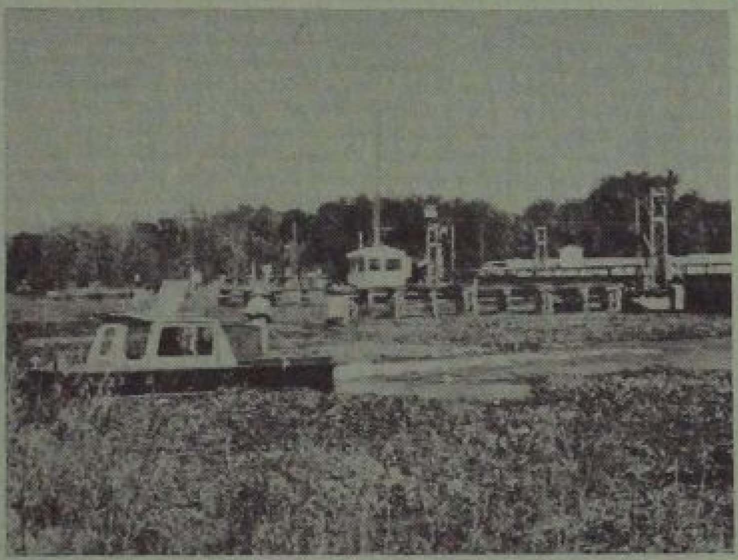
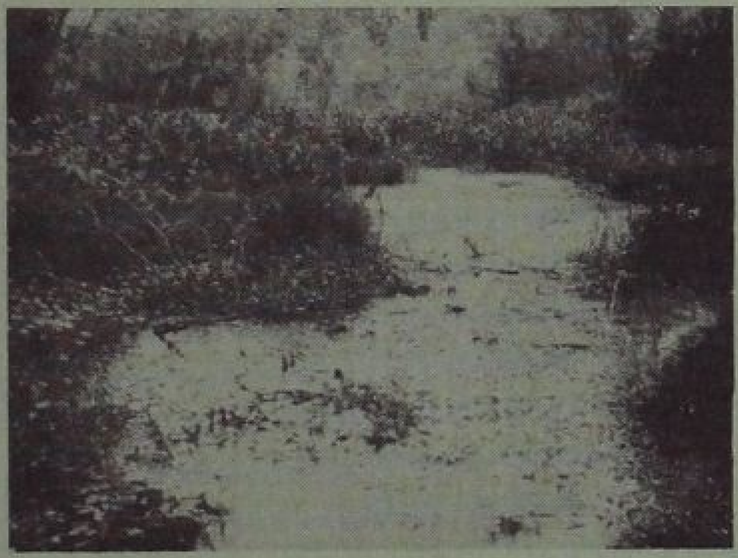
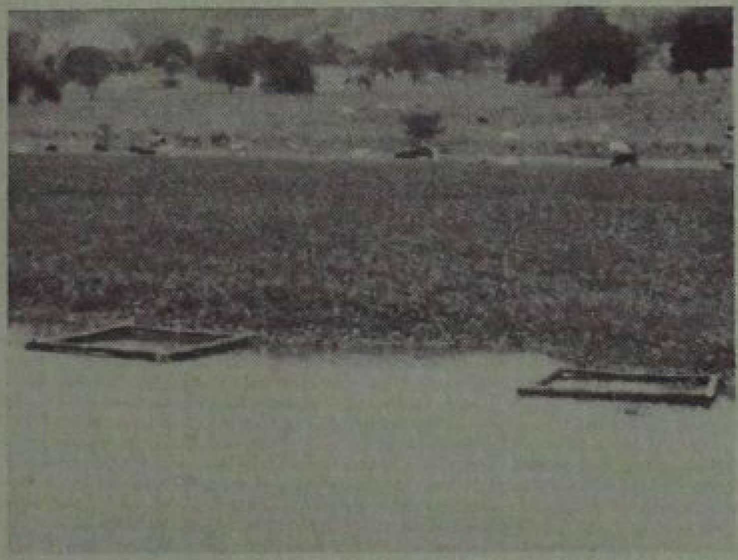
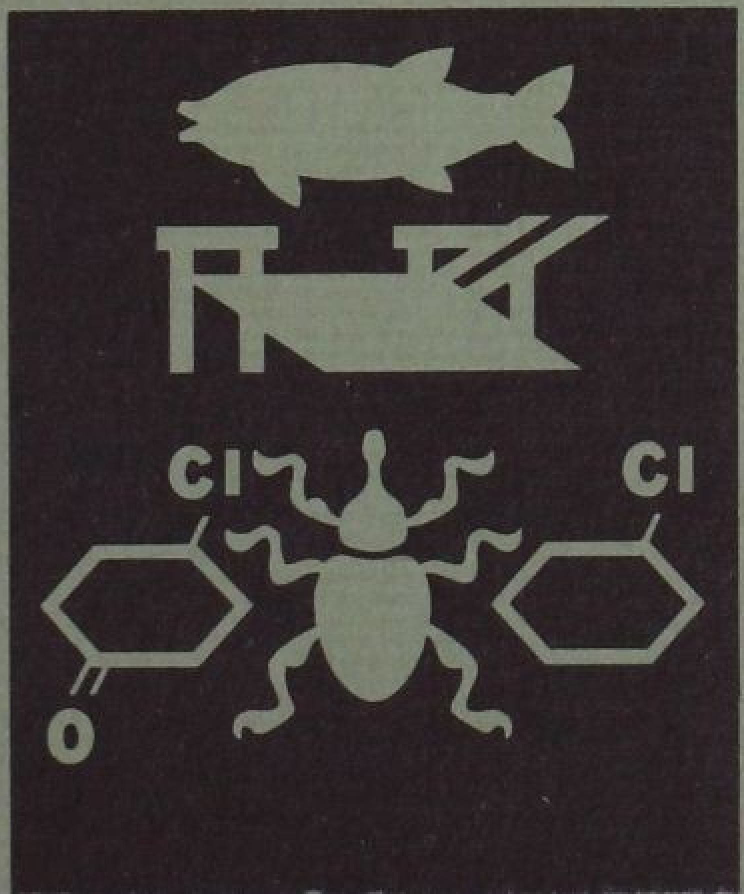
AQUATIC PLANT CONTROL RESEARCH PROGRAM









TECHNICAL REPORT A-79-2

REMOTE SENSING OF AQUATIC PLANTS

By Katherine S. Long

Environmental Laboratory
U. S. Army Engineer Waterways Experiment Station
P. O. Box 631, Vicksburg, Miss. 39180

October 1979

Final Report

Approved For Public Release; Distribution Unlimited

Prepared for Office, Chief of Engineers, U. S. Army
Washington, D. C. 20314

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE (*When Data Entered*)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Technical Report A-79-2	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (*and Subtitle*) REMOTE SENSING OF AQUATIC PLANTS		5. TYPE OF REPORT & PERIOD COVERED Final report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(*s*) Katherine S. Long		8. CONTRACT OR GRANT NUMBER(*s*)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U. S. Army Engineer Waterways Experiment Station Environmental Laboratory P. O. Box 631, Vicksburg, Miss. 39180		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Office, Chief of Engineers, U. S. Army Washington, D. C. 20314		12. REPORT DATE October 1979
		13. NUMBER OF PAGES 98
14. MONITORING AGENCY NAME & ADDRESS(*if different from Controlling Office*)		15. SECURITY CLASS. (*of this report*) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (*of this Report*)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (*of the abstract entered in Block 20, if different from Report*)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (*Continue on reverse side if necessary and identify by block number*)

Aquatic plants
Computerized simulation
Infrared photography
Landsat (Satellite)
Radar
Remote sensing

20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

This report summarizes a 3-year effort in evaluating the various available remote sensing methods for identification and assessment of expanses of aquatic plants. Both materials and techniques are examined for cost effectiveness and capability to sense aquatic plants on both the local and regional scales. Computer simulation of photographic responses was employed; Landsat, high-altitude photography, side-looking airborne radar, and low-altitude

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20. ABSTRACT (Continued).

photography were examined to determine the capabilities of each for identifying and assessing aquatic plants.

Results of the study revealed Landsat to be the most cost effective for regional surveys, although its coarse resolution would be limiting in some cases. High-quality, high-altitude false-color infrared film showed great potential for species identification. Model studies borne out by field demonstrations showed black-and-white infrared photography to have a strong potential for discriminating infested from uninfested areas, with less associated cost than when false-color infrared is used. False-color infrared does show the greatest potential for discriminating among species.

Ground-truth information concerning a specific area aids materially in the mapping. Examples of photographs, maps, and cost analyses of two demonstration projects conducted at Lake Marion, South Carolina, and Lake Seminole, Florida, are included.

PREFACE

The study presented herein was sponsored by the Aquatic Plant Control Research Program of the Civil Works Directorate of the Office, Chief of Engineers (OCE). Funds for the study were provided by the Directorate of Civil Works, OCE, Department of the Army Appropriation No. 96X3122 Construction General.

This report was prepared by Mrs. Katherine S. Long, Environmental Research Branch (ERB), Environmental Systems Division (ESD), Mobility and Environmental Systems Laboratory (MESL), U. S. Army Engineer Waterways Experiment Station (WES), from data collected by WES field teams at Lake Boeuf and Lake Theriot, Louisiana; Ross Barnett Reservoir, Mississippi; Lake Marion, South Carolina; and Lake Seminole, Florida, from September 1975 through September 1977. High-altitude photography, satellite images, and computer-compatible magnetic tapes were purchased from Earth Resources Observation Systems, Sioux Falls, South Dakota. Dr. L. E. Link, Chief, ERB, and Mrs. Long formulated the field data collection methods concerning low-altitude photography and ground-truth. Lending logistical support for the demonstration exercises were Mr. Howard Roach of Santee-Cooper Authority, Moncks Corner, South Carolina, and Messrs. Angus Gholson and Joseph Kight, U. S. Army Engineer District, Mobile. Mrs. Long was responsible for reduction and analysis of the data, and Mr. Carlos Lebron-Rodriguez, ERB, interpreted the photographs and drew the maps. Mr. Albert N. Williamson, Data Handling Branch, Mobility Systems Division, MESL, performed the digital processing of the Rodman Reservoir Landsat images. Aerial photography for the demonstration exercises was flown by the Georgia Air National Guard at Dobbins Air Force Base, Marietta, Georgia, and by the 363d Tactical Reconnaissance Wing, Shaw Air Force Base, South Carolina. Side-looking radar coverage was also flown by Shaw Air Force Base personnel.

All phases of this study were conducted under the general supervision of Messrs. W. G. Shockley, Chief, MESL, and Mr. B. O. Benn, Chief, ESD, and under the direct supervision of Dr. Link. The ERB and the ESD are now part of the newly organized WES Environmental Laboratory of which Dr. John Harrison is Chief.

The Directors of WES during the collection of data and preparation of this report were COL G. H. Hilt, CE, and COL J. L. Cannon, CE. Technical Director was Mr. F. R. Brown.

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
inches	2.54	centimetres
feet	0.3048	metres
miles (U. S. statute)	1.609344	kilometres
square miles (U. S. statute)	2.589988	square kilometres .

REMOTE SENSING OF AQUATIC PLANTS

PART I: INTRODUCTION

Background

1. The efficient control of aquatic plants depends to a large degree on the controller's ability to assess rapidly both the areal extent and species composition of the plants. Decisions concerning the type of control measure to be applied, the magnitude of the application, and the location for application require this information. Currently, no adequate means exist at the operational level for rapidly determining the position, extent, and character of aquatic plant infestations over large areas. In addition, determination of the dynamic character of aquatic plant communities requires the ability to examine large areas repetitively, both to identify areas where rapid growth is occurring and to monitor the effectiveness of ongoing control measures.

2. An important goal of the U. S. Army Engineer Waterways Experiment Station (WES) research efforts in aquatic plant control is the development of an operational capability for mapping the distribution and character of aquatic plants with emphasis on ease of control application, rapid execution, and use of available remote sensor systems and technology. The final product of the study goal will be guidelines for using remote sensors for rapidly extracting and portraying information on aquatic plants.

3. Personnel of Corps Districts and Divisions and WES met at WES in September 1975 to discuss the informational needs of Corps personnel actively engaged in aquatic plant control at the District level. The findings of this meeting are summarized as follows:

- _a_. The types of information desired would optimally be the areal distribution of the various aquatic plant species and a quantitative categorization of their biomass. If neither species nor biomass could be determined, information concerning the areal distribution of emergent and submersed aquatic plants (without species determination) would be useful for planning control measures.

b. The specific plant species of interest include hydrilla (*Hydrilla verticillata* Royle), Eurasian watermilfoil (*Myriophyllum spicatum* L.), Brazilian elodea (*Egeria densa* Planch.), waterlettuce (*Pistia stratiotes* L.), waterhyacinth (*Eichhornia crassipes* (Mart.) Solms.), duckweed (Lemna sp.), waterchestnut (*Trapa natans* L.), and alligatorweed (*Alternanthera philoxeroides* Griseb.).

c. Two scales of information are desired: a regional picture of the distribution and areal extent of aquatic plants for yearly budget planning and analysis, and more frequent detailed information for planning control operations and examining the effectiveness of control measures.

4. Acquisition of the data outlined above requires the ability to: (a) differentiate aquatic plants from their common surrounds, such as water or terrestrial plants, (b) differentiate the various aquatic plant species from one another, and (c) differentiate, for a given species, variations in plant biomass. Obviously, each successive differentiation is more difficult, especially for submersed aquatic plant species. It is also pertinent that these differentiations be made by Corps District personnel in the shortest amount of time and at the lowest possible cost.

5. In view of the above requirements, it is useful to examine the specific properties of remote sensor imagery that allow an investigator to extract information from an image. The informational content of a remote image results from a number of complex and many-faceted interactions. The final controlling factors are the electromagnetic (EM) radiation reaching the sensor system and the sensor system itself. The EM radiation reaching the sensor is the product of a continuous interaction of EM radiation and matter. For example, the sun is the primary source of the EM radiation that eventually exposes the film in an aerial camera. Before impinging on the film, however, the EM radiation from the sun is attenuated by the atmosphere, reflected from complex terrain surfaces, attenuated a second time by the atmosphere, and transmitted through the optical system of the camera. The EM radiation reaching the remote sensor can be detected with a variety of sensor types, each

having unique spectral and spatial sensitivity characteristics. Each of these interactions is complex, and all vary as a function of wavelength.

6. The design of a mission for acquisition of specific types of data necessitates a comprehensive understanding of these interactions, both individually and collectively. Mission design (i.e., specification of the film, filter, altitude, time of day, etc.) has historically relied on a subjective understanding of the interactions previously mentioned. However, an increased awareness of the environment and the need for more quantitative management practices have created a corresponding need for more diverse and quantitative environmental data. Planning remote sensing missions for the acquisition of these data demands a rational, quantitative means for planning the remote sensing mission profile (i.e., it is necessary to fit the system characteristics to the specific data acquisition problem at hand).

7. In response to this need, a methodology for the systematic application of photographic remote sensing techniques to specific problems was developed.[1] The methodology consists of six steps as follows:

a. Problem specification: What problem needs to be solved, what are the specific kinds of information necessary to solve it, and can a remote sensing system be used to obtain any or all of the needed information?

b. Ground control data acquisition and planning remote sensing missions: What types of ground control data are necessary to plan the remote sensing mission, what is the best sensor system to use, and what are pertinent mission profile parameters?

c. Data acquisition: Actual process of collecting ground control data and remote sensing imagery. This step may interact periodically with step b.

d. Data transformation: Putting the data obtained by the remote sensing system into a form suitable for analysis or interpretation.

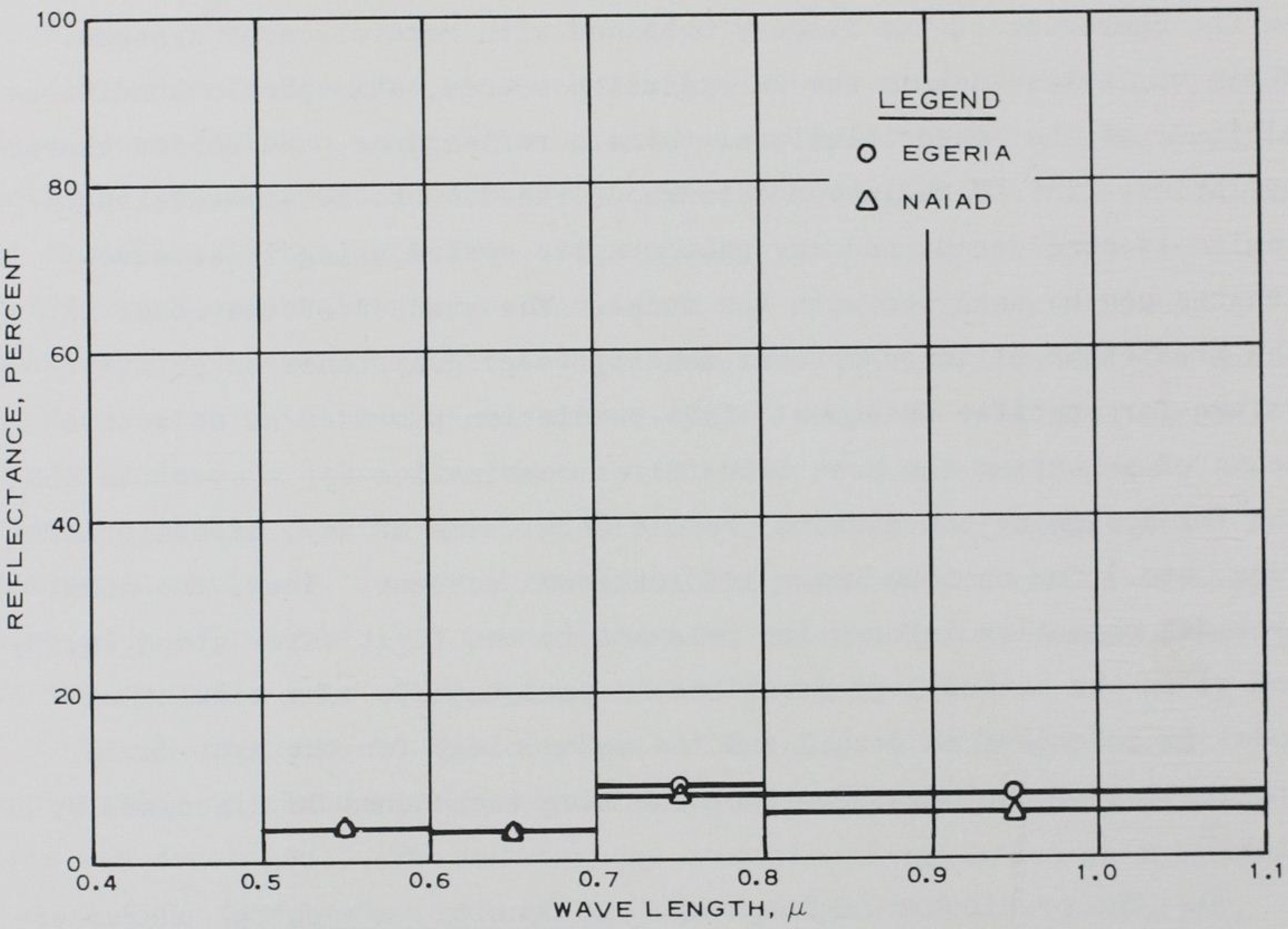
e. Information extraction: Performing the analysis or interpretation to obtain the needed data from the product of the remote sensing system.

f. Information presentation: Putting the extracted data into a form in which it can be used to assist in solving the problem at hand.

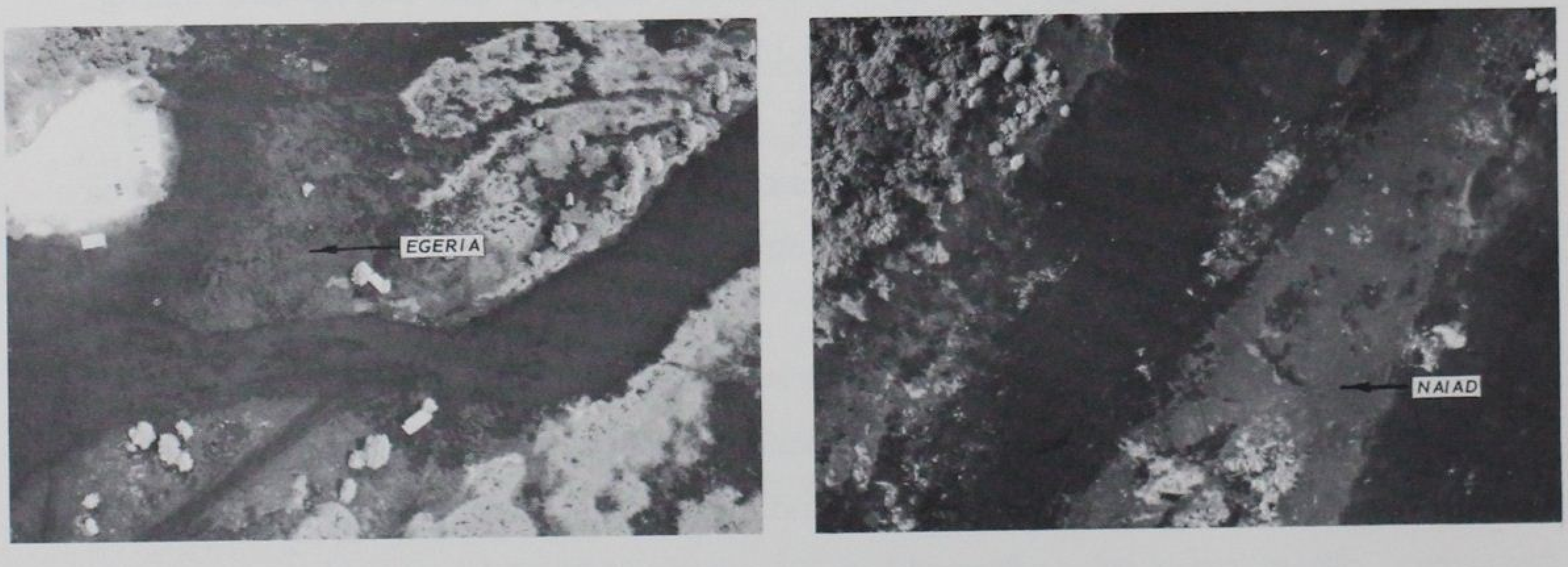
8. A computerized simulation model[1] has been developed at WES that makes possible the evaluation of the impacts of the major variables on the character of the imagery obtained with remote sensor systems. These variables include the EM radiation source, atmospheric conditions, altitude of the sensor platform, terrain reflectance, and sensor characteristics. The EM radiation throughout the 0.4- to 1.0-μm-wavelength region is considered, and any photographic system using these wavelengths can be analyzed with the model. The product of the model is the prediction of image optical density (e.g. gray tones on prints) values for specific features. This prediction provides an objective means of selecting the best film-filter combination for a specific job and for designing the mission profile (e.g. time of day, aircraft altitude, etc.) for optimum image informational content. Thus, the model provides objective information relevant to the first three steps (a, b, and c) in the methodology described in paragraph 7. The simulation model is described in detail and the methodology for the systematic application of photographic remote sensing techniques is discussed by Link.[2]

9. The prediction of image optical density, a spectral characteristic, provided by the model is but one of three types of information that are present on a given remote sensor image, the other two being pattern and association information (Figures 1 and 2). These other characteristics of an image are best described by example, and they draw more heavily on the skill and experience of an interpreter. For this reason the detection of these characteristics in an automated manner is not yet possible.

10. Pattern properties concern regular or irregular groupings of image tones (or colors) or simply tonal "patterns." Tonal patterns are a function of spectral properties and spatial characteristics of the feature. This type of information is exemplified by a comparison of egeria and naiad (Figure 1). Measurement of the spectral properties (reflectance) of each (Figure 1a) and inputting these properties to the optical density contrast prediction model reveals no appreciable difference between them at certain seasons and growth stages. However, upon



a. Measured spectral reflectance



b. Aerial photos of egeria and naiad

Figure 1. Comparison of egeria and naiad of
Lake Marion, South Carolina

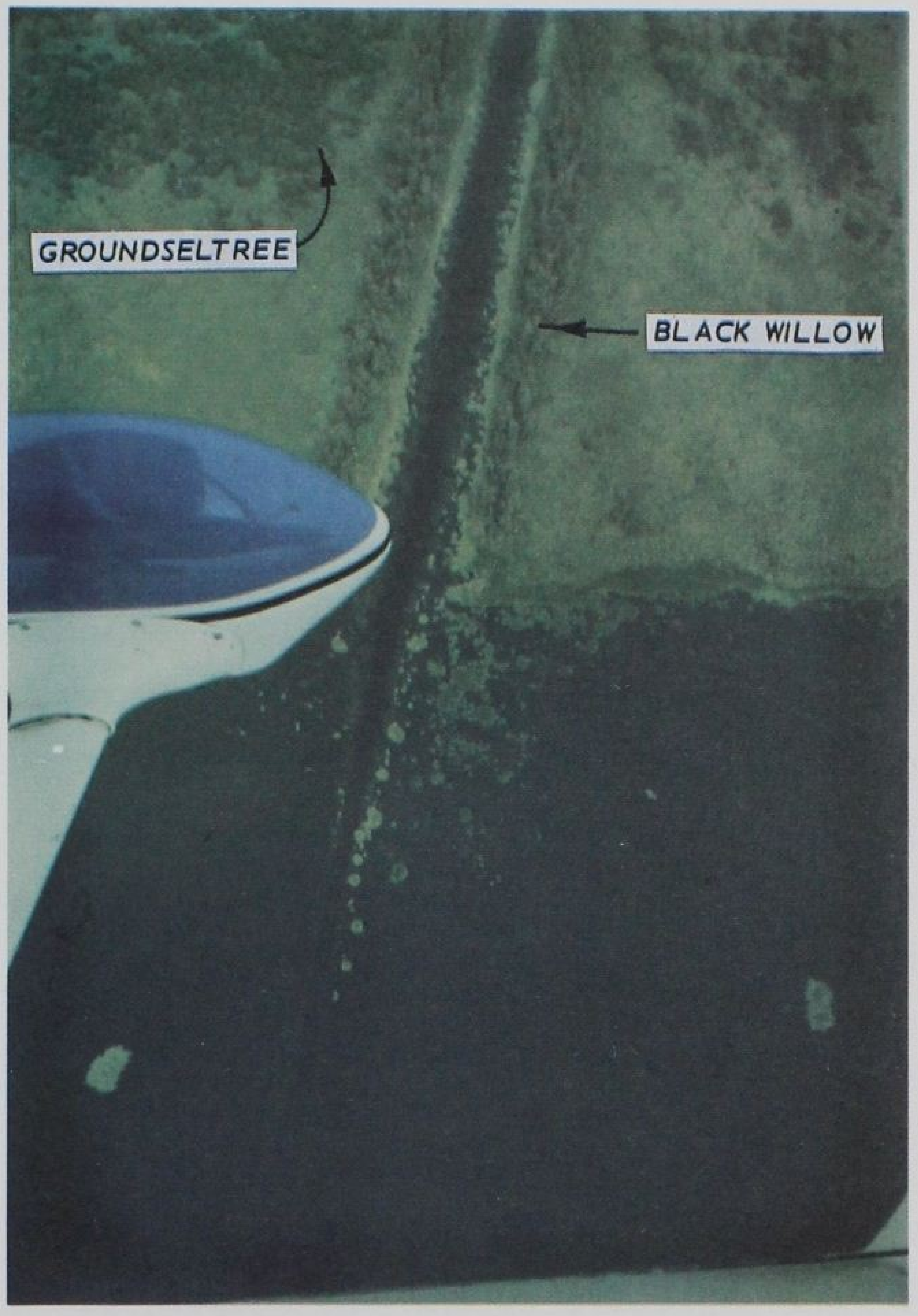


Figure 2. Demonstration of association cues used in species identification

examination of low-altitude photographs (Figure 1b) on which they appear, the difference is readily discernible, although the color (or tone) may be essentially the same for both. The reason they can be readily differentiated is that the naiad has a smooth, continuous texture, almost like a "skim" over the surface of the water, whereas the egeria grows in somewhat broken, mottled clumps imparting a coarse granularity to large-scale photographs.

11. Association provides significant amounts of information for the person doing the interpreting. An interpreter who knows an area and the plants in it well enough can determine the difference between them from the fact that one plant grows along the bank and another

occurs further inland, even though their spectral and pattern characteristics may be identical. For example, Figure 2 shows black willow (Salix nigra L.) and groundseltree (Baccharis sp.) in these respective locations. However, exploitation of the association properties is not as straightforward as exploitation of the scene's spectral and pattern properties, because the knowledge and skill of the interpreter influences the quality of the interpretation.

12. For the purposes of developing an easy-to-apply technique for mapping aquatic plants, it would be beneficial if all the desired information could be obtained by spectral properties alone. This would be the simplest procedure and might also allow, to some extent, automation of the information extraction procedure. It was not anticipated, however, that image spectral properties alone would provide all of the desired information previously outlined in paragraph 3. For this reason, the attention of the remote sensing study was given to all three image properties, although emphasis was placed on the spectral content of images.

Objective and Scope

13. The overall objective of the WES Aquatic Plant Control Research Program's (APCRP) remote sensing work is to develop two capabilities: (a) a detailed survey capability to assess the type and extent of aquatic plant infestations at a level that would be meaningful for application or evaluation of control measures, and (b) a reconnaissance technique to rapidly identify potential aquatic plant problems. This report presents a synopsis of the work accomplished to date to meet these overall objectives.

14. Part II of this report describes the investigation of the detailed survey capabilities, including a literature survey and model studies to aid in the selection of the best remote sensor system for imaging aquatic plants. A description of the field studies to further evaluate the candidate systems is included.

15. Part III describes the demonstration of the remote sensor

system selected in Part II applied to two reservoir systems. Maps of the aquatic plant infestations produced from the interpretation of the imagery as well as detailed cost lists are included. A procedure for planning other remote sensing missions for imaging of aquatic plants is presented.

16. Part IV describes the reconnaissance survey capability investigation including a description of the data acquisition and analysis of both photographic and selected nonphotographic remote sensors.

17. Part V of the report presents the conclusions and recommendations for the studies conducted.

PART II: DEVELOPMENT OF DETAILED SURVEY CAPABILITIES

18. Before applying remote sensing techniques to an aquatic plant data acquisition problem, the user must have the capability to determine if the needed information can be acquired by remote sensing and, if so, how to ascertain the best remote sensing system for his purposes. He also has to be able to take into account the critical mission parameters (how to fly, at what time of day or time of year to fly, etc.) that could affect the quality of the resulting remote sensing products. The development of the capability to select the proper remote sensing technique is complicated by the fact that remote sensors vary considerably in the types of information they can provide and the fact that the "signature" reaching the sensors from the target aquatic plants varies as a function of such things as sun angles, plant growth stage, and biomass.

19. Conventional aerial photographic techniques were considered the most widely available and productive means for conducting aquatic plant surveys over individual water bodies. These sensors operate in the "visible" portion of the EM spectrum and record the energy reflected from the surface of features. The resulting photographs are normally the easiest of all of the remote sensing products to interpret because the films used have roughly the same sensitivity as the human eye; therefore, the interpreter can easily relate ground-truth to what he can see on a photograph. For this reason the primary research need of this was to identify those film-filter combinations that would consistently show the maximum contrast between the target aquatic plants and their surrounds. This part of the study involved three phases: a literature survey, a model study, and field studies.

Literature Survey

20. Various workers in remote sensing were contacted to learn the nature and extent of their experiences in identifying and mapping aquatic plants using readily available photographic techniques. A number of persons have been recently and actively engaged in this and similar

pursuits; the nature of their efforts is briefly summarized in Table 1 and in the following paragraphs.

21. Mr. Glen M. Vause, a botanist at the Kennedy Space Center, under contract to the Florida Department of National Resources, has conducted a study to sense remotely the effects of the white amur in four small ponds in Florida.[3] He used aerial color film at a scale of 1:2000 to photograph the ponds at seasonal intervals. The images were adapted for manipulation on the GE-100, where four channels (bands of the EM spectrum) were used in the analysis. Ground-truth data gathering was performed at the time the images were taken and included such parameters as spectral signatures and species identification. The results seemed to indicate that color photography works as well as false-color infrared (CIR), at least at low altitude, for sensing submersed aquatics. Hydrilla was found to be indistinguishable from egeria. The remote sensing analysis was about 85 percent accurate compared to field surveys using standard transect methods of quantifying vegetation.

22. Dr. Arthur R. Benton, Research Coordinator for the Environmental Monitoring Laboratories, Remote Sensing Center, Texas A&M University, has recently completed an analysis of the hydrilla infestation in Lake Livingston, Texas, under a National Aeronautics and Space Administration (NASA) grant.[4] For the aquatic plant work, he used a 70-mm Hasselblad camera system with CIR film. This work was continued in 1975 and 1976 with the Texas Water Quality Board and the U. S. Army Engineer District, Fort Worth. Benton is currently working under a directed subcontract for Stephen F. Austin University, continuing the study of Lake Livingston. Besides hydrilla, the most significant water weed in the lake, there exist great quantities of coontail (_Ceratophyllum demersum_ L.), pondweed (_Potamogeton_ sp.), and waterhyacinth. In his analysis, Dr. Benton has used image scales ranging from 1:7500 to 1:40,000. The Texas A&M Remote Sensing Center has also been involved in studying the Texas estuaries, Matogorda Bay, San Antonio Bay, and Corpus Christi Bay, using an RC-9 camera to map submersed and emergent plants in the areas of interest.

23. Dr. T. D. Gustafson and M. S. Adams, of the Department of

Botany at the University of Wisconsin, used an aerial 35-mm system (scales of 1:17,000 and 1:34,000) to obtain color and CIR imagery of submersed aquatics in Lake Wingra, Wisconsin, specifically Eurasian watermilfoil. Oedogonium sp., a mat-forming green alga was measured as well.[5] When the plant density obtained from harvest sampling was compared with the imagery, high correlations ($r > 0.80$) were achieved. Density of the photographs was measured using a microdensitometer. The method of photographic standardization found most satisfactory was using a ratio of open-water film density to plant community film density, rather than using reflectance panels on the water surface or density readings from several wavelengths within the plant community. Estimates of aquatic plant density by photographic methods could be accomplished in 6 percent of the time required by conventional methods.

24. Dr. M. P. Meyer of the University of Minnesota tested various film and filter combinations and variations in shutter speed, sun angle, lens focal length, photo scale, vegetation stage, surface wind, and water turbidity to learn the optimum conditions for photographing submersed and emergent vegetation in ponds being studied for their potential as waterfowl habitat.[6] Ektachrome infrared with a Wratten 12 (minus blue) filter was found to be the best film-filter combination for mapping aquatic vegetation. It provided a more visible waterline and better distinction between emergents and submergents. A high sun angle (± 1-1/2 hr of local noon) was found to be undesirable because lack of shadows made scale markers difficult to discern; moreover, water penetration was possible with a low sun angle even with some surface ripples present. Low sun angle was found to accentuate important features; for example, plant height above water and plant shape could be inferred from shadows. These characteristics aided significantly in the identification of plants.

25. Another effort regarding photointerpretation of aquatic plants was reported in March 1977 at the 43rd Annual Meeting of the American Society of Photogrammetry by Markham, Philipson, and Russell of Cornell University.[7] They reported on work in which large-scale, multiyear, color and CIR aerial photographs were used to evaluate changes in

vegetation that have accompanied a reduction in phosphorous input to a lake in New York State. They found that floating vegetation could be distinguished with little or no ground data, but that various submersed types were generally not separable.

26. In summary, previous studies have shown that medium- and low-altitude aerial photography can be used successfully to differentiate among certain aquatic plants, both submersed and emergent, as shown in Table 1. The consensus of previous research indicates vertical sun angle is not desirable, but rather midmorning or midafternoon conditions are preferred to reduce glare and glitter. Moreover, lower sun angles yield shadows that can accentuate emergent plants and aid in their location and identification. For plant identification, the films of choice in the reviewed studies are color and CIR flown at a time of the year when plants are mature. As the turbidity of the water increases, the ability to detect submersed aquatic plants significantly decreases.

27. The results of the studies reviewed and summarized in Table 1 suggested that the objectives of this study were attainable; however, additional information was required to plan missions to image specific aquatic plant infestations in specific locations. The model studies were conducted to gain more definitive information on those film-filter combinations that would best image the identified noxious aquatic macrophytes.

Model Study

28. Since evaluation of the many available film-filter combinations for acquiring information on the multitude of possible aquatic plant associations would be totally impractical from literature and field studies, the simulation model (paragraph 8) was used to screen the film-filter combinations and to pick those having the most potential for detecting aquatic plant infestations from their respective backgrounds and for discriminating among the aquatic plant species of interest. The objective of the model studies was to make an initial

assessment of the ability of available photographic film-filter combinations for discriminating (a) areas with submersed aquatic plant infestations from areas with no submersed aquatic plants, (b) areas with emergent aquatic plants from surrounding water, (c) specific submersed aquatic plant species from one another, (d) specific emergent aquatic plant species from one another, and (e) submersed from emergent plant species.

29. The basic scheme employed in the use of the model is as follows: (a) the spectral reflectance characteristics of a selected noxious aquatic plant and its surrounds are input to the program; (b) geographic location, atmospheric conditions, sensor altitude, and sun angle are selected from options of conditions available; and (c) the model is run. The output of the computer program is a table giving predicted optical density contrast values for the feature and background and for each film-filter combination selected. The films and filters* used in the model study are:

Films:

_a_. 2402 - panchromatic
_b_. 2403 - panchromatic
_c_. 2448 - color
_d_. 2443 - CIR
_e_. 2424 - black-and-white infrared (IR)

Filters:

_a_. Wratten No. 12 - yellow
_b_. Wratten No. 45B - deep blue tricolor
_c_. Wratten No. 58 - green tricolor
_d_. Wratten No. 25A - red
_e_. Wratten No. 3 - light yellow ("haze")
_f_. Wratten No. 87C - visibly opaque
_g_. Wratten No. 89B - visibly opaque

An example of the model output is presented as Figure 3. The rightmost

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* All designators of films and filters are those of the Eastman Kodak Company.

Film	Filter	Optical Density Contrast	
2402 Plus-X Panchromatic	12 Yellow	0.017221	
2403 Tri-X Panchromatic	12	0.013127	
2402	47B Blue	0.178659	
2403	47B	0.164144	
2402	58 Green	0.079427	
2403	58	0.079427	
2402	25A Red	0.032514	
2403	25A	0.014665	
2402	3 Haze	0.063758	
2403	3	0.043076	
2448C Color*	3	0.000578	0.37**
2448Y	3	0.270419	
2448M	3	0.104692	
2443C CIR*	3	0.069592	0.20**
2443Y	3	0.117260	
2443M	3	0.010083	
2443C	12	0.146050	0.21**
2443Y	12	0.067922	
2443M	12	0.004641	
2424 Black-and-white IR	12	0.194452	
2424	25A	0.202076	
2424	87C IR	0.173644	
2424	87B IR	0.213561	

LEGEND

Feature: waterhyacinth, Black Creek, Florida
Background: spatterdock, Black Creek, Florida
Atmosphere: midlatitude, summer, haze: 23 km
Zenith angle: 30 deg
Distance to sensor: 1.50 km

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* C, Y, and M represent the cyan, yellow, and magenta emulsions, respectively, for multiple-emulsion color and CIR film.

** Sum of predicted optical density contrasts for the three emulsions.

Figure 3. Example of sensor model output

column gives the contrast to be expected for the given feature and background from each film-filter combination listed. For single-emulsion films (e.g., film Nos. 2402, 2403, and 2424) the numerical value of the contrast must exceed 0.30 in order for the contrast to be readily detected by the human eye. The model considers each emulsion of multiemulsion films (e.g., Nos. 2448 and 2443) individually. Therefore, the model output includes a contrast value for the cyan (C), yellow (Y), and magenta (M) emulsions of such films. The optical density values for individual emulsions do not give a true measure of the total contrast that occurs on these films for a feature and background. Thus, some combination of values is necessary. For this study, a simple sum of the three (for the three emulsions) to predict optical density values was considered as an approximate value for the total optical density contrast that would occur for the multiemulsion films. The sum of the predicted contrast values was compared with the 0.30 threshold previously mentioned to assess the ability of multiemulsion films to discriminate specific feature-background combinations.

Model inputs

30. Conditions selected for use in the model studies were as follows: geographic location, temperature zone; atmospheric conditions, clear summer day; sun angle, 30 deg from zenith; sensor altitude, 1500 m. Spectral reflectance data of common aquatic plant species and water bodies were obtained in selected locations in New York, Florida, Louisiana, and Texas during the late summer of 1975. Additional data were obtained in Louisiana, South Carolina, Mississippi, and Florida in 1976 and 1977. Figure 4 presents a plot of the reflectance values acquired for spatterdock and waterhyacinth such as would be used as input to the model. A list of those aquatic plant species for which reflectance data have been collected is given as Table 2. The data collected are summarized in Tables 3 and 4. The equipment and techniques used to collect the data are discussed in the following paragraphs.

Data acquisition techniques

31. Spectral reflectance measurements were made from boats using an ISCO spectral radiometer or an ERTS (EXOTECH Model 100) radiometer.

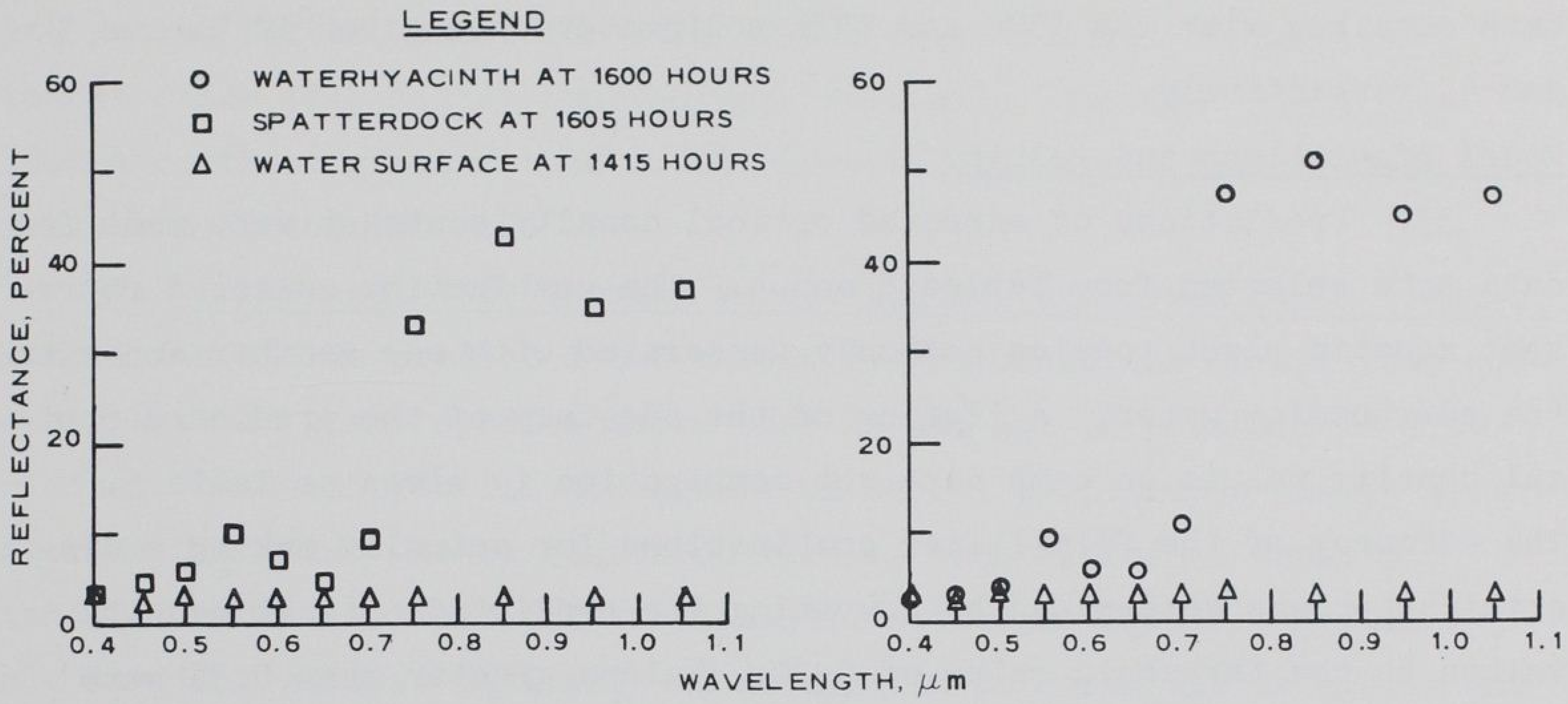

Figure 4. Reflectance of spatterdock and waterhyacinth

The principal difference between the data provided by each of the instruments was that the ISCO measured reflectance from 11 discrete wavelengths ranging from 0.4 to 1.1 μm. In order to determine total reflectance, the radiometers were calibrated at each wavelength or wavelength band for each reading with Kodak Test Cards. The gray side of these cards provides an estimate of total incident energy because it reflects a constant amount (18 percent) of radiant energy received. Percent reflectance by a target (plant, water, etc.) was computed using the following formula:

$$\frac{\text{Percent energy reflected}}{\text{by target}} = \frac{\text{Radiometer reading for target} \times 0.18}{\text{Radiometer reading for gray card}}$$

32. Specifically, the spectral reflectance of an object was determined as follows. The radiometer was set at the desired wavelength band. A gray card reading and a target reading were recorded along with the data and time of day. This process was repeated for each band and each target. Later, the above formula was used to calculate percent reflectance using appropriate gain corrections, the form required as input to the prediction model. Summaries of the measured reflectance

data obtained with the ISCO and ERTS rediometers are given in Tables 3 and 4, respectively.

Model predictions and results

33. Predictions of expected optical density contrast were made for data sets selected from Tables 3 and 4. The combination selected represent aquatic plant species commonly associated with one another and with the surrounding water. A listing of the adequacy of the predicted optical density values on each data set combination is given as Table 5. The adequacy of the film-filter combinations for actually making a discrimination was determined by comparing the predicted optical density values to the threshold value of 0.30. Values greater than 0.35 were judged to indicate that a tonal discrimination was likely with the unaided eye ("X" on Table 5), values between 0.30 and 0.35 were judged to indicate that discrimination capability was marginal ("M" on Table 5), and values below 0.30 were judged to indicate that discrimination was not probable ("0" on Table 5).

34. Table 6 generalizes those combinations that should be strongly discriminated with at least one of the film-filter combinations considered, those combinations where discrimination is problematic, and those combinations where discrimination is not possible.

35. Submersed plant species versus water. Examination of the predicted optical density values for water bodies (for relatively clear water conditions) and specific submersed aquatic plant species shows that species such as hydrilla, egeria, and coontail can usually be discriminated from areas of water not occupied by submersed plants. The best film-filter combinations were color with "haze" filter and CIR film with a yellow filter. The predicted optical density contrast (ODC) values were, for the most part, well above the 0.30 threshold previously mentioned.

36. Emergent plant species versus water. Examination of the predicted ODC values for water bodies and specific emergent aquatic plant species such as waterhyacinth, pickerelweed, and frogbit [Limnobium Spongia (Boxc.) Steud.] can be easily discriminated from water bodies using black-and-white IR film with yellow, red, or IR filters, CIR film

with yellow filter, and color film with a haze filter. In some instances other film-filter combinations were also adequate (i.e., provided a contrast greater than 0.30); however, the above combinations were the most consistent.

37. Submersed plant species versus another submersed plant species. Examination of the predicted ODC values for combinations of specific submersed aquatic plant species shows that it may not be possible to discriminate between hydrilla and egeria on aerial photographs except with color or CIR film. Added confusion results when different density stands of hydrilla yield different tones on the photograph. Similarly, only marginal success is likely in attempting to discriminate egeria and naiad. The highest rate of success in obtaining detectable contrast between two submersed aquatic plants was predicted when using color and CIR film. Marginal success was predicted in some instances with black-and-white IR film.

38. Emergent plant species versus another emergent plant species. Examination of the predicted ODC values between specific emergent (or floating) aquatic plant species shows that in some instances, e.g. waterlettuce and *Salvinia*, duckweed and American lotus [*Nelumbo lutea* (Willd.) Pers.], there was not sufficient ODC to allow visual discrimination on aerial photography with any of the film-filter combinations tested in the model. On the other hand, the predicted ODC values for combinations of other plant species tested indicated they could be discriminated from each other with at least one of the film-filter combinations tested. Success was highest overall with CIR with No. 12 (yellow) filter, followed closely by color film, as shown in the overall success rate in Table 5, sheet 7.

39. Emergent plant species versus submersed plant species. In contrasting emergent and submersed plants, the film-filter combination yielding adequate results for most of the comparisons tested by the model was CIR. Color and black-and-white IR also were predicted to yield detectable contrasts in eight of the ten comparisons made.

40. The results of the model studies suggest that in almost all instances (in clear water conditions), it appears feasible to detect

the presence of most submersed and emergent aquatic plant infestations with readily available film-filter combinations. In some instances, certain species do not create an ODC of sufficient magnitude to allow discrimination of one species from another. However, there are also instances when available film-filter combinations are shown to be quite capable of allowing discrimination among certain aquatic plant species, especially emergent or floating ones. The film-filter combinations that most consistently had the highest predicted ODC values above the 0.30 threshold were CIR film with a yellow (No. 12) filter, color film with a haze (No. 3) filter, and black-and-white IR film with a yellow (No. 12) or red (No. 25A) filter (Table 5). As such, these film-filter combinations were those used for further evaluation in the field tests discussed in the next section.

41. The model studies, while giving valuable additional information concerning the film-filter combinations most likely to yield satisfactory results, could not, in the present configuration of the model, accommodate certain variables peculiar to photographing water bodies. For example, it can be expected that surface waves could cause reflection phenomena that could obscure the very plant targets one wished to image. Another obvious variable was the obfuscation properties of turbid water. How did this influence the sensor's ability to see subsurface aquatic macrophytes? Moreover, did the presence of aquatic macrophytes influence the character of the water above them in a way that could be detected on a photograph, thus giving an interpreter information with which he could infer their presence without actually seeing them on the image?

42. To gain additional confirmation of model predictions, field studies were conducted in which aquatic plant infestations were photographed using some of the more promising film-filter combinations tested in the model.

Field Studies

43. According to model results, many plants can be distinguished from one another purely on the basis of tone. Floating-leaved and

emergent plants would be recognizable from the imagery, given a moderate quantity of current ground-truth information. Submersed plants are, however, more difficult to distinguish from each other. The light incident on a plant leaf is reflected mainly by hydrated cell walls intersecting with intercellular air spaces. Also, contributing to a much lesser degree are the discontinuities among cellular constituents. Variations in the spectral reflectance of a leaf are influenced by several factors, among them stress, maturity, and leaf mesophyll arrangement. The variations in IR reflectance resulting from those factors can be attributed to the physical structure in the leaf, namely, changes in the cell wall-air space interface.[8-12] The expected spectral response of plants in an aquatic habitat is determined by the basic structural arrangement of the leaf constituents. It is generally agreed that aquatic vascular plants (algae, bacteria, and molds excluded) are land plants modified with structural and functional adaptations suiting them for the aquatic environment with one of the most important adaptive trends being a reduction in the vascular system.[13] Thus, it follows that the similarity in structure among various species of submersed plants renders respective reflectance values virtually identical in most of the submersed species. Spectral reflectance measurements of the species differ from each other very little even when they are removed from the water and spectral reflectance is measured without many of the variables introduced by the water (turbidity, glare, absorption, etc.). When reflectance of the plants is measured in situ (i.e. underwater), the minor differences in reflection between corresponding wavelengths are all but eliminated.

44. What these observations suggest is that tone produced on an image by the reflection of a given submersed aquatic plant species will possibly not be sufficient to distinguish it from another submersed plant species; further data are needed. Thus, growth patterns of specific plants may provide a far more reliable clue to the identity of a plant than mere color or tone.

45. Also, it is pertinent to note at this point that the ability to discriminate different plant species based purely on image tone does

not necessarily imply the ability to identify a specific plant species without some additional information, such as prior knowledge of possible species for a given water body or growth patterns of a particular plant. Clearly, attributes of plants other than spectral properties must be considered: namely, pattern and associative properties. These properties are more difficult to quantify than spectral properties since they are more a subjective impression than an easily measurable entity.

46. Because of the limitation of the literature and model studies, field studies were conducted to examine and evaluate further the film-filter combinations selected in model studies to have the most potential for detailed mapping of the type and extent of aquatic plant infestations. The object was to determine the film-filter combinations that could be recommended for operational use and to develop insight and information useful to the establishment of additional guidance that would be pertinent for the effective application of remote sensing to the field study of aquatic plants by Corps District personnel.

Conduct of field studies

47. Film-filter combinations. The field studies consisted of acquiring ground-truth data and aerial photographs at selected locations in Lake Boeuf, Louisiana; Lake Theriot, Louisiana; Ross Barnett Reservoir, Mississippi; and Lake Marion, South Carolina. The ground-truth data activity consisted of noting the location of selected plant species populations at a sufficient number of locations in each water body to permit the evaluation of how well each film-filter combination could discriminate between the target species and its surrounds. In this test series the aerial photographs were taken from a light aircraft using a 70-mm Hasselblad and/or a 35-mm Alpa camera. The specific film-filter combinations used at each study area are given in Table 7. The primary film-filter combinations used included those recommended by the model studies, i.e., CIR film with a yellow filter, color film with a haze filter, and black-and-white IR film with a yellow or red filter. Additional filters were used to provide a basis for comparison of the test results. Further, a polarizing filter was used to help eliminate the interference of glare from the water surface.

48. *Description of test sites.* Four water bodies were selected for conducting the field tests. The water bodies were selected to provide a variety of sizes and a variety of aquatic plant types and associations. The water bodies and some of their characteristics are listed in Table 8. A brief discussion of each follows.

49. Lake Boeuf, a shallow rounded lake, is located in the marsh country of Lafourche Parish in southern Louisiana, in the Atchafalaya-Mississippi floodplain (Figure 5). Personnel of the Louisiana Wildlife and Fisheries (LWF) conducted a study of Lake Boeuf in July 1974 and found egeria infesting 90 percent of the lake's area. Other submersed aquatics found in significant proportions were coontail, pondweeds, and Southern naiad [*Najas guadalupensis* (Spreng.) Magnus]. Waterhyacinth and waterlily (*Nymphaea odorata* Ait. and *Nuphar* sp.) were the principal floating-leaved plants. American lotus [*Nelumbo lutea* (Willd.) pers.] was abundant in certain locations. On higher ground, assemblages consisting of black willow (*Salix nigra* L.), groundseltree (*Baccharis* sp.), and red maple (*Acer rubrum* L.) dominated. Lake Boeuf is used by the oil and gas companies for maintenance activities related to their well and

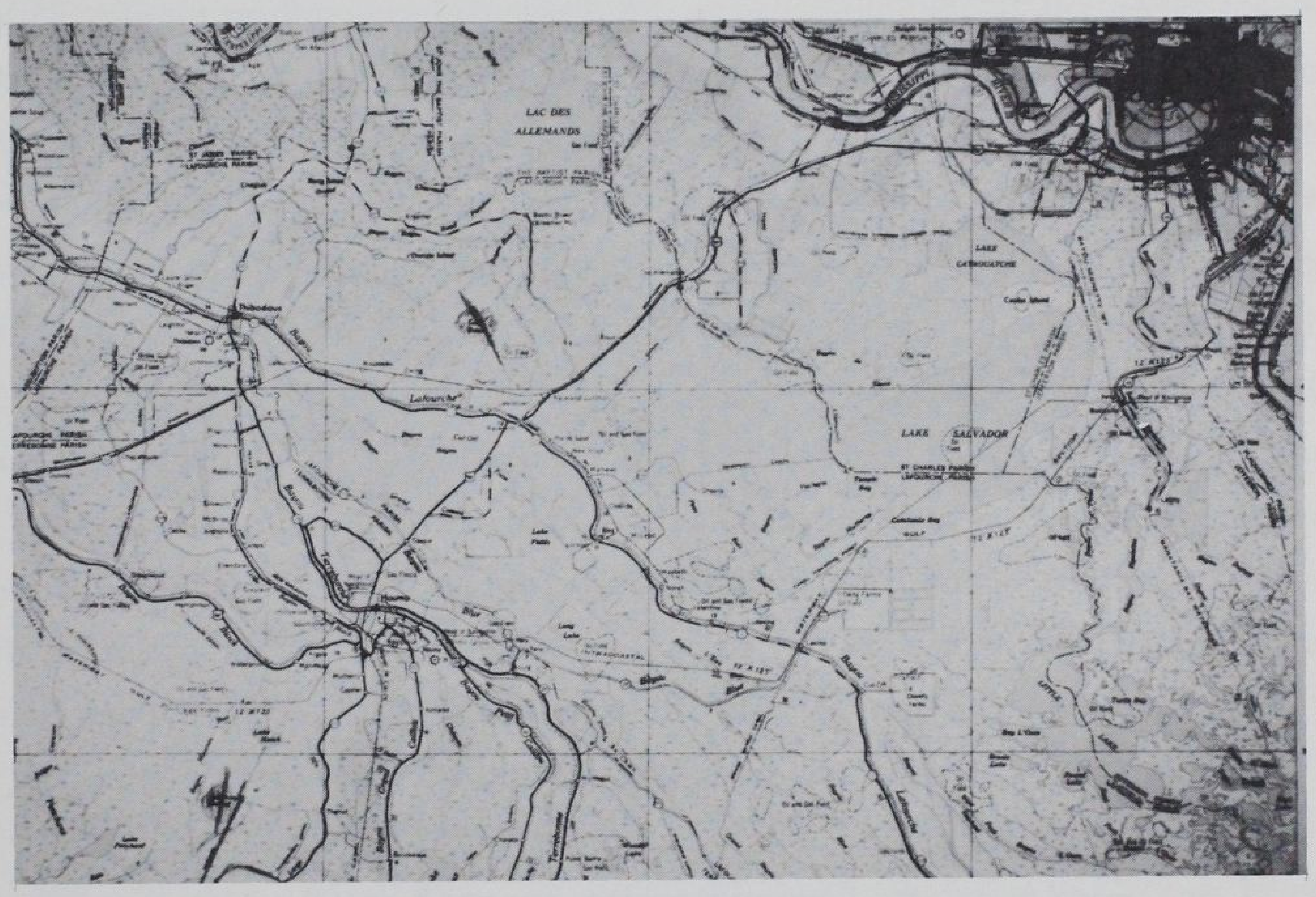

Figure 5. Location map showing Lake Boeuf and Lake Theriot

by hunters and fishermen as a popular local recreation resource. Thus, slowing the aging of Lake Boeuf would yield certain economic and recreational benefits. The New Orleans District had supervised certain control efforts including an extensive 2,4-D spraying program and the experimental application of dequat to small areas. The lake is usually quite calm though boat traffic does disturb the surface occasionally, affecting drifts of floating plants.

50. Lake Theriot is situated southwest of Lake Boeuf in the coastal marshes of Louisiana, north of Lake DeCade and Marmande Ridge, and just south of the Intracoastal Waterway (see Figure 5). The water in the lake is normally fresh, but in years of low rainfall can become slightly saline because of coastal water intrusion. For the past several years (until 1976) the dominant submersed aquatic macrophyte was Eurasian watermilfoil. LWF personnel first discovered and identified hydrilla in Lake Theriot in 1975; when Corps personnel visited the lake in September 1976, hydrilla had become established in about one third of the lake's area, replacing Eurasian watermilfoil as the dominant submersed aquatic. Conspicuous floating-leaves plants included waterhyacinth and yellow waterlily. Like Lake Boeuf, it is used for hunting and fishing and for access to the oil and gas wells located near the lake. A relatively plant-free boat trail approximately bisects the lake.

51. The Ross Barnett Reservoir was created when a dam was constructed across the Pearl River near Jackson, Mississippi, to provide a potable water supply and a recreation resource (Figure 6). The reservoir reached its pool stage of 90 m msl in 1965, with a surface area of approximately 120 km^2. At the time of the field studies (1976), the principal emergent plants were watershield (Brasenia Schreberi Gmel.), American lotus, and duckweed. In some areas of the upper reservoir in the summer, watershield is so abundant as to inhibit the recreational use of the affected areas. Waterhyacinth was noted in a small inlet near the residential area in the southeast portion of the reservoir in the previous growing season. This infestation was, at the time of the field studies, completely absent because each plant had been physically

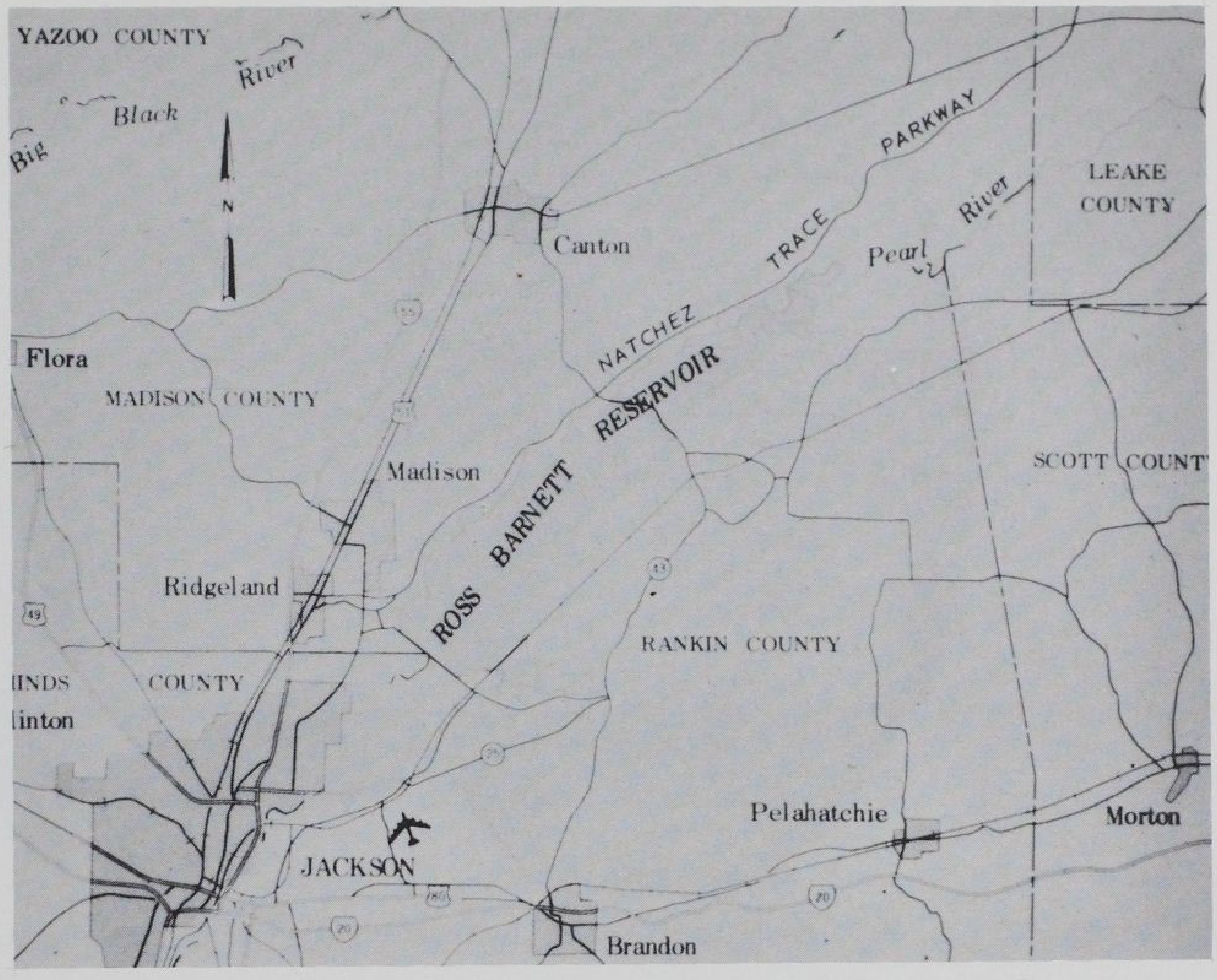

Figure 6. Location map showing Ross Barnett Reservoir

removed, dried, and burned shortly after the infestation had been discovered. Important submersed species include coontail, naiad, and several species of pondweed (Potamogeton spp.). Currently, the predominant aquatic macrophytes of Ross Barnett Reservoir, though locally troublesome, are "native" species. The weed problem of the reservoir is not yet as serious as that of the other three sites, but its high nutrient levels may promote conditions that could allow an introduced submersed exotic such as hydrilla or egeria to become established.

52. Lake Marion, which with Lake Moultrie forms the Santee-Cooper Reservoir system in South Carolina between Charleston and Columbia (Figure 7), provides hydroelectric power and augments riverflow downstream to aid in navigation. The lake was filled shortly after the onset of World War II and includes part of the Santee Swamp. Recently the submersed aquatic egeria has hindered navigation and the sportfishing use of the lake. Another important noxious aquatic is the emergent water primrose [Ludwigia uruguayensis (Camb.)]. Because of the rich

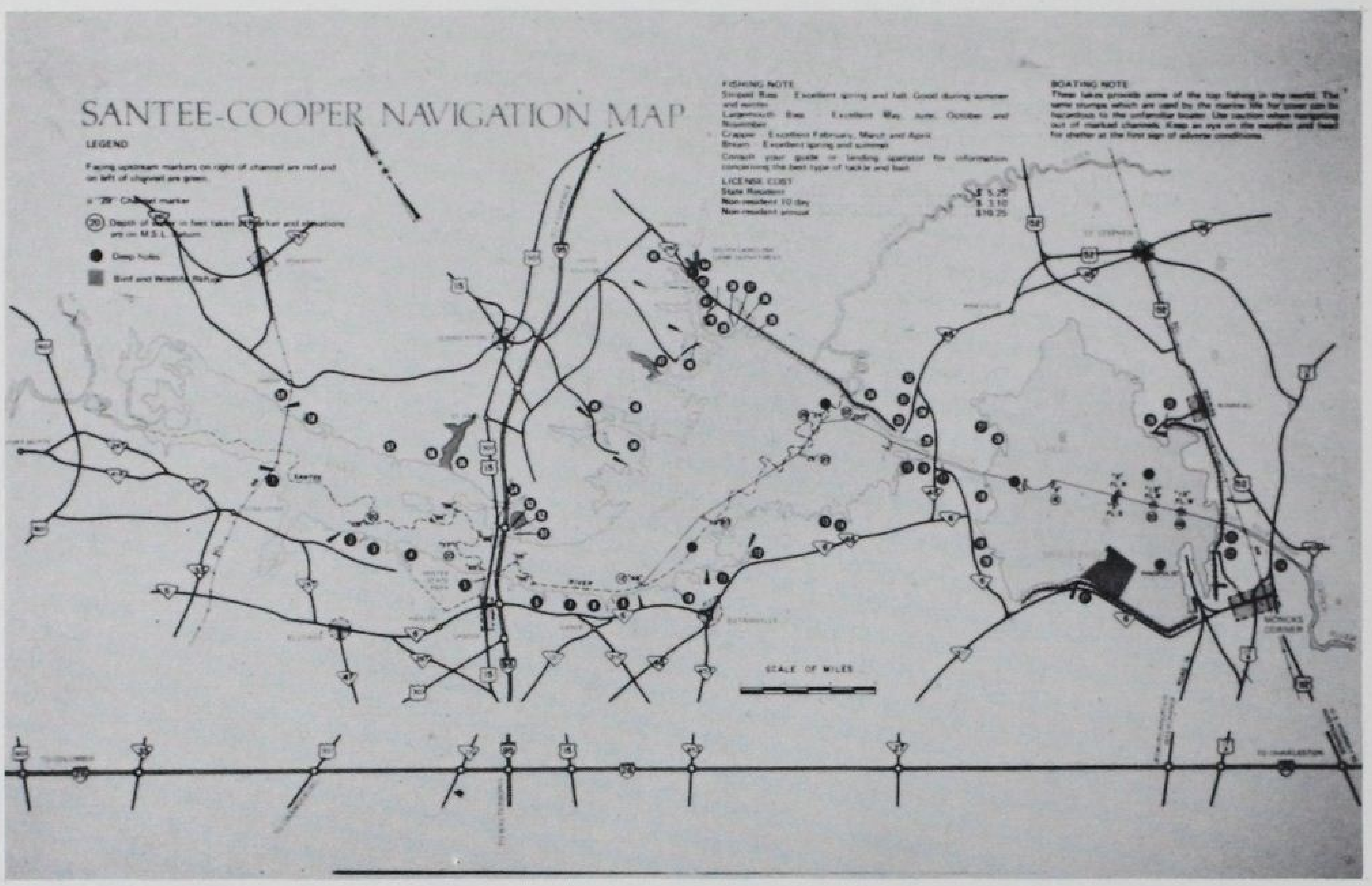

Figure 7. Location map showing Lake Marion

drainage basin of the Santee River above Lake Marion, high nutrient levels prevail in upper Lake Marion. Another contributor to the nutrient load is the demise of the forest flooded when the dam was closed. The forests are principally composed of Southern baldcypress [*Taxodium distichum* (L.) Rich.], slow to wane after being flooded. The thick stands of cypress, along with dead and decaying stumps and logs at or below the water surface, make access to the egeria and waterprimrose difficult or impossible. A major procedure in formulating a management program for aquatic plant control is to determine what kind and how much of the plants exist in the lake; therefore, officials of the Santee-Cooper Authority asked WES for assistance. In July 1976, WES personnel made both aerial and ground inspections of selected trouble spots in upper Lake Marion.

Results of field studies

53. The following paragraphs and Table 9 present summaries of the results of the field studies for the individual water bodies. The images were selected from photographs of Lake Boeuf, Lake Theriot, Ross Barnett Reservoir, and Lake Marion and were used for pictorial summaries of the studies. The images show clearly the typical responses of the

panchromatic color, CIR, and black-and-white IR films. The mission parameters are summarized.

54. Lake Boeuf. The low-altitude photographs of Lake Boeuf, Louisiana (Figure 8), show that the areas of waterhyacinths (pink) and the areas of duckweed (white) were easily distinguished from each other on CIR (with yellow filter), black-and-white IR (with red filter), and color photographs. Because the waterhyacinth and duckweed populations at times covered the water surface, the areas of submersed plants (mostly egeria) were not always detectable. The waterhyacinth infestations had an obvious cloning pattern that resembled the patterns of cloning seen in molds and bacteria growing on agar plates. This analogy is probably not too inappropriate, for the processes producing the two phenomena are quite similar even though the scale is different. The similarity exists probably because reproduction of introduced aquatics is almost totally vegetative, resulting in a spread outward from a central locus. The similarity between molds and bacteria on an agar plate and plants growing in relatively still water such as Lake Boeuf is particularly striking in low-altitude photography (1000 to 2000 ft*). All of the images have not been examined in detail for pattern characteristics, but the evidence to date indicates that growth patterns may be helpful for identification of some species.

55. Lake Theriot. Figure 9 shows examples of the low-altitude aerial photographs of Lake Theriot, Louisiana. Features evident on the photos are a canal entering the lake (near the top of each photo), an area of marsh vegetation (upper half of each photo), and an area of water heavily infested with hydrilla with some local infestation of waterhyacinths (lower portion of each photo).

56. Examination of the photographs in Figure 9 shows that the CIR film with a yellow filter (Figure 9a) produced the best discrimination of the submersed hydrilla from areas with no hydrilla (mainly the canal and its extension into the lake) and the rafts of waterhyacinth.

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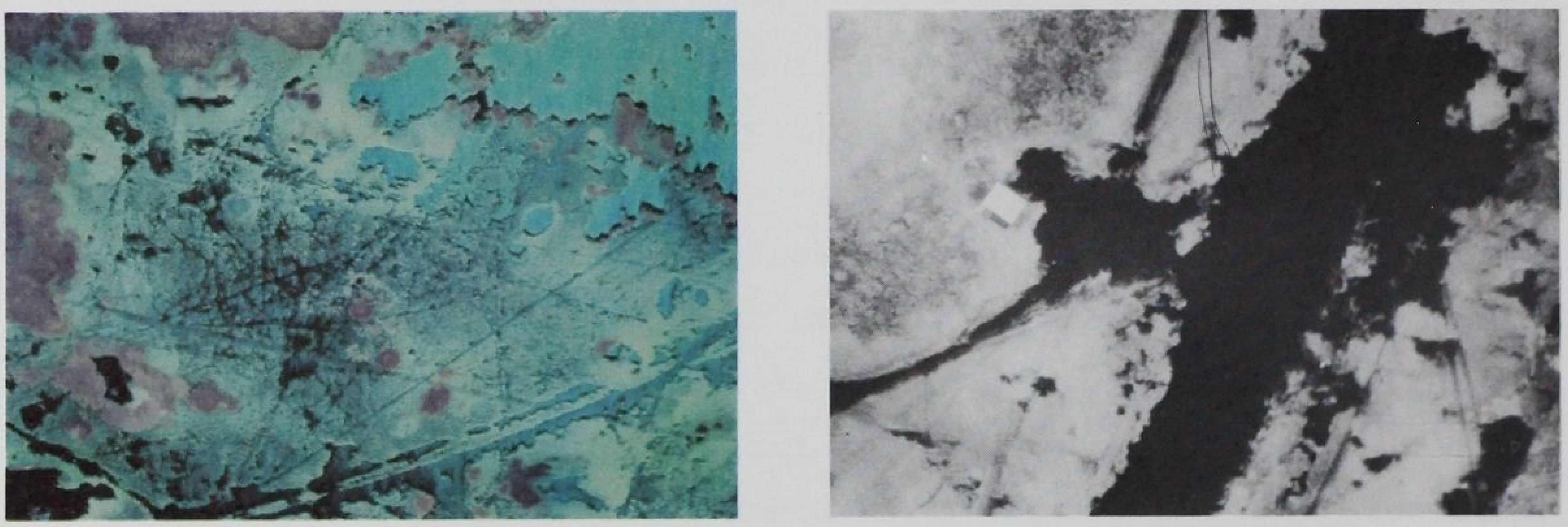
* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 7.



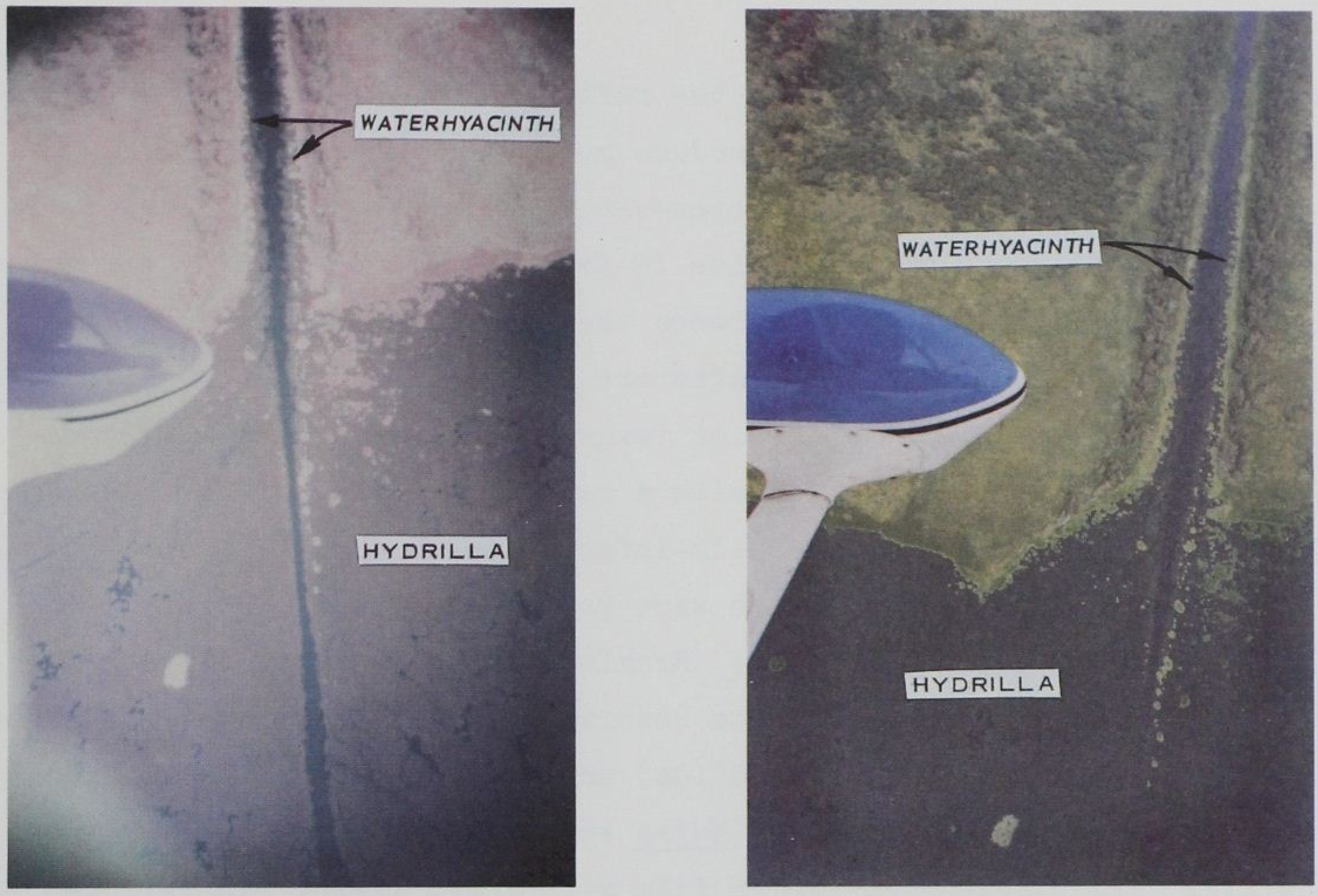
a. CIR film with yellow filter

b. Black-and-white IR film with red filter

c. Color film

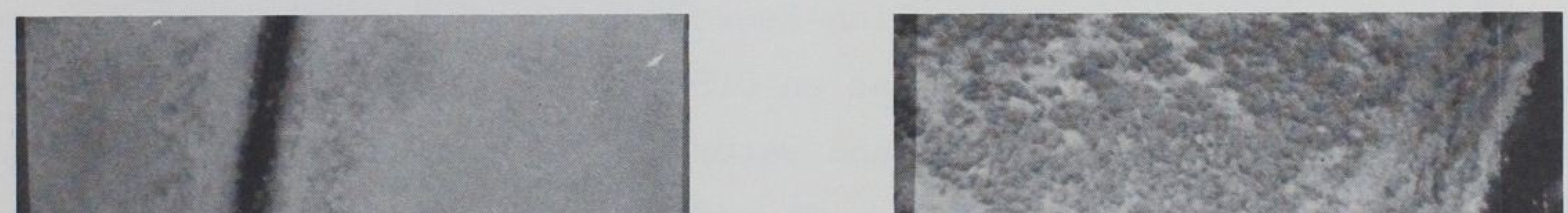
d. Color ground photo

Figure 8. Low-altitude photographs and ground photograph of Lake Boeuf, Louisiana, May 1976



a. CIR film with yellow (Wratten 12) filter

b. Color film



c. Black-and-white IR film

d. Panchromatic film with red (Wratten 25) filter

Figure 9. Low-altitude photographs of Lake Theriot, Louisiana, September 1976

The color film (Figure 9b) shows the rafts and fringe areas of waterhyacinths very well, but does not produce much contrast between the hydrilla-infested areas and the open-water areas, although the hydrilla is detectable. The black-and-white IR film (Figure 9c) was underexposed but did produce good contrast between the hydrilla-infested areas and open water. The waterhyacinth rafts are detectable on the image, but not as well as on the CIR and color images (Figures 9a and 9b, respectively). The panchromatic film with a red filter (Figure 9d) shows little contast between the hydrilla-infested areas and the open-water areas; the areas of waterhyacinth were readily apparent.

57. Ross Barnett Reservoir. Examination of the low-altitude aerial photographs at Ross Barnett Reservoir, Mississippi, revealed that CIR (with a yellow filter, Figure 10a) and color (Figure 10b) film best showed areas of submersed naiad (*Najas* sp.) mixed with *Potomogeton* and *Ludwigia*. The black-and-white IR film with a red filter also allowed identification of naiad infestations (Figure 10c). The ground photograph (Figure 10d) shows the naiad *Potomogeton* and *Ludwigia*. The presence of watershield, a floating-leaved plant, was easily detected on color film (Figure 11a) as well as on CIR film (Figure 11b), and the contrast between American lotus and watershield is more readily discernible on the color photograph. The ground photograph (Figure 11c) is shown for comparison.

58. Lake Marion. Figure 12 shows examples of low-altitude aerial photography obtained at Lake Marion in the area of Low Falls Landing (the launching ramp apparent on the upper left of each photo). The products from the CIR (with yellow filter), color (with haze filter), and black-and-white IR (with red filter) film-filter combinations are shown in the figure. These photos show that infestations of egeria and waterprimrose can be readily detected on all of the photos. It was noted throughout the field tests that slight overexposure of the CIR film produced better contrast between submersed plant infestations and surrounding water or a surrounding surface plant infestation. It is obvious, however, that the submersed plant infestations (egeria) are more apparent on the CIR film and black-and-white IR film than on the

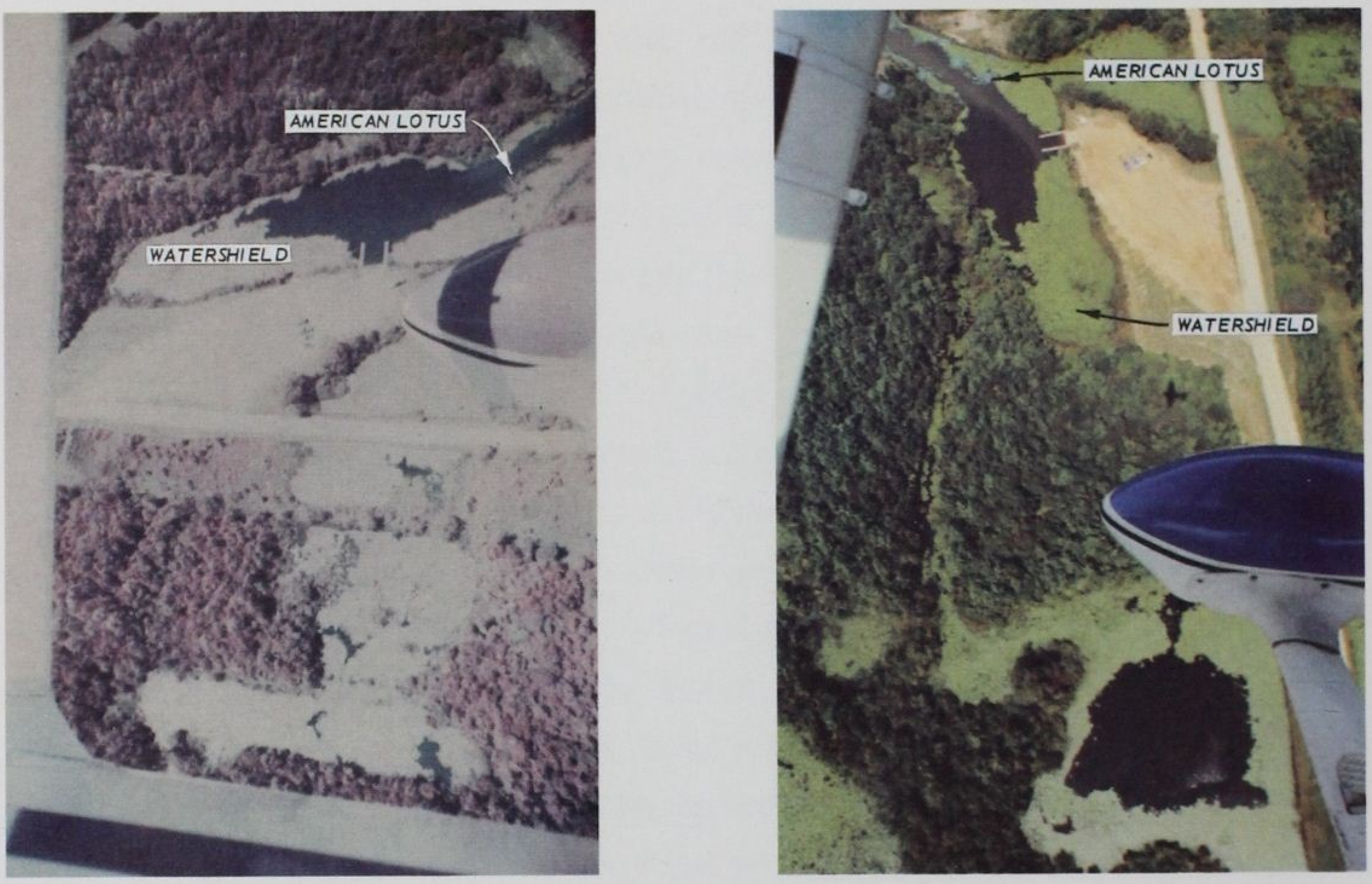
a. CIR film with yellow filter

b. Color film

c. Black-and-white IR film with red filter

d. Color ground photograph

Figure 10. Low-altitude photographs of Ross Barnett Reservoir, Mississippi, compared with ground photograph, September 1976

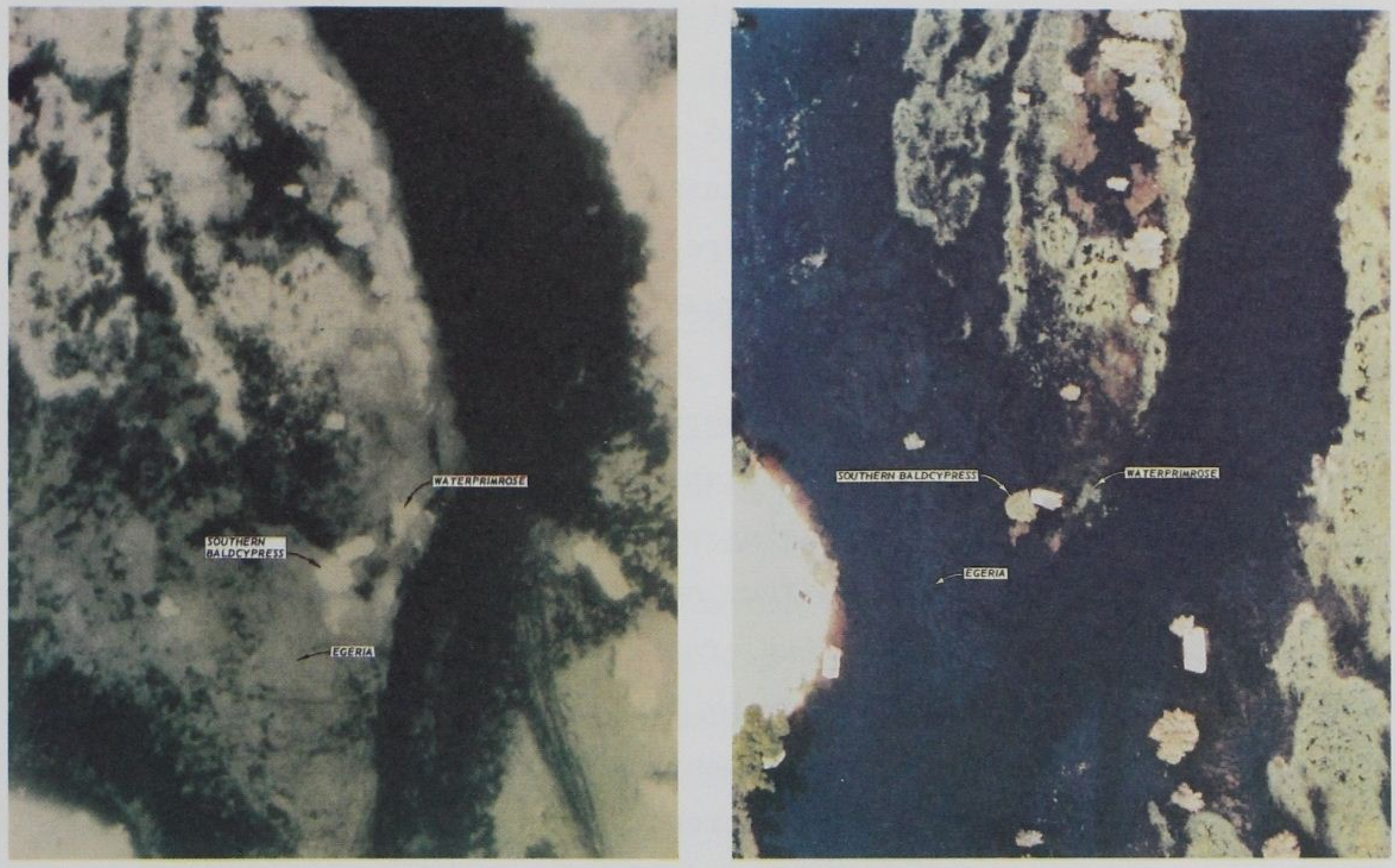


a. Color film

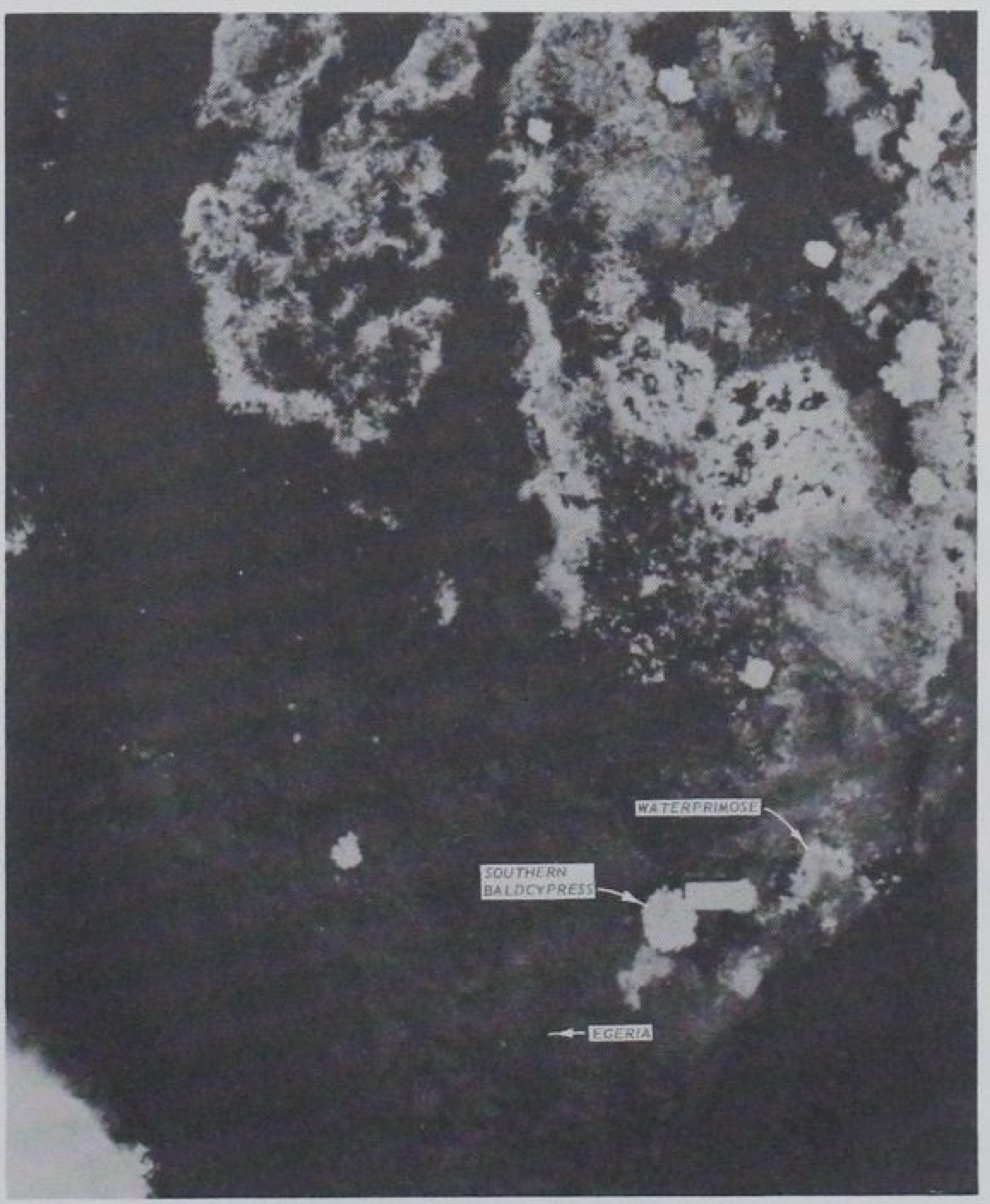
b. CIR film with yellow (Wratten 12) filter

c. Ground photograph

Figure 11. Photographs of Ross Barnett Reservoir, Mississippi, September 1976



a. CIR film with yellow filter b. Color film with haze filter



c. Black-and-white IR film
with red filter

Figure 12. Low-altitude photographs of Lake Marion,
South Carolina

color film. It is also obvious that the CIR film provided better detail for identifying the respective plant species because of easier perception of tone (color) differences and spatial detail. For these reasons CIR film with a yellow filter is considered the film-filter combination best suited for mapping both the type and extent of plant infestations, both submersed and floating or emergent.

Discussion

59. Submersed plant species versus open water. The field tests attempted to help evaluate the suitability of available film-filter combinations for four basic imaging problems as defined in paragraph 4. For detecting submersed plants from open water, all four test sites were used to illustrate the capability of the film-filter combinations tested. Generally, detection was affected by turbidity and depth of the plants. Because no direct contrast measurements were made of the negatives, ranking of the film-filter combinations used in the field studies is subjective. However, CIR, color, and black-and-white IR appear to be adequate for the purpose at the four test sites.

60. Emergent plant species versus open water. Because plant material is highly reflective of near IR wavelengths and because water is highly absorptive of those wavelengths, contrast between emergent plants and open water was greater with IR films. Contrast was adequate for detection with all film filters tested.

61. Submersed plant species versus another submersed plant species. Lake Theriot was the only site at which two submersed aquatic plants appeared on the same scene. A mixture of Eurasian watermilfoil and hydrilla was present. The difference between them was not detectable on the image at this time of the year (late summer). Perhaps at a different season or growth stage some cues could be obtained regarding general growth pattern; however, no such conclusion could be drawn on the basis of the photographs.

62. Emergent plant species versus another emergent plant species. For detecting emergent plants from each other, the cues offered by the color film yielded a definite advantage over the black-and-white film. One outstanding example is shown in Figure 10 when the bluish cast of

the American lotus in the color film sets it apart from the watershield-waterlily assemblage in Ross Barnett Reservoir. This contrast, while detectable on the CIR image, is far more difficult to see than on the true color films. At the other sites, however, CIR offers an adequate means to discriminate other plants.

63. Emergent plant species versus submersed plant species. Emergent and submergent plants were not confused in any of the images obtained. Low sun angle at the time the photography is flown would be a definite advantage for detecting emergent plants. In the Lake Marion figure, for example, one has no difficulty distinguishing water primrose from the submersed egeria, this being accomplished in a variety of ways: (a) the submersed plant image is of a lower exposure level; (b) the colors of the submersed plant are muted; and (c) the character of the water surface above and around the submersed plants can be seen as altered from other parts of the water. Water is often clarified by the presence of submersed aquatics. Also, the pattern of surface waves on the water is often changed as a result of the impeding action of the plants beneath, allowing the interpreter to infer their presence without actually seeing them.

64. The results of the low-altitude aerial photo studies were consistent with the results of the literature survey and the model studies and demonstrate the ability of commonly available photographic systems to obtain information concerning the type and extent of aquatic plant infestations. Examination of the photographs and work with local personnel at the respective water bodies demonstrated that the most effective use of imagery could be made by personnel familiar with the aquatic plant species and water conditions at a given water body. Since visual interpretation of the imagery was shown to be very effective, no sophisticated automated equipment and a minimum of training would be needed to implement the use of photography for detailed aquatic plant surveys.

65. It is emphasized that conditions during which the photography is obtained can have a very significant bearing on the information provided. For example, submersed plants will be more difficult to detect at greater depths and, perhaps, cannot be detected at all during

periods of turbid water. Sun angle should be relatively low (8:30-10:30 LST*) to minimize glare. Significant cloud cover can prevent detection of submersed plant infestations by reducing solar energy available to penetrate to the depths where plants are growing. In addition, the growth stage of a plant will certainly affect its appearance on the photograph. Items such as these must be considered when planning the acquisition of aerial photography.

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* Local Standard Time.

PART III: DEMONSTRATION OF THE DETAILED SURVEY CAPABILITY

66. To test the operational procedure for detailed surveys formulated in the model and field studies, two large-scale demonstration projects were planned. The detailed survey involved implementing the operational procedure consisting of the six steps outlined in paragraph 7. How each step of the procedure was applied to each of the test sites is outlined below.

Procedure

Problem specification

67. The sites chosen were Lake Marion, South Carolina, a part of the Santee-Cooper project of the South Carolina Public Service Authority, and Lake Seminole, a Corps reservoir located on the Florida/Georgia border at the union of the Flint and Chattahoochee Rivers. The surface area of Lake Marion is estimated to be approximately 400 km^2, and the principal noxious aquatic plants are Brazilian elodea and waterprimrose. (Paragraph 52 describes Lake Marion in further detail.) Lake Seminole, a Mobile District project, was formed by the erection of the Jim Woodruff Dam across the Apalachicola River just downstream from the confluence of the Flint and Chattahoochee Rivers (Figure 13). The project is currently used for navigation, electric power generation, and recreation. The surface area of Lake Seminole is approximately 150 km^2. Its aquatic plant population includes waterhyacinth, Eurasian watermilfoil, giant cutgrass [*Zizaniopsis miliacea* (Michx.) Doell & Asch.], hydrilla, and alligatorweed. Chemical control of waterhyacinth in the 1950's was followed by excessive growth of alligatorweed in the 1960's. The alligatorweed flea beetle (*Agasicles hygrophila*) was intorduced in 1967 resulting in effective control of the alligatorweed. These areas formerly containing alligatorweed were once again infested by waterhyacinth. Though relatively young, Lake Seminole supports a diverse population of aquatic vegetation, with about one third of the lake infested. The long growing season, high nutrient level, and connection with sources of infestation are some of

Figure 13. Location map showing Lake Seminole

the factors contributing to this phenomenon. To determine and coordinate the necessary control measures, managers of respective reservoirs need to locate, identify, and measure the extent of noxious aquatic macrophytes. At Lake Marion, the principal noxious species are egeria, waterprimrose, and naiad. At Lake Seminole, the manager specifically wanted a map of the expanse of giant cutgrass, Eurasian watermilfoil, and hydrilla. Therefore, the missions were designed such that these species could be most easily identified on the resulting images. If other species could be identified and delineated on the same images without much additional effort, they were to be included as well.

Planning remote sensing missions

68. To plan a remote sensing mission, several parameters must be specified to the contractor chosen to fly the imagery. These are as follows:

- a. Film.
- b. Filter.
- c. Scale.
- d. Time of day.
- e. Date.
- f. Stereo overlap (normally 60 percent forward lap, 30 percent side lap).
- g. Atmospheric conditions (cloud cover, etc.).

The ERTS radiometer was used to measure reflectance of the selected aquatic plants as well as their surrounds. Also, ground photographs were made at each of several easily relocatable sites and keyed to a 1:24,000 scale map. A "major" aquatic macrophyte was present on at least one of these sites. Species possessing the greater amounts of biomass an any particular site were identified and the area(s) of their approximate location sketched in on the 1:24,000 scale map. The respective reservoir managers provided guidance in locating the ground control areas in "representative" locations.

69. Film-filter combination. As noted earlier, the selection of the appropriate film-filter combination depends upon the target to be imaged and its associated surroundings. At each lake the principal noxious species already had been identified, and the reflectance data gathered were prepared for input to the optical density contrast model as described in paragraphs 28 through 32. Model results indicated that, considering the entire array of species to be imaged at each lake, CIR film with a yellow filter should give the best results.

70. Scale. The scale of a mission was selected considering the allowable ground resolution and size of the area to be imaged so that desired accuracy and the number of photographs to be handled were balanced in the decision. Altitude is a function of the desired scale

and the focal length of the camera. (For a 6-in. focal length, a mission resulting in an image at a scale of 1:20,000 would be flown at 10,000 ft.)[14] A scale of 1:20,000 was chosen because the resolvable ground distance achieved at this scale with CIR film can be estimated to be 0.62 m (Figure 14), precise enough for the desired areal estimates without obliging the photo interpreter to handle a large number of photographs.

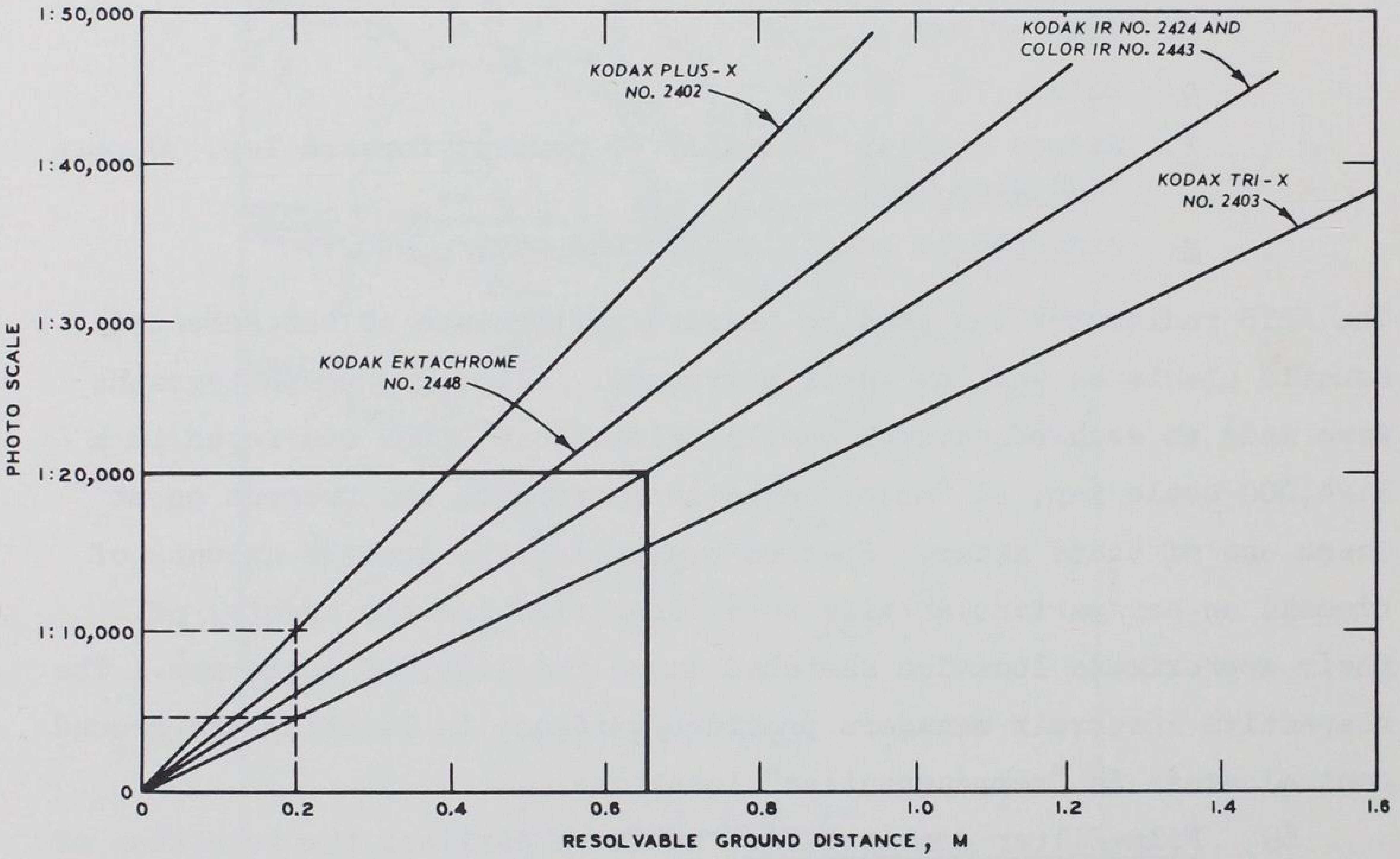

Figure 14. Photo scale versus ground distance for image clarity (from Cress and Link[14])

71. Time of day. At both Lake Seminole and Lake Marion submersed plants in variably turbid water needed to be visible in the resulting images. Therefore, the energy incident on the water surface needed to be of a quantity sufficient to reach the submersed plants and be reflected back. On the basis of the previous field studies and the literature survey, however, a low sun angle was desirable to accentuate the emergent plant population. Thus, 10:00 a.m. LST or 2:00 p.m. LST was selected as the "average" time of day that the photomissions were to

take place to optimize the likelihood of imaging both submersed and emergent plants.

72. Date. The dates of the photomissions reported here were to a degree dependent upon the availability of the contractor (in this case, the Georgia Air National Guard) to fly the mission. Fortunately, they were available in the early, middle, and late growing season for Lake Seminole and in the middle and late growing season for Lake Marion. The initial request was that they fly both lakes every 2 months beginning in April so that seasonal changes might be monitored. If only one mission could be flown in a year, a time should be selected when the plants to be imaged are fully mature, i.e., late summer.

73. Stereo overlap. Stereo overlap was desired in these missions because it aids considerably in plant identification, particularly emergents. On stereo images an interpreter can readily discriminate herbaceous plants from shrubs and trees. This is a definite aid in Lake Marion where flooded forests occupy large portions of the upper lake. Hence, standard stereo overlap (60 percent forward lap, 30 percent side lap) was specified to the contractor.

74. Atmospheric conditions. Atmospheric conditions needed to be as haze- and cloud-free as possible. Since CIR was selected, summer haze was not as great a problem as it would have been using ordinary color film.

Data aquisition

75. Selection of a contractor. For the mapping of Lake Marion and Lake Seminole, the Georgia Air National Guard offered their services on an "as available" basis. Since the Georgia Air National Guard was qualified and agreed to fly the mission with WES's only cost being to replace the film that was used, they were selected. Many agencies, however, may not have at their disposal such a service. In this case, a contractor must be selected. A list of sources of new imagery missions is given by May.[15]

76. Photomissions. The Georgia Air National Guard flew CIR missions over upper Lake Marion, one in November 1976, one in June 1977, and one in November 1977. The imagery was acquired at a scale of

1:20,000. Lake Seminole was covered by the same type of aerial photography in April, June, and September of 1977. The imagery products received at WES were 12.7- by 12.7-cm CIR transparencies on a continuous roll. Additionally, Shaw Air Force Base provided 1:60,000 black-and-white coverage of Lake Marion in September 1977.

77. Figures 15 and 16 are typical examples of the imagery acquired from the photomissions at Lake Marion and Lake Seminole, respectively. Examples of the appearance of aquatic plant infestations are noted on the images.

Data transformation, information extraction, and information presentation

78. After the images were obtained, the task remained to convert them to a product that would benefit the user; in this case, the respective managers of Lake Marion and Lake Seminole wanted a map showing the noxious aquatic plant species. A technician skilled in airphoto interpretation, but not familiar with aquatic plant characteristics, examined the images on a Richards Light Table with magnifying stereoscope and transferred the location and outline of the various plant assemblages to a 1:24,000 scale base map. The technician received interpretation keys from a botanist who made two ground visits to the lakes being mapped and had collected ground-truth data on the target species. In practice, two methods are widely used to extract the pertinent information from the photographs and transfer that information to a map of a suitable scale. One method is to simply identify the aquatic plant infestation on the photograph and transfer its outline to a previously prepared base map of the desired scale. This method requires no sophisticated equipment, but a degree of error is unavoidable. The second widely used method of transferring information from the photographs to the map employs a Bausch and Lomb Zoom Transferscope, an instrument designed to perform the specific function of transferring information from a photograph to a map by projecting the image of the photograph onto a map with scale and distortion adjustments. The interpreter then merely outlines the projected image onto the map. A

Figure 15. CIR scene at Lake Marion, South Carolina

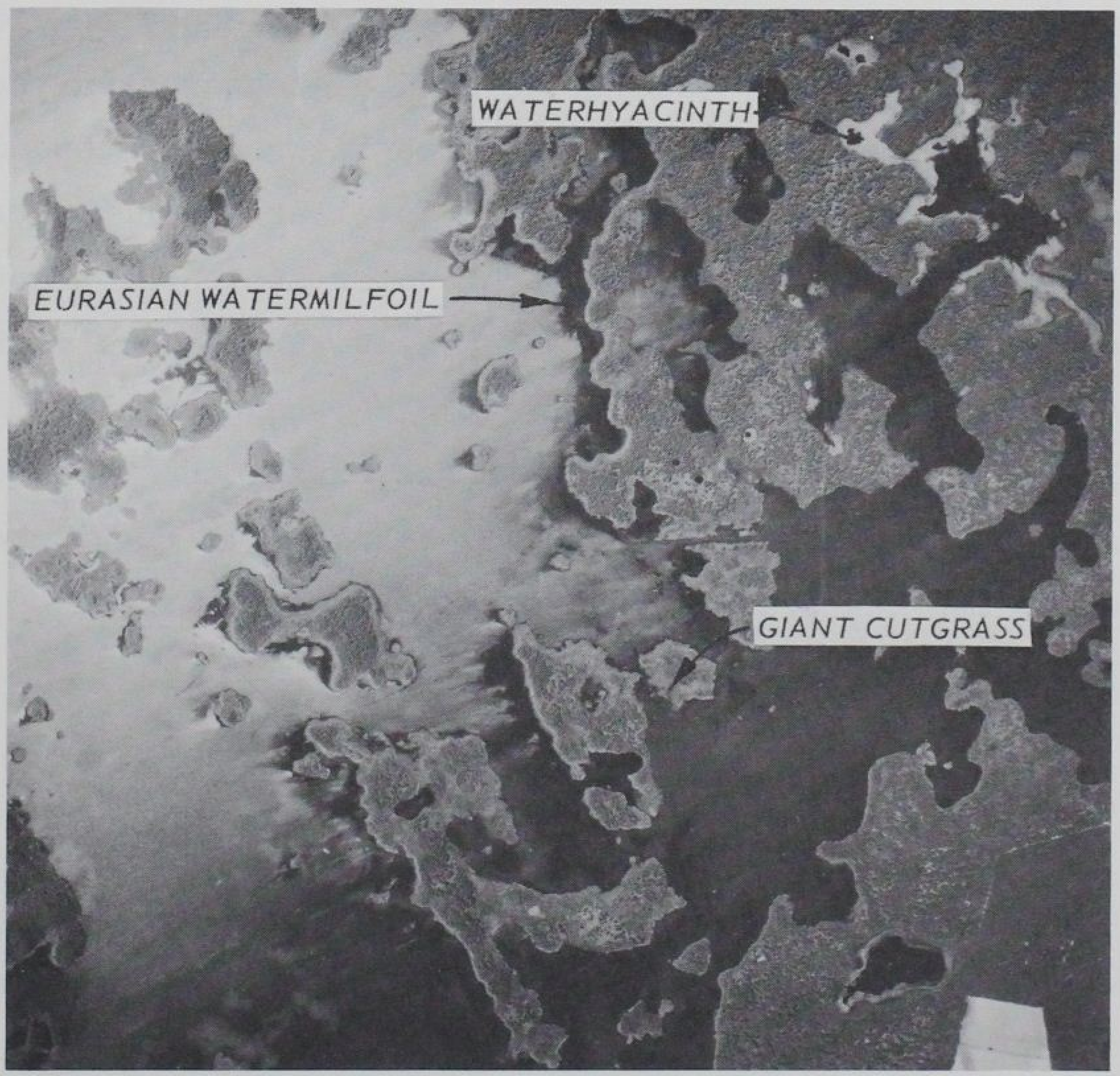

Figure 16. CIR scene at Lake Seminole, Florida

map of the aquatic plant infestations of each lake was produced from each set of aerial photographs by the first method. The area infested by each species was measured and recorded. Figures 17 and 18 are examples of the maps produced for portions of Lake Marion, South Carolina, and Lake Seminole, Florida, respectively, and show the areas of aquatic plant infestations outlined and coded by species. Bruning areagraph charts were used to give rapid areal estimates of the aquatic plant assemblages (Table 10).

Map evaluation

79. Shortly after the maps were completed, they were taken to the respective lakes and compared with actual conditions: that is, the species composition and areal extent of the various plant assemblages. Two basic kinds of errors can occur on a map of this type: errors of identification and errors of delineation. Errors of identification were checked by visiting specific locations and determining if the map showed the proper species identification. Errors of this type were rather rare in the mapping of both lakes. The most prevalent error on the maps was in delineation of submersed aquatics. Although most patches of submersed aquatic plants were correctly identified by species, the submersed patches in reality usually covered a greater area than that detected on the CIR aerial photography. The discrepancy tended to vary with the depth and clarity of the water. In clear water the errors were very small; however, as the depth of water above the plants increased and the clarity of the water decreased, the errors increased. The surface aquatic plant infestations were mapped accurately and with a notable level of detail, primarily because either the technician or the botanist assisting the technician was fairly well acquainted with the study areas and had prior knowledge of the target species infestations.

Cost Summaries

80. The cost of producing a vegetation map from aerial photography of course varies with the complexity of the areas imaged and the scale

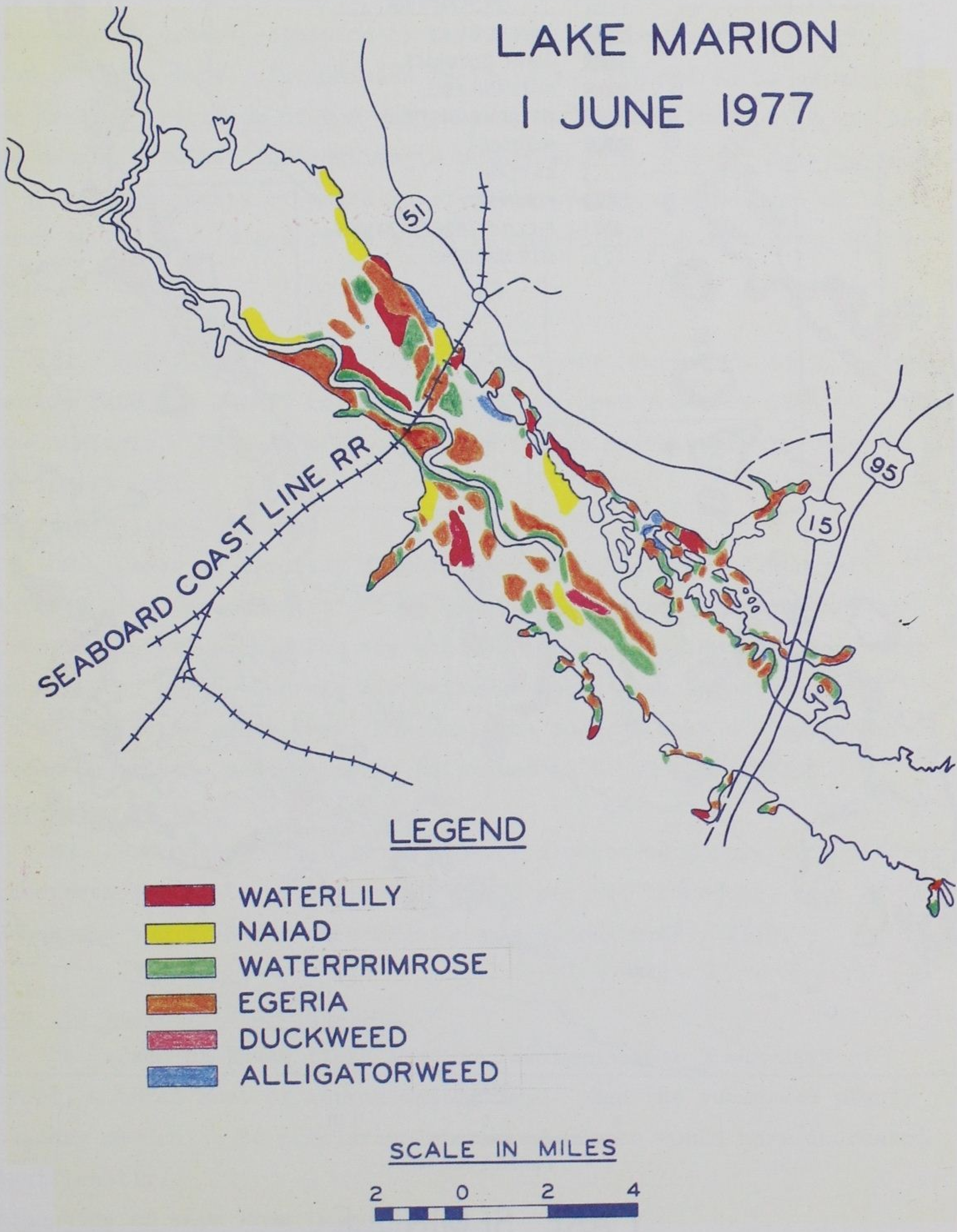

Figure 17. Vegetation map of Lake Marion, South Carolina

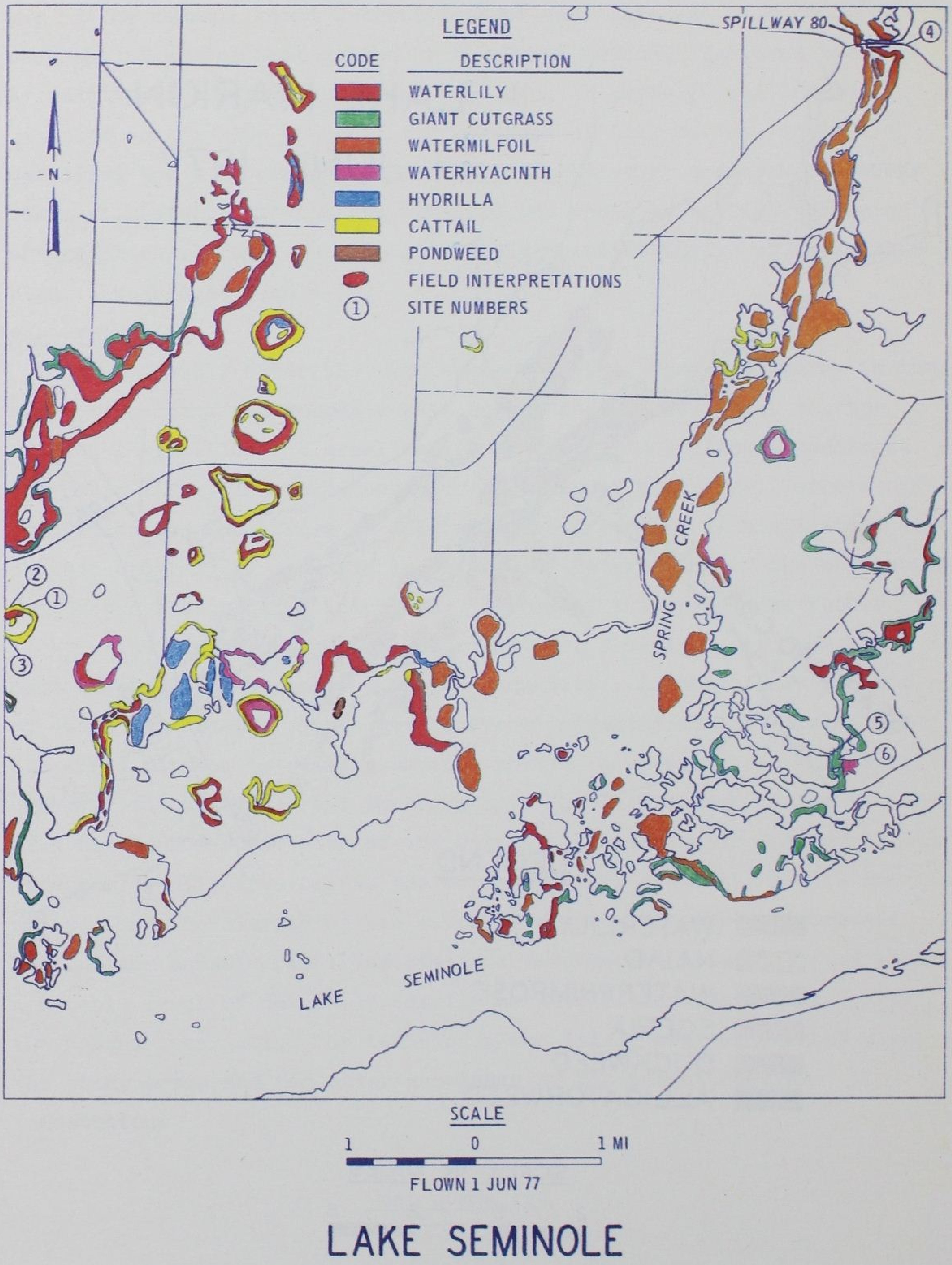

Figure 18. Vegetation map of Lake Seminole, Florida

of the imagery. In general, the costs include the cost of film, the cost of the aircraft flight, processing of the film, collection of ground-truth data, production of maps from imagery, and field verification of those maps. In addition to the size of the area to be mapped, the desired precision of the end product influences both the scale and the detail by which information is transferred to a map. Some guidance on general estimates of costs involved in producing maps such as those shown in Figures 17 and 18 is given in the following paragraphs and in May.[16]

Film

81. CIR film in a 12.7- by 12.7-cm format currently costs approximately $100 per 100-ft roll. One roll was used for each mission at Lake Seminole. Film in a 23- by 23-cm format costs approximately $210 per 100-ft roll.

Aircraft flight

82. Costs of aircraft flights vary with the type of aircraft, distance from the aircraft's home base, and flight time necessary to cover the target area. For the studies reported herein, the equipment and services of the Georgia Air National Guard were supplied as a training mission at no cost; however, the cost of such a mission performed by private contractor is estimated at $1500 per mission.

Processing of film

83. Processing CIR film to produce a continuous roll of positive transparencies costs approximately $1.00 per ft; therefore, cost of processing the film for each mission was approximately $100.

Collection of ground-truth data for imagery interpretation

84. Each of these field studies involved about 3 man-days of effort, a total cost of approximately $650. Had the submersed plant boundary needed to be precisely determined, costs would have increased significantly.

Production of maps from imagery

85. After the film had been processed, each of the map sets require a minimum of 5 man-days to produce, costing approximately $1000.

Field verification of maps after imagery interpretation

86. This parameter depends on how much precision is required. When meticulous ground measurements are required, costs will increase proportionately. In the exercises noted herein, about 3 man-days were taken to check the maps at a cost of approximately $650. When the general guidelines for costs of the study to produce the maps at Lake Seminole were summarized, it was estimated that, using WES personnel, an aquatic plant infestation map costs approximately $4000 for a lake of this size. If the process had been conducted by personnel familiar with the conditions at Lake Seminole, it is possible that the number of days for field checking and initial ground-truth data collection would have been reduced significantly.

Discussion

87. Conclusions reached on the basis of the field studies are as follows:

- a. CIR photography taken with a yellow (No. 12) filter and overexposed by one F-stop provides the most generally applicable tool for mapping aquatic plant infestations, both surface and submersed.
- b. The information derived from the imagery is very much a function of the knowledge of the interpreter. The optimum situation is to have an individual who is very familiar with the aquatic plant situation in a particular water body to interpret the imagery for that area. This will provide the maximum amount of information for the least amount of time and money.
- c. Standard visual photointerpretation procedures are considered for the present time to be the most cost-effective means of extracting information from the aerial photography. This requires no sophisticated machinery and a minimum of training on the part of the individuals who do the interpretation.
- d. The most important aspect of applying aerial photography to detailed surveys is being able to plan the mission to optimize the imagery for the information desired. This means considering climatic conditions, growth stage of the plants, water clarity, cloud cover, and time of day as discussed in paragraphs 71-74.

Recommended Procedure for Future Surveys

88. On the basis of the experience gained in the demonstration projects at Lake Marion and Lake Seminole, the following general guide is recommended for planning remote sensing missions to identify and assess the extent of aquatic macrophytes in specific water bodies. It is recognized that different circumstances may require different applications of the procedure. The following information and Table 11 are offered, however, as a general guide.

Establish the purpose of the mission

89. Is an intensive, exhaustive survey of all aquatic plants desired or a general map showing the most prominent ones? The purpose of the mission determines the specification of many of the mission parameters to maximize information available while minimizing costs. Missions may be flown to accomplish specific imaging tasks, some of which are listed below. Again, the interpretation cues, tone (or color), pattern (or texture), and association information should be derivable from the images. The nature of the target(s) determines how the cues are exploited. Usually the choise of specific imaging tasks is one of the following: (a) a general survey of the water bodies to estimate areas of water surface infested by aquatic plants, (b) estimate areas of submersed and emergent aquatics separately, (c) identify species and estimate areas occupied by each one, or (d) estimate or rank biomass levels by species. Based on the findings of this and previous studies, the following guidance is offered below and summarized in Table 11.

Accumulate available background data

90. Maps produced by the U. S. Geological Survey (USGS) at a 1:24,000 scale exist for most of the United States. Such maps can give valuable information concerning shorelines, topographic details, etc. Another good source of background information, if available, is previous photographs of the study area. A base map should be

constructed from existing maps and/or photographs where other background data as well as the information from the photographs to be acquired can be placed.

91. Ground-truth data-gathering functions should be performed at about the same season, time of day, water level, turbidity, etc., as that anticipated for the remote sensing mission. When possible, knowledge of those persons familiar with the lake should be exploited to make more efficient the locating of "typical" ground-truth data-collecting sites, which should then be recorded on the 1:24,000 scale map. If species lists are available, an illustrated flora manual, such as Corell and Corell[17] or Gleason's Britton and Brown,[18] should be consulted. Each data collection site should be selected on the basis of the presence of target species. Panoramic photographs should be taken of each site and major species identified on them.*

Plan the mission

92. Important mission parameters that need to be specified include scale, film-filter combination, time of year, time of day, stereo coverage, and recommended exposure.

a. The mission purpose determines the scale of the photography; a scale should be specified that ensures that the needed information can be seen on the photographs, while at the same time minimizing the number of photographs that must be handled.

b. The film-filter combination chosen has an influence on the resolution of the resulting image; IR films are grosser than other films at the same scale (Figure 14). Color films cost more than their black-and-white counterparts, but if the mission purpose requires differentiation among several species, then the greater variety of hues available with color films is worth the additional cost.

c. If one wishes to maximize the amount of the plant target to be seen, then late summer or early fall is the best time of the year for such a mission in the temperate zones. If one wishes to document conditions and how they change throughout a growing season, however, missions

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* Biomass estimations may also be made as described by Gustafson and Adams.[5] However, this procedure was not conducted in the study reported herein.

flown every 2 months, with the first flown in early March, are recommended.

d. The water surface is a particularly challenging target to photograph because of its reflecting qualities and potential for great surface variability. An additional constraint is imposed when one wishes to image submerged aquatic plants. A high sun angle has to be avoided to reduce glare and glitter from the water surface. However, a considerable quantity of light energy is needed on the water surface to penetrate the water, pass through it and hit the plant, and pass back through the water and the atmosphere to effect a change in the sensor (e.g., the photographic film). Therefore, a very low sun angle may not provide the necessary energy. Thus, 10:00 a.m. LST or 2:00 p.m. LST is the recommended time for the mission.

e. Stereo coverage of 60 percent forward lap and 30 percent side lap is desired for each kind of mission shown in Table 11. For general surveys for locating surface aquatic plants, however, stereo is not required.

f. General surface plant surveys can be imaged with exposures recommended for terrestrial scenes. However, when attempting to image submersed plants, more contrast between submersed plants and the surrounding water can be achieved by opening the lens 1 F-stop wider than that recommended for a terrestrial scene.

Process the photographs

93. The photographer may also perform this function. The processing recommended is that that is standard for the film chosen. The first-generation product of CIR film (Type 2443) is a continuous roll positive transparency, suitable for viewing on a light table with a stereoscope. Prints may be desired; in this case, an extra cost is incurred.

Interpret the photographs

94. The interpretation function is much more efficient if performed by someone familiar with the area. The 1:24,000 scale maps where ground-truth data collection sites were noted and the accompanying photographs and species lists should be consulted extensively while interpreting the imagery. Locations of known species composition (i.e., the ground-truth data collection sites) are compared to locations of unknown species composition for tone, pattern, and association similarities. If these factors are similar, then the "unknown" area is

considered the same as the "known." Doubtful identifications should be so marked.

Display the information

95. As the interpretations are made, the area on the photograph depicting a particular species or group of species is delineated with a wax pencil or similar device. Or, the information can be transferred to a base map either without a special instrument or by using an instrument such as the Bausch and Lomb Zoom Transferscope, which can magnify or reduce the image on the photograph and project it on the base map where it can be outlined. Patches on the map are labeled with the species occupying them.

96. If necessary, the areas occupied by each species or group of species can be measured and recorded. This will yield an estimate of the area occupied by each species in the water body being mapped.

Evaluate the map

97. After the first draft species map is produced, it should be compared to actual conditions on the ground. Areas of doubtful species identification should be visited to determine the true species composition. Other areas not visited in the initial ground-truth data gathering should also be spot-checked. At this time, the accuracy of the boundaries of infestations can be checked and necessary modifications made. If consistent errors of boundary delineation are discovered (for example, if boundaries of submersed aquatics extend further than shown on the map), this extra area may be extrapolated to include all such plants in the area being mapped. This function of map evaluation can take as much or as little effort as the particular project justifies. If changes on the map are warranted, they should be made on the initial draft map in the field. Upon returning to the office, these areas should again be viewed on the imagery and necessary changes incorporated before the final drafting of the map.

PART IV: RECONNAISSANCE SURVEY CAPABILITY

Introduction

98. The thrust of this part of the study effort was to complete an initial evaluation of the potential of Landsat, side-looking airborne radar (SLAR), and high-altitude aerial photographic imagery for reconnaissance aquatic plant surveys. This evaluation was to serve as a basis for subsequent formulation of an operational methodology for conducting reconnaissance surveys. Like aerial photographs, other sensors, such as the multispectral scanner system in Landsat, record reflected energy and can produce photolike images of the terrain. Landsat differs in that it views the earth's surface from space and the resulting spatial resolution is coarser than for photos acquired from an aircraft; however, Landsat does provide the advantage of covering large areas in a short time.

99. One type of remote sensing concerns the thermal infrared (IR) portion of the electromagnetic spectrum. Thermal IR systems record the energy radiated from terrain materials. The amount and spectral character of the energy are functions of the temperature and radiation characteristics of the material. The SLAR type of remote sensing investigated concerns radar or microwave systems that transmit a pulse of microwave energy to the side of aircraft (perpendicular to the flight path of the aircraft) and record the energy backscattered from the terrain surface. The amount of energy returned is a function of the roughness of the terrain surface. SLAR also allows coverage of large areas in a short period of time.

100. Aerial photos and Landsat images, because of the differences in reflectance characteristics of aquatic plants and their surrounds, can be expected to be effective reconnaisance tools for delineating aquatic plant infestations.

101. SLAR systems may provide a tool for regional type surveys for emergent and floating aquatic plants because of the differences in surface water roughness compared to relatively smooth water surfaces.

Thermal IR sensors are not expected to be very useful. Because of these basic assumptions, aerial photography, Landsat imagery, and SLAR systems are considered to have the most potential for immediate application to the aquatic plant mapping problem. These, therefore, were the candidate remote sensing techniques selected for further study.

102. The evaluations were made by field tests at selected locations in Florida, Louisiana, Mississippi, and South Carolina. Landsat and high-altitude aerial photo imagery of the test areas was obtained from the U. S. Geological Survey Earth Resources Observation Systems Data Center, Sioux Falls, South Dakota. Synthetic aperture SLAR imagery was obtained by Shaw Air Force Base, South Carolina. Ground-truth information was obtained from personnel knowledgeable of the respective water bodies or by site visits for comparison with imagery-derived data on aquatic plant infestations.

Systems Examined

Landsat

103. Previous studies have already shown that band 6 Landsat images could reliably depict the occurrence of aquatic plants in Currituck Sound and the Alligator River in North Carolina.[19] In the WES study, other target species in other locales were examined on Landsat images.

104. In this study, Landsat imagery was evaluated in two ways: first by visual inspection of photographic images and secondly by digital processing of Landsat Computer Compatible Tape (CCT) data. The visual interpretation was accomplished for Lake Boeuf, Louisiana; Lake Theriot, Louisiana; and Ross Barnett Reservoir, Mississippi (for site descriptions see paragraphs 49-51). The digital processing was accomplished for Rodman Reservoir (Lake Ocklawaha), Florida. The following paragraphs first discuss the visual image interpretation experiments and then address the digital data processing experiment.

105. Lake Boeuf and Lake Theriot. Landsat imagery for the area including Lakes Boeuf and Theriot was obtained as 7-in. rhomboid

positive transparencies at a scale of 1:1,000,000. The data were obtained by the satellite on 16 May 1976, and individual images were obtained for bands 4, 5, 6, and 7. A photograph of the band 6 image at the original scale is shown as Figure 19. Lakes Boeuf and Theriot are indicated on the image: note that Lake Theriot is covered by clouds precluding any meaningful interpretation for that area. Because of the scale, it was necessary to enlarge each image to facilitate

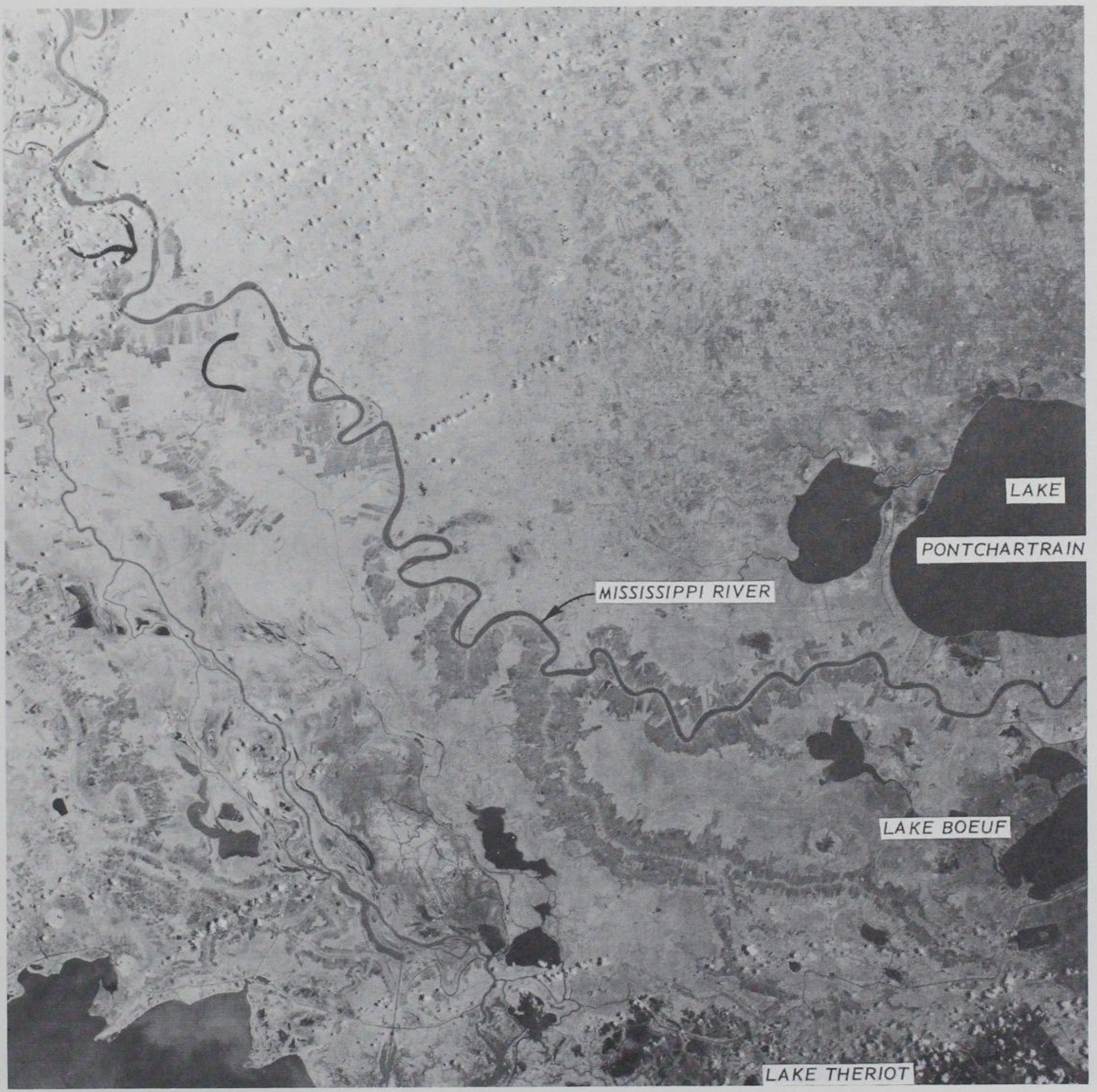


Figure 19. Landsat band 6 image of Lake Boeuf and Lake Theriot (16 May 1976, scale 1:1,000,000)

interpretation. The enlarged Lake Boeuf portion of the band 7 negative image is shown as Figure 20. It is obvious, however, from the image in Figure 19 that the 1:1,000,000 scale imagery offers a rapid means to cover a very large area, a distinct advantage over other imagery types.

106. Ross Barnett Reservoir. Examination of bands 6 and 7 image enlargements of Ross Barnett Reservoir (see Figure 21) showed tonal patterns that related to known infestations of floating-leaved plants, principally watershield. Again, bands 4 and 5 imagery did not provide useful information. The patterns on the Landsat imagery are not very distinct because of the early spring (April 1976) growth stage of the plants when the imagery was obtained.

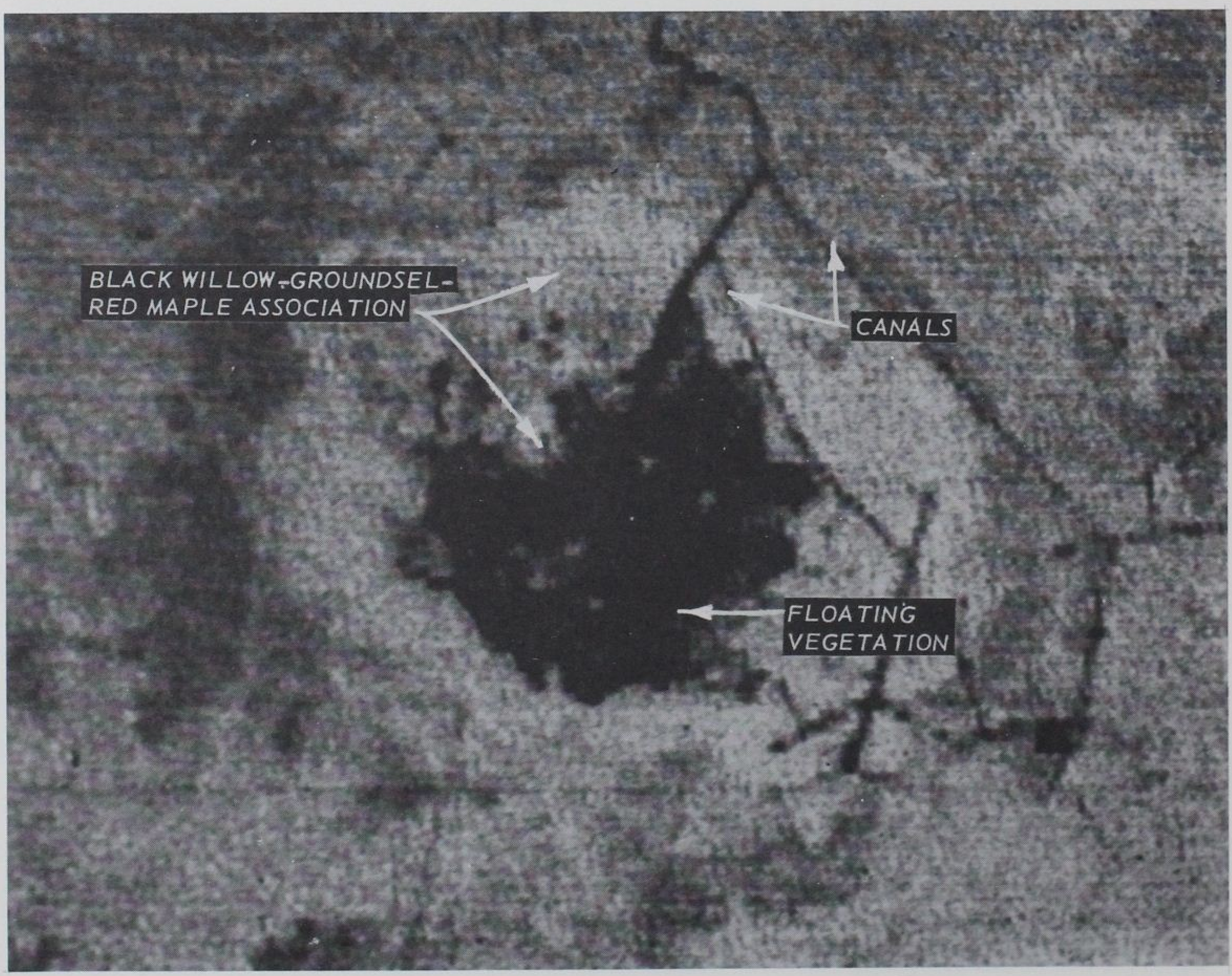
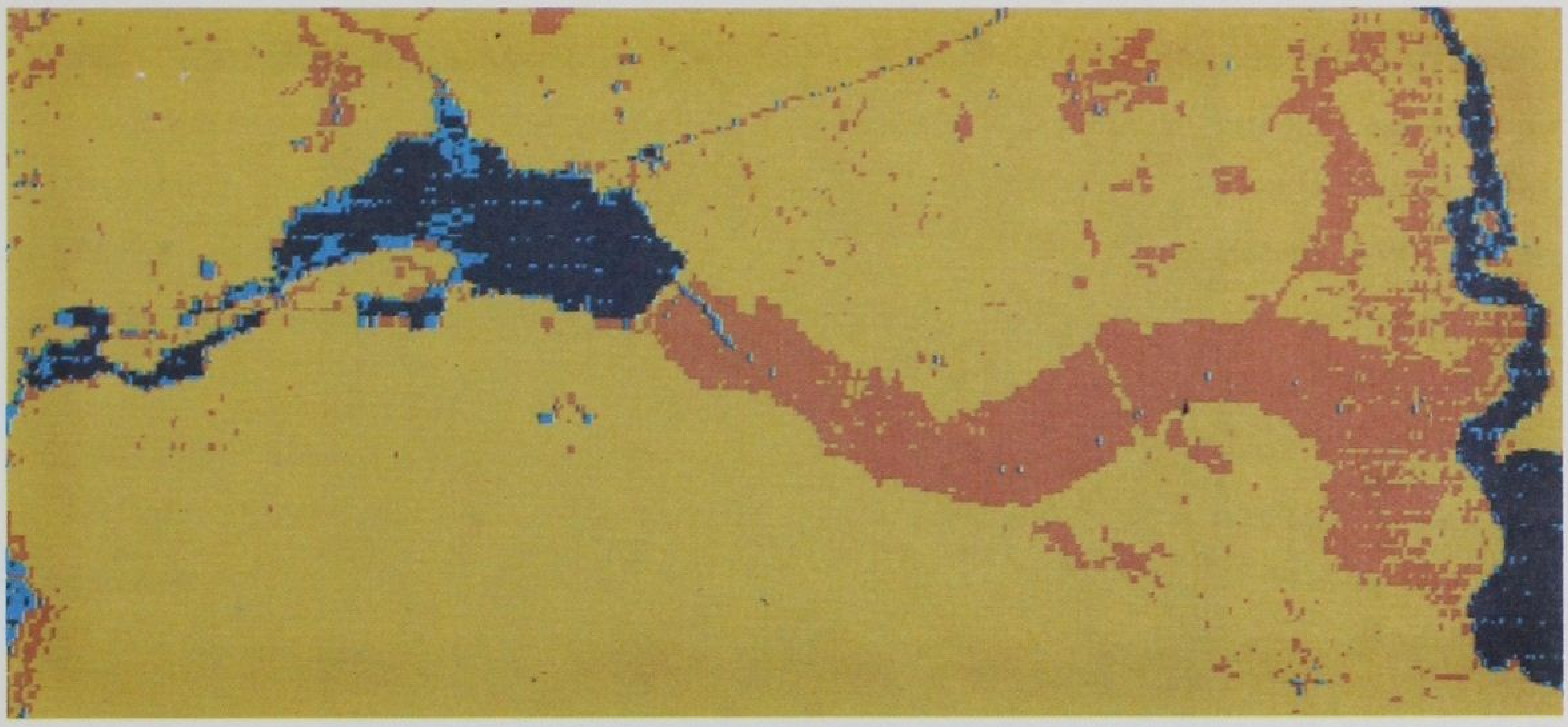


Figure 20. Enlarged Landsat band 7 positive image of Lake Boeuf (16 May 1976)

Figure 21. Enlarged Landsat band 7 positive image of Ross Barnett Reservoir

107. Rodman Reservoir. Landsat CCT's were obtained of an area including Rodman Reservoir, Florida, for the dates 24 December 1972 and 10 April 1973. The Rodman Reservoir (Lake Ocklawaha) is located near the Atlantic Coast end of the Cross-Florida Barge Canal System. Principal aquatic plants are hydrilla, waterhyacinth, waterlettuce, cattail, spatterdock, coontail, *Vallisneria*, pickerelweed, and some grasses. The multispectral scanner onboard Landsat is sensitive to four spectral bands. Band 7, which is sensitive to 0.8- to 1.1-µm wavelengths, is almost totally absorbed by water. Plants, on the other hand, are, for the most part, highly reflective of this band. Thus, band 7 should show vegetation-water contrast. The CCT's covering the Rodman Reservoir area were scanned and pixels were assigned to one of four classes according to their radiance values. The 325- by 492-pixel array defining the study area was digitally enlarged 1.85 times and color photo-maps were produced (Figure 22). This effort produced winter and spring images having definite differences in patterns on the water surface. The patterns on the photo-maps were examined with respect to known conditions at the time the imagery was obtained. The results indicated that the light blue-toned areas were highly correlated to areas of known aquatic plant infestations, chiefly hydrilla, waterhyacinth, and egeria.

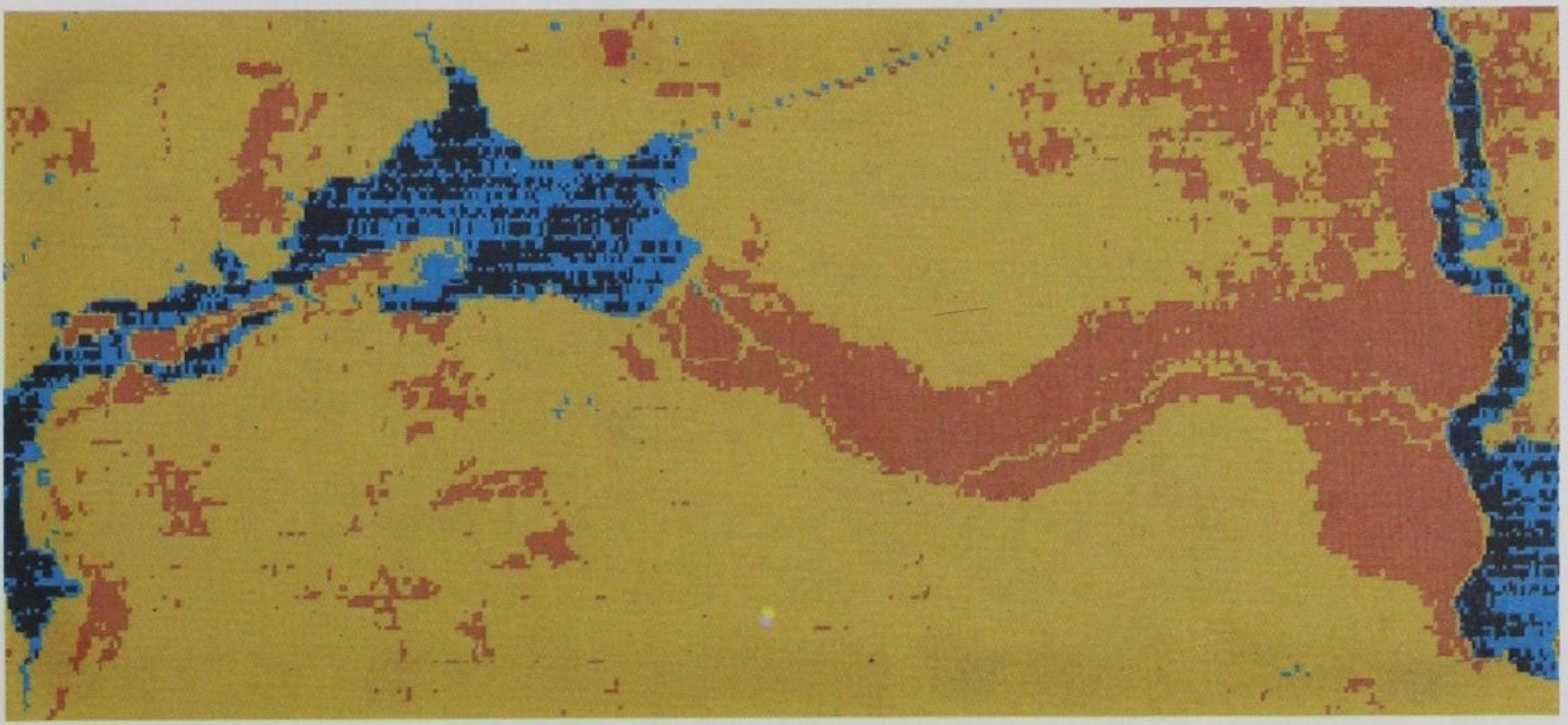
108. Preliminary results indicated that the digital processing techniques can be used effectively to find and document spectral anomalies that may vary with vegetation conditions. Of course, the resolution of a map produced in this manner is limited to the pixel size, which is now roughly that of a football field. Resolution of Landsat images is scheduled to improve, but even then mapping of aquatic plant infestations using this means would be applicable only to rather large water bodies. Each Landsat satellite passes over the same spot on the earth's surface once every 18 days, such that monitoring conditions of the same area on the earth every 9 days is a routine matter of buying the appropriate image from the Earth Resources Observation Systems (EROS) Data Center. For some applications, if fine resolution is not necessary, regional reconnaissance by Landsat could be a



a. 24 DECEMBER 1972

LEGEND

GOLD: PRINCIPALLY SAND HILL SCRUB
ORANGE: SWAMP AND BAY HEADS
DARK BLUE: OPEN WATER
LIGHT BLUE: AQUATIC PLANTS



b. 10 APRIL 1973

Figure 22. Image of Rodman Reservoir, Florida, produced from CCT's

useful, economical alternative to aircraft photographic missions. It should be emphasized here, however, that study results indicate that only areas containing surface aquatic plants may be reliably discriminated from areas containing no surface aquatic plants. A finer detailing, such as discriminating among different types of plants, was not determined to be possible with Landsat.

109. Visual inspection of Landsat images, particularly band 7, can yield information concerning surface vegetation. However, the digital processing of the actual CCT radiance values gives the maximum resolution obtainable with the system.

Synthetic aperture SLAR

110. A radar-imaging mission of the Withlacoochee River Basin, Florida, and the area from Lake Apopka to Orlando, Florida, was executed by the 363d Tactical Reconnaissance Wing, U. S. Air Force Tactical Air Command, Shaw Air Force Base, South Carolina. The SLAR imagery was obtained with the AN/APQ 102 synthetic aperture system, covering a ground swath of approximately 32 km for each flight path and having a resolution of approximately 15 m. A previous study conducted for NASA by the Environmental Research Institute of Michigan demonstrated the feasibility of observing large areas of floating aquatic plants using a very sophisticated and experimental radar system. The U. S. Air Force radar system is more operations oriented in that it has been used for many years as the standard radar-imaging system for Air Force reconnaissance missions. High-altitude aerial photographs of the study areas were obtained to aid in evaluation of the aquatic plant information available on the radar imagery.

111. Figures 23 and 24 show radar images of East Lake Tohopekaliga and Lake Rousseau, respectively. East Lake Tohopekaliga is a "sinkhole" lake located about 30 km south of Orlando, Florida, and adjacent to St. Cloud, Florida. Aquatic species include *Scirpus* sp., waterhyacinth, pickerelweed (*Pontederia* sp.), and *Panicum* sp. Lake Rousseau is a partly artificial impoundment located on the Gulf side of the Cross-Florida Barge Canal. The submersed plant community is dominated by hydrilla with an emergent/tussock distribution over a great portion

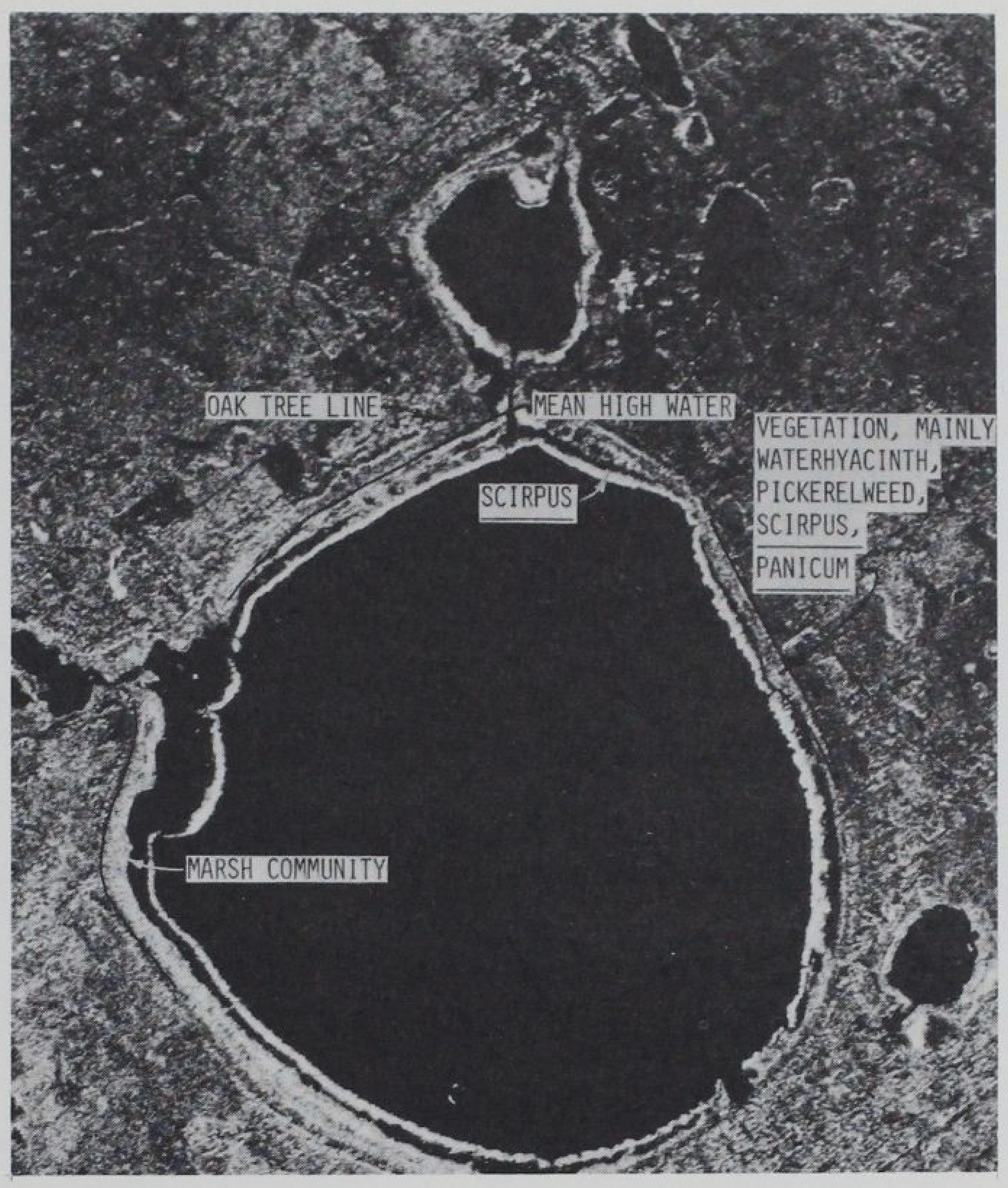


Figure 23. Enlarged SLAR image of East Lake Tohopekaliga, Florida

consisting of a variety of genera -- Typha, Pontederia, Salix, Scirpus, Panicum, and Nuphar. Mats of waterhyacinth and waterlettuce are prominent.

112. The tonal variations evident on the radar images were evaluated by personnel familiar with the aquatic plant conditions at each water body. Mr. Vince Williams, Florida Game and Fresh Water Fish Commission (FGFFC), Kissimmee, Florida, evaluated the imagery of Lake Tohopekaliga and Mr. Lowell Trent, FGFFC, Eustis, Florida, analyzed the imagery of Lake Rousseau. Their analyses indicated that the radar system was capable of detecting large infestations of floating and emergent aquatic plants such as waterhyacinth or waterlettuce. Also, such plants can be distinguished from fields and forests if the interpreter is familiar with the area. However, the radar imagery will probably not be as useful as Landsat because of its relative

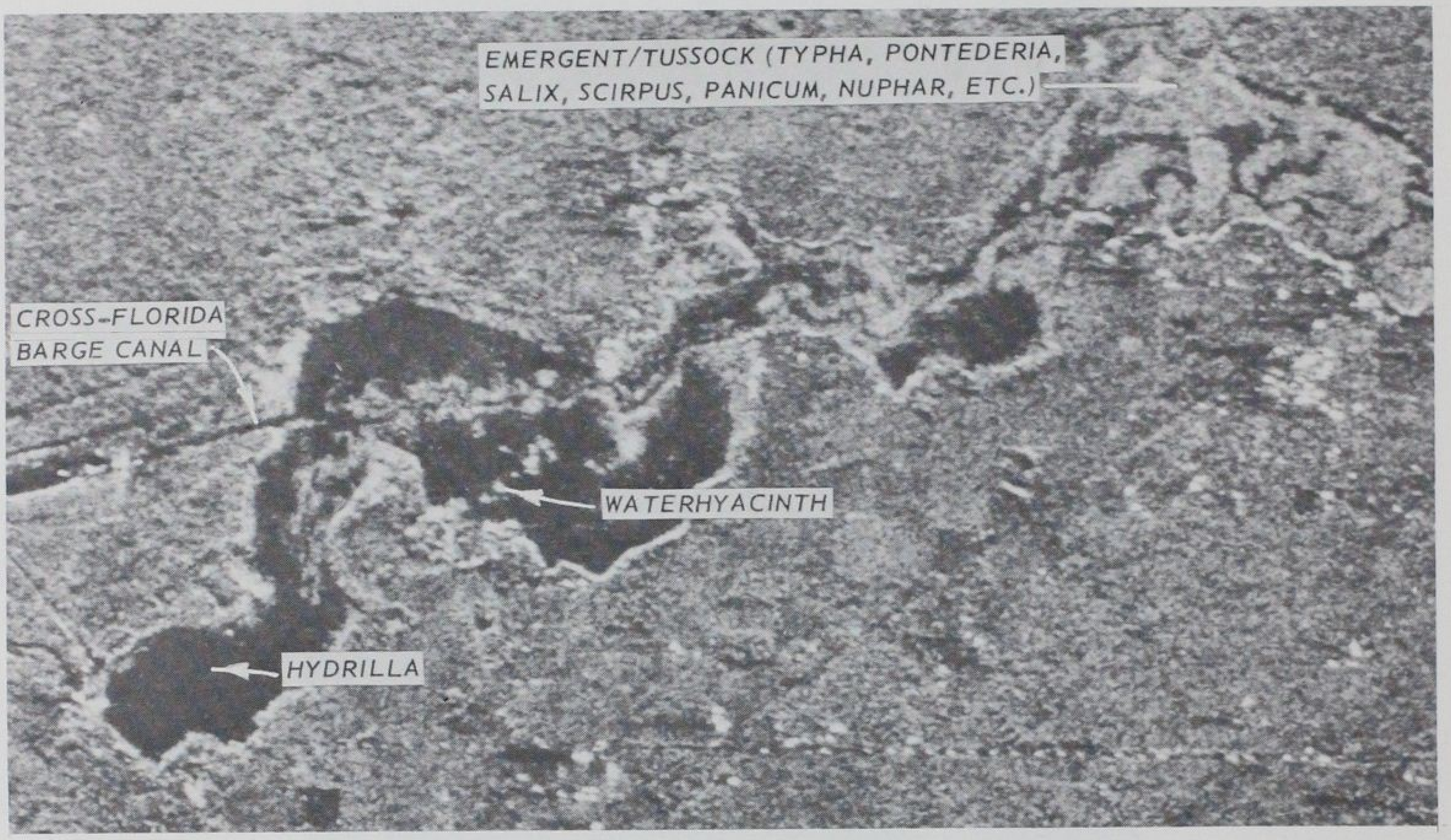


Figure 24. Enlarged SLAR image of
Lake Rousseau, Florida

unavailability. Moreover, such systems are not as mechanically reliable as the Landsat system has proven to be.

High-altitude aerial photography

113. U-2 imagery, primarily CIR photography ranging in scale from 1:76,000 to 1:130,000, was obtained for selected water bodies (Lake Marion, Lake Boeuf, Lake Theriot, and Ross Barnett Reservoir) from the EROS facility in Sioux Falls, South Dakota. The imagery was not available for times compatible with recent WES field surveys at the water bodies; however, good coverage was available for previous years allowing a general evaluation of the information that could be derived from similar high-altitude aerial photography. The following paragraphs discuss the evaluations made for each water body. Since ground-truth information was not available for the exact times that the images were obtained, the evaluations were based on information on previous "known" conditions, supplied by personnel familiar with the respective water bodies.

114. Lake Boeuf. NASA aircraft imagery including Lake Boeuf was obtained for March 1972, September 1974, and October 1974. The quality of the photographs was excellent and seasonal changes were evident. The March 1972 imagery shows definite sedimentation patterns in the lake, but surface vegetation on the lake proper is restricted to young waterhyacinth. The September 1974 image (Figure 25) shows more than one third of the lake surface area covered with plant material not evident in the March image. The October 1974 (Figure 26) image shows as much aquatic vegetation, but the areas surrounding the lake show a decline of green plant material, going from pinkish tones in September to slate blue in October.

115. Lake Theriot. NASA aircraft (U-2) imagery of Lake Theriot was obtained for March 1972 and October 1974. Both photographs were obtained with CIR film and a yellow filter. In a black-and-white enlargement of the March 1972 U-2 CIR photo of Lake Theriot, evidence of what is probably Eurasian watermilfoil at or near the surface is indicated in the southeast quadrant of the lake (Figure 27). A sedimentation plume at the mouth of the access canal is visible on the eastern shore of the lake. Highly reflective floating vegetation, probably waterhyacinth, is also evident along the western and southwestern shore. A line of vegetation following the lineament of an abandoned canal is visible just east of the main canal leading into the northern side of the lake.

116. In a black-and-white enlargement of the October 1974 CIR image (Figure 28), the shadows of submersed vegetation suggested in the March 1972 image (Figure 27) are boldly illustrated. Two giant lobes extending almost the length of the lake indicate Eurasian watermilfoil. The lacy pattern of this feature agrees in general with patterns usually formed by submersed aquatics. The floating-leaved vegetation seen principally in much lighter patches in the upper left quadrant does not appear to be spatially dominant in this lake at the time this photograph was taken.

117. Ross Barnett Reservoir. NASA aircraft (U-2) imagery of the Ross Barnett Reservoir was obtained for August 1973 (Figure 29),

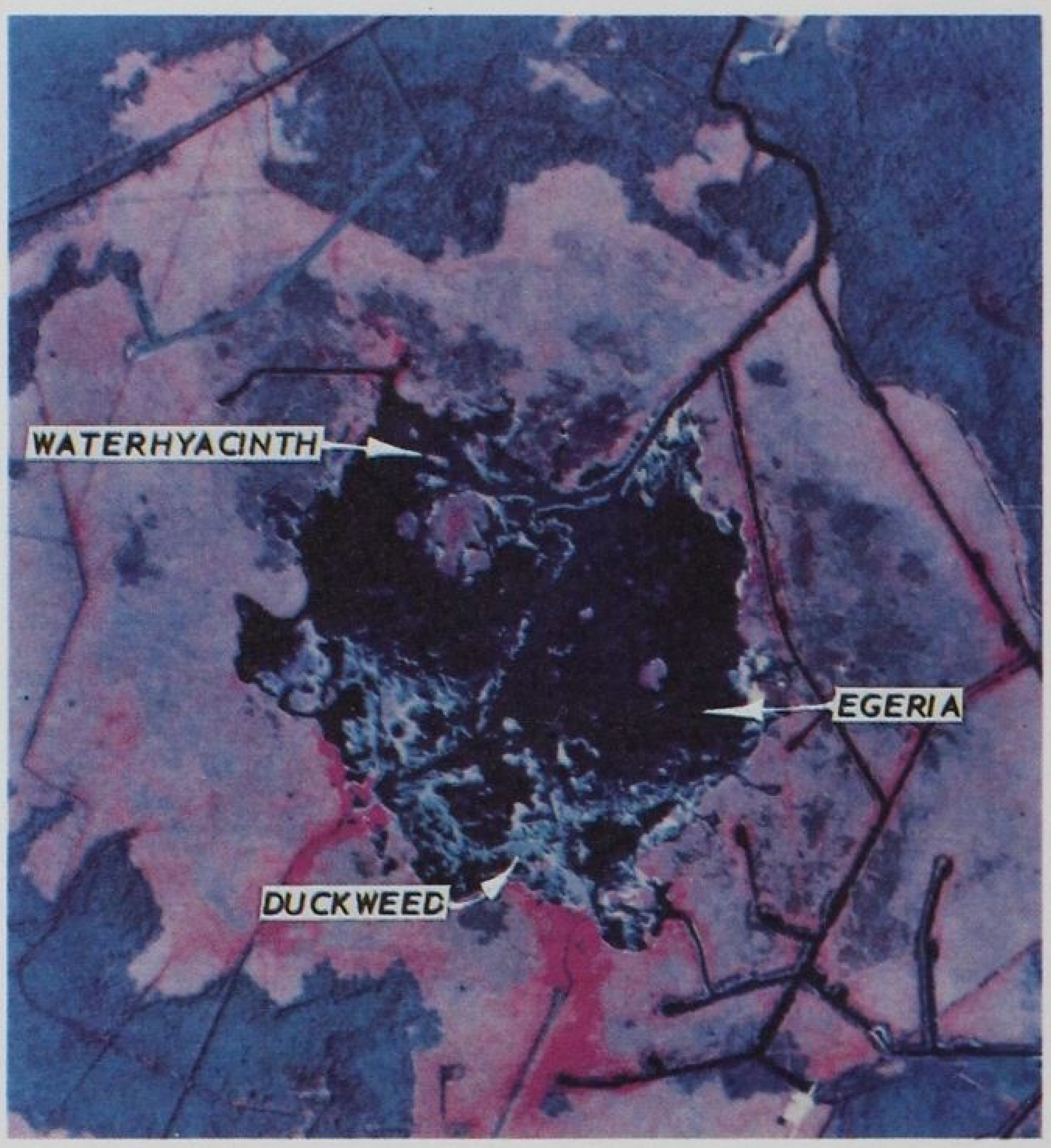


Figure 25. U-2 photograph of Lake Boeuf
(September 1974)

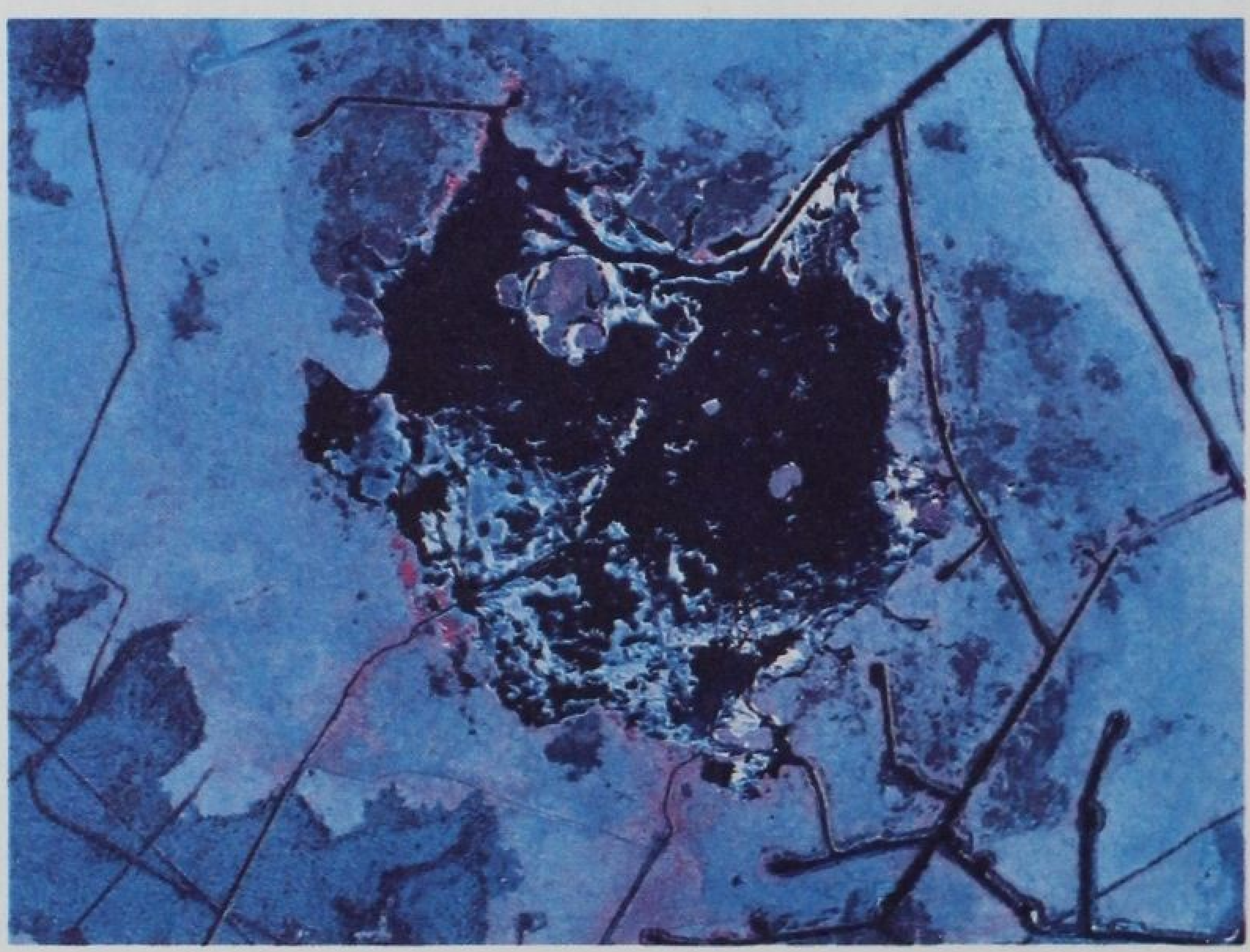


Figure 26. U-2 photograph of Lake Boeuf
(October 1974)

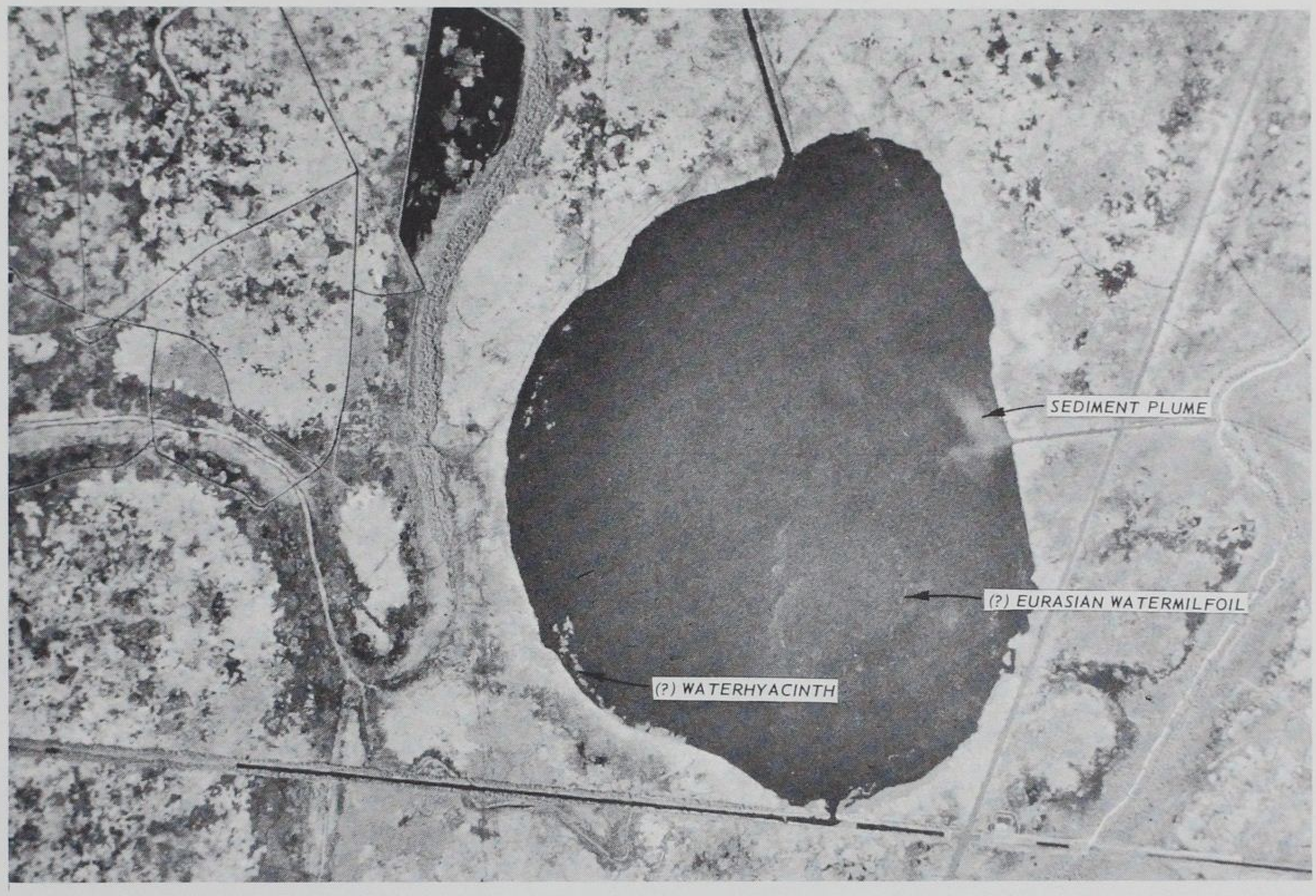


Figure 27. March 1972 U-2 image of
Lake Theriot, Louisiana

September 1974 (Figure 30), and February 1975 (Figure 31).

118. Examination of the U-2 CIR photographs showed that infestations of watershield, lotus, and waterlilies were apparent on the August 1973 and September 1974 imagery. It was not readily apparent if the individual plant types could be identified on the imagery although two distinct tones are evident in the areas known to have been floating-leaved aquatic plant infestations. The February 1975 image does not show any floating vegetation; however, plants were not expected to be evident during the winter months.

119. Lake Marion. NASA aircraft (U-2) imagery of the Lake Marion area was obtained for September 1972 (Figure 32). Examination of the imagery for areas where recent ground surveys had been conducted indicated patterns very similar to those presently observed for the egeria and waterprimrose infestations currently existing on the lake. Larger scale photography obtained in May 1974 (Figure 33) had similar

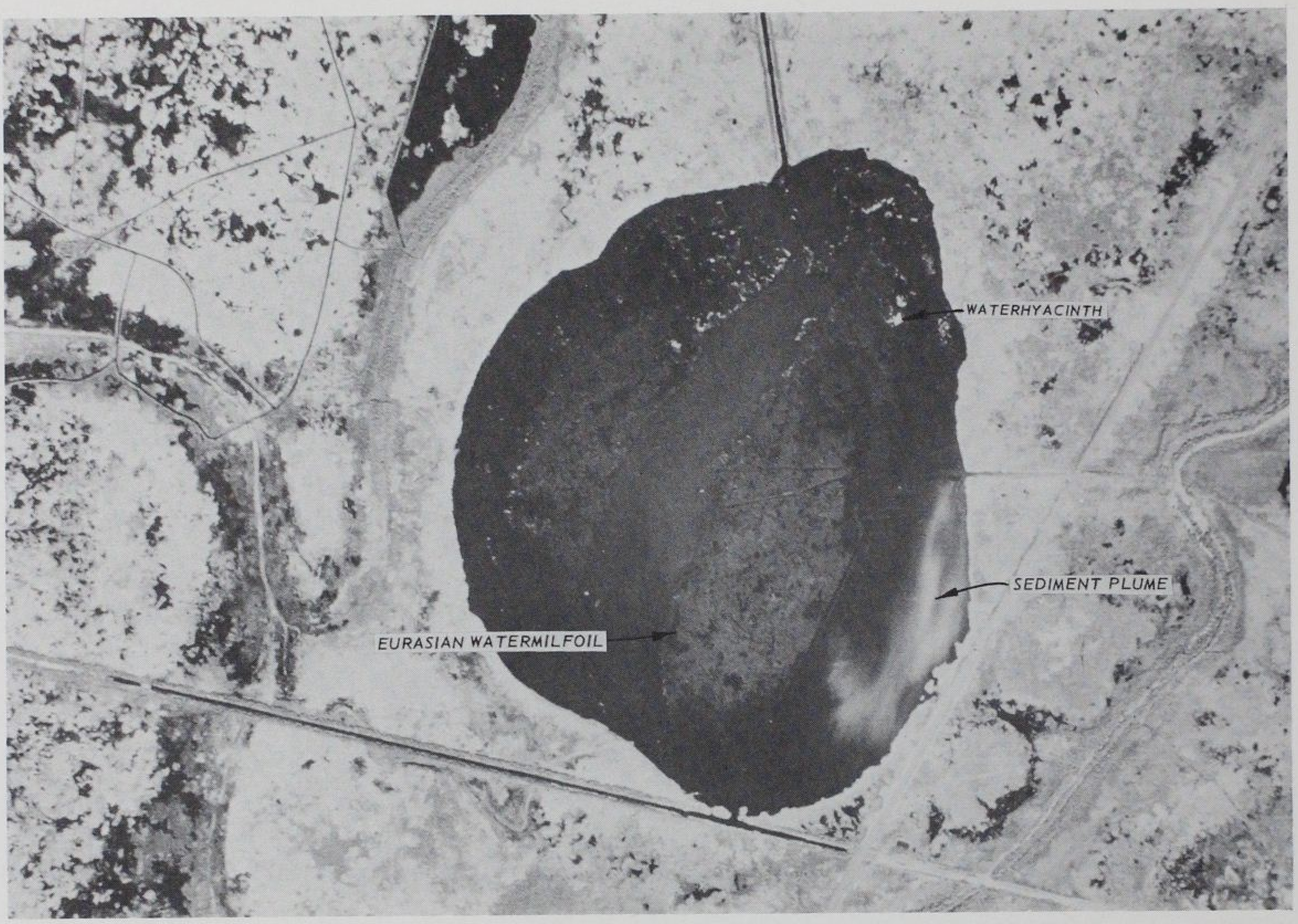


Figure 28. October 1974 U-2 image of
Lake Theriot, Louisiana

patterns in the same areas, implying that the plants may grow out from a locus in a pattern more or less dictated by the plant type and local water conditions. Infestations of both egeria and waterprimrose were evident on the U-2 photography.

Summary of Results

Landsat

120. Results of the field tests showed that Landsat imagery can be used effectively to depict areas with emergent or floating aquatic plant infestations, if the infestations are large enough to be resolved by the sensor system. Plant infestations that are submersed but not near the surface or topped out cannot be detected reliably with the current Landsat imagery. Nonetheless, the easy availability of Landsat images, periodic coverage, and relatively low cost for pictorial

Figure 29. August 1973 U-2 image of Ross Barnett Reservoir, Mississippi

Figure 30. September 1974 U-2 image of Ross Barnett Reservoir, Mississippi

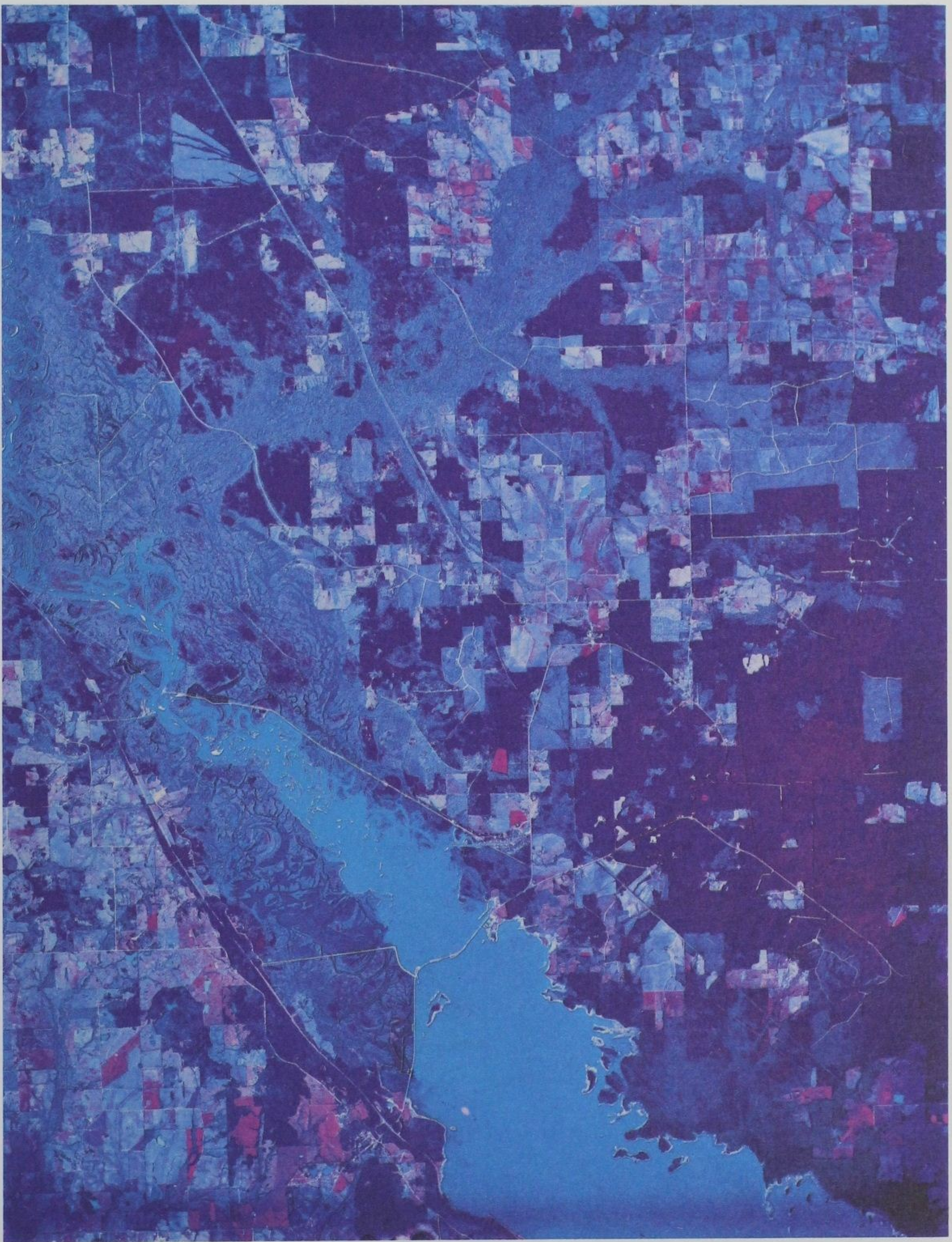


Figure 31. February 1975 U-2 image of Ross Barnett Reservoir, Mississippi

Figure 32. September 1972 U-2 image of
Lake Marion, South Carolina

Figure 33. May 1974 panchromatic image of Lake Marion, South Carolina

products are definite advantages. The inability to consistently detect submersed plant infestations, the inability to spatially resolve small water bodies (less than a few pixels in dimension) sufficiently for visual interpretation, the relatively high cost of digital analyses for larger areas (i.e. many scenes), and the time required to acquire Landsat imagery after it is received from the satellite are disadvantages. Landsat imagery does provide a limited capability for discriminating plant species if the interpreter has prior knowledge of species present in the study area.

Synthetic aperture SLAR

121. Synthetic aperture SLAR imagery is not considered an immediately applicable tool for aquatic plant mapping because it is relatively unavailable to Corps users, would be expensive to acquire, and does not have the capability to detect submersed plant infestations. Radar imagery can detect floating or emergent plant infestations and allows all-weather imaging, day or night.

High-altitude aerial photography

122. High-altitude CIR aerial photography (photo scales from 1:60,000 to 1:120,000) can be used at the original scale for reconnaissance purposes; the same images can be enlarged five times or more to examine smaller areas in more detail. This appears to be a particularly powerful combination. The major disadvantage of the use of high-altitude aerial photos for very large areas is the relatively high cost (compared to Landsat) of acquiring the imagery and the relatively large number of photos that need be handled. Both surface and submersed plant infestations can be effectively delineated on properly acquired CIR photos, and the spatial resolution is considerably better than that of Landsat images.

PART V: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

123. The objective of this study was to investigate existing remote sensor technology for its capability to detect and to identify aquatic plant infestations on both a detailed and regional scale (paragraph 3c).

Detailed survey capability

124. For detailed survey capability four types of discrimination were examined: (a) submersed plant versus water, (b) emergent plant versus water, (c) submersed plant versus submersed plant, (d) emergent plant versus emergent plant, and (e) emergent plant versus submersed plant. Both model studies and field studies showed that CIR with a yellow filter exhibits the highest overall success in achieving discrimination (paragraphs 40 and 58). However, black-and-white IR showed the highest rate of success in discrimination of infested and uninfested areas (paragraph 58).

125. An operational procedure as outlined in paragraphs 88 through 97 works well in mapping the aquatic plants of interest in a given body of water. This procedure gives a rational method whereby the user can plan, execute, and analyze the results of a remote sensing mission. Previous information concerning the species composition of the aquatic vegetation contributes significantly to successful identification and delineation of the various species, particularly among the submersed plants.

126. Rational mission planning is necessary for optimum success of the mission since the information desired must consider climatic conditions, growth stage, water clarity, and time of day as discussed in paragraphs 71 through 74.

127. Standard visual photointerpretation techniques were determined to be the most cost-effective means of extracting detailed survey information from the aerial photography since they require minimum training and equipment.

Regional survey capability

128. The tools shown most promising for regional reconnaissance with respect to adequacy and cost were Landsat and high-altitude CIR photography (paragraphs 120 and 121). For detecting surface aquatic plant infestations, Landsat is the most cost effective, although its rather large resolution unit limits its use to larger water bodies; also, it cannot reliably detect submersed plant infestations. High-quality, high-altitude photography shows strong potential for species identification, perhaps justifying its higher cost in some regional surveys.

Recommendations

129. It is recommended that the following work be undertaken as a result of the information gained by this study:

- a. A handbook should be produced providing regional interpretive keys for the identification of aquatic plants at low, medium, and high altitudes. High-quality color reproduction of this key should be emphasized.
- b. A remote sensing mission planning manual with particular emphasis on aquatic plants should be produced and distributed to each Corps District.
- c. Additional efforts should be undertaken to better define specific methods for reconnaissance survey capabilities.

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Table 1

Summary of Literature Survey

							Plant Genera Imaged	
Reference (No.)	Date(s)	Sun Angle	Photo Scale	Location	Film	Camera	Submersed	Emergent
Vause and Davis (3)	1973-1974	30-50°	1:2000-1:3000	Florida	Color, false-color infrared	KA-2 (9 in.)	Hydrilla Cabomba *Utricularia*	*Nymphaea* *Nuphar* *Eichhornia*
Benton and Newman (4)	1974		1:7500-1:40,000	Texas	Color, false-color infrared	RC-9 and Hasselblad (70 mm)	Hydrilla *Ceratophyllum* *Potamogeton*	*Eichhornia* *Lemna* *Wolffia*
Gustafson and Adams (5)	1972	>± 1-1/2 hr local noon	1:17,000-1:34,000	Wisconsin	Color, false-color infrared	35 mm	*Myriophyllum*	*Oedogonium* (alga)
Meyer, Eng, and Gjersing (6)	1973	>± 1-1/2 hr local noon	1:3000-1:15,000	Minnesota	False-color infrared	Minolta (35 mm)	Only noted presence or absence of submersed and emergent plants	
Markham, Philipson, and Russell (7)	1968-1976		1:5000-1:14,000	New York	Color, false-color infrared	Hasselblad (70 mm)	*Heteranthera* *Potamogeton* *Myriophyllum* *Chara*	*Heteranthera* *Nuphar* *Scirpus* *Typha* *Pontederia* *Sparganium*

Table 2

Aquatic Plants for Which Spectral Reflectance

Data Were Collected

Date	Location	Organism/Feature
September 1975	Florida	Waterhyacinth, alligatorweed, frogbit, waterfern, tapegrass, pickerelweed, hydrilla, pennywort, green algae, cattail, water paspalum, Eurasian watermilfoil, *Salvinia*, spatterdock, waterlettuce, egeria, associated water
September 1975	New York	Waterchestnut, associated water
September 1975	Louisiana	Waterhyacinth, coontail, cabomba, hydrilla, associated water
October 1975	Texas	Waterhyacinth, alligatorweed, associated water
July 1976	South Carolina	Egeria, waterprimrose, waterlily, associated water
September 1976	Louisiana	Waterhyacinth (living and dead), American lotus, egeria, frogbit, duckweed, hydrilla, Eurasian watermilfoil, *Panicum*, associated water

Table 3

Reflectance Data Obtained With ISCO Radiometer

Data Set	Location	Date	Time	Target	Percent Reflectance by Wavelength, um										
					0.400	0.450	0.500	0.550	0.600	0.650	0.700	0.750	0.850	0.950	1.050
					Florida										
1	Salt Springs 3	23 Sep 75	1430	Waterhyacinth	2.0	2.3	2.6	6.5	4.6	3.7	8.9	34.9	41.1	32.6	37.4
2	Salt Springs 4		1500	Alligatorweed	1.9	2.5	3.3	7.5	5.5	4.1	9.4	28.7	29.1	27.0	32.7
3	Lake Ocklawaha 2		1020	Frogbit	1.0	2.5	3.2	8.0	6.3	4.5	11.3	29.4	35.2	29.2	29.6
4	Lake Ocklawaha 3		1050	Waterfern	2.0	2.3	2.5	3.2	4.9	4.6	9.9	24.5	30.6	26.2	34.4
5	Lake Ocklawaha 5		1145	Secchi disc (out of water)	23.0	47.3	41.5	44.4	41.0	41.7	49.6	42.4	43.2	39.1	32.3
6	Lake Ocklawaha 5		1145	Secchi disc (4 in. deep)	0.7	1.6	8.6	13.5	20.5	21.6	25.6	15.4	10.4	1.8	0.6
7	Lake Ocklawaha 6		1210	*Vallisneria*	3.0	3.0	3.2	7.1	5.8	5.8	12.4	36.1	36.0	41.8	49.5
8	Lake Ocklawaha 1		1000	Blooming waterhyacinth	4.9	5.0	4.4	9.7	7.8	7.3	14.9	34.2	28.9	31.0	33.9
9	Lake Ocklawaha 1		940	Pickerelweed	2.0	4.8	4.5	9.1	6.2	4.9	11.6	41.9	53.0	46.8	43.4
10	Lake Ocklawaha 1		0940	Hydrilla (out of water)	2.0	3.0	2.4	5.8	4.9	3.7	11.2	24.9	37.7	38.2	41.3
11	Salt Springs 1		1355	Water pennywort	0.8	0.8	0.7	2.3	1.7	1.1	3.4	17.4	22.2	11.5	21.2
12	Salt Springs 1		1345	Green algae	2.6	2.0	3.3	4.4	3.5	2.8	8.8	13.9	19.7	9.0	11.6
13	St. Johns River 4	22 Sep 75	1540	Cattail	3.3	3.6	5.0	8.1	7.8	8.5	11.2	21.2	25.6	25.2	24.8
14	Black Creek 2		1430	Secchi disc (out of water)	30.2	44.0	45.0	43.4	46.0	44.7	39.5	43.4	41.8	35.0	35.8
15	Black Creek 2		1430	Secchi disc (16 in. deep)	5.0	0.9	0.2	1.8	0.3	1.9	1.8	0.0+	1.3	6.0	1.5
16	Black Creek 1		1400	Water paspalum (clouds)	3.3	3.6	4.0	8.1	5.6	4.9	11.5	49.7	52.9	41.7	48.5
17	Salt Springs 2	23 Sep 75	1415	Eurasian watermilfoil	3.8	3.9	3.9	5.9	5.8	6.0	9.9	18.4	16.9	10.0	12.4
18	Salt Springs 2	23 Sep 75	1415	Eurasian watermilfoil (out of water)	3.0	3.8	4.0	6.1	4.8	4.9	8.2	18.2	17.2	21.9	24.4
19	Black Creek 1	22 Sep 75	1340	*Salvinia*	1.5	2.5	3.5	6.4	6.1	5.1	9.6	17.2	20.6	22.0	25.4
20	Black Creek 5	22 Sep 75	1600	Waterhyacinth	2.6	3.8	4.1	9.8	6.2	5.8	10.7	47.9	51.6	45.3	47.1
21	Lake Ocklawaha 5	23 Sep 75	1150	Water surface	3.6	3.8	4.2	4.9	4.3	4.7	5.7	6.2	4.7	5.1	4.2
22	Black Creek 6	22 Sep 75	1605	Spatterdock	4.1	4.8	6.1	10.3	7.5	5.2	9.9	33.5	43.2	35.1	36.7
23	Peter's Creek 3	22 Sep 75	1505	Alligatorweed (terrestrial)	3.0	2.7	2.7	8.8	5.8	3.8	8.4	37.8	39.0	36.0	37.9
24	Black Creek 2	22 Sep 75	1415	Waterlettuce (clouds)	2.0	2.7	3.9	11.4	6.9	4.9	16.6	40.1	37.1	29.5	36.0
25	Lake Ocklawaha 4	23 Sep 75	1110	Egeria	4.1	3.5	3.5	4.7	3.6	3.3	4.4	16.4	15.0	7.0	10.6
26	Lake Ocklawaha 4	23 Sep 75	1110	Egeria (out of water)	1.7	1.9	1.9	4.3	3.2	2.7	7.8	27.0	34.3	27.3	40.7
27	Lake Ocklawaha 7	23 Sep 75	1230	Hydrilla	3.8	2.7	3.2	4.7	4.3	4.1	5.6	13.5	13.5	10.2	12.1
					Louisiana										
28	Lake Theriot 1	25 Sep 75	1200	Water	2.9	3.0	2.9	2.8	2.8	2.7	2.6	2.7	2.1	1.7	1.7
29	Lake Theriot 1		1115	Waterhyacinth	1.4	2.4	2.6	7.4	5.1	3.4	10.5	37.6	40.8	38.8	40.9
30	Minors Canal 3		1450	Waterhyacinth (3-1/2 ft tall)	2.7	3.1	2.9	8.2	5.1	3.2	8.8	43.4	46.0	38.5	36.0
31	Minors Canal 2		1450	Coontail	5.1	1.6	4.4	5.0	6.2	5.8	6.4	3.2	6.9	4.7	3.4
32	Lake Theriot 1		1300	Secchi disc (in water)	2.8	5.4	10.5	16.6	17.1	17.0	18.4	10.8	10.7	0.6	0.5
33	Lake Theriot 1		1300	Secchi disc (out of water)	37.9	60.6	67.8	60.8	60.9	53.7	63.0	59.0	54.0	48.0	42.9
34	Lake Theriot 2		1400	Coontail (in boat)	1.0	1.6	2.2	3.3	2.7	2.1	4.8	15.3	19.2	19.6	24.9
35	Lake Theriot 2		1400	Coontail	4.5	3.9	4.1	4.8	4.8	4.5	5.3	7.1	5.6	4.5	3.7
36	Lake Theriot 1		1330	Cabomba (in boat)	2.4	2.7	3.4	4.7	4.4	3.6	6.1	8.9	10.0	16.2	18.7
37	Lake Theriot 1		1330	Cabomba (in water)	3.6	3.2	3.8	4.5	3.3	3.7	4.0	5.0	5.2	2.7	3.7
38	Lake Theriot 1		1215	Hydrilla (in boat)	1.7	1.7	1.7	2.6	2.5	2.6	4.9	11.9	14.2	20.8	23.5
39	Lake Theriot 1		1215	Hydrilla	3.8	3.4	3.5	2.8	2.7	2.4	3.7	7.6	8.9	4.3	7.7
					Texas										
40	Trinity River	8 Oct 75	1118	Waterhyacinth	1.9	2.0	2.5	2.5	4.5	3.5	7.8	29.4	33.9	35.0	35.4
41	Galveston 1		1146	Waterhyacinth	0.9	2.1	2.7	5.8	4.7	3.8	7.6	29.4	32.0	32.3	34.3
42	Galveston 1		1200	Waterhyacinth	1.5	1.6	2.0	5.1	4.1	3.1	7.7	28.2	31.1	31.3	31.2
43	Trinity Bridge 1		1220	Water	2.0	0.5	1.2	2.8	2.5	2.7	2.9	3.5	3.4	2.6	2.5
44	Lost and Old River 2		1301	Alligatorweed	1.3	2.4	3.1	6.0	5.3	4.6	8.1	19.5	20.1	19.9	20.3
45	Lost and Old River 2		1316	Alligatorweed	1.7	2.5	3.2	6.3	5.2	4.5	8.8	21.0	20.9	20.6	21.4
46	Lost and Old River 2		1325	Alligatorweed	2.1	2.3	2.8	6.1	5.2	4.3	9.2	21.1	20.9	20.8	21.2
47	Trinity River 3		1440	Secchi disc (out of water)	31.4	60.7	54.2	56.8	58.2	52.4	41.8	41.6	37.0	36.0	28.7
48	Trinity River 1		1516	Waterhyacinth	1.4	1.7	2.1	5.3	3.9	3.0	8.2	26.2	29.4	30.6	31.1

Table 4

Spectral Reflectance Data Obtained with ERTS Radiometer

Data					Percent Reflectance by Wavelength, µm			
Set	Location	Date	Time	Target	0.5-0.6	0.6-0.7	0.7-0.8	0.8-1.1
49	Lake Theriot, La. 1	14 Sep 76	1400	Hydrilla, Site 1	7.1	2.0	14.0	12.9
50	Lake Theriot, La. 2		1409	Hydrilla, Site 1	1.1	1.9	14.2	15.4
51	Lake Theriot, La. 3			Waterhyacinth, Site 1	3.6	3.8	25.6	39.0
52	Lake Theriot, La. 4			Waterhyacinth, Site 1	7.2	4.5	36.0	58.3
53	Lake Theriot, La. 5			Hydrilla, Site 2	2.0	1.9	9.0	9.6
54	Lake Theriot, La. 6			Hydrilla, Site 2	1.8	1.9	9.8	9.6
55	Lake Theriot, La. 7			Waterhyacinth	4.3	3.2	33.7	34.7
56	Lake Theriot, La. 8			Clear water w/hydrilla 10 cm below (overcast)	4.4	3.2	3.1	1.8
57	Lake Theriot, La. 9			Clear water w/hydrilla 10 cm below (overcast)	2.3	2.6	2.9	1.8
58	Lake Theriot, La. 10			Hydrilla w/milfoil, Site 3	2.1	1.6	13.5	12.2
59	Lake Theriot, La. 11			Hydrilla w/milfoil, Site 3 (full sun)	2.4	1.6	11.2	10.3
60	Lake Boeuf, La. 1	15 Sep 76	0840	Open water, Site 16	2.9	2.9	2.1	0.9
61	Lake Boeuf, La. 2		0847	Open water, Site 16	2.8	2.8	2.0	1.0
62	Lake Boeuf, La. 3		9851	Dead waterhyacinth	6.8	9.5	18.0	37.5
63	Lake Boeuf, La. 4		0853	Dead waterhyacinth	4.8	11.2	20.3	31.1
64	Lake Boeuf, La. 5			Duckweed	11.6	12.5	43.2	43.2
65	Lake Boeuf, La. 6		0930	*Panicum*	6.3	7.9	28.3	41.2
66	Lake Boeuf, La. 7			Duckweed	5.9	5.2	15.6	10.6
67	Lake Boeuf, La. 8			Healthy waterhyacinth	3.3	4.4	21.8	41.5
68	Lake Boeuf, La. 9		0916	Thick duckweed	9.5	8.3	25.0	26.0
69	Lake Boeuf, La. 10		0933	American lotus	9.3	6.7	29.0	33.8
70	Lake Boeuf, La. 11			Yellow waterlily over Egeria	5.3	5.0	26.1	28.2
71	Lake Boeuf, La. 12		0958	Frogbit	5.0	5.0	21.4	38.5
72	Lake Marion, S. C.	22 Jul 76		Naiad	4.3	3.0	13.0	7.0
73				Waterprimrose	7.8	6.0	18.0	26.4
74				*Egeria densa*	4.8	4.0	10.1	11.0
75				Water	3.7	6.5	4.0	4.0
76				Yellow waterlily	12.8	11.3	25.0	29.0
77	Lake Marion, S. C. 1	22 Sep 77		Duckweed, alligatorweed over Egeria, Site 1	8.1	7.9	18.0	19.3
78	Lake Marion, S. C. 2			Duckweed, alligatorweed over Egeria, Site 1	8.0	7.6	18.0	20.2
79	Lake Marion, S. C. 3			Waterprimrose over Egeria, Site 1	3.4	4.0	9.5	12.3
80	Lake Marion, E. C. 4			Waterprimrose over Egeria, Site 1	5.6	6.0	21.6	28.4
81	Lake Marion, S. C. 5			Tall waterprimrose over Egeria, Site 1	6.4	7.0	20.6	22.0
82	Lake Marion, S. C. 6			Tall, thin waterprimrose over Egeria Site 1	8.2	6.8	19.1	22.0
83	Lake Marion, S. C. 7			Water, Site 1	7.2	5.9	2.3	1.3
84	Lake Marion, S. C. 8			Water, Site 1	5.2	6.3	2.9	1.6
85	Lake Marion, S. C. 1			Naiad, Site 2	2.3	1.4	3.1	4.0
86	Lake Marion, S. C. 2			Naiad, Site 2	2.1	1.6	3.3	2.9
87	Lake Marion, S. C. 3			Water, Site 2	2.5	2.2	1.3	0.8
88	Lake Marion, S. C. 4			Water, Site 2	2.0	2.0	1.2	0.6
89	Lake Marion, S. C. 1			Egeria, Site 3	3.3	3.3	9.3	9.0
90	Lake Marion, S. C. 2			Egeria, Site 3	11.1	8.5	3.3	3.5
91	Lake Marion, S. C. 3			Water, Site 3	2.7	1.5	0.8	0.5
92	Lake Marion, S. C. 4			Water, Site 3	1.9	1.6	0.9	1.0
93	Lake Seminole, Fla. 1	17 Mar 77		Cattail, Site 1	13.3	1.0	0.8	0.2
94	Lake Seminole, Fla. 2			Cattail, Site 1	1.6	1.6	2.0	1.0
95	Lake Seminole, Fla. 3			Water, Site 1	2.2	1.2	1.0	0.6
96	Lake Seminole, Fla. 4			Water, Site 1	14.4	1.2	0.5	0.9
97	Lake Seminole, Fla. 1			Waterlily, Site 2	2.6	2.3	2.1	2.2
98	Lake Seminole, Fla. 2			Waterlily, Site 2	3.4	3.5	3.3	2.8
99	Lake Seminole, Fla. 3			Waterlily, Site 2	7.7	8.1	30.0	31.5
100	Lake Seminole, Fla. 1			Cattail, Site 3	2.4	7.2	12.0	4.8
101	Lake Seminole, Fla. 2			Cattail, dry, Site 3	9.0	9.0	19.9	4.7
102	Lake Seminole, Fla. 1			Eurasian watermilfoil, Site 4	3.6	3.0	3.6	1.2
103	Lake Seminole, Fla. 2			Eurasian watermilfoil, Site 4	2.5	0.4	2.0	1.7
104	Lake Seminole, Fla. 3			Water, Site 4	3.8	3.4	1.9	2.2
105	Lake Seminole, Fla. 4			Water, Site 4	3.9	4.0	2.9	0.7
106	Lake Seminole, Fla. 1			Giant cutgrass, Site 5	4.2	4.1	9.0	9.3
107	Lake Seminole, Fla. 2			Giant cutgrass, Site 5	3.5	9.3	6.0	19.3
108	Lake Seminole, Fla. 3			Water, Site 5	5.6	7.0	9.0	1.9
109	Lake Seminole, Fla. 4			Water, Site 5	7.2	8.6	3.8	1.9
110	Lake Seminole, Fla. 1			Waterhyacinth (weak), Site 6	13.3	10.8	34.3	19.9
111	Lake Seminole, Fla. 2			Waterhyacinth (weak), Site 6	7.2	20.0	24.4	31.3
112	Lake Seminole, Fla. 3			Water, Site 6	7.5	7.1	3.0	1.7
113	Lake Seminole, Fla. 4			Water, Site 6	7.7	8.1	4.1	1.8
114	Lake Seminole, Fla. 1	29 Apr 77		Water, Site 1	1.2	0.8	0.4	0.2
115	Lake Seminole, Fla. 2			Water, Site 1	1.0	0.9	0.3	0.2
116	Lake Seminole, Fla. 3			Hydrilla, Site 1	1.6	1.1	0.4	0.3
117	Lake Seminole, Fla. 4			Hydrilla, Site 1	1.9	1.2	0.9	0.3
118	Lake Seminole, Fla. 1			Waterlily, Site 2	10.8	9.0	37.1	49.7
119	Lake Seminole, Fla. 2			Waterlily, Site 2	9.0	10.8	36.0	36.0
120	Lake Seminole, Fla. 1			Cattail, Site 3	3.0	2.6	11.4	17.1
121	Lake Seminole, Fla. 2			Cattail, Site 3	3.0	3.0	11.4	18.0
122	Lake Seminole, Fla. 1			Eurasian watermilfoil, Site 4	3.1	5.0	10.8	8.4
123	Lake Seminole, Fla. 2			Eurasian watermilfoil, Site 4	2.8	3.5	7.4	8.1
124	Lake Seminole, Fla. 3			Water, Site 4	2.7	1.5	1.0	0.4
125	Lake Seminole, Fla. 4			Water, Site 4	6.3	5.9	1.7	0.8
126	Lake Seminole, Fla. 1			Giant cutgrass, Site 5	6.9	9.0	15.1	23.2
127	Lake Seminole, Fla. 2			Giant cutgrass, Site 5	6.9	8.7	13.8	15.9
128	Lake Seminole, Fla. 3			Water, Site 5	3.0	2.7	1.3	0.5
129	Lake Seminole, Fla. 4			Water, Site 5	2.9	2.8	0.9	0.5
130	Lake Seminole, Fla. 1			Waterhyacinth, Site 6	4.2	5.2	23.0	30.0
131	Lake Seminole, Fla. 2			Waterhyacinth, Site 6	6.3	5.2	21.6	27.0
132	Lake Seminole, Fla. 3			Murky water, Site 6	6.3	6.0	2.0	0.8
133	Lake Seminole, Fla. 4			Murky water, Site 6	4.4	3.6	1.7	1.0
134	Lake Seminole, Fla. 5			Dead waterhyacinth, Site 6	4.5	8.6	13.9	16.8
135	Lake Seminole, Fla. 6			Dead waterhyacinth, Site 6	5.0	4.7	13.6	12.3

Table 5

Summary of Model Predictions

Species Compared (Data Set Numbers)	Date	Optical Density Contrast Predictions by Film-Filter Combination*																
		Panchromatic										Color	CIR		Black-and-white IR			
		2402 -12	2403 -12	2402 -47B	2403 -47B	2402 -58	2403 -58	2402 -25A	2403 -25A	2402 -3	2403 -3	2448 -3	2443 -3	2443 -12	2424 -12	2424 -25A	2424 -87C	2424 -89B
Submersed Plant versus Water																		
Coontail versus water (35) (28)	22 Sep 75	M	0	0	0	0	0	M	0	0	0	X	X	X	X	X	X	X
Hydrilla versus water (39) (28)	22 Sep 75	0	0	0	0	0	0	0	0	0	0	0	M	X	X	X	X	X
Vallisneria versus water (7) (21)	23 Sep 75	0	0	0	0	0	0	M	0	0	0	X	X	X	X	X	X	X
Naiad versus water (72) (75)	2 Jul 76	0	0	0	0	0	0	0	M	0	0	X	X	X	X	X	0	X
Egeria versus water (74) (75)	2 Jul 76	0	0	0	0	0	0	0	0	0	0	X	X	X	X	X	X	X
Eurasian watermilfoil versus water (122) (104)	2 Jul 76	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	X	0
Eurasian watermilfoil versus water (123) (133)	29 Apr 77	M	0	0	0	X	M	0	0	M	0	X	X	X	X	X	X	X
Hydrilla versus water (117) (114)	29 Apr 77	0	0	0	0	0	0	0	0	0	0	X	X	X	0	0	0	0
Hydrilla versus water (116) (114)	29 Apr 77	0	0	0	0	0	0	0	0	0	0	M	0	0	0	0	0	0
Percent Success		22.2	0	0	0	11.1	11.1	22.2	11.1	11.1	0	77.8	77.8	77.8	66.7	66.7	77.8	66.7
Emergent Plant versus Water																		
Waterhyacinth versus water (29) (28)	22 Sep 75	X	M	0	0	X	M	X	M	X	0	X	X	X	X	X	X	X
Blooming waterhyacinth versus water (8) (21)	23 Sep 75	X	M	0	0	M	0	X	M	X	0	X	X	X	X	X	X	X
Frogbit versus water (3) (21)		0	0	0	0	0	0	0	0	0	0	X	X	X	X	X	X	X
Waterfern versus water (4) (21)		0	0	0	0	0	0	0	0	0	0	X	X	X	X	X	X	X
Pickerelweed versus water (9) (21)		M	0	0	0	0	0	0	0	0	0	X	X	X	X	X	X	X
Thick duckweed versus water (68) (60 and 61)	15 Sep 76	X	X	0	0	X	X	X	X	X	X	X	X	X	X	X	X	X
Healthy waterhyacinth versus water (67) (60 and 61)		0	0	0	0	0	0	X	0	0	0	X	X	X	X	X	X	X
Dead waterhyacinth versus water (62 and 63) (60 and 61)		X	X	0	0	X	M	X	X	X	X	X	X	X	X	X	X	X
American lotus and Yellow waterlily versus water (69) (60 and 61)		X	X	0	0	X	X	X	X	X	X	X	X	X	X	X	X	X
Panicum versus water (65) (60 and 61)		X	X	0	0	X	M	X	X	X	X	X	X	X	X	X	X	X

(Continued)

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* X = values greater than 0.35, tonal discrimination with unaided eye likely; M = values between 0.30 and 0.35, discrimination capability marginal; and 0 = values below 0.30, discrimination not probable.

(Sheet 1 of 5)

Table 5 (Continued)

Species Compared (Data Set Numbers)	Date	Optical Density Contrast Predictions by Film-Filter Combination																
		Panchromatic										Color	CIR		Black-and-white IR			
		2402 -12	2403 -12	2402 -47B	2403 -47B	2402 -58	2403 -58	2402 -25A	2403 -25A	2402 -3	2403 -3	2448 -3	2443 -3	2443 -12	2424 -12	2424 -25A	2424 -87C	2424 -89B
Emergent Plant versus Water (Continued)																		
Frogbit versus water (71) (60 and 61)	15 Sep 76	X	0	0	0	M	0	X	0	X	0	X	X	X	X	X	X	X
Yellow waterlily over egeria versus water (70) (60 and 61)	15 Sep 76	X	0	0	0	X	0	X	0	X	0	X	X	X	X	X	X	X
Waterprimrose versus water (73) (75)	2 Jul 76	0	0	0	0	X	M	0	0	0	0	X	X	X	X	X	X	X
Yellow waterlily versus water (76) (75)	2 Jul 76	X	X	0	0	X	X	X	M	X	X	X	X	X	X	X	X	X
Duckweed, alligatorweed over egeria versus water (78 and 79) (84)	22 Sep 77	0	0	0	0	0	0	0	0	0	0	M	X	X	X	X	X	X
Cattail versus water (93) (95)	17 Mar 77	X	X	0	0	X	X	0	0	X	X	X	X	X	M	0	X	0
Giant cutgrass versus water (126) (128 and 129)	29 Apr 77	X	X	0	0	X	X	X	X	X	X	X	X	X	X	X	X	X
Percent Success		70.6	52.9	0	0	70.6	52.9	64.7	47.1	64.7	41.2	100.0	100.0	100.0	100.0	94.1	100.1	94.1
Submersed Plant versus Submersed Plant																		
Egeria versus Hydrilla (25) (27)	23 Sep 75	0	0	0	0	M	0	0	0	0	0	X	X	X	0	0	0	0
Hydrilla versus Hydrilla (49 and 50) (53 and 54)	14 Sep 76	0	0	0	0	M	0	0	0	0	0	X	X	X	M	M	M	M
Hydrilla versus Hydrilla with milfoil (49 and 50) (58 and 59)	14 Sep 76	0	0	0	0	0	0	0	0	0	0	X	X	X	0	0	0	0
Hydrilla versus Hydrilla with milfoil (53 and 54) (58 and 59)	14 Sep 76	0	0	0	0	0	0	0	0	0	0	X	0	0	0	0	0	0
Naiad versus Egeria (72) (74)	2 Jul 76	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	X	0
Percent Success		0	0	0	0	40.0	0	0	0	0	0	80.0	60.0	60.0	20.0	20.0	40.0	20.0
Emergent Plant versus Emergent Plant																		
Waterhyacinth versus Waterhyacinth (29) (30)	22 Sep 75	X	M	0	0	X	0	X	M	X	0	X	X	X	X	X	X	X
Waterhyacinth versus Alligatorweed (40) (44)	8 Oct 75	0	0	0	0	0	0	0	0	0	0	X	M	M	0	0	M	0
Waterhyacinth versus Alligatorweed (20) (23)	22 Sep 75	0	0	0	0	0	0	0	0	0	0	M	X	X	X	X	X	X
Waterhyacinth versus Yellow waterlily (20) (22)	↓	0	0	0	0	0	0	0	0	0	0	X	X	X	X	X	X	X
Waterhyacinth versus Salvinia (20) (19)	↓	0	0	0	0	0	0	0	0	0	0	X	X	X	X	X	X	X
Waterhyacinth versus Waterlettuce (20) (24)	↓	0	0	0	0	0	0	0	0	0	0	X	X	X	X	X	X	X

(Continued)

(Sheet 2 of 5)

Table 5 (Continued)

Species Compared (Data Set Numbers)	Date	Optical Density Contrast Predictions by Film-Filter Combination																
		Panchromatic										Color	CIR		Black-and-white IR			
		2402 -12	2403 -12	2402 -47B	2403 -47B	2402 -58	2403 -58	2402 -25A	2403 -25A	2402 -3	2403 -3	2448 -3	2443 -3	2443 -12	2424 -12	2424 -25A	2424 -87C	2424 -89B
Emergent Plant versus Emergent Plant (Continued)																		
Watterlettuce (24) versus *Salvinia* (19)	22 Sep 78	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Alligatorweed (23) versus *Salvinia* (19)	22 Sep 78	0	0	0	0	0	0	0	0	0	0	X	X	X	0	0	0	0
Blooming waterhyacinth (8) versus Pickerelweed (9)	23 Sep 75	0	0	0	0	0	0	0	0	0	0	0	M	X	0	0	X	X
Blooming waterhyacinth (8) versus Frogbit (3)	23 Sep 75	0	0	M	0	0	0	0	0	0	0	X	X	X	0	0	0	0
Blooming waterhyacinth (8) versus Waterfern (4)	23 Sep 75	X	0	M	0	X	X	0	0	X	0	X	X	X	0	0	0	0
Thick duckweed (68) versus Healthy waterhyacinth (67)	15 Sep 76	X	X	0	0	X	X	X	M	X	X	X	X	X	0	0	X	0
Thick duckweed (68) versus Dead waterhyacinth (62 and 63)	↓	0	0	0	0	0	0	0	0	0	0	X	X	X	0	0	0	0
Thick duckweed (68) versus American lotus and yellow waterlily (69)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Thick duckweed (68) versus *Panicum* (65)		0	0	0	0	0	0	0	0	0	0	X	X	X	0	0	X	0
Thick duckweed (68) versus Frogbit (71)		M	0	0	0	X	M	0	0	M	0	X	X	X	0	0	M	0
Thick duckweed (68) versus Yellow waterlily over egeria (70)		M	0	0	0	M	0	0	0	0	0	X	X	X	0	0	0	0
Healthy waterhyacinth (67) versus Dead waterhyacinth (62 and 63)		X	X	0	0	0	0	X	X	X	X	X	X	X	0	0	0	0
Healthy waterhyacinth (67) versus American lotus and yellow waterlily (69)		X	M	0	0	X	X	0	0	X	M	X	X	X	0	0	0	0
Healthy waterhyacinth (67) versus *Panicum* (65)		M	0	0	0	M	0	M	0	M	0	X	X	X	0	0	0	0
Healthy waterhyacinth (67) versus Frogbit (71)		0	0	0	0	0	0	0	0	0	0	X	0	M	0	0	0	0
Healthy waterhyacinth (67) versus Yellow waterlily over egeria (70)		0	0	0	0	0	0	0	0	0	0	X	M	M	0	0	M	0
Dead waterhyacinth (62 and 63) versus American lotus and yellow waterlily (69)		0	0	0	0	0	0	0	0	0	0	X	X	X	0	0	0	0

(Continued)

(Sheet 3 of 5)

Table 5 (Continued)

Species Compared (Data Set Numbers)	Date	Optical Density Contrast Predictions by Film-Filter Combination																
		Panchromatic										Color	CIR		Black-and-white IR			
		2402 -12	2403 -12	2402 -47B	2403 -47B	2402 -58	2403 -58	2402 -25A	2403 -25A	2402 -3	2403 -3	2448 -3	2443 -3	2443 -12	2424 -12	2424 -25A	2424 -87C	2424 -89B
Emergent Plant versus Emergent Plant (Continued)																		
Dead waterhyacinth versus *Panicum* (62 and 63) (65)	15 Sep 76	0	0	0	0	0	0	0	0	0	0	0	0	M	0	0	0	0
Dead waterhyacinth versus Frogbit (62 and 63) (71)		0	0	0	0	0	0	M	M	0	0	X	X	X	0	0	0	0
Dead waterhyacinth versus Yellow waterlily over egeria (62 and 63) (70)		0	0	0	0	0	0	M	M	0	0	X	X	X	0	0	0	0
American lotus and yellow waterlily versus *Panicum* (69) (65)		0	0	0	0	0	0	0	0	0	0	X	0	M	0	0	0	0
American lotus and yellow waterlily versus Frogbit (69) (71)		0	0	0	0	X	0	0	0	0	0	X	X	X	0	0	0	0
American lotus and yellow waterlily versus Yellow waterlily over egeria (69) (70)		0	0	0	0	M	0	0	0	0	0	X	X	X	0	0	0	0
Panicum versus Frogbit (65) (71)		0	0	0	0	0	0	0	0	0	0	X	X	X	0	0	0	0
Panicum versus Yellow waterlily over egeria (65) (70)		0	0	0	0	0	0	0	0	0	0	X	X	X	0	0	M	0
Frogbit versus Yellow waterlily over egeria (71) (70)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Duckweed, alligatorweed over egeria versus Waterprimrose over egeria (78 and 79) (80)		0	0	0	0	0	0	0	0	0	0	X	M	X	0	0	M	0
Duckweed, alligatorweed over egeria versus Tall waterprimrose over egeria (78 and 79) (81)		0	0	0	0	0	0	0	0	0	0	M	0	0	0	0	0	0
Waterlily versus Cattail (98) (101)		X	X	0	0	X	X	X	X	X	X	X	X	X	X	X	X	X
Giant cutgrass versus Cattail (126) (120)	29 Apr 77	X	X	0	0	X	X	X	X	X	X	X	X	X			0	0
Waterlily versus Cattail (118) (120)	29 Apr 77	M	0	0	0	0	0	X	0	0	0	X	X	X	X	X	X	X
Waterhyacinth versus Waterhyacinth (alive) (dead) (130) (134)	29 Apr 77	0	0	0	0	0	0	0	0	0	0	X	X	X	M	M	X	X
Percent Success		28.9	15.8	5.3	0.0	28.9	15.8	23.7	18.4	23.7	13.2	86.8	81.6	89.5	23.7	23.7	42.1	23.7

(Continued)

Table 5 (Concluded)

Species Compared (Data Set Numbers)	Date	Optical Density Contrast Predictions by Film-Filter Combination																
		Panchromatic										Color	CIR		Black-and-white IR			
		2402 -12	2403 -12	2402 -47B	2403 -47B	2402 -58	2403 -58	2402 -25A	2403 -25A	2402 -3	2403 -3	2448 -3	2443 -3	2443 -12	2424 -12	2424 -25A	2424 -87C	2424 -89B
Emergent Plant versus Submergent Plant																		
Blooming waterhyacinth versus *Vallisneria* (8) (7)	23 Sep 75	O	O	O	O	O	O	O	O	O	X	X	M	M	O	O	O	O
Waterhyacinth versus Hydrilla (51 and 52) (49 and 50)	14 Sep 76	M	O	O	O	O	O	X	M	M	O	X	X	X	X	X	X	X
Waterhyacinth versus Hydrilla (55) (53 and 54)	14 Sep 76	X	X	O	O	X	X	X	X	X	X	X	X	X	X	X	X	X
Waterhyacinth versus Hydrilla with milfoil (55) (58 and 59)	14 Sep 76	X	X	O	O	X	X	X	X	X	X	X	X	X	X	X	X	X
Waterprimrose versus Naiad (73) (72)	2 Jul 76	X	M	O	O	M	O	X	M	X	O	X	X	X	X	X	X	X
Yellow waterlily versus Naiad (76) (72)	↓	X	X	O	O	X	X	X	X	X	X	X	X	X	X	X	O	X
Waterprimrose versus Egeria (73) (74)	↓	O	O	O	O	O	O	O	O	O	O	X	X	X	X	X	X	X
Yellow waterlily versus Egeria (76) (74)	↓	X	X	O	O	X	X	X	X	X	X	X	X	X	X	X	X	X
Waterlily versus Hydrilla (118) (116)	29 Apr 77	X	X	O	O	M	O	X	X	X	X	X	X	X	X	X	X	X
Waterlily versus Hydrilla (119) (116)	29 Apr 77	X	X	O	O	X	X	X	X	X	X	X	X	X	X	X	X	X
Percent Success		80.0	70.0	0.0	0.0	70.0	50.0	80.0	80.0	80.0	70.0	100.0	100.0	100.0	90.0	90.0	80.0	90.0
Overall Percent Success		41.8	27.8			41.8	26.6	38.0	30.4	32.9	24.0	89.9	86.1	89.9	53.2	51.9	63.3	51.9

Table 6

Discrimination Matrix Derived from Model Studies*

Target	Water	Coontail	*Hydrilla*	*Vallisneria*	Naiad	Egeria	Watermilfoil	Waterhyacinth	Waterhyacinth (dead)	Frogbit	Waterfern	Pickerelweed	Duckweed	American lotus	Yellow waterlily	Waterprimrose	Alligatorweed	Cattail	Giant cutgrass	*Salvinia*	Waterlettuce	*Panicum*	Waterlily
Water		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Coontail																							X
Hydrilla			X			X	X	X															
Vallisneria							X	X															
Naiad						X	X								X	X							
Egeria															X	X							
Watermilfoil																							
Waterhyacinth								X	X	X	X	X	X		X	X	X			X	X	X	
Waterhyacinth (dead)										X				X	X							MX	
Frogbit													X	X	X								
Waterfern													X										
Pickerelweed													0										
Duckweed															X	X						X	
American lotus															X							X	
Yellow waterlily															X							X	
Waterprimrose																							
Alligatorweed																MX				X	0		
Cattail																					X		X
Giant cutgrass																		X					
Salvinia																							
Waterlettuce																				0			
Panicum																							
Waterlily																							

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* Predicted Optical Density Contrast (ODC) codes: X - ODC > 0.35, discrimination likely; M - 0.30 < ODC < 0.35, discrimination marginal; 0 - ODC < 0.30, discrimination not likely; blank - comparison not made.

Table 7

Film-Filter Combinations Used at Each Study Site

Location	Date	Camera	Film	Filter(s)
Lake Boeuf, Louisiana	15 May 76	Hasselblad	CIR	12
			Panchromatic	47
				58
				25
			Color	--
		Alpa	Black-and-white IR	12
				25
			CIR	12
	17 September 76	Alpa	Black-and-white IR	--
				Pol*
				25
			CIR	Pol
				12
			Plus-X Pan	Pol
				12
				25
				--
			Ektachrome-X	--
Lake Theriot, Louisiana	15 May 76	Hasselblad	Tri-X	47
				58
	17 September 76	Alpa	Black-and-white IR	--
				Pol
				25
			CIR	Pol
				12
			Kodacolor II	--
			Plus-X Pan	Pol
				12
				25
			Ektachrome-X	--
Ross Barnett Reservoir, Mississippi	21 April 76	Hasselblad	CIR	12
				47
				58
			Plus-X	12
				25
				--
		Alpa	Kodacolor II	--
			Plus-X Pan	12
				25
				--
			Ektachrome-X	--

(Continued)

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* Polarizing.

Table 7 (Concluded)

Location	Date	Camera	Film	Filters(s)
Ross Barnett Reservoir, Mississippi	10 September 76	Alpa	Plus-X	Pol
				Pol + 12
				Pol + 25
			CIR	Pol
				Pol + 12
				12
			Black-and-white IR	--
				Pol
				Pol + 25
				25
			Ektachrome-X	--
			Kodacolor II	--
Lake Marion, South Carolina	21 July 76	Alpa	Black-and-white IR	Pol
				Pol + 25
				--
				25
			Plus-X Pan	Pol
				Pol + 12
				Pol + 25
			Ektachrome-X	--
			CIR	Pol
				Pol + 12
				12
	18 November 76	Color	Haze	
			CIR	12

Table 8

Test Site Descriptions

Site	Geographic Coordinates	Shoreline Length km	Area km^2	Shoreline Development*	Mean Depth m	Elevation** msl m	Major Aquatic Plants
Lake Boeuf, Louisiana	90°38'W 29°28'N	19.8	7.0	2.01	1.1	0.3	egeria coontail pondweeds naiad waterhyacinth waterlilies lotus
Lake Theriot, Louisiana	90°50'W 29°28'N	10.5	5.7	2.20	1.2	0.3	Eurasian watermilfoil hydrilla waterhyacinth lotus waterlilies
Ross Barnett Reservoir, Mississippi	90°00'W 32°30'N	241.4	121.5	6.10	3.7	90.2	coontail pondweed naiad watershield duckweed American lotus
Lake Marion, South Carolina	80°15'W 33°30'N	293.2	448.1	3.77	7.6	22.9	egeria naiad waterprimrose alligatorweed
Lake Seminole, Florida	84°50'W 30°40'N	400.0	150.0	9.21	2.0	2.3	Eurasian watermilfoil hydrilla waterhyacinth
Rodman Reservoir (Lake Ocklawaha), Florida	28°30'W 81°50'N	84.1	29.3†	3.53		~6.1	hydrilla egeria *Vallisneria* coontail waterhyacinth waterlettuce spatterdock cattail pickerelweed
East Lake Tohopekaliga, Florida	28°16'W 81°25'N	24.3	66.4	1.39		17.4	*Scirpus* waterhyacinth pickerelweed *Panicum*
Lake Rousseau, Florida	82°35'W 29°05'N	42.1	11.3†	3.53		<9.2	hydrilla cattail pickerelweed willow *Scirpus* *Panicum* spatterdock

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* Shoreline development is a dimensionless index (determined by shore length over the square root of 4 times the area times π) that gives an indication of the convolutions along the shore relative to the surface area. A perfectly circular water body would have a value of 1.00.

** Elevation expressed in metres above mean sea level (msl).

† Determined by Bruning areagraph charts from 1:24,000 scale U. S. Geological Survey maps.

Table 9

Summary of Field Studies

						Principal Plant Genera Imaged	
Date	Sun Angle	Altitude, m	Scale	Location	Film/Filter Combination	Submersed	Emersed
May, Sep 1976	30° ± 10°	∿300	1:2000	Louisiana	CIR/12	Egeria	*Eichhornia*
					Color	*Ceratophyllum*	*Lemna*
					Black-and-white IR/12,25	Hydrilla	*Nelumbo*
						Myriophyllum	*Limnobium*
					Panchromatic/12,25,47,58		*Panicum*
Apr, Sep 76	30° ± 10°	∿300	1:2000	Mississippi	CIR/12,47,58	*Ceratophyllum*	*Brasenia*
			1:4000			Cabomba	*Lemna*
					Color	*Potamogeton*	
					Black-and-white IR/25		*Nelumbo*
							Nuphar
						Najas	*Nymphaea*
					Panchromatic/12,25		
Jul, Nov 76	30° ± 10°	∿300	1:2000	South Carolina	CIR/12	Egeria	*Nymphaea*
					Color	*Najas*	*Nuphar*
					Black-and-white IR/25		*Ludwigia*
					Panchromatic/12,25		*Alternanthera*

Table 10

Areal Estimates of Aquatic Plant Assemblages

Location	Species	Imagery Derived Estimates, sq km		
		Nov 76	Jun 77	Nov 77
Lake Marion, S. C. ($448.1 \ km^2$)	Egeria*	49.4	54.9	62.0
	Waterprimrose	37.5	36.6	26.9
	Naiad*	53.1	15.1	14.6
		Apr 77	Jun 77	Sep 77
Lake Seminole, Fla. ($150.0 \ km^2$)	Giant cutgrass	26.1	22.3	11.4
	Waterhyacinth	2.1	7.1	1.7
	Watermilfoil*	16.3	17.1	8.1
	Hydrilla	2.2	0.6	1.2

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* Generally submersed.

Table 11

Design of Aquatic Plant Remote Sensing Survey

Mission Purpose	Locate Areas of Surface Plants	Identify Area of Submersed & Emergent Plants	Species Composition and Areal Distribution	Estimation of Biomass By Species
Background Data				
USGS Maps	D	R	R	R
Existing Photos	D	D	R	R
Base Map	D	R	R	R
Ground-Truth Collection	D	R	R	R
Species List	D	D	R	R
Turbidity Estimates	N	R	R	R
Biomass Samples*	N	N	D	R
Mission Plan				
Scale	$\overline{<}$1:24,000	1:12,000 to 1:24,000	1:8,000 to 1:16,000	1:2000 to 1:34,000**
Film-Filter	CIR-12	CIR-12	CIR-12	CIR-12
Time of Year	Late Summer	Late Summer	Late Summer	Late Summer
Time of Day	2 hr from noon**	2 hr from noon	2 hr from noon	2 hr from noon
Stereo Coverage†	N	D	R	R
Exposure	Same as terrestrial scene	Open lens 1 F-stop wider than for terrestrial scene	Open lens 1 F-stop wider than for terrestrial scene	Open lens 1 F-stop wider than for terrestrial scene
Film Processing				
Standard	R	R	R	R
Print	R	D	D	D
Transparency	D	R	R	R
Image Interpretation				
Coverage Check	R	R	R	R
Collection Point Location	D	R	R	R
Identification Key	N	D	R	R
Extrapolation	N	R	R	R
Information Display				
Sketch on Base	D	D	R or	D
Project to Base	D	D	D	R
Map Evaluation				
Field Check	D	R	R	R
Corrections	D	R	R	R
Photo Re-exam	D	R	R	R
Redraft Map	D	R	R	R

Note: R = Required, D = Desirable, and N = Not Required.

* See Gustafson and Adams.[5]

** Local Standard Time.

† Standard stereo coverage is 60 percent forward lap, 30 percent side lap.