Aquatic Macrophyte Modeling Using GIS and Logistic Multiple Regression

Sunil Narumalani, John R. Jensen, John D. Althausen, Shan Burkhalter, and Halkard E. Mackey, Jr.

Abstract
Aquatic macrophytes are non-woody plants, larger than microscopic size, that grow in water. They are an essential component of wetland communities because they provide food and habitat for a variety of wildlife, and they regulate the chemistry of the open water. Unfortunately, they also hinder human activities by clogging reservoirs and affecting recreational activities. Given their impact on environmental processes as well as on human activities, it is important that aquatic macrophytes be monitored and managed wisely. This research focuses on developing a predictive model, based on several biophysical variables, to determine the future distribution of aquatic macrophytes. Par Pond, a cooling reservoir at the Savannah River Site in South Carolina, was selected as the study area. Four biophysical variables, including water depth, percent slope, fetch, and soils, were digitized into a geographic information system (GIS) database. A logistic multiple regression (LMR) model was developed to derive coefficients for each variable. The model was applied to seven water depths ranging from the 181-foot contour to the 200-foot contour at Par Pond to determine the probability of aquatic macrophyte occurrence at each water level. Application of the LMR model showed that the total area of wetland would decline by nearly 114 ha between the 200- and 181-foot contours. The modeling techniques described here are useful for predicting areas of aquatic macrophyte growth and distribution, and can be used by environmental scientists to develop effective management strategies.

Introduction
Aquatic macrophytes are an essential component of the wetland community. They are non-woody plants, larger than microscopic size, that grow in water. These plants may be free-floating or rooted in bottom sediment and be submerged or protrude from the water (Patterson and Davis, 1991). McLaughlin (1974) has stated that aquatic macrophytes play a crucial role in providing food and shelter for animals as well as regulating the chemistry of the open water.

Unfortunately, aquatic macrophytes can also hinder human activity. They clog reservoirs, reducing water availability for human needs. In addition, the proliferation of aquatic macrophytes can affect recreational activities, obstructing boat propellers and reducing access to the shoreline especially in protected areas such as coves.

Because aquatic macrophytes have an important influence on the physical and chemical processes of an ecosystem (Froedge et al., 1990; Kiraly et al., 1990) while simultaneously affecting human activity, it is imperative that they be inventoried and managed wisely. However, mapping wetlands can be a major challenge because they are found in diverse geographic areas ranging from small tributary streams, to shrub or scrub and marsh communities, to open water lacustrian environments (Cowardin et al., 1979). In addition, the type and spatial distribution of wetlands can change dramatically from season to season, especially when nonpersistent species are present (Mackey, 1990). This research, focuses on developing a model for predicting the future growth and distribution of aquatic macrophytes. The model will use a geographic information system (GIS) to analyze some of the biophysical variables that affect aquatic macrophyte growth and distribution. Data derived from the application of the model will provide scientists information on the future spatial growth and distribution of aquatic macrophytes.

Study Area
The Savannah River Site (SRS) is a 777-km² Department of Energy facility located near Aiken, South Carolina, along the Savannah River (Figure 1). Par Pond (1,000 ha) and L Lake (400 ha) are two former cooling ponds that have received thermal effluent from nuclear reactor operations. Par Pond was constructed in 1958, and natural invasion of wetland has occurred over its 35-year history, with much of the shoreline having developed extensive beds of persistent and non-persistent aquatic macrophytes. There are, however, two species that are dominant in Par Pond — cattails (Typha latifolia) and waterlilies (Nymphaea odorata).

In June 1991, the water level at Par Pond was lowered from its full pool level (maintained at the 200-foot contour) to the 181-foot contour. Several authors have identified the effects of water level change on wetlands, including its impact on species composition and the abundance (or lack) of plant communities (van der Valk, 1981; Keddy and Reznicek, 1986). Nilsson and Keddy (1998) state that changes in water level are an important controlling factor on a wetland ecosystem because their effects on wetland vegetation can be quite pronounced. By lowering the water level at Par Pond by 19 feet (approximately 6.3 m) the existing emergent aquatic macrophyte community was destroyed. Because the

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impact of change in water level is an important factor on aquatic macrophytes, it was critical to identify the ideal water level that would encourage their growth. However, the question remained as to the appropriate water level that should be maintained in order to initiate and sustain a flourishing wetland community. The predictive model developed in this study was applied to seven water levels, including the 181-, 184-, 187-, 190-, 194-, 197-, and 200-foot contour intervals. The 181-foot contour was selected because it is the current Par Pond water drawdown level. The 200-foot contour is chosen because it was the original level of Par Pond prior to the drawdown. The 197-foot and 187-foot contours were considered because they represent the edge of the former cattail and waterlily beds, respectively. Levels of 194-, 190-, and 184-foot contours were selected because they were intermediate levels between the previous four levels. Basically, an average separation of approximately 3 feet was maintained between the contour levels selected for analysis.

### Database Development

Most predictive studies have simply identified the species composition without regard to geographic distribution. A few predictive ecological studies have attempted to retain the spatial information. Libbowitz et al. (1989) modeled the loss of marsh in Louisiana. Constanza et al. (1990) predicted future landscapes in the Atchafalaya delta. Davis et al. (1990) identified biotic communities and species in need of preservation management (gap analysis). Furthermore, many of these studies make extensive use of land-use/land-cover information and occasionally use spatially distributed biophysical data in their models.

The development of a spatially registered geographic information database with biophysical variables is largely dependent on data availability and the ease of incorporation within a GIS. In the case of aquatic macrophytes, several authors have identified the following biophysical variables as having an impact on the growth and distribution of aquatic macrophytes (Pearsall, 1920; Rorslett, 1984; Harvey et al., 1987):

- water depth,
- percent slope,
- exposure (fetch),
- soil types (substrate composition),
- water temperature,
- wave action, and
- suspended sediment

For this study, it was possible to obtain spatial information for the first four variables. In the case of temperature, no data were available for use in this research. The wave action and suspended sediment distribution change so rapidly that, unless an intensive in situ investigation is performed, it is not possible to include these variables in the analysis. For each of these biophysical variables identified, a data layer was developed and digitized into the Par Pond database.

The Par Pond database consisted of seven sub-databases containing information on the four biophysical variables on each designated water level. The full pool level (i.e., 200-foot contour) can be considered as the initial level for which the database was developed. From this, six subsets pertaining to the 181-, 184-, 187-, 191-, 194-, and 197-foot contours were derived.

### Water Depth

Water depth affects the amount of light available for photosynthesis by aquatic plants. Generally, greater depths limit the photosynthesis of the plants (Barko et al., 1982). Hammer (1992) also emphasized that vegetation zonation is largely due to the influence of water depth, and that much of the diversity and spatial heterogeneity of wetland systems is the result of different elevations. According to Moss (1990), depth is an important factor for aquatic macrophytes. Shallow areas of a water body will encourage the growth of aquatic macrophytes because they allow light penetration, assuming that the water is not clouded by sediment. Therefore, depth must be considered as an essential biophysical variable in the predictive model.

Larg-scale (1:1,200) photogrammetrically derived topographic maps (5-foot contour interval) for Par Pond prior to its construction were digitized to develop its digital elevation model (DEM). However, these maps were available for only the lower half of Par Pond, and the topographic information was supplemented from the following sources:

- USGS 1:24,000-scale 7.5-minute topographic quadrangles; and
- Large-scale rectified aerial photographs for July 1991, when the lake level was at the 187-foot contour, and October 1991, when the lake level was at the 181-foot contour.

The composite DEM is shown in Figure 2.

### Slope

Mackey (1990) states that the smaller the slope, the greater the probability of aquatic macrophyte development in shallow water. Steeper slopes will limit the rooting capability of aquatic macrophytes. In most cases the roots are relatively flimsy and can be easily dislodged due to aquatic turbulence. However, gentle slopes allow aquatic macrophytes to retain a stronger hold on the soil, thus preventing their loss.

The slope data layer for Par Pond was derived from the lake's DEM using the ERDAS® 3-D module (Brown et al., 1991). The algorithm computes percent slope for each pixel using the “tangent” trigonometric function. This involves the application of standardized mathematical interpolation techniques as described by Muehrcke (1986) and Burrough

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**Figure 1. Location of Par Pond at the Savannah River Site in South Carolina.**
Figure 2. Digital elevation model (DEM) of Par Pond derived from 1:1,200-scale engineering maps, USGS 1:24,000-scale topographic maps, and large-scale rectified aerial photographs.

(1987). Figure 3 is a slope distribution map of Par Pond. Note that the steeper slopes lie near the dam at the southern end of the lake and in the middle arm of Par Pond.

Exposure (Fetch)
Fetch may be defined as the unobstructed distance that wind can blow over water in a specified direction (Kinsman, 1984). Several authors have expressed the importance of fetch. Keddy (1982) states that the greater the fetch of a specific site, the higher the probability of larger waves or stronger currents developing, thus lowering the probability of aquatic macrophyte development. Harvey et al. (1987) found that sheltered areas along the lake shorelines tend to support more dense communities of aquatic macrophytes because they offer protection from wind and wave action. Bailey (1988) found that wave action along exposed areas of a lake often leads to a reduction in the growth of vegetation in such areas. Scheffer et al. (1992) used exposure as one of the variables to explain the causality of modeled relationships between aquatic macrophytes and environmental factors.

Jensen et al. (1992) developed a robust measurement of fetch which is computed for every point in a water body. The algorithm was applied to the raster dataset of Par Pond, to derive the fetch surface. Using meteorological data from a station located south of the Par Pond dam, wind data pertaining to speed and direction were statistically analyzed to determine the most appropriate dominant wind direction during the growing season of the aquatic macrophytes (May through September) for 1988 through 1991. The average for the four-year period showed that the 5° wedge (221° to 225°) was the dominant wind direction. The application of this algorithm resulted in the creation of a fetch surface for Par Pond which ranged from 0 to 1,100 m. Invariably, pixels in the center of the lake have the greatest fetch (exposure) while those in sheltered coves are protected from the wind and wave action (Plate 1).

Soils (Substrate Composition)
The influence of substrate composition on the growth and distribution of rooted aquatic macrophytes has long been recognized. Brown (1913) and Pearsall (1920, 1929) reported on aquatic plant distribution variability in relation to the nature of the substrate. Recent studies also recognize the importance of substrate composition to aquatic plant growth (Spence, 1982). Sediments provide an important source of nutrients, and the substrate composition (i.e., texture and organic matter content) markedly affects macrophyte growth rates, because of its influence on nutrition (Barko and Smart, 1986).

Unfortunately, soils in the SRS area are predominantly sandy, with a low percentage of clay and silt. An evaluation of the soil texture based on the SCS description revealed that the sand content of the soils in the lake regions ranged from 50 percent to 99 percent (Soil Conservation Service, 1990). According to Brady (1984), soils with less than 90 percent sand content begin to have some loamy texture to them and could therefore provide some suitability for plant growth.

Figure 3. Distribution of slope at Par Pond.
Soils at 200' contour

Figure 4. Distribution of soils at Par Pond derived from qualitative photointerpretation of large-scale, black-and-white photographs for 1958.

Another factor to consider, especially in the case of Par Pond, is the lacustrine environment that the soils have been in over the past three decades. It is inevitable that, as a reservoir ages, the inundated soils change from a terrestrial to an aquatic ecosystem (Gunnison et al., 1985; Kimmel and Groeger, 1986). However, no data are available on the rate of change of the composite soil materials.

Standard techniques for constructing a digital soils database involve the use of Soil Conservation Service (SCS) [e.g., 1:20,000-scale] maps or the interpretation of large-scale aerial photographs or a combination of both. Unfortunately, there were no reliable SCS maps of the Par Pond area available prior to it being filled in 1958. Therefore, large-scale, 1958 black-and-white aerial photographs of the Par Pond taken before the lake was filled were photointerpreted. While it is impossible to specifically label each soil type with this method, a qualitative assessment can be made. This involves the classification of soils into five categories including (1) worst, (2) poor, (3) moderate, (4) good, and (5) best soils. Photointerpretation into each of these classes was performed based on the gray-level appearance of the soil (Avery and Berlin, 1992). Sandy soils are highly reflective and will therefore appear brighter on the aerial photograph. In addition, such soils are the least conducive to aquatic macrophyte growth and can therefore be grouped as “worst” or “poor” soil types. Soils with moderate sand content and low quantities of silt and clay also appear lighter gray on the photograph and were classified as “poor.” Conversely, soils that encourage aquatic macrophyte growth are those with high clay and silt content. They appear darker on the aerial photographs and were classified as the “good” or “best” soils based on their “grayness.” Based on these assessments, the final distribution of soils at Par Pond, as interpreted from the large scale aerial photograph was developed (Figure 4).

Development of Par Pond Database Subsets

Once the main database for Par Pond (full pool, 200-foot contour) was developed, the derivation of the subset databases for the six additional contour levels was easily performed. A binary mask was developed for each of the 181-, 184-, 187-, 190-, 194-, and 197-foot contour levels from the original DEM. Areas within these contour limits were recoded as “1” and all external areas were coded as “0.” The DEM, slope, and soils data layers were not affected by the changing face of the lake, and, therefore, the masks were directly applied on the 200-foot database to derive the distribution of these three biophysical variables for the six water levels.

In the case of the exposure (fetch) data layer, however, new surfaces were computed for each contour level using the algorithm described in the preceding section. As the physical appearance of a water body changes, so will the fetch surface. For Par Pond, the lake has actually become smaller and, therefore, the fetch will be reduced in many areas of the lake where the wind would not traverse the same distance it did at full pool level.

Development and Application of the Logistic Multiple Regression Predictive Model

Braak and Looiman (1987) have described regression analysis as a “statistical method that can be used to explore relations between species and environment, on the basis of observations on species and environmental variables ...” (p. 29). According to Eveleigh and Custer (1985), “regression modeling involves the derivation of a mathematical relationship between a set of independent predictor variables and a specific dependent condition” (p. 451). The technique of ordinary least-squares linear regression attempts to establish a linear relationship between the dependent and independent variables. Subsequently, the linear probability for a point containing a specific dependent condition is based on a matrix of “m” independent variables and is expressed as follows (Eveleigh and Custer, 1985):

\[ P_i = f(x_1, x_2, x_3, ..., x_m) \]  

where \( P_i \) is the probability of location “i” where dependent condition exists and \( x_1, x_2, ..., x_m \) are the set of independent predictor variables. Unfortunately, there are a few drawbacks to this model when applied to a raster database. First, the variance, a measure of dispersion or spread of the variables (Barber, 1988), is not constant from grid cell to grid cell. Second, the probability values computed from this relationship can often fall outside the 0 to 1 range of probability values, which makes it difficult to relate the output to a systematic probability surface.

Another modeling technique that would be appropriate is discriminant analysis (Lowell, 1993) due to the binary nature of the predicted variable (i.e., presence or absence of aquatic macrophytes - both cattails and waterlilies). However, due to the qualitative nature of some variables (e.g., soil type), the logistic multiple regression (LMR) technique may be considered more appropriate (Press and Wilson, 1978). The LMR accepts both dichotomous (binary) and scalar values as the independent variables, which allows for the use of variables that are not continuous or qualitatively derived. In addition, because the probability estimate (\( P \)) al-
ways varies between 0 and 1, a realistic probability surface is produced, unlike the linear regression models where probability values could fall outside the 0 to 1 range.

LMR identifies variables important in predicting the probability of an occurrence, e.g., aquatic macrophytes, by defining the presence or absence of such an occurrence as a dichotomous, dependent variable (Harvey et al., 1987). Pereira and Itami (1991) used LMR to model red squirrel habitat in the Mount Graham, Arizona, study area and obtained good results in the development of the predictive multivariate models. The LMR technique yields coefficients for each variable based on data derived from samples taken across a study site. These coefficients serve as weights in an algorithm which can be used in the GIS database to produce a map depicting the probability of aquatic macrophyte growth.

Quantitatively, the relationship between the “occurrence” and its dependency on several variables can be expressed as

$$P_x = \frac{p(d=1/x)}{1/(1 + \exp\{B_0 + B_1 x_1 + ... + B_p x_p\})}$$

where $d$ is presence/absence (e.g., aquatic macrophytes), $x_1, ... x_p$ are a set of biophysical variables (e.g., depth, slope, etc.), and $B_0, ... B_p$ are coefficients derived from logit regression.

Expressed in simpler terms, $d$ is the dependent variable and $x_1, ... x_p$ are the independent variables. It is, therefore, evident that the logistic multiple regression analysis would be ideal for developing a predictive model in this research.

The model developed in this study is designed to utilize geographically referenced spatial information on the biophysical variables from the application of the LMR technique to the Par Pond 200-foot contour level data. Jensen et al. (1992) produced an aquatic macrophyte predictive model based on Boolean logic, for a reservoir at the Savannah River Site. In their model, all biophysical variables were equally weighted, and the authors concluded that, with the application of a logistic multiple regression technique, coefficients can be derived for each biophysical variable that would act as the weighting factor for each variable.

The geographic information databases of Par Pond contained data on the four independent biophysical variables in a raster format. Each 5- by 5-m pixel was assigned a value based on the observed or interpolated data of the variable at the center of the cell. In order to derive logit coefficients, it was necessary to develop an additional data layer on the presence or absence of aquatic macrophytes. These data were obtained from the 1989 remote sensing derived classification map of Par Pond (Figure 5). All areas with aquatic macrophytes were recoded to “1,” while areas devoid of such vegetation were recoded to “0.” The binary response variable data layer (i.e., presence/absence) could then be used to investigate the relationship between response probability and the explanatory variables.

In order to apply LMR, a stratified random sample of 2,000 pixels was derived from the Par Pond database at the 200-foot contour level. To eliminate bias in the sampling process, an equal number of points (1,000 each, on presence/absence data) were selected. Each sample point had its respective binary value on the presence/absence of macrophytes, as well as information on depth, slope, fetch, and soils.

The Statistical Analysis System (SAS) function LOGISTIC was used to perform the logit operation on the random sample dataset. The following algorithm describes the coefficients of the model for each independent variable:

$$P_x = \frac{p(d=1/x)}{1/(1 + \exp\{-6.9071 + 0.4212(\text{Depth}) - 0.0925(\text{Slope}) + 0.0019(\text{Fetch}) - 0.1136(\text{Soils})\})}$$

In assessing the model fit in Equation 3, the score statistic for the joint significance of the explanatory (independent) variables had a $p$-value of 0.0001. Thus, it can be inferred that depth, slope, fetch, and soils were significant in determining the presence/absence of aquatic macrophytes.

The analysis of maximum-likelihood estimates ($P_x > \chi^2$) shows that the predictor variables depth, slope, and fetch are significant in predicting the probability of aquatic macrophytes occurrence (Table 1). To examine this further, the stepwise LMR was used, and the variables depth, fetch, and slope were considered in that order. Soils were not significant and were eliminated from the stepwise procedure; i.e.,

<table>
<thead>
<tr>
<th>Variable</th>
<th>Individual Model</th>
<th>Stepwise Model</th>
<th>Full Model</th>
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<tr>
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<td>0.0001</td>
<td>0.0001</td>
<td>0.0001</td>
</tr>
<tr>
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<td>0.0005</td>
<td>0.0007</td>
</tr>
<tr>
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<td>0.0001</td>
<td>0.0001</td>
<td>0.0001</td>
</tr>
<tr>
<td>Soils</td>
<td>0.7080</td>
<td>—</td>
<td>0.2052</td>
</tr>
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</table>

**Table 1. Analysis of Maximum-Likelihood Estimates**

Figure 5. Remote sensing derived classification of aquatic macrophytes for Par Pond in 1989.
It is important to consider the fact that soils in the SRS area are predominantly sandy. In fact, the SRS lies in the geographic area known as the sandhills. With the exception of very poor soils (> 90 percent sand content), aquatic macrophytes may have taken root if other physical and chemical properties were ideal for their growth. Under such conditions, soils would not play a major role in determining the spatial distribution of aquatic macrophytes. Another possible reason for eliminating soils is the technique used to develop the data layer. The method, while logical, did not take into consideration the actual soil type based on the sand, clay, and silt content. This would have influenced the qualitative ranking of the soils, thus reducing their significance at the 0.05 level.

The SAS LOGISTIC procedure also tests the association of predicted probabilities and the observed responses using a series of rank correlation indices (SAS, 1990). These statistics assess the predictive ability of a model using Somers' D, Goodman-Kruskal Gamma, Kendall's Tau-a, and the c indices. All correlation indices for the full model reflected a high degree of association between predicted versus observed responses. The Somers' D index is given in Table 2 to illustrate the high degree of correlation between the predicted and observed responses. The statistical analysis of the model, therefore, reflects that its application to the geographic information dataset would produce an accurate probability surface of the spatial distribution of aquatic macrophytes.

Table 2 also shows the Somers' D correlation index derived from applying the LMR technique to the variables individually and in the stepwise procedures. A comparative evaluation between the indices of the full model and the stepwise model shows no variation. However, when each variable is considered individually, depth would determine more than 93 percent of the probability of aquatic macrophyte occurrence, while slope and soils would be minor variables in computing their occurrence.

The coefficients derived for the model in Equation 3 were applied to the GIS database of Par Pond at full pool level to produce a probability surface of the lake, with values ranging from 0 percent to 100 percent. There are several areas in Par Pond which have a very low probability of harboring aquatic macrophyte growth, and it becomes necessary to delineate a cut-off point in the probability surface where aquatic macrophytes would have the greatest likelihood of occurring. This was performed by overlaying the 1989 remote sensing derived classification map (Figure 5) on the percent probability surface. Nearly 88 percent of the total area (268.11 ha of 305.58 ha) of aquatic macrophytes was in regions of greater than 85 percent probability. This value can, therefore, be used as the cut-off probability to model aquatic macrophytes at the six additional levels of Par Pond.

A cell-by-cell comparison of the accuracy of the model was performed to evaluate the predicted versus actual distribution of aquatic macrophytes at the reservoir. The results revealed a total of 107,237 cells (or 86.1 percent) which were within the domain of predicted and actual number of aquatic macrophytes cells in Par Pond. This demonstrates a high degree of accuracy for the model, and it can, therefore, be used effectively as a predictive tool.

The final step in the model development process is the cartographic representation of the probability surface. It should be noted that the information derived from the model will be used in an environmental decision making process. According to Jensen and Narmalani (1962), remote sensing and GIS products should follow basic cartographic principles to facilitate decision making by the end user. Therefore, the >85 percent probability surface can be divided into four distinct classes (i.e., 99 to 100 percent, 96 to 98 percent, 91 to 95 percent, and 86 to 90 percent). The 99 to 100 percent class was selected because it represents the highest probability where aquatic macrophyte growth may occur. Due to the dynamic nature of the variables being studied in environmental science, a >95 percent level of confidence is often considered acceptable. Hence, the selection of the second class interval of 96 to 98 percent. The final two classes (91 to 95 percent and 86 to 90 percent) were equal sized classes. Data presented in this spatial context is easily interpreted by users (Plate 2).

### Table 2. CORRELATION INDICES FOR ASSOCIATION OF PREDICTED PROBABILITIES VERSUS OBSERVED RESPONSES

<table>
<thead>
<tr>
<th></th>
<th>Depth</th>
<th>Slope</th>
<th>Fetch</th>
<th>Soils</th>
<th>Stepwise</th>
<th>Full</th>
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<td>Somers' D</td>
<td>0.933</td>
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<td>0.755</td>
<td>0.017</td>
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Application of LMR Model to Six Water Levels

The main function of any model is its application toward providing a realistic representation of the unknown based on a given set of known circumstances. Information provided by such models is often used at management levels for decision making processes. In this research the LMR model developed
in the preceding section was applied for predicting the future growth of aquatic macrophytes in Par Pond for the six pre-selected water levels. The data derived from this model can provide environmental scientists at the SRS with a statistical as well as a spatial representation to be used for selecting the most appropriate water level at which to maintain Par Pond. In addition, knowledge of the future spatial distribution of aquatic macrophytes can be used to direct the wetland management efforts that are currently underway at the site.

An assessment of change in the potential growth and distribution of aquatic macrophytes at Par Pond for the six water levels shows that there is a steady decline in the total area where the potential growth could occur. When the >85 percent probability constraint is considered, the potential areas of aquatic macrophytes demonstrate a similar decline (Table 3). However, a small increase of approximately 3 ha is detected at the 184-foot contour. Plates 3a to 3f show the predicted areas of aquatic macrophyte growth with >85 percent probability of occurrence.

The analysis of percent change in areas of ≤85 percent versus those with >85 percent probability shows that the rate of decline is greater in areas which are more likely to have aquatic macrophytes growing (Table 3). There are two possible explanations for these observations. First, the total area of the lake is shrinking and, therefore, inevitably the area of potential aquatic macrophytes growth will decline. Second, as the lake area shrinks, the likelihood of less than

<table>
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<th>Contour (feet)</th>
<th>Area in hectares</th>
<th>% change</th>
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<tbody>
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<td></td>
<td>&gt;85%</td>
<td>≤85%</td>
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<tr>
<td>200</td>
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<td>213.97</td>
</tr>
<tr>
<td>181</td>
<td>197.54</td>
<td>198.66</td>
</tr>
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</table>

Table 3. Change in Spatial Distribution of Aquatic Macrophytes at Par Pond (Seven Levels)
ideal conditions for aquatic macrophyte growth (e.g., steep slopes or deep water) may increase.

Conclusions

The GIS modeling techniques described here can be of value when predicting where freshwater aquatic macrophytes could occur in the future. Additional data on the physical and chemical processes can be included to refine the LMR predictive model. For example, turbidity is often considered as an important variable affecting aquatic macrophyte growth. Turbid waters directly affect the amount of light that is available for the photosynthesis processes of aquatic plants (Sculthorpe, 1967). Moran (1981) has also established that turbidity can have a significant influence upon the occurrence and development of aquatic vegetation. Given the importance of turbidity, it can be concluded that, even if a lake or reservoir is shallow, the turbid waters may make it unlikely for an aquatic macrophyte community to flourish.

The chemical composition of a water body also influences the growth and distribution of aquatic macrophytes. Nutrient loadings such as phosphorus, dissolved nitrogen, oxygen, and carbon dioxide have been recognized as having a significant impact on aquatic macrophytes (Swindale and Curtis, 1957; Seddon, 1965). Several studies have illustrated that the chemical composition, as determined by the nutrients present, can influence species composition of aquatic macrophytes (Spence, 1967; Raitala and Lampinen, 1985). Non-point sources such as run-off from agricultural fields or from development areas around the lake can severely affect its nutrient content, which in turn would contribute toward determining where the aquatic macrophytes would grow and what their species composition would be. In addition, the nutrients balance can lead to enriched systems where phytoplankton and algae blooms would reduce the light penetration and limit the growth of aquatic macrophytes (Jupp and Spence, 1977). The inclusion of data on the variables discussed above, such as turbidity and water chemistry, into the GIS will serve to strengthen the model. Consequently, the predicted probability distribution of aquatic macrophytes at Par Pond would change and the spatial distribution maps would be modified accordingly. The incorporation of these data also may explain why aquatic macrophytes are growing in some areas which have been predicted as having a low probability of growth (e.g., 52 to 85 percent).

With reference to the LMR model, it was noted that the soils variable was not considered (P > Chi-Square) at the 0.05 level of significance. In fact, the stepwise LMR eliminated soils from any further analysis. This may be directly related to the methodology with which soils were derived for Par Pond. The technique used, while logical and reasonable, given the data sources available, did not consider the quality of the soils based on their actual sand, silt, and clay content. It was based primarily on the moisture content as derived from the gray-level texture interpretation of large-scale black-and-white aerial photography, and could have resulted in soils being reduced in importance.

The database can be refined by delineating those soils found along the edge of the reservoirs. This operation can be implemented by applying an environmental constraint criteria on the depth variable (Jensen et al., 1992). For example, only soils up to a depth of 4 metres (limit of waterlilies growth) should be considered, while those beyond the specified depth should be masked out. The depth constraint would be based on the species present in the water body. By considering the distribution of soils up to certain suitable depths, their classification into the five categories (ranging from worst to best) would be modified. Data from the application of this technique may provide a more robust measurement on the quality of the soils used in the predictive model.

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