Remote Sensing and Geographic Information System Techniques for Aquatic Resource Evaluation*

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ABSTRACT: The spread of aquatic plants in Lake Marion, South Carolina necessitated an assessment of the trends in vegetation growth and water quality. Aquatic vegetation maps at 1:10,000 and 1:24,000 scale were produced by photogrammetric techniques from color infrared aerial photographs recorded on six dates between 1972 and 1985. These and other vector map products depicting bathymetry and herbicide applications were converted to raster format (25-m grid cells) to form a cartographic database for the 170 km^2 study area. Statistical data on nutrients, dissolved oxygen, biological oxygen demand, and turbidity obtained from South Carolina Department of Health and Environmental Control and U.S. Environmental Protection Agency records were also input to the database. A PC-based GIS was then used to relate macrophyte distributions to environmental factors influencing aquatic plant growth. The procedures employed represent an inexpensive approach that can be applied to other resource management tasks.

INTRODUCTION

WITH THE EVOLUTION of geographic information systems (GIS) technology from an experimental to operational mode, increased recognition is being given to the potential for integrating remote sensing and database methodologies to monitor natural resources. An example of this integration process is the construction of a database from aerial photographic, map, and statistical information, and the development of a lake management information system (LMIS) for monitoring aquatic macrophytes and water quality in the large inland reservoirs of South Carolina.

Concern for the future of major lakes and reservoirs within South Carolina prompted the Department of Health and Environmental Control (DHEC) to instigate a comprehensive water quality study of the Santee-Cooper River Basin, the second largest river basin on the East Coast of the United States. The initial focus of the study was on the relationships between the distribution of aquatic macrophytes and water quality in Lake Marion, a reservoir of some 45,000 ha. A major question has been whether changes in water quality will cause an increase in the already extensive aquatic plant population of upper Lake Marion and promote the spread of undesirable macrophytes to other parts of the system. In order to address that question, DHEC, with support from the U.S. Environmental Protection Agency (EPA), contracted with the Laboratory for Remote Sensing and Mapping Science (LRMS), University of Georgia, to inventory the aquatic macrophytes in upper Lake Marion, determine changes over time, and develop a GIS database that would allow these changes to be related to water quality, bathymetry, and sedimentation (Welch *et al.*, 1985 and 1986; Welch and Remillard, 1986). The methodology used to create an integrated database and develop a prototype LMIS suitable for aquatic resource evaluations is the subject of this paper.

STUDY AREA

Lake Marion was formed when the U.S. Army Corps of Engineers impounded the Santee River in 1941 to provide hydroelectric power in South Carolina. Although large, the lake is relatively shallow and supports a diverse fish and waterfowl population, making it a popular recreational area.

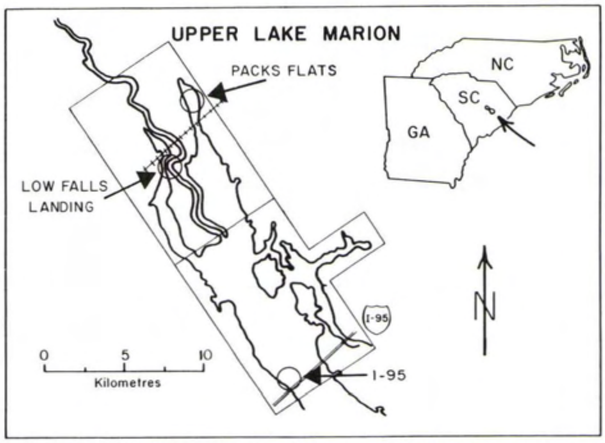

FIG. 1. Location map for the Lake Marion study area.

The specific study area is confined to upper Lake Marion, which extends approximately 23 km northwest of highway I-95 (Figure 1, Plate 1). This 17,000-ha area represents a gradual transition from the alluvial floodplain of the Santee River to the impounded lake (Harvey *et al.*, 1987). Physical characteristics include relatively stable water levels, shallow depths (not exceeding 20 m and averaging less than 3 m), and high turbidity (Patterson and Cooney, 1986). Sediment from the Santee River inflow is deposited in upper Lake Marion as the water velocity of stream flow decreases. The presence of aquatic macrophytes in the lake further encourages deposition which, in turn, creates a favorable habitat for aquatic plant growth.

Aquatic macrophytes are grouped by structure as emergent (rooted plants with leaves extending above or floating on the water surface), submergent (rooted plants growing below the surface), or free floating (non-rooted, surface floating plants). Common emergents found in upper Lake Marion include water primrose (*Ludwigia uruguayensis*), yellow lotus (*Nelumbo lutea*), fragrant water lily (*Nymphaea odorata*), and dollar bonnet (*Bra-*

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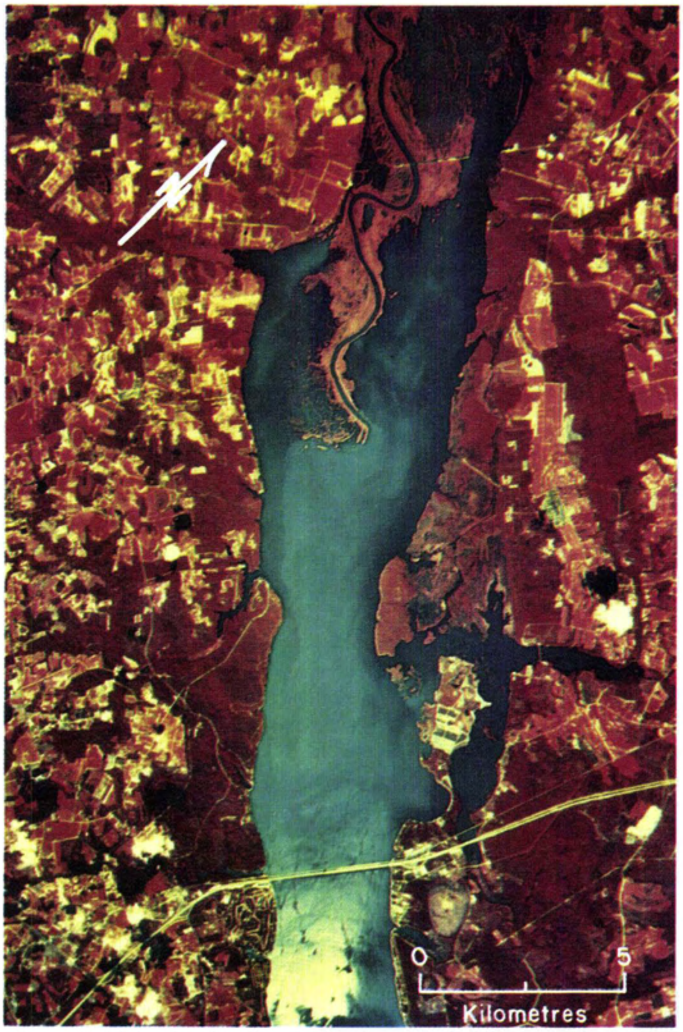


PLATE 1. High altitude color infrared aerial photograph of upper Lake Marion recorded in 1972.

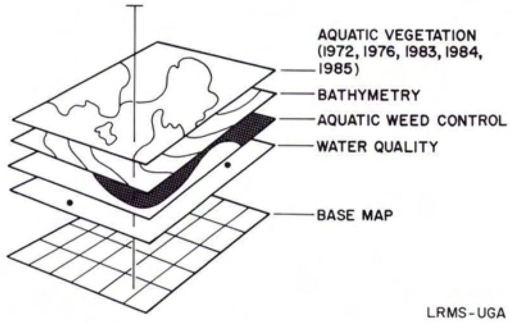


FIG. 2. Data sets in the Lake Marion GIS database.

senia schreberi). Submergent species commonly mixed with the emergents include Brazilian elodea (*Egeria densa*), hydrilla (*Hydrilla verticillata*), coontail (*Ceratophyllum demersum*), Southern naiad (*Najas minor*), and pondweed (*Potamogeton* spp.). Duckweed (*Lemna perpusilla* and *Spirodela* spp.), water-fern (*Azolla caroliniana*), and water-meal (*Wolffia papulifera*) are the dominant free floating species. Taxonomic classification is according to Radford *et al.* (1983).

Previous studies of macrophyte distributions in upper Lake Marion date back to 1977 when general aquatic vegetation maps were produced by the U.S. Army Corps of Engineers Waterways Experiment Station from small format color infrared aerial photographs (Link and Long, 1978). More recently, DHEC performed an extensive field survey to map aquatic macrophytes using a Motorola Miniranger III Automated Positioning System (APS) to record boundary coordinates of aquatic plant populations (Harvey *et al.*, 1983). The APS is labor intensive and limited to relatively open water areas where trees do not block the transmitted signals. Because nearly 65 percent of upper Lake Marion is a dense cypress-tupelo swamp, a more efficient mapping technique was required.

Landsat Thematic Mapper (TM) image data also have been used to map aquatic vegetation (Jensen *et al.*, 1986). However, the relatively poor spatial resolution of the satellite data and the difficulty of obtaining cloud-free coverage during the growing season limit its use to general classification tasks. High resolution airborne multispectral scanner data are also an option, but suffer severe geometric distortions and are costly to acquire. Because of these problems, large scale color infrared aerial photographs were determined to be the most useful and cost effective source materials for mapping aquatic plant species distributions.

DATABASE CONSTRUCTION

A database of biological and physical characteristics for upper Lake Marion is being constructed for use in an LMIS. This database will be employed to assess the ecological relationships between aquatic macrophytes, water quality, and environmental factors.

The layers in the database include maps of aquatic macrophyte distributions prepared from aerial photographs; a bathymetric map; maps depicting areas in which herbicides have been applied since 1982; and statistical data on water quality (Figure 2). Each of these layers is discussed in the following paragraphs.

AQUATIC MACROPHYTE DISTRIBUTION MAPS

Maps of the distribution of aquatic macrophytes were developed from color infrared aerial photographs in film transparency format recorded in 1972, 1976, 1983, 1984, and 1985 (Table 1). Photos acquired since 1983 have been of large scale (1:8,000 to 1:12,000), facilitating the identification of species.

The photographs were interpreted under high magnification with Bausch and Lomb Zoom 70 and SIS 95 instruments, and polygons representing the different types of aquatic vegetation were delineated on clear polyester overlays registered to the aerial photographs. Each polygon was classified according to the type of vegetation: (1) emergent, (2) submergent, or (3) free floating. Individual emergent species were also identified and verified with field data. Submergents, although readily identifiable by type on the photographs to depths of approximately 3 to 4 m, could not be differentiated by species because of their relatively uniform tone and texture. Therefore, only in those areas for which field data existed were submergents labeled by species.

Table 2 summarizes the photo characteristics of aquatic macrophytes commonly found in Lake Marion. Height and texture parameters are similar to those used by Seher and Tueller (1973) in their color infrared photographic key of marsh vegetation. Height categories include floating (leaves floating on the water surface), low (plants extending up to 15 cm above

TABLE 1. COLOR INFRARED AERIAL PHOTOGRAPHIC COVERAGE OF UPPER LAKE MARION

	1972	1976	1983	1984	1985 (June)	1985 (Sept)
Date of Acquisition	9/22/72	11/18/76	9/8/83	9/6/84-9/7/84	6/9/85	9/14/85-10/7/85
Nominal Scale	1:128,000	1:20,000	1:10,000	1:28,000	1:12,000	1:12,000
Flying Height AGL (m)	19,500	3,050	1,525	1,220	1,830	1,830
Camera	Wild RC-10	Fairchild KA-30	Zeiss RMK A 15/23	Wild RC-10	Wild RC-10	Wild RC-10
Total Number of Photos	2	110	170	270	105	139

the surface), medium (15 cm to 1 m), and tall (greater than 1 m). Texture is specified as fine, medium or coarse.

Aquatic macrophyte distribution maps, based on interpretation of the aerial photographs, were produced at 1:10,000 and 1:24,000 scale for 1983, 1984, and 1985, and at 1:24,000 scale for 1972 and 1976. The following method was employed to construct the maps.

A framework of ground control points (GCPs) was identified on a set of 1:28,000-scale color infrared photographs of the study area and their UTM coordinates were digitized from existing 1:24,000-scale USGS topographic maps and transferred to gridded planimetric base sheets of 1:5,000 scale. Numerous additional (pass) points common to the larger-scale photographs on which the polygons were delineated were also annotated on the 1:28,000-scale photographs. The pass points were then transferred to 1:5,000-scale planimetric base sheets using a Bausch and Lomb ZT-4 Zoom Transfer Scope to provide a control network for the large-scale photographs. In a final step, the macrophyte polygons were transferred from the large-scale photographs to the base sheets with the aid of the Zoom Transfer Scope.

TABLE 2. PHOTO CHARACTERISTICS OF AQUATIC MACROPHYTES

Aquatic Macrophyte	Color	Height	Texture
EMERGENT SPECIES			
Dollar bonnet	white to pale pink	floating	fine
Lotus	light to bright pink	floating to medium	fine to medium
Primrose	purple to pink	low to medium	medium
Water lily	white to pale pink	floating to low	fine
Unidentified Emergent	white to bright pink	floating to medium	fine to medium
SUBMERGENT SPECIES			
	Dark blue to black	subsurface to floating	fine
FREE FLOATING SPECIES			
Duckweed	white	floating	fine
MIXED SPECIES			
Emergents Dominant	pink to dark pink	floating to medium	medium
Submergents Dominant	blue to black	subsurface to low	fine to medium
Free Floating Dominant	white to pale pink	floating to low	fine to medium

The base sheets were then photographically reduced by a factor of two and mosaicked together to permit the compilation of maps of 1:10,000 scale for the entire study area. Where necessary, the polygons were generalized to achieve a minimum size mapping unit of 0.01 ha (10 by 10 m).

The completed 1:10,000-scale macrophyte distribution maps were also photographically reduced to 1:24,000 scale to allow registration with existing USGS quadrangles (Figures 3a and 3b). Maps depicting changes in aquatic macrophyte distributions were produced by registering maps of different dates to one another and delineating areas of change in macrophyte classification (Figure 3c).

BATHYMETRIC MAP

A bathymetric map of Lake Marion produced from fathometer recordings taken from boat surveys along transects of the lake was obtained from the U.S. Geological Survey (USGS, 1984). Contours depicted on the map at a 0.6-m interval were adjusted to compensate for the lower summer pool water level at the time the aerial photographs were recorded. This was accomplished by raising all depth contours by one interval or 0.6 m.

HERBICIDE APPLICATION MAPS

Aquatic plant management practices in Lake Marion are directed by the South Carolina Water Resources Commission (WRC) in conjunction with the South Carolina Aquatic Plant Management Council. Specific areas of the lake are sprayed annually with herbicides, such as Diquat, Aquathol-K, and Sonar, to control excessive macrophyte growth. The single largest control effort in South Carolina in 1986 was conducted in upper Lake Marion at a cost of approximately $460,000 (South Carolina Aquatic Plant Management Society Newsletter, 1986). Based on information provided by DHEC and WRC, maps depicting the area of herbicide application were prepared for 1982, 1983, 1984, and 1985 (Figure 4).

WATER QUALITY STATISTICAL DATA

The WRC and DHEC monitor water quality in Lake Marion. Long term sampling stations in upper Lake Marion cluster in

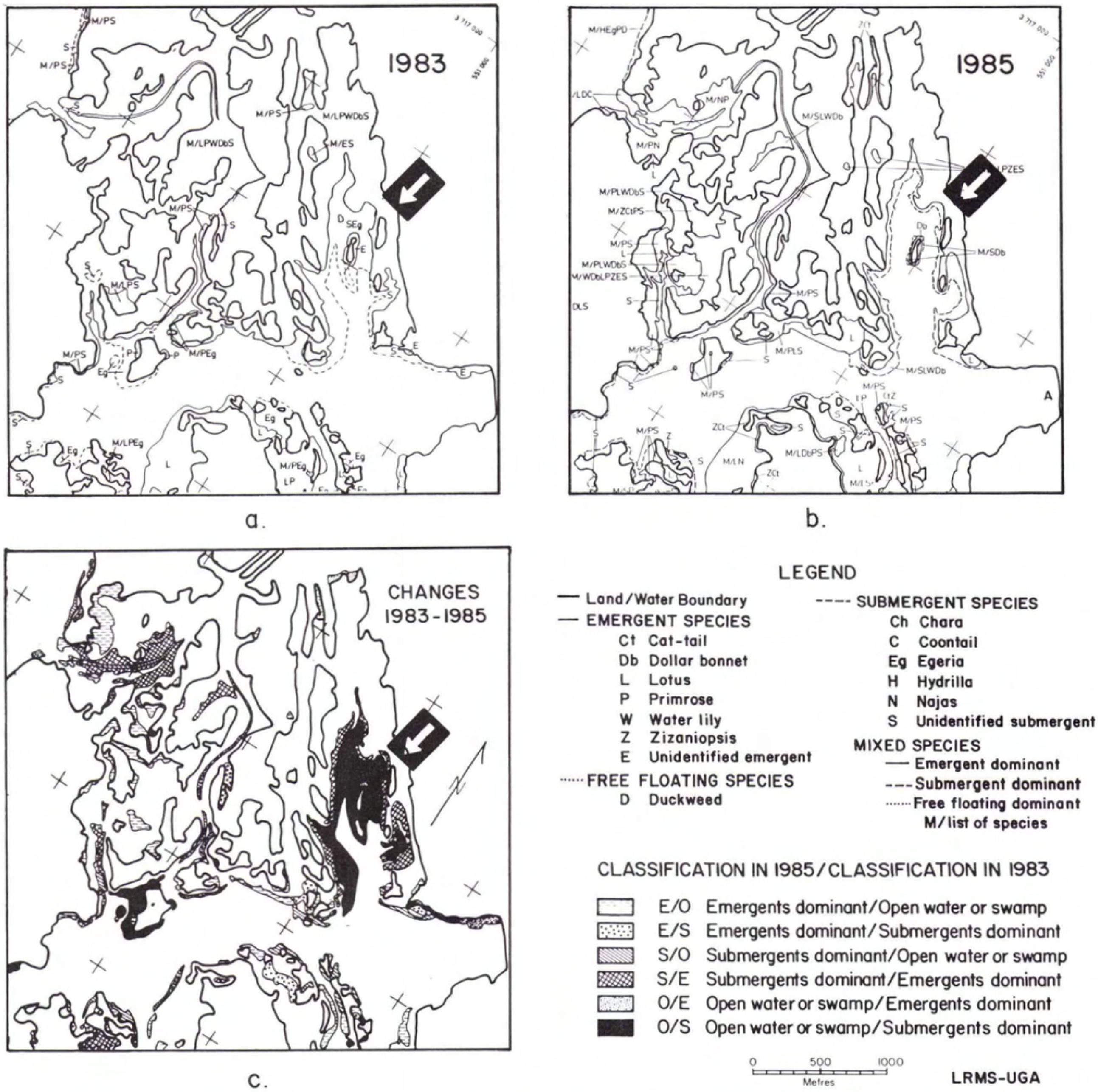


FIG. 3. (a, b) Macrophyte distribution maps for 1983 and 1985, respectively; and (c) Macrophyte change map for 1983 to 1985.

three general areas: I-95 (6 stations), Low Falls (11 stations), and Packs Flats (9 stations) (see Figure 1). These data are stored in the Environmental Protection Agency database, STORET.

Monthly data for April through September (for the 13-year study period) were averaged to obtain an overview of annual growing season trends in nutrients (nitrogen and phosphorus), dissolved oxygen (DO), biological oxygen demand (BOD), and turbidity (Figure 5). These water quality parameters were selected because of their relationships to aquatic macrophyte growth and the availability of consistent records for the study period (Table 3).

In order to create a computer database that could be utilized with the various data sets to assess water quality and the distribution of aquatic macrophytes, all data sets were converted to a raster format compatible with the cell-based GIS software package, pMAP, available from Spatial Information Systems. This package is designed for use on an IBM PC/AT or compatible computer and contains all the necessary analytical functions required for lake management applications. However, it does

TABLE 3. SELECTED WATER QUALITY PARAMETERS

Water Quality Parameter	Relation to Aquatic Plant Growth
Nutrients (Nitrogen and Phosphorus)	Essential elements for plant growth
Dissolved Oxygen	Released by plants and required by flora and fauna for respiration
Biological Oxygen Demand	Index for lake eutrophication
Turbidity	Determines light penetration and plant distribution

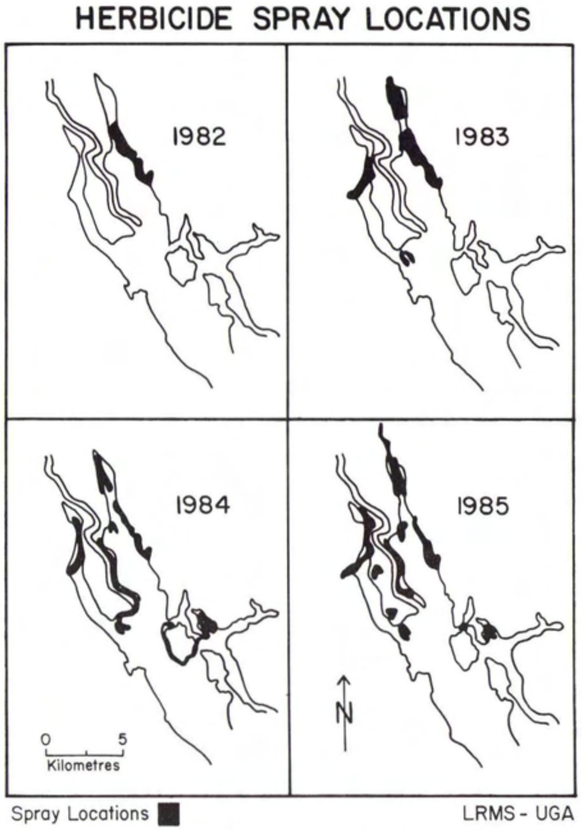


FIG. 4. Herbicide spray locations in upper Lake Marion: 1982–1985.

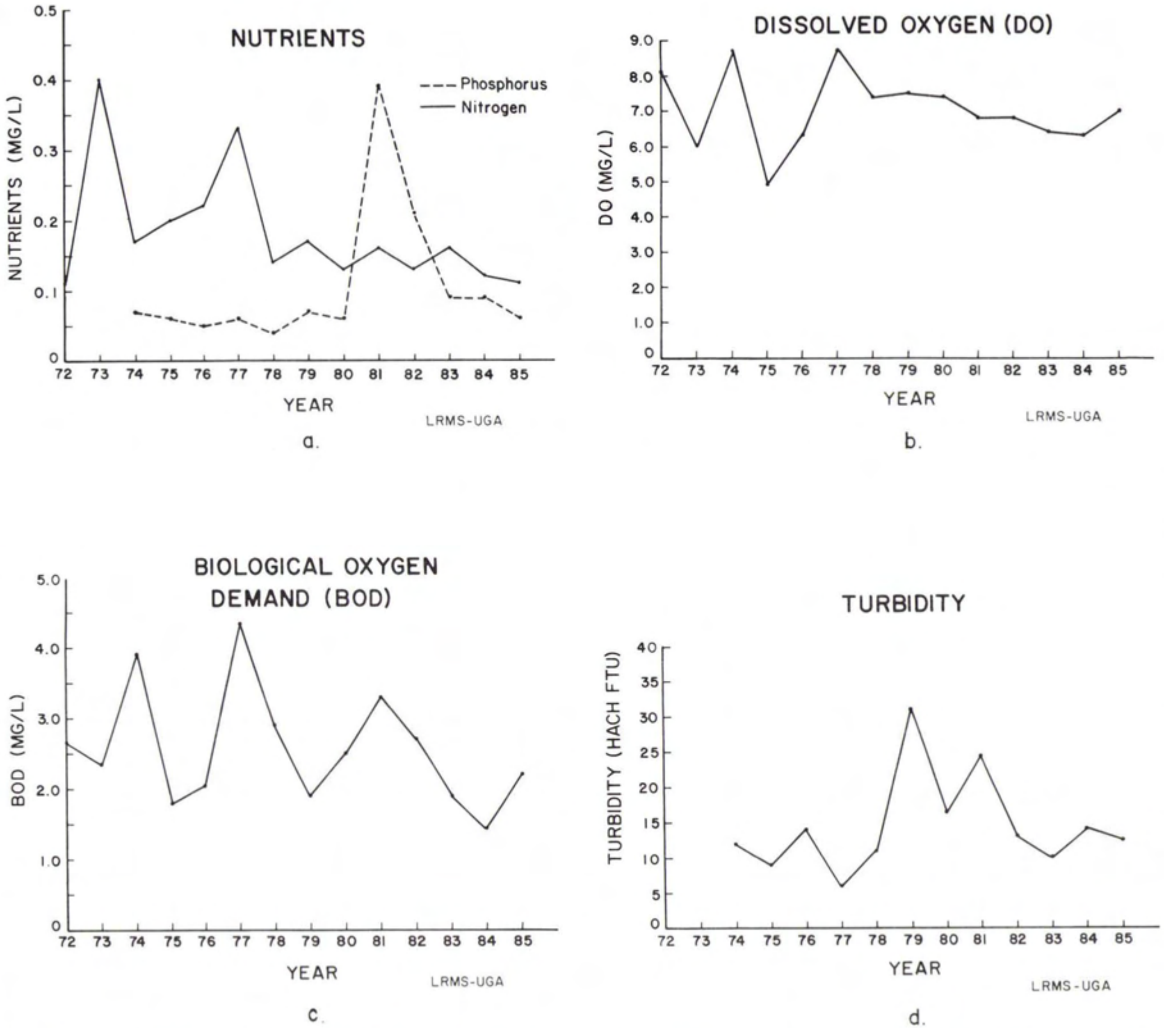


FIG. 5. Annual average growing season levels of water quality parameters: (a) nutrients; (b) dissolved oxygen; (c) biological oxygen demand; and (d) turbidity.

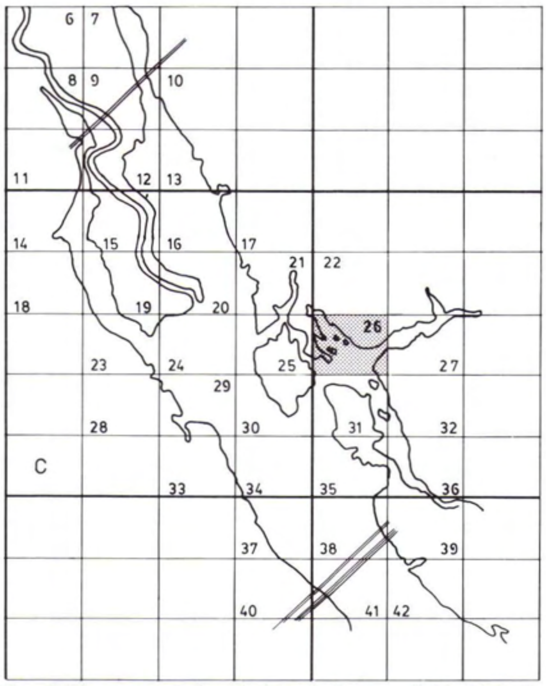


FIG. 6. The upper Lake Marion study area divided into 2- by 2.5-km map segments.

suffer two drawbacks: (1) the lack of a good data capture routine that will rasterize digitized map data in the pMAP format; and (2) an affine black-and-white alphanumeric character output that is difficult to interpret. These problems were rectified by adding the Desktop Digitizing Package (DDP), available from R-WEL, Inc., which features programs for the capture (CAPTURE), rasterization (RASTER), and color display (SHOW) of vector data digitized from maps or photographs. The pMAP/DDP software combination provided an inexpensive, easy to use, GIS capability suitable for resource management tasks.

To facilitate the use of pMAP, upper Lake Marion was divided into 2- by 2.5-km map segments keyed to the UTM coordinate

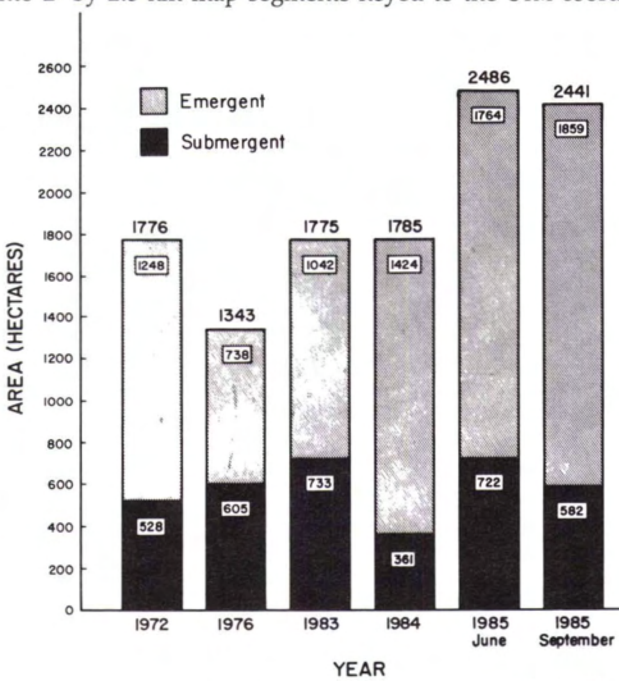


FIG. 7. Total area of aquatic macrophytes: 1972 to 1985.

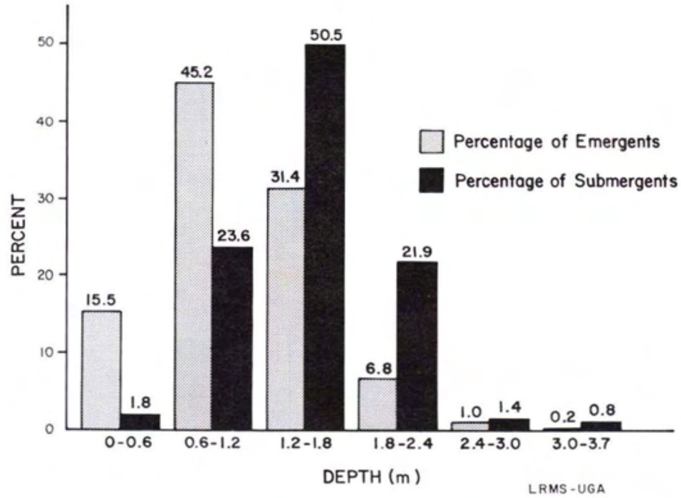


FIG. 8. Depth distributions of emergents and submergents.

system (Figure 6). The maps were manually digitized by segment and the data converted to pMAP format using the CAPTURE and RASTER routines. To accommodate the pMAP format and accelerate processing of the data, a grid cell size of 25 by 25 m was selected for the database (Berry and Reed, 1987). Comparison of raster data sets at 5-m, 25-m, and 50-m resolution have indicated 25 m to be acceptable for analysis tasks based on source maps of 1:10,000 scale and smaller.

ANALYSIS OF MACROPHYTE DISTRIBUTION AND WATER QUALITY

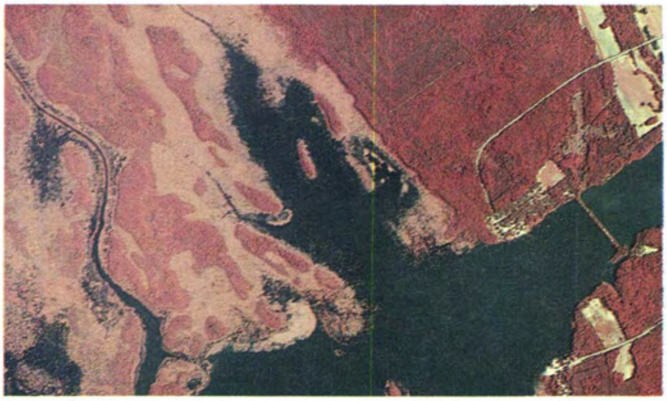
The database was used to assess changes in the distribution of aquatic macrophytes (Plate 2a). Map segments for any two dates (Plates 2b and 2c) can be subtracted and the changes represented as a color display (Plate 2d). Because each pixel represents an area of 0.0625 ha, a simple computer count of the grid cells in each class provides a quantitative measure of the changes in distribution.

Overall, the total areal extent of aquatic macrophytes remained at about 1,800 ha between 1972 and 1984, although the ratio of emergents to submergents did change significantly. As shown in Figure 7, emergents steadily increased, whereas submergents decreased. In 1985, the area covered by emergents alone exceeded 1,800 ha, with submergents showing no apparent increase.

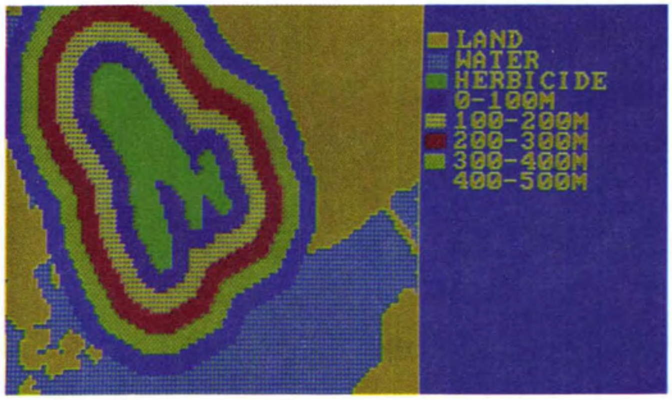
Macrophyte distributions were mapped before (June) and after (September) herbicide applications in 1985 to evaluate weed control efforts. A decrease of about 140 ha in the area of submergents resulted from the herbicide applications; however, emergent and free floating macrophytes increased by 95 ha, yielding a net loss of 45 ha. The decrease in submergents was most dramatic in those areas specifically targeted for spraying.

The effectiveness of the GIS approach for assessing the impact of herbicides is demonstrated for the sample map segment (Plates 2e and 2f). In Plate 2e, the area of herbicide application is shown surrounded by concentric dispersal zones of 100-m width. By overlaying the herbicide dispersal map with the map showing the changes in macrophyte distribution between June and September (Plate 2d), an integrated map product is produced that reveals a substantial decrease in submergents outward for about 200 m from the original spray area (Plate 2f).

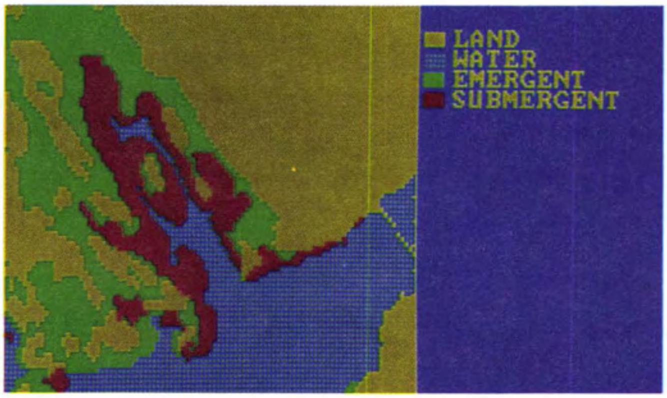
The integrated database approach also may be used to spatially compare aquatic plant growth with other environmental



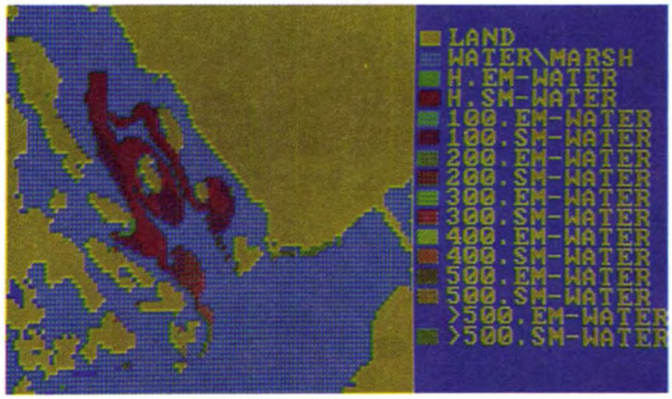
(A) CIR Aerial Photograph



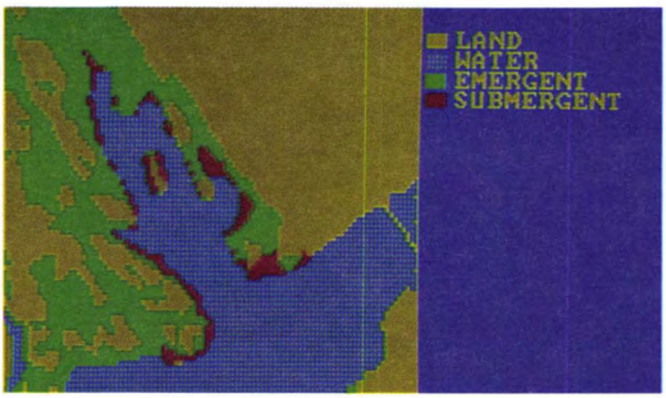
(E) Herbicide Dispersal



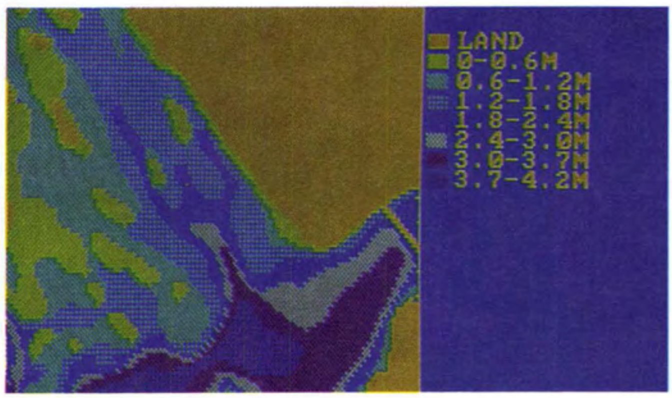
(B) June 1985



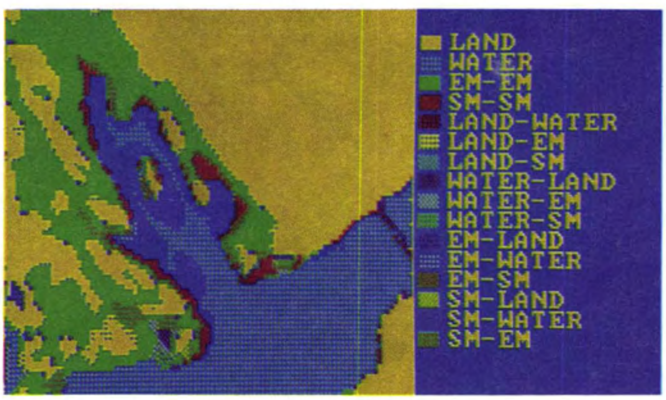
(F) Herbicide and Macrophyte Loss



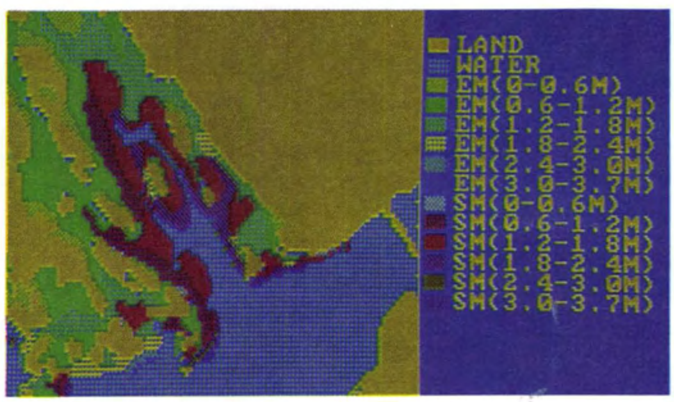
(C) September 1985



(G) Bathymetry



(D) Changes June to September



(H) Bathymetry and Macrophytes

Plate 2. Digital data sets in the lake management information system database: (a) CIR aerial photograph of aquatic macrophytes; (b) and (c) digital map segments of macrophyte distributions for June and September, 1985; (d) changes June to September, 1985; (e) herbicide application, 1985; (f) integrated macrophyte changes and herbicide application; (g) bathymetry; (h) integrated bathymetry and June 1985 macrophytes.

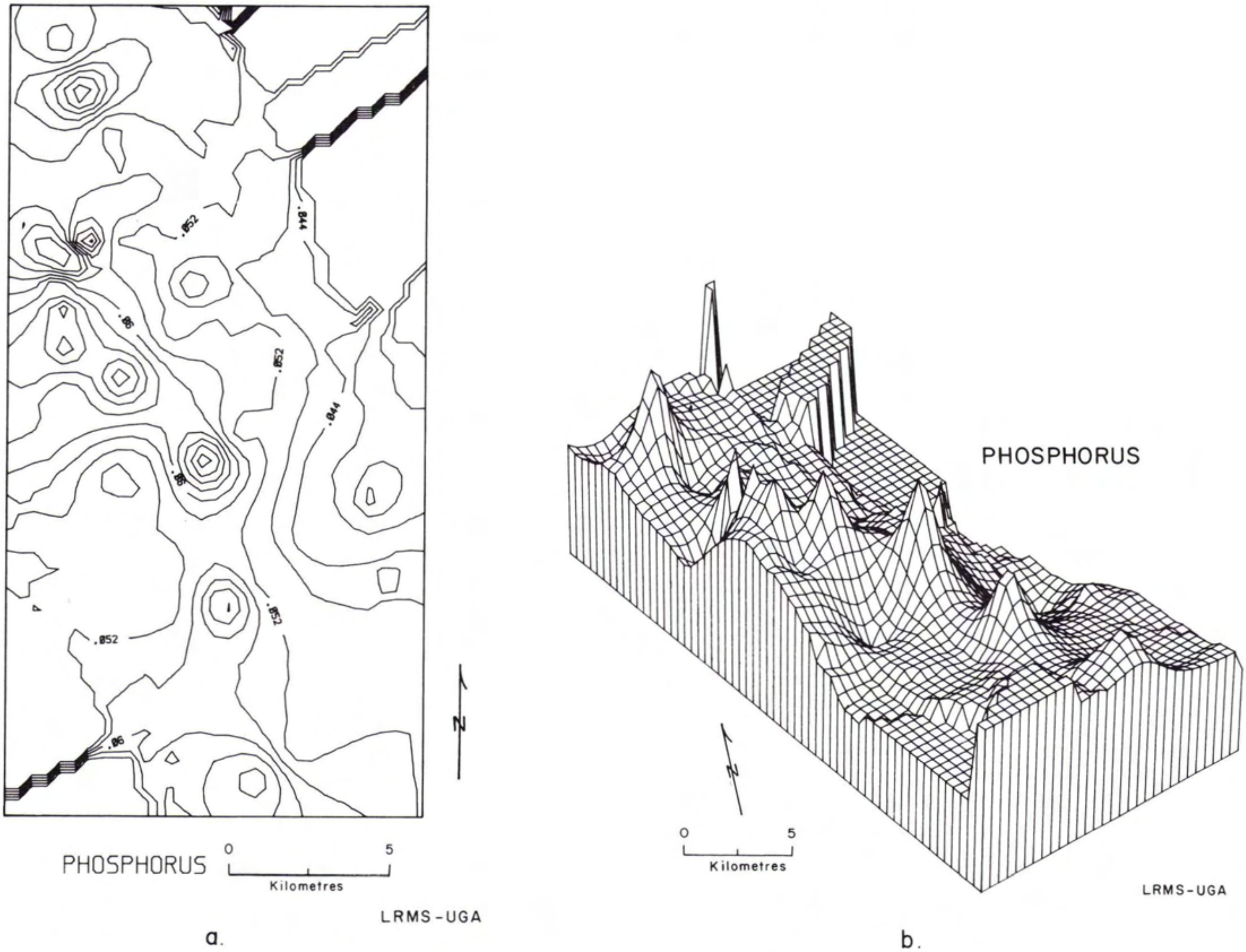


FIG. 9. (a,b) Two- and three-dimensional plots of the distribution of phosphorus in the sample map segment.

factors such as bathymetric data. For example, a map layer for macrophyte distribution in June 1985 (Plate 2b) was overlaid with the bathymetric map (Plate 2g) to establish water depths associated with emergents and submergents (Plate 2h). Based on statistics derived from this composite data set, 92 percent of the emergents were found at depths of 0 to 1.8 m, and 96 percent of the submergents grew at depths of 0.6 to 2.4 m (Figure 8). The maximum depth of macrophyte detection was between 3.0 and 3.7 m for both emergents and submergents. Plants growing at depths greater than 3 to 4 m may not be detectable on color infrared aerial photographs (Martyn *et al.*, 1986). Despite this limitation, the data on macrophyte growth and water depth provide a basis for herbicide selection and application.

Preliminary results of a spatial comparison of macrophyte distributions and water quality indicate that between 1972 and 1985 fluctuations in annual average growing season levels of nitrogen, DO, BOD, and turbidity over the entire study area have not varied significantly and apparently are not related to growth trends noted in upper Lake Marion. Phosphorus levels, however, increased sharply between 1980 and 1983 (see Figure 5a). Because aquatic plants absorb nutrients in part through their foliage, and tend to absorb excessive amounts of essential nutrients (such as phosphorus) that are normally present in low concentrations, the increase in phosphorus may have increased emergent macrophyte growth after 1983 (Figures 9a and 9b) (Barko *et al.*, 1986). Submergent growth, also expected to be enhanced by high phosphorus levels, may have been effectively checked by herbicide spraying.

CONCLUSION

The integration of remote sensing and database technologies allowed the utilization of a GIS approach to monitor water quality and the growth of aquatic macrophytes between 1972 and 1985 for a study area of some 17,000 ha. The procedures employed for this study can be extended to most types of resource inventories, and can be conducted with a suitably equipped IBM PC/AT or compatible machine and inexpensive GIS software designed to work with databases in raster format. Resource managers thus have an alternative to costly minicomputer based GIS systems for inventory tasks.

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