7-1-1996

Hyperspectral remote sensing of a submerged macrophyte.

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HYPERSPECTRAL REMOTE SENSING OF A SUBMERGED MACROPHYTE

A Thesis

Presented to the

Department of Geography and Geology

and the

Faculty of the Graduate College

University of Nebraska

in Partial Fulfillment for the Degree

Master of Arts

University of Nebraska at Omaha

by

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July 1996

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THESIS ACCEPTANCE

Acceptance for the faculty of the Graduate College,

University of Nebraska, in partial fulfillment of the

requirements for the degree Master of Arts,

University of Nebraska at Omaha

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Acknowledgements

First and foremost, I dedicate this thesis to my partners in life: to my soulmate Bob, for all his support and encouragement, and to my beautiful daughter Leighana, for always being so proud of her mommy, and to my son Hunter, for sparing me morning sickness on collection dates!

Second, I would like to wholeheartedly thank my committee and fellow students for the opportunity to begin and complete this segment of my life: Dr. Peake, who got me interested in, and helped me pursue wetlands research, Dr. Rundquist, for letting me "tag along" at Mead and his valuable assistance analyzing my data and editing my thesis, Dr. Schalles for water analysis guidance and Dr. Peterson for believing I was capable of graduate-level work and his "editing extrodinaire". Luoheng, Rollie, Steve, Mike and Lydia for help with site preparation and data collection

Finally, I laud Dr. Geluso and Dr. Ludwig for encouraging me in ways they probably aren't even aware of and the Nebraska Space Consortium for the NASA Graduate Fellowships.

ABSTRACT

This study used a Spectron Industries SE-590 portable spectroradiometer to investigate a common Midwestern wetland species, *Ceratophyllum*. Primary research objectives were: determine the effect of *Ceratophyllum* on the composite spectral signal upwelling from a column of water, determine the depth constraint for remote identification of *Ceratophyllum*, and ascertain the presence of *Ceratophyllum* in chlorophyll-laden water. Characteristic absorption features at 443 nm and 670 nm decreased with increasing depth and also as the algal chlorophyll concentrations increased. A wavelength shift in the NIR, associated with increasing depth was found to exist for water columns relatively free of algal chlorophyll as well as those containing denser concentrations of algal chlorophyll. The depth constraint was not determined and requires further study.

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CHAPTER ONE: Introduction

Wetlands

Wetlands are an essential component of the global ecosystem. They preserve ecological balance by providing flood and sediment control, storing ground and surface water, and furnishing habitat for fish, migrating and nesting birds and other wildlife (Thompson 1992). They may also improve water quality and provide areas of aesthetic value (Leslie and Clark, 1990). Recent studies link wetlands to the local and possibly the global climate through energy, moisture, and gaseous exchanges with the atmosphere (Pulliam and Meyer 1992, Poiani and Johnson 1991). Expanding our understanding of wetlands will help us to fully comprehend their functional role in the global environment.

Submergent macrophytes are a common component of US Midwestern wetlands and are important constituents in the ecology of wetlands ecosystems. Coontail (*Spp. Ceratophyllum*), the submergent macrophyte under study in this investigation, is the dominant plant of temporary and newly formed lakes and ponds containing water rich in organic material. Water fowl are attracted to *Ceratophyllum*; it is a food source for certain species of caterpillars, and *Haliplus* (crawling water beetles) lay their eggs on it (Klots, 1966).

Wetlands and Remote Sensing

The observation, study, and assessment of wetland environments have been enhanced by means of remote sensing technology. Research endeavors incorporating spectral sensors have served to increase our knowledge of wetlands. Gallie et al. (1992), employing a radiometer, investigated the spectra of suspended minerals and chlorophyll *a* concentrations in a wetland environment. In the past, data collection by means of aerial photography followed by airborne and space-based multispectral sensor systems has been the predominant technology for examining wetland environments.

A review of wetlands research using the spectral domain leads one to conclude that a substantial amount of the work is based on analysis of multispectral remotely sensed image data. Although the utilization of hyperspectral (i.e., more than 100 narrow contiguous channels) spectroradiometers has been

limited to date, the potential seems to exist for highly accurate analysis of wetland environments [Rundquist et al. (1990), Goodin et al. (1993) Han (1994)].

Hyperspectral Remote Sensing

Hyperspectral remote sensing is an emerging technology presenting numerous applications in environmental evaluation. These systems are a valuable investigative methodology for appraising selected components of the wetland ecosystem under controlled conditions (Goodin et al., 1993, Han et al., 1994).

High spectral resolution (i.e. hyperspectral) remote sensing devices are preferred over broad-band multispectral systems for many applications and yield results unavailable with conventional multispectral systems. Rundquist, et al. (1995) were able to differentiate the "spectral variations associated with different algal densities and the effect of both bright and dark 'bottoms' at numerous depths" using a hyperspectral system. Using the same sensor system, Han, et al. (1994, 1995) investigated the spectral properties of varying levels of suspended sediment in water with variable densities of chlorophyll.

Literature Review

What follows is a brief discussion of selected efforts on the subject of remote sensing for submergent plants. Also, I intend to underscore the need for focusing research on the hyperspectral responses of macrophytes.

Some close range remote sensing research has been done on hydrophytes (Best et al., 1981) and some submergent species, but not on submergent macrophytes. Studies of submergent macrophytes have used aerial photography as well as broad-band airborne or satellite data: Davis and Brinson (1976), who examined submersed macrophytes in the Pamlico River Estuary of North Carolina; Bartlett and Klemas' (1981) study of tidal wetland grasses; and Andersson (1990), who investigated the macrophytes of Sweden using color IR film.

Abundant articles in professional journals and published research papers discuss the employment of remote sensing and its expanding implementation using a spectroradiometer. Few reports specifically address the spectral characteristics of wetland vegetation in water. Best, et al. (1981) used an Exotech radiometer to investigate the spectral reflectance of hydrophytes. The team conducted this project in the

field, making it somewhat uncontrolled. Philpot (1981) applied a single-scattering volume reflectance model to illustrate how percentage canopy cover and water depth offset the volume reflectance from a water column containing submerged aquatic vegetation. Savastano et al. (1984), using an airborne multispectral scanner, estimated the coverage of submerged macroplant vegetation for the purpose of mapping and estimating biomass. They were able to delineate density of sea grass, bottom types and surface coverage at various water depths. Ackelson and Klemas (1986, 1987) investigated remote sensing of submerged aquatic vegetation. Using a comparative model and a UDT Scanning Radiometer, they analyzed the effects of depth on reflectance from a submerged canopy. With the morphology of the submerged, erectophile (vertical) canopy held constant, the authors found that between 490 and 500 nm "the volume reflectance appears to be insensitive to changes in canopy depth". They also compared (1987) Landsat TM and MSS imagery of submerged aquatic vegetation in the lower Chesapeake Bay area.

Gross et al. (1988) analyzed the effects of solar angle on reflectance from wetland vegetation using a Mark II fixed band radiometer. The authors sampled a wide variety of wetland vegetation including plants from the Genera *Spartina*, *Phragmites*, *Scirpus*, *Salicornia*, *Typha*, *Hibiscus*, and *Polygonum*. They compiled a data set of spectral responses based upon the morphology of the wetland vegetation canopy. Armstrong (1993) conducted research using Landsat Thematic Mapper data to calculate the biomass of seagrass in the Bahamas.

Titus (1993) offered a methodology for determining distribution of submergent macrophyte vegetation in the field and follow-on verification of field data, a method of direct relevance to my own research as the ability to spectrally differentiate submergent vegetation including *Ceratophyllum* was a partial impetus for this study.

Penuelas et al. (1993), using a Spectron Engineering 590 spectroradiometer fitted with 15° field of view optics, looked at the *in situ* spectral response of several common wetland plants. The *in situ* nature of their experiment necessitates the consideration of outside variables when analyzing the spectral responses of the data. Compared to the other wetland plants characterized, *Ceratophyllum* exhibited a low response in all wavelengths analyzed (500 - 1100 nm) . However, in comparison with other submergent vegetation

the spectral response of *Ceratophyllum* was high. While these research endeavors yielded copious amounts of information, much is still unknown about the spectral characteristics of wetland environments, specifically, *Ceratophyllum*. This unattached submergent freshwater macrophyte is significant because it can completely cover the bottom of aquatic environments, altering spectral responses of lake bottoms (Cook 1974).

Objectives

My research addresses three principal objectives. I attempt to: 1) determine the effect of a submerged canopy of vegetation (specifically, *Ceratophyllum*) on the composite spectral signal (visible and near-infrared) upwelling from a column of clear water; 2) establish the depth constraint(s) for identification of submerged *Ceratophyllum* from remote platforms in clear water; and 3) determine whether or not it is possible to discern the presence of *Ceratophyllum* in the water column when the water is not clear (i.e., when algal phytoplankton are present). Because these objectives are quite specific, an element of precision was required. Therefore, my data were collected with a hyperspectral instrument operating at close-range in a controlled, artificial aquatic mesocosm.

This study represents a small portion of an on-going project to investigate spectral characteristics of Midwestern wetland ecosystems and individual wetland components in a controlled setting. By controlling extraneous factors, useful baseline data can be gathered.

Because of the strong absorptive properties of water, the spectral response will vary with changing depth, and differences in the density of algal chlorophyll. This made it necessary to investigate the effects of an increasing water depth over the *Ceratophyllum*, on the spectral irradiance, particularly in the red and NIR portions of the electromagnetic spectrum, where vegetation exhibits the strongest responses (Campbell 1987).

Depending on various amounts of vegetation, sand or mud, the composition of wetland bottoms can be expected to differ. Different bottoms possess different reflective properties. This of course affects the volume reflectance based on the bottom composition being investigated. Therefore it is essential to utilize a controlled environment for discerning exact bottom reflectance, to accurately quantify and

measure component contents like suspended sediment or chlorophyll in the water. Similarly, algal chlorophyll densities vary among sites. This necessitates a joint investigation of comparative reflectance responses of *Ceratophyllum* under varying densities of chlorophyll in the water.

CHAPTER TWO: Methodology

The Macrophyte Panel

Harvesting of the vegetation, *Ceratophyllum,* used for this experiment occurred at a quiet pond in Allwine Prairie Preserve, located at 168th and State Street, Omaha, Nebraska. The collection took place in early May of 1993. Due to the multiplicity of species of *Ceratophyllum* and the difficulty in field classification of each form, it was not feasible to key the vegetation to the specific level. *Ceratophyllum* was keyed only to the generic level. The vegetation was transported to a research site near Mead, Nebraska. It was placed in a 9500 liter pool, which served as a nursery. Fertilizer was periodically added to the pool. While it is typical for the pools at the research site to become heavily laden with algae, the *Ceratophyllum* nursery maintained a clear, clean appearance. This leads one to the assumption that the nursery environment was such that the *Ceratophyllum* were able to grow and maintain themselves in a manner similar to a natural environment.

The site where the mesocosms are located is the Agricultural Research and Development Center (ARDC) of the University of Nebraska-Lincoln. Staff of The Center for Advanced Land Management Information Technologies (CALMIT) and Creighton University Department of Biology constructed artificial pools at ARDC. Each pool is 3.66 meters in diameter and 0.91 meters deep.

The research pools are intended to simulate shallow sheltered aquatic ecosystems. Simulated ecosystems that can be controlled and manipulated are commonly referred to as mesocosms. The mesocosm holding the *Ceratophyllum* was allowed to winter over unattended. It proved healthy, reproducing a good crop of vegetation in the spring of 1994. The crop remained stable until the time of the experiment in the summer of 1994.

A "macrophyte panel" was fabricated using the following techniques: Randomly selected individual plants of *Ceratophyllum* were systematically tied, using black nylon thread, approximately 5 centimeters (cm) apart to a black wire mesh panel (with hexagonal one inch openings). The panel, 1.524

meters by 1.524 meters in size, was attached to black rigid plastic pipe 3.81 centimeters in diameter. The macrophyte panel was returned to the nursery and maintained there until the time of data collection.

To minimize extraneous reflectance, black nylon rope was used to attach the macrophyte panel to pulleys positioned outside the pool. The pulleys were intended to facilitate the raising and lowering of the panel during the data gathering procedures explained below.

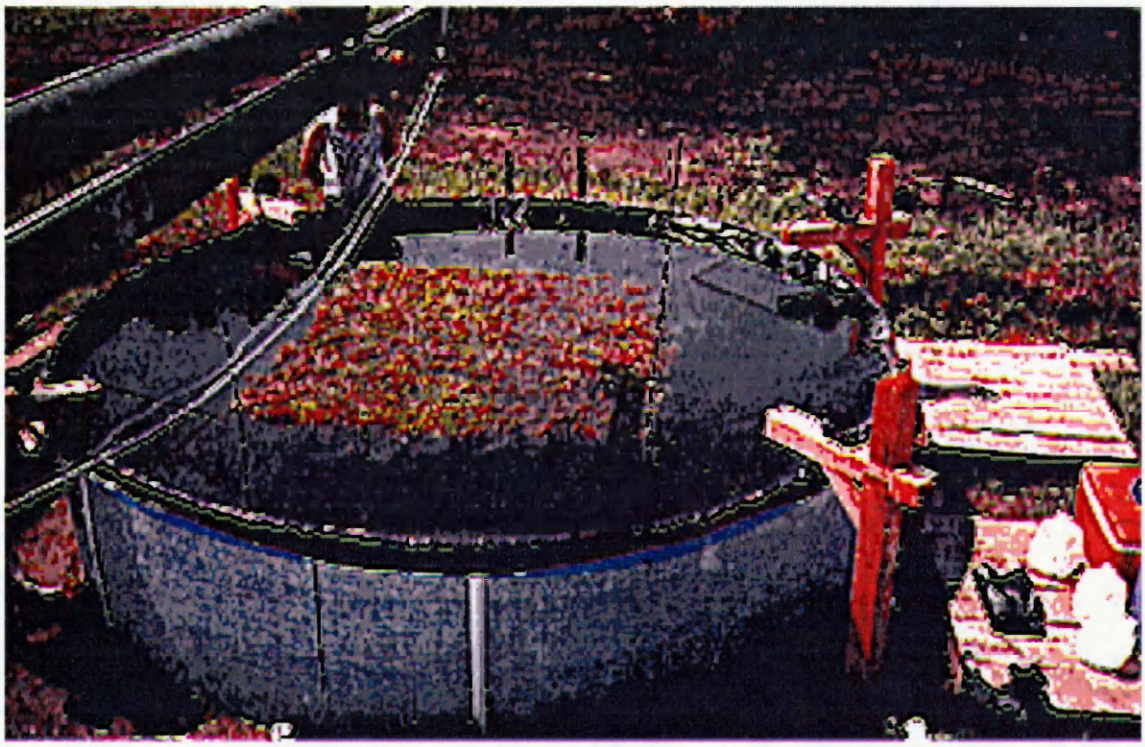
Data Collection Procedures

The macrophyte panel was placed in a pool identical in size and shape to the nursery pool. A black liner (4 mil black polyethylene film) was inserted into the pool during data collection. The black liner is necessary to minimize side and benthic reflectance. Diminution of benthic reflectance is especially important, since one of the primary aims of this research was to investigate the macrophyte, not the *actual* bottom surface of dark mud, etc. According to Ackelson et al. (1987), a water depth of greater than 1.9 meters is the juncture at which the bottom reflectance is no longer a factor in the spectral responses of submerged vegetation. The artificial mesocosms at Mead are not this deep, necessitating the elimination of the bottom as a reflectance component.

A Spectron Industries SE-590 portable spectroradiometer was employed to acquire spectral data. The SE-590 has 256 channels, four of which are reserved for header information. The remaining 252 channels allow contiguous sensing over a wavelength range of 368.40 nanometers (nm) to 1111.37 nm. Nominal band width is 2.95 nanometers (Han et al. 1994).

The SE-590 was attached to a truck-mounted telescoping boom for precision targeting. The sensor was approximately 1.45 meters above the water surface of the pool. A 15 degree optic device was attached to the sensor, yielding an instantaneous field of view (on the water surface) of approximately 28.67 cm^2. During data collection, the truck was oriented east to west, with the boom facing south. This reduced any shadowing within the area of interest (Figure 1).

Figure 1. Experimental Set-Up



Solar angle influences the reflective responses of some types of wetland vegetation (Gross et al. 1988). Water also exhibits different reflective properties based on solar altitude. When the sun is low on the horizon, water is highly reflective. Conversely, high sun angle results in stronger absorption of solar radiation. This necessitated the collection of data within 4 hours of solar noon to diminish such effects.

The "ideal" for collection of close-range hyperspectral data is a completely clear sky. The development of clouds, especially high cirrus, is often a problem during the growing season in Nebraska, and this was a problem during the summer of 1994. Continual monitoring for this condition was necessary, as it could greatly alter the results of the study. The most common monitoring procedure, a visual check of sky conditions at fifteen minute intervals, was utilized. Additionally, a Li-Cor Pyranometer was used to detect fluctuations in the incoming solar radiation.

Spectral data were acquired as the macrophyte panel was lowered in increments of ten (10) centimeters, from a minimum depth of 2 centimeters to a maximum depth of 75 centimeters. Two centimeters was selected as the minimum point because at this depth the *Ceratophyllum* was covering the surface, but fully suspended in the water. This reduced the possibility of the panel affecting the angle of reflectance of the macrophytes. Seventy-five centimeters was the point at which the panel came to rest on the bottom of the pool. A complete depth of 91 centimeters was not attained because space had to be allocated for water displacement caused by the macrophyte panel and weights. Four concurrent scans of the target area were taken at each depth and meaned.

Duggin and Philipson (1982) suggest the use of a calibration panel during the data collection procedures. A Kodak 18 percent gray card (25 cm by 25 cm), cross referenced to a Barium-Sulfate (BaSO4) panel (70 cm by 70 cm), was used in calibrating spectral data to solar downwelling radiation. The equivalent wavelength-specific radiance for the BaSO4 reference panel ($S(\lambda)$) was computed using a regression model in the form of

$$S(\lambda)=a(\lambda)+b(\lambda)*G(\lambda)$$

where G(λ) is the measured wavelength-specific radiance from the gray-card, and a(λ) and b(λ) are the regression coefficients. Thus, bi-directional reflectance factors (R(λ), in percent) were calculated using the following equation:

$$R\lambda = \frac{L\lambda}{S\lambda} Cal\lambda \times 100$$

where L(λ) is the wavelength-specific target radiance and Cal(λ) is the calibration factor for the BaSO4 panel. The latter allowed correction both for the non-Lambertian properties of the panel and the slight changes in the solar-zenith angle. Two replicate scans were taken at each depth and the mean of the two was used in the data analysis (Rundquist, et al. 1995).

Water samples were taken at various times throughout the experiment. For the June experiment (see below), a water sample was procured by vertical integration before the macrophyte panel was introduced to the pool. Another sample was obtained during the scanning and a third sample was collected when scanning was complete. During the July experiments (see below), samples were taken as in the June experiment, but also after each dilution. These samples were kept in a cool dark place, to minimize degradation prior to being transported to the laboratory for filtration and analysis. Forms of aquatic algae are known to "cling" to the *Ceratophyllum* during harvest, so analysis of the water was necessary to determine its chlorophyll content due to the unavoidable presence of algae in the water.

When scanning was complete on each of the days that data were collected, a 50 cm by 50 cm sample of biomass of *Ceratophyllum* was harvested from the panel. The area of biomass removed was within the field of view of the spectroradiometer. The biomass was placed in an airtight container in a cool dark place, until it could be taken back to the lab to be weighed, oven-dried at 40 degrees Celsius for 48 hours, and re-weighed.

June Data Acquisition

The first set of spectral data was collected on June 20, 1994. The pool in which the scans were to be taken was drained and scrubbed clean. It was then filled with clear water from a nearby well. The black

liner was washed, placed in the pool and weighted down with cement blocks covered in black poly. The pool was then ready for the experiment.

June 20th began with a thin layer of cirrus clouds over the research site, but these soon dissipated. The first calibration scan was taken at 1105 (Table I), followed by a scan of the clean, clear water in the pool. This was done as a baseline, prior to introducing the macrophyte panel into the lined pool and to insure that the spectroradiometer was in working order. The panel was then placed in the pool and lowered to the bottom (75 cm).

The first scan of the vegetation occurred at 1120 (Table I). The panel was moved to 72 cm and another scan was taken and data collection proceeded in this manner until the panel was at a depth of 2 cm. Once scanning of the vegetation began, all data were recorded at approximately 1 minute intervals (Table I). Additional scans were taken with the panel just breaking the water surface and again at the point at which the panel was just completely out of the water. A final calibration scan was taken at 1136 (Table I).

After the June experiment, the macrophyte panel was returned to the nursery mesocosm. *Ceratophyllum* plants, residing in the nursery, were tied to the panel as previously illustrated, to replace those plants that were harvested after the scanning. This was done to prepare the panel for further experiments.

TABLE I: JUNE DATA COLLECTION: CLEAR WATER		
TIME	DEPTH	CONDITION
1105	N/A	CALIBRATION
1107	N/A	CLEAR TANK
1120	75 cm	PANEL
1121	72 cm	PANEL
1123	62 cm	PANEL
1124	52 cm	PANEL
1126	42 cm	PANEL
1127	32 cm	PANEL
1128	22 cm	PANEL
1130	12 cm	PANEL
1131	2 cm	PANEL
1132	SURFACE	PANEL
1133	ABOVE SURFACE	PANEL
1136	N/A	CALIBRATION

July Data Acquisition

Prior to acquisition of a second data set on July 21, 1994 the experimental pool was allowed to develop an algal bloom so that a dilution series similar to that performed by Rundquist, et al. (1995) may be conducted. The sky conditions were similar to those of the June experiment date. Some cloud cover could be detected, but prior to the start of data collection, the skies cleared.

The black liner was removed, cleaned and placed back into the experimental pool. A water sample was collected before placing the macrophyte panel in the pool. The panel was lowered to the bottom, a

depth of 74 cm. The bottom depth varied by one centimeter from the June experiment due to an error in measuring the water prior to the experiment. A second water sample was taken, and data was collected, duplicating the procedures for the June data series (Table II).

TABLE II: JULY DATA COLLECTION:

CHLOROPHYLL-LADEN WATER

TIME	DEPTH	CONDITION
0952	N/A	CALIBRATION
0954	74 cm	PANEL
0956	72 cm	PANEL
0958	62 cm	PANEL
1002	52 cm	PANEL
1003	42 cm	PANEL
1006	32 cm	PANEL
1007	22 cm	PANEL
1008	12 cm	PANEL
1010	2 cm	PANEL
1010	ABOVE SURFACE	PANEL
1035	N/A	CALIBRATION

The macrophyte panel was removed from the pool and deposited in the nursery to minimize stress to the vegetation while the pool was pumped and refilled. Ten (10) centimeters of water were then pumped out of the pool and replaced with clean, clear well water. During the pumping, some white sediment was noted to appear in suspension in the water. This sediment appeared to be stirred up from the bottom of the pool. The panel was returned to the experimental pool and lowered to bottom depth of 74 cm. A water

sample was collected and stored as formerly described. Spectroradiometer scans were then collected as specified above. This procedure was replicated two additional times, to produce a series of four scans for each depth, on this date.

When scanning was complete for the dilution series, a 30 cm by 30 cm area of biomass was removed from the panel. During the harvest an error occurred resulting in collecting a smaller amount of vegetation than during the June experiment. As with the June data, the area of biomass removed was within the field of view of the spectroradiometer. Once collected, the vegetation was manipulated in the same manner as described for the June data collection.

CHAPTER THREE: Results and Discussion

Data Collection

Data were collected on June 20 and July 21, 1994, but all data collected for the panel at a depth of 2 cm were discarded because the June data file for 2 cm was corrupt. For consistency, the July 2 cm files were also deleted.

Water depth varied one centimeter between the June and July acquisition dates. Because of this, data collected with the macrophyte panel resting on the bottom of the mesocosm were also discarded.

Significant electronic noise at wavelengths shorter than 400 nm and longer than 900 was detected, so data in these wavelengths were eliminated in the analysis. Other researchers (Goodin 1993, Han 1994, Rundquist 1996) have used a similar approach.

The data was referenced to the calibration panel as described earlier and converted to reflectance values using Han's computer program, SPECREF. All data values were then plotted and statistically analyzed using Microsoft Excel.

All data, except the first set, collected during the July experiment had to be rejected for analysis in this endeavor. When these data sets were plotted, the resultant curves were not consistent with typical curves for submersed vegetation. It is suspected that sediment from the bottom of the pool came into suspension during the dilution series, causing the spectral responses to deviate. While this is an interesting addition needing investigation, it is not within the scope of this research to include it for analysis.

Water Analysis

Analysis of the water in the mesocosm revealed chlorophyll concentrations as evidenced in Table III. Evidently the clean, clear water in the tank still contained some suspended algal chlorophyll. Once the panel was placed in the tank, the concentration increased slightly. This is due to chlorophyll going into suspension from the macrophyte panel. The water sampled from the July data series contained over twice the amount of suspended algal chlorophyll as that of the June data.

TABLE III: CHLOROPHYLL CONTENT OF WATER SAMPLES		
DATE	**CONDITION OF PANEL**	**AVERAGE CHLOROPHYLL CONTENT [(UG/L) MAY INCLUDE PHEOPHYTIN]**
6/20/94	NO PANEL	8.25
6/20/94	PANEL	9.6
7/21/94	1^{ST} DILUTION	16.75

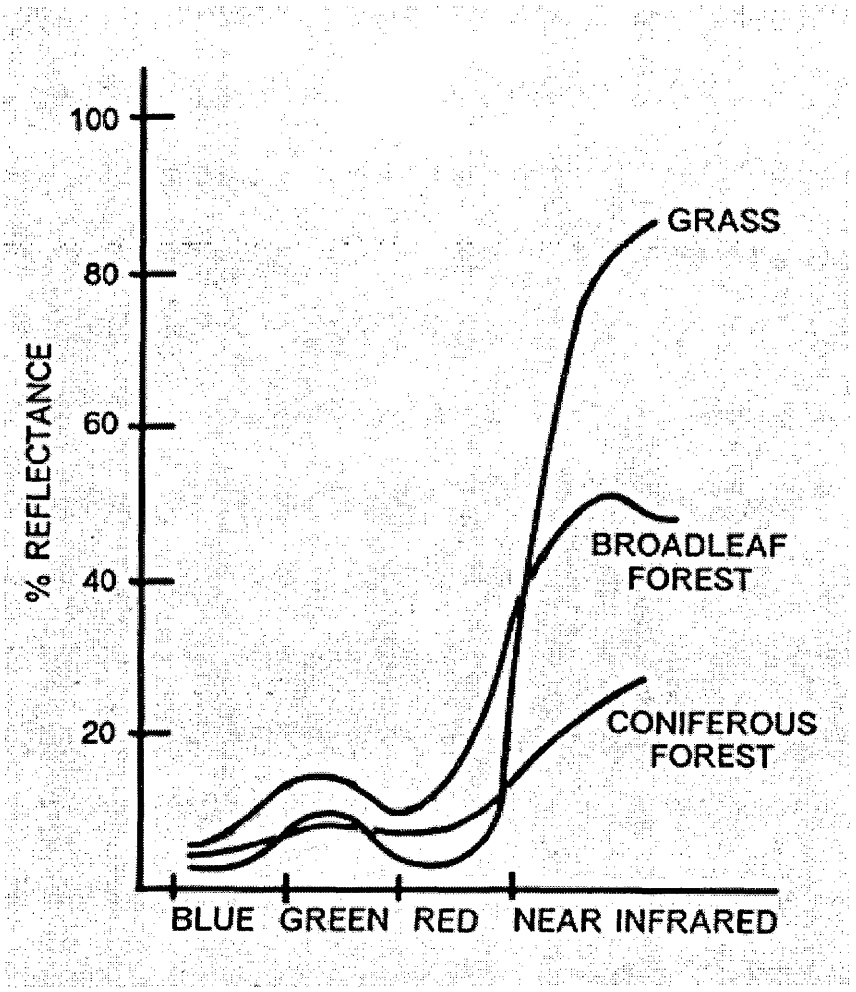
Biomass Analysis

The biomass of the *Ceratophyllum* for the June data collection was 0.0115 g/cm^2. The biomass for July was 0.0172 g/cm^2. An increase in biomass was expected since data collection occurred during the height of the Midwestern growing season.

Spectral Reflectance Of Terrestrial Vegetation

The spectral reflectance of healthy, green terrestrial vegetation is characterized by numerous absorption features. Two of these features, associated with chlorophyll absorption of visible light, are centered near 443 nm (blue) and 670 nm (red). Terrestrial vegetation, particularly grass (Figure 2) is further characterized by a strong spectral reflectance in the NIR, with a peak at 705 (nm). While submerged aquatic vegetation (SAV) generally exhibits spectral responses similar to terrestrial vegetation, the responses tend to be of a lower magnitude. For example, dense healthy grass can exhibit a spectral response in the NIR of up to 90%. SAV's, such as *Potamogeton* routinely reflect in the NIR at a rate of less than 39% (Campbell, 1987). A spectral response of 10 % - 20% is typical in the green portion of the EM for terrestrial vegetation, while *Potamogeton* typically exhibits a reflectance of approximately 5% in the same location of the electromagnetic spectrum.

Figure 2: Characteristic Terrestrial Vegetation Reflectance Curves



After Campbell 1987

Spectral Characteristics Of Clear And Algal Water

A spectral profile for clean, clear water is characterized by a gradual decline in reflectance across the EM spectrum from greater than 3% at 400 nm to approximately 1% at 900 nm (Mittenzwey, et al. 1992). A water curve, devoid of macrophytes but laden with algal chlorophyll, is markedly different. Figure 3 is a plot of the clear water data taken with the SE-590 on June 20, 1994. It is characteristic of water curves containing small amounts of chlorophyll in suspension as substantiated by Rundquist, et al. (1995). They found water containing algal chlorophyll to exhibit the following spectral features: "low reflectivity between 400 and 500 nm due to absorption of blue light, maximum green reflectivity between 560 and 570 nm, a minor inflection at about 640 nm, classic red absorption near 676 nm, prominent NIR reflectivity at about 697 nm, and a minor NIR reflectance feature at about 810 nm". These findings indicate that while clean well water was used for this experiment, it was not devoid of chlorophyll.

Deep water that is completely free of chlorophyll will not significantly reflect in the NIR (Campbell 1987). While this experiment did not encompass deep water, volume reflectance with a bottom influence was negated by lining the artificial mesocosm with black vinyl. The volume reflectance in the NIR of the water is minimal, less than 2%. Compared with the curve of the terrestrial vegetation, which characteristically reflects strongly in the NIR, this reflection is negligible.

***Ceratophyllum* in Clear Water**

Figure 4 represents a plot of the usable data of *Ceratophyllum* in clear water. This chart discloses a general trend of decreasing reflectance relative to an increase in depth. As the depth at which the *Ceratophyllum* was immersed increased, the percentage of spectral reflectance decreased across the spectrum. This finding is not unexpected because of the strong absorptive properties of water.

Figure 3: Clear Water

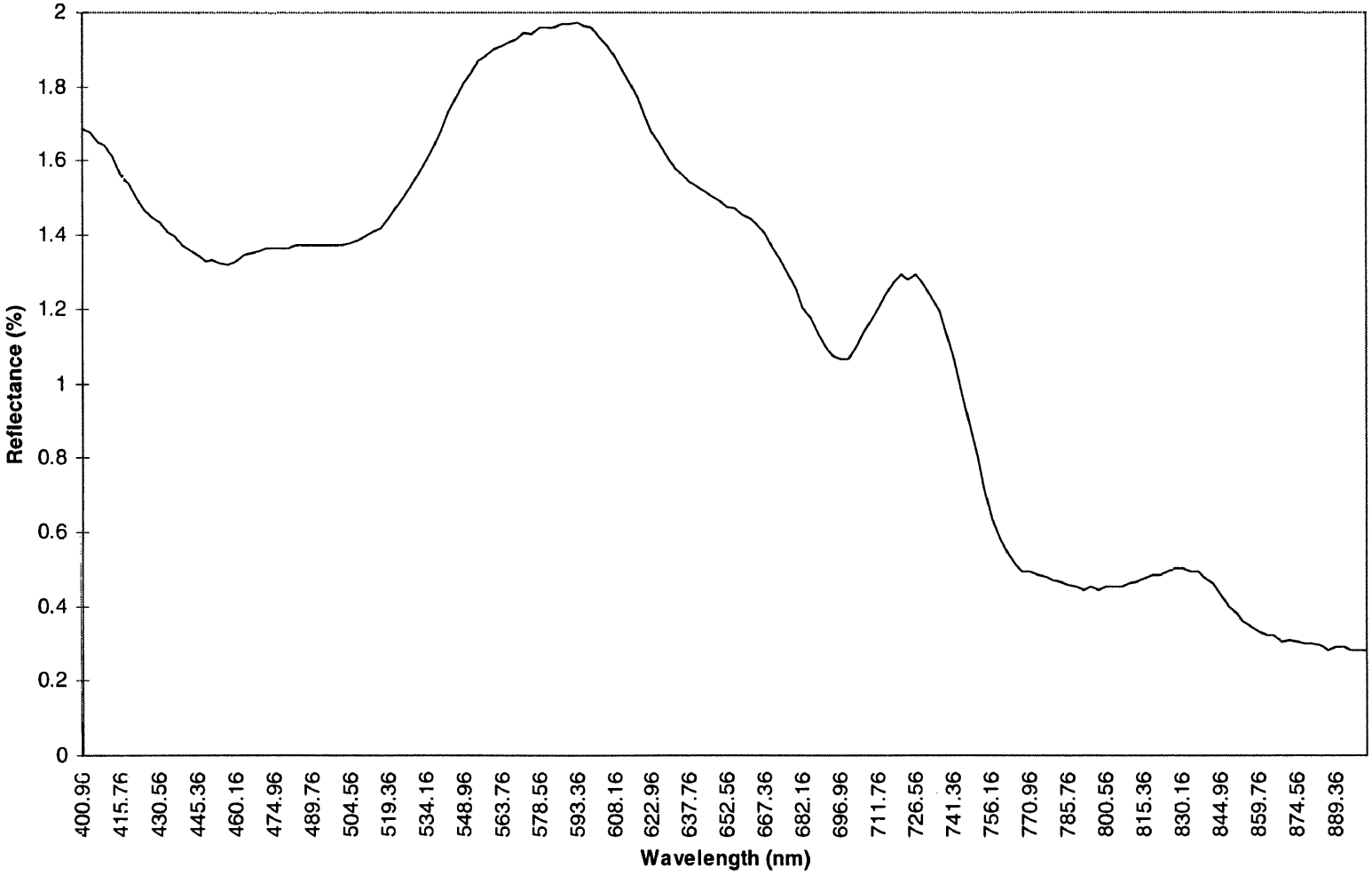
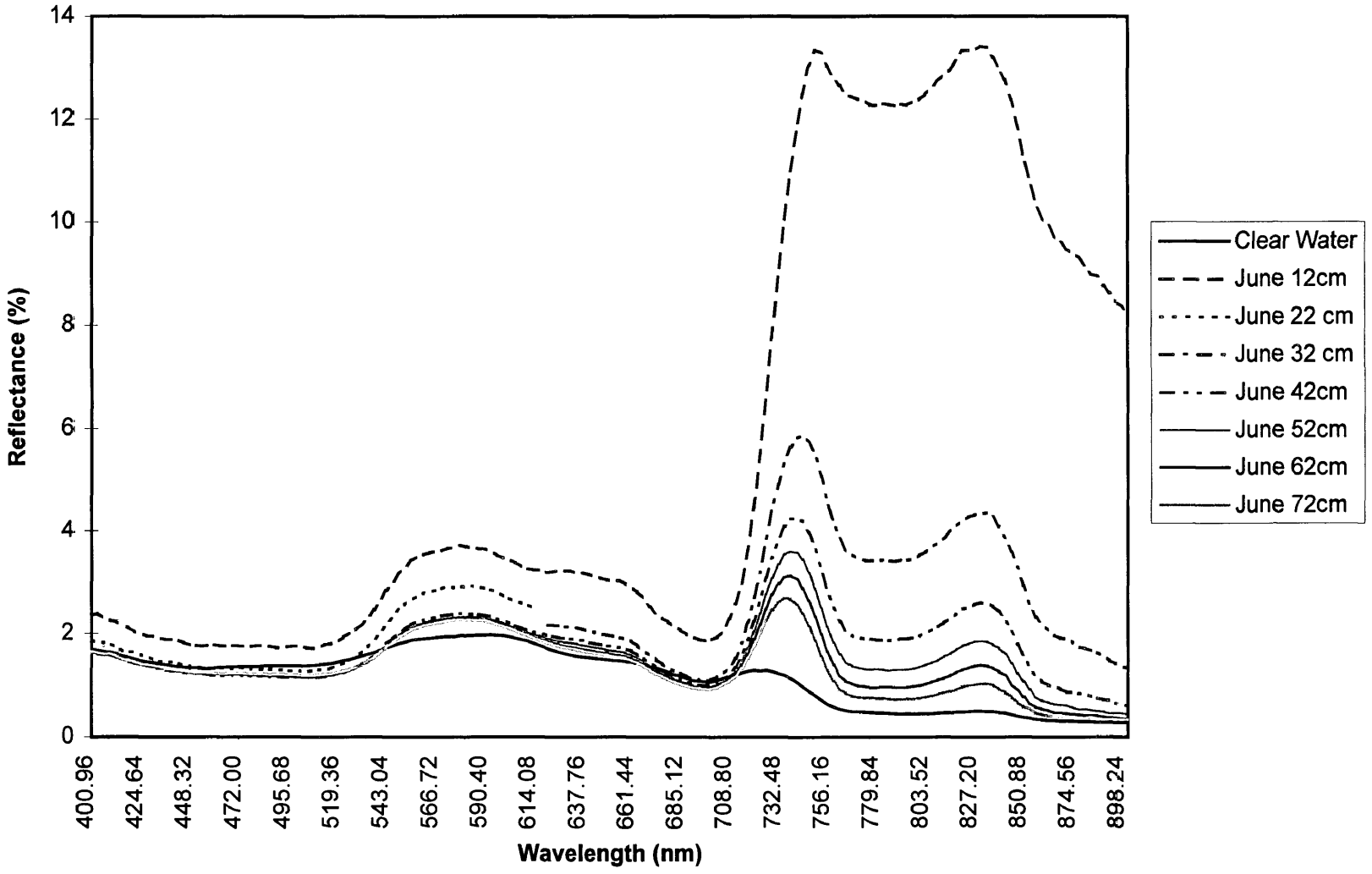


Figure 4: *Ceratophyllum* in Clear Water 12-72 cm



Gross et al. (1988) found different spectral responses based upon the morphology of the wetland vegetation canopy. They classified the canopy as being either planophile or erectophile. A planophile canopy is one that is horizontal in nature. An erectophile cover is generally vertical. In my experiment, as the water depth at which the macrophyte panel decreased, the *Ceratophyllum* canopy changed from primarily erectophile (vertical) in nature to a more planophile (horizontal) structure. The most dramatic decrease in reflectance is noted between 12 cm and 22 cm in depth, seemingly due to the change in the *Ceratophyllum* canopy structure.

Comparing the spectral responses through all wavelengths, at 12 cm in depth the vegetative response exceeds that of the clear water (Figure 5). At 22 cm and 32 cm the vegetative response again exceeds that of the clear water, except where chlorophyll-a absorption is noted at 415 nm (Figure 6). The volume reflectance of water continues to exceed that of the vegetation well into the green portion of the EM, at 534 nm. At this wavelength range (415-534 nm), the reflectance attributable to vegetation is unaffected by further changes in depth (Figure 6).

Overall, the dominant peak in the NIR region shifts to a shorter wavelength as depth increases (Figure 4). Rundquist et al. (1995) investigated the spectral response at varying depths in clear water over a dark and light bottom. The results presented in Figure 4 are consistent with the findings of Rundquist, et al. (1995) over a dark bottom. The dominant peak at 12 cm of depth is at 750 nm (Table IV). A gradual shift in the peak of approximately one nominal bandwidth per 10 cm depth increase is evident. The result is a reflectance of approximately 2.7 percent at 738 nm for the *Ceratophyllum* at 72 cm, compared with a reflectance of greater than 13% at 750 nm for the panel resting in water at 12 cm.

Figure 5: *Ceratophyllum* in Clear Water at 12,22 and 32 cm

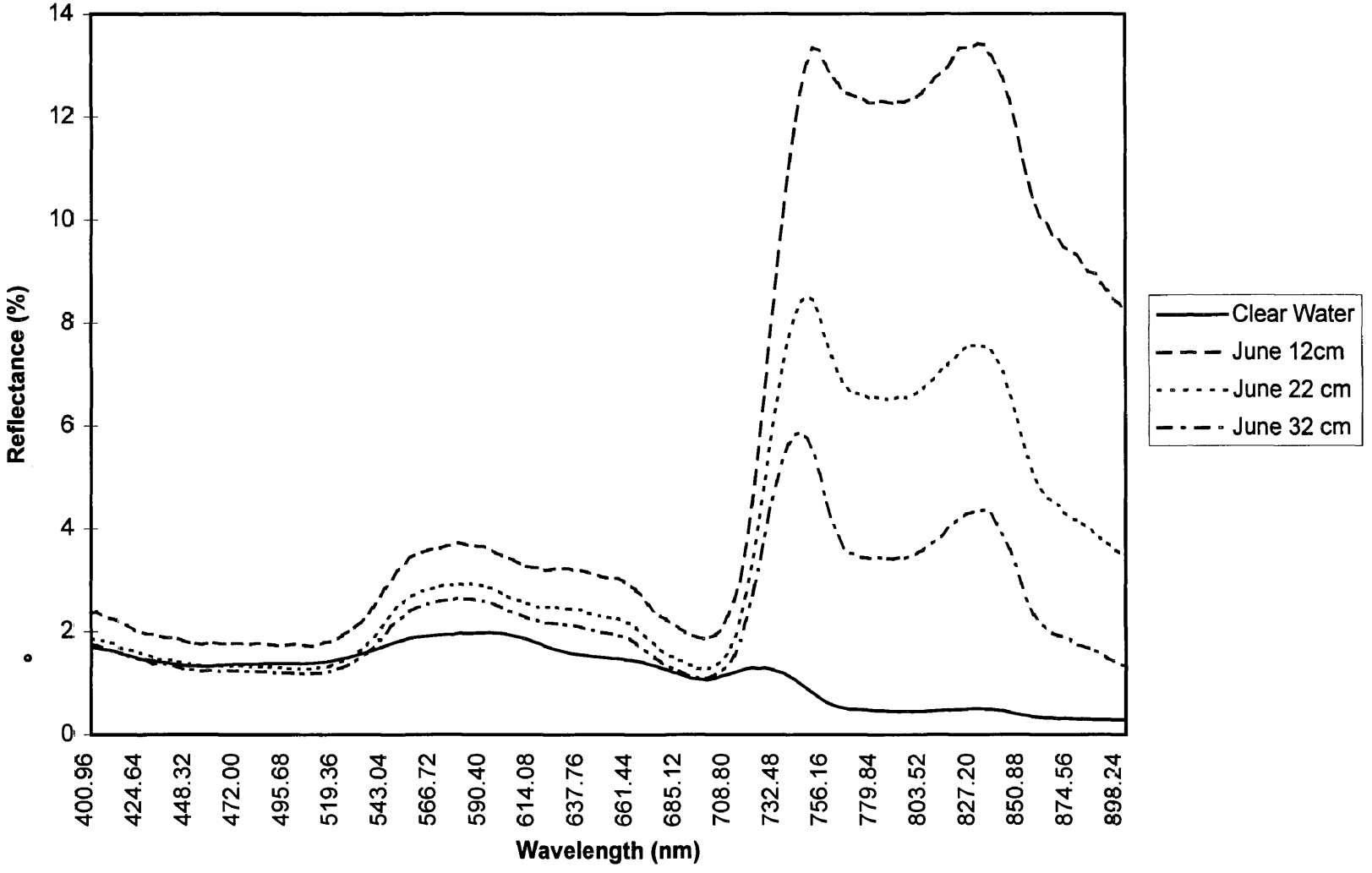


Figure 6: *Ceratophyllum* in Clear Water at 415 to 537 nm

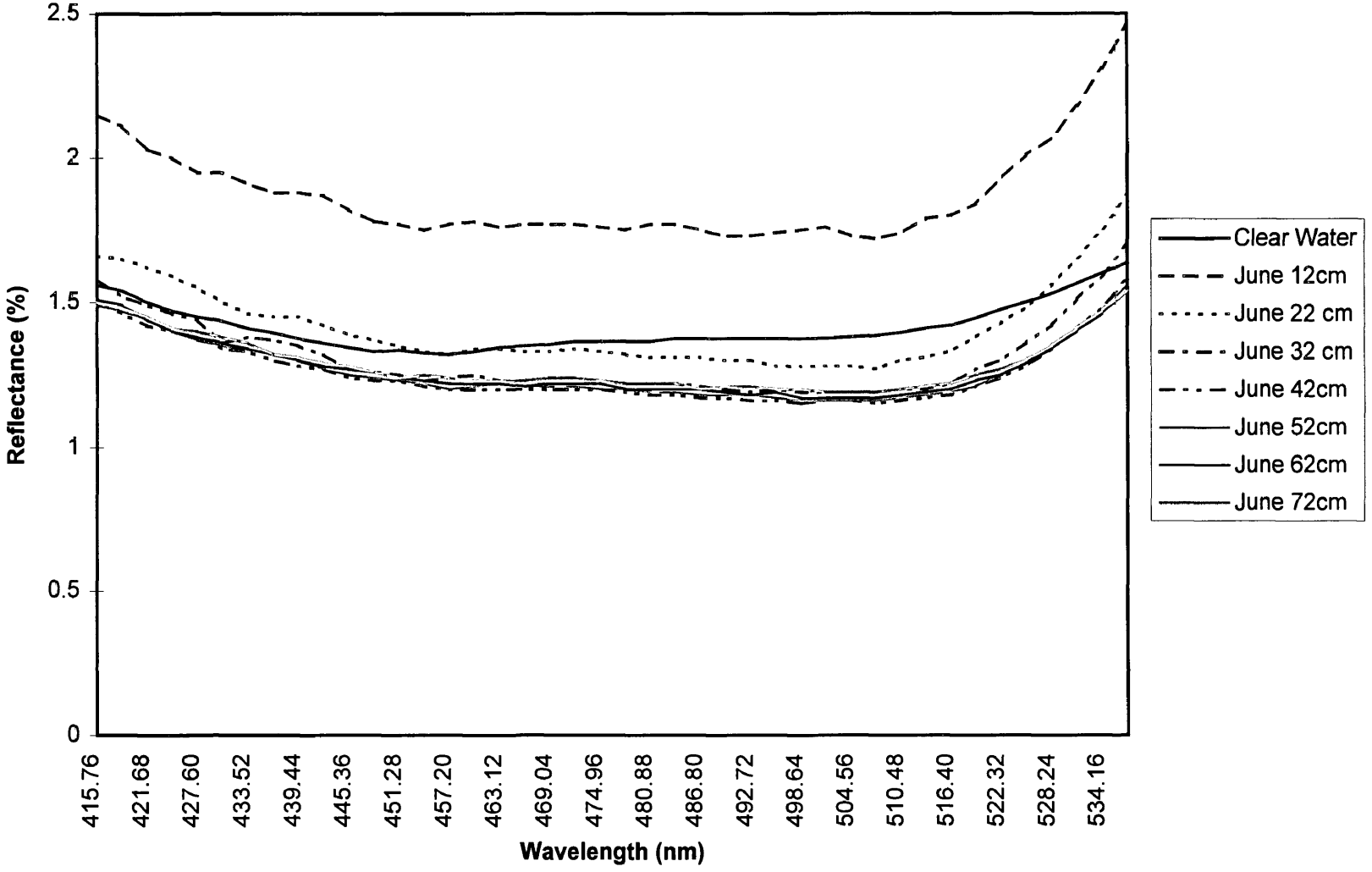


TABLE IV: NIR PEAK SHIFT FOR *CERATOPHYLLUM* IN CLEAR WATER

(Table Values Are Percent Reflectance)

	DEPTH (cm)						
WAVELENGTH OF PEAK R (nm)	**12**	**22**	**32**	**42**	**52**	**62**	**72**
735	10.05	7.16	5.33	4.09	3.53	***2.97***	***2.69***
738	10.94	7.7	5.64	4.23	***3.6***	3.13	2.68
741	11.8	8.14	5.81	***4.25***	3.57	3.06	2.57
744	12.49	8.4	***5.86***	4.18	3.44	2.88	2.39
747	13.04	***8.51***	5.74	3.97	3.19	2.64	2.15
750	***13.34***	8.43	5.49	3.65	2.86	2.33	1.86

Rundquist et al. (1995) and Mittenzwey et al. (1992) found that, as chlorophyll concentrations increased, the maximum reflectance for the NIR peak near 705 nm shifted to longer wavelengths. These findings are significant because increasing water depth influences the spectral response (in this portion of the EM) inversely to that of increasing algal chlorophyll content.

Figure 7 depicts *Ceratophyllum* at all depths in clear water scanned at 443 nm. The level of absorption increases from 12 to 42 cm in depth. After this point the level of absorption is diminished through 72 cm. Saturation is not attained at 72 cm for this spectral feature giving impetus to repeating the experiment at a deeper depth.

Figure 8 shows *Ceratophyllum* in clear water at 670 nm, the area of red absorption. A general trend of increasing absorption can be seen with increasing depth. The most dramatic change is again between 12 and 22 cm. Unlike the area of blue absorption, saturation is not reached and the absorption continues through 72 cm. This too suggests the need to repeat the experiment at deeper depths.

Figure 9 illustrates the spectral feature of NIR reflection at 705 nm. As depth increases, the amount of reflectance from the vegetation is diminished and the NIR absorption by the water increases. Again, it does not appear that saturation is reached at this wavelength.

Figure 7: *Ceratophyllum* in Clear Water at 443 nm

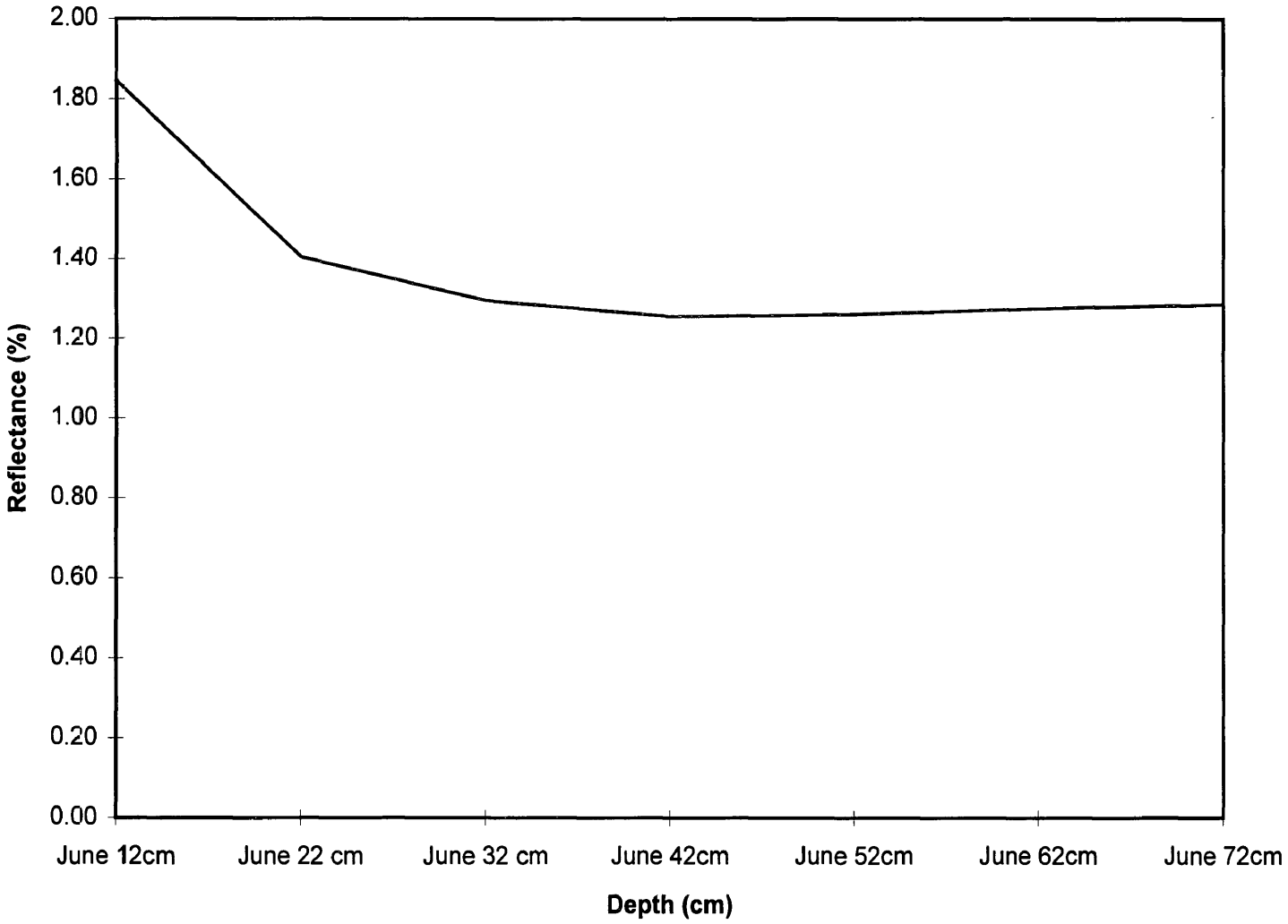


Figure 8: *Ceratophyllum* in Clear Water at 670 nm

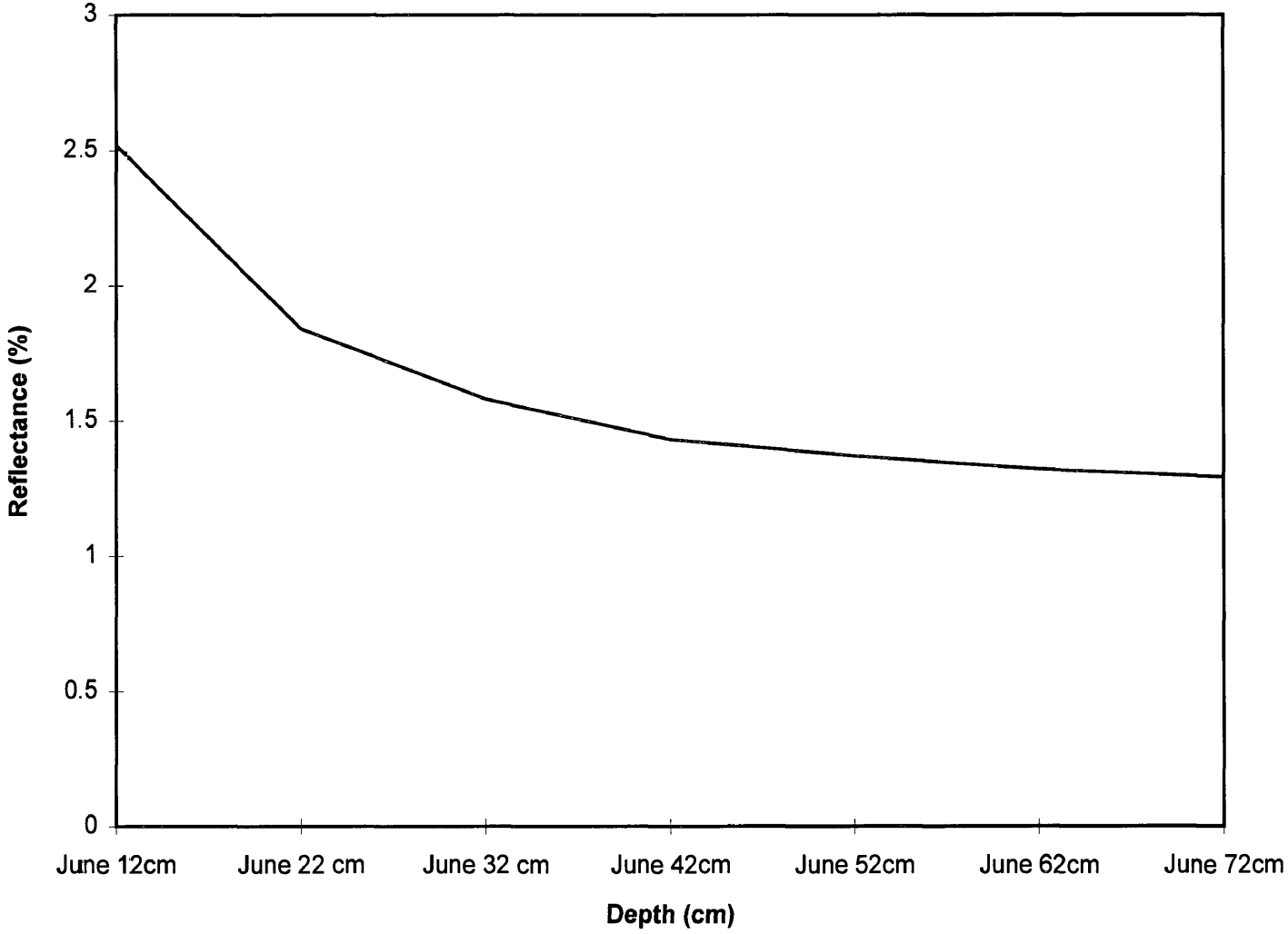
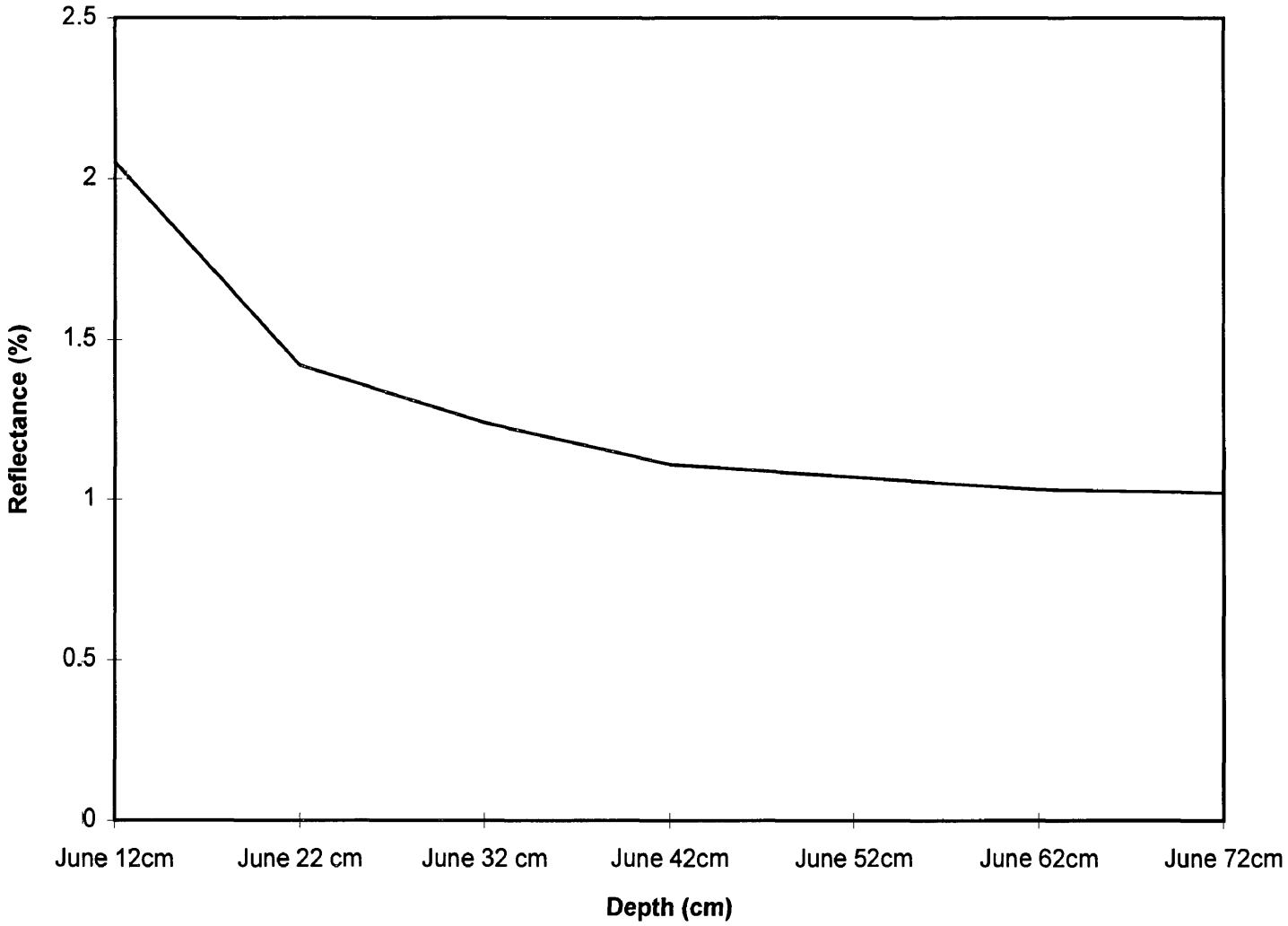


Figure 9: *Ceratophyllum* in Clear Water at 705 nm



Ceratophyllum in Chlorophyll-laden Water

The general shape and trend of the reflective responses of *Ceratophyllum* in the chlorophyll-laden water are the same as those of the clear water (Figure 4, Figure 10). For example, the *Ceratophyllum* at 12 cm exhibits a markedly stronger response than for the succeeding depths, similar to that of the clear water response. There are, however, numerous detailed changes to observe.

As with the clear water, a shift in the dominant peak NIR reflectance is observed (Table V). The dominant peak shifts to a longer wavelength as the *Ceratophyllum* depth increases. Indicative of the clear water, a gradual shift in the peak of approximately one nominal bandwidth per 10 cm depth increase is evident. The resultant reflectance is approximately 2.8 percent at 738 nm for the *Ceratophyllum* at 72 cm, compared with a reflectance of greater than 10% at 750 nm for the panel resting in water at 12 cm. Interestingly, the maximum reflectance at these wavelengths is less than the clear water reflectance, while the minimum reflectance is greater than the clear water response. Further comparison of Tables IV and V shows the dominant peak for the chlorophyll-laden water to be at a longer wavelength than for the clear water. This shift may be attributable to the increase in chlorophyll-a in the water, which characteristically increases the spectral response in this portion of the EM spectrum and is certainly consistent with the findings of Rundquist et al. (1995) and Mittenzwey et al. (1992), as previously mentioned.

Figure 10: *Ceratophyllum* in Chlorophyll-Laden Water

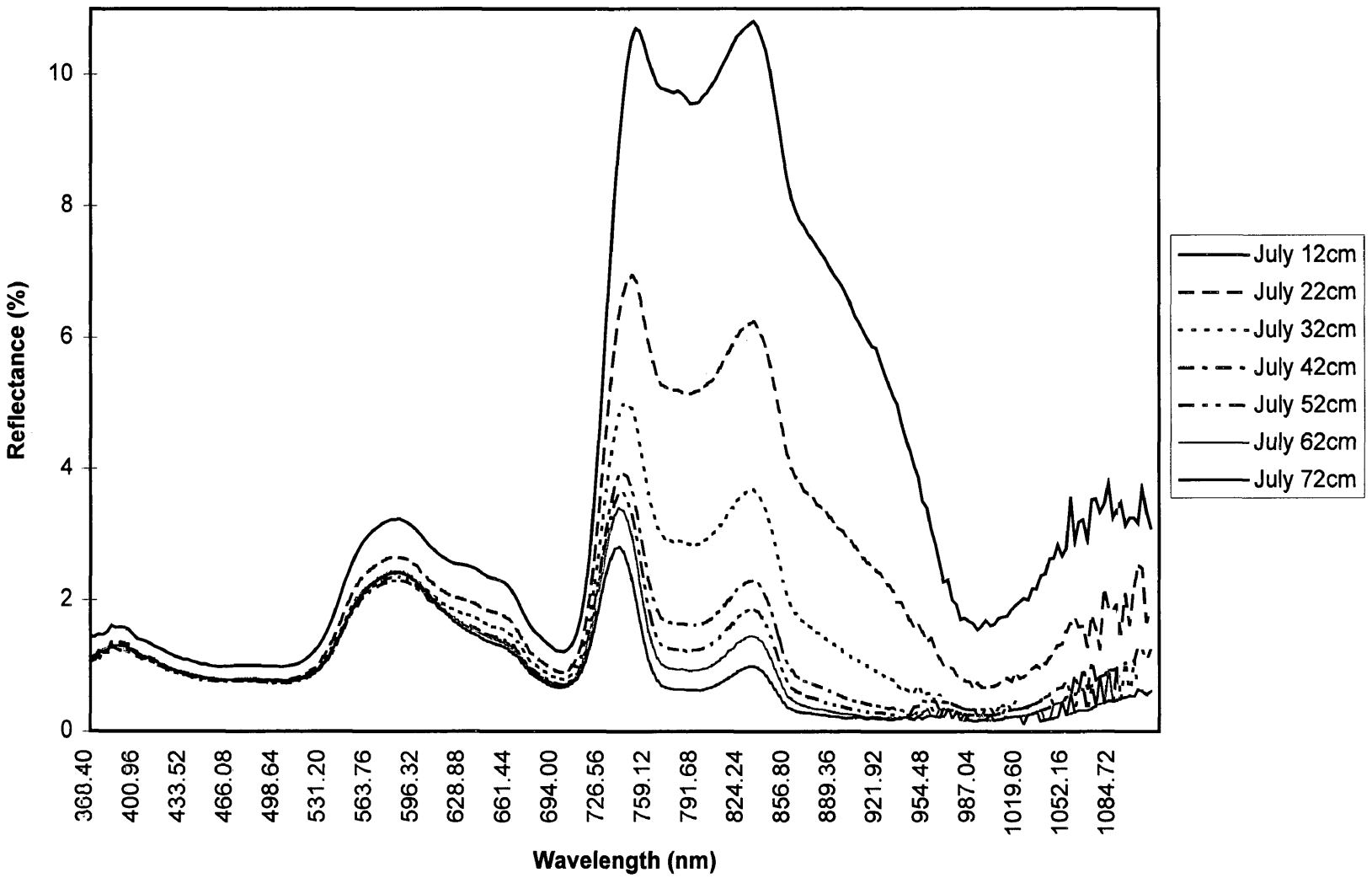


TABLE V: NIR PEAK SHIFT FOR *CERATOPHYLLUM* IN CHLOROPHYLL-LADEN WATER

(Values Are Percent Reflectance)

	DEPTH(cm)						
Wavelenth (nm)	**12**	**22**	**32**	**42**	**52**	**62**	**72**
738.4	8.93	6.33	4.83	3.89	***3.62***	***3.39***	***2.80***
741.36	9.59	6.67	4.97	***3.93***	3.61	3.35	2.73
744.32	10.13	6.88	***5.00***	3.87	3.50	3.21	2.55
747.28	10.51	***6.94***	4.92	3.70	3.30	2.96	2.31
750.24	***10.70***	6.86	4.70	3.40	2.98	2.62	2.00
753.20	10.66	6.60	4.36	3.04	2.60	2.23	1.66

A comparison of Figures 10 and 4 makes it apparent that the reflectance found in the data for the chlorophyll-laden water has been reduced in all wavelengths at all depths. Specifically, the changes in the signal as depth changes in the green portion of the EM have diminished compared to the clear water data set. The general slope of the curve for the chlorophyll set is also steeper in this part of the EM spectrum. The absorption of chlorophyll in the blue and red is also greater for the curves of the *Ceratophyllum* in the chlorophyll-laden water. Increased absorption in the blue and red regions of the EM spectrum is consistent with an increase in chlorophyll content in the water (Rundquist et al., 1995). The reflectance in the NIR is also diminished. Typically, an increase in chlorophyll is indicative of a stronger spectral response in the NIR (Rundquist et al., 1995). It appears the absorptive properties of the water eclipse an increase in the response due to the augmentation of chlorophyll in the water.

To fully investigate the significance that chlorophyll in the water has on the spectral response of *Ceratophyllum*, it is necessary to compare each depth for which data was collected to the responses in the

clear water. At 12 cm (Figure 11), the reflectance of *Ceratophyllum* in the chlorophyll-water mirrors that of the clear water. The obvious difference is in the signal strength. In the blue and short end of the green portions of the EM, the absorption by the clear water does not exceed the reflectance of the *Ceratophyllum*. The reflectance of *Ceratophyllum* in the chlorophyll laden water is less than that of the clear-water *Ceratophyllum*.

Figure 12 is a depiction of *Ceratophyllum* at 22 cm in both water qualities. The signal of *Ceratophyllum* under both conditions is overshadowed by the clear water response in the longer half of the blue region of the electromagnetic spectrum. In the upper end of the red domain (approximately 694 nm), the chlorophyll response is less than the clear water response, but still mirrors the reflectance of *Ceratophyllum* in clear water. Looking at this region at 32 cm (Figure 13), the clear water reflectance of *Ceratophyllum* comes very close to the reflectance of plain water, while the chlorophyll-water response is diminished even further than at the 22 cm depth.

At 42 cm in depth (Figure 14), the gaps between the peaks and valleys of the responses under both aquatic conditions diminish. This is particularly evident in the NIR region. It is also observed that the signal from the clear water *Ceratophyllum* and that from the chlorophyll-laden water were completely overcome by the clear water signal at the two critical absorption features in the blue and red portions of the EM (see discussion below).

Figure 15 graphs *Ceratophyllum* at 52 cm. At this depth, many perturbations are noted. The absorptive properties of water exceed the reflectance of *Ceratophyllum* in the entire blue and a good portion of the green region of the EM. The peaks and valleys of the chlorophyll-laden responses found throughout the spectrum exceed the clear water reflectance of *Ceratophyllum*. Specifically, the peak reflectance of *Ceratophyllum* in the chlorophyll-laden water in the green section of the EM exceeds the clear water response of *Ceratophyllum*. In the NIR region the two peaks have nearly identical responses. The additional chlorophyll in the water causes a higher reflectance, thus overcoming the absorptive properties of water in the near infrared area.

At 62 cm (Figure 16), the chlorophyll-laden water peak in the green and NIR is even more predominant, completely surpassing the clear water responses. Again, this is attributable to the strong absorptive properties of clear water and the reflective properties of chlorophyll in solution. The *Ceratophyllum* at 72 cm (Figure 17) mirrors, at a weaker reflectance, the response at 62 cm.

Figure 11: *Ceratophyllum* at 12 cm

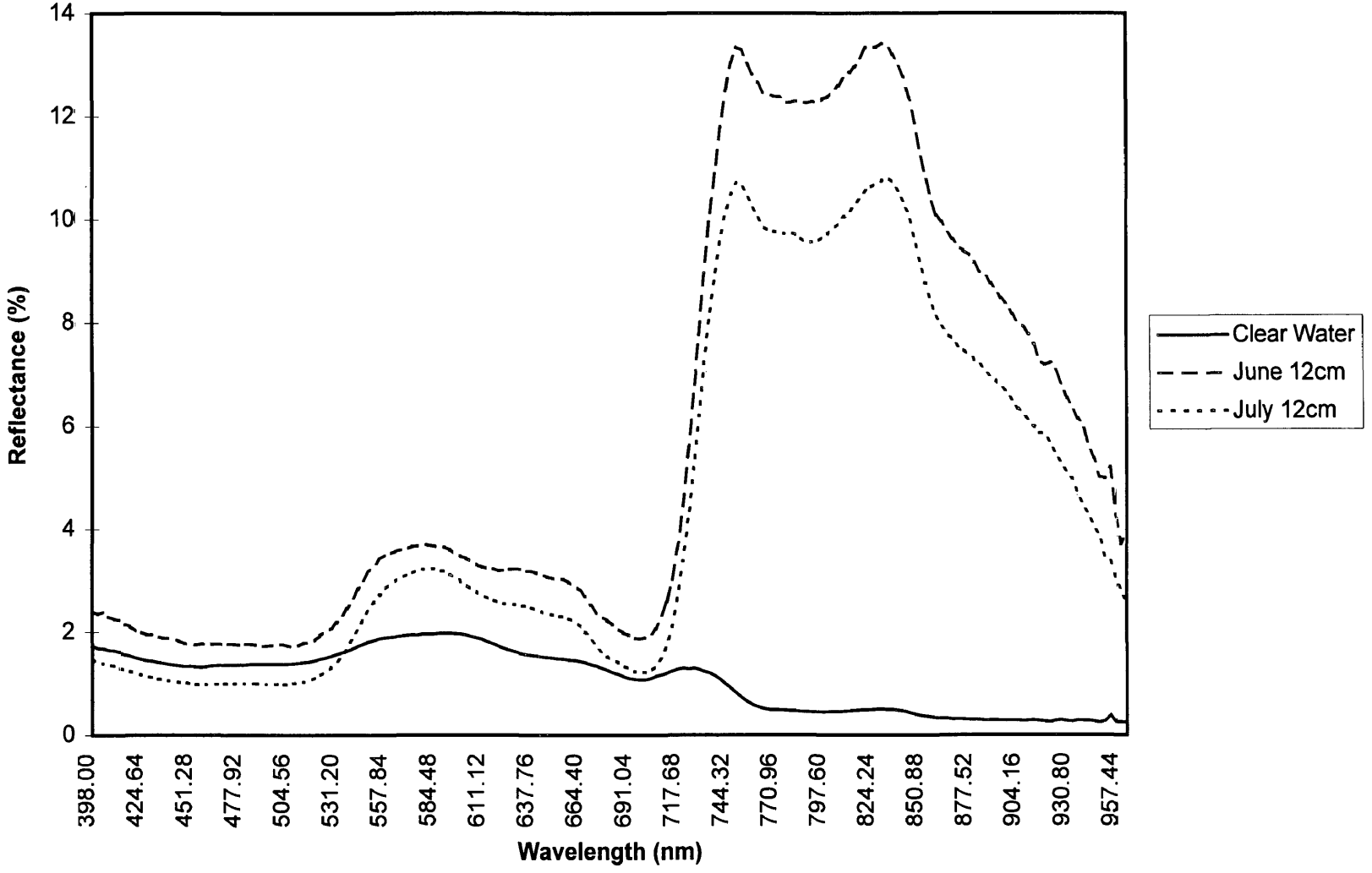


Figure 12: *Ceratophyllum* at 22 cm

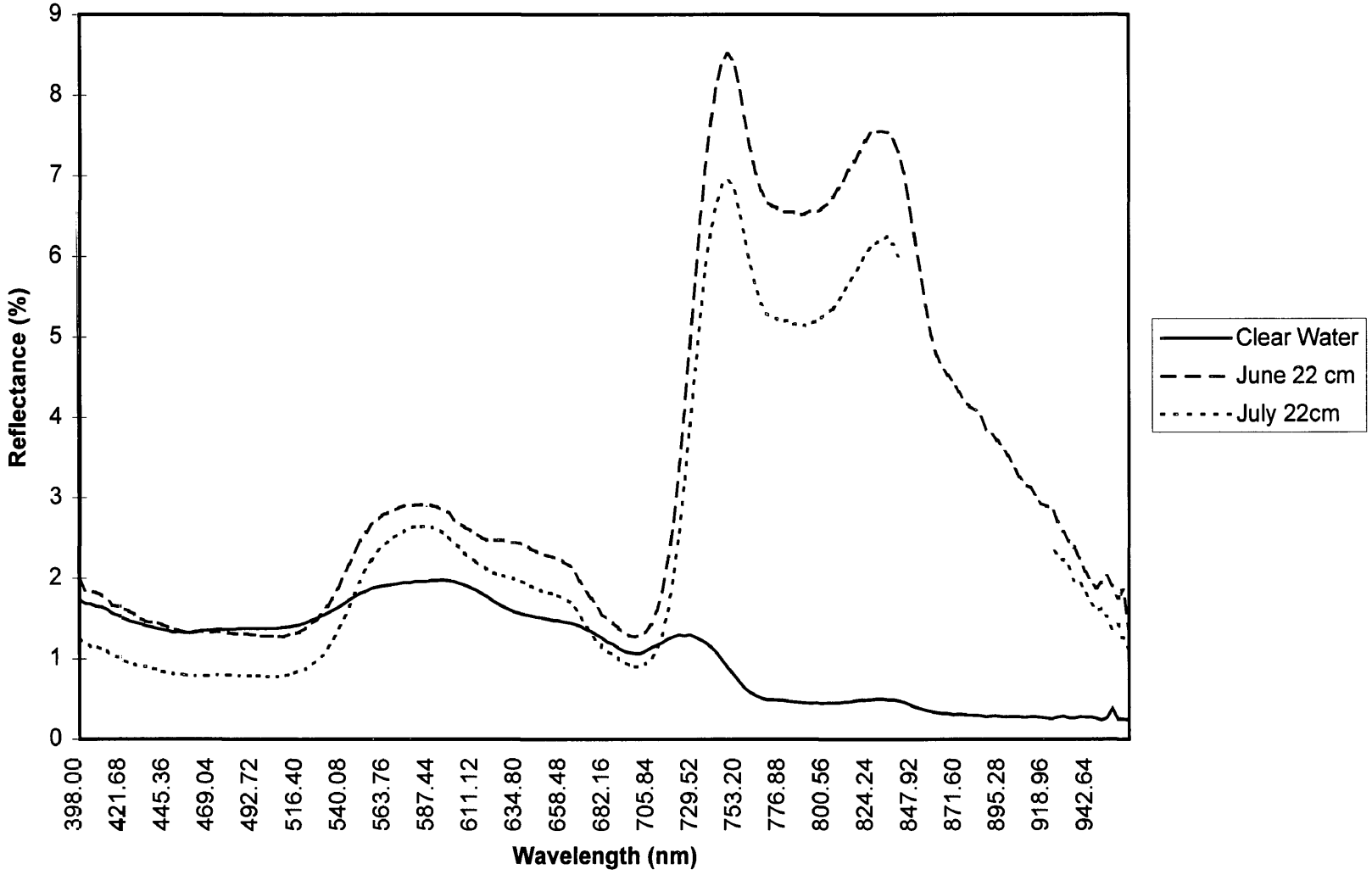


Figure 13: *Ceratophyllum* at 32 cm

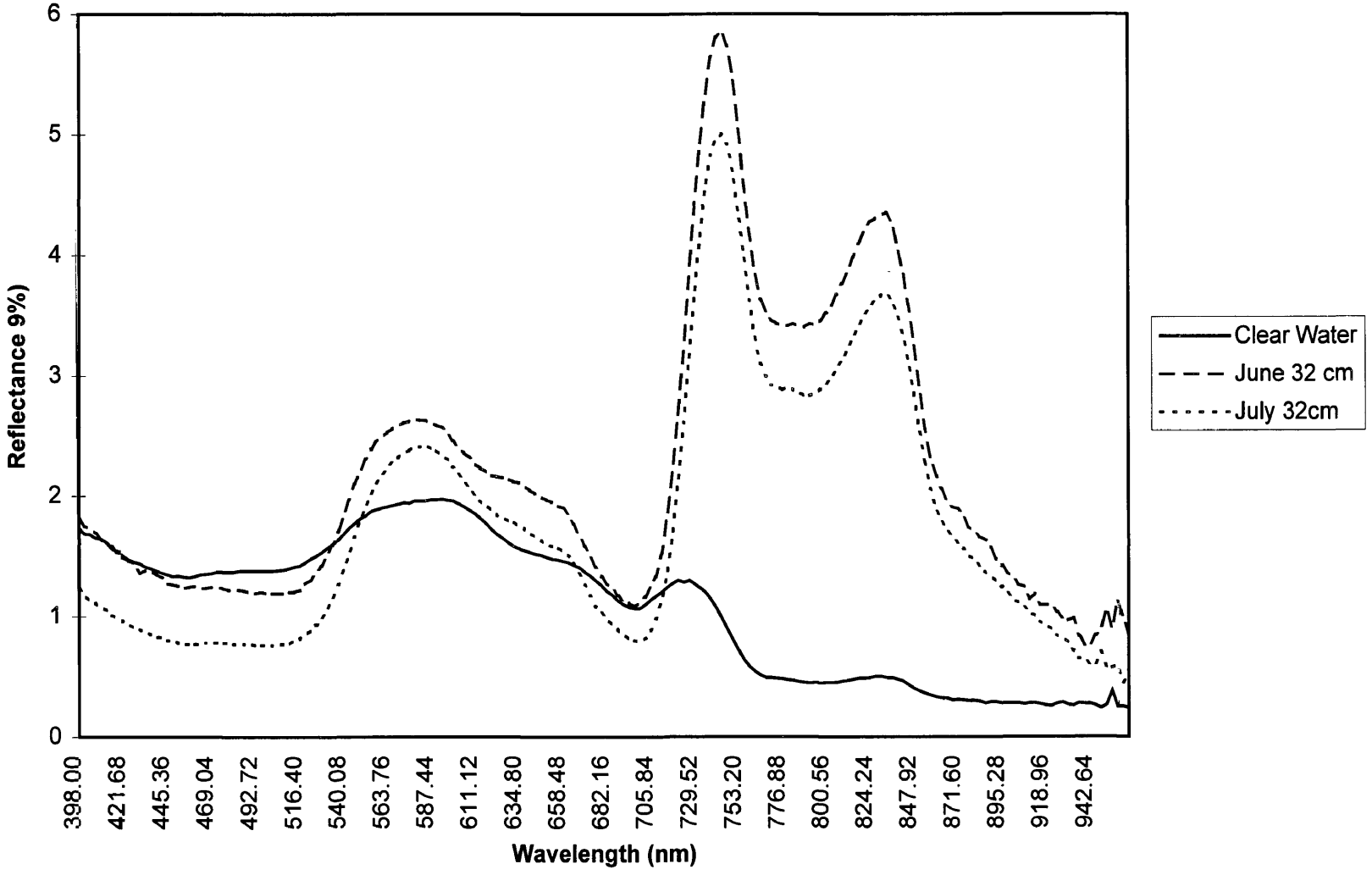


Figure 14: *Ceratophyllum* at 42 cm

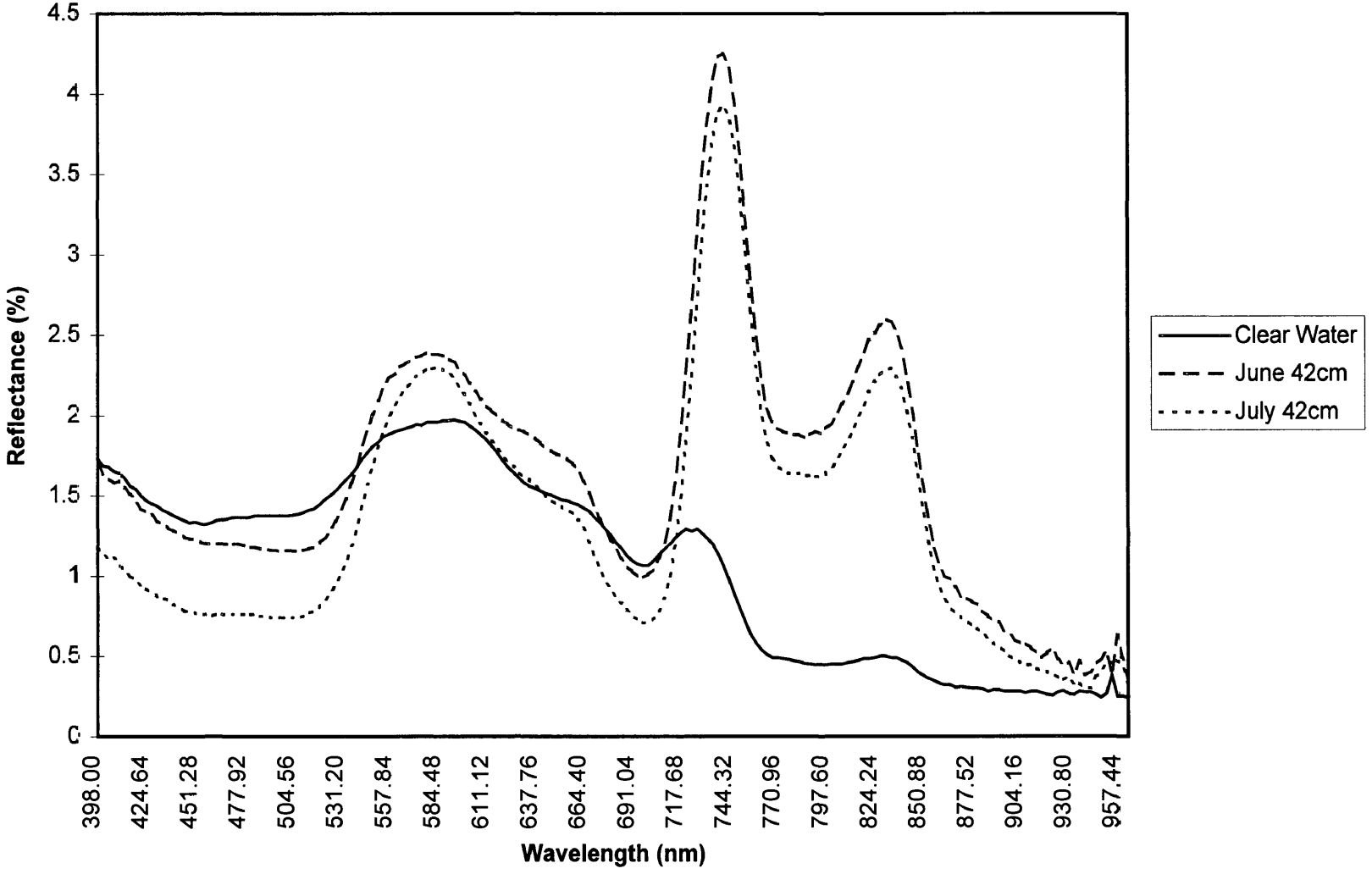


Figure 15: *Ceratophyllum* at 52 cm

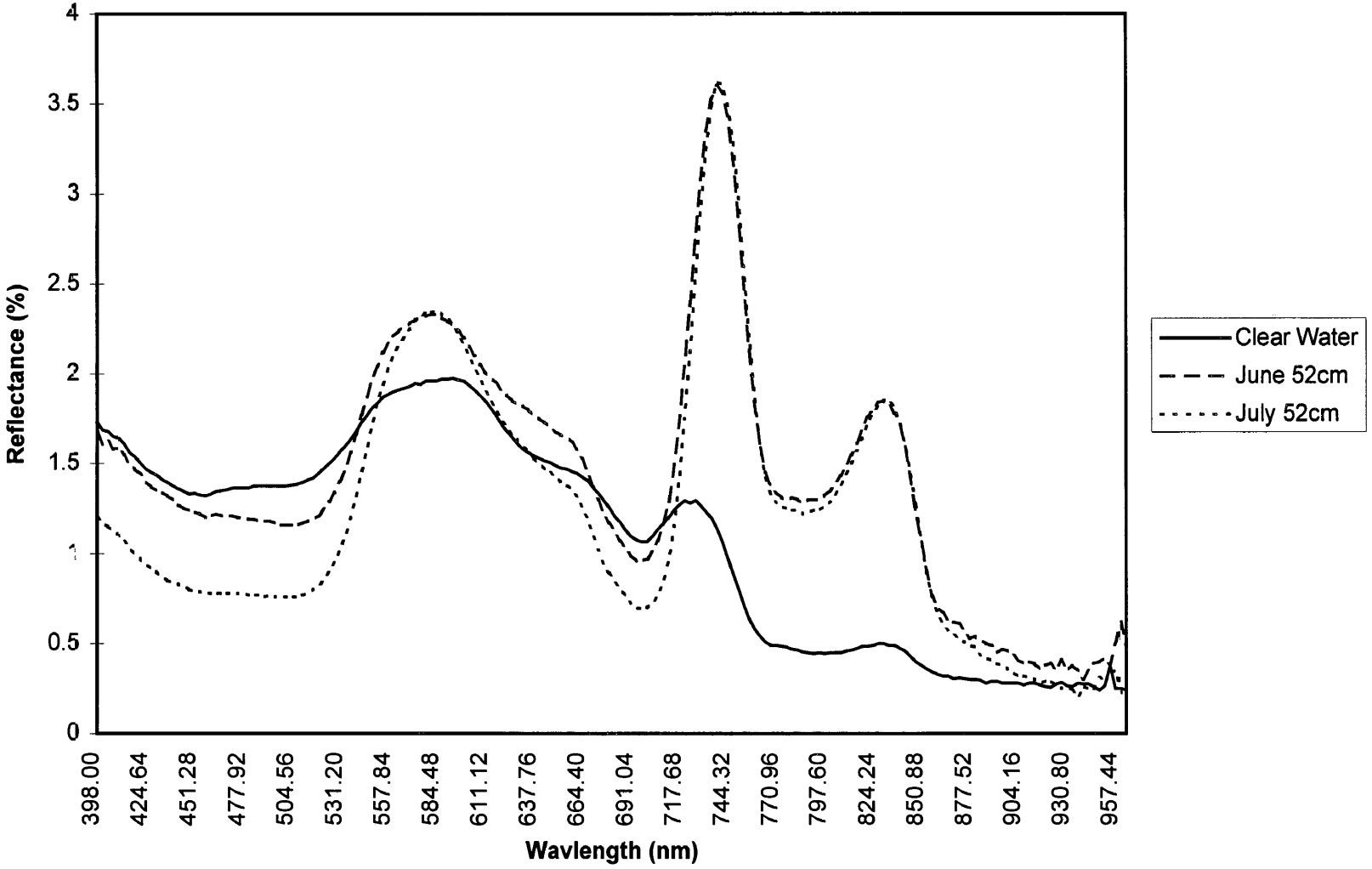


Figure 16: *Ceratophyllum* at 62 cm

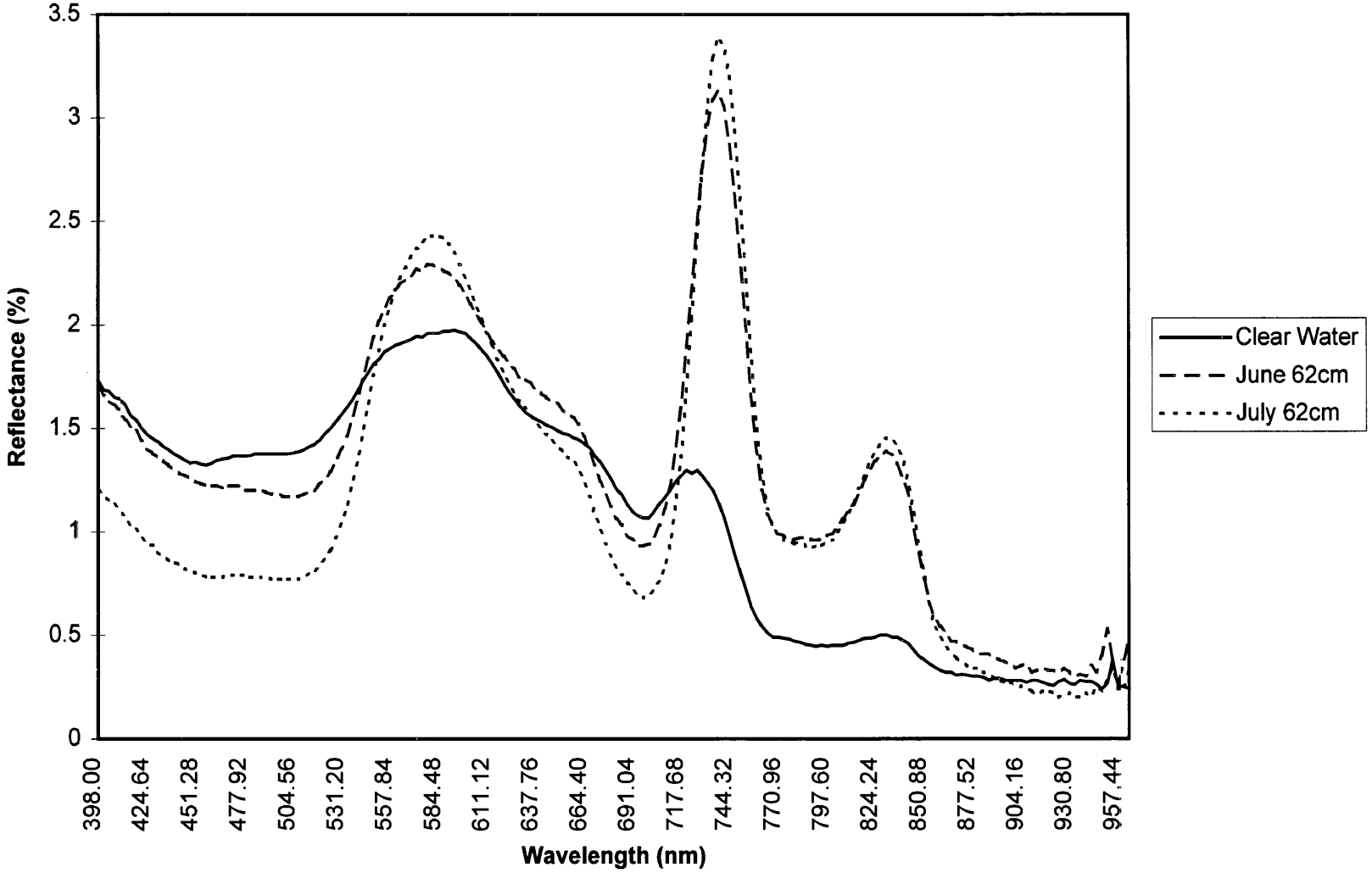


Figure 17: *Ceratophyllum* at 72 cm

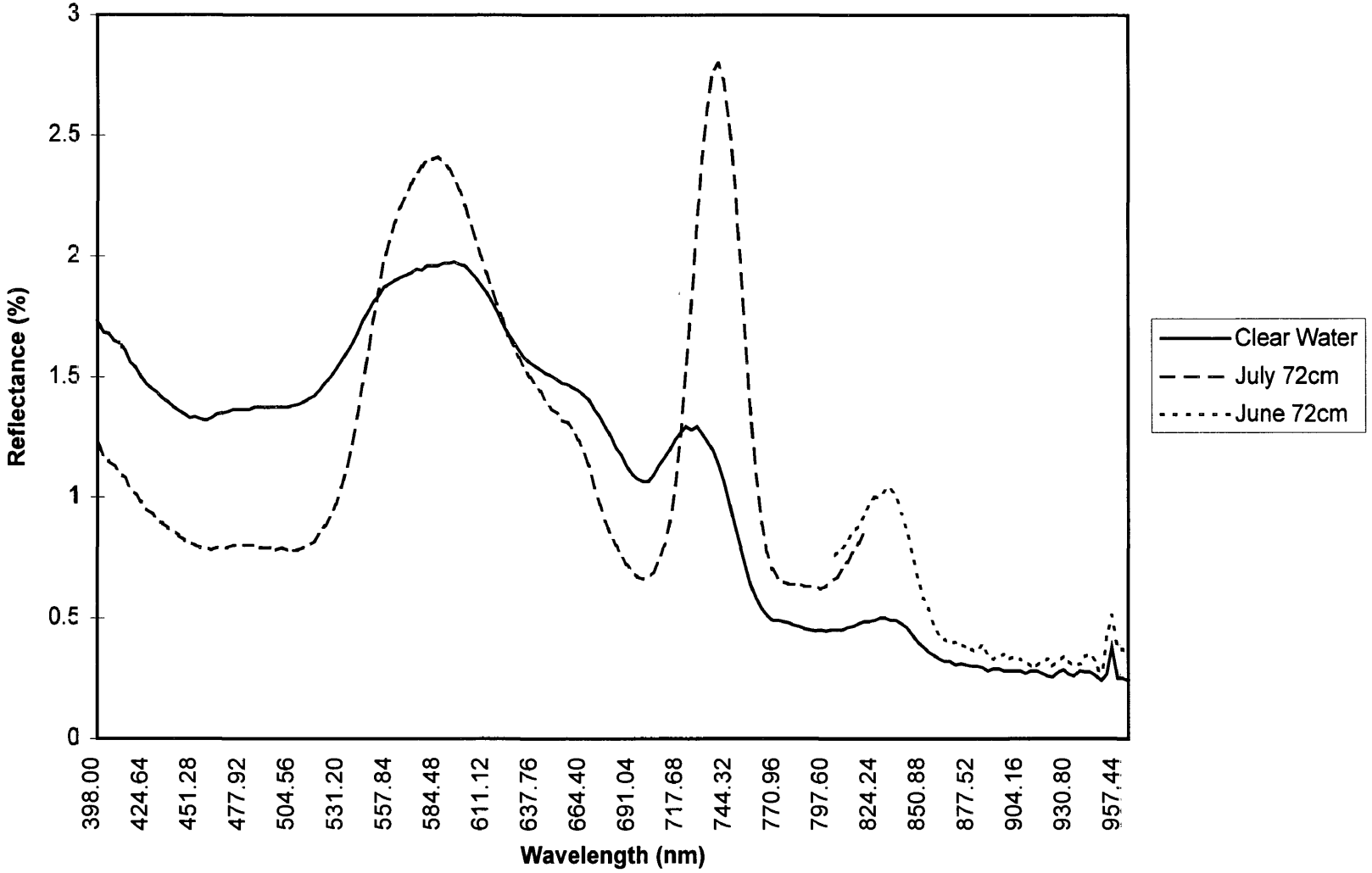


Figure 18 depicts *Ceratophyllum* at all depths in clear and chlorophyll-laden water scanned at 443 nm, a point characteristic of blue absorption. The absorption in increased by up to one percent in the shallower depths. Note the distinctive drop at 22 cm and the rise at 52 cm in the chlorophyll-laden water. At the deeper depths, while the absorption is higher than the clear water, there is a diminution of it beginning at 42 cm and continuing through 62 cm.

The red absorption feature (Figure 19) of *Ceratophyllum* in chlorophyll-laden water mimics the clear water curve. The only difference is again in the intensity of absorption. The increased absorption of up to 0.7 percent is attributable to an increase in chlorophyll in the water.

Figure 20 illustrates the spectral feature of NIR reflection at 705 nm. As depth increased, the reflectance decreased for both water qualities. As mentioned earlier (Figure 9), this is expected for the clear water curve, given the absorptive properties of water. Interestingly, the incidence of NIR reflectance (at this wavelength) did not exceed the clear water response with an increase in chlorophyll in the water.

Both the data sets are highly correlated, as can be expected from the previous discussions (Figure 21). The general trend is one of decreasing correlation between the clear water spectra and the spectra of the chlorophyll-laden water as depth increases. *Ceratophyllum* at 12 cm in both water qualities has a correlation coefficient of 0.99034. The correlation decreases to a minimum of 0.95457 at 62 cm and increases slightly to 0.95523 at 72 cm. Given the trends discovered upon comparison of each depth for clear and chlorophyll water, these correlation coefficients are congruent with the previously discussed findings.

Figure 22 shows the variance at all wavelengths between the clear and chlorophyll-laden water for each depth. In the clear water, as depth increased the variance decreased. The same was true for the algal water. It appears the strong absorptive properties of water diminished the signal strength as the depth increased. It is noted, with one exception, that the degree of variance among the depths in the chlorophyll-laden water is less than that of the clear water (Table VI). The exception is at 62 cm, which had a higher variance in the chlorophyll-laden water than the clear water.

Investigating the variance for each depth, some points of interest are noted. The 12 cm canopy had the largest variance of nearly six points. The variance dramatically decreased at a depth of 22 cm. This trend continued through the depths, with the exception noted above, to a nearly equal variance at 72 cm.

Figure 18: Blue Absorption Feature (442 nm)

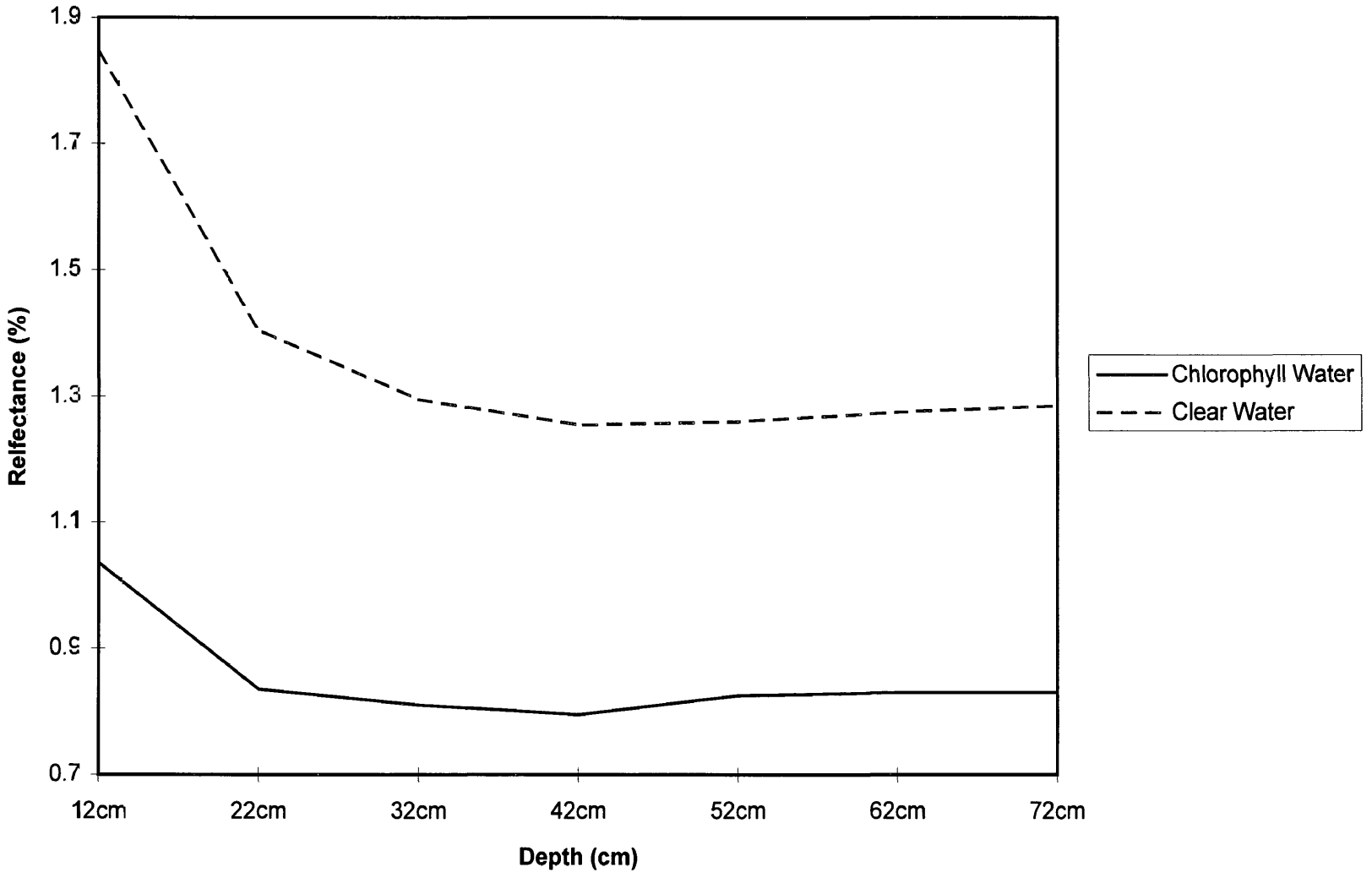


Figure 19: Red Absorption Feature (670 nm)

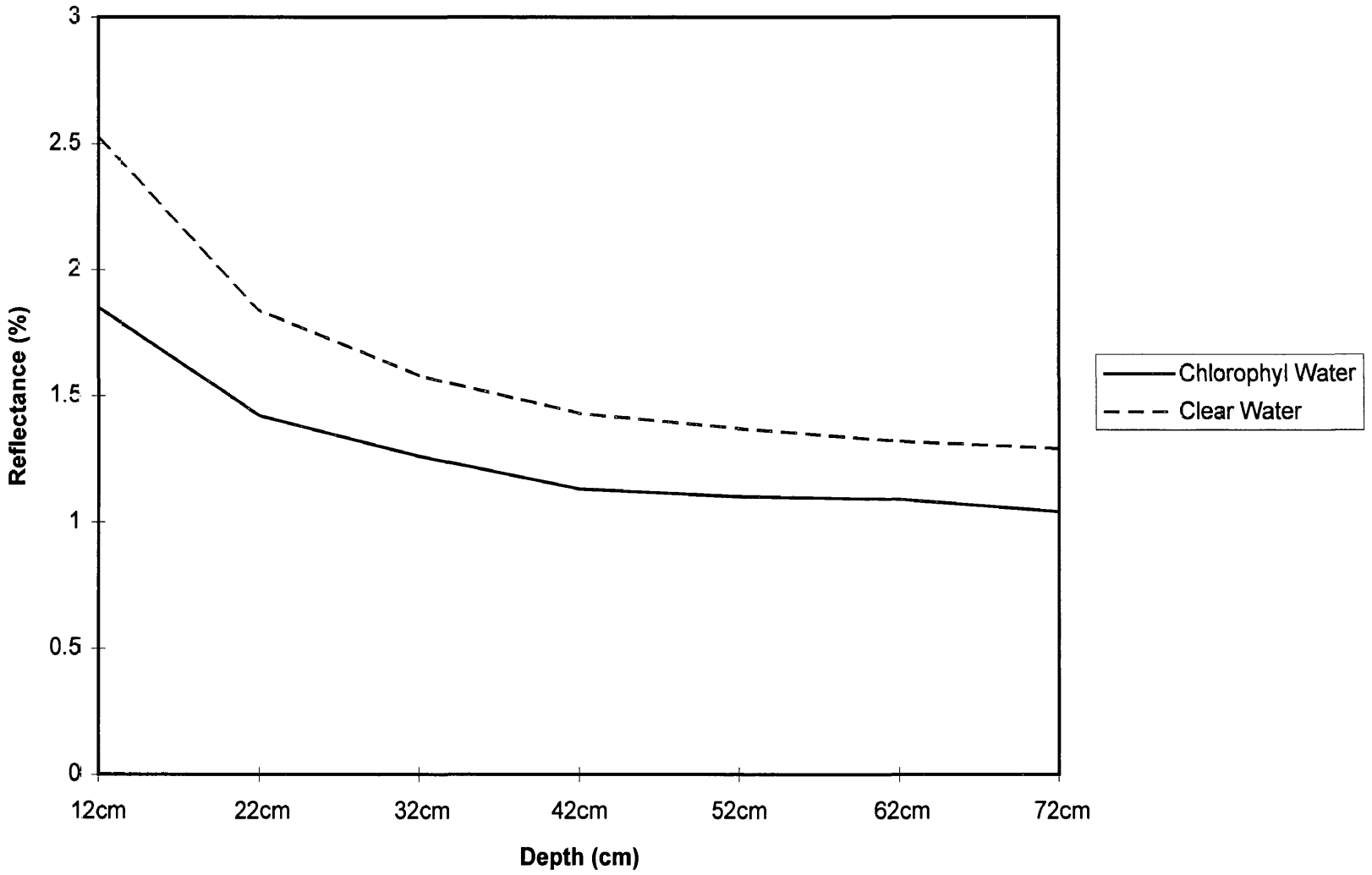


Figure 20: NIR Reflection (705 nm)

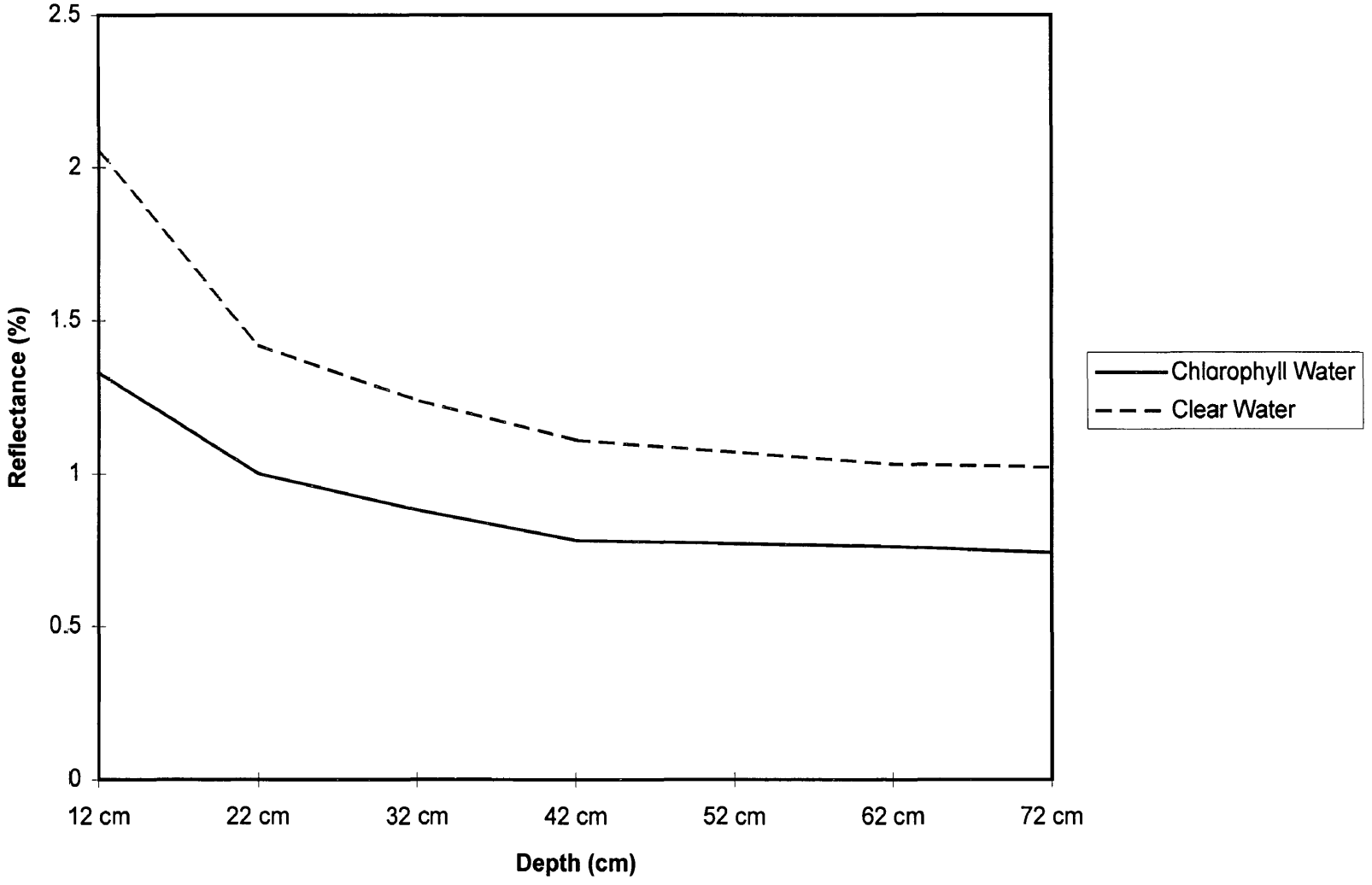


Figure 21: Correlation of *Ceratophyllum*

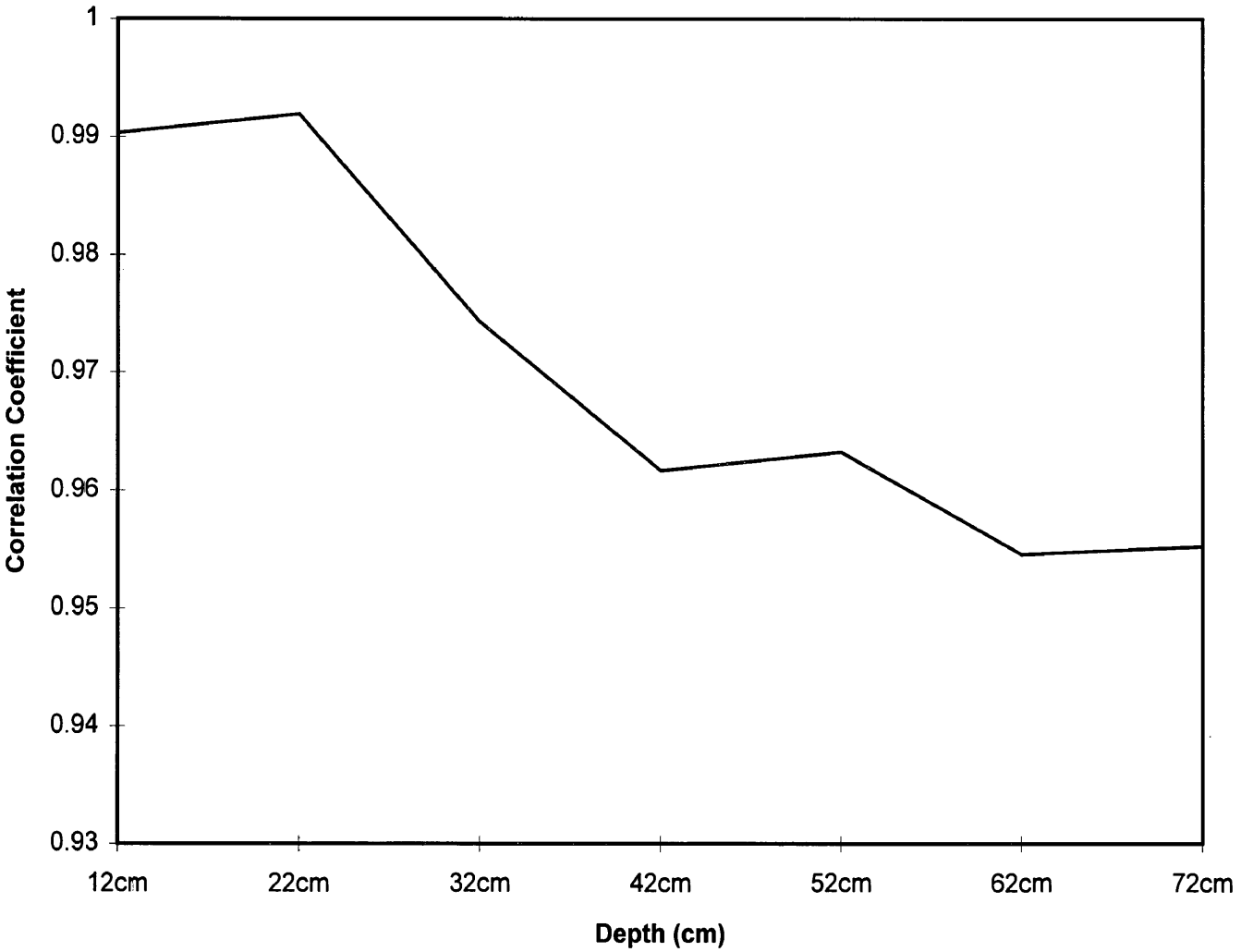


Figure 22: Variance of *Ceratophyllum*

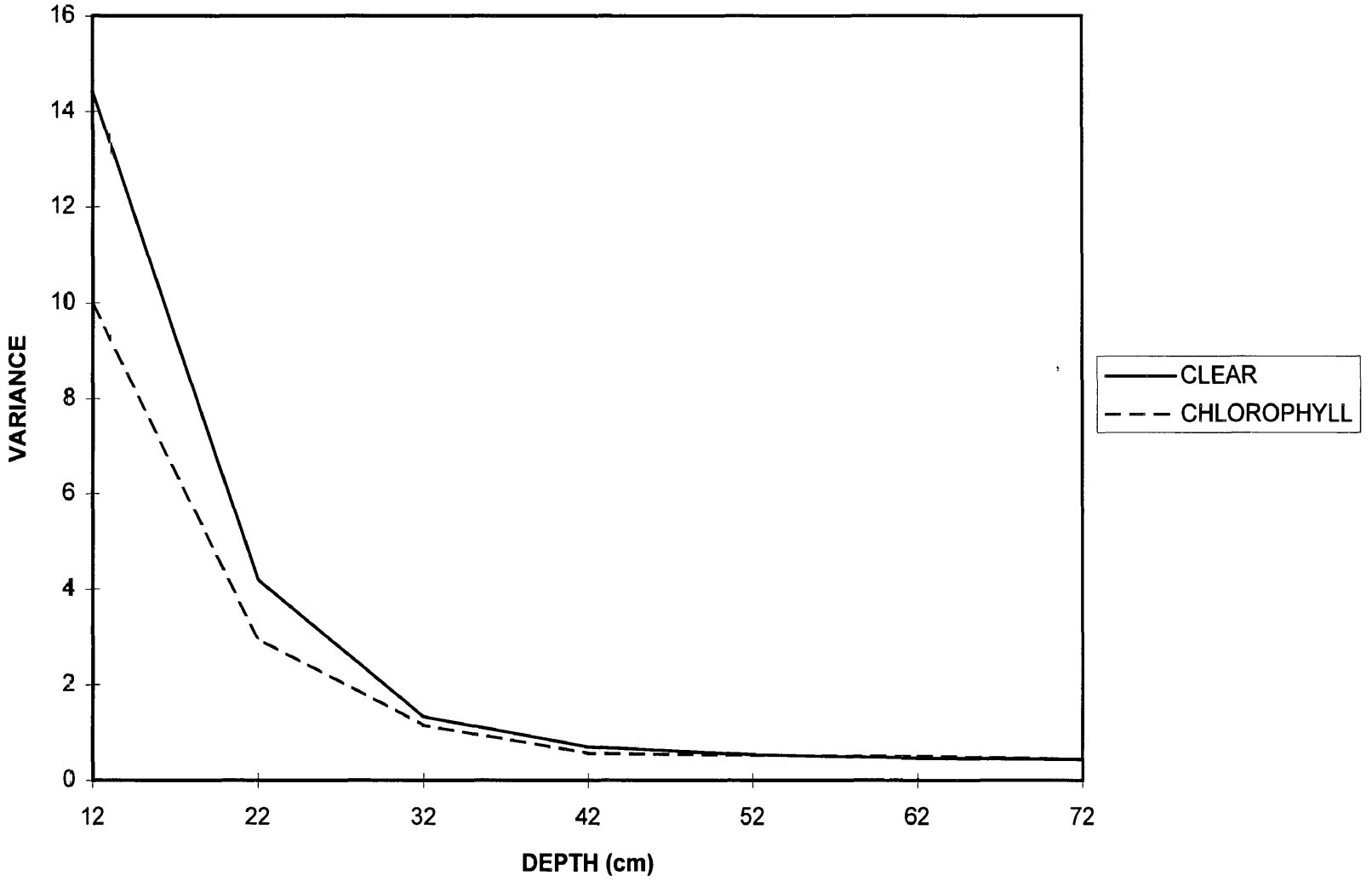


TABLE VI: VARIANCE ANALYSIS		
WATER QUALITY		
DEPTH (cm)	**CLEAR**	**CHLOROPHYLL**
12	14.40457228	9.941563731
22	4.186152019	2.954599728
32	1.335318591	1.153924075
42	0.699308232	0.568934522
52	0.542073591	0.530613411
62	0.467774211	0.510164983
72	0.433090925	0.43375064

CHAPTER FOUR: Conclusions

Close-range hyperspectral remote sensing allows one to investigate the most minute details and changes occurring in wetland environments. Findings in this study support the objectives of my research to determine the effect of a submerged canopy of *Ceratophyllum* on the composite spectral signal upwelling from a column of clear water and to determine whether or not it is possible to discern the presence of *Ceratophyllum* in the water column when the water is laden with algal phytoplankton.

This study did not, however, fully meet the objective of establishing the depth constraint(s) for identification of submerged *Ceratophyllum* from remote platforms in clear water. In certain portions of the electromagnetic spectrum, a depth at which the spectral response no longer fluctuates was not ascertained. Clearly further studies using deeper mesocosms need to be conducted.

Additional information gleaned from this experiment includes the determination that with increasing depth the signal decreases, regardless of water quality and the fact that both data sets are highly correlated to one another. The findings of this study provide a basis for further research to continue to assess the wetland environment. For example, this experiment needs to be replicated using numerous dilutions of algal-chlorophyll solutions and *Ceratophyllum* in order to verify the previous findings. Certainly, the need exists to investigate the saturation point of various vegetative bottoms, using a plethora of water conditions. Goodin et al. (1993) investigated suspended sediment, as did Han (1994). Additionally, Han added chlorophyll to the equation. The next natural step is to combine the findings and research of Han and Goodin to include submerged aquatic macrophytes, eventually building up to the investigation of a complete wetland ecosystem.

Combining these two objectives will result in a more clearly defined ability to assess wetland environments using close-range hyperspectral remote sensing. This is important, as stated before, in order to fully comprehend wetlands' functional role in the global environment

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