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Modeling wetland vegetation community response to water-level change at Long Point, Ontario

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ABSTRACT

Three spatially-explicit wetland models were developed in a geographic information system (GIS) to simulate wetland vegetation response to water-level fluctuations at the Long Point, Ontario wetland complex. They included: a rule-based model that used a series of if-then statements related to pre-existing vegetation, water depth and wetland vegetation community tolerance ranges; a vegetation state probability model based on likelihood of certain wetland vegetation communities occurring at specific water depths; and a vegetation transition probability model based on likelihood of wetland communities changing to another community under declining or rising water level conditions. The accuracy of the models was evaluated by comparing area and spatial distribution of the simulated wetland landscape to digital historical wetland vegetation data from air photo interpretation. The accuracy of the models ranged from over 80% of the cells correctly classified by the vegetation transition probability model and rule-based model to about 55% correctly classified by the vegetation state probability model. The vegetation transition probability model was marginally more accurate than the rule-based model when assessed on a cell-by-cell basis, but the rule-based model replicated the spatial distribution of vegetation communities more accurately and may be more broadly applicable. Recommended improvements include: additional environmental factors (wave exposure and substrate) incorporated in the decision rules and more detailed input data for the digital elevation model (DEM). Spatially-explicit modeling such as the rule-based model can explore management issues related to climate change and water-level regulation impacts on wetlands in the Great Lakes basin and elsewhere.

Introduction

Great Lakes coastal wetlands, located along the dynamic interface between terrestrial and aquatic environments, are characteristically influenced by water-level fluctuations (Environment Canada, 2002). The frequency, timing, duration and magnitude of these fluctuations influence water depth and duration of flooding, key factors that shape the composition and extent of wetlands, and more specifically influence the abundance and spatial distribution of vegetation communities within a wetland complex (Burton, 1985; Casanova and Brock, 2000; International Lake Erie Regulation Study Board, 1981; Jaworski et al., 1979; Keddy and Reznicek, 1986; Keough et al., 1999; Mortsch et al., 2006; Wilcox, 2004). Persistent long-term water-level declines or increases, compression of the natural water-level range, and changes in the seasonal cycle can be detrimental to the functioning and biodiversity of wetland systems (Farrell et al., 2010; Leira and Cantonati, 2008; Mortsch, 1998; van der Valk et al., 1994; Wilcox, 1993).

A number of studies have explored the implications of water-level changes for Great Lakes wetlands and wetland-dependent species, and the associated management challenges. Wilcox et al. (2005) and Wilcox and Xie (2007) assessed the impact of water-level regulation on wetland plant communities in Lake Ontario. The International Upper Great Lakes Study (IUGLS) for the International Joint Commission (IJC) needed to understand the ecological implications of multiple water-level scenarios to inform regulation plan formulation for Lake Superior (ETWG, 2009). Other studies have focussed on the impact of water-level change on wetland vegetation and fish communities (Doka et al., 2006; Midwood and Chow-Fraser, 2012), wetland remediation (Chow-Fraser, 2005), invasive species in wetlands (Wilcox et al., 2003) as well as the broader implications for wetland ecosystems of projected water-level alterations due to climate change (Mortsch et al., 2006). Yet, studies exploring the ecological effects of annual water-level fluctuations in the Great Lakes are limited and there are fewer still that try to quantitatively model these effects (Ciborowski et al., 2009).

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This paper presents the development and evaluation of spatially-explicit models of wetland vegetation community response to historical inter-annual water-level change at the wetland complex at Long Point on the Ontario, Canada side of Lake Erie. Drawing upon modeling techniques identified in the literature, three models were developed in a geographic information system (GIS) — a rule-based model, a vegetation state probability model, and a vegetation transition probability model. Our goal is to explore how these three models perform in replicating the observed wetland vegetation community response in a large, well-studied wetland complex. Spatially-explicit wetland models may emerge as a useful tool for developing a better fundamental understanding of wetland ecosystems and informing resource management decision-making related to climate change, water-level regulation, wetland restoration and invasive species in the Great Lakes.

Wetland vegetation communities

Wetland–water-level relationships have been developed for the lower Great Lakes and the St. Lawrence River – through air photo interpretation, field studies and biological inventories – and conceptualized in plant community displacement models that depict major wetland vegetation communities and their response to water-level change (Herdendorf et al., 1981; Hudon, 1997; Jaworski et al., 1979; Keddy and Reznicek, 1986; Mortsch et al., 2006; van der Valk, 1981).

Wetland plant species have been organized into broad vegetation communities – submerged aquatic vegetation, emergent, meadow marsh, and shrub – reflecting similar tolerances to environmental conditions (Wilcox, 2004). The tolerance ranges of dominant wetland plants are most readily linked to duration of flooding and dewatering, and moisture requirements (Bolsenga and Herdendorf, 1993; Euliss et al., 2004; Grosshans and Kenkel, 1997; Herdendorf et al., 1981) as well as other physical and chemical factors such as substrate type and nutrients (Keddy, 2000; Mitsch and Gosselink, 2000). Wetland vegetation communities are distributed along a water depth-moisture continuum from shallow open water to the shoreline (standing water or high water table) and further inland to meadow, upland shrub and/or treed conditions (rarely flooded) (Fig. 1). In the dynamic coastal environment, the communities respond to water-level changes by shifting, expanding, and contracting along this continuum (Keddy and Ellis, 1985). However, wetland vegetation community zonation – relative position reflecting the sequence of water depth tolerances – is maintained and there is not a total re-assortment of species as during a drawdown (Keddy and Reznicek, 1985).

During extreme water-level conditions certain vegetation communities dominate on an areal basis: submerged vegetation during periods of high lake levels, and meadow and shrub species during low (Burton, 1985; Hudon, 1997; Mortsch et al., 2008). This reveals the optimum hydrologic conditions for vegetation communities and the upper and lower extent of plant community zonation along a water depth gradient (Herdendorf et al., 1981; Jaworski et al., 1979; Keddy and Reznicek, 1986). The quantitative modeling approaches developed in this paper are informed by these theories of wetland vegetation community response to water-level changes.

Wetland modeling

A variety of techniques have been employed to model wetland systems in both a non-spatial or spatial context. Regression-, process-, probability-, and rule-based modeling approaches with water-level applications are briefly surveyed; where possible, examples specific to the Great Lakes–St. Lawrence basin are used to illustrate the state of modeling for this region.

Regression analyses (logistic, multiple, and linear) have been used to develop many ecological models. Logistic regression can be used to predict the absence or presence of certain wetland species or communities (Narumalani et al., 1997; Özesmi and Mitsch, 1997), while linear regression can be used to predict wetland area and develop relationships between variables (e.g., water-levels) and wetland vegetation change. In the Great Lakes–St. Lawrence Basin, regression models have been developed to study the impact of water-level fluctuations on coastal wetlands (Bukata et al., 1988; Frieswyk and Zedler, 2007; Hudon, 1997; Lyon et al., 1986). These studies commonly predict aggregated changes in total wetland area and/or the area of specific vegetation communities but vegetation changes at a specific location in a wetland are not estimated.

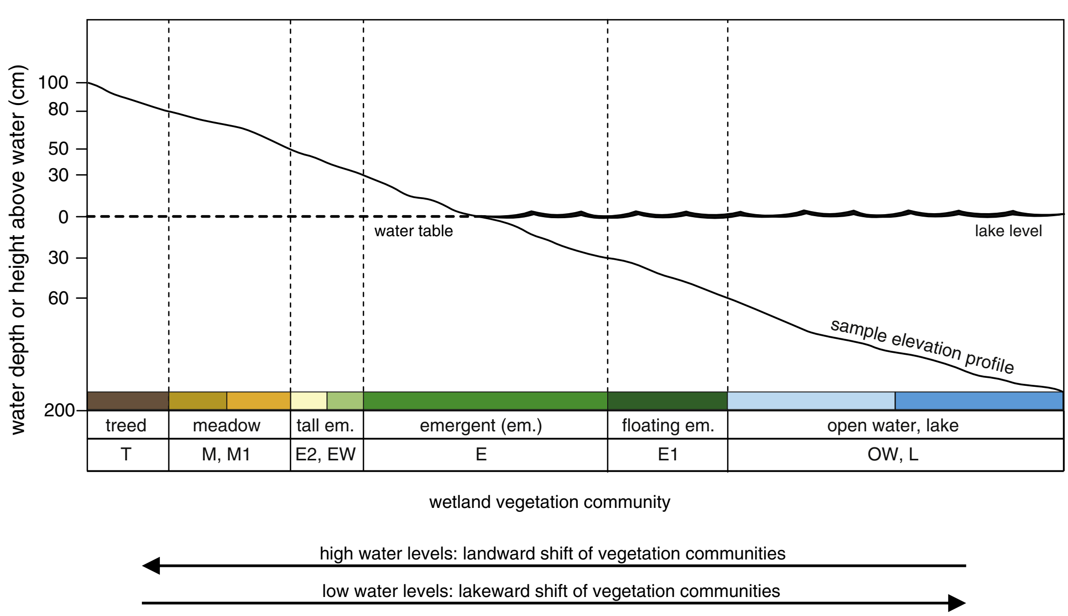

Fig. 1. Conceptualization of water-level and elevation influence on the wetland vegetation continuum in a typical Great Lakes marsh, with water depth ranges synthesized from the literature. L = lake; OW = open water; E1 = floating emergent; E = emergent; EW = tall wet emergent; E2 = tall dense dry emergent; M1 = short wet meadow; M = meadow; T = treed; U = upland.
(Continuum adapted from Bolsenga and Herdendorf (1993)).

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Process-based models describe physical, chemical, and biological dynamics such as exchanges of water, nutrients and energy in a wetland ecosystem. In these models, landscapes are compartmentalized – usually into grid cells – and location-specific algorithms are used to model interchanges between cells (Sklar and Costanza, 1991). Such complex modeling efforts have not been undertaken in the Great Lakes region but have been applied in the Mississippi Delta to simulate habitat change (Martin et al., 2000) and to explore succession of wetland vegetation related to water-level changes in south Louisiana (Sklar et al., 1985; Costanza et al., 1986, 1988, 1990) and the Florida Everglades (Fitz et al., 2004).

Although probability modeling is more commonly used in terrestrial landscape modeling exercises, it has been used for wetland applications. Transition probabilities represent the likelihood of certain wetland plant communities changing or transitioning to another community type over time. For example, Ellison and Bedford (1995) developed a set of probability transition rules based on water depth, seed bank germination and seed dispersal to simulate plant community response to disturbances in a Wisconsin wetland.

Rule-based modeling is an alternative approach to predicting wetland vegetation change in a spatial context. It does not use statistical relationships but a series of rules to define wetland vegetation response. For example, Poiani and Johnson (1993a, 1993b) and Johnson et al. (2005) used a series of if-then statements combining existing vegetation type, water depth, and duration of inundation to predict changes in vegetation cover and distribution in a Prairie pothole wetland. In the Great Lakes, Sabila (2005) developed rule-based models of vegetation response to water-level change for three fens in Lake Huron.

Wetland vegetation dynamics are best understood in a spatially-explicit context (Mitsch et al., 1982; Trepel et al., 2000). Traditionally, wetland models for the Great Lakes region have not incorporated a spatial component in the selection of input variables and few have produced spatially distributed modeling results (Lyon and McCarthy, 1995) but GIS technology now makes this possible. A GIS can handle large volumes of diverse and spatially-oriented data, geographically anchor processes occurring across space and time (Payn et al., 1999), and interface with simulation models for predictive analysis (Johnson, 1990). In this paper, we develop three spatially-explicit modeling approaches, assess their performance in predicting wetland vegetation community response to water-level change, and evaluate the applicability of the approaches to future modeling efforts in the Great Lakes.

Study area

The Long Point wetland complex (42° 35′ N, 80° 25′ W), situated on the northern shore of Lake Erie near Port Rowan, Ontario, Canada, is one of the most significant remaining wetland complexes within the Great Lakes region (Fig. 2) since many other wetlands in the region have been drained or degraded by human activities (Snell, 1988; Lake Erie LaMP, 2004).

Long Point is a very large freshwater sand barrier/spit complex that extends 37 km eastward into the deepest part of Lake Erie (Kreutzwiser and Gabriel, 2000). This long sand spit promotes wetland development since it protects Inner Bay from high wave energy created by long fetches over the open water of Lake Erie. As a result, a rich mosaic of wetland vegetation has developed under a range of hydrologic and physiographic conditions (Catling and Reznicek, 1981).

The climate, unique landforms and diverse vegetation at Long Point interact to provide exceptional habitat for many wildlife species. Long Point is an important refuge and staging area for many North American shorebirds and migratory waterfowl. Additionally, the sheltered wetland environment and shallow waters of Inner Bay provide important spawning and nursery habitat for many fish species in Lake Erie. Long Point has been recognized as a Wetland of International Significance under the Ramsar Convention (1982), a World Biosphere Reserve (1986), and a Globally Important Bird Area (1996).

A number of factors make the Long Point wetland complex an ideal case study site for modeling wetland vegetation response to water-level change using a GIS. First, it has developed along the coast of Lake Erie – an unregulated Great Lake – where water-level fluctuations are largely due to natural forcing factors such as climatic variability. Environmental responses, including wetland vegetation community development and distribution, are not confounded by large-scale human influences like regulated outflows and water levels. As a result, much of Long Point represents an ecosystem adapting to natural hydrologic regimes over time. The exception is Big Creek National Wildlife Area (NWA) where the wetland is diked and water-levels are artificially regulated to preserve critical habitats. Second, the Long Point complex remains one of the least developed coastal wetlands in Southern Ontario. While there are anthropogenic disturbances, little of the shoreline is severely degraded due to development and hardening. The physical–environmental relationships developed at this site can more readily characterize "natural" ecological responses to water-level change and provide insights on ecological change in an undisturbed wetland. Lastly, the area is data rich.

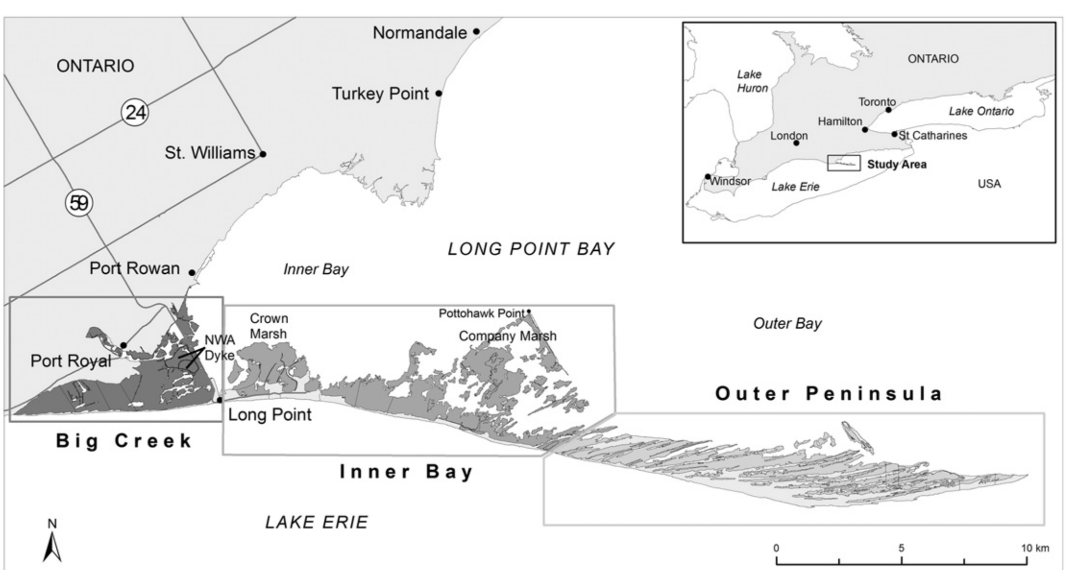

Fig. 2. Study area — the Long Point wetland complex (key features — Big Creek, Inner Bay, Outer Peninsula — delineated by boxed areas).

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The historical data record captures both periods of low and high water-levels and supports assessments of wetland change (Whillans, 1985; Wilcox et al., 2003). Many types of data – field observations, interpreted air photos, digital bathymetry and topography – can be integrated in a GIS to support quantitative model development.

The resource management issues addressed by the IJC IUGLS illustrate the value of modeling wetlands and the specific role of the Long Point wetland complex. Innovation through spatially-explicit modeling of wetland vegetation community response helps to develop our knowledge of complex responses to water-level change and informs decision-making. Specifically, modeling the Long Point wetland complex in its relatively pristine state, contributes to understanding the sensitivity and natural responses of wetland vegetation to water-level change without the confounding effects of water-level regulation and serves as a baseline from which to assess the future impacts of climate change on wetland ecosystem responses.

Methods

The GIS-based models required three key inputs: digital wetland vegetation community data, a contiguous topographic and bathymetric coverage of the Long Point region, and a time series of annual average Lake Erie water levels. These data sources are described further below.

Data preparation

A wetland vegetation database was developed by interpreting and digitizing wetland vegetation and land use classes from historical aerial photographs (Hebb, 2003; Snell and Cecile Environmental Research, 1992; Wilcox et al., 2003). Black and white aerial photographs for 1945, 1955, 1964, 1978, 1985, 1995, and 1999 were interpreted and classified into detailed wetland vegetation community and land use classes. The class delineations were transcribed as polygons onto 1:10,000 scale Ontario Base Maps (OBMs) which were digitized or scan-vectorized (using semi-automatic tracing) and georeferenced to Universal Transverse Mercator (UTM) coordinates to produce digital coverages of the Long Point wetland complex. Each coverage was associated with a mean annual water-level condition on Lake Erie representing a year with low, average, or high water-level conditions as well as declining or rising conditions.

For the modeling application, the multiple wetland vegetation and land use classes were aggregated into ten classes. Nine were wetland classes tending from lake to drier inland conditions including lake (water depth greater than 2 m and wetland vegetation not likely), open water (submergent vegetation evident or possible but limitations in air photo interpretation of this class preclude accurate detection), floating emergent (e.g., *Lemna* spp, *Nuphar* spp, *Nymphaea* spp, *Zizania* spp), emergent (e.g., *Sparganium* spp, *Scirpus* spp), tall wet emergent (e.g., *Typha* spp, grass/sedge interspersed with water), tall dense dry emergent (e.g., *Typha* spp, grass/sedge, *Phragmites*), short wet meadow, meadow, and treed. The tenth was a broad upland class combining all other non-wetland and non-water categories.

Since the outer boundaries of the wetland for each year of coverage were not exactly aligned, a boundary coverage was created to clip all of the wetland data to the same spatial extent. The common clipped boundary did not affect modeling of wetland migration since the lakeward boundary could move into open water or lake while at the landward edge barriers – a cliff or road – prevented upslope movement.

A digital elevation model (DEM) of the Long Point wetland complex was constructed by integrating data from three sources: a digital bathymetric contour map of the lake provided by the National Oceanic and Atmospheric Administration (NOAA), a DEM of the terrestrial areas at Long Point (12 m resolution) provided by the Ontario Ministry of Natural Resources (OMNR), and a point coverage containing spot elevation values derived from OBMs of Long Point. Elevation points from all three data sources were converted to meters and subtracted from chart datum (173.5 m IGLD85) to obtain an elevation above mean sea leve (asl). From this DEM, a topographic coverage with a 12-m grid cell size was generated using TOPOGRID (Fig. 3a). A low pass filter was applied to smooth the surface and remove noise. Lake depth grids (and elevation above water) were derived for each year of historical wetland data by subtracting the mean annual water-level for that year from the elevation in the topographic coverage (Fig. 3b); these data were the input for modeling. Average annual whole-lake water levels were derived from monthly mean coordinated water levels (provided by R. Moulton, Environment Canada).

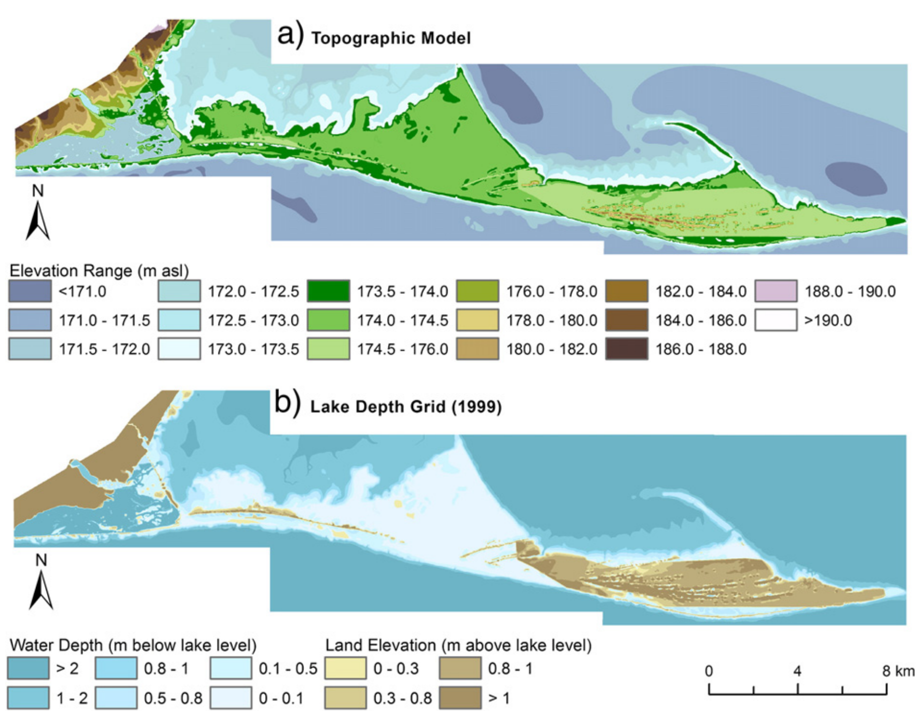

Fig. 3. a) Topographical elevation (m asl) and b) bathymetric elevation relative to lake level used as input for vegetation models.

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Table 1
Decision rules for wetland vegetation community response (rule-based model).

(1) *Fate of lake*:
IF VEG = L AND WDC ≥ 6 THEN VEG = L
IF VEG = L AND WDC ≤ 5 THEN VEG = OW
IF VEG = L AND WDC ≤ 5 AND ADJ = U THEN VEG = U
(2) *Fate of open water*:
IF VEG = OW AND WDC ≥ 6 AND ADJ = L THEN VEG = L
IF VEG = OW AND WDC ≥ 6 THEN VEG = OW
IF VEG = OW AND WDC ≤ 5 THEN VEG = E1
(3) *Fate of floating emergent*:
IF VEG = E1 AND WDC ≥ 6 THEN VEG = OW
IF VEG = E1 AND WDC = 5 THEN VEG = E1
IF VEG = E1 AND WDC ≤ 4 THEN VEG = E
(4) *Fate of emergent*:
IF VEG = E AND WDC ≥ 6 THEN VEG = E1
IF VEG = E AND WDC = 4 or 5 THEN VEG = E
IF VEG = E AND WDC ≤ 3 THEN VEG = E2
(5) *Fate of tall emergent (wet and dense dry emergent)*:
IF VEG = EW or E2 AND WDC ≥ 7 THEN VEG = E
IF VEG = EW or E2 AND WDC = 6 THEN VEG = EW
IF VEG = EW or E2 AND WDC = 4 or 5 THEN VEG = E2
IF VEG = EW or E2 AND WDC ≤ 3 THEN VEG = M
(6) *Fate of meadow (including short wet meadow)*:
IF VEG = M1 or M AND WDC ≥ 7 THEN VEG = E2
IF VEG = M1 or M AND WDC = 6 THEN VEG = M1
IF VEG = M1 or M AND WDC = 3 or 4 or 5 THEN VEG = M
IF VEG = M1 or M AND WDC ≤ 2 THEN VEG = T
(7) *Fate of treed*:
IF VEG = T AND WDC ≥ 6 THEN VEG = M
IF VEG = T AND WDC = 2 or 3 or 4 or 5 THEN VEG = T
IF VEG = T AND WDC = 1 THEN VEG = U
(8) *Fate of upland*:
IF VEG = U AND WDC ≤ 4 THEN VEG = U
IF VEG = U AND WDC = 5 or 6 THEN VEG = T
IF VEG = U AND WDC ≥ 7 THEN VEG = L
IF VEG = U AND WD* ≥ 0 cm AND ADJ = L THEN VEG = L

VEG = wetland vegetation community, WD = water depth in centimeters (cm), WDC = water depth category, ADJ = cell adjacency.
Wetland communities (VEG): L = lake, OW = open water, E1 = floating emergent, E = emergent, EW = tall wet emergent, E2 = tall dense dry emergent, M1 = short wet meadow, M = meadow, T = treed, U = upland.
Water depth categories (WDC): (1) ≤ −100 cm, (2) −99 to −80 cm, (3) −79 to −50 cm, (4) −49 to −30 cm, (5) −29 to 30 cm, (6) 31 to 60 cm, (7) 61 to 200 cm, (8) > 200 cm; a negative "water depth" value indicates height above lake level.
WD* (water depth): ≥ 0 cm — cell contained water (flooded or below water level).

The 10-class wetland coverages were converted to 12-m raster grids to match the resolution and extent of the elevation and lake depth grids. The grids were aligned in order to allow a cell-by-cell inter-comparison and processing of the elevation, lake depths and vegetation data layers. Diked areas, where water levels are artificially manipulated, and upland areas sufficiently high in elevation to be unaffected by water level change were masked from the final grids and were not used in the modeling.

Model development in GIS

The overall structure of the three GIS simulation models is the same. Each requires a lake level as input to set initial conditions and each simulation produces wetland vegetation surfaces as raster grid outputs. The vegetation state probability model is the simplest. The lake level input is used to determine water depth or elevation above water in each cell and from that the likely occurrence of a particular wetland vegetation community. The rule-based model is more complex. It uses the lake depths in combination with a series of if-then statements related to pre-existing vegetation and vegetation depth tolerance ranges to determine wetland vegetation communities. The vegetation transition probability model uses the lake-level elevation and whether the water levels are declining or rising to determine the likelihood of wetland communities changing to another community.

Rule-based model

The concept for the rule-based model was based on the vegetation component of a wetland simulation model developed by Poiani and Johnson (1993a, 1993b) for a Prairie pothole wetland. For the Long Point model, changes in wetland vegetation community were also determined based on a set of rules, coded as a series of if-then statements (see Table 1). These rules were applied to each cell in the model and changes to the cell were conditional based on pre-existing wetland vegetation, water depth, water depth tolerance ranges of the wetland vegetation communities and adjacency of lake, open water and upland cells. The tolerance ranges of water depth for the wetland vegetation communities were synthesized from the literature (Dane, 1959; Geis, 1985; Hebb, 2003; Kadlec and Wentz, 1974; Newmaster et al., 1997; Ould and Holbrow, 1987; United States Environmental Protection Agency, 2000).

Generally, the existing vegetation tended to a wetter wetland community if the depth of the water in the cell was greater than 30 cm. If the depth of the water was less than 30 cm and within one drier depth category of the community's optimal range, the vegetation remained the same. If the depth of the water was less than 30 cm and greater than one drier depth category away from of the community's optimal range, the vegetation tended to the next drier community.

The model is initialized with pre-existing vegetation (a raster grid of vegetation community distribution) from the most recent air photo previous to the year being modeled (e.g., 1995 digital vegetation community data were used to initialize the model for 1999). First, the rules generally permit a wetland vegetation community to transition to the next wetter community if water levels increase more than 30 cm in a particular cell — cells that were open water transition to lake, floating emergent to open water and meadow to short wet meadow, etc. Second, if water levels increase less than 30 cm or decrease by any amount in a cell and the resultant water depth or height above water is more than one drier water depth tolerance category, the wetland vegetation transitions to the next driest vegetation community. For example, if the water level in a cell declined to a depth of 10 cm, lake would transition to open water, open water to floating emergent, wet meadow to meadow, etc. Third, rules related to adjacency were also incorporated for lake, open water and upland categories to constrain changes along the shoreline. If lake was adjacent to upland and if the cell was dewatered more than 30 cm then the cell would transition to upland. Similarly, if an upland cell was adjacent to lake it would transition to lake if flooding in a cell was more than 30 cm; open water adjacent to lake changes to lake if depth in a cell was more than 30 cm below lake level.

Vegetation state probability model

The vegetation state probability model was based on the likelihood of certain wetland vegetation communities occurring at specific depth ranges. Data from 1985 and 1995 were used to develop the model — a set of probability mass functions, conditional on a cell's depth category. The wetland conditions in air photos from 1985 represent a high water-level condition after a period of rising water levels while the 1995 air photo represents a period of lower water-levels due to declining water levels. To determine probabilities, the vegetation community raster grids for 1985 and 1995 were overlaid with lake depth grids, calculated using the observed mean annual whole-lake water level for these years. The wetland vegetation community in each cell was associated with the cell's depth category (these categories are identical to those used in Table 1). Each wetland vegetation community was counted, cell-by-cell, and binned by each cell's depth category. By dividing the total area of each wetland vegetation community within each depth category by the total area of each depth category across all depth categories, the probability of a wetland community occurring within the depth category was calculated. This process produced the conditional probability of the presence of a wetland community given a water depth range. The process was repeated for each wetland community and each depth category. For each depth category, conditional probabilities of each wetland community were combined to produce a probability mass function. By performing this process for the years of 1985 and 1995, separate sets of conditional probability mass functions were developed for rising and declining water level conditions.

To initialize this model, only two parameters are set: a lake level and the lake level trend (rising or declining). Unlike the other models presented in this paper, the vegetation state probability model does not require a base vegetation coverage to initialize the model. It uses the specified lake level and the DEM for Long Point to calculate water depth or height above water level in each cell and samples the appropriate probability mass function to output a vegetation community. This process was performed for each cell in the study area to produce a classified vegetation community raster.

Vegetation transition probability model

This model was developed to determine the likelihood of a wetland vegetation community changing to another wetland community in relation to declining or rising water levels. While the process of developing transition probabilities was similar to that of determining the static vegetation community probabilities, instead of calculating the conditional probability of the presence or state of a vegetation community, this approach derived the conditional probability of the *transition* over a period of time between paired cells representing wetland communities. The inter-community vegetation transitions were derived using the GIS to overlay pairs of wetland vegetation grids from 1978, 1985 and 1995 digitized air photos. The changes between 1978 and 1985 represent vegetation response to rising water levels and 1985 to 1995 the response to declining water levels.

Vegetation transition probabilities were calculated by dividing the number of cells that represented every transition from one wetland community to another by the total number of pixels of that wetland community for the base year. This produced a probability mass function, conditional on water depth category and initial vegetation community unlike the vegetation state probability model, where probability distributions were conditional on the cell's water depth category alone.

In running the model, an initial water level and base vegetation community raster as well as a water level trend (rising or declining) were specified. The model simulated the resultant vegetation communities based on probability functions for each cell appropriate for the water depth and initial vegetation community.

Model runs and evaluation

Six simulations, one for each available map year, were run using the rule-based model. This was related to availability of historical digital wetland vegetation data to set the initial wetland vegetation conditions. For example, the 1945 coverage was used to initialize the 1955 simulation and 1995 the 1999 simulation. Fewer simulations were run for the vegetation state probability and vegetation transition probability models; 1985 and 1995 were omitted from the simulations since they were used to calibrate the models. Model evaluation included comparing the area and spatial distribution of the simulated wetland vegetation communities to the historical digital wetland vegetation community coverages. The simulated grids were overlaid with the historical grids to calculate the percentage of correctly classified cells within each wetland community at the class level.

For the rule-based model, classification accuracy was averaged across all years of historical data to determine model accuracy; for the vegetation state and vegetation transition probability models, the accuracy was averaged for all years not used for calibration. The magnitude of the difference between historical and modeled wetland community values and the spatial distribution of the errors were examined to determine the location of errors. Aggregate area statistics were also generated for the classified wetland vegetation communities and compared to historical area to determine amount of over- or under-estimation. Finally, the simulated wetland surfaces were visually compared to the historical wetland vegetation community and land use data.

Results

Metrics on model performance are summarized in Table 2. The wetland maps presented in Fig. 4 allow for inter-comparison of the simulation results for 1999.

Rule-based model

The rule-based model was 82% accurate in simulating wetland vegetation response with the percentage of correctly classified cells ranging from 79% in 1964 to 85% in 1999. Eighteen percent of cells were incorrectly simulated by the model but 71% of these cells were within one or two dryness or wetness classes from the expected (historical) wetland community. The model was good at classifying the lake, open water, and upland communities and moderately successful in classifying meadow, tall dense dry emergent, emergent, floating emergent and tall wet emergent vegetation. Short wet meadow and treed vegetation communities were classified poorly. The model under-estimated the areas of tall dense dry emergent vegetation and upland and over-estimated the areas of emergent and treed vegetation in all years. The wetland communities – tall wet emergent and short wet meadow – with the smallest overall area in the wetland were consistently over-estimated by more than double the expected (historical) areas. Areas along the lakeward shoreline of Long Point were correctly classified as lake, and deeper sections of the Inner Bay as open water. During high water levels, the simulations showed widespread inundation along the shore; wetland vegetation classes were appropriately transitioned to the wetter classifications of lake or open water. However, there were obvious location-specific errors. For example, (non-diked) areas in the Big Creek Marshes were classified as wetter wetland communities compared to the historical vegetation cover while areas in the Crown and Company Marshes were classified as drier wetland communities. These errors are likely due to inaccuracies in the DEM as these areas have particularly poor bathymetric and topographic coverage.

Vegetation state probability model

The vegetation state probability model produced the poorest results with the lowest overall accuracy in simulating the wetland vegetation communities. On average, 56% of the cells were classified correctly with performance ranging from 54% for 1955 to 59% for 1999. Results were modestly better for years with declining water levels (58%) than rising (54%). The model had the fewest number of communities classified with good to moderate success — three, and they were the non-wetland communities namely lake, open water and upland. Of the 44% of output cells that were incorrect classified, over 50% were three or more classes wetter or drier than the expected value. Visually, the spatial distribution of the wetland communities did not compare favorably with the historical wetland maps. The contiguous, large patches of single vegetation communities characteristic of a wetland complex were not replicated. Instead the model output was very noisy and the landscape resembled a mosaic of individual cells. Several filters were tested to remove some of the noise, but no noticeable improvements were observed.

Vegetation transition probability model

The vegetation transition probability model had an 83% overall accuracy in simulating wetland vegetation community type and distribution; the percentage ranged from 82% for 1978 to 86% for 1999. The overall accuracy of the model was high but when a cell was incorrectly classified only 19% were within one drier or wetter vegetation

Table 2
Metrics inter-comparing performance of the rule-based model, vegetation state probability model and vegetation transition probability model.

Considerations for model	Percent (%) of cells correctly classified by community[b]				Amount of error[a]	Observations
	Overall	Good	Moderate	Poor		
Rule-based model • Existing wetland vegetation • Lenient water depth tolerance ranges • Incorporate cell adjacency between lake, open water and upland	81.8	L: 98.5 OW: 84.0 U: 63.8	M: 29.6 E2: 25.3 E: 22.3 E1: 22.2 EW: 20.3	T: 11.3 M1: 11.2	1: 39.9 2: 71.5	• Overestimates area of E, T • Underestimates area of E2, U • Shoreline areas and deeper sections of Inner Bay correctly classified • Landward areas along the shore washed inundated in wet years • Simulates drier emergent vegetation for marshes in Big Creek and Inner Bay • Good definition of patches (all sizes) and features in landscape
Vegetation state probability model • Water depth ranges • Ranges from >200 cm in depth to >100 cm above lake level • Depth intervals based on tolerance ranges	55.7	L: 75.1 U: 56.9	OW: 37.8	M1: 1.0	1: 38.4 2: 48.5	• Poor definition of features and patches in landscape; significant noise • Few contiguous patches of similar communities, except for L and U • Overestimates area of OW, U • Underestimates area of L
Vegetation transition probability model • Existing wetland vegetation	83.4	L: 99.1 OW: 79.5 U: 77.4 E2: 54.9	M: 22.9 T: 22.6	E: 5.3 EW: 4.4	1: 19.0 2: 49.1	• Least amount of difference between historical and modeled aggregate areas • Reduction in noise (compared to probability model) • Large contiguous areas well-defined • Fair definition of smaller patches and some features in landscape

Wetland vegetation community: L = lake; OW = open water; E1 = floating emergent; E = emergent; EW = tall wet emergent; E2 = tall dense dry emergent; M1 = short wet meadow; M = meadow; T = treed; U = upland.

[a] Amount of error is the total percentage of incorrectly classified cells within one or two communities from the historical (expected) value.

[b] The percent of cells correctly classified by community are listed according to good success (over 50% of the cells were correctly classified), moderate success (20 to 50% correctly classified) and poor success (<20% correctly classified).

class and 49% within two categories. The simulation results were good for lake, open water, upland and tall dense dry emergent vegetation; moderate for meadow and treed vegetation communities and poor for emergent and tall wet emergent vegetation. The model was marginally better at determining vegetation response under declining water-level conditions (84%) than rising conditions (82%), although the simulation of open water and tall wet emergent vegetation communities was better during rising water-levels (correctly classified cells increased approximately 7%). The large patches of wetland vegetation communities within the landscape were generally well-defined although the extent of smaller patches was masked because of noise in the output surfaces.

Inter-comparison of models

Performance of the rule-based model and the vegetation transition probability model were comparable and both performed better than the vegetation state probability model in most respects (Table 2). While the vegetation transition probability model demonstrated slightly higher performance on the aggregate classification accuracy than the rule-based model, a number of other factors indicate that the rule-base model may be better at simulating wetland vegetation community response to water-level change. First, the rule-based model was able to simulate all ten wetland communities with eight in the good to moderate success range. Second, when a cell was incorrectly simulated more than 70% were within one or two wetness or dryness classes of the expected historical values. Lastly, the rule-based model replicated the spatial patterns of real-world wetland systems (based on the historical digital data) better than other models. Patches of all sizes were delineated successfully and were easily identifiable in the simulated surfaces. The model was also able to depict other physical features in the landscape, such as linear channels and islands. In our opinion, the rule-based model holds the most promise for future modeling.

Discussion

This study has identified a number of important challenges that must be addressed to improve the performance of the spatially-explicit models described here. Transition probabilities have modeled broad, aggregate changes in wetlands and landscapes quite successfully but there are issues simulating spatially-explicit changes using transition probabilities. First, changes in landscapes (represented in our case by the more detailed cells/rasters) are not strictly Markovian; future states of a cell are not independent of its current state and are also influenced by the state and transition of the surrounding cells — contagion effects. In our case as shown in Fig. 4, the poor replication of the actual landscape – highly fragmented or mosaic-like effects – most obviously by the vegetation state probability model supports what was observed by Turner (1987). In addition, transition rates may not be constant through time (Sklar and Costanza, 1991; Turner, 1987) as we assumed for the vegetation transition probability model. It would be more realistic to use multi-year sequences of data to estimate transition probabilities (Sklar and Costanza, 1991).

All three models were effective in simulating the general response tendencies of the wetland communities to water level fluctuations. During periods of declining water levels, the simulated wetland tended toward drier communities and during periods of rising water levels it tended to wetter communities. All of the models were also effective at simulating the spatial distribution and extent of lake, open water, and upland, but the models could not classify the distribution of the more important wetland vegetation communities with a high degree of accuracy. The wetter emergent and drier meadow communities were

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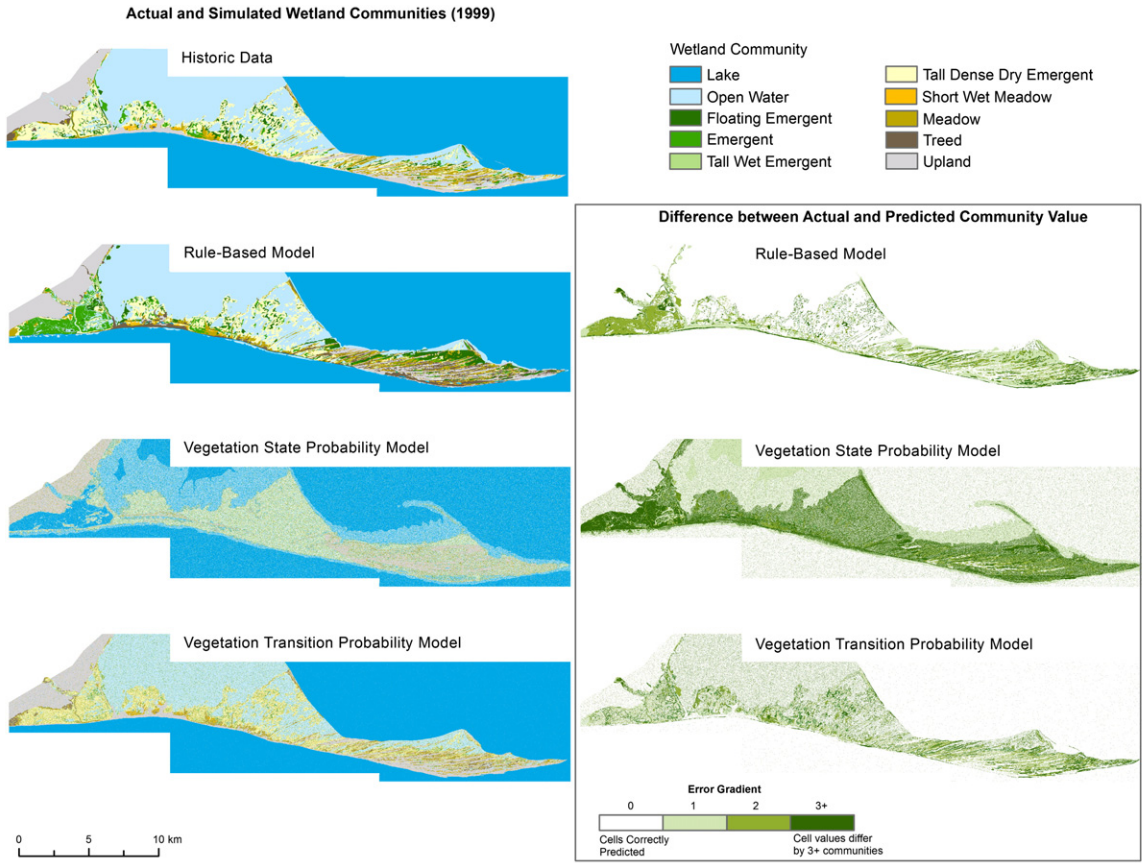

Fig. 4. Wetland vegetation community modeling results for Long Point, 1999. On the left are historical and modeled vegetation community distribution maps and on the right are differences between historical and the three model outputs reported as an error gradient. The error gradient scale distinguishes whether the model predicted, at the raster level, the expected (historical) wetland vegetation community correctly (0), within one drier or wetter community class (1), within two drier or wetter community classes (2) or three or more drier or wetter community classes (3+).

predicted with the least amount of confidence. A number of factors may have contributed to these errors.

At the Long Point site, the model could be improved with more accurate elevation, and bathymetry data in nearshore areas, where emergent vegetation is particularly dense. More broadly the model could be improved by enhancing the decision rules and vegetation tolerance ranges with field work. Errors in the topographic model (DEM) may have led to inaccuracies since it is critical to the calculation of water depth or elevation above water — a prime factor in determining wetland community type. The zone of poorest data coverage is the nearshore — the interface where the land elevation and bathymetry data meet and where key wetland communities occur. Acquiring more accurate and detailed topography for the nearshore as well as lake and upland areas from field surveys or detailed remotely sensed imagery, such a LIDAR, would enhance future modeling efforts.

The models were developed with a few input variables. The rule-based and vegetation state probability models considered water depth in relation to topography and the vegetation transition probability model related wetland community transitions to water level changes. However, many other factors influence wetland vegetation response including: geomorphic form of the wetland, substrate, seed banks, slope, wave exposure, and soil and water chemistry. Incorporating information on substrate type and wave exposure may be the easiest and most productive improvement for wetland modeling in the near future.

In the rule-based model, the decision rules, especially for the emergent and meadow classes, could be improved by collecting field data related to biological, physical and chemical conditions in these vegetation communities or undertaking experimental manipulation of water-levels in plots. Sampling of plants as well as soils and other attributes along specific elevation transects in a hydrologic gradient would help establish the unique flooding and dewatering characteristics of wetland plant communities.

The models were based on several assumptions and caveats that may affect their performance. The design of the models did not allow accounting for one-time natural or anthropogenic events in the wetland, such as the effects of Hurricane Hazel in 1954 and the construction of the Big Creek NWA dike in 1985. The DEM is also a static representation of the topography in the study area. Long Point is constantly changing due to erosion and sediment transport and these processes are not captured by the models. Also, the influence of water-levels is not uniform throughout the Long Point wetland complex. The Big Creek Marshes can be influenced by rain and runoff events, water levels in the NWA dike are controlled, and natural water-level fluctuations are important in the Inner and Outer Bay of Long Point.

Water-level fluctuations are a key factor influencing the form, distribution, functioning and biodiversity of Great Lakes coastal wetlands. Spatially-explicit modeling, using the GIS tool, offers a structured environment for integrating multiple sources of wetland and environmental data, exploring relationships between factors and simulating wetland vegetation community response. Out of the three modeling approaches developed and assessed for the Long Point wetland complex the rule-based model performed best in replicating the spatial response of wetland vegetation at the cell-by-cell level and broader landscape perspective. It holds the most promise for future modeling efforts; subsequently, a modified rule-based model for the Long Point-Turkey Point wetland complex was developed for the IUGLS. It was used to determine critical water-level thresholds that may result in significant changes to wetland communities and as a benchmark for potential impacts of climate change. While the Long Point wetland complex was the case study, the rule-based approach could be applied to other wetlands, in

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the Great Lakes region and more broadly, with the requisite long-term digital data sets. Model simulations can be valuable for understanding the vulnerability of wetland ecosystems and informing resource management decisions in the Great Lakes and other regions facing challenges related to water-level regulation, invasive species, and climate change.

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