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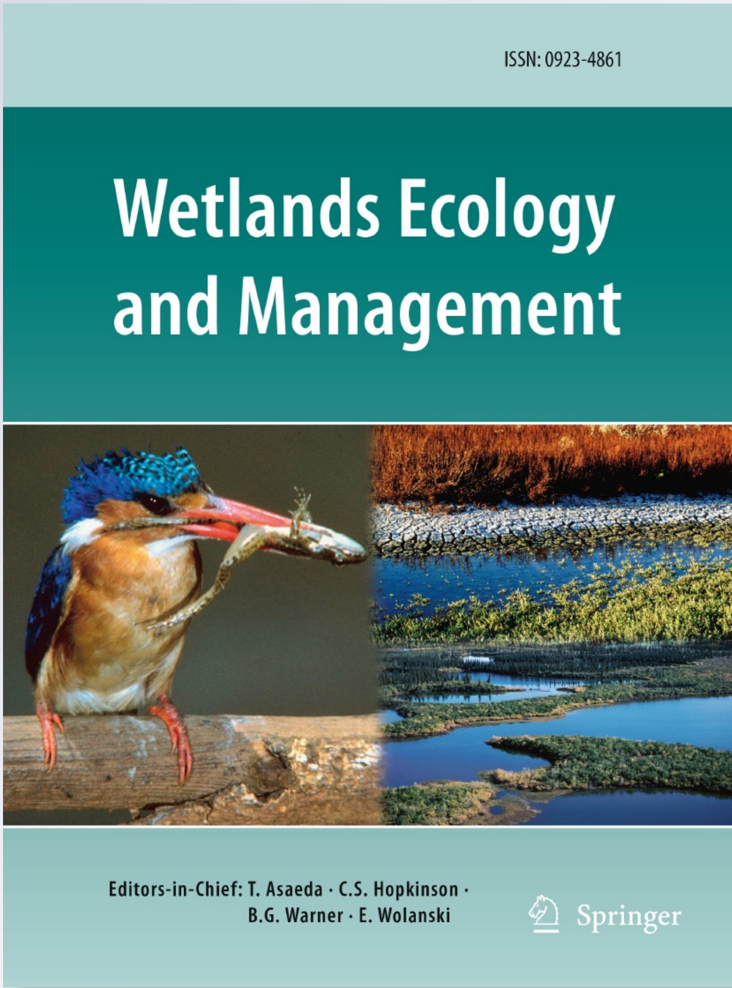

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ORIGINAL PAPER

Simulated changes in extent of Georgian Bay low-marsh habitat under multiple lake levels

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Abstract The extent of coastal wetlands in Georgian Bay is controlled primarily by the water level of Lake Huron, which directly affects the amount of critical habitat available for fish and wildlife communities. Lake-levels have historically fluctuated by nearly 2 m and that range could increase in the future. This prompted us to investigate how quantity and quality of wetland habitat in Georgian Bay may be affected by different lake-level scenarios. The extent of low-marsh habitat was modeled with a generalized linear model that used hydrogeomorphic features (i.e. depth, slope, and exposure) as predictors. We simulated lake levels between 175.5 m and 177.5 m at 0.5 m-increments, and found that the total area of low marsh peaked at 176.0 m (7113 ha) and declined sharply as lake levels increased or decreased. In contrast, low-marsh volume was highest at 176.5 m (3.84×10^7 m^3) but remained relatively stable across all modeled lake levels. We derived an average elevation profile for low-marsh habitat across the study area that showed a shallow "step" between 175.5 and 176.0 m, flanked by steeper upslope and downslope sections. At historically low lake levels low-marsh habitat would have been dominated by shallow water (< 0.5 m), whereas at higher lake levels it would have been dominated by deeper (0.5–2.0 m) water. The geomorphology at low lake levels (i.e. 176.0 m) appears to favour large areas of shallow habitat at the expense of deeper habitats that could have supported more structurally complex, submersed aquatic vegetation.

Keywords Coastal wetlands · Georgian Bay · Water levels · Low marsh · Habitat · Climate change

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Introduction

Water levels in the Great Lakes naturally fluctuate on short-term scales of hours to days (Trebitz 2006), over seasons (Minc 1997), and annual and multi-decadal time frames (Baedke and Thompson 2000; Hanrahan et al. 2010; Quinn and Sellinger 2006). These fluctuations are largely driven by natural cycles of climate, precipitation, and evaporation. Beyond these natural fluctuations in lake level there are also anthropogenic factors at play. Regulation of lake levels with dams and locks have dampened historic fluctuations; additionally, dredging of connecting channels like the St. Clair River has led to increased erosion and outflow from Lake Michigan-Huron, while human-induced changes to climate have been linked to changes in evaporation (e.g. through warmer winters and less ice-cover; Mortsch and Quinn 1996). The long-term mean lake level in Lake Michigan-Huron from 1860 to 2017 is 176.6 m (International Great Lakes Datum 1985)

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(Canadian Hydrographic Service dataset) with a range of approximately 2 m between extreme high and low waters (∼ 175.5–177.5 m). The dynamic nature of lake-level fluctuations is a key feature of the Great Lakes ecosystem and plays an important role in shaping coastal habitats.

From 1999 to 2013, Lake Michigan-Huron experienced a prolonged period of stable low water levels (Sellinger et al. 2008). A wide array of potential impacts of low lake levels were identified by Hartmann (1990), including the loss of coastal wetland habitat that provides many ecosystem services and supports high biodiversity (Environment Canada 2002). Low-marsh, the permanently inundated component of coastal wetlands that is dominated by floating-leaf and submersed aquatic vegetation (SAV) (Ontario Ministry of Natural Resources 2014), provides habitat for the majority of Great Lakes fish species (Jude and Pappas 1992; Wei et al. 2004) and thus supports economically, recreationally, and culturally valuable fisheries. The aquatic vegetation that occurs in low-marsh habitat provides physical structure that supports macroinvertebrates and a diverse community of prey species, making it important foraging habitat for piscivores (Dibble et al. 1997; Eadie and Keast 1984). Since the aquatic vegetation community is a determinant of fish assemblages (Cvetkovic et al. 2010) the amount and type of available low-marsh habitat is a key consideration for Great Lakes fisheries. No other region exemplifies this better than the eastern and northern shores of Georgian Bay (Lake Huron), where there are thousands of high quality coastal marshes (Cvetkovic and Chow-Fraser 2011; deCatanzaro and Chow-Fraser 2011; Midwood et al. 2012) that have remained relatively free from human disturbances.

The impact of varying lake levels on wetland vegetation dynamics has been well documented. Persistent lake-level fluctuations are necessary to maintain high diversity in the wetland plant community (Keddy and Reznicek 1986) and periods of stable water levels in a typically dynamic water-level environment can lead to a loss of diversity and dominance of certain plant species (Midwood and Chow-Fraser 2012; Wilcox and Meeker 1991; Wilcox and Nichols 2008; Wilcox et al. 2008). This in turn can lead to subsequent shifts in the wetland fish community (Midwood and Chow-Fraser 2012; Wilcox and Meeker 1992). The types of vegetation present within a wetland have also been documented to change with water level; SAV tends to dominate in periods of high water as the emergent and meadow species are inundated and die back, whereas under low water the amount of SAV declines as emergent and meadow vegetation expand into the new areas released by the receding water levels (Hudon et al. 2005). Ultimately, the structure of coastal wetland vegetation is closely linked to lake levels and their fluctuations.

Given the importance of low-marsh habitat and the uncertainty in future water-level trends, managers need to understand how the amount and distribution of low-marsh habitat might change over the next few decades. The McMaster Coastal Wetland Inventory (MCWI; Midwood et al. 2012), the most comprehensive estimate of the amount of wetland habitat in eastern and northern Georgian Bay, was derived from high-resolution satellite imagery acquired during a period of stable low water levels in the early-mid 2000s. There is no comprehensive inventory of wetland habitat under other historic water-level conditions, nor for lake levels outside the historic range. For this study we used a model developed by Weller and Chow-Fraser (2019) to simulate changes in the extent of low-marsh habitat in response to a range of potential lake levels in Georgian Bay.

Methods

Weller and Chow-Fraser (2019) developed a generalized linear model (GLM) that used hydrogeomorphic features (i.e. depth, slope, wave exposure) to predict the presence of low-marsh habitat. Hydrogeomorphic features were derived under a target lake elevation from a digital elevation model (DEM). A threshold value was used to classify the model's probability outputs as either "low marsh" or "open water". Low marsh was defined using the Ontario Wetland Evaluation System (Ontario Ministry of Natural Resources 2014) as the area of a wetland that is permanently flooded and provides habitat for fish throughout the year. Operationally, this means that the boundary between low marsh and high marsh (e.g. wet meadow) was set by the lake elevation and not by the presence or absence of certain species or taxa of wetland vegetation. Seasonally inundated wetland area (i.e. high marsh) does provide important spawning and nursery habitat for some fish species but Weller and Chow-

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Fraser's model (Weller and Chow-Fraser 2019) was only designed to identify low-marsh habitat. Open water was considered to be any area where the probability of low marsh occurring was below the threshold value and was expected to support little to no aquatic wetland vegetation. The model was trained with the low-marsh habitat layer from the MCWI (Midwood et al. 2012), a spatial inventory of coastal wetland habitat in eastern and northern Georgian Bay. The MCWI was delineated from IKONOS satellite imagery acquired during the summer months of 2002, 2003, 2005, and 2008. Mean monthly water levels in Lake Michigan-Huron at the time ranged from 176.04 to 176.33 m with a mean of 176.17 m. Since the training data were acquired during a period of stable lake levels, the model assumes that water levels have been relatively stable near the target lake elevation for at least 3 years. The model was validated with a subset of MCWI data that had been withheld and with independently acquired DEMs of two sheltered embayments in eastern Georgian Bay. The GLM performed well (area under the curve of 0.831); the classified model correctly identified 80% of low marsh and 75% of the open-water habitat. Full details of the development, validation, and assumptions of the model can be found in Weller and Chow-Fraser (2019). We maintained the same study area used by Weller and Chow-Fraser (2019): Severn Sound in the southeast to MacGregor Bay in the north (Fig. 1), excluding areas with insufficient bathymetric information. Two stretches along the north shore of Georgian Bay were excluded because of gaps in the MCWI coverage (Midwood et al. 2012): French River to Beaverstone Bay and Killarney to MacGregor Bay.

We used ArcMap 10.5 (ESRI, Redlands, California) to run the GLM models and perform spatial analyses at five lake-level scenarios, ranging from 175.5 to 177.5 m (International Great Lakes Datum 1985) in 0.5 m intervals. This range of lake levels encompassed the historic highs and lows that have been recorded in Lake Michigan-Huron (1860–2017; Great Lakes Water Level Dashboard, Gronewold et al. 2013). Furthermore, this range includes lake levels that are predicted to occur over the next century (Angel and Kunkel 2010). Depth, slope, and wave exposure parameters were derived from the DEM for each lake level as described by Weller and Chow-Fraser (2019). The GLM produced a probability surface that was then classified as either low-marsh or open-water habitat based on the threshold value.

To address errors stemming from inaccuracies in the DEM, we used several mask layers to exclude obvious misclassifications of low marsh or open water. Although the majority of the shoreline within the study area was undeveloped land there were some built-up areas present, most notably in Severn Sound and Parry Sound. We used the "Community/Infrastructure" classification from the Ontario Land Cover Compilation v2.0 (Ontario Ministry of Natural Resources and Forestry 2016) and a 10-m buffer around the Ontario Road Network (Ontario Ministry of Natural Resources 2009) to clip out these built-up areas. We excluded these areas because they occurred at a higher elevation than indicated by our DEM or were built-up areas that would have been protected or hardened against high-water conditions. We also used the Wooded Area dataset (Ontario Ministry of Natural Resources 2006) to clip out forested area (i.e. trees or shrubs > 2 m in height). We assumed that forests should normally occur above the high-water mark for Georgian Bay and are therefore outside our range of target elevations. We removed all masked areas from our habitat projections for each lake-level scenario.

We divided the predicted low-marsh habitat into 0.5 m depth zones between shore and 2-m deep and considered 2–5-m deep as a single depth zone. Weller and Chow-Fraser (2019) used a 5-m water depth as the maximum depth limit for their low-marsh model; over 99% of predicted low-marsh habitat occurred in water less than 2-m deep under their original model scenario. We then derived hypsographic curves for the total low-marsh area and volume for each scenario. To estimate the average elevation profile, we rescaled the low-marsh area from each scenario to approximate a fringing wetland (i.e. a rectangle) where the length of the shoreline and each depth zone was held constant. Essentially, we stacked the hypsographic area curves from each scenario using elevation values that corresponded to the respective depth measurements (e.g. 0 m for the 176.0-m scenario would correspond to the 0.5-m contour for the 176.5-m scenario; the curve for the 176.0-m scenario was shifted laterally and vertically to align these points). All five hypsographic curves were aligned then smoothed to produce a representative elevation profile. We calculated the total area and volume of the low marsh within the study area for each lake-level scenario. Absolute and

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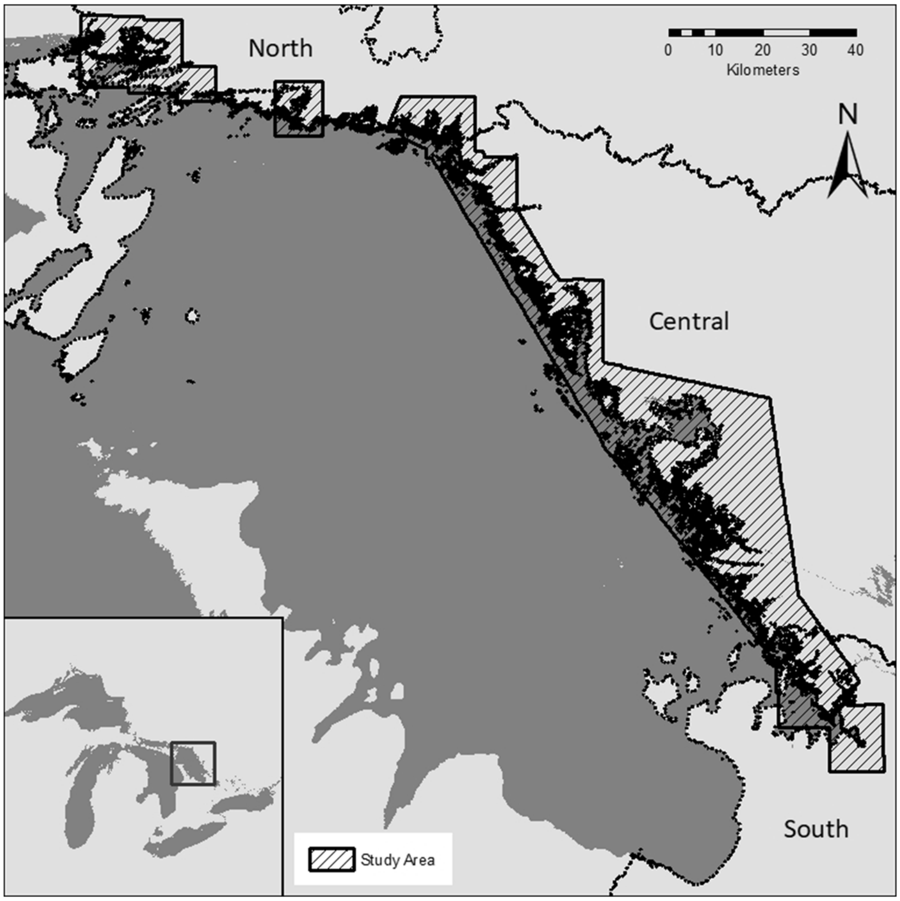

Fig. 1 Simplified outline of study area (hatched area) along eastern and northern shoreline of Georgian Bay, Lake Huron (inset: Laurentian Great Lakes). Study area was divided into South, Central, and North to evaluate regional differences in simulated low-marsh habitat

proportional area and volume were calculated for each depth zone.

We used the depth zones as a coarse proxy for the types of wetland vegetation that would be expected to occur in each zone (Table 1) and how that might translate to the suitability or quality of fish habitat. The low-marsh model predicts the probability that a location will support low-marsh habitat based on local hydrogeomorphic features, but it does not make any predictions regarding the composition of the wetland vegetation community or presence of certain species. Operationally, the model predicted which areas were likely to support low-marsh habitat under a given lake level and we used the associated depth zones with that predicted low-marsh area to make inferences as to the vegetation community expected at that location. These inferences were based on extensive wetland macrophyte sampling conducted in the study area (Boyd 2017; Croft and Chow-Fraser 2007; Cvetkovic and Chow-Fraser 2011) concurrent with the acquisition of the satellite imagery used to develop the MCWI (Midwood et al. 2012). Many wetland plant species demonstrate tolerance to a broad range of water depths so the type and species associated with each depth zone (Table 1) are only meant to be representative of the typical wetland community in each depth zone and does not mean that those species or types are limited to only that depth zone.

We further broke down our study area into three regions (Fig. 1) to investigate differences in low-marsh habitat across the study area. The areas were grouped according to the tertiary watershed boundaries (Ontario Ministry of Natural Resources 2010). Watersheds for Nottawasaga and Black River Lake Simcoe have been consolidated into the “South” region (essentially Severn Sound), where nearshore

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Table 1 Dominant types of wetland vegetation and species that are typical of each depth zone of the low marsh. Wetland vegetation associated with each depth zone was based on field surveys within the study area and are meant to be broadly representative of the types of vegetation typical to each depth zone

Depth zone (m)	Dominant type	Typical species
0.0–0.5	EM	*Pontederia cordata*
		Schoenoplectus sp.
		Typha sp.
	FL	*Brasenia schreberi*
		Nuphar variegate
		Nymphaea odorata
0.5–1.0	FL	*Nuphar variegate*
		Nymphaea odorata
		Sparganium fluctuans
	SAV	*Isoetes sp.*
		Najas flexilis
		Potamegeton robbinsii
1.0–1.5	SAV	*Bidens beckii*
		Myriophyllum spicatum
		Potamegeton robbinsii
1.5–2.0	SAV	*Potamogeton amplifolius*
		Potamogeton richardsonii
		Myriophyllum spicatum
2.0–2.5	SAV	*Potamogeton amplifolius*
		Potamogeton crispus
		Potamogeton richardsonii

EM emergent; *FL* floating-leaf; *SAV* submersed

areas are more gently sloping than the rest of the study area and support some of the largest coastal wetland units in Georgian Bay. The Muskoka and Magnetewan watersheds were grouped into the "Central" region, spanning the eastern shore of Georgian Bay from north of Severn Sound to Key River. The French River, Killarney, and Manitoulin Island watersheds were grouped into the "North" region, which contained the shoreline along the north shore of Georgian Bay between French River and the North Channel. For each region, we (1) evaluated the proportional depth zone composition, (2) calculated the area of low-marsh habitat per shoreline length, and (3) determined the mean slope. The area-to-shoreline ratio provided an estimate of the length of the average elevation profile in each region (i.e. distance from shore to lakeward extent of low-marsh).

Results

There were marked changes in the morphological structure underlying the simulated low-marsh habitat across the five lake-level scenarios. There was a shift from predominantly shallow (< 1-m deep) to deeper (> 1-m deep) low-marsh area between 176.0 and 177.5 m (Fig. 2). At 176.0 m, over 60% of the low-marsh area occurred at depths between 0 and 0.5 m, with each subsequent 0.5-m depth zone making up a progressively smaller proportion of the total area. In contrast, at 177.5 m the majority of low-marsh habitat (50% by area and 65% by volume) occurred below the 1.5-m depth contour. At the intervening lake levels of 176.5 m and 177.0 m the majority of the low-marsh area occurred at intermediate depth zones of 0.5–1.0 m and 1.0–1.5 m, respectively. At 175.5 m there was a relatively even distribution of low-marsh area between shore and the 1.5-m depth contour, with the majority of habitat volume occurring below the 1-m depth contour.

Changes in depth-zone composition with lake level were consistent with the average elevation profile derived from the hypsographic curves (Fig. 3a). There was a gradually-sloping section between 176.0 and 175.5 m that essentially formed a "step" in the elevation profile. The upslope of the step (176.0–177.5 m) increased progressively with each scenario, which resulted in a greater proportion of

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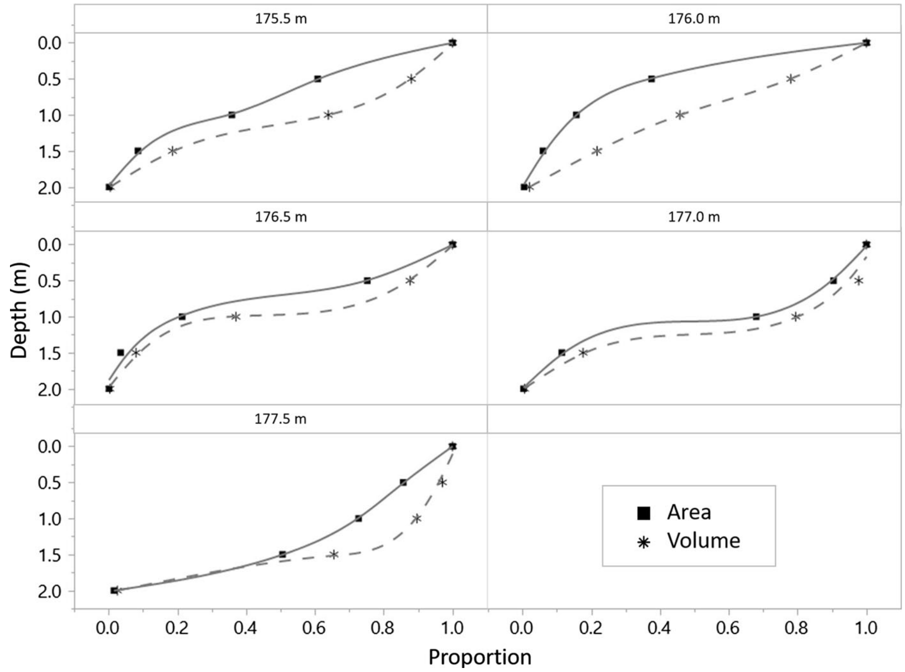
Fig. 2 Smoothed hypsographic curves of proportional area (solid line) and volume (dashed line) of simulated low marsh under five lake-level scenarios (indicated at top of each panel; m IGLD85). Calculation of proportional area (squares) and volume (stars) were made at 0.5 m intervals from 0 – 2 m. The 2 – 5 m depth zone was omitted



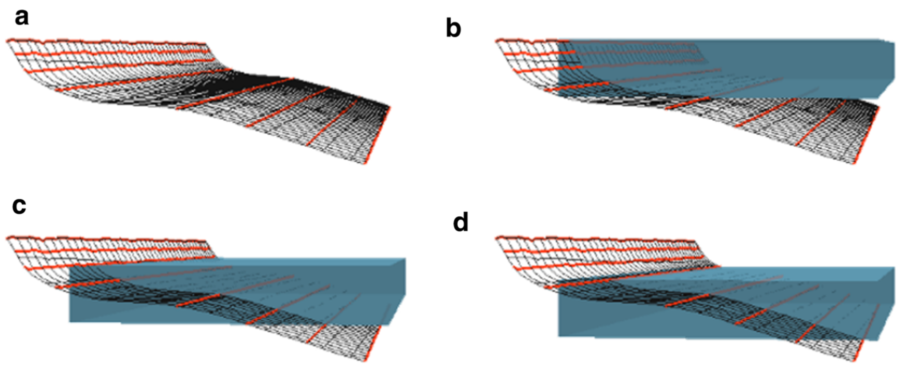


Fig. 3 Average elevation profile for simulated low marsh in Georgian Bay. **a** Wire-mesh surface illustrates the simplified geomorphology underlying simulated low marsh. Elevation contours (thick lateral lines) are in 0.5 m intervals between 177.5 m (top) and 174.0 m (bottom). Approximate depth window corresponding to low marsh habitat (0 – 2 m deep; polygon) illustrates shift in depth composition from **b** deep-dominant (177.5 m), **c** intermediate (176.5 m), to **d** shallow-dominant (176.0 m)

deeper habitat (1.5–2.0 m) at higher lake levels. The downslope of the step was less steep and resulted in a more even distribution of low-marsh in the 175.5-m scenario. The position of the step relative to the lake level was an important factor determining whether composition of the depth zone was predominantly deep, intermediate, or shallow (Fig. 3b, c, d respectively).

In addition to shifts in morphology of the low-marsh habitat with different lake levels, we also projected large changes in overall low-marsh area (Fig. 4). At the approximate long-term mean lake level (176.5 m), we projected a total area of 5201 ha. We found that total area peaked at 7113 ha under the 176.0 m scenario and was smallest at 1752 ha under the 177.5 m scenario. Relative to the long-term mean, this amounted to a change in areal cover of low marsh by + 37% and − 66%, respectively. These are the corrected low-marsh areas that excluded built-up or forested areas. Progressively more low-marsh area had

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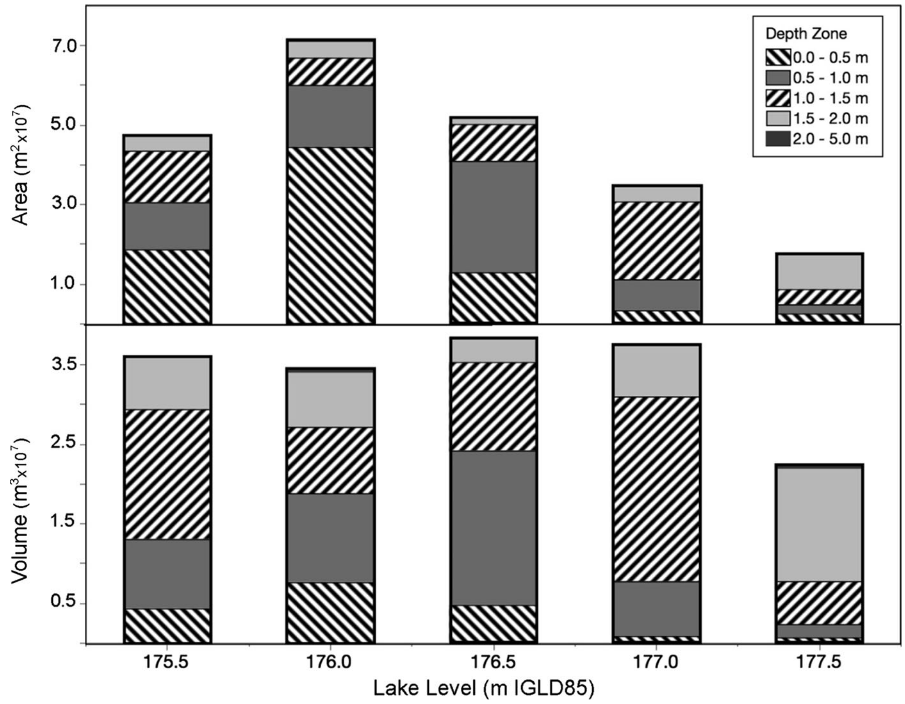

Fig. 4 Total area (m^2) and volume (m^3) of modeled low marsh habitat across the Georgian Bay study area for five lake-level scenarios. Area and volume measurements are partitioned by 0.5 m depth zones between 0 and 2 m; depths from 2-5 m were treated as a single unit

to be excluded as lake level increased (min: 5.8 ha at 175.5 m; max 340 ha at 177.5 ha).

The total volume of low marsh was relatively consistent across the lake-level scenarios (Fig. 4). Total volume was greatest under the 176.5-m scenario (38.4×10^6 m^3). Total volume did not drop below 90% of the maximum volume under other lake levels, except at 177.5 m where the volume was 58% of the maximum. The 176.0 m-scenario was associated with the second smallest volume, but the greatest low-marsh area. At 176.0 m the majority of low-marsh area was shallow (< 1 m), whereas at higher lake elevation, the low-marsh habitat was dominated by deeper water (> 1 m). The volume of low marsh appeared consistent across water-level scenarios because losses in area at higher lake levels were offset by the shift to predominantly deeper low-marsh habitat. Area and volume of low-marsh habitat were most reduced at 177.5 m but the ratio of volume to area was highest at 1.28. The smallest volume-to-area ratio was 0.49, which corresponded to a lake level of 176.0 m.

The proportional area and volume for each depth zone was relatively consistent between the South, Central, and North regions of the study area (Fig. 5). Despite differences in absolute area and volume of low marsh among regions, the consistent proportional composition by depth zone suggests that the average elevation profile (Fig. 3a) is applicable to all three regions in study area. Mean slope of the low-marsh zone was consistently steepest in the Central region, followed by the North, then South regions; the only exception was at 177.5 m where the mean slope for the North was lower than that for the South (Table 2). Given there are differences in mean slope among regions the average elevation profile would have to be laterally stretched or compressed to appropriately represent the different regions. The area-to-shoreline ratios (i.e. length of the average elevation profile) were highest in the South and lowest in the Central region (Table 2). The elevation profile lengths were consistent with mean slope calculations. For a given lake level the length of the average elevation profile in the South region was approximately twice that in the North region and three times that in the central region.

Discussion

A basic assumption of our simulations is that marsh zonation is largely dependent on water depth, corrected for wave exposure and slope (Weller and

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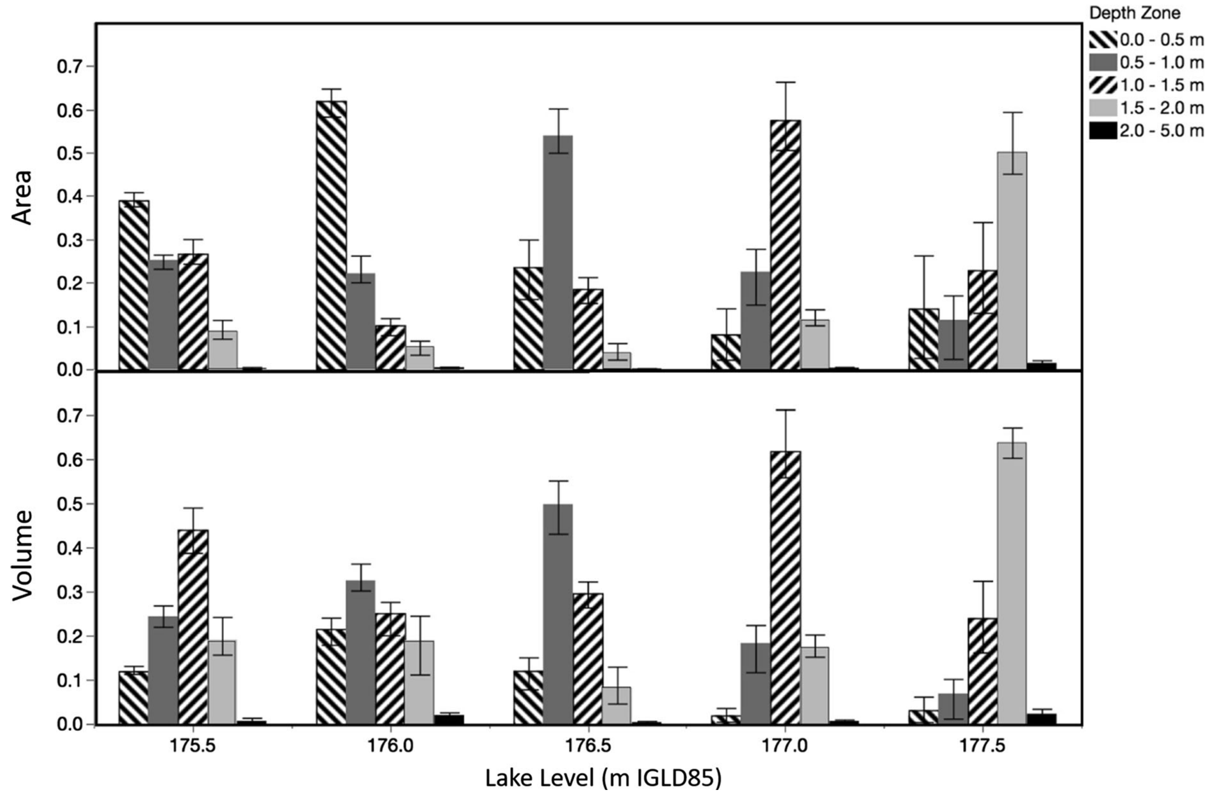

Fig. 5 Proportional breakdown of low-marsh area and volume by depth zone for each lake level scenario. Displayed proportions are means of all three regions (South, Central, North), with range error bars

Table 2 Mean (± SE) slope (% rise) and average elevation profile length in simulated low-marsh zone for each lake level scenario and region of the study area. Average elevation profile length was calculated as the low-marsh area-to-shoreline ratio and approximates the mean distance from shore to the lakeward edge of the low-marsh zone

Lake level (IGLD 1985)	Mean slope (%)			Average profile length (m)		
	South	Central	North	South	Central	North
175.5	$0.96 \pm 2.11 \times 10^3$	$1.68 \pm 2.36 \times 10^3$	$1.42 \pm 3.43 \times 10^3$	34.78	8.79	12.71
176.0	$0.90 \pm 1.99 \times 10^3$	$1.45 \pm 1.99 \times 10^3$	$1.22 \pm 2.77 \times 10^3$	28.57	7.98	8.94
176.5	$0.87 \pm 2.36 \times 10^3$	$1.55 \pm 2.15 \times 10^3$	$1.19 \pm 2.94 \times 10^3$	34.67	11.16	18.12
177.0	$0.70 \pm 2.43 \times 10^3$	$1.29 \pm 2.38 \times 10^3$	$0.93 \pm 2.82 \times 10^3$	23.81	9.28	14.43
177.5	$0.82 \pm 3.99 \times 10^3$	$1.11 \pm 3.34 \times 10^3$	$0.69 \pm 3.28 \times 10^3$	14.40	6.64	10.52

Chow-Fraser 2019). The position of the step in the average elevation profile (Fig. 3) relative to the lake level was the key determinant of the areal cover of low marsh. The literature has generally upheld the notion that under low water-level conditions low marsh (aquatic habitat) would retreat in favor of high marsh (wet meadow), given that emergent and meadow vegetation would colonize previously inundated areas (Hudon et al. 2005; Keddy and Reznicek 1986). During the sustained low water period in Lake Michigan-Huron (1999–2013), Fracz and Chow-Fraser (2013) raised concerns that the low lake levels would result in a loss of access to wetland fish habitat in Georgian Bay, notably fish spawning and nursery,

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as water levels decreased below the rock sill opening of protected wetlands. Further concerns were spurred by observations that the plant and fish assemblages during prolonged draw down in Georgian Bay wetlands had changed significantly to ones dominated by dense floating vegetation and fish communities that are tolerant of dense vegetation (Midwood and Chow-Fraser 2012). Leblanc et al. (2014) also documented changes in wetland vegetation and fish communities in wetlands in southeastern Georgian Bay that were attributed to the sustained low water conditions.

Simulations from our modeling can now provide a more complete understanding of what might happen. At 176.0 m (a value that is slightly lower than the mean lake level during the 1999–2013 period), the area of low marsh was actually greater than those corresponding to higher and lower levels. Since total low-marsh area did not decline with water level but instead pivoted around 176.0 m the total *area* of aquatic habitat may not be appropriate to assessing impacts of declining waters. Rather, we propose that the elevation profile is more appropriate for explaining why both fish and plant communities were less diverse after prolonged exposure to water levels at or near 176.0 m (Midwood and Chow-Fraser 2012). Under the 176.0 m scenario over 60% of the low-marsh area occurred in less than 0.5 m of water, whereas under higher lake levels the aquatic habitat was dominated by deeper waters (i.e. > 0.5 m). We hypothesize that during the sustained-low-water period from 1999–2013 there was loss of overall high-quality habitat for fish that depend on structurally complex SAV that require deeper water to flourish (e.g. Kapuscinski and Farrell 2014; Leblanc 2015).

Low-marsh habitat is fundamentally a three-dimensional environment and most structurally-oriented fish use and move through it in three-dimensions. The depth zones provided a coarse approximation of the types of wetland vegetation that might be present as well as the sort of structure that might be used by fish. Intermediate densities of submersed aquatic vegetation promote the greatest diversity of fish species (Dibble et al. 1997; Eadie and Keast 1984; Smokorowski and Pratt 2007) and we would expect to see more of this vegetation type in deeper areas of the wetland (i.e. > 0.5 m), whereas emergent and floating vegetation would be more prevalent in shallower waters (i.e. < 0.5 m). We observed a tradeoff between area and volume as a result of the low-marsh geomorphology; as lake levels approached the step at 176.0 m total low-marsh area increased but the inundated area was shallower, resulting in lower volume. At this lake elevation, with 60% of the low-marsh area below 0.5 m, the SAV community would have been compressed to a very small area while dense floating vegetation would have dominated. These conditions are known to be favorable to benthic-oriented species (e.g. yellow perch *Perca flavescens*, brown bullhead *Ameiurus nebulosus*, and round goby *Neogobius melanostomus*). Therefore, consistent with Midwood and Chow-Fraser's (2012) findings, during the period of sustained low water levels in Georgian Bay there was loss in volume of suitable high-quality fish habitat even though there had not been loss in areal extent of low-marsh habitat.

The above observations are consistent with the response of wetland communities to water level stabilization in other areas (Keddy and Reznicek 1986; Leira and Cantonati 2008; Mortsch 1998; Wilcox and Meeker 1991; Wilcox et al. 2008). We propose that the stability of the lake levels occurring at a low lake level (i.e. 176 m) exacerbated these effects as they relate to suitable fish habitat. Submersed aquatic vegetation provides more complex structure than floating or emergent vegetation and intermediate densities of submersed aquatic vegetation maximize fish species richness (Eadie and Keast 1984). At low lake levels the low-marsh bathymetry favored the establishment of shallower-growing vegetation (i.e. floating and emergent), which provide less complex structure, and the lack of lake level fluctuation allowed the subsequent homogenization of that community that likely further reduced the structural complexity and fish habitat quality. Under normally-fluctuating lake levels, low water conditions would support a more diverse array of vegetation types as individual species responded to the changing lake levels (Gathman et al. 2005). The shallow-dominated bathymetry at low lake levels would have a small volume-to-area ratio of low-marsh habitat but would still represent a volume 90% of average lake levels (i.e. 176.5 m) and support a more structurally complex vegetation community than under stable lake levels. Further, the abundance of shallow habitat area under low lake levels facilitates the establishment of invasive species including *Phragmites australis* (Tulbure and Johnston 2010) and *Typha X glauca* (Lishawa et al. 2010) that

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can form large, persistent stands that limit the establishment of higher quality fish habitat.

Our modeling does not take into consideration interannual fluctuations in lake levels since the GLM was developed with a dataset derived from a period of sustained low water levels (Weller and Chow-Fraser 2019). Lake-level fluctuations play a key role in structuring wetland vegetation communities (Keddy and Reznicek 1986; Leira and Cantonati 2008) so we must be cautious interpreting our simulations. Since the wetland inventory used to train the GLM was derived from imagery acquired between 2002 and 2008 (Midwood et al. 2012) and the sustained-low-water period began in 1999, the model assumes that lake levels had been stable for at least 3 years. A three-to-five-year lag time has been observed for wetland vegetation communities in response to changes in lake level (Gathman et al. 2005; Quinlan and Mulamoottil 1987; Wilcox and Nichols 2008), so we assumed that our training data (Midwood et al. 2012) are representative of a vegetation community that had adapted to a lower water regime. Functionally, this means that our low-marsh projections for each lake level assume that the lake level has been stable for at least 3 years and that vegetation classes in the community have shifted laterally to their optimal depth zones. Periods of stable, low lake levels are predicted to be more frequent in the future (Angel and Kunkel 2010; Mortsch 1998) such that the somewhat novel conditions under which the model was developed (i.e. stable, low lake levels) may become more common.

Considering the lagged response of wetland vegetation, if lake levels shifted from low to high then we would expect our simulated low-marsh extents to be underestimates since the lakeward edge of the low marsh at the lower water level would not yet have shifted shoreward. If lake levels shifted from high to low then our modeled extent would be an overestimate since lakeward boundary of low-marsh vegetation would not yet have shifted to the new outer depths. We felt it necessary to acknowledge this limitation since lake-level fluctuations are such a fundamental aspect of coastal wetland systems.

We limited our lake level evaluations to historically observed lake levels and those likely over the next century. Lower lake levels appear to be the most consistent prediction for future lake levels (Angel and Kunkel 2010, Lofgren et al. 2002; Lofgren and Rouhana 2016). Fracz and Chow-Fraser (2013) predicted massive losses of coastal wetland area as lake levels fell from 176.5 m to 173.0 m, because of limited space to shift lakeward or a loss of hydrologic connection to Georgian Bay proper. We did not directly calculate the amount of low marsh that would be lost due to the stranding of wetland habitat, because our low-marsh simulations only included areas that had a direct surface-water connection to Georgian Bay proper. Between our 176.5 m and 175.5 m low-marsh simulations there is evidence of protected-embayment wetlands that have been stranded as a result of the low water levels. The loss in overall habitat area that we modeled from 176.0 m to 177.5 m can be attributed to a loss of wetland area due to stranding and from the reduced habitat area as the low-marsh zone advances over the lakeward edge of the step in the average elevation profile. While we did not consider any lower lake levels in this paper, we would expect to see substantial declines in low-marsh area due to drying or stranding of wetlands, consistent with findings by Fracz and Chow-Fraser (2013). In the case of fringing wetlands, those less susceptible to stranding, we expect some capacity for them to shift lakeward as deeper, submersed vegetation species occur beyond the lakeward boundary of coastal wetlands (i.e. 2 m), and at depths of up to 5 m in Georgian Bay (Midwood 2012). However, the loss of access to some wetlands due to stranding may have consequences for fish habitat for species that exhibit some level of site fidelity during certain life stages, notably important sport-fish (e.g. muskellunge spawning; Weller et al. 2016). In the event of extremely high lake levels, we would expect to see a compression of low-marsh habitat area against the steeper upslope morphology of the study area. The South region has a more gently sloping nearshore that might allow for some shoreward migration of low-marsh habitat, however the prevalence of hardened shorelines and break-walls to protect waterfront properties and structures would be expected to limit such movement.

This is the first attempt at modeling changes in low-marsh habitat across different lake levels in Georgian Bay at a regional-scale. Mapping efforts for coastal wetland vegetation have been achieved with satellite imagery (Midwood and Chow-Fraser 2010; Midwood et al. 2012; Rokitnicki-Wojcik et al. 2011; Wei and Chow-Fraser 2007) as well as site-specific bathymetry-based modeling (Boyd 2017; Fracz and Chow-Fraser 2013). Most wetland vegetation modeling that

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has incorporated hydrogeomorphic parameters focused on finer-scale vegetation modeling (e.g. Hebb et al. 2013; Wilcox and Nichols 2008) but we have not seen it applied at a broader-scale. The GLM that we used for our modeling was established as effective for a lake level of 176.17 m (Weller and Chow-Fraser 2019). The low-marsh projections for our lake level scenarios were largely consistent with expectations from field observations and comparison with satellite imagery, suggesting good model performance at other lake levels. The vertical and horizontal accuracies of the data used for the DEM were better for the bathymetric data (i.e. < 176.0 m) than for the topographic data (i.e. > 176.0 m), which is why we used the mask layers to exclude any erroneous elevations in the DEM. While higher resolution elevation data for this modeling effort would have been ideal, the DEM that was derived by Weller and Chow-Fraser (2019) was the best available for the study area. The increasing amount of low-marsh habitat removed by the masks at the higher lake levels can be attributed to resolution issues in the underlying data. Projections to lower lake levels (< 176.0 m) should be more accurate due the higher-resolution data, and should be valuable for modeling possible future, low-water scenarios. The low-marsh projections for the higher lake levels (176.5–177.5 m), while less accurate, are still a useful tool for evaluating low-marsh extent at historic lake levels. If and when higher-resolution DEM becomes available, it would be useful to incorporate them and rerun our model.

One of the most important findings in this study is that habitat volume was a more informative parameter than habitat area in understanding the impact of water levels in Georgian Bay, especially in reference to suitable fish habitat. It is apparent from our work that the interaction between lake level and the nearshore geomorphology is a key driver determining low-marsh size and composition. The range of likely lake levels that have been forecast over the next century are largely within the range of historic observations (1860–2017), and possibly just beyond recorded extremes. With respect to fish habitat, it appears the greater concern is the *quality* of available low-marsh habitat rather than the total areal cover of low marsh. Sufficient low-marsh habitat should persist through this range of lake levels but the hydrographic regime may ultimately determine the suitability of that habitat for Georgian Bay fish species.

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