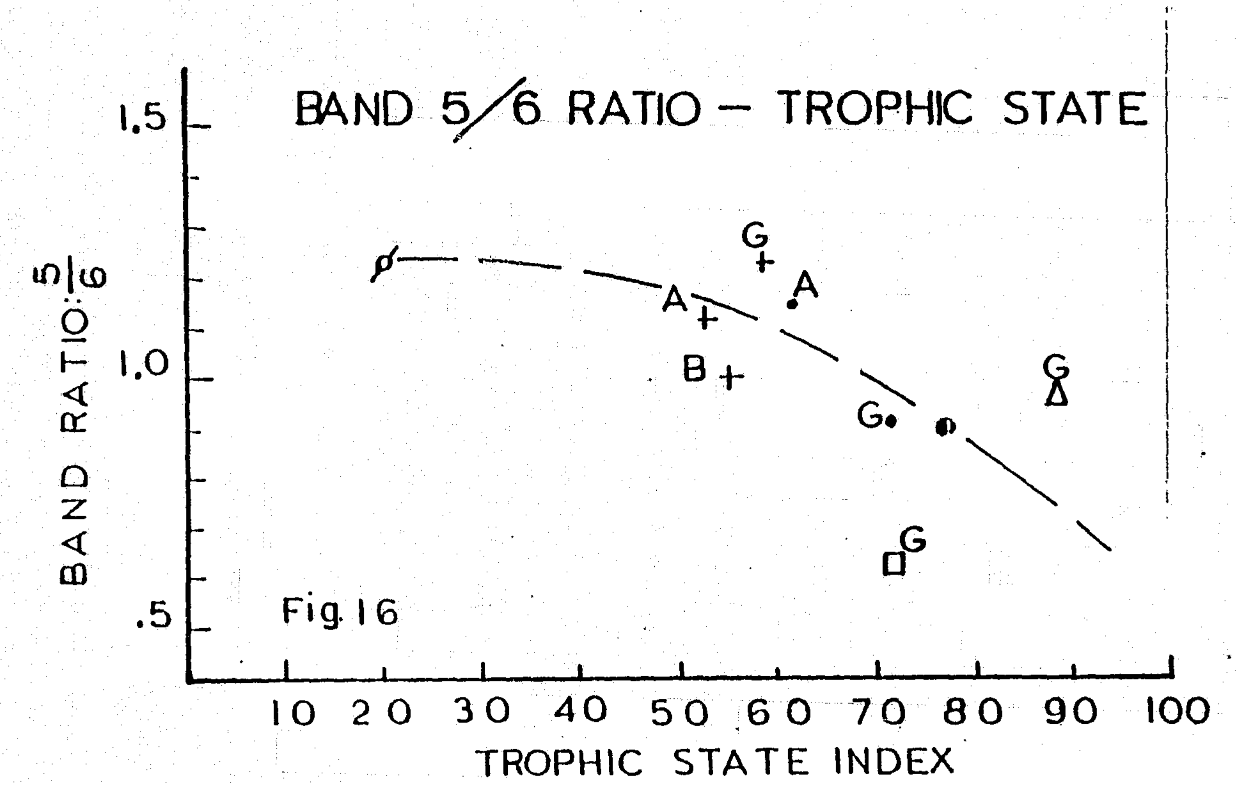
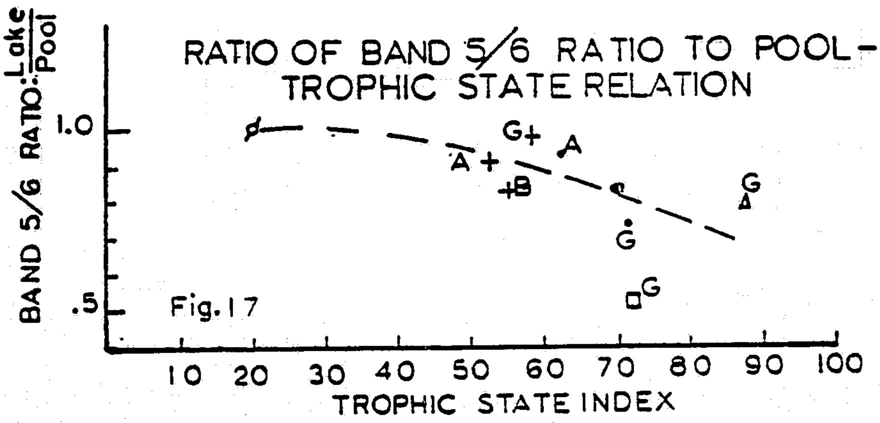
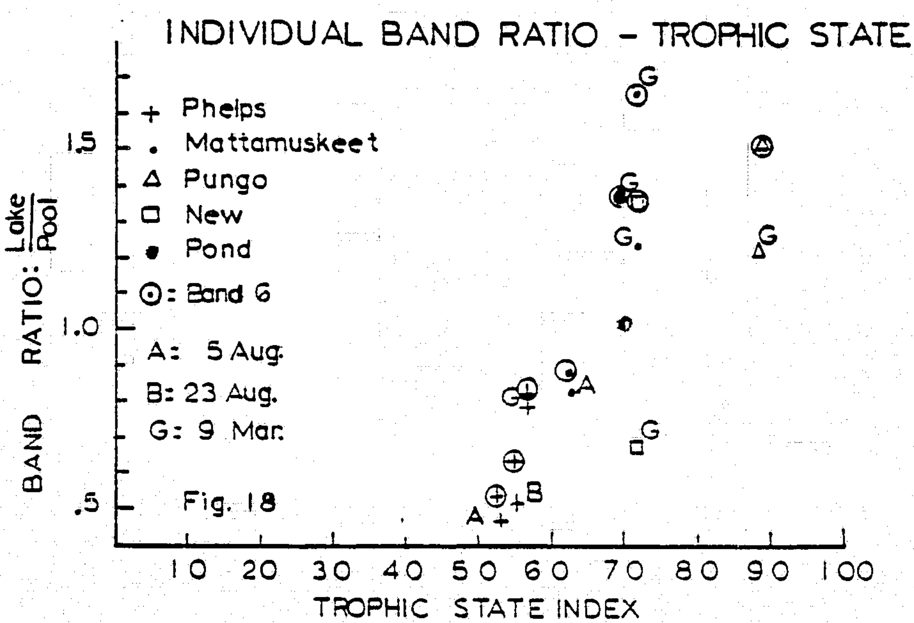


Fig. 16

LEGEND Figs. 16 - 18

ø Pool	A: 5 Aug.
● Pond	B: 23 Aug.
• Mattamuskeet	G: 9 Mar.
Δ Pungo	
□ New	
+ Phelps	


RATIO OF BAND 5/6 RATIO TO POOL-TROPHIC STATE RELATION
BAND 5/6 RATIO: Lake/Pool
1.0
.5
Fig. 17
10 20 30 40 50 60 70 80 90 100
TROPHIC STATE INDEX


INDIVIDUAL BAND RATIO - TROPHIC STATE
BAND RATIO: Lake/Pool
1.5
1.0
.5
+ Phelps
. Mattamuskeet
Δ Pungo
□ New
● Pond
⊙: Band 6
A: 5 Aug.
B: 23 Aug.
G: 9 Mar.
Fig. 18
10 20 30 40 50 60 70 80 90 100
TROPHIC STATE INDEX

The dairy farm pond has been monitored over a period of several years for phytoplankton, and normally in August a blue-green phytoplankton bloom occurs. Associated with this bloom are chlorophyll-a levels about 40 - 50 μg/l (A.M. Witherspoon, personal communication, June 1977). From Table 5 this concentration gives the pond a TSI of between 60 and 70. If the various ratios for the pond are used to enter the several curves (Fig. 16, 17, 18), the TSI values for the pond determined from curves are seen to fall within the range estimated from the field observations.

The spectroradiometric study suggests strongly that a standard feature can be used to measure changes in the reflectance characteristics of the shallow coastal lakes. It appears that once an internal standard is established all subsequent reflectance measurements can be referred to it. It does not appear necessary to have the standard located on the images being studied if spectroradiometric measurements are being utilized for the determination of the trophic states of the lakes and for the determination of changes in the trophic states of individual lakes through the seasons.

This study of the spectroradiometric measurements and the trophic levels of the lakes suggests that for a given scene it may be possible to utilize an "internal standard" to which all the imagery is normalized. Such normalization would eliminate problems associated with sun angle differences and with atmospheric conditions. Study of Fig. 16 and 17 indicates that for lakes with TSI values of less than 40 or 50 the spectral characteristics probably cannot be expected to delineate the trophic state accurately. The plots of the TSI values against the several ratios flattens in the lower TSI range. This means that for those lakes which are classified as meso-oligotrophic or oligotrophic (a swimming pool would fall into the latter category) the reflectance characteristics recorded on the satellite imagery may only be able to indicate that the lakes are in the lower trophic state. For those lakes whose Trophic State Index is above about 50 it seems possible to separate the lakes in terms of their trophic state and to monitor them using space-acquired data.

4.8 Color Additive Approaches

In view of the fact that density measurements alone on a single band could not be normalized so that trophic states and/or water quality parameters from different dates could be compared through the imagery, attention was given to conjunctive use of Band 5 and Band 6 in a color additive format. It was thought that if the color additive viewer could be calibrated in some way and a method developed for comparing colors from image date to image date, then the trophic states of the lakes could be ascertained and monitored with the satellite imagery. Because of the possible difficulties with bottom reflections and in consideration of the fact that the Band 5 imagery probably did not record bottom reflections if the waters were even moderately turbid, it was decided that a two-band combination of imagery would be appropriate for the quantification study using the color additive approach. Even so, some errors may have been introduced on the 23 August imagery because of bottom reflections (see Appendix). Consideration of the characteristics of the various bands and of the information about the lakes that each was likely to possess led to the decision to use Band 5 and Band 6.

Work with both the positive and the negative standard 70 mm transparencies indicated that the negatives would prove more useful. The reason for this relationship is that in general the water bodies are of low reflectance and thus dark on the positive transparencies; in contrast, light is relatively easily transmitted through the low density areas of the negatives representing the water bodies. Suspended matter in the water which gives higher reflectances than the water itself is darker on the negatives and acts as a filter, decreasing the amount of light passing through the negative transparency in proportion to the amount of energy reflected back to the satellite from the water body. Earlier work with Landsat-1 imagery (Welby, 1976) also indicated that the negatives should prove more useful.

Since the technique to be used was dependent upon the characteristics of the light passing through the color additive viewer system, it became necessary to learn the spectral characteristics of the several light-lens-filter systems that comprise the viewer. Accordingly, both spectroradiometric measurements and brightness measurements were made of the viewing screen.

The spectral determinations were made with the ISCO spectroradiometer used for field spectroradiometric measurements. A standard for determining possible instrumental variations was established on a light table. Between each series of filter measurements a series of measurements were made on the light table standard. The spectral measurements of the color additive viewer were made on the center of the viewing screen with each lens placed somewhere near the midpoint of its focusing and scale ranges.

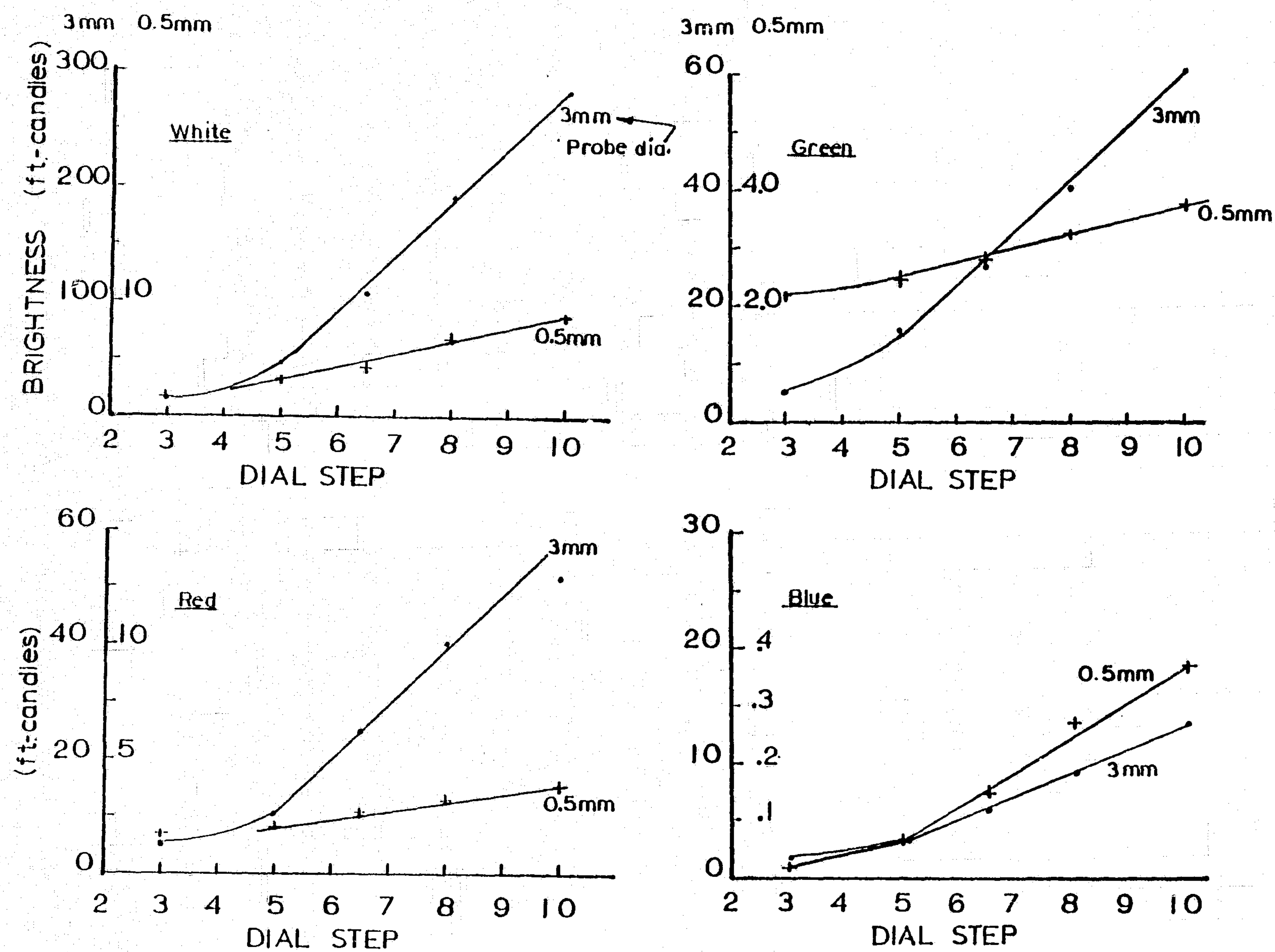
For each lens a series of spectroradiometric measurements was made on each of the four filters at different light intensities. The 1.9 m filter optics probe used for field measurements was placed directly against the viewer screen. A typical series of curves is presented in Fig. 5.

The purpose of this part of the calibration was to determine the general pattern of the spectrum coming through each lens-filter combination through the range of light intensities, and the information was used in deciding which lenses should be used for the color additive viewing and associated measurements of the Band 5 and Band 6 imagery. Initially it was thought possible that the information might be useful in developing a system by which the colors of the four lakes could be described and eventually compared within the image of the same date or between two images of different dates.

Since there is some light intensity fall-off across the screen, measurements were made vertically, horizontally, and randomly across the viewer screen, and it was determined that for the area within which the lakes would fall on the screen the spectral characteristics were sufficiently constant so that no serious error would be introduced by the inherent variations within the system.

Brightness measurements were made on the viewer screen at the same settings and lens-filter combinations as were used for the spectroradiometric measurements. A Spectra Lumicon Series II light meter with a fiber optics probe was utilized in these measurements. Both the full 3 mm diameter probe and the probe covered with a cap in which a 0.5 mm diameter hole centered in the cap had been drilled were used for this measurement. The 0.5 mm probe was used for the measurements determining the color difference between the four lakes. Typical curves are shown in Fig. 19.

The purpose of this part of the investigation was calibration of the viewer so that the investigator could use the dial settings and the filter characteristics to describe the color of each lake in numerical terms. If such a technique were to be developed, then it would be possible to describe the reflective characteristics of each lake on a



C.A.V. FILTER BRIGHTNESS

Fig. 19

given image or of each lake on different images. This information could be utilized in describing the trophic state differences between lakes and/or changes in each lake with time.

It was felt that when the negative transparencies were placed in the viewer the different levels of gray in the transparencies would act as neutral density filters of unknown density and would alter the intensity of the spectrum in a way that could be measured in terms of the color seen on the viewer screen. It was believed that brightness measurements made on the lakes and various parts of them would provide the clue to the color combination. It was also believed it might be possible to determine the x and y coordinates of the CIE color system from the brightness measurements and the knowledge of the mix of colors in the system. If this approach had been possible, then a unique number would have described each lake at a given time, and by comparison of the numbers one could make the necessary determinations about the trophic states of the lakes.

Because of the complexity of converting the various intensities and areas beneath the spectroradiometer curves into numbers that would be meaningful this part of the experiment was discontinued.

Work with the color additive viewer and the negative transparencies indicated that the four lakes showed different colors when Band 5 was used with a green filter and when Band 6 was used with a red filter. The color differences cannot be easily described verbally, but experimentation eventually led to the conclusion that a color chart of some sort might be useful in describing the colors and that brightness measurements would assist in separating the several similar colors. Also, consideration of the fact that it was difficult to make evaluations of the information contained in the Landsat data between images of different dates led to a method for normalizing the imagery to a common reflectance. Comparison of the spectroradiometric curves, including those of the Lake Phelps dock road and the pavement on the causeway across Lake Mattamuskeet, together with the information provided by the spectroradiometric study of the lakes (e.g., Fig. 4) indicated the probably feasibility of this approach.

As described in the Procedures Section (3.3.1), the Texasgulf phosphate mine site near Aurora, N.C., was chosen as the internal standard. The brightness measurements were made with the 0.5 mm diameter probe. A standard position on a light table was used to check variations on the light meter, and possible instrumental variations on the viewer screen were checked by measuring a standard spot on the screen after each series of imagery measurements. These measurements were made with the filter combination and light intensities used in analysis of the imagery and with just the white light in the system but at the intensity for each lens that was used in the image analysis. The Texasgulf normalization standard was always measured so that the probe's cap was tangent to the shore on the northwest part of the mine area.

Examination of the imagery in the color additive viewer disclosed that the colors of the step wedges of combined Bands 5 and 6 varied, a fact suggesting that the brightness of the several steps could be utilized in the normalization procedure. Accordingly, for each scene not only was the brightness of the Texasgulf mine determined but the brightness and color of each of the first ten steps were determined. A curve was then prepared by plotting the step number and the brightness measurement on log-log paper. The first step, the least dense on the negative, and the last three steps often fell off the straight line portion of the curves. However, for most of the images the brightness measurements of the four lakes and of the Texasgulf mine fell on the straight line portion of the curves. Figure 7 illustrates two of the characteristic curves, one from the 5 August 1976 imagery and one from the 9 March 1977 imagery.

The characteristic curves derived from the step wedges were then used to normalize the imagery to a common date. Once the curves were plotted, the brightness readings of the lakes and the Texasgulf mine were placed on the curve for the appropriate date. The 5 August 1976 curve was chosen as the one to which all of the other imagery should be normalized, and it was constructed on a sheet of paper separate from that of the other curves. By placing the curves from the other dates over the curve for 5 August 1976 and matching the points representing the Texasgulf mine, the investigator can read from the 5 August curve the normalized values for the brightness and the step wedge values for each of the lakes. Since the Texasgulf mine was not imaged for 23 August, the best fit of the 5 August and 23 August curves was used as the match.

Color differences displayed on the color additive viewer are important for differentiating between and among the four lakes; consequently, it became imperative that a method for describing the color be found. As the approach through the spectroradiometric characteristics of the lens-filter combinations could not be used, color charts were investigated. Various Munsell color charts were tried, but those available did not have the proper colors, and the numbers used in describing the color do not lend themselves to the type of arithmetical manipulation that seemed required.

One readily available color chart is found in Kerr (1959). The colors are described in terms of the retardation in micrometers (μm) of birefringent minerals. From the chart it is possible to determine the color of the individual lake, or a portion thereof, by comparing the chart with the color of the lake as found on the color additive viewer screen. Once the color is determined, it can be described in terms of the retardation wavelength (in μm), providing an unique number which is related to a color as viewed by the eye. The brightness aspect of the color seen on the viewer screen was determined both in terms of the normalized step wedge value and the brightness measurements. The first step of the wedge had a retardation color between 1475 and 1500 μm (third order interference colors) on the imagery made in August through October. For the imagery used from December through 9 March the initial step had a color that fell in the 900 μm range (second order interference colors). For most of the second set of imagery the second step was a yellowish gray, and the gray dominated the color of the higher steps. In some cases steps 9 and 10 were barely separable visually, and the light meter did not detect a consistent brightness difference between them. Most of the normalized step wedge values for the lakes fell within the first five steps of the standard wedge.

4.8.1 Step Wedge vs. TSI

Plotting of various ratios and differences determined from the normalized step wedge values of the lakes indicated that a ratio of the retardation wavelength for the color to the normalized step wedge value would be one parameter that could be useful in comparing trophic states of the lakes. Figure 20 is the resulting plot, each symbol representing a different lake and each associated letter indicating the date of the sampling and image acquisition. Because of the relatively small number of points involved in the plot only a best-fit line has been drawn by eye.

It is believed that there are instrumental errors and errors associated with the groundtruth measurements of the order of 10 percent. Thus it is felt that at this early state in the development of the technique the plot can be used to determine the trophic states of the shallow coastal lakes in terms of distinguishing between classes of TSI values. Thus if a TSI value is determined from the plot, the value may be expected to fall within ±5 units on either side of the value determined. It is probable that any ratio of retardation color to step wedge number can be expected to range ±25 units from a computed value.

The curve as presented here is suitable only for the particular color additive viewer used and for the particular light meter used. Each set of instruments must be calibrated. Any color chart which shows the spectrum as a continuous set of colors would be useful so long as the range of colors found on the color additive viewer is present in a form in which rather subtle differences can be recognized. One method by which the accuracy of the retardation color determination could be improved would be to prepare a series of color transparencies of the retardation colors. These transparencies could be made by photographing the interference colors made in a polarizing petrographic microscope by a quartz wedge. The transparencies could be held against an appropriate part of the viewer screen and compared with the lakes more directly than can a chart on an opaque printed page. As an example of the use of the curve data from the 27 December 1973 Landsat image is given in Table 8. The TSI values have been determined from the curve by entering into it with the Color No./Step No. ratio.

4.8.2 Brightness vs. TSI

To arrive at a color number which takes into account the brightness measurements on the viewer screen and the color determinations using the interference color chart, the color retardation wavelength was multiplied by the normalized brightness measurement which was determined from the curvefitting technique. Figure 21A illustrates the results of plotting the TSI against the color number determined in this fashion and Table 9

TROPHIC STATE — COLOR NO. (Step) RELATION

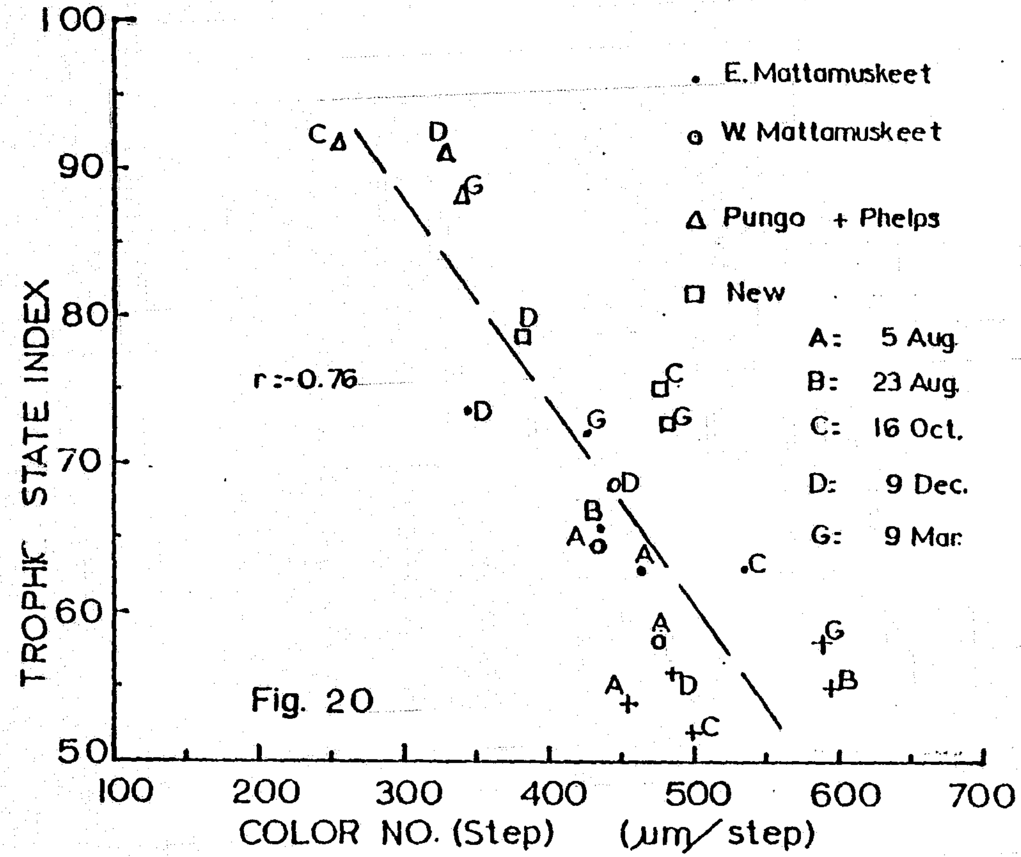


Fig. 20

Table 8

27 December 1976 Image

Data for Color Number and Normalized Step Wedge

Lake	Retardation Color Number (μm)	Step No.	Color No. / Step No.	TSI
Phelps	1025	2.2	475	68
East Mattamuskeet	850	2.86	297	90
West Mattamuskeet	950	2.40	396	78
Pungo	930	2.92	318	88
New	950	2.4	395	78

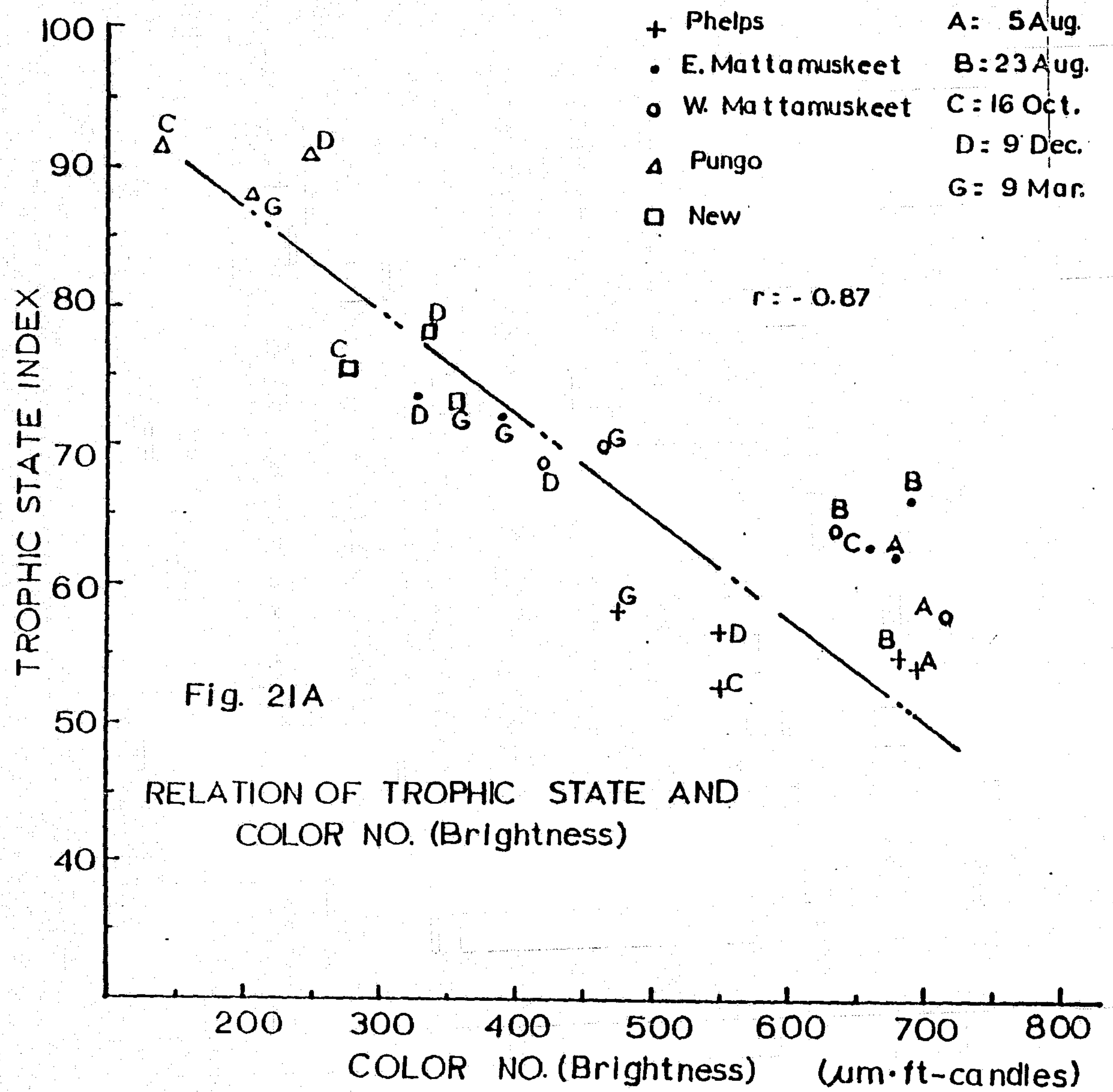


Fig. 21A

RELATION OF TROPHIC STATE AND COLOR NO. (Brightness)

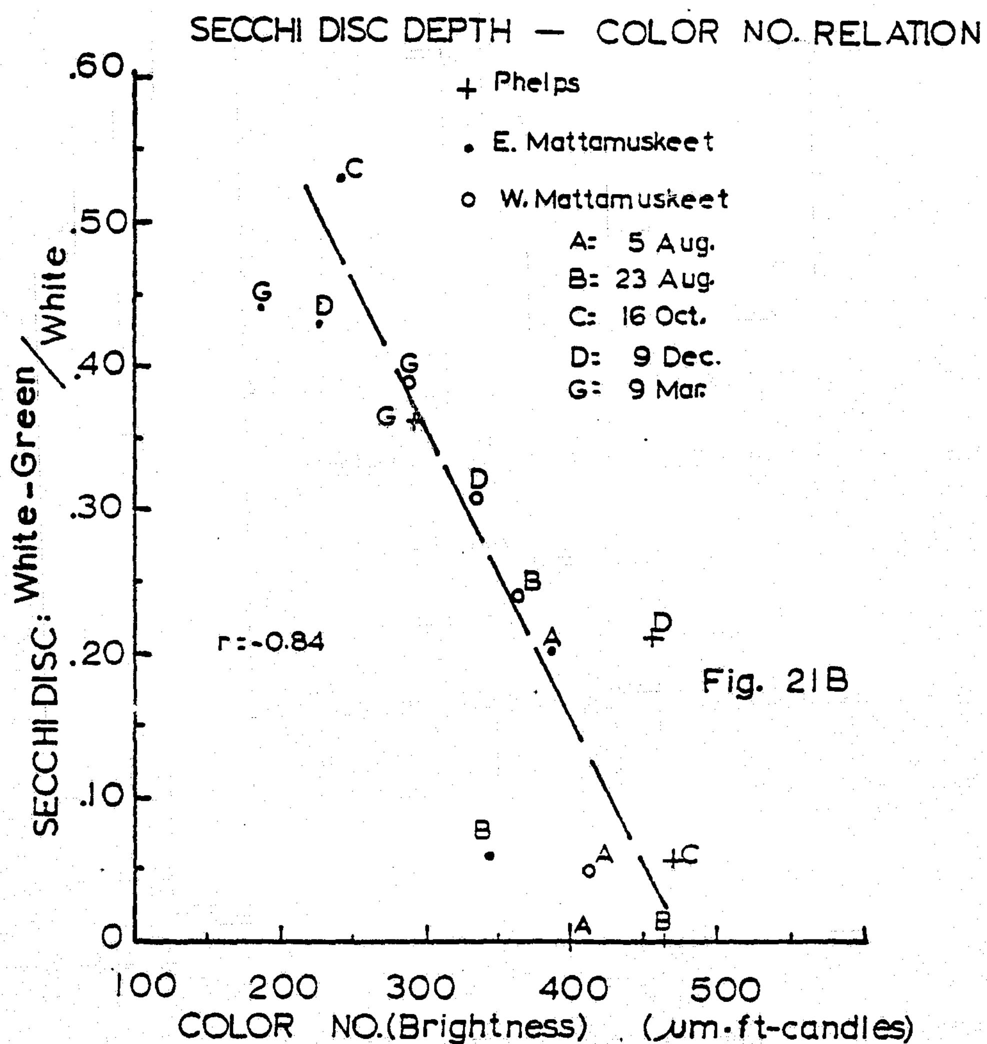

SECCHI DISC DEPTH — COLOR NO. RELATION
+ Phelps
• E. Mattamuskeet
o W. Mattamuskeet
A: 5 Aug.
B: 23 Aug.
C: 16 Oct.
D: 9 Dec.
G: 9 Mar.
r=-0.84
SECCHI DISC: White-Green/White
COLOR NO.(Brightness) (μm-ft-candles)
.60
.50
.40
.30
.20
.10
0
100
200
300
400
500
Fig. 21B

Table 9

27 December 1976 Image

Data for Color Number and Normalized Brightness

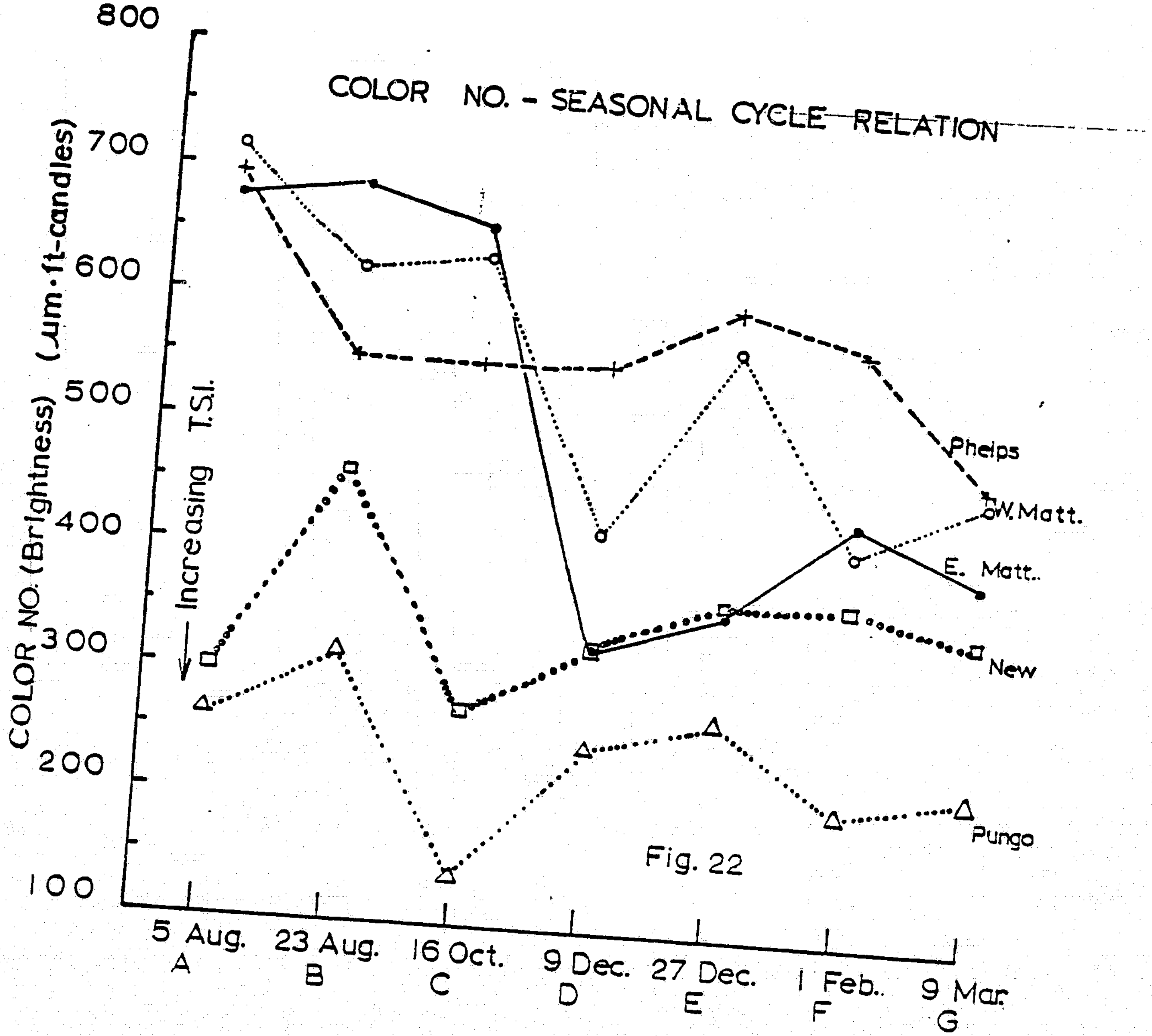
Lake	Retardation Color No. (µm)	Brightness (ft.-candles)	Color No. X Brightness (µm x ft.candles)	TSI
Phelps	1025	.52	533	64
East Mattamuskeet	850	.24	204	83
West Mattamuskeet	950	.36	342	76
Pungo	930	.23	214	84
New	950	.325	309	78

lists the color number data for the 27 December imagery as well as the TSI values determined from this curve.

Secchi disc measurements are frequently used as guides to the turbidity level of a given body of water with sun angle and viewing angle affecting the results. In an attempt to relate the Secchi disc measurements to the space-acquired imagery, the colored Secchi disc was used. Secchi disc transparencies for both the green and white quadrants were plotted as were the differences between the depths for these two colors. Although there were some general indications that there existed a systematic relationship, the scatter on the plots suggested that perhaps a ratio of the difference against the white depth might be useful. Figure 21B shows the plot of this ratio against the color number (brightness) for Lake Mattamuskeet and Lake Phelps. The curve through the points has been fitted by eye.

Because one purpose of the investigation was to determine if it was possible to monitor seasonal, if not monthly, changes in the trophic state of the individual lakes as well as trophic state differences between individual lakes, comparison of the trophic state patterns for the individual lakes with their color number (brightness) value patterns was made. The resulting graphs are shown in Fig. 22. As might be expected by the nature of the data and the several instrumental and analytical variations inherent in the technique, the correspondence between the trophic states as determined from the satellite imagery and the groundtruth data (Fig. 10) is not perfect. However, there are several general trends which may be recognized. The most important trend is the fact that the trophic states indicated by the color number (brightness) values fall into the same broad pattern for the four lakes as the trophic states do. Thus Pungo Lake is indicated to possess the highest trophic state of the four lakes, and Lake Phelps shows the lowest trophic state, with New Lake falling in between, but closer to Pungo Lake than Phelps.

The data from Lake Mattamuskeet indicate a considerable variability, a fact which would seem to be related to the shallow nature of this lake and its response to wind stirring of the bottom. However, Lake Mattamuskeet, both its west and east ends, does exhibit patterns which suggest that its varying trophic state can be monitored with the space-acquired data.


COLOR NO. - SEASONAL CYCLE RELATION
COLOR NO. (Brightness) (μm·ft-candles)
Increasing T.S.I.
800
700
600
500
400
300
200
100
5 Aug.
A
23 Aug.
B
16 Oct.
C
9 Dec.
D
27 Dec.
E
1 Feb.
F
9 Mar.
G
Phelps
W. Matt.
E. Matt.
New
Pungo
Fig. 22

If one considers that the important trophic state differences are those found on a seasonal basis and if one examines the time plots of trophic state (Fig. 10), one can separate the trophic levels into two broad categories, one lower than the other. Then if the TSI values for the two categories are averaged along with the corresponding color number (brightness) values, and a graph drawn (Fig. 23), it becomes apparent that there is an approximate linear relationship between the reflectance and the trophic states of the individual lakes through the seasons. Thus seasonal monitoring of the trophic states of the lakes becomes possible.

Figure 24 shows color additive renditions of the 5 August 1976 and the 9 March 1977 images in the standard format: Band 5 = green (Intensity 6) and Band 6 = red (Intensity 8).

Other possible combinations of the positives and negatives in the color additive viewer were investigated to bring out differences between the lakes and to determine seasonal differences. No brightness measurements were made of the several combinations because of time limitations. However, one possible useful combination is one which uses the negatives of Band 5 and Band 6 and the positive of Band 4. Figure 25 is an example of this combination with a green filter for Band 4 positive, a red filter for Band 5 (negative), and a blue filter for Band 6 (negative). Projection lamp intensities were approximately equal.

Other Relationships

Plots of the several physical and biological parameters against the color numbers did not disclose any striking relationships. However, a curvilinear distribution of points seems to be represented by a plot of color numbers against the suspended matter. This curve (Fig. 26) suggests that for the shallow coastal plain lakes suspended matter loads can be measured with Landsat satellite data between concentrations of approximately 10 to 350 mg/l if the color additive approach described is used. Lower and higher concentrations can be measured, but errors introduced in the retardation color determination will cause significant errors at the lower and higher concentrations. On the otherhand, the relationship between suspended material loads and Secchi disc depths (Fig. 9) implies that the exact relationship may be lake-specific.

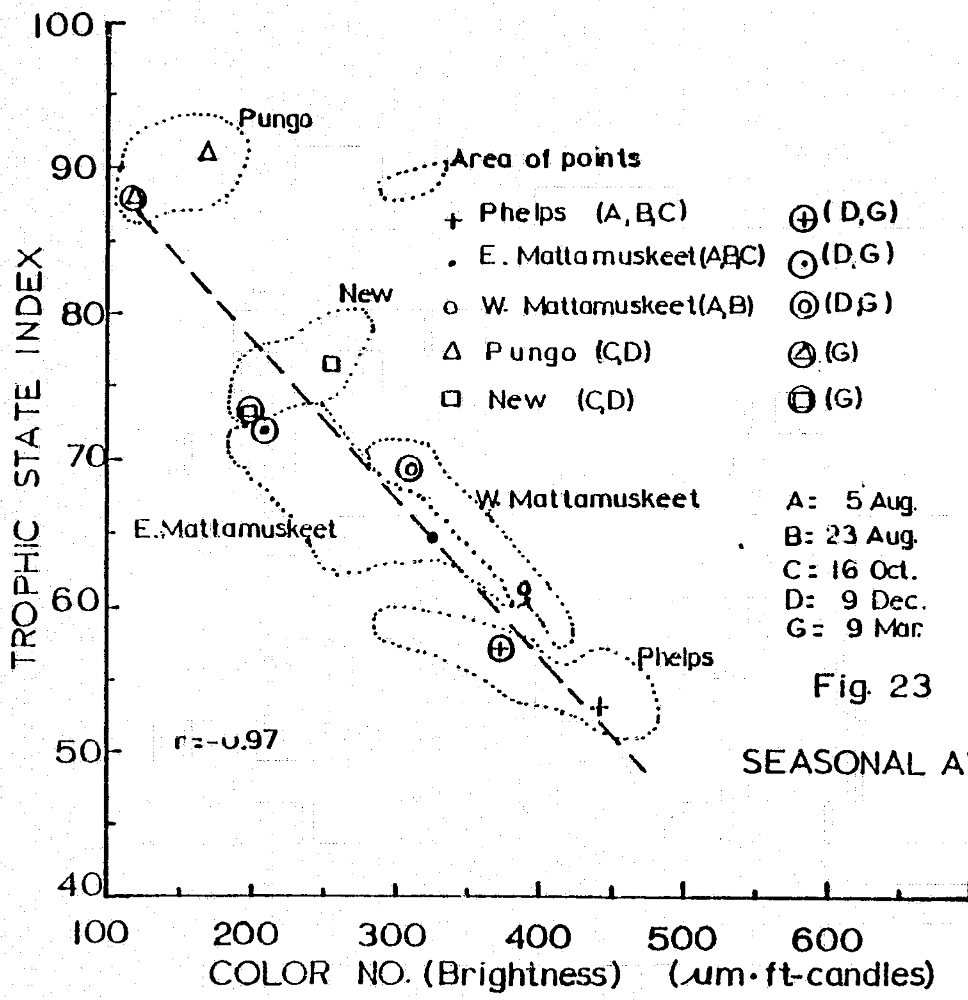
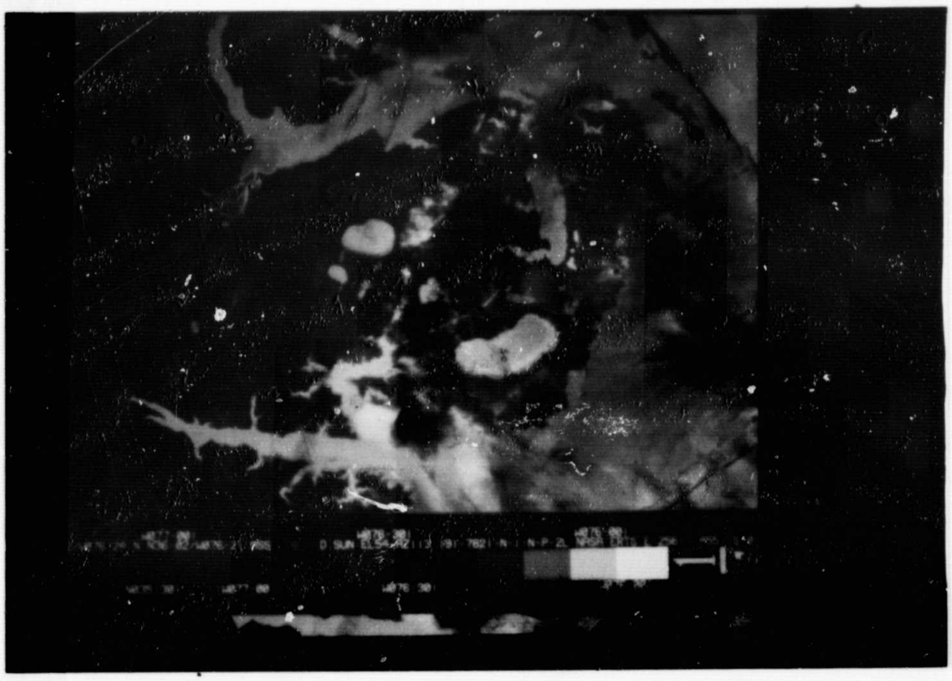


Fig. 23

SEASONAL AVERAGES

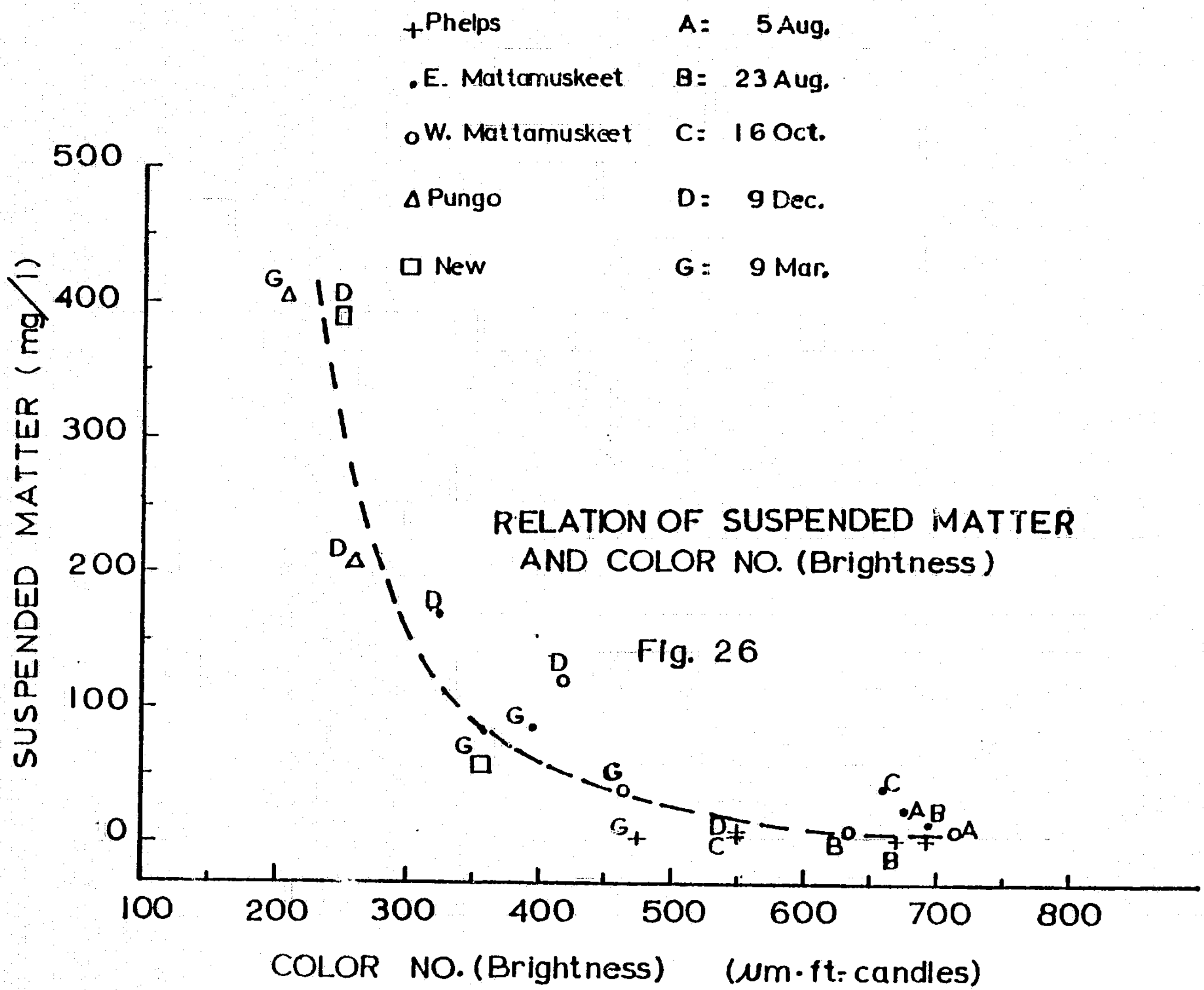


A. 5 August 1976: Band 5 = Green (6); Band 6 = Red (8)

B. 9 March 1977: Band 5 = Green (6); Band 6 = Red (8)

Fig. 24. Standard Color Additive Renditions

Fig. 25. 9 March 1977
Band 4 Positive : Green
Band 5 Negative : Red
Band 6 Negative : Blue



RELATION OF SUSPENDED MATTER AND COLOR NO. (Brightness)

Fig. 26

4.9 Density Slicing Experiment

All imagery through 9 March 1977 was density sliced on a twelve step Spatial Data Systems EyeCom Image Scanner, Model 700 SV. The CRT display was photographed on 35 mm color slide film, and the slides were later studied singly or two or more were compared by simultaneous projection onto a common screen. Both 35 mm projectors and a color additive viewer were used. In the latter case density slices from different bands of the same scene or from the same band of different scenes were compared. By projecting either through the viewer or with two 35 mm projectors, the investigator could not only compare two density slices, but he could also compare the density slices conveniently with slides of color additive renditions of the same image.

Because the standard step wedges placed on the imagery varied significantly from band to band for the same image and from image to image, a calibrated step wedge was used to standardize the density slicing procedures. The characteristic curve of the step wedge, which was prepared by NASA for the SKYLAB program, is given in Fig. 27. A standard setting for the image enhancer was chosen, and the colors associated with the midrange of the step wedge were noted. A transparency of one of the bands was density sliced, and a photographic record made of the CRT screen. Between the density slicing of each image the step wedge was inserted into the system and the instrumental settings adjusted for any minor instrumental drift. Thus it was possible to compare the reflections from the several bands of one scene and from the several scenes through a common measure of the density distribution.

The technique does not account for density differences between images of different dates attributable to sun angle and/or atmospheric effects, nor does it allow for corrections to be made for atmospheric effects on a given date. Neither can differences attributable to the processing of the 70 mm transparencies be corrected for. Nonetheless, it appears that for the purposes of distinguishing significant water quality differences within each lake and in most cases between lakes shown on the same scene that the technique gives acceptable results.

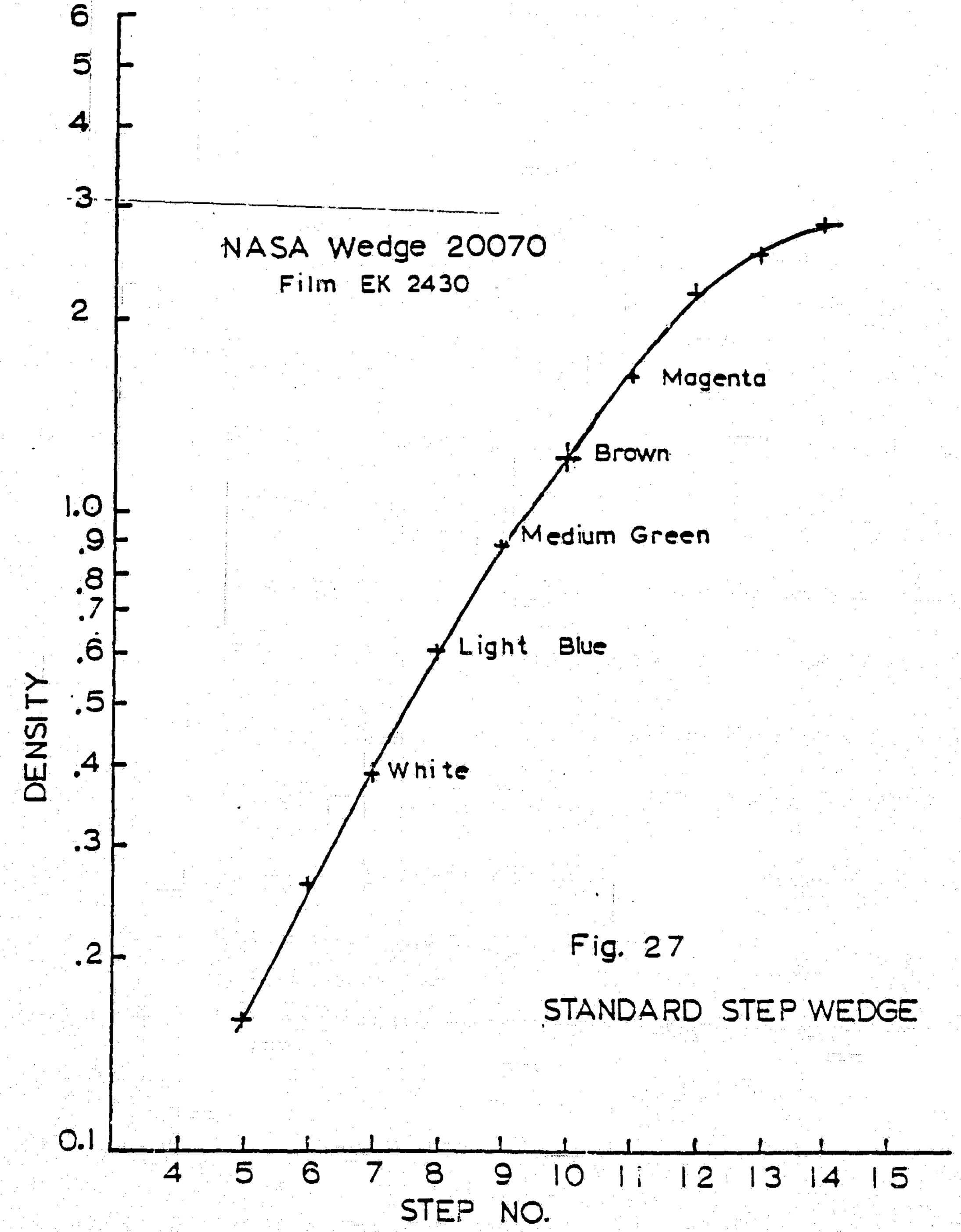


Fig. 27

STANDARD STEP WEDGE

Suspended matter and the Trophic State Index (TSI) appear to compare most favorably with the density measurements. Table 10 gives density values, suspended sediment load, biomass concentration, and TSI values for the five best images.

Because the reflections returned to the satellite are influenced by the nature of the material suspended in the water and because different materials in different combinations can give reflections of similar intensities in any one band, density slicing of one image alone need not differentiate among and between the lakes. Thus it is necessary to examine the record of two or more bands before any definitive conclusions can be drawn about the meaning of reflectance similarities and differences. However, once the general parameters of a given lake are understood, it should be possible to utilize only one band to monitor any changes.

Bottom reflections present a problem that must continuously be considered in working with shallow coastal lakes. If turbidity levels are sufficiently high, then bottom reflections are not important, but if the turbidity levels are low, then some of the lower densities shown by positive images of the lakes record reflections from the bottom. Again an understanding of the individual lake system is important to interpretation of the imagery.

From consideration of the penetration characteristics of the four Landsat bands and from observations of the imagery itself, the conclusion was made that Band 6 imagery would provide the best information about the nature of the water masses in each lake and about the trophic states of the lakes. The use of Band 5 for mapping aquatic plants has been discussed in Section 4.6.

In a multispectral photographic experiment it was found that the Band 6 part of the spectrum was absorbed within water depth of less than approximately 2.5 m in a clear swimming pool. Similarly, the lens recording the equivalent of Band 5 energy recorded low levels of reflection from the bottom of a one meter deep sewage settling pond. The settleable solids were of the order of 5 to 10 mg/l in the pond (Welby, 1976). The spectroradiometric curve for the Faculty Club swimming pool (Fig. 4) shows a flattening of the reflectance at about 700 μm, implying that reflectances from the bottom of the pool are not important in water depths greater than 2.5 to 3 m. Thus it appears

Table 10

Lake	Density		Suspended Matter	TSI	Biomass
	MSS-5	MSS-6	(mg/l)		($10^3 \mu^3$/ml)
	Date: 5 August 1976				
Phelps	1.35	1.50	4.9	54.0	18,683
East Mattamuskeet	1.15	1.43	19.7	62.7	39,183
West Mattamuskeet	1.48	1.58	10.2	58.2	11,333
New	cloud cover	- -	- -	- -	- -
Pungo	1.20	1.04	- -	- -	- -
	Date: 23 August 1976				
Phelps	1.71		6.7	54.8	31,418
East Mattamuskeet	1.13		12.7	65.5	19,746
West Mattamuskeet	1.74		11.0	64.4	15,236
New	1.65		- -	- -	- -
Pungo	1.54		- -	- -	- -
	Date: 16 October 1976				
Phelps	2.33	2.70	1.9	52.4	14,456
East Mattamuskeet	2.27	2.70	42	62.8	3,040
West Mattamuskeet	2.33	2.70	- -	- -	- -
New	2.27	2.34	38	74.6	- -
Pungo	2.01	2.34	82.5	91.5	- -
	Date: 9 December 1976				
Phelps	1.61	1.83	2.6	56	9,397
East Mattamuskeet	1.41	1.52	183.0	73.5	10,118
West Mattamuskeet	1.49	1.56	118.0	68.7	6,107
New	1.59	1.62	388.0	78.8	5,172
Pungo	1.61	1.62	770.0	91.0	10,735
	Date: 9 March 1977				
Phelps	2.28	2.28	6.0	58.1	27,295
East Mattamuskeet	2.06	2.11	76.0	72.0	13,618
West Mattamuskeet	2.30	2.31	39.0	80.0	12,872
New	2.30	2.28	64.0	72.7	4,218
Pungo	1.89	1.89	400.0	87.9	34,040

Table 10. Image density measurements

reasonable to assume that bottom reflections are associated only with shallow lakes with relatively clear water and that in those cases where the water is of moderate turbidity (10 mg/l and above) that the reflections can be assumed to come primarily from within the water column.

Of the lakes utilized in this investigation Lake Phelps appears to possess consistently water of sufficient transmittance so that reflections can be expected from the bottom with some consistency through time. On occasion, as for the 23 August 1976 image, the water in Lake Mattamuskeet is sufficiently transparent so that the bottom returns energy in Bands 4 and 5. The Secchi disc measurements for Pungo and New lakes show that the images of these lakes probably record energy return to the satellite from only the upper one meter or so. From the relationship between turbidity and penetration of the Band 5 portion of the spectrum and from the fact that the energy reflected in the Band 6 part of the spectrum must come from even shallower water depths and probably even in clear water from approximately the upper meter, it appears that Band 6 is the best single band with which to evaluate water quality parameters from the density slices of the shallow coastal lakes.

Multispectral photography of the upper Chowan River, north-northwest of the four lakes, demonstrated that irradiance in the Band 6 portion of the spectrum from a water column containing 10 or more mg/l of suspended solids and displaying Secchi disc depths of 0.5 m or less was from the upper few centimeters of the water column (Welby, 1976).

Consideration of the spectroradiometric curves for both the Faculty Club swimming pool and for Lake Mattamuskeet and Lake Phelps (Fig. 4) show that the bulk of the reflections coming from the water itself is in the upper portion of Band 6, for a relative absorption occurs between 700 and 750 μm. On 5 August the bottom of Lake Phelps was visible (Appendix) and in general the reflectance values are low compared to those for Lake Mattamuskeet which had a higher suspended matter load. Except for two stations the bottom of Lake Mattamuskeet was not visible, and it must be assumed that the reflectances shown for this date (Fig. 4) record the turbidity. Thus the ratios of lake water reflectance to swimming pool reflectance which can be calculated from Fig. 4 for each of the lakes shows Band 6 to be a sensitive measure of the turbidity of the water of these lakes. The decrease in reflectance associated with the spectrum above 700 μm in the swimming pool is attributed to the absorption by the water of the energy in this part of the spectrum. When the water is more transparent and the bottom is dark-colored, less energy is reflected from the lake than when the water is more turbid and filled with reflecting material. Thus as the reflectance within the Band 6 range approaches that of a spectral standard such as a white-bottomed swimming pool, the greater is the turbidity indicated. Also with the addition of reflecting suspended material the water absorption peak between 700 and 750 is overridden.

Yost, et al (1971) report that the band from 800 to 900 μm was useful for detecting phytoplankton as well as inorganic materials in suspension in comparative multispectral photography of Louisiana coastal waters. Tabor (1975) shows reflectance curves for clay suspensions, phytoplankton, and combined clay and phytoplankton. The reflectance from the combined samples is nearly twice that from either alone in the 700 to 800 μm band. This relationship implies that the reflectances from a mixture of inorganic and organic materials can be additive in an algebraic sense.

Blanchard and Leamer (1973) point out that increasing concentrations of sediment and algae are accompanied by decreases in reflection intensity, and according to Polcyn and Lyzenga (1973) the reflection from dead organic material ("yellow substance") decreases in the blue region with increasing concentration of organic matter. For the red portion of the spectrum (Band 5) the balance between scattering and absorption is more dependent upon particle size (Jerlow, 1974, p. 82). On the other hand, phytoplankton reflect ten percent or more of the light received by them in the 600 to 700 μm range (Polcyn and Lyzenga, 1973;) Blanchard and Leamer, 1973). Thus if suspended organic materials are giving rise to the bulk of the reflections, one would expect that the water with dead organic matter dominant would appear dark in all bands and that water with smaller amounts of dead organic matter and more phytoplankton would reflect strongly in the green to red portions of the spectrum.

It appears that the energy transmitted to the satellite is controlled by the relative abundance of dead and live organic matter with the relative proportions of organic matter and inorganic matter and the combined reflecting characteristics associated with the form of the of the particulate matter. Polcyn and Lyzenga (1973), citing Suits (1973), indicate that the phytoplankton and sand reflectances become about equal at 700 nm in water and that with increasing phytoplankton content the reflectances increase in the 650 to 700 μm range. The curves presented suggest that above 700 μm there is a similar increase in phytoplankton reflectances, a fact born out by the curves presented by Tabor (1975, p. 99).

Citing work by Clarke et al (1969) Polcyn and Lyzenga (1973, Fig. 5) show that the dead organic matter has a low reflectance above 700 μm. Thus the amount of energy reflected into the atmosphere from the shallow coastal lakes in which a significant amount of suspended inorganic particulate matter and significant amounts of phytoplankton occur can be expected to have an important component in the 700 to 800 μm range. It can be anticipated that only a small proportion of the reflections will be from the dead organic matter, even if there is a large proportion of this material present in the water.

Examination of the groundtruth data for the four lakes for 9 December 1976 and 9 March 1977 suggests that Pungo Lake should have the highest reflectance in Band 6 because of the total suspended load and the total biomass. Density slicing of Band 6 for these two dates does indicate this relationship, and the eastern component of Lake Mattamuskeet has the next highest reflectance in accord with the groundtruth.

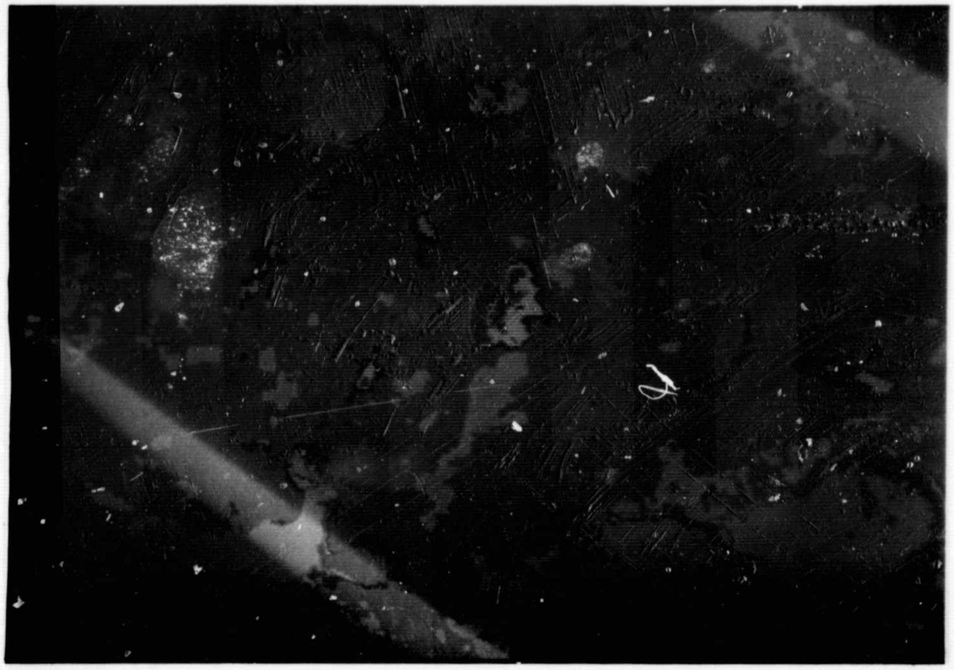
The relative proportions of low reflecting dead organic matter and high reflecting inorganics and phytoplankton control the total amount of energy leaving the lake waters. If the water reflectance is dominated energy-wise by the dead organic matter, then the Band 6 reflectamce should be low; if the water and its suspended particulate matter is dominated by the more highly reflective material, the Band 6 reflectance will be relatively high. The response of the water and its contained particulate matter would seem to be controlled by not only the relative proportions of the several types of particulate matter but also by the absolute amounts.

Since Band 4 and 5 have the potential for recording reflections from the bottom of the shallow lakes and since Band 6 reflections appear to come from no more than the upper one meter of the lakes, it is concluded that Band 6 imagery can be used for water quality determinations and as a trophic state indicator provided the trophic state can be determined on the basis of the amount and characteristics of the suspended materials in the water. Intralake differentiation seems possible within a given image as does interlake differentiation. However differentiation between images depends upon some means of normalization of the images made at different times.

Figure 28 illustrates the differentiation for 5 August 1976 and 9 March 1977. Comparison with Fig. 10, the graph of the Trophic State Index through time, shows that the higher reflectances correspond with the higher Trophic State Index values for a given date.

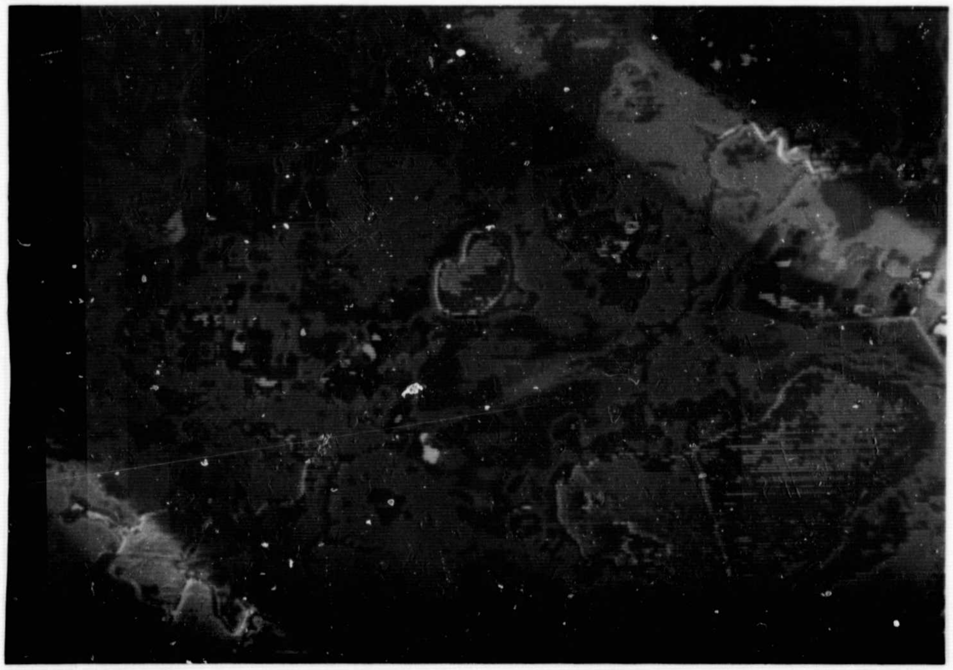
Comparison of the Trophic State Index from month to month on the basis of the satellite imagery and density slicing techniques does not seem possible without an effective method of normalizing the several images. Normalization could probably be accomplished by utilization of two or more features with consistently different reflectances in the Band 6 spectrum but each of which could be considered to have a consistent reflectance throughout the year. Ideally, such features would be two or more steps on a giant neutral gray scale. Since such a gray scale is nonexistent, a man-made feature, such as complex of buildings or an airport could be used. The density slicer could then be adjusted to these features so that the range of densities between the standards was always the same.

In the current work no attempt was made during density slicing procedures to normalize the several images as suitable features do not exist adjacent to the lakes, and the roadways used as standards for the spectroradiometric measurements are too small to be reliable for this purpose. The reflectance curve of 12 August 1976 for the dairy pond (Fig. 4) shows a peak in the Band 6 part of the spectrum. The pond had a blue-green algal bloom in progress at the time of the spectroradiometric measurement. Separation of the reflectances from the swimming pool and the dairy farm pond gives insight to what might be the difference between relatively clear water of Lake Phelps at one time and more turbid, phytoplankton-rich water at another, or between Lake Phelps and Lake Mattamuskeet when the water of the latter has a higher biomass content.



A. 5 August 1976. Band 6 Density slice - Sequences of reflectance, lowest to highest: -

tan - yellow - brown - green. Green and yellow over lakes represent clouds.



B. 9 March 1977. Band 6 Density slice - Sequence of reflectance, lowest to highest: -

purple - violet - red - tan - brown - yellow.

Fig. 28. Density Slices

4.10 12 June 1976 Image - Chowan River Bloom

Althouth the present study was not concerned with the trophic conditions of the Chowan River (Fig. 1), a major algae bloom occurring on the river in June 1976 provided an opportunity to study casually what might happen on a shallow coastal plain lake if its trophic state were sufficiently high.

Figure 29 is a negative print of Band 6 of the 12 June image. It shows the distribution of the bloom at the time of the satellite overpass, and density slicing permits the determination of the concentration pattern. Since the bloom was on the surface, Bands 4, 5, and 7 also record its presence.

The dominant phytoplankton species present at this time are Anabaena sp. (biomass $5.4 \times 10^6 \mu^3$/ml) both blue-green algae (A. M. Witherspoon, personal communication, June 1977). The seasonal nutrient pattern for the Chowan River is similar to that given in Fig. 8 for the shallow lakes. Thus it is expected that the nutrient levels (phosphorus and nitrogen) are probably low for this stretch of the river where the phytoplankton are concentrated.

Weiss and Kuenzler (1976) classify the reach of the Chowan River between U.S. 13 bridge and Albemarle Sound as α-eutrophic. The average TSI value for August 1974 computed from their data following Carlson's (1977) teachnique is 60. It was near the center of this section of the river that the phytoplankton bloom illustrated in Fig. 29 occurred on 12 June 1976.

Fig. 29. Phytoplankton bloom. Chowan River, 12 June 1976. Species of <u>Anabaena</u> and <u>Anacystic</u> dominate. Negative Print of a portion of Image No. 2507-14564, Band 6.

5.0 CONCLUSIONS

The chief conclusion derived from this study is that Landsat imagery can be used to monitor trophic states of shallow coastal plain lakes. The lakes can be separated among themselves in terms of their individual trophic levels, and seasonal monitoring, if not monthly, can be accomplished with the imagery. In most cases satellite monitoring may be more accurate than monitoring based upon a few water samples taken randomly, although further detailed study would be required to prove this statement conclusively. Clues to variations in trophic states within the lakes are also recorded by the imagery, and the satellite data can be utilized to show these variations.

It appears that the imagery can be used effectively to monitor individual lakes through not only seasons but also over a period of years. In addition the land use patterns around the lakes can be determined and monitored to develop any relationship that might exist between changing land use patterns and changes in trophic states. If a phytoplankton bloom occurs on the surface of the lakes, all four bands can be utilized to study its distribution and to provide information about its particular concentration patterns.

Photo-optical methods of study appear to be a useful approach to the problem of monitoring shallow coastal plain lakes. Combination of Band 5 and Band 6 imagery in a color additive viewer and description of the resulting color not only in terms of hue and chroma but also in terms of brightness is one approach that can be effectively used. Not only does the color characterization correlate with Trophic State Index, but the ratio of the difference between the green quadrant depth and the white quadrant depth to the white quadrant's extinction depth on a modified Secchi disc can be related to the Landsat imagery systematically.

The photo-optical approach allows for a convenient curve-fitting procedure to be used so that normalization of the several images required for monitoring can be carried out. Spectroradiometric measurements made during the course of the investigation tend to support the normalization procedure utilized in the color additive approach.

For direct density measurements to prove useful as a monitoring tool there first needs to be established a clear-cut relationship between the material suspended in the water masses of the lakes and the various trophic state indicators such as biomass, chlorophyll-a, and nutrients. The seasonal cycle of the lakes suggests that the probability of such a systematic correlation useful in trophic state monitoring may be difficult to establish.

The Trophic State Index (TSI) as modified from Carlson (1977) has been shown to have a meaningful relationship to the energy reaching the satellite from the lakes. No definitive positive correlations have been found between suspended loads in the water masses of the lakes and various biological and chemical parameters. Chlorophyll-a which is often used as an indicator of biomass becomes lower when the dinoflagellates dominate the phytoplankton. There is a corresponding change in the form of the botanically related reflectance in Band 5 because of the difference in pigments.

When the turbidity of the lakes is sufficiently low and bottom reflectances are recorded by the satellite, bottom vegetation mapping becomes feasible down to depths of approximately 3 meters. Shallow water macrophytes can also be mapped and conveniently monitored with the present Landsat configuration of sensors within limitations of the scanner resolution. As the library of satellite imagery is built up, it is to be supposed that the imagery will prove to be an effective tool for monitoring macrophyte changes within resolution constraints.

It cannot be emphasized enough that, in utilizing the Landsat imagery for lake trophic level monitoring, the investigator must have a good understanding of the probable seasonal cycle of the individual lake and its environment. The fact that the Landsat multispectral scanner bands are moderately broad and that total irradiance from the lakes is an algebraic sum of a number of smaller irradiances requires judicious interpretation of a given density pattern within the context of a particular lake. Once the individual lake characteristics have been established and normalization techniques have been set up so that imagery from different times can be compared, it is then possible to use the imagery for monitoring trophic states of shallow coastal plain lakes.

6.0 RECOMMENDATIONS

Recommendations for further investigations of the use of satellite-acquired imagery for the monitoring of shallow coastal plain lakes are described below.

1. Further study should be undertaken of the chlorophyll-suspended material load relationship and how the satellite imaging systems report the relationship. Studies should be undertaken to establish whether the relationship is lake-specific, seasonal, as is suggested by this study, or whether there is a random relationship.

2. The study should be expanded to other North Carolina lakes so that a state-wide monitoring system using satellite imagery may be established.

3. Density slicing procedures may prove to be an effective way to monitor the lakes through the year, but such procedures require that the imagery be normalized to a standard internal gray scale. Work needs to be done to establish the scale of and type of cultural features that can be used. It appears that normalization through the step wedges on the imagery may have some pitfalls.

4. For a cost-effective method of monitoring shallow coastal lakes from satellite imagery color additive viewing techniques appear to offer considerable advantages over other approaches. Additional work needs to be undertaken in the use of various combinations of negatives and positives in differentiating the lakes. It may be possible to develop a combination of standard color settings that will distinguish between lakes of very similar Trophic State Index (TSI).

5. Application of the satellite imagery to the monitoring of water quality and trophic state of colored lakes needs to be investigated.

6. Further investigations should be conducted upon the effects of bottom reflections on the imagery so that this information can be utilized in establishing the trophic states of the lakes from satellite imagery.

7. Studies of the reflectance characteristics of the different algae color groups during their dominant stage should be undertaken in order to establish how the different color groups are recorded on the satellite imagery. Such studies should also address themselves to the effects of mixes of the various groups.

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Appendix I

Date: 5 August 1976

Lake Phelps

Parameter	Station No. 1	2	3	4	5	6	7	8
I. Temp. (°C)	25.5	25.5	26	25.2	25.5	25	25.8	25.2
Transparency* (cm.)	140	193	208	157	193	216	160	213
light meter	250	125 250	125 250	250	250	250	250 500	250 500
Suspended matter (mg/l)	6	3.6	3.6	5.2	5.6	5.6	5.2	4
Total solids (mg/l)	3.5	1.5	1.0	42.5	5.6	6.0	24	8.5
Weather condition	clear,	hot →						
wind direction	N.E.	→						
wind speed (mph)	2-5	→						
Color (Plat. Cobalt units)								
II. Oxygen (ppm)	8.1	8.35	8.7	8.4	8.1	8.3	8.4	8.3
% saturation	98	100	106	101	98	99	102	99
Conductivity (microhos/cm)	94	95	94	94	95	92	94	92
pH	5.25	5.55	5.30	5.35	5.25	5.20	5.35	5.15
Chlorophyll-a (μg/l)	6.52	6.86	5.11	7.32	- -	5.78	4.77	5.11
Sulfate (mg/l)								
Chloride (mg/l)	8.00	8.80	9.00	10.60	9.20	8.60	8.40	8.70
Total K Nitrogen (mg/l)	0.59	0.60	0.90	0.89	0.57	0.62	1.22	0.71
Ammonia (mg/l)	0.02	0.02	0.02	0.02	0.01	0.01	0.03	0.01
Nitrate (mg/l)	0.006	0.010	0.002	0.004	0.004	0.004	0.00	0.00
Nitrite (mg/l)	0.002	0.002	0.004	0.002	0.006	0.004	0.004	0.004
Total Phosphorus (mg/l)	0.06	0.06	0.07	0.06	0.07	0.06	0.07	0.05
Ortho-phos. (mg/l)	0.01	0.01	0.00	0.00	0.00	0.01	0.07	0.00
III. Algae (no. cells/ml.)		3,771		4,991				2,370
Algae biomass ($10^3\mu^3$/ml)		15,907		29,403				10,739

* A circled number indicates the bottom was visible.

Date: 23 August 1976

Lake Phelps

Parameters	Station No. 1	2	3	4	5	6	7	8
I. Temp. (C°)	24.5	24	24	25	24.5	24.5	24.5	24.5
Transparency circle bottom visible (cm)	132 ↓	198 ↓	211 ↓	175 ↓	203 ↓	211 ↓	183 ↓	198 ↓
light meter	250	125	250	250 500	250 500	250 500	250 500	250 500
Suspended matter (mg/l)	17.6	5.2	6.4	4	5.2	5.2	4.4	5.2
Total solids (mg/l)	30	36	32	45	28	36	32	27
Weather condition	Hazy and sunny →				clear and sunny →			
wind direction	0 →							
wind speed (mph)	0 →							
Color (Plat.Cobalt units)								
II. Oxygen	8.45	8.8	8.6	8.7	8.78	8.6	8.68	8.8
% saturation	100	104	101	104	104	102	103	104
Conductivity (microhms/cm)	100	103	102	102	99	103	99	101
pH	5.0	5.2	5.2	5.45	5.35	5.3	5.25	5.25
Chlorophyll-a (μg/l)	3.81	2.66	6.76	9.96	6.03	4.99	2.80	8.56
Sulfate (mg/l)								
Chloride (mg/l)	8.6	11.1	10.1	9.0	9.0	9.6	10.0	9.2
Total K Nitrogen (mg/l)	0.86	1.1	0.80	0.90	0.89	0.93	0.98	1.28
NH_3 (mg/l)	0.03	0.21	0.02	0.02	0.03	0.06	0.04	0.04
NO_3 (mg/l)	0.004	0.127	0.009	0.015	0.001	0.012	0.465	0.008
NO_2 (mg/l)	0.00	0.00	0.00	0.006	0.001	0.002	0.001	0.002
Total Phosphorus (mg/l)	0.07	0.10	0.06	0.07	0.06	0.07	0.07	0.08
Ortho-phos. (mg/l)	0.01	0.01	0.01	0.00	0.00	0.01	0.01	0.01
III. Algae (no. cell/ml.)		2,434		5,536				3,853
Algae biomass ($10^3\mu^3$/ml)		24,211		49,634				41,480

Date: 16 October 1976

Lake Phelps

Parameters	Station No. 1	2	3	4	5+	5-	6	7	8
I.									
Temp. (C°)	17	16.5	16.5	16.9	18	16.8	17	17	17.1
Transparency (cm.)*	145	145	196 183 163 147	168	99 97 76 66	91	193	168	180
light meter	250	500 1000	250	125 250	250 500	125 250	250 500	250 500	250
Suspended matter (mg/l)	2.4	1.6	1.2	1.2	3.6	2.8	0.8	2.0	1.2
Total Solids (mg/l)	61	50	57.5	- -	- -	- -	- -	- -	- -
Weather conditions	clear and hazy →								
wind direction	S.W. →								
wind speed (mph)	4	4	4	4	0	0	6	1	0
Color (Plat.-Cobalt units)									
II.									
Oxygen (ppm)	9.4	9.5	9.7	9.8	9.4	9.8	9.8	9.7	9.8
% saturation	97	96	98	101	99	101	101	100	101
Conductivity (microhms/cm)	88	89	89	88	86	88	88	88	89
pH	5.3	5.3	5.3	5.3	5.4	5.45	5.3	5.0	5.1
Chlorophyll-a (μg/l)	1.70	1.56	2.20	1.34	3.21	2.27	2.21	1.54	1.45
Sulfate (mg/l)									
Chloride (mg/l)	1.07	10.4	10.5	9.9	11.5	10.1	9.9	10.4	10.2
Total K Nitrogen (mg/l)	0.80	0.89	0.72	0.83	1.58	.98	1.20	0.83	0.90
NH_3 (mg/l)	0.05	0.04	0.04	0.02	0.18	0.10	0.05	0.04	0.05
NO_3 (mg/l)	0.012	0.007	0.017	0.003	0.030	0.008	0.005	0.003	0.00
NO_2 (mg/l)	0.006	0.004	0.005	0.006	0.006	0.006	0.004	0.004	0.005
Total Phosphorus (mg/l)	0.08	0.07	0.08	0.06	0.08	0.08	0.08	0.08	0.06
Ortho-phos. (mg/l)									
III.									
Algae (no. cells/ml.)		3,520		5,010					4,333
Algae biomass ($10^3\mu^3$/ml.)		13,604		16,096					13,673

* A circled number indicates that the bottom was visible.

Date: 9 December 1976

Lake Phelps

Parameters		Station No. 1	2	3	4	5+	5-	6	7	8
Temp. (C°)		6.2	5.8	6.0	5.7	6.0	5.5	6.0	5.5	
Transparency (cm.)	white	137	180	173	145	117	76	188	155	147
	red	137	↓	165	145	117	↓	188	↓	147
	blue	122	160	147	127	107		170	140	132
	green	109	155	122	109	91	500	145	127	112
light meter		125 250	250	250	125 250	1000	1000	250	1000	1000
Suspended matter (mg/1)		1.2	2.4	3.2	4.8	2.0	0.8	2.4	1.6	2.8
Total solids (mg/1)		59	40	--	--	--	45	--	--	--
Weather condition		clear	→							
Wind direction		0	→							
Wind speed (mph)		0	→							
Color (Plat.Cobalt units)		5	5	5	5	5	5	5	5	5
II. Oxygen (ppm)		12.2	12.6	12.3	12.5	12.4	12.7	12.4	12.4	12.4
% saturation		98	100	98	100	99	100	99	98	100
Conductivity (microhos/cm.)		90	91	91	90	90	89	88	90	90
pH		4.7	4.7	4.75	4.8	4.9	4.9	4.9	4.9	5.0
Chlorophyll-a (μg/1)		4.68	4.31	3.82	3.60	4.43	4.40	3.85	4.22	5.06
Sulfate (mg/1)										
Chloride (mg/1)		8.0	7.0	7.0	7.1	6.8	6.7	8.0	8.3	8.0
Total K Nitrogen (mg/1)		0.86	0.95	1.11	0.74	0.98	1.13	0.74	1.20	0.71
NH_3 (mg/1)		0.06	0.02	0.01	0.01	0.01	0.01	0.02	0.03	0.02
NO_3 (mg/1)		0.037	0.027	0.015	0.006	0.015	0.017	0.013	0.025	0.012
NO_2 (mg/1)		0.002	0.00	0.002	0.016	0.02	0.01	0.014	0.012	0.014
Total Phosphorus (mg/1)		0.09	0.09	0.09	0.07	0.08	0.10	0.08	0.11	0.09
Ortho-Phos. (mg/1)		0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
III. Algae (no. cell/ml.)			6923		6,109					11,897
Algae biomass ($10^3 u^3$/ml.)			7069		23,920					15,436

Date: 9 March 1977

Lake Phelps

Parameters		Station No. 1	2	3	4	5+	5-	6	7	8
I. Temp. (C°)		10	9.8	10	9.9	10	9.5	10.1	10	10.3
Transparency (cm.)	white	147	152	170	163	53	81	152	152	132
	red	147	152	170	163	53	↓	152	152	132
	blue	112	117	130	122	43		112	107	102
	green	102	102	102	97	36		89	84	76
light meter		500	500 1000	500 1000	250	250	125 250	125	250	125
Suspended matter (mg/l)		4.0	3.6	3.6	3.2	27.2	2.8	2.8	3.2	5.2
Total solids (mg/l)		163	88	80	90	- -	89	77	- -	78
Weather conditions		clear and hazy (light) →								
wind direction		S.W. →								
wind speed (mph)		5.5	5.5	8	7	9	9	9	9	8
Color (Plat. Cobalt units)		5	5	5	5	8	5	5	5	5
II. Oxygen (ppm)		10.7	10.4	10.5	10.2	10.4	10.9	10.6	10.6	10.6
% saturation		95	90	93	90	92	95	94	94	95
Conductivity (microhos/cm.)		87	87	88	87	90	86	89	87	89
pH		6.0	6.1	5.9	5.9	6.7	6.3	6.0	6.0	6.3
Chlorophyll-a (μg/l)		12.91	12.85	13.63	12.17	17.21	14.66	14.66	14.35	15.39
Sulfate (mg/l)		8	- -	- -	10	8	4	- -	- -	11
Chloride (mg/l)		7.5	7.4	7.4	7.5	8.2	7.3	7.4	7.5	7.5
Total K Nitrogen (mg/l)		1.19	0.80	0.90	1.26	1.65	0.95	0.68	1.10	1.04
NH_3 (mg/l)		0.04	0.04	0.04	0.04	0.16	0.04	0.03	0.02	0.03
NO_3 (mg/l)		0.11	0.11	0.12	0.11	0.12	0.11	0.12	0.12	0.12
NO_2 (mg/l)		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total Phosphorus (mg/l)		0.06	0.04	0.05	0.11	0.05	0.04	0.04	0.04	0.10
Ortho-phos. (mg/l)		0.01	0.01	0.01	0.02	0.02	0.01	0.01	0.02	0.02
III. Algae cells (no./ml.)			40,850		48,705					58,581
Algae biomass ($10^3\mu^3$/ml.)			27,050		27,873					26,964

Date: 5 August 1976

Lake Mattamuskeet

Parameters	Station No. 1	2	3	4	5	6	7	8	9	10	11	12
I.												
Temp. (C°)	22	21.5	22	22	21.8	22.1	22	22	22	22	23	22.5
*Transparency (cm.) white	56	56	58	69	64	61	64	61	64	76	99	94
red	51	53	56			58	61	58	61	74		94
blue	48	46	51			51	53	56	56	69		91
green	43	43	43	58		46	48	51	53	64		84
light meter	125 250	250	250	250 500	250 500	250	250	250 500	250 500	250 500	125 250	250 125
Suspended matter (mg/l)	22.5	20.8	27.2	15.2	10.8	18	20.8	22.8	17.6	21.2	9.2	11.2
Total Solids (mg/l)	2583	6148	2302	2531	2921	2303	2337	2398	2352	2405	2005	2024
Weather condition	clear,	fair										
wind direction	N-NE											
wind speed (mph)	2-5											
Color (Plat. Cobalt units)												
II.												
Oxygen (ppm)	7.8	7.9	7.9	8.0	8.0	8.1	8.1	8.0	7.9	8.0	8.1	8.1
% saturation	88	89	90	91	91	92	92	91	90	91	92	93
Conductivity (microhos/cm)	4061	4281	4241	3910	3871	3871	3910	3910	3910	3910	3466	3350
pH	7.05	7.05	6.85	6.95	6.90	6.95	6.75	6.85	6.85	7.0	7.0	7.0
Chlorophyll-a (μg/l)	10.52	12.61	11.30	10.62	3.67	11.30	10.08	11.69	12.53	12.54	5.54	5.91
Sulfate (mg/l)												
Chloride (mg/l)	1,286	1,406	1,164	1,198	1,284	1,260	1,312	1,1[illegible]8	1,232	1,220	1,040	1,100
Total K Nitrogen (mg/l)	1.47	1.35	1.40	1.3.	1.08	1.17	1.40	1.49	1.25	1.11	1.13	1.14
NH_3 (mg/l)	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.02	0.01
NO_3 (mg/l)	.012	.014	0.00	.010	.008	.008	.008	.008	.008	.008	.006	.006
NO_2 (mg/l)	0.10	0.08	0.08	0.08	0.06	0.08	0.10	0.10	0.08	0.07	0.07	0.08
Total Phosphorus (mg/l)	0.10	0.08	0.08	0.08	0.06	0.08	0.10	0.10	0.08	0.07	0.07	0.08
Ortho-phos. (mg/l)	0.02	0.00	0.01	0.00	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.01
III.												
Algae (cells/ml.)			2,099,496			2,298,358						919,343
Algae biomass ($10^3 \mu^3$/ml)			56,456			21,910						11,333

* A circled number indicates the bottom was visible.

Date: 23 August 1976

Lake Mattamuskeet

Parameters	Station No. 1	2	3	4	5	6	7	8	9	10	11	12
I.												
Temp. (C°)	31	31	29.5	29.5	30.5		29	29	29	29	28.2	28.2
*Transparency (cm.) white	74	85	81	81	74		76	84	89	86	107 ↓	109 ↓
red							76	84		81		
blue							74	79		76	91	89
green							71	76		71	81	83
light meter	250	125 250	250	250 500	250		250 500	250 500	250	500 1000	125 250	500
Suspended matter (mg/l)	10	13.2	13.6	12.4	10.8		13.6	12	13.2	15.6	9.2	11.6
Total Solids (mg/l)	1677	1851	2542	2117	2162		2105	2034	2249	2345	1794	1813
Weather condition	sunny, clear →											→
wind direction	0 →			→	S.E.		→				→	
wind speed (mph)	0 →			→	2-5		→				→	
Color (Plat. Cobalt units)												
II.												
Oxygen (ppm)	7.9	7.8	8.3	8.2	8.0		8.0	8.1	7.9	8.1	8.3	8.3
% saturation	105	104	108	106	106		103	104	101	104	105	105
Conductivity	3964	3461	3933	4074	3707		3489	3489	3748	3911	3233	3289
pH	6.4	6.5	6.45	6.6	6.6		6.6	6.5	6.6	6.7	6.65	6.8
Chlorophyll-a (µg/l)	7.77	9.84	10.30	10.92	8.30		14.00	12.61	14.77	10.74	9.52	7.97
Sulfate (mg/l)												
Chloride (mg/l)	1,002	1,066	1,046	1,332	1,408		1,144	996	1,002	1,460	1,116	1,088
Total K Nitrogen (mg/l)	0.98	1.34	1.08	1.13	1.10		1.25	1.14	1.35	1.19	1.34	1.73
NH_3 (mg/l)	0.03	0.02	0.06	0.04	0.01		0.02	0.03	0.04	0.06	0.03	0.01
NO_3 (mg/l)	0.042	0.003	0.018	0.013	0.158		0.048	0.031	0.105	0.020	0.004	0.184
NO_2 (mg/l)	0.002	0.002	0.009	0.003	0.003		0.004	0.012	0.001	0.003	0.001	0.003
Total Phosphorus (mg/l)	0.07	0.05	0.05	0.06	0.08		0.08	0.06	0.06	0.06	0.07	0.08
Ortho-phos. (mg/l)	0.01	0.01	0.01	0.01	0.01		0.01	0.01	0.01	0.01	0.01	0.00
III.												
Algae (cells/ml.)			1,098,902					940,441				1,251,533
Algae biomass ($10^3 \mu^3$/ml.)			12,613					26,880				15,286

* A circled number indicates the bottom was visible.

Date: 16 October 1976

Lake Mattamuskeet

Parameters	1	2	3	4	5	6	7	Station No. 8	9	10	11	12
I. Temp. (C°)								22				
Transparency (cm.) White								91				
Red								61				
Blue								48				
Green								43				
light meter				NO DATA				30			NO DATA	
Suspended matter (mg/l)								42				
Total solids (mg/l)								--				
Weather condition								Partly Cloudy				
wind dir.								S.W.				
wind speed (mph)								2-5				
Color (Plat. Cobalt units)								--				
II. Oxygen (ppm)								10.2				
% saturation								116				
Conductivity (micromos/cm.)								3483				
pH								6.55				
Chlorphyll-a (μg/l)								12.43				
Sulfate (mg/l)								--				
Chloride (mg/l)								1264				
Total K Nitrogen (mg/l)								1.82				
NH_3 (mg/l)								.04				
NO_3 (mg/l)								.001				
NO_2 (mg/l)								.003				
Total Phosphorus (mg/l)								0.11				
Ortho - Phos. (mg/l)								0.01				
III. Algae (cells no./ml.)								[illegible],474				
Algae biomass $10^3\mu^3$/ml.								3,040				

Date: 9 December 1976

Lake Mattamuskeet

Parameters	Station No. 1	2	3	4	5	6	7	8	9	10	11	12
I.												
Temp. (C°)	3.8	3.8	3.8	3.8	3.8	4.[illegible]	3.9	3.5	4.0	4.0	5.0	5.0
Transparency (cm.) white	10	13	10	13	18	10	13	28	10	10	23	28
red	10	13	10	13	18	10	13	28	10	10	23	28
blue	5	8	8	10	15	8	10	23	8	8	18	23
green	3	8	5	8	13	5	8	18	5	5	15	20
light meter	500 250	500 1000	500 1000	1000	500 1000	250 500	250 500	250 500	250 500	250 500	250	125
Suspended matter (mg/1)	324	221	171	109	69	231	188	85	148	186	101	134
Total solids (mg/1)	2591	- -	2591	- -	2141	- -	- -	-	- -	- -	- -	- -
Weather conditions	clear	→										
wind direction	N.W.	→										
wind speed (mph)	8-10	→										
Color												
II.												
Oxygen (ppm)	11.7	12.6	12.5	12.6	12.2	12.5	12.4	12.6	12.4	12.4	12.2	12.0
% saturation	89	96	95	96	39	95	95	94	95	95	95	94
Conductivity (microhos/cm.)	3849	3915	3915	3915	3783	3915	3849	3318	3783	3783	3318	3318
pH	6.1	6.5	6.7	6.15	6.3	6.35	6.3	6.3	6.3	6.3	6.3	6.2
Chlorophyll- a (µg/1)	5.42	5.98	6.28	6.30	5.46	3.93	5.72	3.74	6.14	5.60	4.29	3.72
Sulfate (mg/1)												
Chloride (mg/1)	1310	1256	1240	1118	1280	1362	1318	1120	1298	1338	1356	1118
Total K Nitrogen (mg/1)	3.30	2.15	2.40	2.75	2.48	2.85	2.99	1.95	2.88	3.24	2.84	2.49
NH_3 (mg/1)	0.25	0.06	0.07	0.07	0.14	0.20	0.06	0.05	0.09	0.13	0.06	0.06
NO_3 (mg/1)	0.012	0.00	0.024	0.001	0.005	0.058	0.028	0.007	0.021	0.017	0.002	0.002
NO_2 (mg/1)	0.012	0.012	0.012	0.010	0.004	0.012	0.012	0.008	0.008	0.008	0.012	0.012
Total Phosphorus (mg/1)	0.26	0.26	0.28	0.28	0.19	0.33	0.32	0.16	0.26	0.33	0.25	0.19
Ortho-phos. (mg/1)	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
III.												
Algae cells (no./ml.)						1,061,537		1,300,908				1,198,285
Algae biomass ($10^3 \mu^3$/ml.)						5,840,301		11,017				6,450

Date: 9 March 1977

Lake Mattamuskeet

Parameters	Station No. 1	2	3	4	5	6	7	8	9	10	11	12
I.												
Temp. (C°)	11.5	11.5	11.9	11.8	11.9	12.1	12.1	13.2	12.2	12.2	12.2	12.0
Transparency (cm.) white	20	23	18	20	18	15	13	23	18	23	30	36
red	20	23	18	20	18	15	13	23	18	23	30	36
blue	15	15	13	15	13	10	10	15	13	18	20	25
green	10	10	10	13	10	8	8	13	10	13	15	20
light meter	250 125	500	250	250	500	250	125	1000	250	250	500	125
Suspended matter (mg/l)	78	70	90	49	96	94	93	68	84	42	37	40
Total solids (mg/l)	1973	2092	2243	1636	1602	2126	2501	1980	2096	2037	1933	1904
Weather conditions	clear	→										
wind direction	S.W.	→										
wind speed (mph)	6	6.5	5.5	5	4	6.5	7	3	5.5	3	8	5
Color (Plat. Cobalt units)												
II.												
Oxygen (ppm)	11	10.6	10.4	10.5	10.5	10.7	10.5	10.4	10.4	10.6	10.6	10.6
% saturation	100	96	96	97	97	99	97	98	96	98	98	98
Conductivity (microhos/cm.)	2782	2990	2990	2921	2851	2990	2990	2851	2990	2990	2851	2851
pH	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6
Chlorophyll-a (µg/l)	15.75	13.19	11.36	12.46	17.59	12.83	15.76	11.36	11.73	11.73	15.39	13.56
Sulfate (mg/l)	88	- -	98	- -	98	100	- -	100	- -	- -	- -	100
Chloride (mg/l)	563	638	658	635	624	589	649	624	630	630	592	574
Total K Nitrogen (mg/l)	1.95	1.64	1.58	1.49	1.70	1.29	1.58	1.94	1.28	1.53	1.10	1.29
NH_3 (mg/l)	0.14	0.16	0.17	0.18	0.18	0.15	0.15	0.21	0.17	0.16	0.15	0.16
NO_3 (mg/l)	0.33	0.33	0.35	0.33	0.28	0.36	0.36	0.25	0.35	0.34	0.24	0.26
NO_2 (mg/l)	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.02	0.02	0.00	0.00
Total Phosphorus (mg/l)	0.17	0.18	0.14	0.12	0.15	0.13	0.17	0.22	0.18	0.20	0.15	0.18
Ortho-phos. (mg/l)	0.02	0.02	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.05
III.												
Algae cell (no./ml.)			114,264					140,955				214,292
Algae biomass ($10^3\mu^3$/ml.)			14,608					12,628				12,873

Date: December 8, 1976

Lake: New	Parameters	Station No.	1	2	3	Lake: Pungo	Station No.	1	2
(morning)	I. Temp. (C°)		9.1	8.0	8.0	(afternoon)		10.2	10.4
	Transparency (cm.)	White	18	3	3			3	3
		Red	↓	↓	↓			↓	↓
		Blue	↓	↓	↓			↓	↓
		Green	↓	↓	↓			↓	↓
	light meter							30 8	15 8
	Suspended matter (mg/1)		110	712	343			1333	207
	Total solids (mg/1)		156					576	
	Weather conditions		Cloudy Snow	→ →	→ →			Cloudy Rain	→ →
	wind dir.		N.W	→	→			N.W	→
	wind speed (mph)		15-20	→	→			8-15	→
	Color (Plat. Cobalt units)		70	100	120			500	500
	II. Oxygen (ppm)		11.8	12	12			11.5	11.5
	% saturation		102	101	101			102	103
	Conductivity (microhos/cm.)		75	80	80			117	123
	pH		4.8	4.8	4.8			5.2	5.2
	Chlorophyll-a (μg/1)		5.23	5.61	5.61			14.94	14.94
	Sulfate (mg/1)								
	Chloride (mg/1)		8.2	7.5	7.0			10.2	12.1
	Total K Nitrogen (mg/1)		3.75	8.79	7.17			12.72	10.05
	NH_3 (mg/1)		0.03	0.03	0.03			0.03	0.02
	NO_3 (mg/1)		0.057	0.062	0.058			0.243	0.234
	NO_2 (mg/1)		0.012	0.010	0.012			0.016	0.020
	Total phosphorus (mg/1)		0.30	0.60	0.56			0.90	0.02
	Ortho-phos. (mg/1)		0.02	0.02	0.02			0.02	0.02
	III. Algae cell (no./mL)				10533			22883	
	Algae biomass ($10^3 \mu^3$/ml.)				5,088			12,005	

Date: 8 March 1977

Lake: New	Parameters	Station No. 1	2	3	Lake: Pungo	Station No. 1	2
(morning)	I. Temp. (C°)	11.2	11.2	11.4	(afternoon)	11.8	11.5
	Transparency (cm.) white	10	10	18		3	3
	red / blue / green	↓	↓	↓		↓	↓
	light meter	125	250	250 500		500	500 250
	Suspended matter (mg/l)	76	52	40		375	430
	Total solids (mg/l)	126	129	94		451	516
	Weather conditions	clear	→	→		clear	→
	wind direction	N.E.	→	→		N.W.	→
	wind speed (mph)	7	0	8		0	6
	Color (Plat. Cobalt units)	80	75	70		460	460
	II.						
	Oxygen (ppm)	10.7	9.9	9.9		10.4	9.9
	% saturation	96	89	90		96	90
	Conductivity (microhos/cm.)	76	78	75		108	107
	pH	5.1	5.1	5.2		6.2	6.2
	Chlorophyll-a (μg/l)	3.42	4.11	4.68		7.23	7.47
	Sulfate (mg/l)	--	9	--		--	32
	Chloride (mg/l)	6.4	6.4	6.4		7.3	7.3
	Total K Nitrogen (mg/l)	1.65	3.11	1.20		5.72	6.77
	NH_3 (mg/l)	0.14	0.03	0.02		0.05	0.06
	NO_3 (mg/l)	0.17	0.18	0.18		0.82	0.77
	NO_2 (mg/l)	0.00	0.00	0.00		0.00	0.00
	Total Phosphorus (mg/l)	0.20	0.36	0.18		0.77	0.83
	Ortho-phos. (mg/l)	0.02	0.02	0.02		0.09	0.02
	III.						
	Algae cell (no./ml.)			8,908		15,272	
	Algae biomass ($10^3\mu^3$/ml.)			4,704		11,004	

Appendix II

Percent Organic Matter

Procedure - total solids determined by evaporating 200 ml. water sample in evaporation dish at 30-60°C till dry. This sample was then placed in an oven at 600°C for two hours.

Formula - total solids - burned dish wt. = total organic matter.

Results - Lake Phelps had about 61% of the total solids (62 mg/l) being organic

Lake Mattamuskeet had about 32% of the total solids (1829 mg/l) being organic

New Lake had about 60% of the total solids (116 mg/l) being organic

Pungo Lake had about 67% of the total solids (483 mg/l) being organic

Data	Sample	Water volume(ml.)	Total solids(g.)	Burned wt.(g.)	Total organic(mg/l)	% organic
3/9/77	P-1	230	.0376	.0098	120.87	26.0[2]
	M-5	350	.5607	.1847	1074.23	32.9[1]
	M-8	350	.6931	.2276	1329.93	32.8[1]
	M-12	350	.6667	.1882	1367.07	28.2[1]
	N-1	350	.0442	.0273	48.28	61.7[1]
	N-2	350	.0451	.0275	50.28	61.0
	N-3	350	.0329	.0193	38.86	58.6
	Pu-1	350	.1578	.1054	149.71	66.8
	Pu-2	350	.1806	.1198	173.71	66.3

Data	Sample	Water Volume(ml.)	Total solids(g.)	Burned wt.(g.)	Total organic(mg/l)	% organic
3/27/77	P-8	230	.0143	.0087	24.35	60.8
	M-1	350	.5876	.1676	1199.94	28.0[1]
	M-5	350	.7521	.2724	1370.50	36.2[1]
	M-6	350	.7416	.2490	1407.36	33.6[1]
	M-11	350	.7502	.2885	1319.08	38.5[1]
	M-12	350	.6694	.2210	1218.08	33.0[1]

P - Lake Phelps   M - Lake Mattamuskeet   N - New Lake   P - Pungo Lake

1. Low percent of organic matter in Lake Mattamuskeet due to the mineral layer surrounding the lake and a three percent sea-strength salinity raising the amount of total solids.

2. Low percent of organic matter in Lake Phelps due to lake bottom contamination of sand in water column sample.