J. Aquat. Plant Manage. 32: 61-66

Mapping aquatic macrophytes through digital image analysis of aerial photographs: an assessment[1]

TERRY R. MARSHALL[2] AND P. F. LEE[3]

ABSTRACT

Distributional maps of aquatic vegetation are commonly produced from aerial photographs using visual interpretive techniques. Image analysis represents an alternative technique through which this process can be automated. The photographs are first digitized, and the system trained to recognize a set of spectral patterns or 'signatures' which are unique for particular macrophyte species or groups. All pixels which comprise the image are then classified on the basis of their conformance with these signature values; this results in a map or GIS overlay of aquatic plant distribution. We assessed the utility of the image analysis approach for mapping macrophytes of lakes of northwestern Ontario. The boundaries of plant beds could be defined with precision using this method, which contributed to a more accurate estimation of total plant cover and production. While submersed species proved difficult to classify, delineation to the species level was feasible for some floating-leafed and emergent forms, and the further partitioning into density classes may at times be possible. At this level of detail, however, spectral signatures are not transportable over space or time. Under the tested conditions, it was possible to produce maps of emergent vegetation more accurately and efficiently with the image analysis technique than with the visual interpretive method.

Key Words: inventory, remote sensing, classification, Geographic Information System.

INTRODUCTION

Aerial photography has become increasingly popular as a tool by which to map aquatic vegetation, as it can be obtained rapidly and at relatively low cost, and provides a permanent record of current conditions (e.g. Andrews et al. 1984, Schloesser et al. 1988). Visual qualities such as shape, tone, and texture are used to distinguish vegetation from other features in the photographs, and to identify particular taxa and define the boundaries of individual plant beds. This information is manually recorded by the photo-interpreter on an outline map of the water body to produce a distributional map of the macrophytes. However, even with a knowledge of photo interpretation techniques and a familiarity with local field conditions, there is much room for error in this process. It has been reported that submersed macrophytes are correctly recorded only 56%-70% of the time using this approach (Macomber and Fenwick 1979, Haegele and Hamey 1980, Schloesser et al. 1987). In addition, the manual preparation of maps is exceedingly time-consuming, and while scale-dependant, the boundary resolution of plant beds is fairly limited.

Forsgren and Wallsten (1987) introduced a means of automating this process, which promised higher precision and shorter evaluation times than the manual approach. Their technique employed sophisticated scanning equipment and a mini-computer, along with some simple image processing algorithms, to aid in the classification and mapping functions. The advantages include improved map resolution through the pixel-level delineation of boundaries of plant beds, and increased accuracy through the identification of macrophyte taxa based on differences in tone and shading that are near-indistinguishable to the human eye.

Recent advances in technology allow the application of Forsgren and Wallsten's (1987) technique using affordable, off-the-shelf computer hardware and software (Welch 1989). The process can be considerably refined and automated, which makes it an increasingly attractive alternative to the manual mapping technique, feasible even for small-scale studies. Three steps are involved in this operation, beginning with an analog-to-digital conversion of the colour aerial photographs. This is accomplished through use of an optical-mechanical scanner or video digitizer, which produces a digital image of the scene which is recognizable to the computer.

Secondly, image processing software is employed to enhance the image and extract the required thematic information, which in this case are regions of vegetative cover, classified to plant type. This is accomplished through analysis of the spectral characteristics of the three colour bands which comprise the image. Aquatic plants demonstrate unique spectral reflectance properties, or 'signatures', which differ subtly among taxa, and in turn differ grossly from the open water, non-vegetated areas. Once these signatures are defined for a plant species or group, all pixels across the

[1] Contribution No. 93-05 of the Ontario Ministry of Natural Resources, Aquatic Ecosystem Research Section, Research, Science, and Technology Branch, P.O. Box 5000, Maple, Ontario, Canada L6A 1S9. Received for publication October 29, 1993 and in the revised form June 10, 1994.

[2] Ontario Ministry of Natural Resources, Centre for Northern Forest Ecosystem Research, Lakehead University, 955 Oliver Road, Thunder Bay, Ontario, Canada P7B 5E1

[3] Department of Biology, Lakehead University, 955 Oliver Road, Thunder Bay, Ontario, Canada P7B 5E1

image with similar values are assigned the same classification. The process of signature definition and pixel classification is then repeated until all macrophyte beds have been charted.

Thirdly, a digital map of the lake is generated, with the regions of aquatic plant coverage defined. This represents an overlay suitable for placement in a Geographic Information System (GIS), and when in this format distributional maps of aquatic vegetation can be selectively printed and statistical summaries produced.

This paper evaluates the performance of the computer image analysis approach to the classification and mapping of aquatic macrophytes. For test purposes, colour aerial photographs were taken of two northwestern Ontario lakes that differed substantially in their depth, water colour, and plant community composition. Image analysis was utilized to classify the aquatic plants and to generate a map of their distribution. For each lake, the ability to differentiate among different types of aquatic vegetation and to accurately record their distributional patterns using this technique is assessed. The area of plant cover and production estimates determined in this manner are compared with those obtained using the conventional, visual interpretive method. The advantages and disadvantages of the automated approach are discussed, including mapping accuracy and precision, time efficiencies, and required skill and knowledge.

METHODS

Two lakes typical of the boreal forest region of Canada were selected near Thunder Bay, in northwestern Ontario. These lakes present a range of conditions through which to test the utility of the image analysis technique (Table 1). Walkinshaw Lake is moderately deep, with highly stained water, and dominated by floating-leafed vegetation occurring largely in shallow nearshore areas. Big Pearl Lake is shallow throughout, with quite transparent water, and with a mixture of macrophytes, including dense colonies of submersed plants occurring in the mid-basin of the lake.

Aerial photography was carried out following the recommendations of Marshall (1994). A seasonal window spanning late July through early August was selected, as this represents the period of peak biomass for most macrophytes of this region. To ensure maximum light penetration, photographs were taken near high noon on bright, sunny days, relatively free of wind and haze. Colour infrared film was found to provide slightly better differentiation of floating and emergent

TABLE 1. LIMNOLOGICAL AND MORPHOMETRIC CHARACTERISTICS OF WALKINSHAW AND BIG PEARL LAKE.

	Walkinshaw Lake	Big Pearl Lake
Area (ha)	35.4	50.6
Mean depth (m)	3.3	1.2
Maximum depth (m)	11.7	2.8
Water colour (Pt$\cdot$L^{-1})	71	13
Turbidity (JTU)	1.5	2.1
Secchi depth (m)	2.3	3.6[1]

[1] Could not be measured due to shallow depth; calculated as:
Secchi depth = 7.37 - 2.22 * Log_{10} (Colour) - 4.15 * Log_{10} (Turbidity)

plants, but true colour film was selected as the preferred film type for this study due to its superior depth penetration which rendered far better detail of submersed species. The lakes were photographed at an altitude of 280 m with a 645 format camera fitted with a 45 mm lens. This provided a scale of 1:5000, which, following a 4X enlargement of the negatives, yielded sufficient spatial resolution for identification of plant taxa (Olson 1964, Bogucki and Gruendling 1978). As an example, high tension hydro-electric lines could be readily discerned on these prints. Ground coverage of each photograph was 1120 m by 830 m.

Initial plant distributional maps were created through visual interpretation of these photographs. Macrophyte beds observable on the photographs were traced on a digitizing tablet, along with the lake boundary, to produce a map of plant cover. The composition and abundance of plants comprising the macrophyte community were then determined through a field sampling exercise. Collections were made using a plant biomass sampler (Marshall and Lee 1994), with sites located randomly across a grid within representative macrophyte beds. The plants collected were subsequently identified to species and biomass estimates obtained by oven-drying to constant weight at 80 C.

Image analysis was performed using the VGA ERDAS™ software package, which incorporates functions of both image processing and a raster-based GIS. The hardware platform comprised a 50 MHz 80486DX personal computer with a graphics adapter capable of displaying 1024 pixels by 768 pixels in 256 colours. Photographs were digitized using a Howtek™ or a Hewlett-Packard Scanjet IIC™ flatbed scanner, cropping to include only the essential lake coverage and to minimize the size of the digital image. A scan density of 75 pixels$\cdot$cm^{-1} was selected for the whole-lake images, and a density of 200 pixels$\cdot$cm^{-1} for the detailed mapping of the northwest bay of Walkinshaw Lake. At 1:5000 scale, this translates into an actual ground area covered per pixel of 0.67 m^2 and 0.25 m^2, respectively.

A rectification procedure corrected geometric distortion of the images by relating pixel coordinates of ground control points with their map coordinate counterparts. The images were then mosaicked and georeferenced to these UTM map coordinates. Prior to analysis, the photomosaic image was enhanced by examining the spectral histogram and adjusting an equalization filter to provide maximum visual colour contrast. Shorelines were then traced on-screen to produce two broad classes separating aquatic and non-aquatic regions. A mask of the non-aquatic class was generated so that terrestrial features would not complicate the classification of the aquatic vegetation.

Image data was subjected to both supervised and unsupervised multispectral classification methods. Supervised classification is an interactive process, requiring the skills of an operator knowledgable of conditions in the field. The operator identifies training sites which represent a homogeneous example of a particular vegetation type, and the spectral characteristics of these areas are used to 'train' a classification algorithm to recognize similar vegetation at other locations within the lake. After training samples have been analyzed for each of the vegetation classes, each pixel within the image is evaluated and assigned to the class of which it has the highest likelihood of being a member. For our trials, a minimum of six training sites were selected for each vegetation type. The sites were of variable size, but care was taken to ensure that 30 or more pixels of training data were provided for each class, as suggested by Jensen (1986).

The unsupervised classification method applied a sequential clustering algorithm, which is an automated procedure whereby pixels are examined sequentially, and the spectral distance calculated between the current pixel and that for previously defined clusters of pixels. Based on this spectral distance, the pixel is either placed into an existing cluster or begins a new cluster. The process continues until all pixels are examined, with clusters merged if too many are formed. To insure maximum differentiation of aquatic plants, a total of 65 clusters were initially specified. The clusters were then examined by overlaying each, in turn, on an image of the original aerial photograph. Based on the operators prior knowledge of the actual plant distribution (through field sampling), each cluster was recoded to a class indicative of a specific macrophyte taxa, or, alternatively, the open water zone.

As a final step in the classification process, names were assigned to the emergent classes, and a GIS file created. Annotation was gridded to this file, and distributional maps of the aquatic macrophytes were generated by computer and output to a colour printer. Using these maps with their redefined plant boundaries, macrophytes were once again field sampled, applying a similar sampling strategy as for the visually interpreted maps.

RESULTS

The aquatic plant community of Walkinshaw Lake was dominated by floating-leafed forms - two species of water lily, *Nymphaea odorata* and *Nuphar variegatum*, and a pondweed, *Potamogeton natans*. Occasional submersed species occur, such as *Scirpus subterminalis* and *Utricularia vulgaris*, but these were widely scattered and comprised but a small proportion of the total macrophyte biomass. Equally minor were emergent species, which consisted largely of small patches of *Eleocharis palustris* and *Typha latifolia*.

The extensive colonies of floating-leafed plants contrasted well with the darkly stained lake water on the aerial photographs. As such, they could be readily distinguished and plotted, as a group, using visual interpretive methods. The three species forming this group were often interspersed, however, and even at high magnification it was difficult to separate the taxa and define their boundaries with any level of precision. The two species of water lily were particularly difficult to differentiate, and had to be combined as a single class when a vegetation map was produced manually.

A second vegetation map was produced using the image analysis approach. Experimentation with supervised and unsupervised classification methods demonstrated that comparable results could be obtained using either procedure. However, the process of selecting representative training sites and performing the subsequent signature evaluation, as required by the supervised method, proved to be a fairly time-consuming process. Repeated selection of training samples and manipulation of signature values were required to ensure their robustness. In contrast, the interpretation of plant classes could be carried out rapidly when applying the unsupervised sequential clustering method, and this classification method was used exclusively during the remainder of these trials.

A comparison of plant coverage determined using the visual interpretive technique versus the image analysis approach revealed a marked difference (Table 2). A greater total coverage was recorded for the floating-leafed plants when manual methods were employed. This is not unexpected, as it is impossible to resolve fine detail when visually plotting plant distribution. The common approach is to trace the boundaries of plant beds to encompass all vegetation, which, by default, would include open patches of water in low density zones where plants are somewhat dispersed. This ultimately inflates the overall estimate of plant cover. In contrast, the computer generated map provided much greater boundary detail, even of finely dissected plant beds. The interstices between plants are properly classified as water, hence a more accurate estimate of plant cover would be expected. Field observations at 10 m intervals along transects revealed a high degree of correspondence (r=0.80; n=39) between the actual pattern of plant distribution and that indicated on the classification map. It was noted, however, that the mapped boundaries of *P. natans* beds were slightly exaggerated in shallow water underlain with lightly coloured sediments.

The difference in resolution between the two mapping techniques resulted in a great disparity in plant biomass estimates (Table 3). Values were much lower when the boundaries of plant beds were interpreted visually, largely as a consequence of including null samples in the biomass estimate. This occurred when one of the sampling points, randomly preselected from the plant cover map, corresponded with an open water interstice between plants. The highly

TABLE 2. A COMPARISON OF COVER ESTIMATES FOR THE MAJOR MACROPHYTES OF WALKINSHAW LAKE, DETERMINED THROUGH UNSUPERVISED IMAGE ANALYSIS AND THE VISUAL INTERPRETIVE TECHNIQUE.

	% of Total Lake Area		
	Image Analysis Technique	Visual Interpretive Technique	Difference (%)
Nymphaea odorata & Nuphar variegatum	4.93	5.36	+ 8.7
Potamogeton natans	1.34	1.91	+ 42.5
Emergent *spp.*	0.90	0.73	- 18.9

TABLE 3. ESTIMATES OF AVERAGE BIOMASS (DRY WEIGHT) WITHIN THE DEFINED PLANT BEDS AND WHOLE LAKE PRODUCTION FOR FLOATING-LEAFED MACROPHYTES IN WALKINSHAW LAKE, AS DETERMINED USING DISTRIBUTION MAPS GENERATED THROUGH UNSUPERVISED IMAGE ANALYSIS VERSUS THE VISUAL INTERPRETIVE TECHNIQUE.

	Image Analysis Technique		Visual Interpretive Technique	
	Biomass ($g{\cdot}m^{-2}$)	Production (kg)	Biomass ($g{\cdot}m^{-2}$)	Production (kg)
Nymphaea odorata & Nuphar variegatum	134.2	2341.6	46.5	882.7
Potamogeton natans	27.2	129.2	11.2	75.6

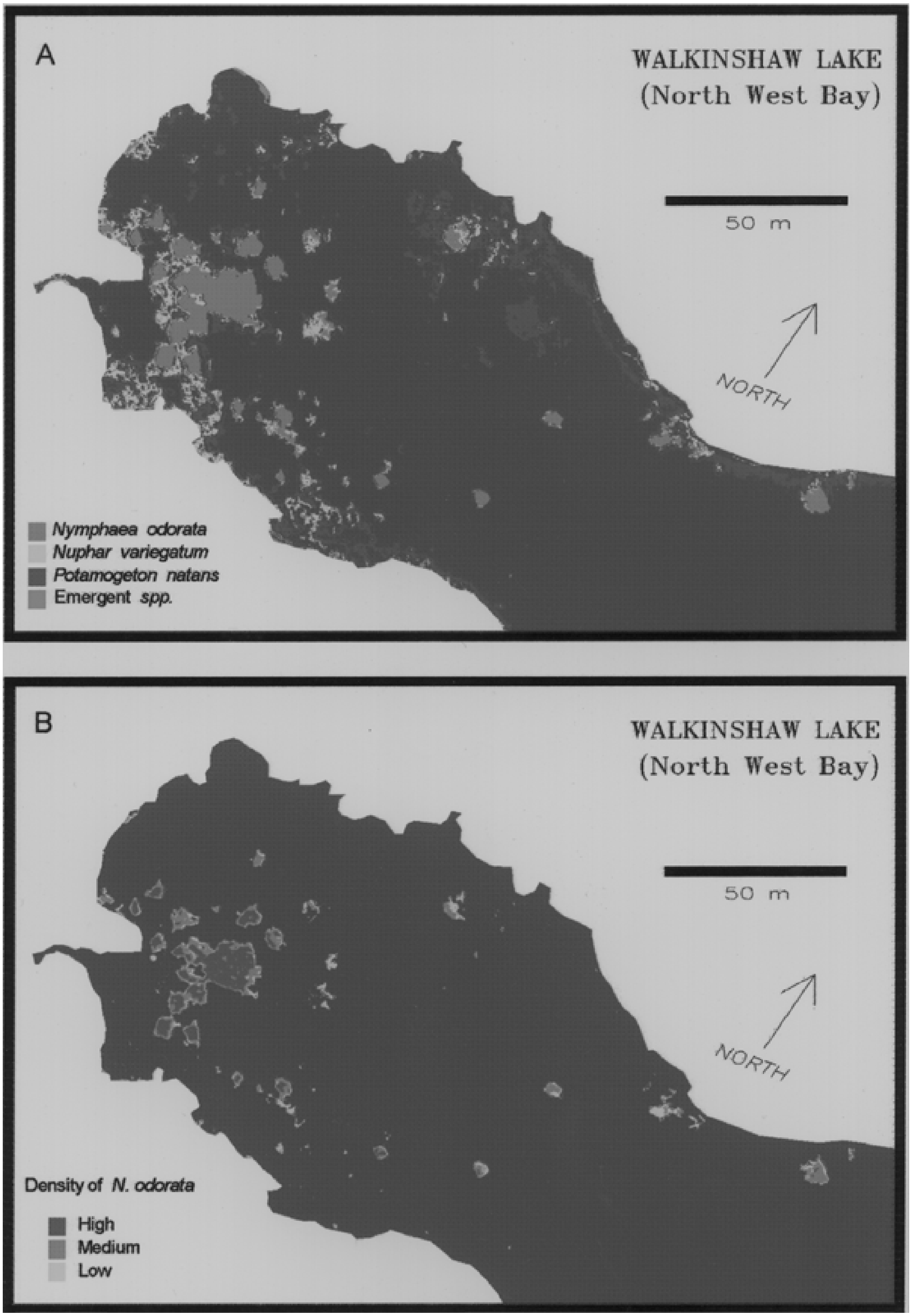

Figure 1. Classification maps of the northwest bay of Walkinshaw Lake, illustrating (A) species-level differentiation of floating-leafed macrophytes, and (B) density zonation of *N. odorata*.

detailed boundary of plant beds produced through image analysis excluded such spaces, and precluded the occurrence of null samples. The inflated areas of plant coverage recorded by the manual technique compensated somewhat for this phenomenon, but even so, the estimate of total lake production of floating-leafed plants was substantially less than that determined using the image analysis approach.

Signature values for the two species of water lily, along with *P. natans*, were sufficiently unique to allow their differentiation through image analysis. A high density scan (1 pixel=0.25 m^2) of the northwest bay of Walkinshaw Lake provides an example of classification to the species level (Figure 1(A)). To determine the statistical validity of this map, a classification accuracy assessment is required (Jensen 1986, Aronoff 1989). Ideally, this would take the form of a contingency table, which compares plant classes randomly located on the ground with those represented by corresponding pixels on the classification map. Such a formal assessment was not performed, however a field cruise of the lake provided a means of subjective error assessment, and revealed a high level of concordance between the true species distribution and that defined on the classification map.

Field surveys indicated that the density of vegetation, especially *N. odorata*, varied considerably from site to site. Not surprisingly, spectral signature values for this species were also found to differ on the basis of these density patterns. In its most profuse state, solid green mats are formed on the lake surface. Under more moderate growth conditions, small interstices of water appear amongst the leaves, modifying the signature value. These interstices are more frequent and of larger size under conditions of sparse growth, shifting the signature still. It was therefore possible to create a classification map of *N. odorata* density through analysis of this signature variation (Figure 1(B)). Calibration of these classes in terms of actual biomass values has not yet been attempted, but close agreement has been noted between this classification map and *N. odorata* densities as assessed visually in the field.

As a further evaluation of the image analysis approach, a second lake with a distinctly different macrophyte community was examined. Big Pearl Lake supports vast submersed beds of *Potamogeton robbinsii*, with *Potamogeton pectinatus* and a submersed form of *Potamogeton gramineus* also occurring occasionally. Two emergent species, *Equisetum fluviatile* and *Scirpus validus*, were also very common, with *T. latifolia* occurring in occasional nearshore locations. Floating-leafed plants were a less conspicuous component of the community, comprised entirely of *P. gramineus*, *P. natans*, and *N. variegatum.*

The classification of these plants proved more difficult than those of Walkinshaw Lake. Due to its highly transparent waters and shallow depth, light penetrates to the bottom throughout Big Pearl Lake, and substrate zonation patterns are readily discernible on the aerial photographs. In contrast to the uniformly dark water of Walkinshaw Lake, the reflectance of light from the substrate resulted in a wide range of spectral values being recorded for the non-vegetated, open-water portion of Big Pearl Lake. Some of these values closely resembled the signatures of the submersed vegetation, and confounded the classification process. To minimize this effect, a mask was manually traced on the image to block off large sections of the lake where macrophytes were known to be absent. Following this operation, it was possible to identify signatures representing the major plant categories, and a vegetation map for this lake was produced. The creation of this mask, however, was a time-consuming chore which demanded intimate prior knowledge of macrophyte distribution, and also introduced manual error; this negated many of the gains associated with the image analysis approach.

TABLE 4: A COMPARISON OF COVER ESTIMATES FOR THE DIFFERENT MACROPHYTE GROUPS OF BIG PEARL LAKE, DETERMINED THROUGH UNSUPERVISED IMAGE ANALYSIS AND THE VISUAL INTERPRETIVE TECHNIQUE.

	% of Total Lake Area		
	Image Analysis Technique	Visual Interpretive Technique	Difference (%)
Submersed *spp.*	6.45	6.65	+ 3.1
Floating-leafed *spp.*	0.53	1.00	+ 88.7
Emergent *spp.*	0.09	0.12	+ 33.3

The results of this exercise were compared with those obtained from manual photo-interpretation, and revealed quite similar areas of submersed plant cover (Table 4). This agreement can be attributed to the fairly regular and clearly-defined boundary associated with the *P. robbinsii* beds, which allow them to be traced with accuracy through manual means. The floating-leafed species, as with Walkinshaw Lake, were more scattered and had ill-defined boundaries. Once more, this contributed to an inflated area of plant cover when maps were produced using the visual interpretive approach.

Neither method adequately mapped the distribution of emergent plants in Big Pearl Lake. Extensive beds of *E. fluviatile* and *S. validus* were present, which are spike-like in appearance, arising from the water as erect, naked stems. While highly visible when viewed laterally, these types of plants are difficult to discern when positioned directly overhead, especially during windless periods when they are near perpendicular to the water surface. The aerial photography was taken under such conditions, and these plants formed a very indistinct image, if at all, on the photographs. In contrast, leafy emergent plants stood out clearly on the photographs and could be readily mapped using the image analysis technique.

DISCUSSION

The mapping of macrophytes and other aquatic features using computer image analysis represents a promising new application. Highly detailed vegetation maps could be produced using this technique, especially for floating-leafed and leafy-emergent varieties. Once proficiency is gained with the software, it may also prove much more time efficient than the manual mapping approach. For example, the entire classification procedure for Walkinshaw lake, beginning with the scanning and mosaicking of photographs and ending with the printing of the vegetation maps, was accomplished by one person in a single day.

This technique, however, is not without its drawbacks. Although it was possible to define a robust set of signature values for broad vegetation classes (e.g. large-leafed floating plants) which could be applied across all lakes, species-level signatures were not fully transportable to other lakes. Effects such as the developmental stage of the plants, differences in the clarity and colour reproduction of the aerial photographs, and environmental influences (i.e. sun angle, haze, and wave glitter) together act to subtly alter the spectral reflectance patterns of plants from lake to lake. It would appear that for differentiation at the species level, a custom set of signatures may have to be defined for each lake. Submersed species represent another problem area, with water colour and substrate reflection affecting the classification performance. Lakes that support a very high diversity and biomass of aquatic vegetation, as are common in southeastern United States, may present additional challenges.

Another drawback is the steep learning curve associated with use of much of the currently available image analysis software. It is expected that the 'user friendliness' will improve as these products gain in popularity and become more highly developed. Even so, for proper application of this technique at least a basic knowledge of image analysis theory is required. There are many variations in methods which may influence the success of the operation and require careful consideration, such as photographic scale, scanning density, image enhancement, and classification method (Jensen 1986).

There are a vast variety of image enhancement algorithms and clustering methods which were not fully investigated as part of this exercise, and it is quite possible that better classification methods may exist for this type of application. An improvement in classification and mapping accuracy might also be expected if higher scanning densities were used. A degree of compromise is required, however, as the digital image quadruples in file size with a doubling in the scan density. A 10 cm by 20 cm colour image, for example, would require 1.5 MBytes of storage space if scanned at a density of 50 pixels$\cdot$cm^{-1}; the same image would require 24.0 MBytes of storage if scanned at 200 pixels$\cdot$cm^{-1}. Similarly, an increase in the photographic scale would improve map resolution, but also at the expense of image size. Large images tax computer resources, both in terms of storage capacity and processing time, and some trade-offs must be made.

Lastly, it must be emphasized that this approach does not negate the need for ground surveys. An exception would be the simple broad classification of all floating-leafed and emergent vegetation, for which a 'generic' signature could be defined for broad spatial application. For more detailed mapping, some prior knowledge of plant distribution is required, regardless of which classification method is selected. A reduction in field sampling effort may be possible, though, for most distributional studies. An initial visual scan of the photographs will reveal contrasting vegetation patches, and the species composition of each can be determined through selective field sampling of representative areas. With this limited knowledge, aquatic vegetation maps and GIS overlays of the entire lake can then be generated using image analysis. Density classification of select taxa may be an added benefit, and could lead to a refinement in stratified survey designs for macrophyte production studies.

LITERATURE CITED

Andrews, D. S., D. H. Webb, and A. L. Bates. 1984. The use of aerial remote sensing in quantifying submersed aquatic macrophytes. Pages 92-99, *In* W. M. Dennis and B. G. Isom (eds.) Ecological Assessment of Macrophyton: Collection, Use, and Meaning of Data, ASTM STP 843, Philadelphia, PA.

Aronoff, S. 1989. Geographic information systems: A management perspective. WDL Publications, Ottawa, Can. 294 p.

Bogucki, D. J., and G. K. Gruendling. 1978. Remote sensing to identify, assess, and predict ecological impact on Lake Champlain wetlands. Final Report of Project C-6075, Office of Water Research and Technology, Washington, D.C. 191 p.

Forsgren, P., and M. Wallsten. 1987. Computer aided interactive classification and mapping of aquatic areas. Int. Revue Ges. Hydrobiol. 72: 257-262.

Haegele, C. W., and M. J. Hamey. 1980. Shoreline vegetation on herring spawning grounds in Barkley Sound in 1978 compared with similar assessments for 1974 and 1975. Fish. Mar. Serv. MS Rep. 1549. 37 p.

Jensen, J. R. 1986. Introductory digital image processing: A remote sensing perspective. Prentice-Hall, Englewood Cliffs, New Jersey. 379 p.

Macomber, R. T., and G. H. Fenwick. 1979. Aerial photography and seaplane reconnaissance to produce the first total distribution inventory of submersed aquatic vegetation in Chesapeake Bay, Maryland. Pages 498-503, *In* Proceedings of the American Society of Photogrammetry. Volume II. 45th Annual Meeting, March 18-24, 1979, Washington, D.C.

Marshall, T. R. 1994. The use of aerial photography to map aquatic macrophytes: Technical considerations and recommendations. Ontario Ministry of Natural Resources, Rep. No. 50512, Toronto, Ont. 25 p.

Marshall, T. R., and P. F. Lee. 1994. An inexpensive and lightweight sampler for the rapid collection of aquatic macrophytes. J. Aquat. Plant Manag. 32: 77-79.

Olson, D. P. 1964. The use of aerial photographs in studies of marsh vegetation. Bulletin 13, Tech. Series. Maine Agricultural Experiment Station. 62 p.

Schloesser, D. W., C. L. Brown, and B. A. Manny. 1988. Use of aerial photography to inventory aquatic vegetation. J. Aerosp. Eng. 1(3): 142-150.

Schloesser, D. W., B. A. Manny, C. L. Brown, and E. Jaworski. 1987. Use of low-altitude aerial photography to identify submersed aquatic macrophytes. Pages 19-28, *In* Color Aerial Photography in the Plant Sciences and Related Fields: Proc. of 10th (1985) Biennial Workshop, Univ. Michigan, Ann Arbor.

Welch, R. 1989. Desktop mapping with personal computers. Photogramm. Eng. Remote Sens. 55(11): 1651-1662.