ASSESSING THE VULNERABILITY OF GREAT LAKES COASTAL WETLANDS TO CLIMATE CHANGE

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Abbreviations and acronyms

CPCAD	Canadian Protected and Conserved Areas Database
CWRM	Coastal Wetland Response Model
DEM	Digital Elevation Model
ECCC	Environment and Climate Change Canada
IPCC	Intergovernmental Panel on Climate Change
RCP	Representative Concentration Pathway
SAV	Submerged aquatic vegetation

Executive summary

The ability to identify ecologically vulnerable coastal wetlands is a significant advancement in conservation and environmental management for the Great Lakes ecosystem. In this study, a team of Environment and Climate Change Canada (ECCC) scientists used a novel, science-based framework to assess the vulnerability of 20 Canadian coastal wetlands to climate change across Lakes Ontario, Erie, St. Clair, and Huron, as well as the St. Marys, Detroit, and St. Lawrence Rivers. Two coastal wetland study sites originally selected for Lake Superior were not included in the final assessment. The study improves the understanding of climate change vulnerability by integrating new regional climate and lake-level projections, modelled wetland responses and sensitivity, and the capacity of wetlands to adapt to climate disturbances based on current biological and physical factors.

To assess coastal wetland vulnerability to projected climate change, an intermediate greenhouse gas concentration trajectory was selected, wherein emissions are predicted to peak around 2040, then start to decline around 2045 (Representative Concentration Pathway 4.5). To account for modelling variability, both upper- and lower-bound RCP 4.5 scenarios were selected to describe a range of future possible lake-levels. The results indicate that the general patterns of change in hydroclimate variables experienced across the Great Lakes over the past few decades are projected to continue. These include warmer air and water temperatures, increasing over-lake precipitation and evaporation. For the set of climate scenarios used, the results show average lake-levels are expected to change, with a minor to moderate decrease for the period 2070 to 2099 relative to the reference period (1961-2000) under the lower-bound scenario, and a significant increase under the upper-bound scenario.

Coastal wetland response model outputs were used in a geographic information mapping system to examine changes to valued wetland ecological attributes: 1) total wetland area, 2) volume of the submerged and floating aquatic vegetation, 3) wetland interspersion, 4) wetland vegetation community diversity, and 5) meadow marsh area. In general, an increase in average lake-levels forces an upland migration of wetland classes, but will likely result in more frequent declines in wetland area at modelled sites due to land use types that prevent landward migration (i.e. agriculture and urban areas). All ecological attributes were found to be sensitive to projected lake-level changes (to varying degrees), especially area based attributes of total wetland area and meadow marsh area. Consequently, all wetland study sites were sensitive, and are therefore at risk to future climate change. The most sensitive wetland sites and those that are projected to experience the greatest loss in area are located in Lake Erie at Long Point (-55%), Rondeau Bay (-33%), and on the eastern shoreline of Lake St. Clair (-40%). Frequent instances of future wetland loss is expected with higher lake-levels, where the surrounding land use, geology, or topography is unsuitable for landward migration.

Based on current land cover, plant diversity, invasive *Phragmites*, migration potential, and level of land protection, coastal wetlands with the lowest relative adaptive capacity are located in eastern Lake St. Clair, the Detroit River, and western Lakes Erie and Ontario. Wetlands in these regions were characterized as having a high migration potential, but relatively poor for protection, biological condition, and landscape condition. No single indicator was a driving factor

behind wetland adaptive capacity, suggesting that adaptation strategies will differ depending on species richness, local land uses, topography, and geology.

A novel index consisting of a composite of multiple quantitative indicators was constructed to describe the vulnerability of the 20 coastal wetland sites in this study. Under the RCP 4.5 climate simulation associated with stable or slightly lower lake-levels (lower-bound), thirteen of the 20 coastal wetlands were evaluated as low or very low vulnerability, six wetlands were considered moderately vulnerability, and one wetland ranked as highly vulnerable. Under the RCP 4.5 climate simulation with projections for higher water-levels (upper-bound), wetlands of eastern Lake St. Clair, the Detroit River, and western Lake Erie had a very high vulnerable score. One site on western Lake Ontario was evaluated as high vulnerability, and eight wetlands had a moderate vulnerability to future climate change.

Loss of coastal wetlands equates to a loss in wetland-dependent habitat for native species, including species at risk that are currently undergoing regional population declines. The impact of more frequent and extreme wetland loss over time can result in loss of biodiversity and valued ecosystem services if adaptation conservation is ignored. The results of this study will help to ensure that resource managers and policy-makers are guided by informed decisions so that wetlands are resilient to climate change impacts. This vulnerability assessment creates new opportunities for coastal wetland conservation to safeguard the provision of wetland goods and services for the benefit of social, economic, cultural, and freshwater ecosystem outcomes.

1.0 Introduction

Overwhelming evidence shows that the Earth has warmed during the Industrial Era (IPCC, et al., 2021). The main cause is human influence, and mitigation of greenhouse gases will largely determine the magnitude of climate change over the next century (IPCC, et al., 2021). As global temperatures increase, changes in climate will persist and, in most cases, intensify over the coming decades (Bush et al., 2019). Climate change in the Great Lakes region is causing extremes in lake-levels, storm surges, and air and surface water temperatures that are detrimental to aquatic vegetation communities and the native species they support (Environmental Law and Policy Centre, 2019; Lam & Dokoska, 2022).

Great Lakes coastal wetlands are at particular risk given their location at the land-water interface (Figure 1). These treasured resources face a systemic threat from climate change and from the multiple and repeated disturbances and loss from agriculture, shoreline development and alteration, pollution, and invasive species. As the conservation community plans for climate change, it is crucial that wetlands are resilient and continue to provide valued ecosystem services for the benefit of social, cultural, economic, and freshwater ecosystem outcomes. To achieve wetland resilience, conservation requires a management approach that differs from the traditional, including integration of regional climate data, vulnerability assessments, and adaptation approaches that reduce adverse climate change effects. While this goal is challenging, its attainment is more likely if the conservation community is able to make well-informed decisions and investments.

Figure 1. *Aerial photo of Long Point, Lake Erie with abundant coastal wetlands (ECCC).*

To this end, Environment and Climate Change Canada initiated a novel science-based study, “Assessing and Enhancing the Resilience of Great Lakes Coastal Wetlands”. The study purpose was to improve the understanding of wetland vulnerability to future climate change, defined as *“the degree to which wetlands are susceptible to and unable to cope with adverse climate change impacts”* (IPCC, et al., 2014).

This report summarizes the modelling and geospatial analyses from a series of Environment and Climate Change Canada technical reports on coastal wetland vulnerability to climate change. New downscaled climate and lake-level projections were developed for a range of future scenarios to the end of the twenty-first century to determine climate exposure (ECCC, 2022a). An integrated coastal wetland response model (ECCC, 2022b) and sensitivity analysis (ECCC, 2022c) identified plausible changes to the extent, structure, and diversity of wetland plant communities under a range of lake-levels and landscape factors. When combined with an analysis of current conditions that influence wetland ability to adjust and cope with a changing climate (ECCC, 2022d), the vulnerability to future climate change was determined for 20 coastal wetland sites of the Canadian Great Lakes.

The study results serve as an early detection of potentially damaging climate change impacts to coastal wetlands across the Canadian Great Lakes shoreline. The assessment results are also fundamental to formulating a suite of nature-based adaptation solutions for wetland managers, found in a separate report *“Adapting to Climate Change: Solutions to Enhance Great Lakes Coastal Wetland Resilience”* (ECCC, 2022e).

2.0 Methods and Results

2.1 Study site selection

Coastal wetland vulnerability can differ across the Great Lakes region, driven by patterns of land use, land cover, geology, topography, current conditions, and climate exposure. Therefore, twenty coastal wetlands from Lakes Huron, St. Clair, Erie and Ontario, as well the St. Marys, Detroit and St. Lawrence Rivers were selected to serve as surrogates for other wetlands of similar type and land use influence (Figure 2). Lacustrine and riverine wetlands were the focus of this study, as barrier-protected wetlands are sheltered from the open water and therefore could not be effectively modelled. Two coastal wetland study sites originally selected for Lake Superior were not included in the final assessment.

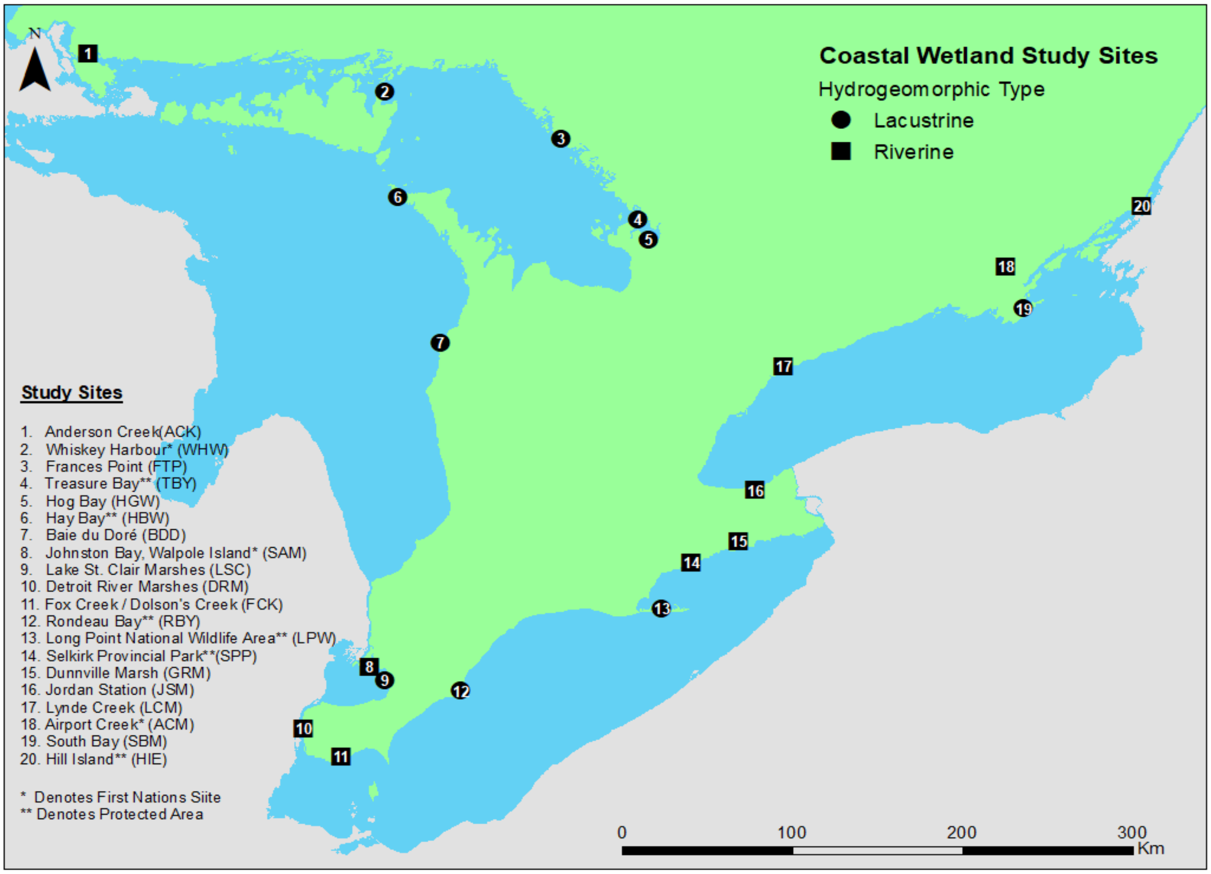

Figure 2. *Twenty Canadian Great Lakes coastal wetland study sites selected for the climate change vulnerability assessment, including acronyms used elsewhere in this report.*

2.2 Vulnerability assessment approach

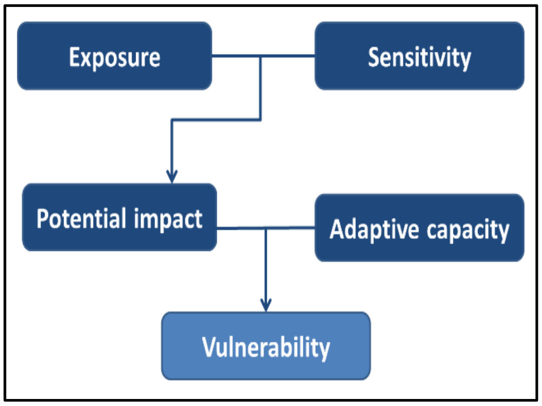

Figure 3. *A framework for climate change vulnerability showing the integration of exposure, sensitivity, and adaptive capacity.*

Understanding the factors that contribute to climate change vulnerability is essential for decision-makers to prepare for, and adapt to, climate change impacts. This study deconstructed the complexity of vulnerability into its three components (Figure 3). Combining climate change, lake-levels, wetland survey and remote sensing data, integrated ecosystem response modelling, and geographic information systems, coastal wetland vulnerability was determined to the end of the 21st century. The methodology and results for each component of the vulnerability assessment are explained in detailed technical reports (ECCC, 2022a; b; c; and d). A focus on the social system is limited to examining climate adaptation strategies and options for consideration by coastal wetland conservation practitioners (ECCC, 2022e).

2.2.1 Climate change exposure

In the context of this study, exposure to climate change refers to changes in temperature, precipitation, and water-levels across the Great Lakes over time. Given that the scale of global and national climate assessments are too large to reflect the Great Lakes region, climate projections were developed from Regional Climate Model (RCM) simulations forced by Global Climate Models (GCMs). This study selected two forcing scenarios called Representation Concentration Pathway (RCPs): 1) an intermediate future greenhouse gas concentration trajectory wherein emissions peak around 2040 then begin to decline (RCP 4.5), and 2) an increasing emissions trajectory, or business as usual scenario (RCP 8.5). In terms of an increase in global average near-surface air temperature, RCP 4.5 projects warming of 2.5°C above pre-industrial levels by 2100, whereas RCP 8.5 projects a 5 °C increase.

The method used 13 RCM-GCM combinations in the climate prediction process. Data for over-lake precipitation, over-lake evaporation, and watershed runoff into the lake were extracted from the RCMs to calculate 'net basin supply' for each lake (total precipitation on the lake surface plus the runoff coming into the lake from the surrounding watersheds, minus over-lake evaporation). The Coordinated Great Lakes Routing and Regulation Model was used to calculate lake-levels and flows for connecting channels (ECCC, 2022a).

The results below are a summary of how over-land air temperature, over-lake precipitation, and lake-levels have changed within the Great Lakes Basin and how they may continue to change until the end of the century. For details on climate and lake-level modelling, refer to the technical report "*Future hydroclimate variables and lake-levels for the Great Lakes using data from the Coupled Model Intercomparison Project Phase 5"* (ECCC, 2022a). Associated data visualizations are available in a complementary report, "*Climate Change in the Great Lakes Basin"* (Lam & Dokoska, 2022).

Over-land air temperatures are projected to increase significantly across the Great Lakes compared to the reference period (1961-2000). Under RCP 4.5, average annual land air temperatures could increase by approximately 3˚C over the Lake Erie basin, to 3.5˚C over the Lake Superior basin by the end of the century. While under RCP 8.5, average annual land air temperatures could increase by 4.8˚C over the Lake Erie basin, to 5.6˚C over the Lake Superior basin under the most extreme climate change scenarios. Warming temperatures may result in warmer winters, earlier spring warming, extreme heat, heavier precipitation, and less ice cover.

Table 1. *Plausible annual average increase in over-land air temperature (ºC) for relative to the historical measured data, under RCP 4.5 and RCP 8.5 and mid to late 21st century.*

	Scenario, Period, Average Temperature ºC				
	Annual Historical	**RCP 4.5**		**RCP 8.5**	
LAKE	**1961-2000**	**2036-2065**	**2066-2095**	**2036-2065**	**2066-2095**
Superior	2.4	5.2	5.9	5.9	8.0
Huron	6.2	8.9	9.8	9.5	11.4
Erie	9.1	11.6	12.1	12.2	13.9
Ontario	7.3	9.8	10.3	10.4	12.2

Over-lake precipitation is anticipated to increase in all seasons and over time for both climate scenarios for all lakes. Under RCP 4.5, annual total over-lake precipitation could increase by 9% over Lake Erie to 20% over Lake Superior by the end of the century. While under RCP 8.5, annual total over-lake precipitation may increase even further by 18% over Lake Erie to 24% over Lake Superior by the end of the century. With warmer winters, snowfall is expected to decrease, with more precipitation falling as rain. Lake effect snow may increase for regions within the Ontario Snow Belt such as eastern portions of Lakes Superior and Huron, including eastern and southern Georgian Bay. Lakes Superior and Ontario may see the greatest increase in over-lake precipitation under both climate scenarios.

Table 2. *Projected % change in annual mean over-lake precipitation for Canadian Great Lakes, relative to (1961-2000), under RCP 4.5 and RCP 8.5 and for mid- to late 21st century.*

	Scenario, Period, Change (%)				
	Annual Historical (mm)	**RCP 4.5**		**RCP 8.5**	
LAKE	**1961-2000**	**2036-2065**	**2066-2095**	**2036-2065**	**2066-2095**
Superior	755.1	19	20	18	24
Huron	808.3	13	13	12	19
Erie	909.6	10	9	10	18
Ontario	846.6	15	15	15	22

Lake-levels have fluctuated by as much as two metres for some lakes (i.e., Lake Huron) between the maximum and minimum monthly average over the historical period of water-level monitoring. However, a greater degree of frequency and extremes have been observed over the past two decades for all lakes (Lam & Dokoska, 2022). Key hydroclimate variables used to determine lake-levels included over-lake precipitation, runoff into the lake, evaporation, water flow, and the regulation of Lakes Superior and Ontario outflows.

Lake-level projections indicate significant deviations from lake-specific, long-term averages, with an upward trend on all lakes in the latter half of the century (Table 3). Lake-levels are projected to increase in variability resulting in even more extreme high and low levels with a warming climate. Extreme changes in hydroclimate variables and water-levels occur most markedly under high emission scenarios (i.e., under RCP 8.5 ; in extreme cases, roughly one metre above historical extremes are possible by the end of the century), while lake-level changes under more moderate climate change scenarios (RCP 4.5) may result in water-level extremes up to 0.5 metres. Unregulated Lakes (i.e., Michigan-Huron, Erie, and St. Clair) show the greatest variation under both climate scenarios, which is consistent with its historical lake-level fluctuations and large watershed. These expanding range of extremes should be considered when developing conservation and adaptation plans likely to be impacted by future lake-levels.

There are various sources of uncertainty in climate and lake-level projections, ranging from socio-economic assumptions on emissions, mitigation, and modelling uncertainties, to regional scale adaptation and assumptions about how the Great Lakes would respond under the extreme climate scenarios. It is also important to note that projections do not predict water-levels for a certain year, but rather provide a range of possible values. Additionally, just because these extreme levels are possible, it does not necessarily mean they will occur.

Table 3. *Projected change in annual lake-levels (metres) for Canadian Great Lakes relative to the reference period (1961-2000), under RCP 4.5 and RCP 8.5 and for mid to late 21st century.*

	Scenario, Period, Mean Change (5TH and 95th Percentile) (Metres)			
	RCP 4.5		**RCP 8.5**	
LAKE	**2036-2065**	**2066-2095**	**2036-2065**	**2066-2095**
Superior	0.1 (-0.3, 0.5)	0.2 (-0.3, 0.5)	0.1 (-0.3, 0.4)	0.2 (-0.3, 0.6)
Huron	0.2 (-0.5, 0.6)	0.2 (-0.7, 0.5)	0.1 (-0.9, 0.7)	0.5 (-0.1, 1.9)
St. Clair	0.2 (-0.3, 0.5)	0.2 (-0.4, 0.4)	0.1 (-0.5, 0.5)	0.5 (-0.2, 1.4)
Erie	0.3 (-0.2, 0.6)	0.3 (-0.3, 0.6)	0.2 (-0.4, 0.6)	0.5 (-0.1, 1.3)
Ontario	0.3 (-0.1, 0.9)	0.3 (-0.1, 1.0)	0.2 (-0.2, 0.9)	0.3 (0.0, 1.0)

Great Lakes ice cover can also influence air temperature, precipitation, wind, wave energy, and wetland exposure to erosion and long-term damage. Since the 1970s, the maximum ice cover has decreased by 5% per decade, and some lakes are losing ice cover faster than others including Lakes Superior, Huron, St. Clair, and Erie (Di Liberto, 2018). Under RCP 8.5, average ice cover could decrease by 8% to 30% by the end of the century. While average ice cover in the spring could decrease by 3% to 18% by the end of the century (Lam & Dokoska, 2022).

Coastal wetland response modelling

Coastal wetland plant community classes are structured along an elevation gradient (relative to water-level within a wetland) in which plant species persist along a narrow vertical (<2 m) range (Figure 6). Thus, wetland structure and plant spatial distribution are sensitive to changes in elevation relative to lake-levels (Grabas & Rokitnicki-Wojcik, 2015). An accurate three-dimensional characterization of elevation within and around a coastal wetland is critical in modelling plant response. This characterization is done through high definition digital elevation models (DEMs), wherein a grid where each cell value represents the terrain elevation (Figure 4).

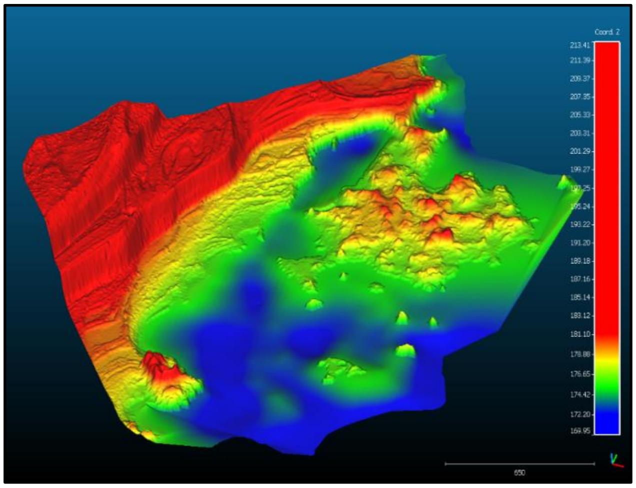

Figure 4. *A digital elevation model for the Treasure Bay coastal wetland (Georgian Bay) showing the bare-earth topographic surface including rock shoals at a vertical exaggeration of 10x.*

A second component is the Coastal Wetland Response Model (CWRM simulates wetland change under future possible lake-levels; Figure 5). The CWRM integrates physical (lake-levels, water depth, waves, and topography) and ecological (wetland plant class distribution through field, topographic, and bathymetric data) conditions spatially and over time to understand successional processes and the spatial distribution of wetland classes from the recent past to the end of the century under various climate scenarios. The CWRM relies on historically observed physical and biological conditions to elucidate the relationship between these two important ecosystem dimensions and allows for a numerical representation of wetland ecosystem and hydrological processes. In doing so, it is possible to link large-scale climate and lake-wide dynamics to small-scale wetland ecosystem processes that are foundational for the spatial analysis of coastal wetland sensitivity.

Due to the large uncertainty in modeled lake-levels for Lake Ontario under the higher emission scenario (RCP 8.5), climate simulations produced by Global Climate Models were selected from an ensemble of models to account for the range of potential future conditions under the intermediate emission scenario (RCP 4.5). Within this climate scenario, projections made by the Canadian Earth System Model (CanESM2) were selected to represent a *"lower-bound"* RCP 4.5 scenario, wherein changes in lake-levels may be stable or slightly lower than the long-term average. Conversely, projections made by the Geophysical Fluid Dynamics Laboratory Earth System Model (GFDL-ESM2M) were selected to represent an *"upper-bound"* of the RCP 4.5 scenario, wherein projected changes in lake-levels are higher than the long-term average.

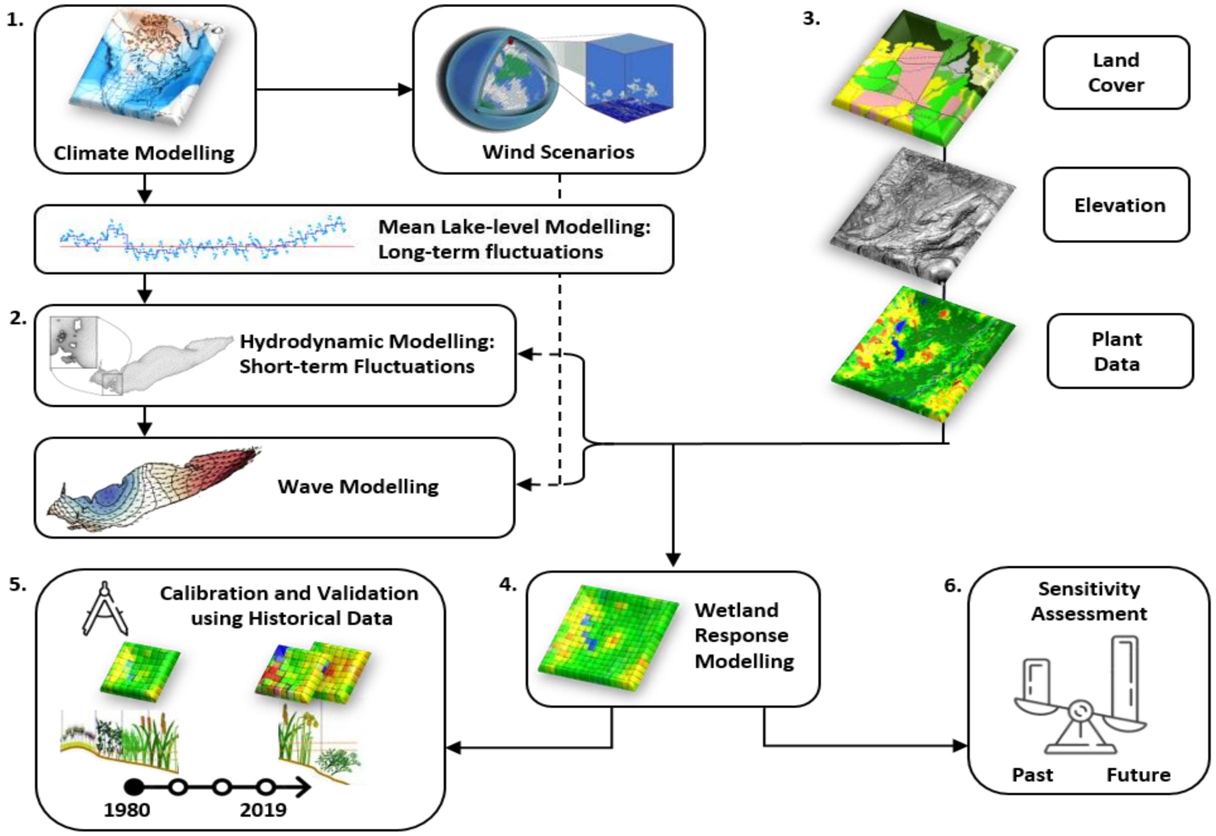

Figure 5. *A schematic of the Coastal Wetland Response Model. (1) Climate modelling was downscaled to model regional wind patterns and average lake-levels. (2) Short and long-term wind effects were used to model water-level variations, waves, and water dynamics near the shoreline. Environmental variables included the frequency, magnitude, and duration of flood and drought periods. (3) Land cover, elevation, and wetland plant survey data (2018-2019) were combined to understand where key wetland plant classes currently exist and under what environmental conditions. (4) Using supervised machine learning, changes in the size and distribution of wetland plant classes were forecasted in response to changing environmental variables. (5) The CWRM was calibrated and validated by simulating the observed past and comparing with historical observations made through field surveys and remote sensing. (6) Forecasted wetland succession was then compared to the simulated past to detect climate - driven wetland responses.*

Short and long-term wind effects, such as wind setup and seiche activity, were used to model low and high frequency lake-level variations, as well as the wave climate that shapes coastal wetlands. Variables including the frequency, magnitude, and duration of flood and drought periods, were extracted from hydrodynamic simulations using wavelet analysis at a quarter-monthly scale for the observed and simulated periods. Data on land cover/use, elevation, and wetland classes were integrated to understand where large wetland classes currently exist, and under what environmental conditions. Using supervised machine learning, the CWRM forecasted changes in the size and distribution of wetland plant communities (Table 4, Figure 6). The CWRM was calibrated and validated by simulating the observed past (1980-2018) and comparing those simulations with historical observations made through field surveys and remote sensing.

Table 4. *A description of the wetland plant communities modelled with examples of plant species.*

Community		**Description**	**Examples**
Submerged aquatic vegetation (SAV)		Submerged and floating-leaved rooted plants, stoneworts and coontails	Leafy pondweed (*Potamogeton foliosus*), White water lily (*Nymphaea odorata*), Northern watermilfoil (*Myriophyllum sibiricum*) Slender naiad (*Najas flexilis*)
Emergent marsh		Plants with above substrate growth that emerge from the water column	Broadfruit bur-reed (*Sparganium eurycarpum*) Broadleaf arrowhead (*Sagittaria latifolia*), Hard-stem bulrush (*Schoenoplectus acutus*) Broadleaf cattail (*Typha latifolia*)
Meadow marsh		Sedges, grasses, ferns and forbs	Tussock sedge (*Carex stricta*) Canada bluejoint (*Calamagrostis canadensis*) Canada anenome (*Anenome canadensis*) Sensitive fern (*Onoclea sensibilis*)
Swamp	**Shrubby swamp**	Woody perennials with low-branching stems	Red-osier dogwood (*Cornus stolonifera*) Buttonbush (*Cephalanthus occidentalis*)
	Treed swamp	Woody perennials with high-branching stems	Green ash (*Fraxinus pennslyvanica*) Crack willow (*Salix fragilis*)

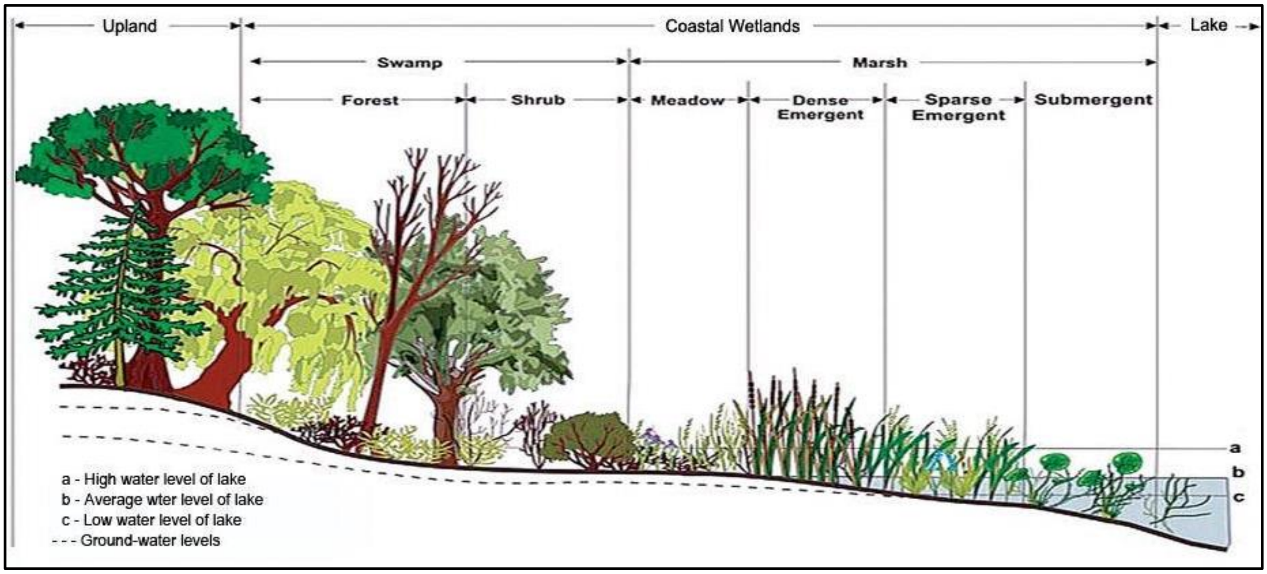

Figure 6. *The vertical profile of a typical Great Lakes coastal wetland showing the transitions between plant communities in relation to lake-level* (Wilcox, et al., 2002).

Changes in wetland vegetation classes between the simulated past (1980-2010) and future (2070-2100) were compared to detect an adverse response to climate change as well as risk to the continued provision of valued ecosystem services (Figures 7 and 8). A detailed description of the methodology to create DEMs and the CWRM, as well as model results, can be found in *"Great Lakes coastal wetland response to climate change using a coastal wetland response model (CWRM)"* (ECCC, 2022b).

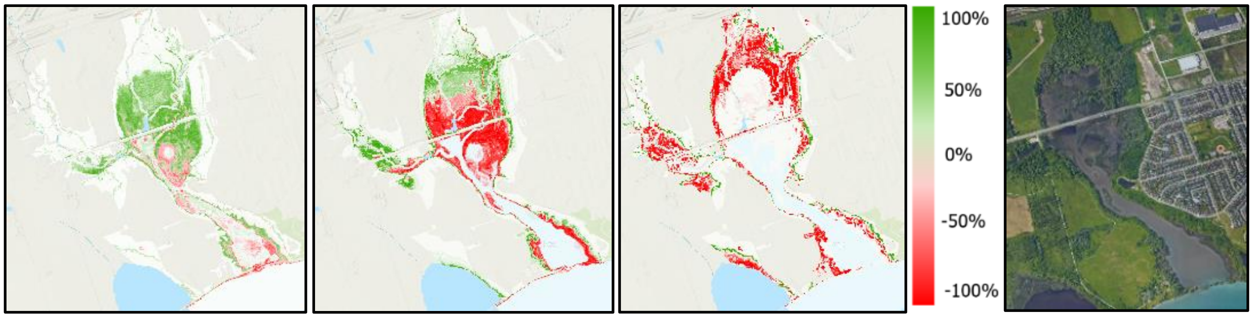

Figure 7. *Changes in wetland class distribution between recent past and simulated future under the upper-bound RCP 4.5 scenario for Lynde Creek, Lake Ontario (red: loss, green: gain). Left panel shows upland migration of emergent marsh. Middle-Left panel shows loss of submerged aquatic vegetation. Middle-right panel shows a loss of swamp. Right panel is a Google satellite image of Lynde Creek.*

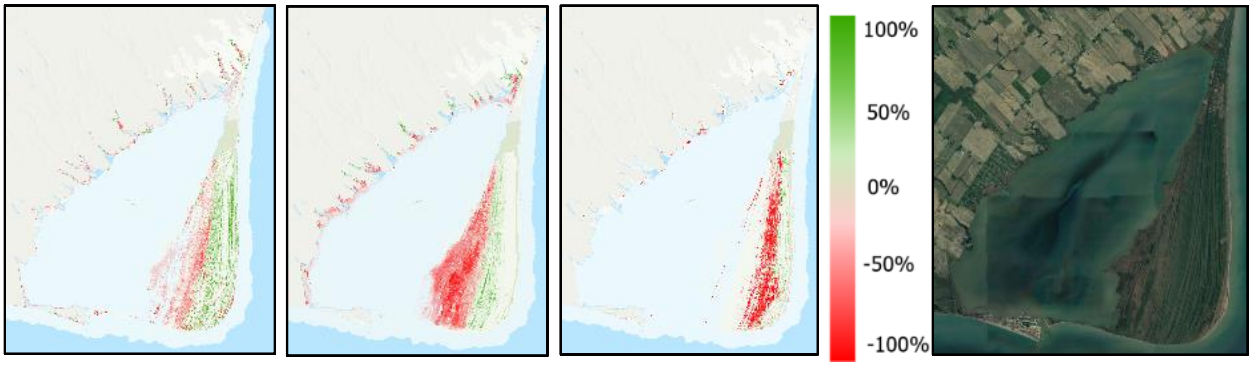

Figure 8. *Changes in wetland class distribution between recent past and future under the upper-bound RCP 4.5 scenario for Rondeau Bay, Lake Erie (red: loss, green: gain). Left panel shows upland migration and increase in emergent marsh. Middle-Left panel shows loss of submerged aquatic vegetation. Middle-right panel depicts a loss of shrub swamp due to the low availability of land at a higher elevation. Right panel is a Google satellite image of Rondeau Bay.*

2.2.2 Coastal wetland sensitivity

Sensitivity is defined as "*the degree to which a system or species is affected, either adversely or beneficially, by climate variability or change*" (Glick, Stein, & Edelson, 2011). In the context of this study, wetland sensitivity was assessed by selecting valued ecological attributes of healthy wetland habitat (Table 5, Figure 11), and by extracting the modelled outputs to quantify possible negative impacts to wetland extent, structure, and function.

A negative change in each ecological attribute was determined by comparing the simulated past (1980 to 2008) to the projected future (2071 to 2098) under the lower and upper-bounds of the RCP 4.5 scenario. To determine if an ecosystem attribute responded adversely, the 10th percentile was calculated for past simulations and applied to future projections as a threshold for detecting an extreme negative state (Figure 9). The 10th percentile allows for the frequency of annual attribute scores less than 90% of those observed in the simulated past to be categorized. The frequency of attribute scores below the change-detection threshold were added and expressed as a proportion of the total number of forecasted years to arrive at an overall index of coastal wetland sensitivity.

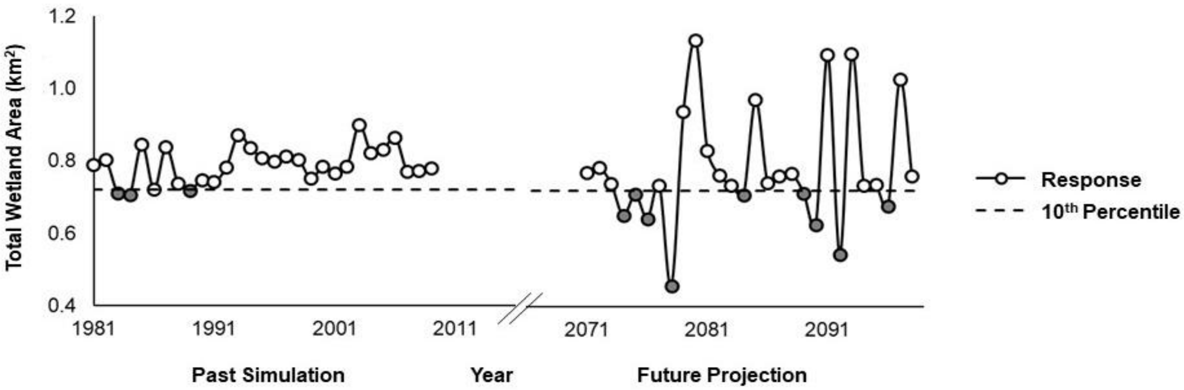

Figure 9. *Simulated response in the total wetland area (km^2) of South Bay, Lake Ontario for the RCP 4.5 upper-bound climate scenario. To determine if wetland area responded adversely, the 10th percentile was calculated across the simulated past and applied to the future projection as a threshold for detecting negative change. In this case, nine of the 28 forecasted years (32%) exceed the change-detection threshold, indicating moderate sensitivity and a risk of future wetland loss.*

Attribute and sensitivity index scores were classified as low (*no detectable risk*), moderate (*at risk*), or high (*critical risk*) risk to future climate change impacts and the delivery of wetland ecosystem services (Figure 10).

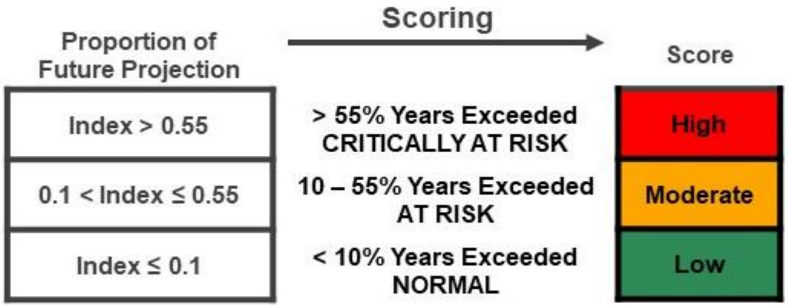

Figure 10. *Scoring for ecological attributes and wetland sensitivity indices. Ecosystem attribute and wetland sensitivity index scores were classified as high, moderate or low; and critically at risk, at risk and no detectable risk.*

Table 5. *A summary of valued ecological attributes with rationale used to assess the sensitivity of coastal wetlands to climate change.*

Attribute	Description	Value / rationale for evaluation
Total wetland area	The two-dimensional areal measurement of a coastal wetland study site.	Larger wetlands support higher species diversity, abundance, and ecosystem functions and services. Lake-level fluctuations drive wetland extent.
Vegetation community diversity	The number and relative proportion of plant communities measured through the Shannon Diversity Index.	Vegetation community diversity provides for species diversity, ecosystem function, stability, and resilience by providing an array of habitats and refugia for wetland wildlife.

Submerged aquatic vegetation (SAV)	The three-dimensional extent of the flooded, low marsh that supports submerged and floating-leaved plants.	SAV improves water quality by storing and releasing nutrients and oxygen. The root system provides stability to sediments and reduces turbidity. SAV provides spawning, nursery, and foraging habitat and refugia for amphibians, reptiles and fish.
Wetland interspersion	Also referred to as edge density, interspersion is the ratio of wetland vegetation to open water.	A measure of habitat structural heterogeneity associated with increased diversity and abundance of marsh birds and waterfowl. Interspersion is dependent upon lake-level fluctuations, and is often the focus of wetland restoration and management.
Meadow marsh	The two-dimensional extent of the wet meadow plant community dominated by sedges and grasses.	The meadow marsh plant community is highly sensitive to lake-level fluctuations, supports the highest diversity of wetland plants and provides important foraging and breeding habitat for birds.

Figure 11. *Examples of wetland attributes. From left to right: Submerged aquatic vegetation (SAV), interspersion, and meadow marsh habitat.*

The following is a summary of the results of the sensitivity analysis. For a comprehensive understanding of the methodology and results the reader is directed to the technical paper “Assessing the Sensitivity of Great Lakes Coastal Wetlands to Climate Change (ECCC, 2022c).

The sensitivity analysis revealed that all wetland ecological attributes were sensitive to climate change, demonstrating a risk to wetlands and associated ecosystem services (Figure 12, Table 6). Wetland sensitivity was generally higher under the upper-bound scenario associated with higher lake-levels. All coastal wetland study sites were at risk in at least one simulation, and five wetland sites were critically at risk in at least one simulation.

Wetland sites on Lake Ontario were the least sensitive, as no site was evaluated as critically at risk in either simulation. Airport Creek Marsh was the only site to be considered at low risk in the upper-bound simulation. In contrast, wetland sites on Lake Erie, Lake St. Clair, and the Detroit River showed the highest wetland sensitivity in both simulations. Seven sites were considered to be at risk in the lower-bound simulation, while four sites were evaluated as critically at risk in the upper-bound simulation. All wetland sites on Lake Huron and the St. Marys River were assessed as being at risk in the upper-bound simulation, except Whiskey Harbour on Manitoulin Island, which scored critically at risk (note that sensitivity may have been overestimated due to coarser-grained resolution of land cover data used in the coastal wetland response model).

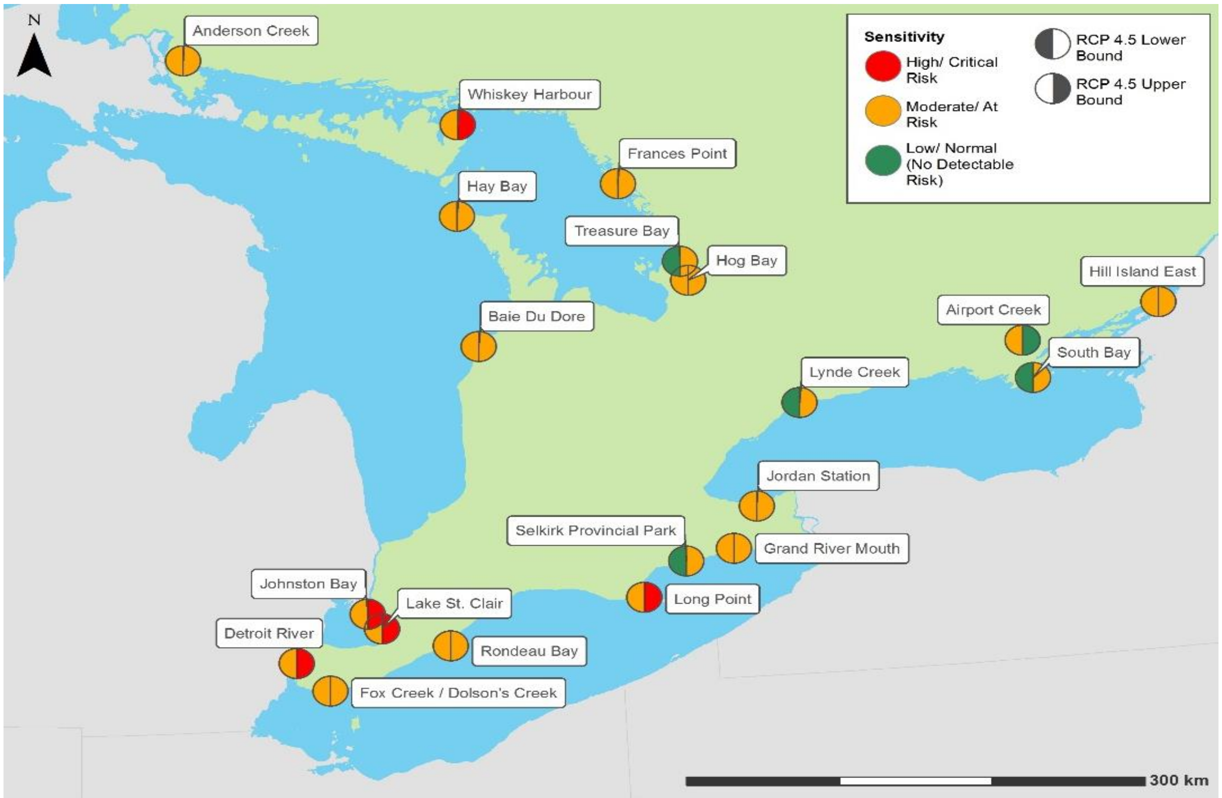

Figure 12. *Sensitivity scores for Great Lakes coastal wetland sites. The left side of each circle shows the sensitivity for the lower-bound climate simulation associated lower lake-levels. The right side of each circle shows the sensitivity for the upper-bound climate simulation associated with higher lake-levels. Red reflects high sensitivity (critical risk), orange reflects moderate sensitivity (at risk) and, green reflects low sensitivity (no detectable risk).*

Table 6. *Coastal wetland sensitivity scores and risk classifications by lake, wetland, and type. Index scores are on a continuum starting at 0.00, with 1.00 being the theoretical maximum (Figure 8). Where model-specific risk classifications differ, overall sensitivity is expressed as a range.*

Basin	**Wetland name**	**Wetland Type**	**RCP 4.5 lower-bound**		**RCP 4.5 upper-bound**		**Overall sensitivity**
St. Marys River	Anderson Creek	Open Drowned River-mouth	0.29	Moderate	0.15	Moderate	Moderate
Lake Huron	Baie du Doré	Open Embayment	0.21	Moderate	0.41	Moderate	Moderate
	Frances Point	Protected Embayment	0.19	Moderate	0.23	Moderate	Moderate
	Hay Bay	Protected Embayment	0.19	Moderate	0.18	Moderate	Moderate
	Hog Bay	Protected Embayment	0.14	Moderate	0.36	Moderate	Moderate
	Treasure Bay	Protected Embayment	0.08	Low	0.28	Moderate	Low - Moderate
	Whiskey Harbour	Protected Embayment	0.20	Moderate	0.67	High	Moderate - High
Lake St. Clair	Johnston Bay	Delta	0.12	Moderate	0.67	High	Moderate - High
	Lake St. Clair	Open Shoreline	0.15	Moderate	0.71	High	Moderate - High
Detroit River	Detroit River	Open Shoreline	0.15	Moderate	0.69	High	Moderate - High
Lake Erie	Fox/Dolson's Creeks	Barred Drowned River-mouth	0.15	Moderate	0.54	Moderate	Moderate
	Grand River Mouth	Barred Drowned River-mouth	0.21	Moderate	0.44	Moderate	Moderate
	Long Point	Sand-spit Embayment	0.16	Moderate	0.63	High	Moderate - High
	Rondeau Bay	Sand-spit Embayment	0.19	Moderate	0.31	Moderate	Moderate
	Selkirk	Barred Drowned River-mouth	0.09	Low	0.34	Moderate	Low - Moderate
Lake Ontario	Airport Creek	Open Drowned River-mouth	0.27	Moderate	0.08	Low	Low - Moderate
	Jordan Station	Barred Drowned River-mouth	0.37	Moderate	0.43	Moderate	Moderate
	Lynde Creek	Barred Drowned River-mouth	0.04	Low	0.14	Moderate	Low - Moderate
	South Bay	Open Embayment	0.04	Low	0.29	Moderate	Low - Moderate
St. Lawrence River	Hill Island East	Protected Embayment	0.25	Moderate	0.52	Moderate	Moderate

2.2.3 Potential climate change impact on coastal wetlands

Wetland area is expected to fluctuate over time with both gains and losses; however, this analysis shows that there will be more years with less wetland area relative to the past. A loss in total wetland area was projected under the upper-bound scenario for all wetland study sites, with 12 sites classified as critically at risk. The extent of meadow marsh followed a similar trend under the upper-bound scenario, with 10 highly sensitive sites (Figures 14A and 14D, Table 8).

The projected change in wetland area ranged from a decrease of 55% to an increase of 30% (Figure 13). For the upper-bound scenario, which has an associated average water-level rise of 54.5 cm for all lakes, there is an average wetland loss of 16%, ranging from -55% to 12%. In contrast, the lower-bound scenario has an average water-level decrease of 10.3 cm for all lakes and an associated average wetland gain of 7% ranging from -1% to 29% across all sites. For Lake Erie, there was a 31% loss of wetland area, while for Lake St. Clair, wetland area decreased by 35%. Lake Huron showed an average loss of 11% under the upper-bound scenario. Conversely, the rise in water projected for Lake Ontario level under the upper-bound RCP 4.5 scenario resulted in an average increase in wetland area of 8% (ECCC, 2022b).

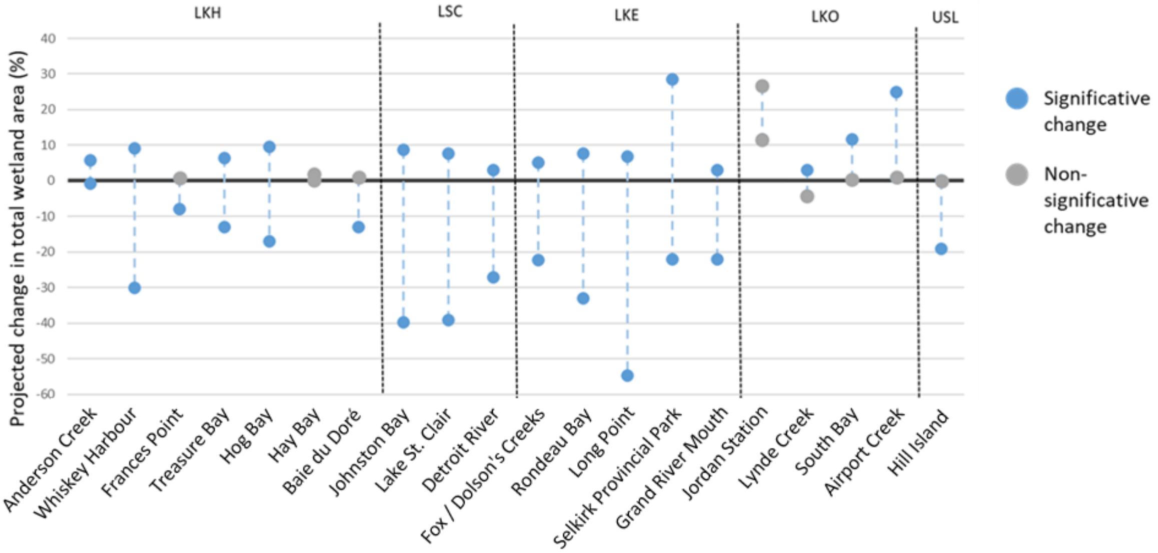

Figure 13. *The range of relative projected change in wetland area (%), defined as the difference in annual distributions between the future (2070–2099) and the recent past (1980–2009) (ECCC, 2022b).*

Interspersion and the volume of submerged aquatic vegetation were least responsive. Under the lower-bound scenario, 12 wetlands showed a loss of interspersion (Figure 14E, Table 7). This decreased to nine wetlands under the upper-bound scenario; however, Hay Bay, Detroit River and Long Point were highly sensitive (Figure 14E, Table 8). Submerged aquatic vegetation volume was more responsive under the lower-bound scenario, with 14 sites projecting a loss (Figure 14 B, Table 7). This decreased to 10 wetlands under the upper-bound scenario (Table 8); however, Fox Creek/ Dolson's Creek and Lake St. Clair sites were highly sensitive.

Wetland plant community diversity was moderately responsive to projected climate changes. Under the lower-bound scenario, nine wetlands showed a decrease in community diversity, with one location (Jordan Station) being highly sensitive (Figure 14C, Table 7). For the upper-bound scenario, this increased to 14 sites, with six highly sensitive wetlands (Figure 14C, Table 8).

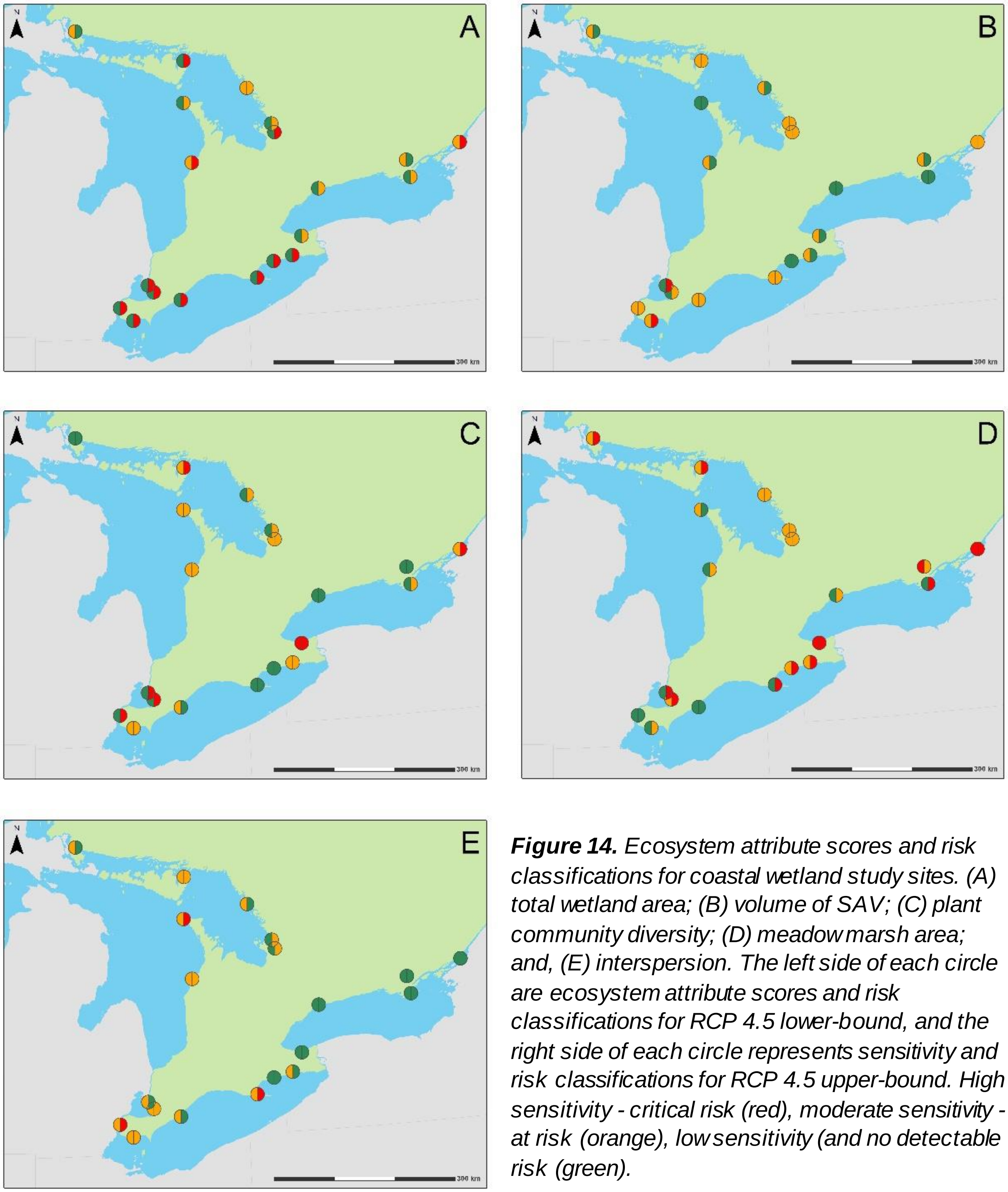

Figure 14. *Ecosystem attribute scores and risk classifications for coastal wetland study sites. (A) total wetland area; (B) volume of SAV; (C) plant community diversity; (D) meadow marsh area; and, (E) interspersion. The left side of each circle are ecosystem attribute scores and risk classifications for RCP 4.5 lower-bound, and the right side of each circle represents sensitivity and risk classifications for RCP 4.5 upper-bound. High sensitivity - critical risk (red), moderate sensitivity - at risk (orange), low sensitivity (and no detectable risk (green).*

***Table 7**. Ecological attribute scores and risk classifications for wetlands sites organized by Great Lake region under the RCP 4.5 lower-bound scenario. Sensitivity index represent the proportion (from 0.00 to 1.00) of extreme lows predicted for each attribute over the modeled scenario. Risk classifications are based on the scoring regime in Figure 9.*

Basin	**Wetland Name**	**Total wetland area**		**Volume of SAV**		**Vegetation community diversity**		**Meadow marsh area**		**Interspersion**	
St. Marys River	**Anderson Creek**	0.11	Moderate	0.43	Moderate	0.04	Low	0.46	Moderate	0.43	Moderate
Lake Huron	**Baie du Doré**	0.25	Moderate	0.14	Moderate	0.25	Moderate	0.04	Low	0.39	Moderate
	Frances Point	0.18	Moderate	0.18	Moderate	0.07	Low	0.32	Moderate	0.18	Moderate
	Hay Bay	0.07	Low	0.07	Low	0.36	Moderate	0.14	Moderate	0.32	Moderate
	Hog Bay	0.04	Low	0.18	Moderate	0.25	Moderate	0.18	Moderate	0.04	Low
	Treasure Bay	0.07	Low	0.11	Moderate	0.00	Low	0.18	Moderate	0.04	Low
	Whiskey Harbour	0.04	Low	0.29	Moderate	0.18	Moderate	0.29	Moderate	0.21	Moderate
Lake St. Clair	**Johnston Bay**	0.07	Low	0.07	Low	0.07	Low	0.00	Low	0.39	Moderate
	Lake St. Clair	0.07	Low	0.07	Low	0.07	Low	0.11	Moderate	0.43	Moderate
Detroit River	**Detroit River**	0.07	Low	0.32	Moderate	0.07	Low	0.00	Low	0.29	Moderate
Lake Erie	**Fox / Dolson's Creeks**	0.04	Low	0.39	Moderate	0.11	Moderate	0.00	Low	0.21	Moderate
	Grand River Mouth	0.04	Low	0.25	Moderate	0.39	Moderate	0.29	Moderate	0.11	Moderate
	Long Point	0.07	Low	0.29	Moderate	0.04	Low	0.07	Low	0.32	Moderate
	Rondeau Bay	0.07	Low	0.18	Moderate	0.18	Moderate	0.07	Low	0.43	Moderate
	Selkirk Provincial Park	0.04	Low	0.04	Low	0.00	Low	0.29	Moderate	0.07	Low
Lake Ontario	**Airport Creek**	0.39	Moderate	0.11	Moderate	0.07	Low	0.71	High	0.07	Low
	Jordan Station	0.00	Low	0.14	Moderate	0.68	High	0.96	High	0.07	Low
	Lynde Creek	0.07	Low	0.04	Low	0.00	Low	0.00	Low	0.07	Low
	South Bay	0.04	Low	0.07	Low	0.07	Low	0.00	Low	0.04	Low
St. Lawrence River	**Hill Island East**	0.14	Moderate	0.25	Moderate	0.21	Moderate	0.64	High	0.00	Low

Table 8. *Ecological attribute scores and risk classifications for wetlands sites organized by Great Lake region under the RCP 4.5 upper-bound scenario. Sensitivity index represent the proportion (from 0.00 to 1.00) of extreme lows predicted for each attribute over the modeled scenario. Risk classifications are based on the scoring regime in Figure 9.*

Basin	**Wetland Name**	**Total wetland area**		**Volume of SAV**		**Vegetation community diversity**		**Meadow marsh area**		**Interspersion**	
St. Marys River	**Anderson Creek**	0.00	Low	0.00	Low	0.00	Low	0.68	High	0.07	Low
Lake Huron	**Baie du Doré**	0.82	High	0.00	Low	0.18	Moderate	0.54	Moderate	0.50	Moderate
	Frances Point	0.50	Moderate	0.04	Low	0.36	Moderate	0.25	Moderate	0.00	Low
	Hay Bay	0.11	Moderate	0.00	Low	0.11	Moderate	0.07	Low	0.61	High
	Hog Bay	0.64	High	0.29	Moderate	0.39	Moderate	0.25	Moderate	0.21	Moderate
	Treasure Bay	0.39	Moderate	0.21	Moderate	0.21	Moderate	0.29	Moderate	0.29	Moderate
	Whiskey Harbour	0.64	High	0.46	Moderate	0.96	High	1.00	High	0.29	Moderate
Lake St. Clair	**Johnston Bay**	1.00	High	0.71	High	0.64	High	1.00	High	0.00	Low
	Lake St. Clair	1.00	High	0.50	Moderate	0.86	High	0.93	High	0.25	Moderate
Detroit River	**Detroit River**	1.00	High	0.46	Moderate	1.00	High	0.00	Low	0.96	High
Lake Erie	**Fox / Dolson's Creeks**	0.89	High	0.93	High	0.18	Moderate	0.32	Moderate	0.36	Moderate
	Grand River Mouth	0.93	High	0.07	Low	0.46	Moderate	0.68	High	0.04	Low
	Long Point	1.00	High	0.29	Moderate	0.04	Low	1.00	High	0.82	High
	Rondeau Bay	0.96	High	0.50	Moderate	0.00	Low	0.00	Low	0.07	Low
	Selkirk Provincial Park	0.89	High	0.00	Low	0.04	Low	0.79	High	0.00	Low
Lake Ontario	**Airport Creek**	0.04	Low	0.00	Low	0.04	Low	0.29	Moderate	0.04	Low
	Jordan Station	0.32	Moderate	0.07	Low	0.86	High	0.89	High	0.00	Low
	Lynde Creek	0.50	Moderate	0.00	Low	0.04	Low	0.14	Moderate	0.00	Low
	South Bay	0.32	Moderate	0.00	Low	0.32	Moderate	0.79	High	0.04	Low
St. Lawrence River	**Hill Island East**	0.79	High	0.29	Moderate	0.64	High	0.89	High	0.00	Low

2.2.4 Coastal wetland adaptive capacity

Coastal wetland vulnerability not only depends on the exposure to climate change variables and wetland sensitivity, but also on the capacity of wetlands to cope with shocks and disturbances. This is influenced by current wetland condition, structure, and function, as well human factors. In the context of this study, adaptive capacity is *"the ability of a coastal wetland in its current state, to adjust and maintain its ecological regime under changing climatic conditions, including variability and extremes"*. This is a critical component of building ecosystem resilience and crucial to wetland management.

Adaptive capacity is a theoretical concept and difficult to measure for complex coastal wetlands. Previous studies operationalize adaptive capacity by using surrogate variables to infer ecosystem adaptive capacity (Angeler, et al., 2019). In this study, eight variables of wetland adaptive capacity were selected based on empirical studies of wetland condition and input from coastal wetland experts. The variables cover a broad range of influences, and encompass the characteristics of the wetland and surrounding environment that are likely to have the greatest impact on adaptive capacity. These variables were grouped into four sub-indicator categories (Table 9) and then aggregated into a composite indicator (i.e., a weighted combination of variables) to quantify adaptive capacity for comparison across wetland study sites.

Five indicators were assessed using Geographic Information System mapping and analysis (Figure 16) including, the amount (area) of invasive *Phragmites* within and surrounding each wetland, the amount (area) of protection within and surrounding each wetland site (ECCC, 2019), and the extent of natural land cover surrounding each wetland. Upslope and downslope wetland migration potential was also measured by determining the vertical migration limits based on lake-level projections and adjacent land use (Zuzek Inc, 2020). Wetland plant species richness was determined from two-years of field surveys (Figure 15). A composite indicator score was developed by aggregating the sub-indicators and variables. The result of this analysis was a relative numerical score for each of the four sub-indicators as well as relative categorical scores of high, moderate and low adaptive capacity across the 20-wetland sites assessed (Table 10 and Figure 17). For complete details on the coastal wetland adaptive capacity assessment methodology, refer to *"Assessing the Adaptive Capacity of Great Lakes Coastal Wetlands to Climate Change"* (ECCC, 2022d).

Figure 15. *An example of transects and quadrats for the purpose of biological and physical data collection.*

Table 9. *Variables used to assess the adaptive capacity of Great Lakes coastal wetlands to climate change. Variables have been grouped into four sub-indicators based on their influence on adaptive capacity. A description of each attribute used to measure each variable is provided.*

Sub-indicator	**Variable**	**Influence on adaptive capacity**
Landscape condition	The proportion of natural land cover (e.g., forests, grasslands and adjacent wetlands) within 5 km of a coastal wetland	Developed landscapes adversely affect habitat quantity and quality, which can reduce the size of local wildlife populations as well as their persistence and genetic diversity. Coastal wetlands situated in highly developed landscapes can have plant and wildlife populations less adaptable to climate change disturbance.
Biological condition	The proportion of invasive *Phragmites* cover within a coastal wetland	Dense stands of invasive Phragmites reduce biodiversity by displacing native wildlife. Phragmites in surrounding habitats increases the probability of an invasion. A loss of biodiversity decreases the probability of species adapting to or accommodating a disturbance, limiting a coastal wetland's ability to moderate climate change impacts.
	The proportion of invasive *Phragmites* cover within 5 km of a coastal wetland	
	Plant species richness within a coastal wetland	Plant species diversity increases the likelihood that one or more species exist that can resist a disturbance or that have differing responses to a disturbance. Both contribute to resilience and increase the probability that a coastal wetland will be able to adapt to climate change while maintaining key ecosystem functions.
Wetland migration potential	The potential for upland migration during high water-level periods	Wetland plant communities adapt by migrating upland or waterward in response to changing water-levels. Should their migration be impeded by barriers or land development, local extirpations or the loss of an entire plant community may occur. This would reduce the ability of a wetland to maintain key ecosystem functions and compromise its ability to adapt to climate change.
	The potential for lakeward migration during low water-level periods	
Protection	The proportion of area protected within a coastal wetland	Relative to unmanaged areas, Canadian protected areas have a greater capacity to conserve biological and geological diversity, and offer protection against habitat degradation and non-climatic stressors. By mitigating non-climatic stressors, such as habitat loss, habitat fragmentation, invasive species and water quality impairment, protected areas leave coastal wetland wildlife better able to adapt to climate change.
	The proportion of area protected within 5 km of a coastal wetland using data from the Canadian Protected and Conserved Areas Database (CPCAD, 2019)	

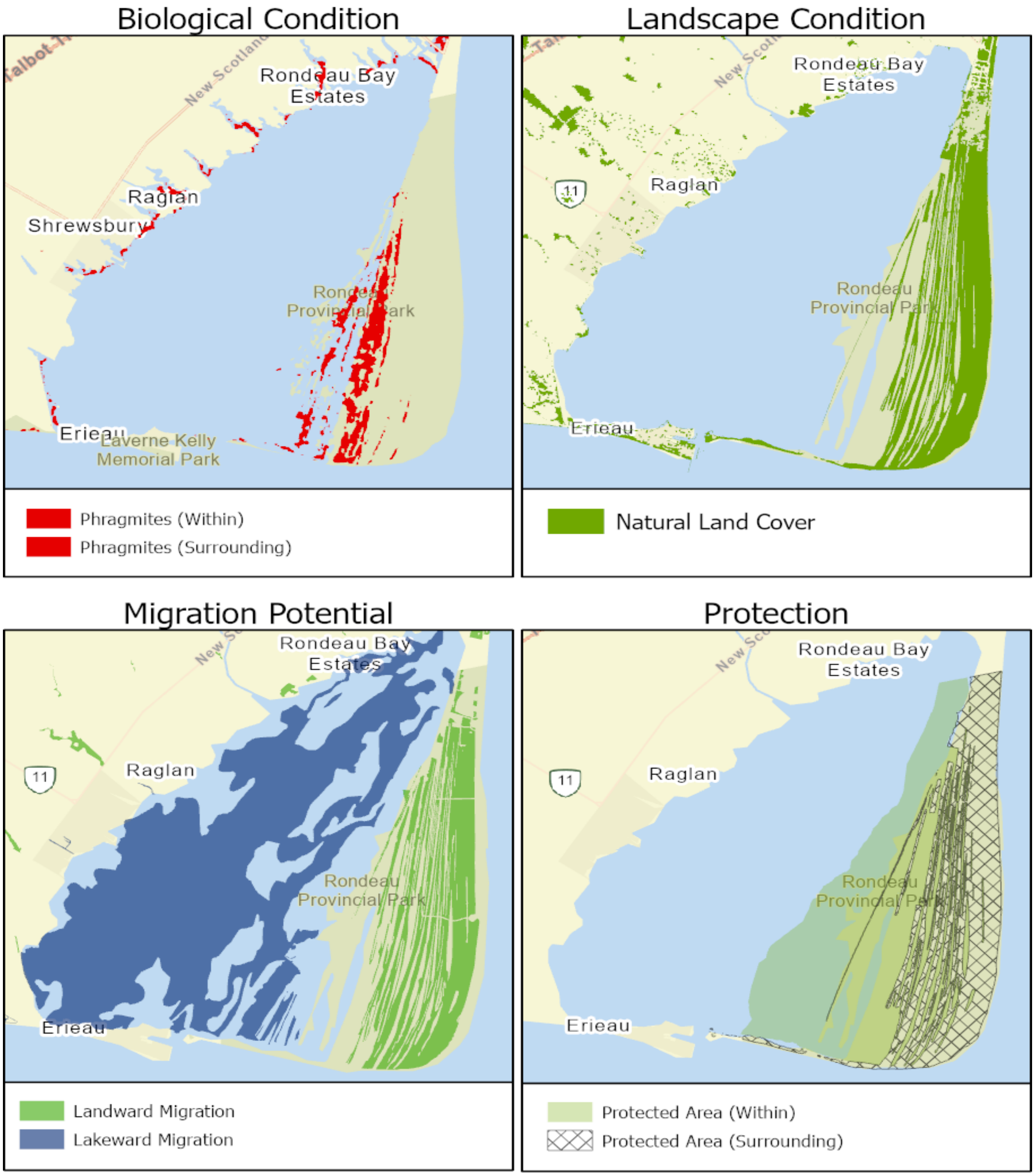

Figure 16. *Examples of spatial map outputs for adaptive capacity sub-indicators for Rondeau Bay, Lake Erie.*

The results of the adaptive capacity analysis show that the lowest scoring wetland sites are located in Lake St. Clair, Detroit River, and western Lakes Erie and Ontario (Figures 17 and 18, Table 10). These deltaic and open shoreline coastal wetlands scored mid to high for migration potential, but poor for biological condition, landscape condition, and protection.

Wetland study sites with a moderate adaptive capacity score are found across all Great Lakes and connecting channels. These sites did not reflect the same underlying sub-indicator trends and often had at least two poor to mid-range scoring sub-indicators (Table 10). This suggests that no single sub-indicator was the driving factor behind the moderate adaptive capacity scores and climate adaptation strategies will consequently differ across wetlands.

Wetland sites with a high adaptive capacity score were found across Lakes Huron, Erie, and Ontario (Figure 17, Table 10). Despite relative high adaptive capacity scores, one or more sub-indicator scored in the mid to low range. Lake Huron study sites have relatively high biological condition, and two sites are partially protected by their respective National Parks (Georgian Bay Islands and Fathom Five). However, Treasure Bay and Hay Bay are considered to have moderate to low migration potential due to the bedrock geology hindering the ability to migrate. Long Point, which includes Big Creek and Long Point National Wildlife Areas, has a low landscape condition score. Airport Creek, South Bay and Baie du Doré are unprotected wetlands. Airport Creek and South Bay were the only wetlands on Lake Ontario to receive a high adaptive capacity evaluation. Both have relatively high biological and landscape condition, as well as a relatively high potential to migrate. However, the biological and landscape condition scores are consistent with the east to west water quality and land cover gradient along the north shore (Cvetkovic, Rokitnicki-Wojcik, & Midwood, 2017; Harrison, et al., 2020).

While certain study sites are considered to have a relatively high adaptive capacity, these wetlands can still benefit from adaptation actions that improve overall climate resilience. The adaptive capacity of wetland sites in Lake Huron can be enhanced by addressing protection, migration potential, and landscape condition. Coastal wetlands that received the overall lowest relative biological condition scores in Lake St. Clair and western Lakes Erie and Ontario are a result of the surrounding agriculture and urban impacts and the proportion of invasive *Phragmites* at these sites. The lack of formal coastal wetland protection at many wetland sites illustrates the need for more land securement, which would increase the likelihood of increased vigilance and management action under a changing change.

The final adaptive capacity score represents the theoretical ability for a coastal wetland to adapt to climate change through a relative comparison of the aggregated variables. Categorical scores of high, moderate and low adaptive capacity can assist wetland managers in identifying coastal wetlands with poor adaptive capacity and general resilience to climate change (Figure 18). Additionally, reviewing the underlying sub-indicators and variables that contributed to adaptive capacity can inform the development and prioritization of adaptation strategies and actions.

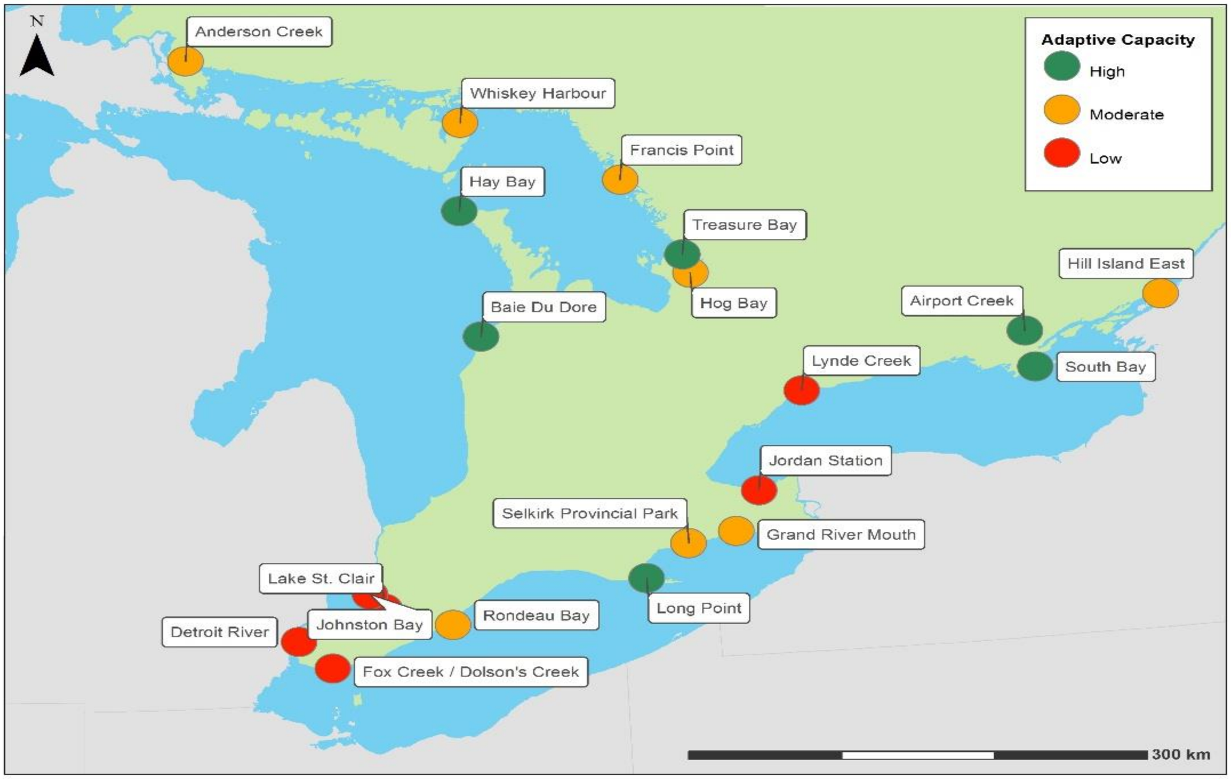

Figure 17. *Adaptive capacity scores and categorizations for coastal wetland study sites. Green reflects high, orange reflects moderate, and red reflects low adaptive capacity categorizations.*

Table 10. *Adaptive capacity sub-indicator scores for coastal wetland study sites, including biological condition, landscape condition, migration potential, and degree of protection.*

Basin	Wetland name	Biological condition	Landscape condition	Migration potential	Protection
St. Marys River	Anderson Creek	0.90	0.74	0.18	0.00
Lake Huron	Baie du Doré	1.00	0.42	0.58	0.00
	Frances Point	0.80	1.00	0.25	0.00
	Hay Bay	0.78	0.94	0.23	0.32
	Hog Bay	0.89	0.57	0.45	0.00
	Treasure Bay	0.97	0.98	0.48	0.50
	Whiskey Harbour	0.96	1.00	0.20	0.00
Lake St. Clair	Johnston Bay	0.21	0.12	1.00	0.00
	Lake St. Clair	0.42	0.00	0.98	0.63
Detroit River	Detroit River	0.26	0.11	0.83	0.00

Lake Erie	Fox / Dolson's Creeks	0.34	0.07	0.35	0.00
	Grand River Mouth	0.46	0.27	0.75	0.00
	Long Point	0.70	0.31	0.85	0.60
	Rondeau Bay	0.64	0.04	0.88	0.84
	Selkirk Provincial Park	0.85	0.11	0.35	0.65
Lake Ontario	Airport Creek	0.86	0.60	0.70	0.00
	Jordan Station	0.56	0.17	0.35	0.00
	Lynde Creek	0.70	0.10	0.48	0.00
	South Bay	0.72	0.57	0.58	0.00
St. Lawrence River	Hill Island East	0.85	0.85	0.10	0.74

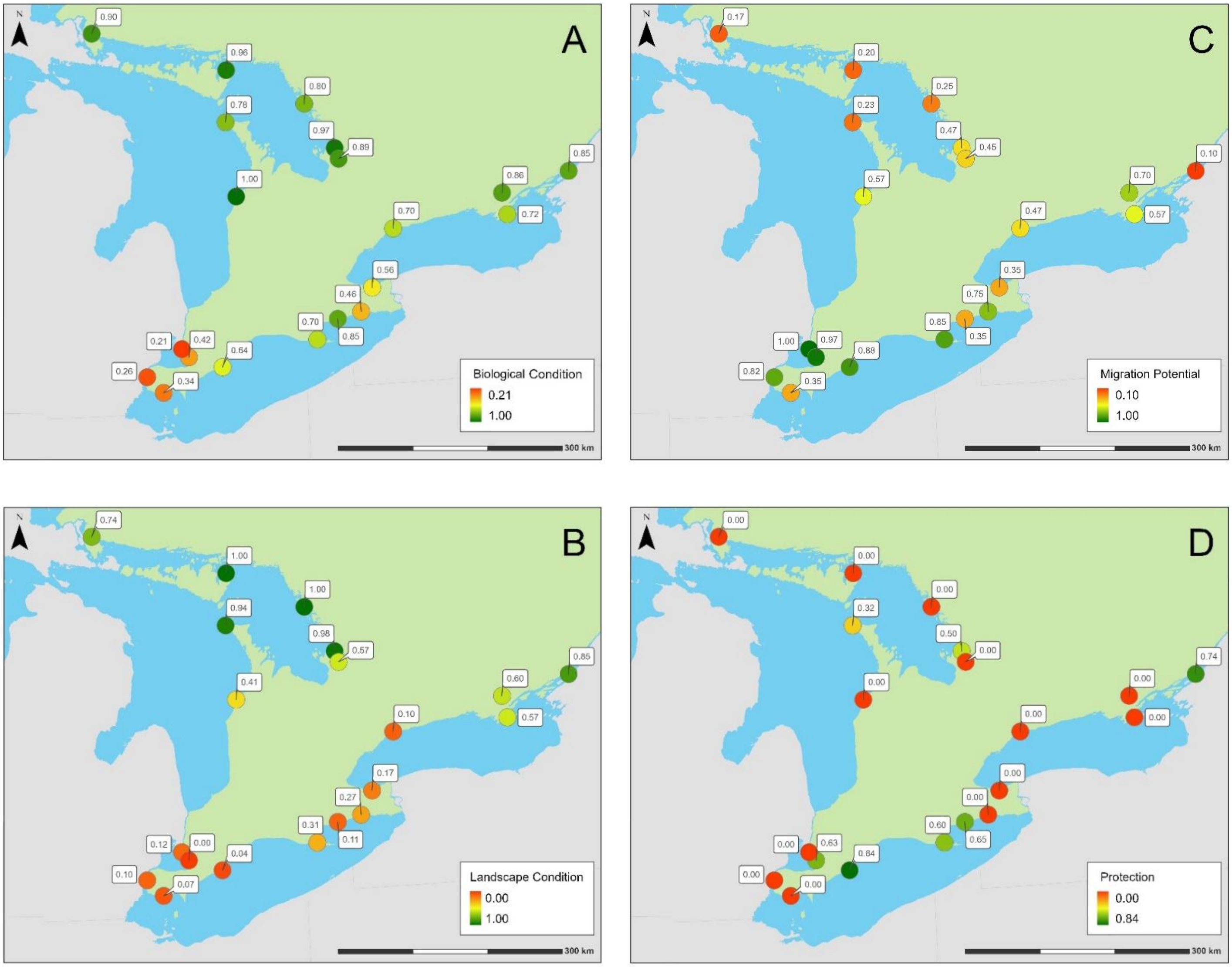

Figure 18. *Adaptive capacity sub-indicators scores for coastal wetland study sites. (A) Biological condition ranged from 0.21 to 1.00), (B) landscape condition (from 0.00 to 1.00), (C) migration potential (from 0.10 to 1.00), and (D) protection (from 0.00 to 0.84). Scores are symbolized using an unclassified continuous colour gradient to identify geographical trends and to establish place-based priorities for supporting climate change adaptation actions. Scores associated with the red end of each gradient (low scores) are expected to decrease the capacity to adapt, thereby increasing vulnerability. Conversely, scores associated with the green end of each gradient (high scores) are expected to have the capacity to adapt and confer resilience to climate change impacts.*

3.0 Coastal wetland vulnerability

This study was the first of its kind for Great Lakes coastal wetland that integrates simulated climate and lake-level projections, the modelled response and sensitivity of wetland plant communities, and measures of coastal wetland adaptive capacity, into a vulnerability assessment of climate change impacts. The assessment organizes a series of sub-analyses into a coherent structure to shed light on key components of vulnerability so that each can be evaluated individually or in combination. The assessment arrives at a five-level series of scores (i.e., very high, high, medium, low, and very low), wherein very high vulnerability results from combining high impact with low adaptive capacity, and low wetland vulnerability results from combining low impact with high adaptive capacity (Figure 21).

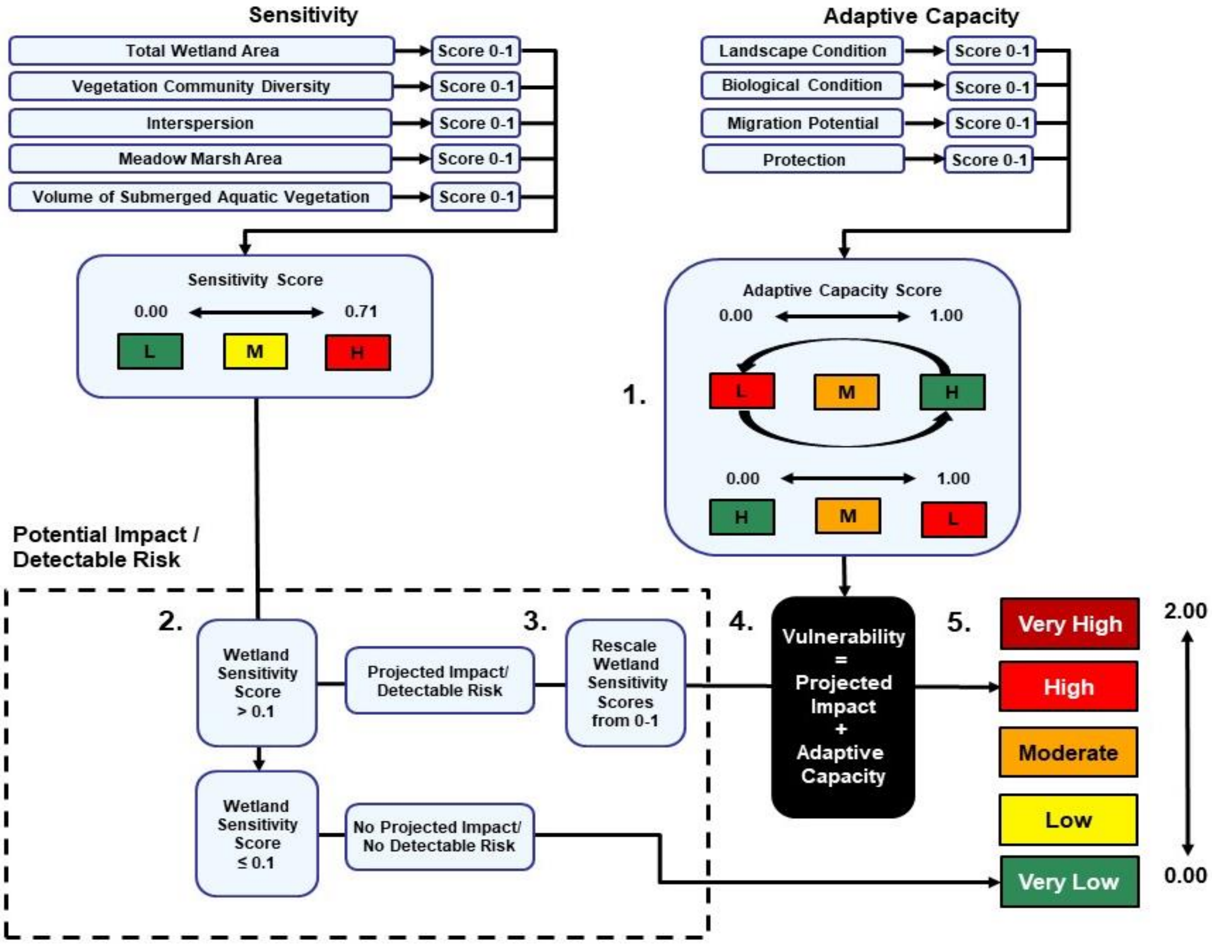

Figure 19. *Great Lakes coastal wetland vulnerability assessment framework: 1) Adaptive capacity scores were inverted for consistent directionality with sensitivity and adaptive capacity indices. (2) Sensitivity scores were rescaled; scores less than or equal to 0.1 were rescaled to zero. (3) Sensitivity scores greater than 0.1 were rescaled from zero to one for equal weighting between the adaptive capacity and sensitivity indices. (4) Site- and model-specific sensitivity and adaptive capacity index scores were combined to arrive at a vulnerability index from 0.00 to 2.00. (5) Using equal intervals, vulnerability index scores were classified into 5 levels of vulnerability: very low (green), low (yellow), moderate (orange), high (red) and very high (dark red).*

3.1 Coastal wetland vulnerability under RCP 4.5 lower-bound scenario

Under the lower-bound RCP 4.5 climate simulation associated with stable or lower lake-level averages, four wetlands scored very low in vulnerability (Figure 21, Table 11). These include Treasure Bay on Lake Huron, Selkirk Provincial Park on Lake Erie, and Lynde Creek and South Bay on Lake Ontario. Each of these wetlands were evaluated as having low sensitivity and no detectable risk across most ecosystem attributes. Treasure Bay and South Bay were considered to have high adaptive capacity, whereas Selkirk and Lynde Creek were considered to have moderate and low adaptive capacity, respectively. Both Selkirk and Lynde Creek scored relatively high for biological condition, but poor landscape condition.

The majority of the wetlands assessed had a low vulnerability score under the RCP 4.5 lower-bound simulation (9 of 20 sites). All nine of these wetlands were moderately sensitivity with most of the measured ecological attributes at risk. Five of these wetlands are found in Lake Huron, including Whiskey Harbour, Hay Bay, Baie du Doré, Frances Point and Hog Bay in eastern Georgian Bay. Notably, Frances Point and Baie du Doré were responsive in terms of wetland loss. Baie du Doré and Hay Bay received a high adaptive capacity score, whereas Whiskey Harbour, Frances Point, and Hog Bay showed moderate adaptive capacity. These wetlands are unprotected, and Whiskey Harbour and Frances Point are limited ability to migrate in response to lake-level changes.

The other four wetlands that received a low vulnerability score were Rondeau Bay and Long Point on Lake Erie, Airport Creek on Lake Ontario, and Hill Island on the St. Lawrence River. Airport Creek and Hill Island East were responsive in terms of wetland loss, and highly responsive in terms of meadow marsh loss. Long Point and Airport Creek showed a high adaptive capacity largely due to their high biological condition and ability to migrate, whereas Rondeau Bay and Hill Island East had a moderate adaptive capacity, due to the relatively poor landscape condition and a limited ability for wetland migration.

Six wetlands showed a moderate climate change vulnerability under the RCP 4.5 lower-bound simulation, including Anderson Creek on the St. Marys River, Johnston Bay on Lake St. Clair, Detroit River, Fox Creek and Dolson’s Creeks, and the marshes at the mouth of the Grand River. With the exception of Anderson Creek, all of these wetlands are located in Lake St. Clair, Detroit River, and Lake Erie. All six wetlands were of moderate sensitivity in terms of a loss of wetland interspersion. None of these locations scored high in adaptive capacity. Anderson Creek and the Grand River marshes had a moderate adaptive capacity. Anderson Creek showed a relatively high biological and landscape condition, a limited ability to migrate, and lack of land protection. Conversely, the Grand River marsh illustrated an ability to migrate, but scored low in landscape condition and land protection. Situated in areas of low elevation relief, Johnston Bay on Lake St. Clair and the Detroit River marshes had a high migration potential, but low landscape condition. Fox Creek and Dolson’s Creek wetlands are unprotected, have a moderate biological condition and migration potential, but poor landscape condition.

Jordan Station was the only coastal wetland considered to be highly vulnerable under the RCP 4.5 lower-bound simulation. This wetland showed a moderate sensitivity, with the plant community diversity and meadow marsh area critically at risk. With poor landscape condition and no formal protection, Jordan Station also scored low in adaptive capacity.

3.2 Coastal wetland vulnerability under RCP 4.5 upper-bound scenario

Under the RCP 4.5 climate simulation associated with higher lake-level averages (upper-bound scenario), Airport Creek on Lake Ontario, was the only wetland that scored very low in vulnerability (Figures 20 and 21, Table 11). This wetland displayed low sensitivity (no detectable risk across all ecological attributes other than meadow marsh area. Airport Creek also scored highly adaptive, given its relatively high biological condition and migration potential.

Five wetlands were assessed as having low climate change vulnerability under the RCP 4.5 upper-bound simulation (Figure 21, Table 11), and all but one are found in Lake Huron (including the St. Marys River). These include Anderson Creek, Frances Point, Treasure Bay and Hay Bay, and South Bay in Lake Ontario. All locations displayed moderate sensitivity with most ecological attributes at risk. Anderson Creek and South Bay exhibited frequent and extreme losses in meadow marsh. Interspersion was highly responsive and considered to be critically at risk in Hay Bay. Treasure Bay, Hay Bay and South Bay are all considered to be highly adaptive, whereas Anderson Creek and Frances Point are considered to be moderately adaptive. All five wetlands scored moderate to high in biological and landscape condition; however, Anderson Creek and Frances Point showed a low migration potential and protection.

Eight wetlands were assessed as having moderate climate change vulnerability under the RCP 4.5 upper-bound simulation (Figure 21, Table 11). These include Hog Bay and Baie du Doré on Lake Huron, Rondeau Bay, Long Point, Selkirk Provincial Park and the Grand River mouth on Lake Erie, Lynde Creek on Lake Ontario, and Hill Island on the St. Lawrence River. Long Point scored high in sensitivity, whereas the other locations were of moderate sensitivity. Total wetland area, meadow marsh area, and interspersion were highly responsive at Long Point and considered to be critically at risk. It should be noted that Long Point is internationally recognized as one of the most important staging grounds on the continent for waterfowl. Several ecological attributes were highly responsive among these wetlands. All but Lynde Creek exhibited frequent and extreme wetland loss. Hill Island exhibited a frequent and extreme loss in plant community diversity, and Selkirk, the Grand River, and Hill Island exhibited frequent and extreme meadow marsh loss. This is expected to reduce ecosystem function and stability for Hill Island, and for all locations, a potential reduction in the amount of foraging and breeding habitat for wetland birds.

The adaptive capacity scores for all wetlands with moderate climate change vulnerability were also highly variable. Baie du Doré and Long Point were considered to be highly adaptive, whereas Hog Bay, Rondeau, Selkirk, the Grand River and Hill Island were moderately adaptive. All locations have relatively high biological condition, but the evaluations for the other sub-indicators varied considerably. The wetlands on Lake Erie are currently considered to have relatively poor landscape condition, and the marshes at the mouth Grand River are not protected. Situated in bedrock geology (Frontenac Arch) with high vertical relief, Hill Island is considered to have a low migration potential. Hog Bay has moderate landscape condition and migration potential, but like the Grand River, it remains to be protected. Lynde Creek scored low in adaptive capacity due to the current poor landscape condition and its unprotected status.

Whiskey Harbour and Jordan Station scored high in vulnerability under the RCP 4.5 upper-bound simulation (Figure 21, Table 11). Whiskey Harbour displayed high sensitivity whereas Jordan Station displayed moderate sensitivity. Several ecological attributes were highly responsive at each site, and considered to be at risk or critically at risk. Both wetlands exhibited frequent and extreme losses in plant community diversity and meadow marsh area. Whiskey Harbour also exhibited frequent and extreme losses in total wetland area. With relatively high biological and landscape condition, Whiskey Harbour is considered to be moderately adaptive and has limited migration potential. Jordan Station is considered to have a low adaptive capacity given it relatively poor landscape condition and that considering it remains to be protected.

Four wetland received very high climate change vulnerability scores under the RCP 4.5 upper-bound simulation (Figure 21, Table 11). These include Johnston Bay located in eastern Lake St. Clair, the Detroit River and Fox Creek/ Dolson's Creek at western Lake Erie. Fox Creek/ Dolson's Creek displayed moderate sensitivity whereas the other three locations displayed high sensitivity. Several ecological attributes were highly responsive at each wetland, and considered to be at risk or critically at risk. All locations exhibited frequent and extreme wetland loss. Johnston Bay and Fox Creek/ Dolson's Creek exhibited frequent and extreme losses in the volume of submerged aquatic vegetation. Johnston Bay, eastern Lake St. Clair both exhibited extreme and frequent losses in plant community diversity and meadow marsh area. The Detroit River exhibited frequent and extreme losses in plant community diversity and interspersion.

All four locations were evaluated as having very high vulnerability with a low adaptive capacity. All have relatively poor landscape and biological condition, and all sites, except portions of the eastern Lake St. Clair shoreline remain to be protected. Johnston Bay, eastern Lake St. Clair, and the Detroit were evaluated as having a high migration potential. However, these evaluations were influenced by the potential of these wetlands to migrate lakeward during low lake-level periods, which were infrequently observed in the RCP 4.5 upper-bound simulation (ECCC, 2022d).

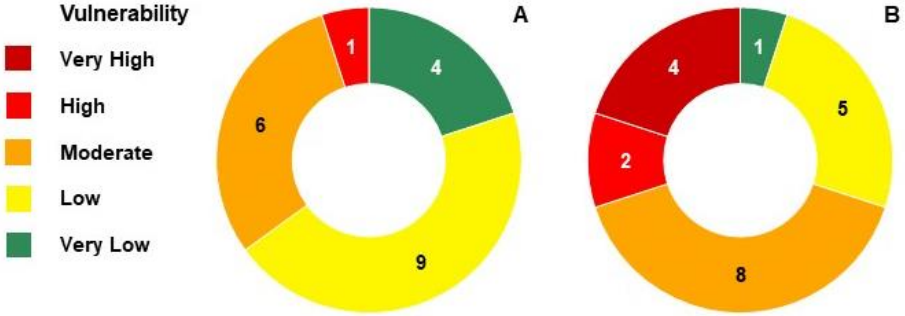

Figure 20. *The proportion of coastal wetlands assessed as having very high, high, moderate, low and very low vulnerability under: (A) the RCP 4.5 lower-bound; and, (B) the RCP 4.5 upper-bound.*

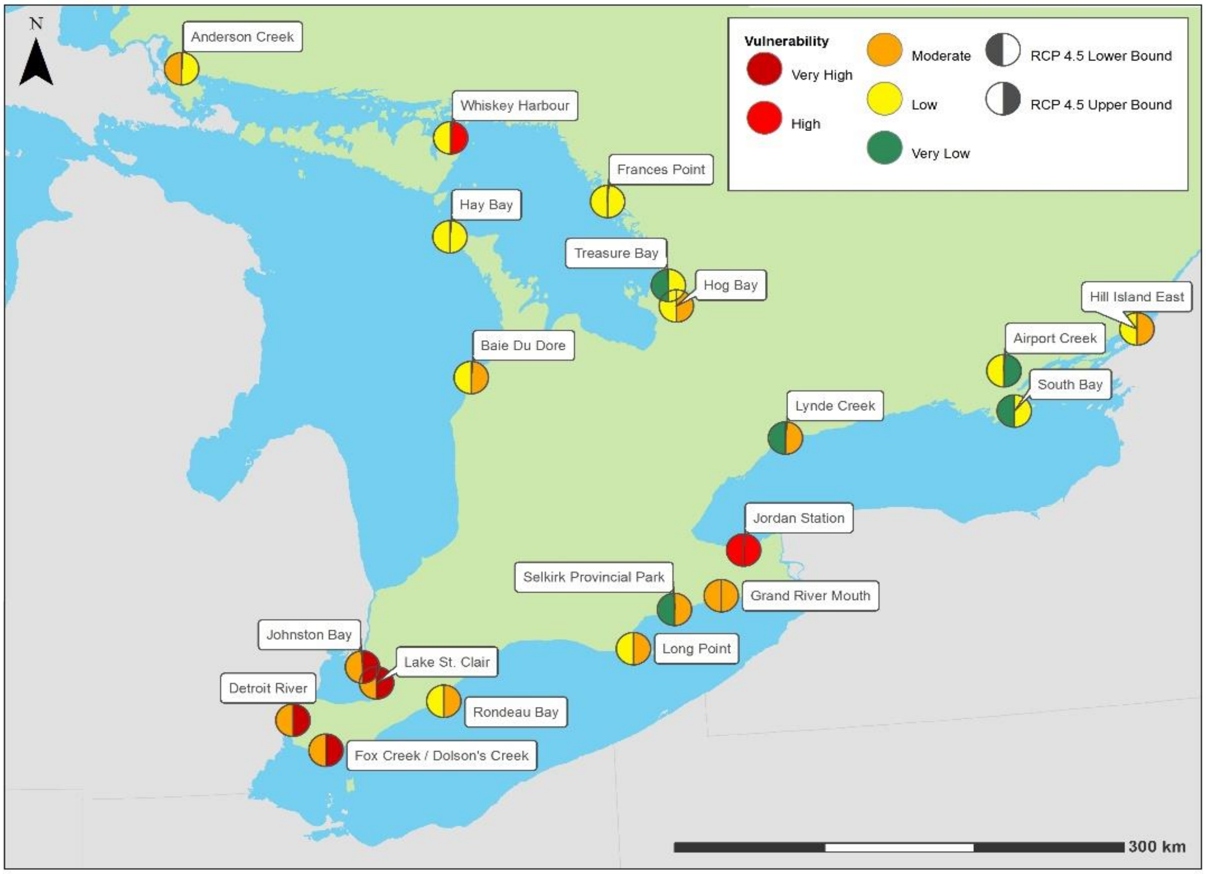

Figure 21. *Vulnerability categorizations for all coastal wetlands assessed. The left-hand side of each point are vulnerability categorizations for the RCP 4.5 lower-bound, and the right-hand side of each point are vulnerability categorizations for the RCP 4.5 upper-bound. Dark red reflects very high vulnerability; red reflects high vulnerability; orange reflects moderate vulnerability; yellow reflects low vulnerability; and, green reflects low climate change vulnerability.*

Table 11. *Vulnerability index scores for all coastal wetlands assessed. Sites are organized by Great Lakes basin and hydrogeomorphic classification following Albert, et al. (2005). Vulnerability occurs on a continuous range from 0.00 to 2.00. Vulnerability scores for each model (very low to very high) were assigned based on the methodology described in Figure 19. Where model-specific vulnerabilities differ, overall vulnerability has been expressed as a range.*

Basin	**Wetland**	**Wetland type**	**Model-specific vulnerability**				**Overall vulnerability**
			RCP 4.5 lower-bound		**RCP 4.5 upper-bound**		
St. Marys River	Anderson Creek	Open Drowned River-mouth	0.77	Moderate	0.54	Low	Low - Moderate
Lake Huron	Baie Du Dore	Open Embayment	0.49	Low	0.81	Moderate	Low - Moderate
	Frances Point	Protected Embayment	0.48	Low	0.55	Low	Low
	Hay Bay	Protected Embayment	0.43	Low	0.40	Low	Low
	Hog Bay	Protected Embayment	0.37	Low	0.73	Moderate	Low - Moderate
	Treasure Bay	Protected Embayment	0.00	Very Low	0.29	Low	Very Low - Low
	Whiskey Harbour	Protected Embayment	0.51	Low	1.29	High	Low - High
Lake St. Clair	Johnston Bay	Delta	0.81	Moderate	1.71	Very High	Moderate - Very High
	Lake St. Clair	Open Shoreline	1.04	Moderate	1.95	Very High	Moderate - Very High
Detroit River	Detroit River	Open Shoreline	0.88	Moderate	1.76	Very High	Moderate - Very High
Lake Erie	Fox / Dolson's Creeks	Barred Drowned River-mouth	1.08	Moderate	1.72	Very High	Moderate - Very High
	Grand River Mouth	Barred Drowned River-mouth	0.69	Moderate	1.05	Moderate	Moderate
	Long Point	Sand-spit Embayment	0.25	Low	1.03	Moderate	Low - Moderate
	Rondeau Bay	Sand-spit Embayment	0.67	Low	0.87	Moderate	Low - Moderate
	Selkirk Provincial Park	Barred Drowned River-mouth	0.00	Very Low	0.91	Moderate	Very Low - Moderate
Lake Ontario	Airport Creek	Open Drowned River-mouth	0.49	Low	0.00	Very Low	Very Low - Low
	Jordan Station	Barred Drowned River-mouth	1.16	High	1.25	High	High

	Lynde Creek	Barred Drowned River-mouth	0.00	Very Low	0.78	Moderate	Very Low - Moderate
	South Bay	Open Embayment	0.00	Very Low	0.62	Low	Very Low - Low
St. Lawrence River	Hill Island East	Protected Embayment	0.55	Low	1.00	Moderate	Low - Moderate

A separate modelling exercise was undertaken to understand climate change impacts on the amount of suitable habitat, and the population growth and expansion, of invasive common reed (*Phragmites australis* subsp. *australis)* and hybrid cattail (*Typha* x *glauca*) (ECCC, 2022b). While the former was addressed using a suitable habitat model, the latter was explained through a population growth model that simulates the impact of invasive species on wetlands. While the results of this modelling were not used in the vulnerability assessment, the future of coastal wetlands under threat from invasive plant species sheds light on adaptation needs. The results are briefly summarized for each lake below, and a detailed description of the methodology and results can are found in a technical report *"Great Lakes coastal wetland response to climate change using a coastal wetland response model (CWRM)"* (ECCC, 2022b).

Higher average lake-levels for the Upper St. Lawrence River and Lake Ontario may favor the expansion of invasive plant species. At higher projected lake-levels, habitat conditions become particularly suitable for *Phragmites*, and is expected to become more abundant than *Typha* by the end of the century. Simulations under both climate scenarios indicate a significant increase in *Phragmites* habitat at all locations except for Jordan Station, with increases up to 150%. Additionally, *Phragmites* expansion could threaten sites where the species is not yet established. Without significant changes in mean lake-level and inter-annual variability, *Typha* will likely remain dominant in Lake Ontario.

Projections under the lower-bound scenario indicate that most sites on Lake Erie will have suitable habitat conditions for even greater *Phragmites* abundance as well as significant *Typha* expansion if the mean lake-levels remain stable or decrease by the end of the century. In Rondeau Bay, the modelling suggests that *Phragmites* invasion is not amplified with a projected water-levels decrease, but rather, it is primarily due to the exponential growth inherent to this competitive species. In contrast, a projected increase in lake-levels would slow the growth of *Phragmites* and *Typha* in this embayment and force upland migration of these species. Johnston Bay wetland in Lake St. Clair shows no response to climatic factors, and *Phragmites* invasion would depend primarily on the extensive natural growth of this plant species. Higher mean water-levels could potentially reduce *Phragmites* and *Typha* expansion in all Lake St. Clair and the Detroit River wetland sites.

The rugged topography of Georgian Bay generally appears less favorable to *Phragmites* and *Typha* invasion than study sites in the Lower Great Lakes. Under the upper-bound climate scenario, a decrease in future *Phragmites* suitable habitat area is projected for sites on Lake Huron, Manitoulin Island, and the St. Marys River. *Typha* suitable habitat area is also predicted to decrease or have no significant changes.

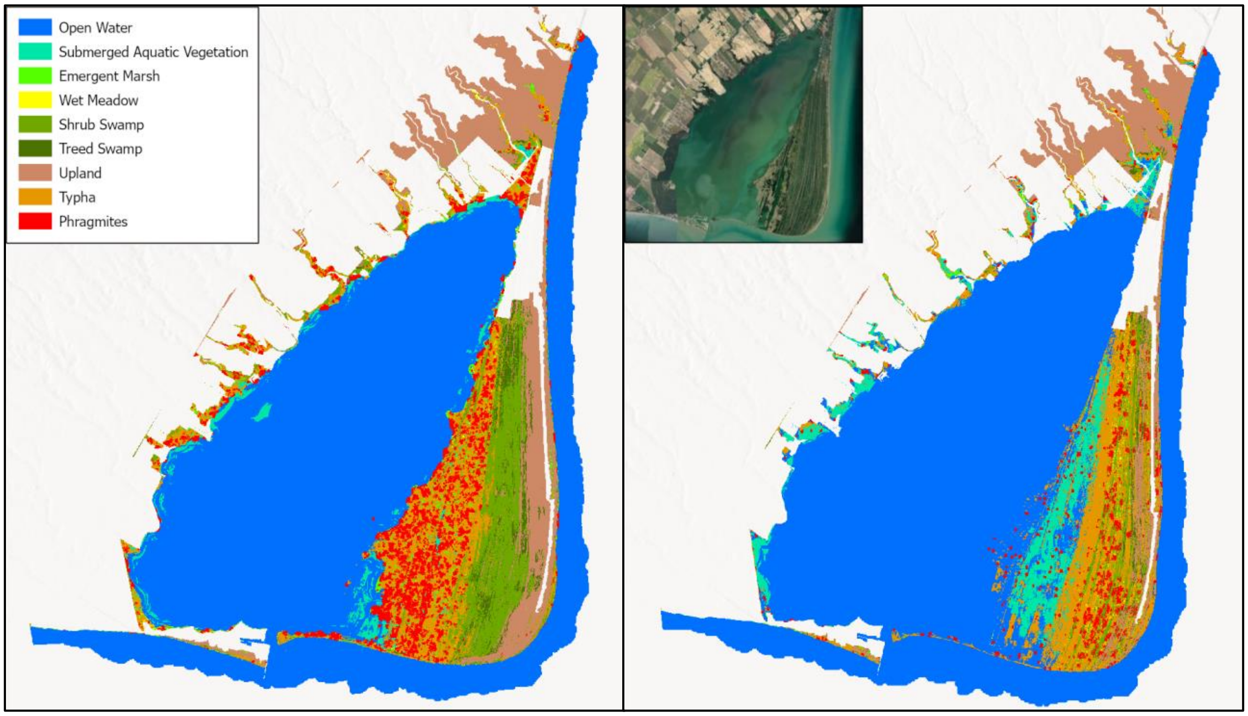

Figure 22. *Example of invasive species model output showing the end of century (2099) spatial distribution of Phragmites (red) and Typha (orange) for a section of the Long Point National Wildlife Management Area under RCP 4.5 lower-bound (left) and upper-bound (right) climate scenarios.*

4.0 Conclusions

Despite the remarkable value of coastal wetlands, they continue to be lost to development and degraded by shoreline alteration, pollution, and invasive species. Climate change intensifies current non-climatic stresses and represents a critical threat to habitat and native species. In this study, Environment and Climate Change Canada scientists used a novel and science-based framework to systematically deconstruct the complexity of climate vulnerability into its constituent components.

Firstly, this assessment confirms that risks to coastal wetlands will increase as the Great Lakes climate warms; and the greater the warming, the greater the risks. Over-land air temperatures are projected to increase significantly compared to the study reference period (1961-2000). Over-lake precipitation is anticipated to increase in all seasons and over time for both climate scenarios (RCP 4.5 and RCP 8.5) and for all lakes. Lake-levels are projected to increase in variability under a changing climate resulting in more extreme highs and lows. Unregulated lakes (i.e., Huron, Erie, and St. Clair) show the greatest variation, with greater variation for Lake Huron, which is consistent with the historical lake-level fluctuations and the large watershed.

Secondly, a coastal wetland response model simulated the spatiotemporal succession of large plant community classes based on the results of water-level modelling under the intermediate greenhouse gas concentration trajectory (RCP 4.5). The model data outputs were foundational to a sensitivity analysis that revealed both high and low lake-levels are projected to have an adverse effect on valued wetland ecological attributes (i.e., total area, meadow marsh area, submerged aquatic vegetation, plant community diversity, and interspersion). All study sites showed sensitivity to projected lake-level changes (to varying degrees) and are therefore considered to be at risk. Coastal wetlands in Lake St. Clair, the Detroit River, and western Lake Erie are highly sensitive and critically at risk, with potentially more frequent instances of future wetland loss than in the past. Frequent instances of wetland loss may be expected with higher lake-level scenarios where the surrounding land use prevents the colonization and landward migration of plant communities. This means that further land development surrounding coastal wetlands will likely exacerbate climate-driven wetland loss.

Thirdly, current natural and anthropogenic factors (i.e., land cover, wetland plant diversity, invasive *Phragmites*, wetland migration potential, and level of land protection) were selected to operationalize the concept of coastal wetland adaptive capacity, or the ability of a wetland in its current state to adjust and cope with changing climate conditions, variability, and extremes. The coastal wetlands with the lowest relative adaptive capacity scores are located in eastern Lake St. Clair, the Detroit River, and western Lakes Erie and Ontario. Coastal wetlands in this region were characterized as having a high migration potential but scored poorly for protection, biological condition, and landscape condition.

Lastly, this assessment was the first of its kind for Great Lakes coastal wetlands that integrates climate-driven lake-level projections, modelled wetland plant community responses, wetland sensitivity, and coastal wetland adaptive capacity into a vulnerability assessment framework to understand possible climate change impacts. Under the lower-bound scenario associated with future stable or lower lake-levels, 13 of the 20 coastal wetlands were evaluated as having low or very low vulnerability, six wetlands were considered to have moderate vulnerability, and one wetland was ranked as having high vulnerability. In contrast, under a higher lake-level scenario, four wetland sites were evaluated as very high climate change vulnerability, all of which are located in Lake St. Clair, the Detroit River, and western Lake Erie.

Coastal wetland loss represents a reduction in habitat for native wildlife species that require wetlands for a least one part of their life cycle; several of which are undergoing regional population declines, or are listed as federal or provincial species at risk. The cumulative impact of more frequent and extreme wetland loss over time could result in significant wildlife population declines, regional biodiversity loss, and the loss of ecosystem services to nature and the Great Lakes human population. Local loss of coastal wetlands could have disproportionate effects on regional wildlife populations. For example, Long Point and Lake St. Clair are recognized as important stopover habitat for several eastern populations of migratory waterfowl, monarch butterflies, bats, and forest birds. Long Point is projected to lose up to 55% wetland area in some years, placing eastern populations of migratory species at risk.

While there are uncertainties and assumptions inherent in climate projections and ecosystem response modelling, they are necessary to show the general trends, conditions, understand potential impacts, and to guide adaptation planning. The methodology, indicators, and results of this study help to ensure that resource managers and policy-makers are guided by informed decisions so that wetlands can adjust, reassemble, and maintain biodiversity and functionality in the face of climate shocks and disturbance. This vulnerability assessment creates new opportunities for coastal wetland conservation to safeguard the provision of wetland goods and services for the benefit of social, economic, cultural, and freshwater ecosystem outcomes.

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