J. Great Lakes Res. 33:751–773
Internat. Assoc. Great Lakes Res., 2007

Predicting Wetland Plant Community Responses to Proposed Water-level-regulation Plans for Lake Ontario: GIS-based Modeling

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ABSTRACT. *Integrated, GIS-based, wetland predictive models were constructed to assist in predicting the responses of wetland plant communities to proposed new water-level regulation plans for Lake Ontario. The modeling exercise consisted of four major components: 1) building individual site wetland geometric models; 2) constructing generalized wetland geometric models representing specific types of wetlands (rectangle model for drowned river mouth wetlands, half ring model for open embayment wetlands, half ellipse model for protected embayment wetlands, and ellipse model for barrier beach wetlands); 3) assigning wetland plant profiles to the generalized wetland geometric models that identify associations between past flooding / dewatering events and the regulated water-level changes of a proposed water-level-regulation plan; and 4) predicting relevant proportions of wetland plant communities and the time durations during which they would be affected under proposed regulation plans. Based on this conceptual foundation, the predictive models were constructed using bathymetric and topographic wetland models and technical procedures operating on the platform of ArcGIS. An example of the model processes and outputs for the drowned river mouth wetland model using a test regulation plan illustrates the four components and, when compared against other test regulation plans, provided results that met ecological expectations. The model results were also compared to independent data collected by photointerpretation. Although data collections were not directly comparable, the predicted extent of meadow marsh in years in which photographs were taken was significantly correlated with extent of mapped meadow marsh in all but barrier beach wetlands. The predictive model for wetland plant communities provided valuable input into International Joint Commission deliberations on new regulation plans and was also incorporated into faunal predictive models used for that purpose.*

INDEX WORDS: *GIS modeling, generalized wetland geometric models, lake-level regulation plans, mathematical modeling, plant community profile.*

INTRODUCTION

Human activities have modified natural water-level fluctuations in the Great Lakes through excavation of connecting channels and regulation at the outlets of Lakes Superior and Ontario. Regulation of Lake Ontario began around 1960 with operation of the St. Lawrence Seaway. Lake levels are largely controlled at the Moses-Saunders hydroelectric dam between Cornwall, Ontario and Massena, New York. Under the current regulation plan (Plan 1958D with deviations), high lake levels normally experienced during high water-supply periods have been lowered and low lake levels during low water-supply periods raised. The lake-level range has been compressed from approximately 1.5 m to 0.7 m, or half of what it was prior to regulation or would have been without regulation (Wilcox *et al.* 2005).

Water-level fluctuations are a natural phenome-

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non in the Great Lakes due to natural climatic variability. For example, Lake Michigan was less than half its current size during the mid-Holocene warming period about 8,500 years ago, and lake levels were more than 4 m higher than today during the Nipissing II phase 4,500 years ago. Since that time, the lake has experienced extreme high and low lake levels approximately every 150–160 years and lesser events approximately each 30–33 years (Thompson and Baedke 1997, Baedke and Thompson 2000). Water-level changes such as these directly affect the biological communities of the Great Lakes (Working Committee 2 1993, Wilcox 1995, Maynard and Wilcox 1997, Environment Canada 2002). The effects are greatest in shallow water, where even small changes in lake level can result in conversion of a standing water environment to an environment in which sediments are exposed to the air, or vice versa, resulting in death by flooding or in plant seed-bank germination (Keddy and Reznicek 1986, Wilcox 1995). Lake-level regulation disrupts this natural process.

There is a real need to understand the correlation between water-level patterns and biological processes that determine wetland plant community diversity, abundance, and distribution. This information can then be linked to habitat requirements for wetland fish and wildlife communities. Together, the information gained would enable development of water-regulation criteria important to wetland communities and assessment models for use in evaluating alternative water-regulation plans (Wilcox *et al.* 2005, Hudon *et al*. 2006).

In 2001, the International Joint Commission (IJC) undertook a bi-national study of the regulation plan for Lake Ontario, with the potential objective of developing a new plan that better serves the interests of hydropower, shipping, water supply, recreational boaters, riparian landowners, and the environment. Some of the wetland-related objectives of the environmental portion of the study were to demonstrate qualitative and quantitative changes in wetland plant communities resulting from past regulation (factoring out other environmental influences), to determine water-level patterns that best maintain faunal habitat diversity (as determined by plant community diversity, abundance, and distribution), and to develop predictive models and performance indicators to evaluate proposed new regulation plans for the lake.

This paper focuses on the conceptual foundation of the predictive models, based on generalized geometric (combined bathymetric and topographic) wetland models, and technical procedures for creating the models on the platform of ArcGIS. In the following sections, we present the general approach behind the modeling effort, the nature of input data, model design and the model mathematical foundation, the construction of geometric models for individual wetland sites, and the processes used for building generalized wetland geometric models of four wetland geomorphic types. We then describe how the models and mathematical routines generate predictions of plant communities that would result under new regulation plans and describe the model accuracy and possible error sources. We also provide an illustration of the predictive model to evaluate one Lake Ontario lake-level regulation plan and test the results against independent data.

GENERAL APPROACH

Many challenges were encountered in a previous effort to study the responses of Lake Ontario wetland ecosystems to water-level changes (Wilcox *et al.* 1992, Wilcox and Meeker 1995), including a) time-consuming manual construction of wetland models and manual calculation of wetland areas between different elevation intervals; b) inflexibility when adjusting model parameters; c) non-scalable, two-dimensional data sets; d) lack of an interactive visual means to display findings readily; and e) most profoundly, the inability to adopt an integrated and comprehensive approach due to the lack of data exploration and modeling capability that GIS now provides (Batty and Xie 1994). Therefore, these challenges led us to develop integrated wetland mathematical models based on GIS geo-processing techniques to search for systematic and effective solutions. The integrated, GIS-based mathematical model predicting the responses of wetland plant community to proposed new water-level regulation plans is depicted in Figure 1. The scientific logic underlying this mathematical modeling makes a presumption of continuity of natural transformations (Berkhout and Hertin 2000).

Field measurements from representative wetland study sites were needed for modeling work; 32 sites were selected and segregated into four geomorphic types (drowned river mouth, open embayment, protected embayment, barrier beach) for development of four models, each specific to a geomorphic type (Wilcox *et al*. 2005, Hudon *et al*. 2006). The models operate under the assumption that the reactions of wetland plant communities to future water-level changes will be consistent with their reactions in

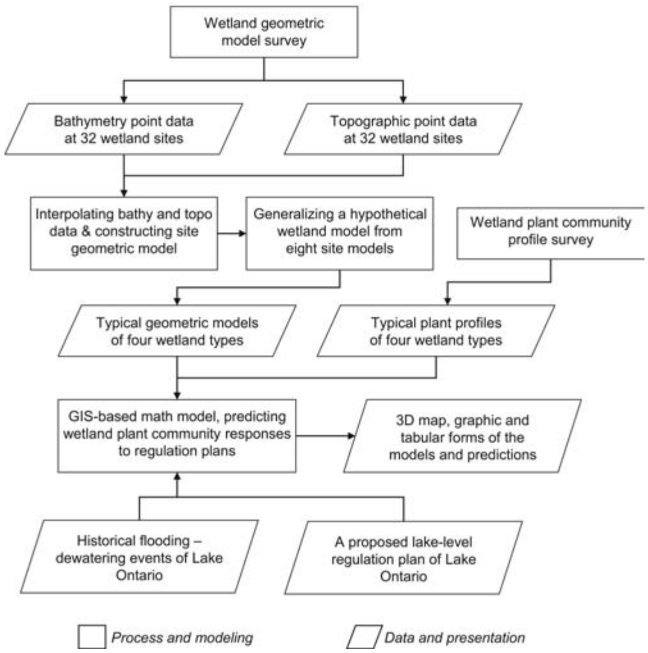

FIG. 1. Flow chart for the GIS-based mathematical model predicting responses of wetland plant communities to regulated lake-level changes.

the past. Using the approach of Wilcox and Meeker (1991) for studies on regulated reservoirs, quantitative vegetation sampling was conducted along transects that follow elevation contours with specific past lake-level histories (number of years since last flooded and since last dewatered during the growing season). Plants respond to water depths, not to lake-level elevations, so associations between lake levels and topographic/bathymetric information were also needed. Using field data and GIS methodologies, topographic/bathymetric models for each individual study site were constructed and then combined by geomorphic type to develop four generalized, three-dimensional, geometric models. The geometric models convert any instantaneous lake level to area or percent of wetland with specific water depths or water-depth histories. Proposed new regulation plans supply data in the form of predicted lake levels (average static level in each of 48 quarter months of each year) over a 101-year period, so computer codes were entered into the model to identify the periodic high lake levels in those data sets that would flood wetlands and the lowest growing-season lake levels that would dewater them. Those specific lake levels and their periodicities were then tied to the plant community responses observed in the field, and areal portions of the geometric models were assigned to specific plant community types. Repeated iterations of this routine in the models, for each of the 101 years in a regulation plan, resulted in time-weighted predictions of the area/percent of wetland of each geomorphic type that would be occupied by the plant communities identified in field sampling.

STUDY SITES

The 32 study sites selected for this work were distributed across the Lake Ontario-Upper St. Lawrence River area upstream from the dam and included eight wetlands of each of four geomorphic types: open embayment, protected embayment, barrier beach, and drowned river mouth (Fig. 2). Half of the sites for each geomorphic type were in Canada and half were in the United States. The sites available for study within each geomorphic type were restricted to specific reaches of the shoreline for which topographic and bathymetric data would be obtained as part of the overall IJC study. Private land ownership added further constraints at some locations. Among the available sites, wetlands were selected that retained hydrologic connection to the lake even in low lake-level years and were least impacted by other human disturbances (thus affected primarily by lake levels and restricting effects from human alterations in the watershed (Wei and Chow-Fraser 2005)). These sites are intended to represent most of the total of 879 geomorphically distinct wetlands, totaling 25,847 hectares, identified in a wetland inventory developed in this study (Appendix A; view appendix at http://iaglr.org/jglr/appendices/). That inventory is a seamless, digital, vector-based coastal wetland database created for the entire Lake Ontario basin and Upper St. Lawrence using a combination of existing Ontario and New York wetland databases and aerial photo interpretation (Wilcox *et al.* 2005). Later analyses that extended the lakeward edge of the wetlands to match the depth boundaries of the models increased the total area of wetland to 31,652 ha. We recognized that some Lake Ontario wetlands that are greatly impacted by human activity (Wei and Chow-Fraser 2005) may not respond to a new regulation plan in the same manner as those used for constructing the model. However, there was no means to control for those differences, and selection of any given regulation plan likely would not affect the outcome in the impacted sites.

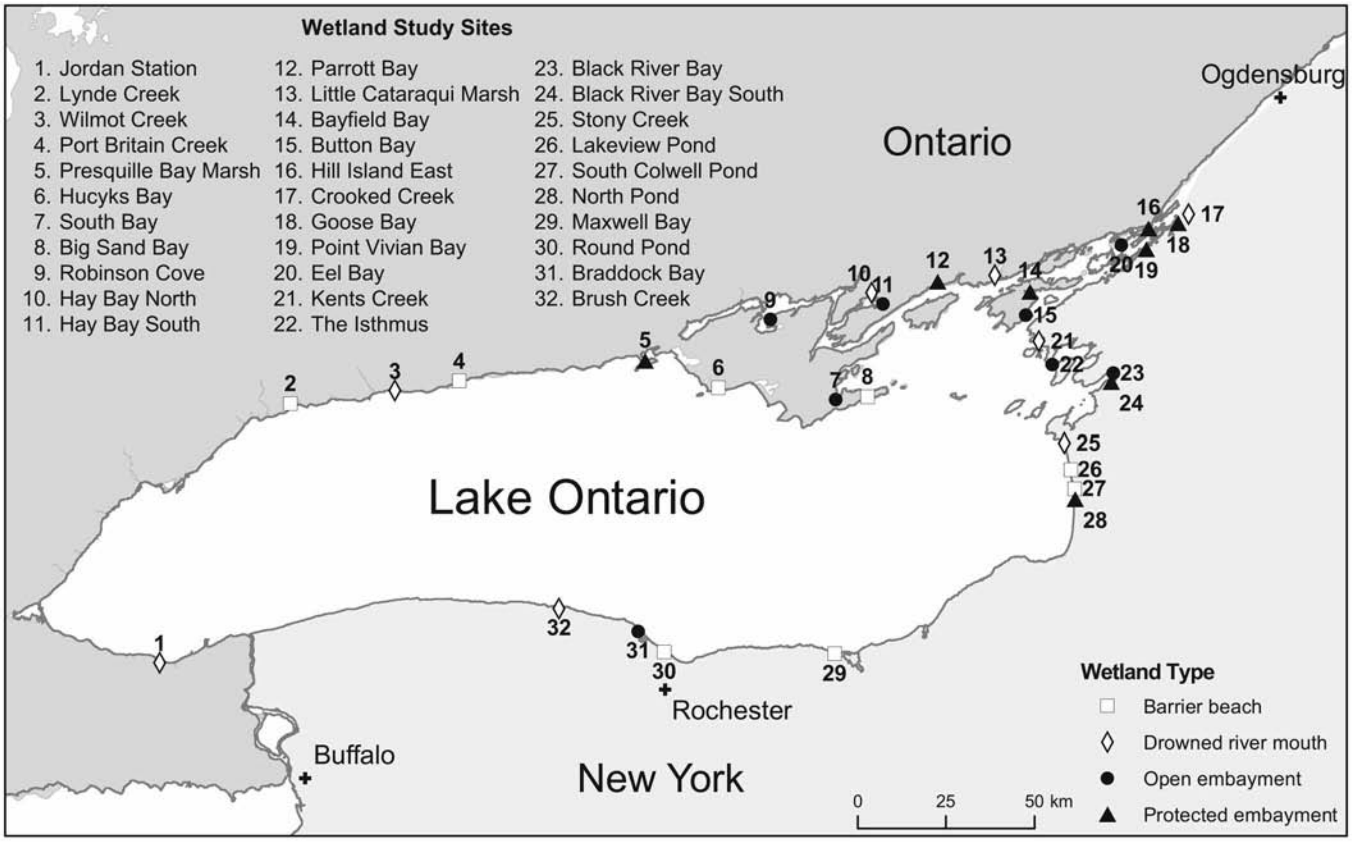

FIG. 2. Map of wetland study sites along the shore of Lake Ontario and the Upper St. Lawrence River.

SITE GEOMETRIC WETLAND MODELS

The predictive model requires construction of site-specific geometric models for each sampled wetland, based on both topographic and bathymetric features. The morphometry of each site within a given wetland type can vary greatly. Therefore, the geometries of eight sites were used to generate the models for each type. The models are intended to represent average wetlands within a type and not be faithful to any specific site. Topographic and bathymetric data for this effort were collected using airborne LIDAR and boat-based depth soundings as part of a larger IJC effort that included the need for elevation data for assessing shoreline erosion issues, as well as for specific wetlands. Unlike depth soundings, LIDAR data do not have point-specific accuracy, but it was not necessary for creation of generalized models. Three steps are involved in constructing a wetland site geometric model using these data: interpolating the topographic surface, interpolating the bathymetric surface, and merging the topographic and bathymetric surfaces. Several concepts and techniques are important in these processes: how to design the sample points, which interpolation method is appropriate, and what special considerations must be made when merging the topographic and bathymetric surfaces.

Topographic and bathymetric surfaces are commonly constructed from data points, which are collected through field sampling and observation (Petrie 1991). In practice, there are two steps for locating sample points, transect lines first and then sampling locations. In this study, transect lines were placed in areas where they provided the best representations of terrain and plant community characteristics of specific wetlands. In addition, the full coverage of the study area was taken into consideration. The spacing between the sampling transect lines was commonly 100 m. The sampled points on the transect lines for both topography and bathymetry were usually densely spaced (about 5–10 m), and the spacing was close enough to produce a grid of half-meter elevation increments for most interpolation methods. The topographic and bathymetric data were reviewed carefully to detect obvious anomalies. The most accurate and best suitable data

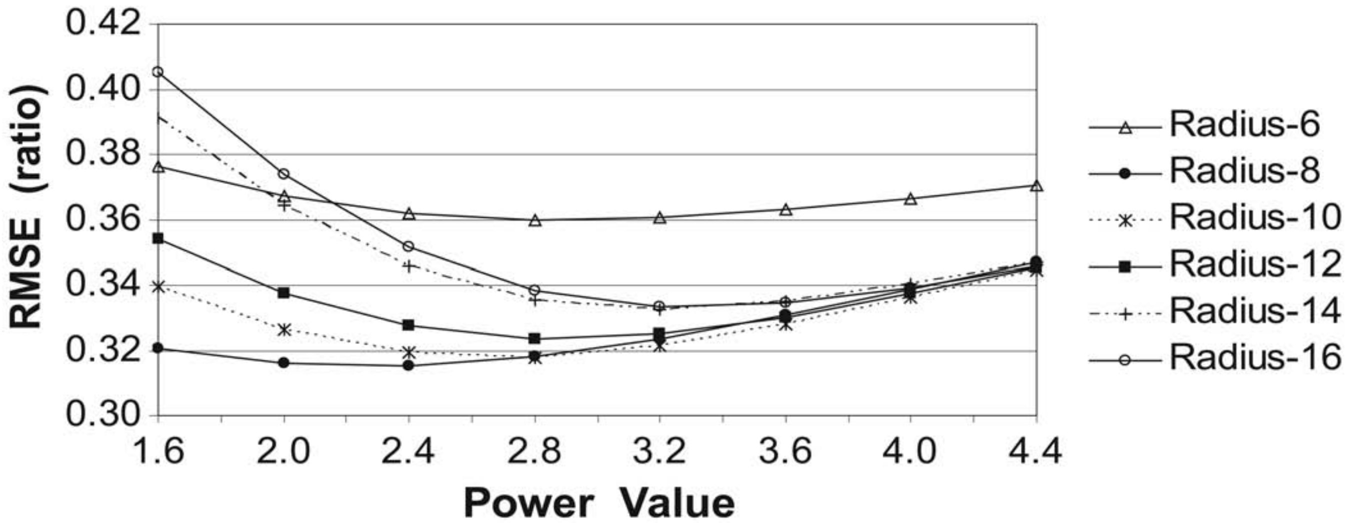

FIG. 3. Calibration results of the IDW interpolation parameters: radius and power. Different permutations and combinations of the Power (1.6 to 4.4 at an increment of 0.4) and the Radius (6–16 with an increment of 2) values were tested on a dataset randomly chosen from 32 wetlands. On the X-axis, Power shows eight values, 1.6, 2.0, 2.4, 2.8, 3.2, 3.6, 4.0, and 4.4. A power value of 2.4 and the radius value of 8m gave the smallest RMSE (the root mean square error).

were selected for the analysis according to the principle that uneven but adequate density of measured points should be matched with local roughness of the terrain surface (Makarovic 1977).

There are two major groups of interpolation methods—global and local. The global methods fit a particular mathematical function to the entire data set in such a manner that all data points exist on this chosen functional surface (Hardy 1971, Lam 1983, McCullagh 1991, ESRI 2004). The local interpolation functions assume there exists an autocorrelation effect in the surface that decreases with distance away from the point where the interpolation is made. One of the local interpolation methods, IDW (inverse distance weighted), was chosen in this study because the IDW method is intuitive and efficient and works best with relatively densely and evenly distributed points. Moreover, in the context of topographic/bathymetric modeling, IDW explains best the linear feature of slope changes. IDW interpolation explicitly implements the assumption that things that are close to one another are more alike than those that are farther apart. To predict a value for any unmeasured location, IDW uses the measured values surrounding the prediction location. Those measured values closest to the prediction location have more influence on the predicted value than those farther away. Thus, IDW assumes that each measured point has a local influence that diminishes with distance. It weights the points closer to the prediction location greater than those farther away, hence the name inverse distance weighted.

The diminishing local influence of IDW is calibrated through two parameters, the neighborhood size (the radius) and the power. The radius is the distance in map units specifying that all input sample points within the specified radius will be used to perform interpolation. The power parameter controls the significance of the surrounding points upon the interpolated value. A higher power results in a steep curve, which defines less influence from distant points. A measure of Goodness of Fit is calculated to determine the best combination of the two parameters automatically for the IDW interpolations. For each interpolation, about 100 sampling points were randomly removed from the data set. Different permutations and combinations of the Power (1.6 to 4.4 at an increment of 0.4) and the Radius (6–16 with an increment of 2) values were tested on a randomly chosen wetland for each wetland type (Fig. 3). Then, we computed RMSE (the root mean square error, Equation 1) to see which combination of the parameters generated the smallest RMSE.

$$\text{RMSE} = N^{-1}\sum_{i=1}^{N}\left[(P_i - O_i)^2\right]^{-1/2} \qquad (1)$$

N is the number of randomly chosen sampling points; P_i is the interpolated value at i sampling point; and O_i is the originally observed value at i sampling point. A power value of 2.4 and the radius value of 8 m were selected for final interpolation based on RMSE because this pair gave the least variance. We then used these parameters to interpolate the topography and bathymetry of the eight wetlands of each geomorphic type.

The separation line between bathymetry and topography data follows a contour line, and the watered portion of a wetland was usually small compared with the drier portion. Because of these considerations and the spacing characteristics of the sampling transects and points, separate topographic and bathymetry interpolation processes were implemented instead of a seamless interpolation method to avoid dominance of topographic data in interpolation at the edges of bathymetric and topographic data. Bathymetric and topographic boundaries were created and used as mask polygons during the interpolation process. Mask polygons help in restricting the area of interpolation.

The above procedures of creating wetland site geometric models were implemented in ArcGIS Spatial Analyst following these steps: go to "Options" in Spatial Analyst; select the boundary file as the Analysis Mask; in the extent tab, select "same as boundary file" (remember to change options for the bathymetry and topographic interpolation with their respective boundary files before interpolating); leave other fields with default values and click "OK"; use "Interpolate" to execute the interpolations with the output grid cell size of 0.5 m; and merge the two interpolated topographic and bathymetry grids using Calculator in Spatial Analyst "sitegrid = merge([bathy_grid], [topo_grid])."

GENERALIZING WETLAND GEOMETRIC MODELS

Generalized geometric models created from the site-specific models were needed for each of the four types of coastal wetland for use in predicting plant community distributions and calculating the areas occupied by each plant community. The generalized models should accurately measure areas and approximately characterize topographic shapes of specific wetlands. The first requirement dictates that the generalized models observe the area ratios between various elevation ranges to allow accurate prediction of wetland areas. The second requirement is more for representation purposes so that the generalized geometric models help visualize the wetland types in study. Several geo-processing techniques were integrated to generate the geometric wetland models: 1) averaging areas between elevation intervals for the four types of wetlands in study and producing a summary table of the areas between various intervals; 2) averaging and graphing the slope (distance-depth) profile for these types of wetlands; and 3) constructing a generalized geometric model for these types of wetlands based on the results from Steps 1 and 2.

First, we needed to compute average areas between various elevation intervals so that we could have quantitative measures for generalizing a geometric model, which support the area calculation requirement. A routine, Query-Area-By-Elevation-Intervals, was developed to perform spatial query of surface areas between elevation intervals and to compute average values (Appendix B; view appendix at http://iaglr.org/jglr/appendices/). In brief, this code queries the wetland area at 0.25-m elevation intervals (the range of main interest and, thus, model development is between 73.00 m and 75.75 m International Great Lakes Datum 1985 (IGLD 1985). The routine then loops through eight sample wetlands of a specific type calculating the average areas between elevation intervals. The final results are written as tables of average areas between the elevation intervals. The query results for the drowned river mouth wetlands are given in Table 1 as illustration.

Second, we needed to know the slope (depth) profile of a wetland type in study, which helps to visualize the geometric shape of this wetland type. It is a straightforward task to create the slope (depth) profile because the area average values are computed against specific elevation intervals. All data that are needed to create a profile exist in the summary tables. From the tables, the percentage and distance curves could be easily developed with any spreadsheet or GIS software. The slope-distance profiles can be generated directly using ArcGIS GRID (Spatial Analyst) profile tool (Fig. 4).

Third, wetland types within the Great Lakes reflect the influences of watershed hydrology and shoreline geomorphology (Keough *et al.* 1999, Albert *et al.* 2005). Within Lake Ontario—Upper St. Lawrence River, four distinct geomorphic types are common. They include wetlands protected from wave attack by barrier beaches, thus retaining organic sediments and developing a flatter topographic profile; protected wetlands in river mouths that are back-flooded by the lake and also have or-

TABLE 1. Query results for drowned river mouth wetlands presenting elevation range (Z, m International Great Lakes Datum 1985) and area and percent of wetland. The area of wetland is based on the average total area in square meters between the model boundaries (73.0–75.75 m) of the eight wetlands used to generate the model.

Z Range	Average Area	Percentage
73–73.25	17321.50	1.87
73.25–73.5	27763.53	2.99
73.5–73.75	27989.44	3.02
73.75–74	46621.59	5.02
74–74.25	98994.59	10.66
74.25–74.5	58171.91	6.27
74.5–74.75	32755.34	3.53
74.75–75	103036.19	11.10
75–75.25	143240.53	15.43
75.25–75.5	136238.22	14.68
75.5–75.75	111458.75	12.01
75.75–76	92844.19	10.00
Total*	928333.47	96.56

* The total average area (928333.47) is the sum of the average areas between all elevation intervals from 70 to 80 m at 0.25 m intervals. Therefore, the total percentage between the elevations 73–76 m is not equal to 100.

ganic sediments and a flatter topographic profile; wetlands exposed to wave attack in open embayments, thus having predominantly inorganic sediments and a steeper topographic profile; and wetlands of intermediate wave exposure in protected embayments that typically have flatter topographic profiles and organic sediments. We wanted to visualize various wetland types using different geometric shapes, so that we would have intuitive and realistic presentations of the wetland types in study. However, due to varied shapes of the wetlands, selecting a geometric form for a wetland shape is a rough approximation. Four generalized geometric models were chosen to approximate four wetland types from the perspectives of approximated topographic shapes and wetland hydrologic characteristics (Fig. 5): drowned river mouth = rectangle; open embayment = half circle; protected embayment = half ellipse; and barrier beach = ellipse. The four geometric models were constructed by using the Circle, Ellipse, and Rectangle drawing tools in ArcGIS, respectively. In this paper, we use the drowned river mouth wetland type as an example to introduce the basic steps of creating the bands between elevation contours. As described previously (see Table 1), the area percentage between any two contours with a specific elevation range is required to calculate the areas accurately. In other words, the area percentage values are used to determine the widths (radii) of the elevation bands. The area percentages are standardized into the band widths based on a chosen mapping scale or size. The depth (slope) information is embedded in the elevation bands. Therefore, we only needed to compute the radii of bands (Table 2).

Four steps in ArcGIS were needed to create the bands. First, two empty shape files (one point and one polygon) were created in ArcCatelog for future use. Second, a point was created in the point shapefile using ArcGIS Editing Tool. Third, bands were created in the polygon shapefile by using the Buffer Tool with reference to that point and by entering radii values that are prompted by the Buffer Tool. Fourth, the attribute table of the polygon shapefile was opened (the newly created bands) and two new fields added: Begin-Elevation and End-Elevation. Fifth, the elevation values of each band were entered into the attribute table. Because the area percentage values (or the band radii) are averaged over the eight sampled wetlands for each wetland type, the constructed hypothetical geometric rings are topological approximations of a specific type of wetland in study.

For the 3D visualization and mathematical modeling, the four shape files (rectangle for drowned river mouth, half circle for open embayment, half ellipse for protected embayment, and ellipse for barrier beach) were processed further to generate TINs (triangulated irregular networks), which can be extruded to create 3D views in ArcGIS 3D Analyst or other 3D authoring packages (Fig. 5). Using the drowned river mouth wetland model as an example, we opened 3D Analyst in ArcGIS and selected "Create TIN." We then checked the generalized band dataset and selected End-Elevation as "Height Source," as well as "Tag Value Field" and "Soft Clip" for Triangulate Option. We created a TIN by defining these parameters. After the TIN dataset was created, we opened ArcGIS ArcScene to explore 3D view of the generalized geometric wetland model through defining (adjusting) "Scene Properties," "View Settings," and "Layer Properties." Following these general procedures, we created the 3D views of the four generalized wetland geometric models in Figure 5.

The TIN datasets needed to be rasterized (exported to ArcGIS) into GRID files for calculations of area in the wetland mathematical modeling. The generalized GRID file of each wetland type is the

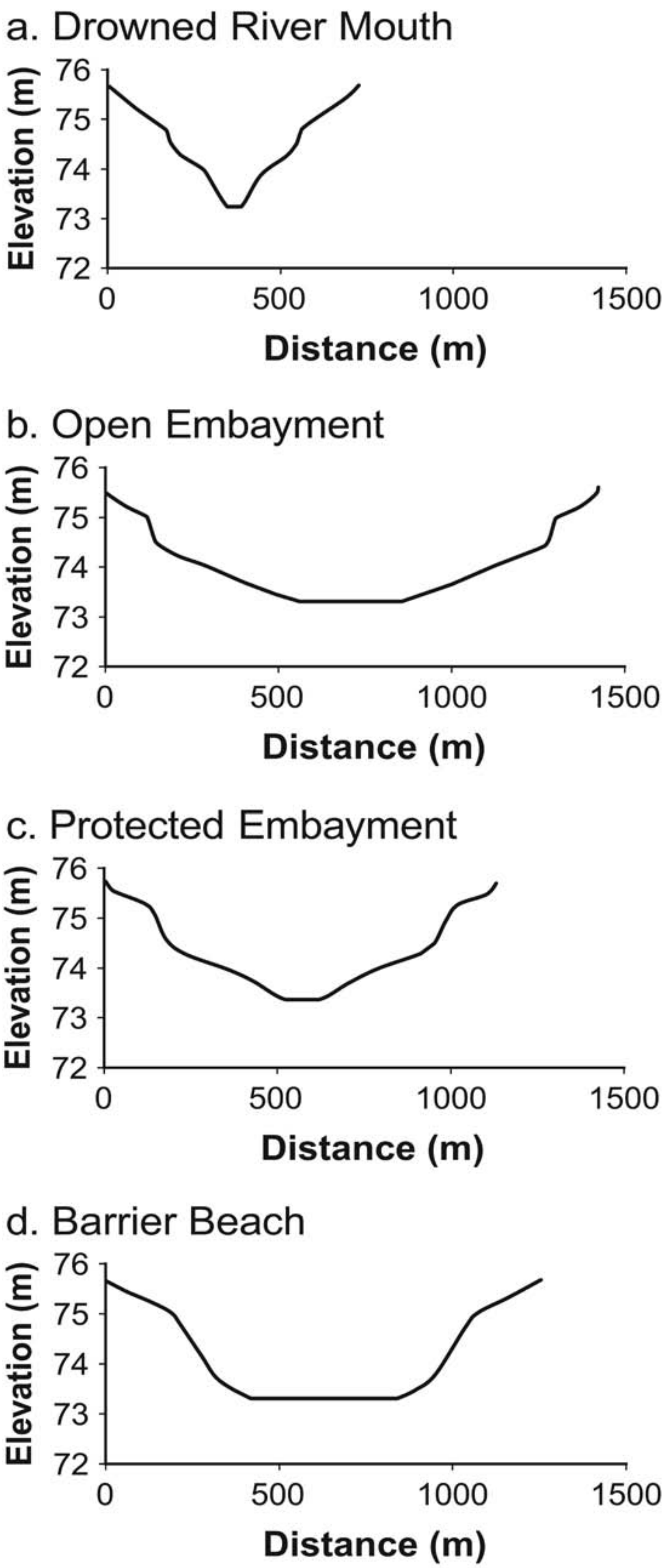

FIG. 4. Slope-distance profiles of the four wetland geomorphic types.

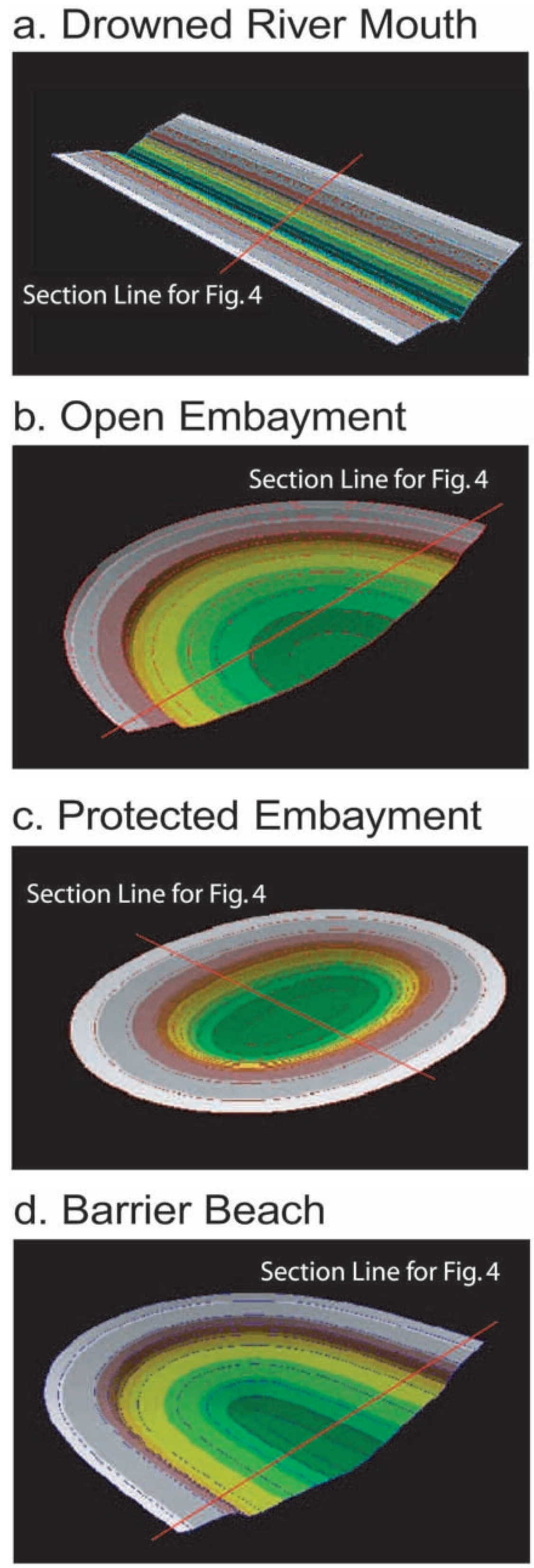

FIG. 5. Three-dimensional depictions of topographic models of four wetland geomorphic types showing cross-sections depicted in Figure 4.

TABLE 2. Elevation ranges (m, International Great Lakes Datum 1985), areas (m2 based on the average total area between the model boundaries), and widths (m) of the generalized rings model for the drowned river mouth wetlands generated with data from eight wetland sites.

MinElev	MaxElev	Area	Area_sum	Ring Width	Sum Ring Width
73.00	73.25	17321.50	17321.50	12.37	12.37
73.25	73.50	13881.77	31203.27	9.92	22.29
73.50	73.75	13994.72	45197.99	10.00	32.28
73.75	74.00	23310.80	68508.79	16.65	48.93
74.00	74.25	49497.29	118006.08	35.36	84.29
74.25	74.50	29085.95	147092.03	20.78	105.07
74.50	74.75	16377.68	163469.71	11.70	116.76
74.75	75.00	51518.10	214987.81	36.80	153.56
75.00	75.25	71620.26	286608.07	51.16	204.72
75.25	75.50	68119.11	354727.18	48.66	253.38
75.50	75.75	55729.38	410456.56	39.81	293.18

Ring Width = Area / Length
Sum Ring Width = Area_sum / Length
The long dimension of the drowned river mouth wetlands is 1,400 m on average from the samples (i.e., Length = 1,400 m).

final data input to the respective GIS mathematical models (see the next section). The rasterization was done in ArcGIS 3D Analyst by selecting "TIN to Raster" and entering 0.5 m as "Cell Size" and 1.0 as "Z Factor."

PLANT COMMUNITY INPUT DATA

Plant community data were collected by sampling in quadrats along transects that followed topographic contours representing different flooding/dewatering histories associated with past lake-level changes (Wilcox *et al.* 2005). Selection of sampling elevations was dictated and constrained by actual lake-level history, as a flooding or dewatering event that is exceeded in succeeding years is eliminated from consideration (see Figure 6 for visual interpretation). Since the existing wetland vegetation in the lake developed in response to the history of high lake levels and low lake levels, the selected elevations reflect lake-level history. The elevations (IGLD 1985) used for sampling in 2003 are shown in Figure 6 and are as follows: A) 75.60 m, last flooded 30 years ago; B) 75.45 m, last flooded 10 years ago; C) 75.25 m, last flooded 5 years ago; D) 75.00 m, last flooded 1 year ago and last dewatered during growing season 2 years ago (variable flooding and dewatering over past 3 years; E) 74.85 m, last dewatered during growing season 4 years ago; F) 74.70 m last dewatered during growing season 38 years ago; G) 74.25 m, last dewatered during growing season 68 years ago.

In each of 20 randomly placed 0.5 × 1.0 m quadrats/transect/study site, set with the longer side following the elevation contour, the plant species present were identified and percent cover estimations were made by visual inspection. Vegetation survey data were analyzed using summary statistics and ordination/classification procedures (Wilcox *et al.* 2005). Importance Values (IV) were calculated for each taxa on each transect as the sum of relative frequency and relative mean cover ratings; these values were used in the ordinations/classifications. Correlations between specific elevations and accompanying plant communities were assessed across all wetlands sampled to determine the range of elevations in which the most diverse plant communities occurred and to identify any specific habitat requirements of individual plant species, including invasive taxa. Any correlations with other physical habitat parameters, such as bulk density and percent organic matter of soil, were identified also.

When vegetation data were analyzed by species prominence and non-metric multidimensional scaling (NMDS), transects A, B, and C (see above) showed similarities across geomorphic types; transects E and F were similar in all types except protected embayments; and transect G was distinct from all other transects (Wilcox *et al.* 2005). Data

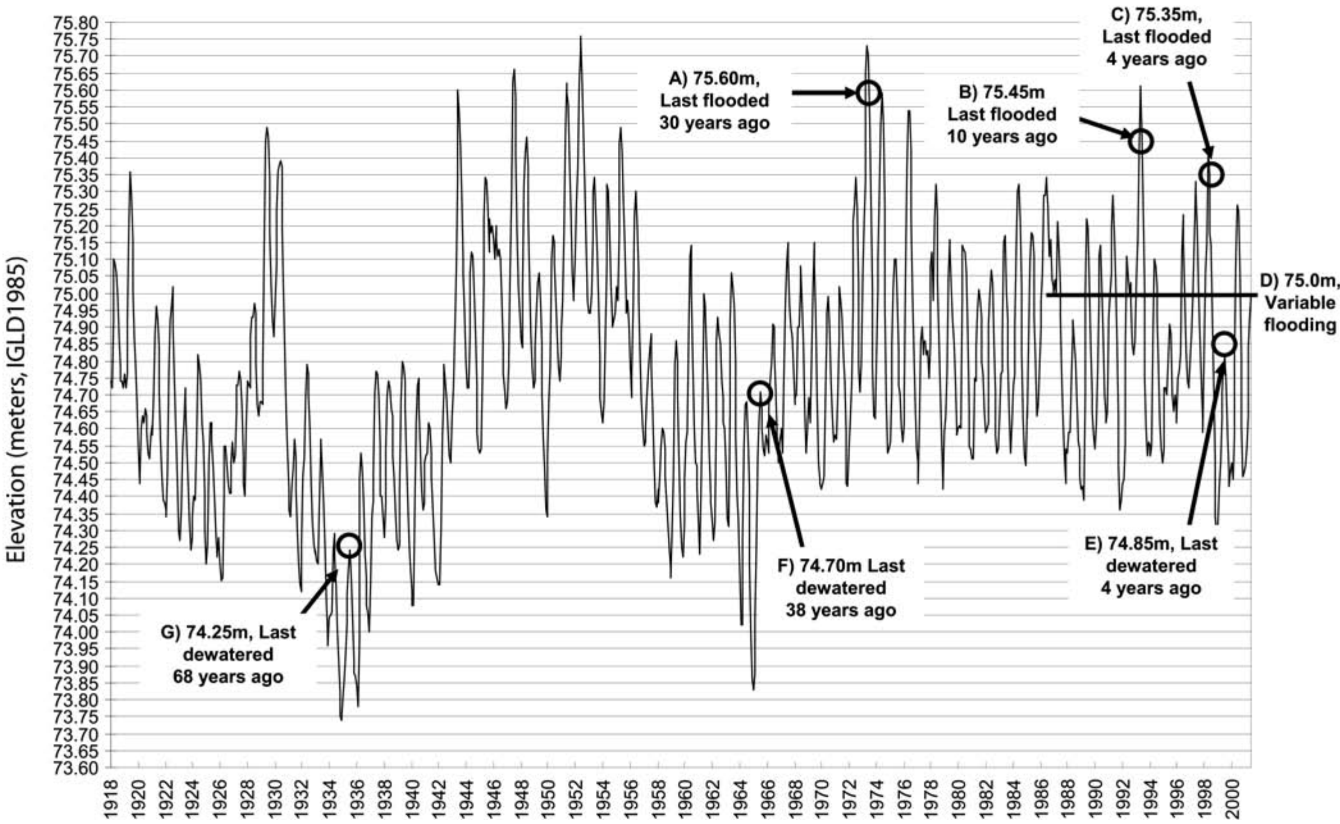

FIG. 6. ***Hydrograph for Lake Ontario (1918–2000) showing elevations selected for transects to sample wetland plant communities.***

were analyzed to ascertain similarities among wetlands of the same geomorphic type for use in the model. In general, the plant communities at elevations that had not been flooded for 5 or more years (transects A, B, and C) were dominated by sedges and grasses (meadow marsh), and those that had not been dewatered for 4–38 years (transects E and F) were dominated by cattails. The intervening transect D that was intermittently flooded and dewatered over a 5-year span was also dominated by cattails but also contained a combination of sedges, grasses, and other emergent species. Plant communities that had not been dewatered in the growing season for many years (transect G) were dominated by floating and submersed species. We recognized that seasonal and short-term (seiche) water-level changes may affect plant communities. However, they occurred across the entire past lake-level history upon which the models were based and thus are inherently captured within the models.

PREDICTING WETLAND PLANT COMMUNITY RESPONSES TO LAKE-LEVEL REGULATION PLANS

With generalized geometric models created and wetland plant communities associated with actual flooding and dewatering histories defined, the next step is to predict the area of each plant community that will occur with future flooding and dewatering patterns generated by proposed new regulation plans.

Proposed Future Lake Levels

For each new regulation plan for Lake Ontario, the IJC Hydrologic and Hydraulic Technical Working Group provided 101 years of data (labeled 1900–2000) representing modeled lake levels in which the regulation criteria in a new plan were applied to the net basin supply data from 1900 through 2000. The data were presented as quarter-monthly lake-level elevations referenced to IGLD 1985.

To evaluate the effects on upland and emergent vegetation from flooding during high lake-level years, our computer program was coded to identify the highest quarter-monthly value in the entire plan and assign all elevations above that value to vegetation category U (never flooded, transition to upland). The three adjacent (four total) highest values were then identified, and the elevation of the lowest of those quarter-monthly values was selected to represent an elevation that had been flooded for four quarter months during that peak lake-level year, which was likely long enough to affect upland herbaceous vegetation and many upland woody species, as well as some wetland species (Penfound *et al*. 1945, Kadlec and Wentz 1974, Crawford 1982, Jackson and Drew 1984, Kozlowski 1984). A similar process was used to evaluate other years with high lake levels; the specifics are described in a later section illustrating use of the models.

To evaluate the effects of low water years on submersed and floating vegetation, the computer program identified the lowest peak quarter-monthly value occurring during the growing season in the entire plan and assigned all elevations below that value to vegetation category G (never dewatered over the past 68 years). Elevations above this value were dewatered during the growing season, thus affecting submersed aquatic and floating vegetation. Again, a similar process was used to evaluate other low lake levels in the plan.

The yearly water-level values described above are saved as a list called The Real Data List. Then, this list is examined with reference to the potential wetland plant community responses to generate two class lists, "The Flood Class List" and "The Dewater Class List." These lists are generated by the subroutine that can be viewed in Appendix C at http://www.glsc.usgs.gov/_files/publications/ontariogis07.pdf and are used in the fourth sub-routine to match with a lake-level regulation plan, as will be discussed in the following sections on plant community response and illustration of use of the models. Identification of the highest water-level years and the lowest growing season peak years in a plan (The Plan Data List) provides assessment criteria on flooding and dewatering to which vegetation responds. The method is analogous to that used to detect historical flooding and dewatering events, which were used to determine elevation contours for plant sampling.

Plant Community Response

Matching of high water levels in a regulation plan with plant community response is illustrated in the pseudo codes (Appendix C; view appendix at http://iaglr.org/jglr/appendices/). The match with the flooding events first starts with finding the highest planned water level in The Plan Data List (derived from the lake-level regulation plan in study). When the highest water level is found, the highest elevation that remains flooded for at least one quarter-month becomes known, along with the year in which it occurs. Starting with the most recent year in the plan data (2000), the number of years since the highest flood and its water-level elevation allow us to match the flood event with a wetland plant community identified from the transect sampling. Within the generalized geometric model, this elevation determines the area of wetland affected by this water level as well. Therefore, the impact of the planned (regulated) highest lake level on the upland/wetland plant communities is predicted. See the illustration in a later section for step-by-step detailing of these and the remaining procedures and outputs from running the model.

The next step is to determine the remaining planned high water levels and match them with other flooding events. The algorithm is to truncate (or extract) a sub-dataset from The Plan Data List, which is the portion of the data from the previously identified highest water level to the plan year being evaluated (2000). In other words, this sub-dataset contains data points between the most recent planning year and the year immediately after the year when the highest water level was previously identified. Then, a routine similar to that described in the first step is applied to this truncated sub-dataset to find the next highest water level, the year planned, and the water level (the height value); to match with a flooding event; to relate to the associated wetland plant community; and to calculate the wetlands area affected. This same procedure is looped until all planned high water levels are matched with the plant communities, which finishes a complete run.

The study beginning year is then moved backward one year to 1999 and another run is completed. This process continues until it reaches the first plan year (1900). To provide data for early plan years, the entire lake-level sequence in The Plan Data List is appended at the beginning of the lake-level data set. Overall, the procedures described above are applied to get model results for each year in the 101-year plan sequence, as the process is executed until all plan years are exhausted and the number of the model outcome sets equal to the number of the plan years. In addition to model results for each individual year, the average area and percent wetland values for each plant community type over the 101-year sequence are calculated. The very same procedure (beginning with the most recent year in the plan and working sequentially backward to prior years) can be applied for matching with the dewatering events except for starting with the lowest growing season high water levels, which denote dewatering. The pseudo code and explanation for matching with the dewatering events are similar to the match with the flooding events.

MODEL SENSITIVITY AND ERROR SOURCES

All modeling activities involve some levels of uncertainty (Burrough *et al.* 1996, Zhang and Goodchild 2002, Longley *et al.* 2005). This uncertainty can come from a lack of complete understanding of the phenomena being studied, error in the source (input) data, errors in geo-processing processes, and erroneous specifications of parameter values in the model. The input data in this research were produced by federal agencies of the United States and Canada and were processed with highly professional quality control measures and with excellent meta-data. We are not attempting by any means to guarantee that errors in the input data are trivial. We explained the mathematical foundation of this integrated wetland modeling approach in a previous section. Here, we focus on the uncertainties that may arise from wrong selections of parameters or from geometric generalizations.

The parameters (the power and the radius) for the IDW interpolation methods that were used to generate wetland site geometric models in this study were determined by running against the datasets randomly chosen across the 32 wetland samples. We also tested the IDW parameters randomly among the datasets of each wetland type (drowned river mouth, Fig. 7a; open embayment, Fig. 7b; protected embayment, Fig. 7c; and barrier beach, Fig. 7d), respectively. The statistics used in the error detection were the root mean square errors (RMSE).

The different patterns of RMSE curves (Fig. 7) revealed three findings. First, the RMSE curves were rising with the increase of the power values, which suggests that most sample wetlands in study had gentle slope changes because small power values had better performances.

Second, the RMSE displayed varied patterns along with the increase of radius values. For instance, the RMSE decreased with the increase of the radius values in the drowned river mouth wetland model, but increased with the increase of the radius values in the open embayment wetland. The other two wetland types show more complex change patterns. For the barrier beach wetland, Radii 6 and 8 generated lower RMSE ratios, Radii 10 and 12 created higher RMSE ratios, and Radii 14 and 16 had intermediate ratios. For the protected embayment wetland, the RMSE first decreased when the radius value increased but reversed the trend when the power value passed 2.4. This finding suggests that the size of neighborhood had different impacts on the IDW interpolation results. A larger radius value worked better for the drowned river mouth wetland. The RMSE curves converged better for the protected embayment wetland, and the low-middle radius values (8.0–10.0) generated the smallest RMSE. However, the radius values for the other two wetland types showed noticeable fluctuations. Third, the open embayment and the barrier beach wetlands displayed high RMSE values. The drowned river mouth and protected embayment wetlands showed much lower RMSE values. In brief, the performances of the generalization for the protected embayment wetlands and the drowned river mouth were much better than the open embayment and the barrier beach wetlands. The model procedure worked best for the protected embayment wetlands.

Averaging the area percentages between various elevation intervals to construct the generalized geometric models for each wetland type is another concern of the model sensitivity. We used the statistics of the standard deviation as a measure of the extent to which a distribution varies from its mean (Fig. 8). For each generalized geometric model (of a wetland type), the horizontal bar is the mean area percentage in an elevation interval, and the extended line is the standard deviation (SD) over the eight samples. The generalized model for drowned river mouth wetlands has highly concentrated areas at upper elevation zones (74.75 m–76.00 m) and a single large area at the elevation interval 74.00 m–74.25 m. The SD values over four of the six zones are between 9.61 and 16.40. The generalized model for open embayment wetlands also has six zones over which the area percentages are greater than 10.00. Four of those zones are between 73.50 m and 74.50 m, and the other two are between 75.00 m and 75.50 m. However, the SD values are much lower (around or slightly higher than 5.00) than those of the drowned river mouth model. The generalized model for protected embayment wetlands only has three elevation zones that have high area percentages. The three zones span 73.75–74.00 m, 74.00–74.25 m, and 75.25–75.50 m. The corresponding SD values are also much higher, reaching 15.22. Moreover, there are three zones that have lower area percentages but higher SD values (74.75–75.00 m, 75.00–75.25 m, 75.50–75.75 m). The generalized model for barrier beach wetlands has three consecutively highly concentrated zones, which are located in the upper portions between 75.00 and 75.75 m. The SD values are quite high also. Moreover, the 74.50–74.75 m elevation zone has a very high SD value.

When compared, the four wetland geometric models are distinct in terms of percent area distributions along the model elevation profiles. Within the open and protected embayment geometric models, lower elevation portions account for more of the total model area. Relative to the other wetland types, the open embayment wetlands are more exposed to wave attack and ice scour, which reduces the amount of organic sediment deposition. For this reason, the open embayment wetlands are expected to have a steeper topographic profile within the upper contour elevations and shallower slopes at lower elevation contours. The open embayment wetlands are more regularly shaped, and thus, the open embayment geometric model is more stable and predictable. However, the protected embayment model seems to be very sensitive to the protection, which depends on coastal shorelines and geomorphologic conditions. The study wetlands displayed

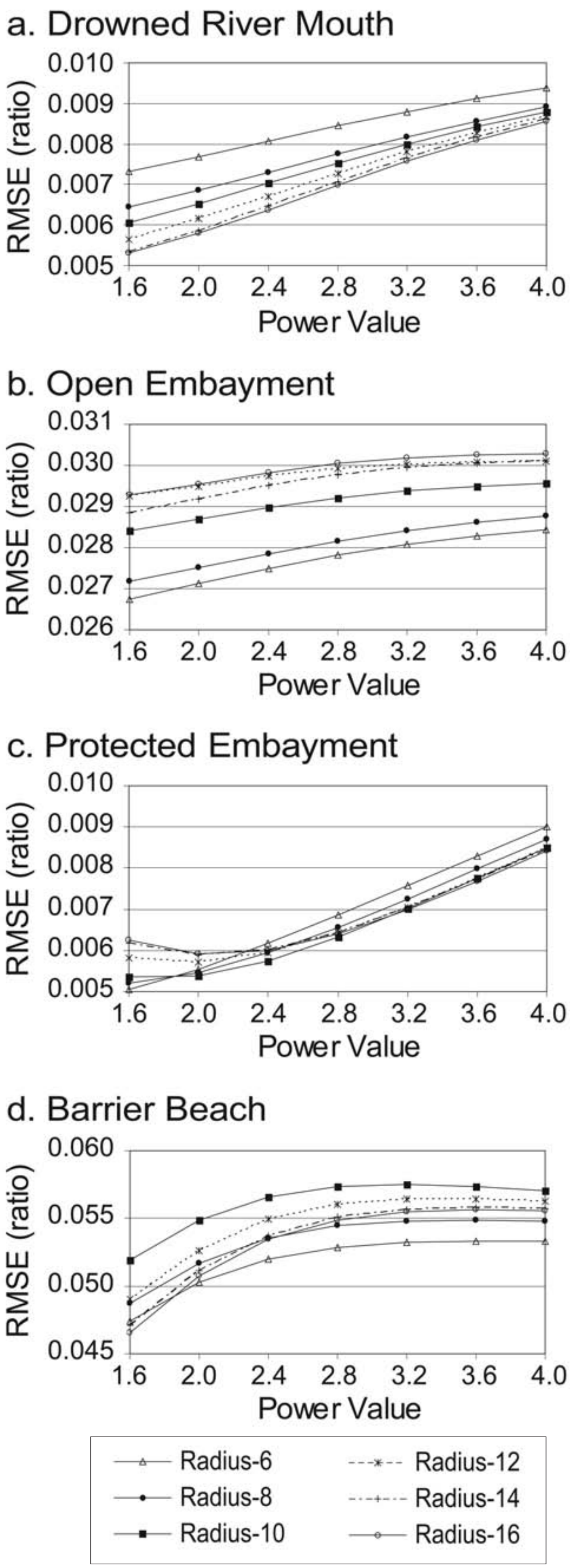

FIG. 7. ***Calibration of the IDW Interpolation Parameters for four wetland geomorphic types. Different permutations and combinations of the Power (1.6 to 4.0 at an increment of 0.4) and the Radius (6–16 with an increment of 2) values were tested on a dataset randomly chosen from each wetland type. The X-axis indicates seven power values; the Y-axis shows root mean square error (RMSE) as ratios. The six curves reflect the changes in RMSE at six radius values. The ratios for each wetland type are lower than the total RMSE ratios for thirty-two wetlands (see Fig. 3) because they are computed for the eight wetlands of the same type.***

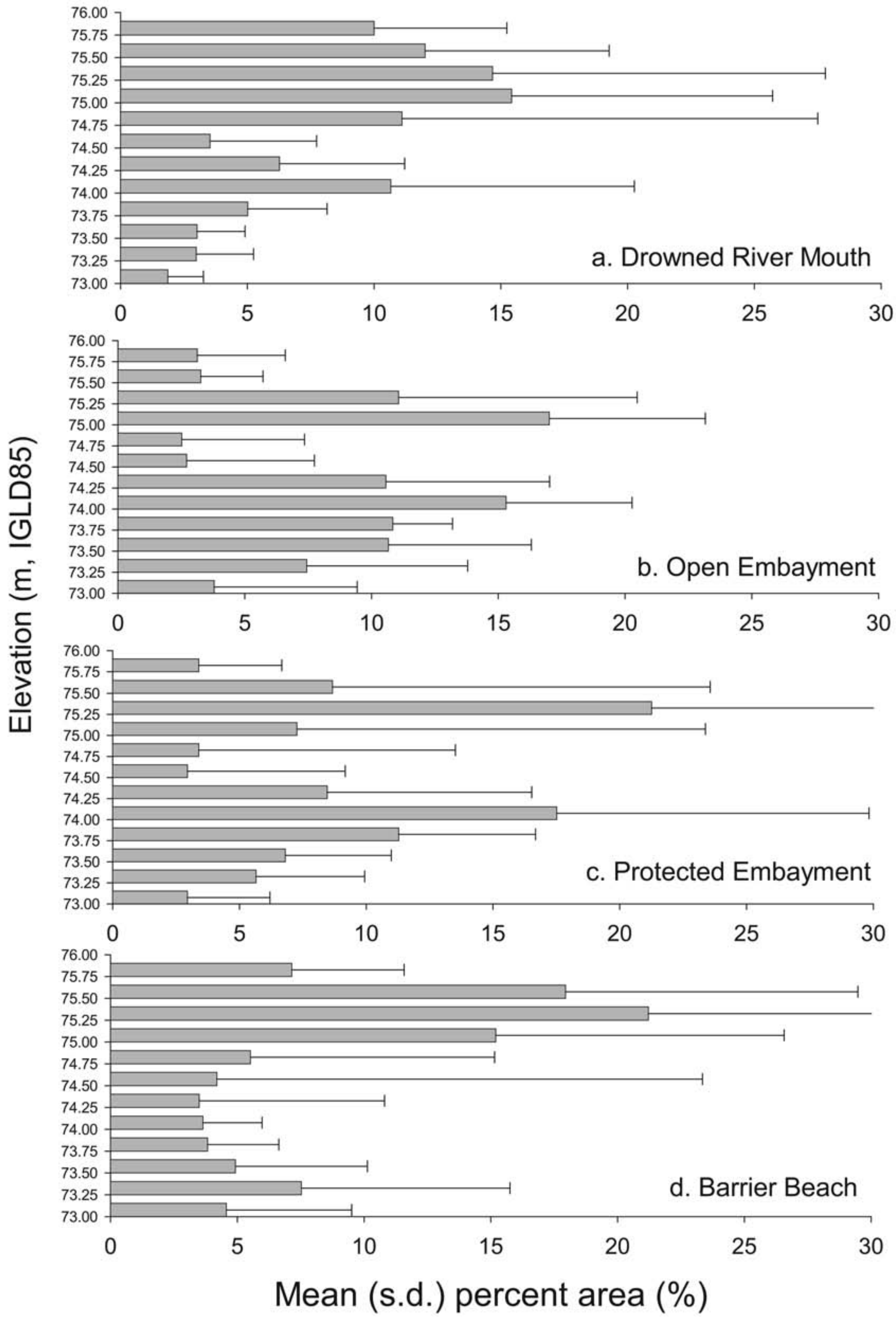

FIG. 8. Mean percent areas and standard deviations within elevation intervals of the four generalized geometric models. Mean percent areas are the averaged percentages of area in a specific elevation interval vs. the total wetland area. Eight sample wetlands were used in calculations for each wetland type.

obvious deviations in the area percents from the mean.

Drowned river mouth and barrier beach wetlands are typically well-protected from wave attack. The protection features allow for thick sediment accumulation and result in a shallower topographic profile within the upper elevation contours of the model range (Wilcox *et al.* 2005). In the context of model sensitivity, the drowned river mouth model performed relatively stably. The barrier beach model showed large fluctuations.

AN ILLUSTRATION USING THE PREDICTIVE MODELS TO ASSESS ALTERNATIVE WATER REGULATION PLANS

The predictive models for each of the four wetland geomorphic types were tested using potential regulation plans for Lake Ontario. The plans tested were the current Plan 1958D with deviations (1958DD) and two plans (X and Y) developed by using 1958DD as a base. The differences in lake level among any proposed regulation plans are dictated by how much water is released to the lower St. Lawrence River under any given net basin supply (the amount of water entering Lake Ontario from its immediate watershed and from the upper Great Lakes). Plans X and Y simulated releasing more water to the lower river than did 1958DD in 1900–1903, the 1920s, 1930s–early 1940s, 1960s, and late 1990s when basin supplies were low (IJC data), thus resulting in more years with low lake levels. More years with low levels were added in Plan Y than in Plan X (Fig. 9). The low lake levels added to Plan 1958DD were never lower than those that actually occurred during post-regulation; high lake levels never exceeded those of 1958DD. Based on existing knowledge of moisture requirements of the plant species involved, as well as observations and data from the Lake Ontario studies, testing of these plans should show an increase in area of meadow marsh (ABC) and a decrease in cattail (EF) vegetation as more low lake levels are added.

Predictions for Plan Y Using Drowned River Mouth Wetland Model

As an illustration of the model procedures, we present the results for testing the drowned river mouth wetland model using hydrologic input data from the test Plan Y, along with details regarding each step in the process. First, we summarize the results of data analyses from quantitative sampling of plant communities. Analysis of NMDS ordinations and mean percent cover data for the most prominent species identified four distinct plant communities—ABC, D, EF, and G (Wilcox *et al.* 2005). Transects A, B, and C were quite similar in species composition, with sedges, grasses, and some upland species. In transect D, these sedges, grasses, and the cattails present in EF comprised the prominent species. Transects E and F were largely dominated by cattails, with some submersed species and a few sedges and grasses. In transect G, submersed and floating-leaf vegetation (e.g., water lilies) were much more prominent than emergent vegetation, and sedges and grasses were not observed. The demarcation between the EF and G vegetation types at the study sites was typically very distinct. Although we did not sample elevations above 75.72 m that had not been flooded for more than 30 years due to the constraints imposed by actual past lake levels, we recognized that they were still within the potential range of extreme high Lake Ontario water levels. The plant communities at those unflooded elevations showed strong transition to upland vegetation and were given a separate category (U). Similar actual lake-level constraints, as well as shallower basins, prevented sampling at lower elevations that had not been dewatered for more than 68 years; however, on-site observations suggested that transect G represented those areas well.

Based on past flooding/dewatering history that resulted in these five communities, we set the following rules and procedures for assigning vegetation types to portions of the drowned river mouth geometric model (not individual sites) in any given year in a regulation plan. Professional judgment based on discussions among prominent Great Lakes wetland scientists was used to determine break points between some classes.

1. Elevations above the highest peak in the entire regulation plan: assign to U (transition to Upland) and go up to elevation of 75.75 m (top of model)
2. For other peak lake levels used to make "last flooded" determinations, use lowest of four adjacent quarter-month values (including peak). Starting with the next highest lake level following the highest peak and then moving sequentially to each more recent peak value, assign vegetation types as follows.

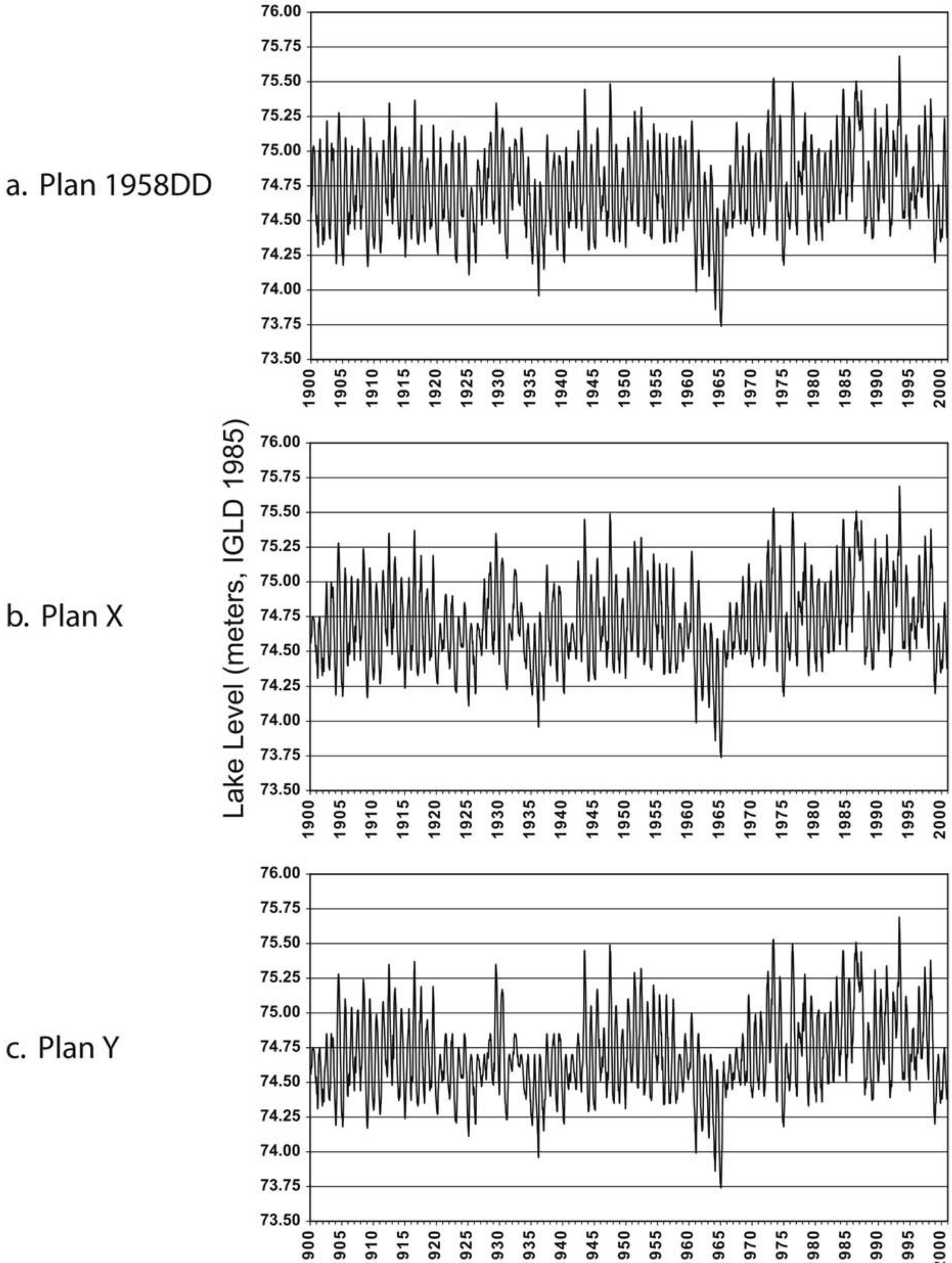

FIG. 9. Hydrographs for Lake Ontario showing predicted lake levels if regulation plans 1958DD, X, and Y were implemented using total basin supplies for the period 1900–2000. Plans X and Y were created from 1958DD but allowing more low lake levels to occur during low water-supply periods.

TABLE 3. Model output for calculation of area and percent wetland in vegetation types U, ABC, D, EF, and G using 1900–2000 quarter-monthly lake level data from Plan Y and the drowned river mouth model. Results are shown for year 2000, as well as the summary calculation that appears at the end of 101 years of prediction output. Elevation is in meters International Great Lakes Datum 1985; area is based on the average total area in square meters between the model boundaries of the eight wetlands used to generate the model. In the 101-year calculation, Sum and % refer to area.

Calculation For Year 2000:

	Year	Elevation	Years	Class	AREA	Percentage
Flood	1993	75.69	Forever	U	26750.63	3.3
	1998	75.33	7	ABC	177353.55	22.1
	2000	74.75	2	D	289877.61	36.1
Dewater	1964	74.59	Forever	G	288686.69	35.9
	1965	74.65	36	EF	7863.08	1.0
	1999	74.70	35	EF	6552.57	0.8
	2000	74.75	1	D	6552.57	0.8
CLASS	U	ABC	D	EF	G	Total
Area	26750.63	177353.55	296430.18	14415.65	288686.69	803636.69
(%)	3.33	22.07	36.89	1.79	35.92	100.00

Calculation Results for 101 Planning Years:

Class	U	ABC	D	EF	G	Total
Sum	10766821.34	13640033.98	20499700.06	6230592.84	30030157.83	81167306.06
(%)	13.26	16.80	25.26	7.68	37.00	100.00

a. Last flooded > 30 years: assign to U (transition to Upland)
b. Last flooded 5–30 years: assign to (ABC)
c. Last flooded < 5 years or last dewatered in growing season < 4 years: assign to (D)
d. If the final most recent "last flooded" peak year selected is < 5 years ago and its elevation selected from the four highest quarter-month values is less than the most recent dewatered year elevation, use the single maximum quarter-month value for making the "last flooded" determination.

3. Elevations below the smallest growing season peak value in the entire plan: assign to G (never dewatered during growing season) and go down to elevation of 73.0 m (bottom of model).
4. For other lower growing season peak lake levels used to make "last dewatered" determinations, use single maximum quarter-month value of the peak and assign vegetation types as follows.

a. Last flooded < 5 years or last dewatered in growing season < 4 years: assign to (D)
b. Last dewatered in growing season 4–39 years: assign to (EF)
c. Last dewatered in growing season 40 years or more: assign to (G)

When the quarter-monthly lake levels for Plan Y were entered into the mathematical routine of the drowned river mouth model, the model started in year 2000 to make assignments of wetland area/percent to portions of the drowned river mouth geometric model (see Figs. 5a and 9c, Table 3). The steps for making "last flooded" assignments in Plan Y proceeded as follows (see Table 3): **1**) identified the highest lake level that occurs in the plan (75.69 m, 1993; see Fig. 9c), determined the wetland area (and percent wetland) between that elevation and the upper limit of the topographic/bathymetric model (75.75 m, 3.3%), and assigned the area/percent wetland to U (never flooded, transition to Upland); **2**) identified the next most recent peak lake level (1998), selected the lowest of the four quarter-monthly lake-level values surrounding and including that peak (75.33 m), determined the wetland area (and percent wetland) between that peak

(75.33 m) and maximum peak value of 75.69 m (22.1%), determined the number of years from the year being analyzed (2000) and the last peak used to assign area/percent wetland (1993, 7 years), and assigned the area/percent wetland to ABC (last flooded 5–30 years ago); **2**$_{i}$) identified the next most recent peak lake level (2000), recognized it as the last peak < 5 years ago and with selected elevation (74.75 m) less than the most recent dewatered year elevation, invoked criterion 2d above and selected actual peak value for analysis (74.75 m), determined the wetland area (and percent wetland) between that peak (74.75 m) and last peak value assessed (75.33 m, 36.1%), determined the number of years from the year being analyzed (2000) and the last peak used to assign area/percent wetland (1998, 2 years), and assigned the area/percent wetland to D (last flooded < 5 years or last dewatered in growing season < 4 years).

The steps for making "last dewatered" assignments proceeded as follows: **3**) identified the lowest growing season peak lake level that occurs in the plan (74.59 m, 1964; see Fig. 9c), determined the area (and percent wetland) between that elevation and the lower limit of the topographic/bathymetric model (73.0 m, 35.9%), and assigned the area/percent to G (never dewatered during growing season); **4**) identified the next most recent lower growing season peak lake level (1965), determined the wetland area (and percent wetland) between that peak (74.65 m) and the lowest growing season peak value of 74.59 m (1.0%), determined the number of years from the year being analyzed (2000) and the last peak used to assign area/percent wetland (1964, 36 years), and assigned the area/percent to EF (last dewatered in growing season 4–39 years); **4**$_{i}$) identified the next most recent lower growing season peak lake level (1999), determined the wetland area (and percent wetland) between that peak (74.70 m) and the last growing season peak value assessed (1965, 0.8%), determined the number of years from the year being analyzed (2000) and the last peak used to assign area/percent wetland (1965, 35 years), and assigned the area/percent to EF (last dewatered in growing season 4–39 years). **4**$_{ii}$) identified the next most recent lower growing season peak lake level (2000), determined the wetland area (and percent wetland) between that peak (74.75 m) and the last growing season peak value assessed (1999, 0.8%), determined the number of years from the year being analyzed (2000) and the last peak used to assign area/percent wetland (1999, 1 year), and assigned the area/percent to D (last flooded < 5 years or last dewatered in growing season < 4 years).

The 'last flooded" and "last dewatered" procedures were then repeated for each remaining year in Plan Y (1999–1900), with yearly assignments of vegetation types to percentages of the drowned river mouth geometric model. When evaluating early years in a regulation plan, there are limited numbers of prior years from which to make calculations. This problem was overcome by attaching a copy of the regulation plan at the beginning of the plan under evaluation because each regulation plan is considered in the IJC study protocols to be derived from a repetitive sequence of 101-year net basin supplies.

The model output is annual predictions of the area and percent of vegetation/time classes that will occupy the elevation range (73.0–75.75 m) given in the model (Table 3). These predictions were then time-weighted by summing the areas/percents for each vegetation/time class and dividing by the number of years analyzed. The final output is time-weighted percent of wetland expected to fall into each vegetation/time class during the period portrayed by the regulation plan. In addition to the calculations shown in Table 3, summary tables are generated that display the four highest quarter-month values for each year and the elevation selected for analysis per Step 2 above (Table 4) and the percent wetland assignments for each of the individual 101 years evaluated (Table 5).

Comparison of Plan Results

As a requirement of the overall IJC study, a wetland habitat performance indicator (Area of Meadow Marsh Vegetation) was developed using study results. This indicator was selected because it is sensitive to hydrologic change (Wilcox *et al.* 1984, Keddy and Reznicek 1986, Keddy 2000), it represents a habitat that supports the greatest diversity of plant species, it can contain a diversity of structural habitats that support a wide range of fauna, and it is the plant community shown to have been affected most by regulation of lake levels. To make the performance indicator more sensitive to the hydrologic conditions that promote meadow marsh expansion (low lake levels), calculations of Area of Meadow Marsh Vegetation were made for only those years in which low total basin supplies provided an opportunity for low lake levels to occur. To meet these criteria, a time span began four years after the average quarter-monthly total

TABLE 4. Model output for determination of lake-level in each year (1900–2000) of Plan Y that is selected to represent the "last flooded" elevation used in the model. The annual peak and three adjacent quarter-monthly levels are identified, and the lowest of the four values is selected. Years 1991–2000 are shown.

Year	Water levels (m, International Great Lakes Datum 1985) for four quarter-months including and surrounding the annual peak				Selected lake level
2000	74.75	74.75	74.75	74.73	74.73
1999	74.68	74.70	74.68	74.67	74.67
1998	75.36	75.38	75.37	75.33	75.33
1997	75.29	75.33	75.32	75.29	75.29
1996	75.18	75.19	75.19	75.18	75.18
1995	74.88	74.89	74.89	74.88	74.88
1994	75.09	75.11	75.12	75.11	75.09
1993	75.65	75.69	75.68	75.65	75.65
1992	75.15	75.14	75.13	75.12	75.12
1991	75.33	75.34	75.32	75.28	75.28

TABLE 5. Model output showing summary of percent wetland assigned to vegetation types U, ABC, D, EF, and G using 1900–2000 quarter-monthly lake level data from Plan Y and the drowned river mouth model. Results are shown for years 1991–2000 are shown.

Year	U	ABC	D	EF	G
2000	3.33	22.07	36.89	1.79	35.92
1999	3.33	22.07	36.89	1.79	35.92
1998	3.33	0.00	50.96	9.79	35.92
1997	3.33	0.00	50.96	9.79	35.92
1996	3.33	0.00	50.96	9.79	35.92
1995	3.33	0.00	50.96	9.79	35.92
1994	3.33	0.00	36.76	23.99	35.92
1993	12.21	0.00	25.75	26.13	35.92
1992	12.76	16.03	9.16	26.13	35.92
1991	12.76	8.57	30.19	11.84	35.92

basin supply during the January–June period was less than 7,100 m^3/s and ended whenever the supply exceeded 8,000 m^3/s. This resulted in 22 individual years being selected for use in calculating the performance indicator, which thus measures the comparative ability of regulation plans to generate the low growing-season lake levels required by the meadow marsh community during time periods when water supplies are low and low lake levels are possible. Greater supplies in the remaining 79 years would not have allowed an increase in the area of meadow marsh vegetation under any regulation plans that might be developed. When results from the entire 101-year regulation plan period are compared, there is an increase in the average percent of meadow marsh (ABC) vegetation from 1958DD (12.8%) to the plan with additional low lake-level years (Plan X: 14.2%) to the plan with even more low lake-level years (Plan Y: 16.81%), which is the expected result. However, when using the performance indicator that uses data only for the 22 years when differences between regulation plans might allow more meadow marsh to develop, the increase in average percent meadow marsh is more profound (1958DD = 18.4%; X = 24.2%; Y = 35.2%).

Testing the Model

We recognize the importance of also testing model results against independent data. However, no alternative regulation plans for Lake Ontario have been implemented yet, and 101 years is a long time to wait for data suitable for testing. Therefore, another approach was taken as the next best alternative. In the initial phase of the IJC study, U.S. and Canadian researchers assessed vegetative change in the 32 study wetlands, including eight drowned river mouths, related to regulation using retrospective photointerpretation of aerial photographs at approximately decadal intervals from 2001 to the middle/late 1950s (Ingram and Patterson 2003, Wilcox *et al*. 2003). The identifiable vegetation types that were ground-truthed in 2002 included those dominated by cattails and by sedges/grasses (meadow marsh), paralleling the EF and ABC categorizations of vegetation types for transect sampling used to develop the model.

Unfortunately, there are inherent problems in comparing data sets of different origin. Retrospective photointerpretation often loses resolution in older photographs, as vegetation signatures may be less distinct in some historic photographs and backtracking vegetation types by signature and location is halted. In addition, sampling percent cover in quadrats along transects allows equal representation of taxa of short physical stature and taller, canopy-dominating taxa, while photointerpretation is generally influenced primarily by those taller plants. Nevertheless, the photointerpretation data provided potential for testing the model.

We ran the drowned river mouth wetland model described above using actual lake-level quarter-monthly data from 1900 to 2004. If the model operates as expected, there could be a correlation between the percentages of meadow marsh and cattail identified by photointerpretation and the percentages predicted by the model for the same years despite the inherent problems with different data sets. To overcome the problems mentioned above, the data were handled as follows. Photointerpretation data from the Crooked Creek site were not used in comparisons of either meadow marsh or cattail because this site was not used in model development due to its status as an outlier in the ordinations (Wilcox *et al*. 2005). The Brush Creek and Jordan Station sites were considered inappropriate for comparisons for meadow marsh because they showed very little meadow marsh even in pre-regulation photographs, perhaps due to loss of resolution during backtracking. Canopy influences on photointerpretation were handled by two actions. We added the vegetation type mapped as shrub swamp to meadow marsh percentages because field observations indicated that shrubs were generally an invader of meadow marsh at higher elevations, with meadow marsh still present but masked by shrub cover in the photographs. We also recognized that the model distinguishes between D and EF vegetation types because of understory differences, but the canopy in both is dominated by cattails and would have been mapped as cattails. Therefore, for comparisons with photointerpreted cattail percentages, model predictions for D and EF were combined.

We conducted a simple linear regression to compare percent meadow marsh mapped by photointerpretation in specific years with percent ABC predictions from the model for those years. We also ran a regression to compare mapped cattail with modeled D + EF in specific years but confined the analysis to post-regulation years because the model was constructed based on plant communities that already contained large areas of cattail associated with regulation (Wilcox *et al*. 2005). The predictive model is intended to be representative of the spectrum of sites and is not expected to have site-specific accuracy; however, percent mapped meadow marsh among specific sites did indeed show a significant correlation with modeled percent ABC (R^2 = 0.266; p = 0.007) (Fig. 10). The low value for R^2 is likely a result of scatter caused by comparing site-specific mapping data with model data based on averaged site geomorphometries that are not intended to be site-specific. For example, three data points that would result in a reduced R^2 had predicted (model ABC) values of zero; the ob-

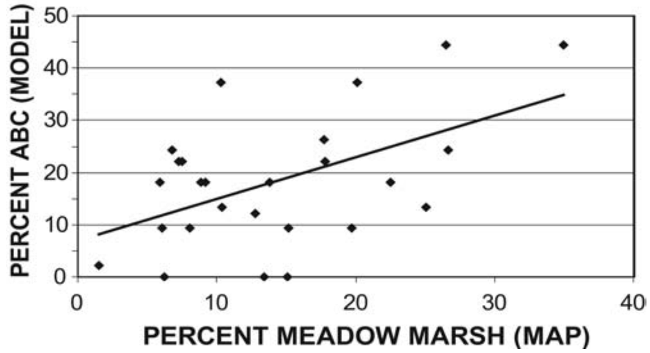

FIG. 10. Percent of wetland mapped as meadow marsh in 26 aerial photographs from five drowned river mouth wetlands (1953–2001) vs. percent ABC vegetation type derived from running the drowned river mouth model using actual quarter-monthly lake levels (1900-2004). Linear regression: R2 = 0.266, p = 0.007, Y = 0.7969X + 6.928.

served values of 6, 13, and 15% from mapping were from photographs taken in 1953 and 1954. Very high lake levels in 1952 (Fig. 6) would cause the model to predict no meadow marsh in subsequent years, but if the individual morphometry of those three sites included some area that was not flooded too deeply in 1952, meadow marsh could have survived and appeared in photographs from 1953 and 1954. Averaged morphometry in the model is not expected to duplicate actual morphometry at any one site; existence of a significant correlation was encouraging given those conditions. Percent mapped cattail was not significantly correlated with modeled percent D + EF (R^2 = 0.030; p = 0.415), as few data points had small values for either mapped or modeled percent cattail, resulting in a clumped distribution of points. Floating mats of cattail occurred at some sites along the edge adjacent to the water and likely do not respond to water-level changes. We also note that this use of photointerpreted changes in percent cattail as water levels vary with time may not be a valid measure for comparison with model results because most cattail invasion was landward rather than lakeward (Wilcox *et al*. 2005). These regression results suggest that the performance indicator (Area of Meadow Marsh Vegetation) selected for use in evaluations of potential new regulation plans for Lake Ontario was valid for drowned river mouth wetlands within the constraints under which it was developed. Similarly, mapped percent meadow marsh for open embayment wetlands (R^2 = 0.116; p = 0.037) and pro-

TABLE 6. Mean percent cover by combined transects for unique structural groups of plants found in drowned river mouth wetlands (excludes Crooked Creek) derived from sampling quadrats along transects A-G in 2003 (from Wilcox* et al. *2005).

Structural Category	A, B, C MEAN COVER (420 quads)	D MEAN COVER (140 quads)	E, F, MEAN COVER (280 quads)	G MEAN COVER (140 quads)
Tree/shrub	18.99	3.78	0.07	0.00
Vines	5.29	0.78	0.84	0.00
Ferns	1.16	0.00	0.00	0.00
Moss	0.07	0.00	0.00	0.01
Forbs	28.74	4.77	0.57	0.00
Grasses	13.71	8.19	8.19	0.09
Sedges	7.96	1.96	0.26	0.00
Broad Leaf Emergent	0.21	0.37	0.41	0.19
Thin-Stem Emergent	2.97	0.25	0.39	0.02
Thin-Stem Persistent Emergent	1.42	50.91	39.36	0.55
Floating	0.00	8.68	25.73	20.99
Submerged Broad-Leaf	0.00	0.00	0.00	0.55
Submerged Narrow-Leaf	0.00	0.00	0.64	36.67
Algae	0.00	0.00	0.00	21.18
Miscellaneous	1.39	0.82	0.04	0.00
Total Mean Cover	81.92	80.51	76.49	80.26

tected embayment wetlands ($R^2 = 0.107$; $p = 0.047$) also showed significant correlations with modeled percent ABC. The correlation with barrier beach wetlands ($R^2 = 0.065$; $p = 0.159$) was not significant, which is not surprising because there is considerable variability in geomorphometry among the barrier beach wetlands, and again, the model was not intended to apply to the geometry of any of them individually. Correlations of percent mapped cattail with modeled D + EF were not significant for open embayment, protected embayment, or barrier beach wetlands, perhaps for reasons similar to drowned river mouths.

APPLICATION OF MODEL RESULTS

The regulation plans proposed for consideration by the International Joint Commission were evaluated by models for each wetland geomorphic type as described above. The Integrated Environmental Response Model (IERM) developed by the IJC Environmental Technical Working Group also incorporated these models (LimnoTech, Inc. 2005), along with performance indicators for many faunal groups. However, the IERM converted the percentages of meadow marsh community across all geomorphic types to area of meadow marsh for the entire Lake Ontario/Upper St. Lawrence River basin by making use of the wetland inventory (Wilcox *et al*. 2005, Appendix A; view appendix at http://iaglr.org/jglr/appendices/). That inventory shows 9,157 ha of drowned river mouth wetland, 7,002 ha of barrier beach wetland, 3,337 ha of open embayment wetland, and 6,352 ha of protected embayment wetland. We recognize, however, that model results are not meant to apply to any specific wetland and that other factors may influence vegetation changes at highly disturbed sites.

The abundance of other predicted wetland vegetation types was also important in alternate plan evaluation, as was the structural nature of the plant communities. Using quadrat data from sampling along transects in 2003, the mean vegetative cover was sorted by structural category to represent different habitat types (e.g., Table 6; drowned river mouth) (Wilcox *et al*. 2005) so that model results for each regulation plan could be converted to percent of wetland in each habitat type. Those habitat predictions were incorporated into several faunal models used in the overall IJC study and in the IERM. Faunal performance indicators such as the black tern, Virginia rail, and least bittern reproductive indices incorporated comparisons of the relative supply of deep and shallow emergent marsh habitats among alternate water-level regulation plans. Yellow rail and king rail preferred breeding habitat indices incorporated changes in plant community structure. Models for spawning habitat supply for various fish guilds and northern pike young-of-year net productivity also incorporated the relative availability of structural vegetation types (LimnoTech, Inc. 2005).

The development of quantitative relationships between water levels and wetland plant communities, generalized geometric wetland elevation models, and estimates of wetland area within the study region provides powerful predictive tools to evaluate potential impacts of alternate water-level regulation plans on Lake Ontario-Upper St. Lawrence coastal wetland habitats. Manipulations of the current Plan 1958DD water-level regulation criteria clearly demonstrate that small changes in specific criteria can have dramatic impacts on coastal wetland plant communities.

The regulation plans used for testing the predictive models were developed with recognition that the IJC Study Board and Commissioners must evaluate the interests of all stakeholders and avoid undue impacts to any interest. Therefore, potential regulation plans likely are viable options only if they do not exceed extreme lake levels that would otherwise be produced under the current regulation plan. From the wetland standpoint, viable plans should place the frequency of high and low lake levels in concert with total basin supplies. Such an approach represents a realistic opportunity to address problems facing this important and complex ecosystem.

ACKNOWLEDGMENTS

We thank Kurt Kowalski, Joel Ingram, and Martha Carlson for insights provided during development of these models. Reviews of an early draft of this manuscript were provided by Joel Ingram, Jan Keough, and Bill Werick. Jeff Schaeffer provided statistical advice, and Martha Carlson prepared many data files used in our analyses, as well as some of the figures in the manuscript. Heather Morgan also prepared figures. Environment Canada (Canadian Wildlife Service) also provided figures. Field data used in developing and testing the model were collected jointly by USGS and Environment Canada, with major input from Kurt Kowalski, Jim Meeker, and Joel Ingram. Helpful suggestions were provided by three anonymous reviewers and Associate Editor Christiane Hudon. This manuscript is contribution #1433 of the USGS-Great Lakes Science Center.

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Submitted: 4 December 2006
Accepted: 28 June 2007
Editorial handling: Christiane Hudon