Approaches for Conducting Vulnerability Assessments in the Great Lakes Basin:

A Review of the Literature

2018

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1.0 Executive Summary

Climate change and climate variability have potential serious implications for water quality and ecosystem health of the Great Lakes. While there is no consensus on how to measure the vulnerability of Great Lakes ecosystems to climate change, a variety of methods have been developed and applied by scientists over the past several decades.

A binational literature review and analysis of 22 climate change vulnerability assessments spanning the past 10 years was conducted to report on the approaches, tools, and methods used to assess the vulnerability of ecosystems in the Great Lakes Basin to climate change. Included in a section on observations and recommendations are examples of best practices, limitations, advantages, and other considerations of the approaches, methods and tools as discussed in the literature. This report also includes a case study demonstrating the development and application of a method for assessing vulnerability at the scale of local watersheds in the Arctic.

The findings of the literature review suggest that while there are common components and frameworks used in the approaches to assess vulnerability, a combination of methods were applied and varied substantially depending on the ecosystem scale and research objectives. Most often, researchers used a multidisciplinary approach that typically involved a combination of modeling (climate models, biophysical models, and/or both); primary research (field work); secondary research (literature reviews); development of, or application of existing indicators; and/or expert knowledge and consultation. An overview of key findings are found in Figure 1.

This report establishes a list of 'themes' (see Section 6.2) to help readers identify information of particular interest on assessing vulnerability in the GLB. The findings of the review show that 20 of the 22 studies focused on more than one theme for their vulnerability assessments, with the exception of Stewart et al. (2016) (Habitats and Species only) and Rempel and Hornseth, (2017) (Habitats and Species only). Nineteen of the 22 reports explored the vulnerability of Habitats and Species, while the theme with the least focus was Toxic Chemicals at only three studies (Tu et al. 2017, Crossman et al. 2017, and Carlson Mazur et al., 2014).

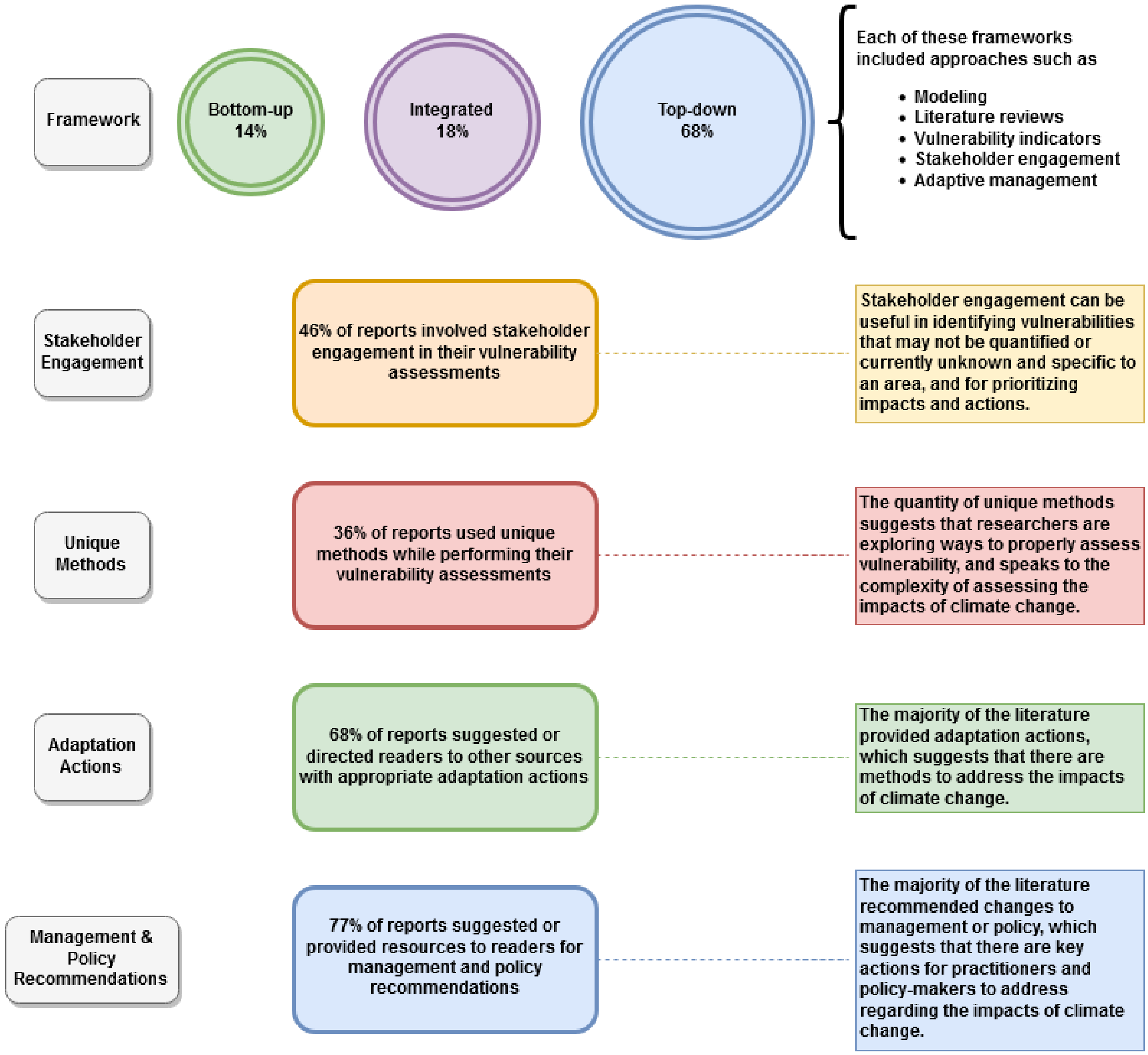

Figure 1: Overview of key findings

This report does not recommend or endorse any particular approach or process to conducting a vulnerability assessment in the Great Lakes Basin or elsewhere. It also does not offer recommendations or best practices except for those suggested by the authors of the literature reviewed. Readers interested in a more detailed summary of the studies are encouraged to refer to the original studies and/or review the Vulnerability Assessment Literature Review spreadsheet.

The following is a list of additional findings of the literature review:

- The geographic scales of study included 10 studies that took place in the U.S. and 10 in Canada, and two studies were binational (U.S. and Canada). The ecosystem scales varied considerably, ranging from studies on groundwater, streams, and/or watersheds, to studies that are basin-wide.
- Project affiliations were diverse, including academic institutions; provincial, federal, and state government agencies/departments; conservation authorities; scientific research centers; and non-profit organizations. The Ontario Ministry of Natural Resources and Forestry was the most frequent project affiliation (a total of five projects).
- Fifteen of the 22 studies used a top-down approach, an approach that analyzes scientific data to quantify current and future physical vulnerability; three used a bottom-up approach, an approach that applies socio-economic indicators to assess adaptive capacity and social vulnerability; and four applied an integrated approach, a combination of the top-down and bottom-up approaches.
- While the majority of the studies developed their own methodology, three studies we reviewed used the NatureServe Climate Change Vulnerability Index (CCVI) tool and three used an adaptive management framework.
- A unique method is defined as a method, tool, approach or characteristic of the study that is not used in more than one study. A select number of studies, 8 of 22, applied a unique method when performing vulnerability assessments. For instance, while many studies used short and long-term future time periods (i.e. 2011-2040, 2041-2070, and 2071-2100) for climate analysis, Crossman et al. (2013) was the only study to apply shorter 9-year time periods (i.e. 2021–2029, 2031–2039, 2061–2069 and 2091–2099) for their climate projections.
- Indicators are used to make the theoretical concept of vulnerability operational and thereby assessing vulnerability. The results of the literature review found that 16 of the 22 studies applied the use of ecological or socio-ecological indicators as a measure of quantifying vulnerability.
- The provision of observational and future climate conditions formed essential components of all 22 studies reviewed. Overall, data from observations and statistical records proved important for understanding ongoing trends and key processes within ecosystems. Historical and baseline climate information formed the basis of the studies' research on climate impacts and were applied for various specific purposes (e.g. as a reference for future climate projections, calibrating and validating models, and assessing historical impacts and trends). The majority of the studies used periods of 30 year durations, which is consistent with the World Meteorological Organization (WMO) guidelines for climatological analysis. Seventeen studies undertook their own climate modeling, while five incorporated the results of climate projections sourced from secondary literature (e.g. Tu et al. 2017 used projections from Auld et al. 2015).

- Stakeholder engagement was undertaken in 10 of 22 studies, which all varied in the extent of stakeholder involvement and purpose (e.g. throughout entire project length, to define the scope of the project, and/or validate findings).
- Thirteen studies quantified adaptive capacity of either the biophysical and/or social aspects of the system in focus. Adaptive capacity is a component of the vulnerability scoring used in NatureServe's CCVI and was therefore automatically included in the studies that used the tool.
- Fifteen of the 22 pieces of literature included suggestions on potential adaptation actions to climate change. This indicates that vulnerability assessments are useful for identifying and prioritizing adaptation actions for species or biotic communities of concern in the GLB.
- Most of the literature (18 of 22) also recommended ways to incorporate climate change into management and policy actions to improve the resiliency of the GLB. Ultimately, for the GLWQA Annexes, mainstreaming has the potential to result in co-benefits that include more transparent decision-making; better cross-annex collaboration; increased awareness on climate risks; changed perceptions; efficient use of resources; and improved decision-making (Benson et al., 2014). Furthermore, driving climate change decisions through opportunities within existing policies, plans and programs helps to avoid trade-offs between climate change adaptation and the objectives of the Agreement.
- A number of authors reflected on the advantages and/or limitations of their approaches, techniques, and overall process. Section 7.0 'Observations and Recommendations', includes best practices, limitations, and general lessons as reflected on by the authors. For example, Herb et al. (2016) observed key benefits to resource managers by applying a layered approach to stakeholder engagement. They noted that one-on-one interviews provided the opportunity for open-ended observations about the connection between research and science. The formal and informal presentations of research – at a symposium and in workshops – provided opportunities to learn and critique research. And finally, the interaction portion of the workshop provided informed feedback about how the research would provide managers critical information.

Overall, the diverse applied methodology for assessing climate change in the GLB reflects that there is a lack standardization of vulnerability assessments which would be useful when connecting and comparing results in similar locales (i.e. the Great Lakes Basin). In sum, researchers are exploring new ways to assess vulnerability, which alludes to the idea that vulnerability assessments are still in their infancy in the context of the GLB.

2.0 Report Purpose and Background

The purpose of this report is to inform the development and implementation of vulnerability assessments by members of the Great Lakes research community, resource managers, practitioners and decision-makers. The information provided in this report is intended to increase understanding of the various types and approaches available when undertaking a vulnerability assessment in the Great Lakes, including commonalities or differences in approaches, processes, frameworks, methods, tools, models (e.g. species, hydrological, climate), data, and other aspects complementary or supportive of undertaking a vulnerability assessment.

This report also contributes to and informs the implementation of the Canada-U.S. Great Lakes Water Quality Agreement (GLWQA). The GLWQA, first signed in 1972, was amended in 2012 to better identify and manage current environmental issues. A Climate Change Impacts Annex (Annex 9 to the Agreement) was added at that time in recognition of the observed and potential magnitude of impacts to water quality in the Great Lakes basin caused by climate change.

Through the GLWQA, Canada and the U.S, in cooperation and consultation with other levels of government, Indigenous peoples, non-governmental entities and the public, work to restore and protect Great Lakes water quality and ecosystem health. The 2012 GLWQA includes commitments to both short-term and long-term action; enhances transparency and accountability; reflects current knowledge and understanding; and focuses on anticipating and preventing new problems.

The Agreement is organized by 10 issue annexes: Areas of Concern; Lakewide Management; Chemicals of Mutual Concern; Nutrients; Discharges from Vessels; Aquatic Invasive Species; Habitat and Species; Groundwater; Climate Change Impacts; and Science. Climate change is a cross-cutting issue across all Annexes. We know, for example, that climate change impacts and exacerbates other stressors to the Great Lakes. The purpose of the Climate Change Impacts Annex is in part to support the objectives of the other Annexes to better understand and address the implications of climate change on the work of their Annex.

The Climate Change Impacts Annex, through its Sub-committee, coordinates efforts to identify, quantify, understand, and predict the climate change impacts on the quality of the Waters of the Great Lakes. This information is shared with Great Lakes resource managers who are proactively addressing these impacts while implementing the Agreement through their respective domestic programs.

One of the key commitments of this Annex is the development and improvement of analytical tools to understand and predict the impacts, and risks to, and the vulnerabilities of, the quality of the Waters of the Great Lakes from anticipated climate change impacts.

The Parties to the GLWQA (Canada and the U.S.) identify binational priorities for science and action every three years in consultation with the Great Lakes Executive Committee, to address current and future threats to the quality of the Water of the Great Lakes based on an evaluation of the state of the Great Lakes, input received during the Great Lakes Public Forum and recommendations of the International Joint Commission.

The 2016-2019 priorities for science and action includes a commitment to "identify key areas across the issues of the GLWQA where consideration of climate change needs to be considered and integrated into issue strategies and actions". Discussions about this priority during the Annex Subcommittee calls led to the development of this report for the purpose of both informing efforts of other GLWQA Annex Subcommittees to assess climate related vulnerabilities related to their Annex, and providing information to resource managers and decision makers across the basin.

3.0 Introduction

The Laurentian Great Lakes of North America form the largest group of freshwater ecosystems on Earth spanning two Canadian provinces and eight states in the United States (U.S.). Together the Great Lakes contain nearly 20% of the planet's freshwater and provide important ecosystem services to one-tenth of the population of the U.S. and one-quarter of the population of Canada (Beeton et al. 1999; Collingsworth et al. 2017). The Great Lakes consist of five different bodies of water, including Lake Superior, the second largest lake in the world by area; Lake Michigan, the largest lake in the world that is entirely within one country; Lake Huron; Lake Ontario; and Lake Erie (Figure 2).

Figure 2: Map of the Great Lakes St. Lawrence River Basin (Angel and Kunkel, 2010)

More than 30 million Americans and 10 million Canadians live within the Great Lakes drainage basin and approximately 4000 species of plants and animals call this region home.

The Great Lakes directly support significant hydroelectric generation, shipping, agriculture, fishing, tourism and recreation industries. These and other industries in the Great Lakes region generate $6 trillion annually - equivalent to 30% of the economic output of Canada and the U.S. combined. In fact, this system represents an economy so large that if the Great Lakes Region were a country, it would have the 3rd largest economy globally behind only the U.S. and China.

The Great Lakes region is part of the region's physical and cultural heritage. Residents depend on them for drinking water, recreation, transportation, power and economic opportunities. Yet, the demands of a large population in this region have taken their toll over time. The impacts of industrialization, climate change, invasive species and toxic contaminants, among other pressures, are evident. Continued action is key to the future economic prosperity and health of Canadian and U.S. citizens.

4.0 Background

4.1 Climate Change Impacts on the Great Lakes Basin

In recent decades, climate change impacts across the GLB have generally consisted of higher temperatures, increased precipitation, reduced snow cover, decreased annual lake ice coverage, increased wind speeds and waves, and an increased amount of extreme events (e.g. snow storms, ice storms, thunderstorms, hail storms, high wind speed events, etc.) (Assel et al. 2003; Austin and Colman 2007, 2008; Ghanbari and Bravo 2008; Gronewold et al. 2013; Hofmann et al. 2008; Sellinger et al. 2007; Wang et al. 2012; Wilcox et al. 2007; Wang et al. 2017). These changes have implications for the physical, chemical, and biological processes in the Great Lakes, which have the potential to affect the overall quality of water and thus can be detrimental to habitat, wildlife, and human health, as well as the economy. For example, warmer surface and lake temperatures can provide welcoming conditions for non-native aquatic and terrestrial species, creating the potential to become invasive and outcompete native species. A similar change in lake temperatures can lead to water quality degradation by facilitating the formation of algal blooms. If combined with increased runoff, this can cause hypoxic environments for fish and benthic dwellers (Paerl et al. 2016; Butcher et al. 2015). Increasing air temperatures and altered precipitation patterns can further alter the timing and magnitude of runoff and soil moisture, and can change lake levels and groundwater availability (Gleik, 1989; Taylor et al. 2013). These physical changes have cumulative impacts that can ultimately affect the quality of water in the Great Lakes (IJC, 2017).

The impacts of climate change on water quality in the GLB are becoming a growing concern for resource managers and policy makers as changing climate and hydrological regimes have the potential to influence the success of management strategies (Murdoch et al., 2000). In order to effectively address climate change and retain the quality of water in the GLB, researchers and resource managers must work together through existing mechanisms, such as the Great Lakes Water Quality Agreement, to develop appropriate adaptation strategies.

4.2 Purpose of Vulnerability Assessments

In accordance with the Intergovernmental Panel on Climate Change (IPCC)'s definition, this report recognizes 'vulnerability' as the degree to which a system is susceptible to, or unable to cope with, the adverse effects of environmental change. Vulnerability is a theoretical concept and there is no current consensus on how to measure vulnerability to climate change. The vulnerability of a natural and socio-economic system can be determined by the character, magnitude, and rate of a threat's development, but also by the system's sensitivity, exposure, and adaptive capacity (Figure 3) (IPCC, 2001).

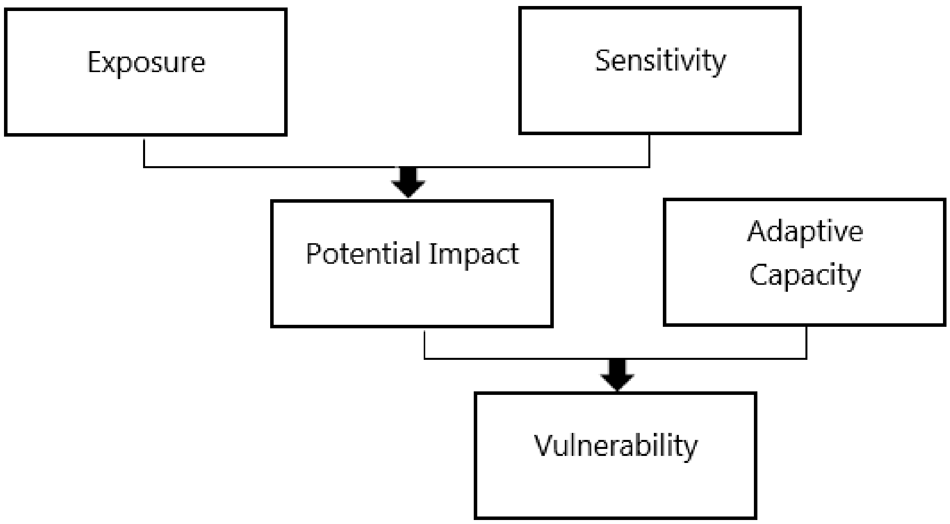

Figure 3: The relationship between vulnerability and its defining concepts (recreated from Glick et al. 2011)

In the context of climate change, vulnerability is the degree to which geophysical, biological and socio-economic systems are susceptible to, and unable to cope with, adverse impacts of climate change (Füssel and Klein, 2006). Vulnerability may then also refer to the vulnerability of a system itself, the impact of the system, or the mechanism causing these impacts (IPCC, 2007).

Vulnerability assessments are a key tool for informing climate change adaptation planning and enabling stakeholders to make informed decisions (Lemieux et al. 2014). According to Gleeson et al. (2011), vulnerability assessments can support adaptation planning by:

- Identifying areas most likely to be impacted by projected changes in climate;
- Building an understanding of the indicators that define these areas as vulnerable, including the interaction between climate change, non-climatic stressors, and cumulative impacts;
- Assessing the effectiveness of previous coping strategies in the context of historic and current changes in climate; and
- Identifying target adaptation measures to systems with the greatest vulnerability.

5.0 Methodology

5.1 Scope of Review

A review of published and grey literature on existing vulnerability assessments of the GLB was conducted between August and December 2017. The literature review identified source materials spanning the previous 10 years. Key word chains were applied (e.g., climate change, GLB, vulnerability, assessments, impacts, water quality, etc.) to identify candidate materials. Material was also elicited through 'a call for literature' to members of the Annex 9 (Climate Change Impacts) committee and subcommittee for literature. Documents were selected on the basis of the reviewer's assessment of the abstract or summary. Emphasis was placed on a review of literature in Canada and the United States. Other significant or relevant bodies of water that are connected to the Great Lakes were also included (e.g. Lake Simcoe, Georgian Bay, Lake St. Clair, Nipigon River, St. Lawrence River). The literature review included vulnerability assessment frameworks, tools, approaches and techniques, and management approaches related to adaptive actions. Elements of characterizing and measuring vulnerability of water quality were also included, such as aquatic habitats, nutrients, invasive species, pollution, freshwater ecosystems, watershed, and coastal wetlands. Literature with research topics that included a focus on human systems (e.g. built infrastructure), land use, and non-aquatic species and habitats (e.g. forest cover), were only included in this report if the research clearly demonstrated how these variables impact water quality.

5.2 Compiling the data: approach and supporting material

Upon review of each piece of literature, observations were compiled into the Vulnerability Assessment Literature Review Excel spreadsheet to summarize and compare the results of the information. The spreadsheet was used to extract similarities and differences in processes, approaches and frameworks applied in vulnerability assessments conducted in the Great Lakes Basin.

This report was initially set out to be formatted according to the research themes (see Section 5.3) as to support the interests of each Annex. However, the nature of the results of the research themes by studies (i.e. multiple themes per study; see Section 6.2) indicated considerable overlap and this format would have made for redundancy.

This report does not recommend or endorse any particular approach or process to conducting a vulnerability assessment in the Great Lakes or elsewhere. It also does not offer recommendations or best practices except for those suggested by the authors of the literature reviewed. Readers interested in a more detailed summary of the studies are encouraged to refer to the original studies and/or request a copy of the Vulnerability Assessment Literature Review spreadsheet. For interest, Table 1 provides a description of the contents of each section found in the spreadsheet.

Table 1: Overview of sections in the 'Vulnerability Assessment Literature Review' Excel spreadsheet

Section	Description
1.0 Literature Overview	An overview of major project aspects, components and methods.
2.0 Themes	A list of themes and corresponding research focus of each study. The themes were selected in consideration of the nine Great Lakes Indicators of Ecosystem Health described in the State of the Great Lakes 2017 Highlights Report. They also align with the 10 Annex groups in the GLWQA. Sub-indicators were matched with their most appropriate theme (e.g. forest cover is an observable or indicating variable of water quality but also of habitats and species). The report is available at: https://binational.net/wp-content/uploads/2017/06/SOGL_17-EN.pdf
3.0 Tools and Methods	A comparison of the various tools and methods used in the literature to assess vulnerability. It compares indicators, vulnerability indices, climate data and projections, data and other models, and stakeholder engagement.
4.0 Management and Policy: Mainstreaming Climate Change Adaptation	Examples from the literature of actions to incorporate climate change into management actions and policy. The "areas" of management actions and policy were organized around the themes of Organizational Readiness outlined in Gray, 2012. The report by Gray, 2012 provides a framework that practitioners can use to assess their respective organizations' readiness to adapt to the effects of climate change. Paper: Gray, P.A. 2012. Adapting Sustainable Forest Management to Climate Change: A Systematic Approach for Exploring Organizational Readiness. Canadian Council of Forest Ministers, Ottawa, Canada. 31p. Available at: http://www.ccfm.org/pdf/Gray_OrganizationReadiness_FinalEng.pdf
5.0 Lessons Learned	An overview of the limitations, benefits, disadvantages/advantages as discussed in the literature.

The spreadsheet contains additional detailed information from the literature, including:

- Recommended adaptation actions and measures
- Unique approaches adopted in the methodology
- Extent of stakeholder consultation
- Evaluation of adaptive capacity (yes/no)
- Project support/affiliation
- Geographic area of study
- Ecosystem/water body of study
- Tools and methods
    - Use of indicators
    - Data and other models
    - Climate data/projections
    - Use of maps/surveys
    - Use of literature
    - Vulnerability scoring method
    - Other relevant tools and methods

> To receive a copy of the spreadsheet, please contact:
>
> Ontario Centre for Climate Impacts and Adaptation Resources
> www.climateontario.ca

5.3 List of Themes

The vulnerability assessment literature review was undertaken to support the purpose of Annex 9 (Climate Change Impacts) that is to contribute to the achievement of the General and Specific Objectives of the GLWQA, and to consider the role of Annex 9 in supporting matters of interest to the other Annexes. As such, this report establishes a list of 'themes' to help readers identify information of particular interest to their Annex on assessing vulnerability in the GLB.

The list of themes in this report was developed by combining the objectives of the 10 Annexes set out in the GLWQA with nine science-based ecosystem indicators used to assess the most recent status and trends of the Great Lakes basin in the State of the Great Lakes 2017 report (SOGL) (Figure 4). The governments of the U.S. and Canada, together with their many partners in protecting the Great Lakes, have agreed to a set of nine indicators of ecosystem health supported by 44 sub-indicators. The list of themes developed for this report excludes socio-economic, non-aquatic, or terrestrial components of the GLB (e.g. population growth, urban sprawl), as these are not areas of focus in the GLWQA Agreement. To avoid overlap or redundancy, some annex topics and State of the Lakes Ecosystem Conference (SOLEC) indicators are represented in the list of themes under alternative titles (e.g. 'discharges from vessels' is represented as 'toxic chemicals').

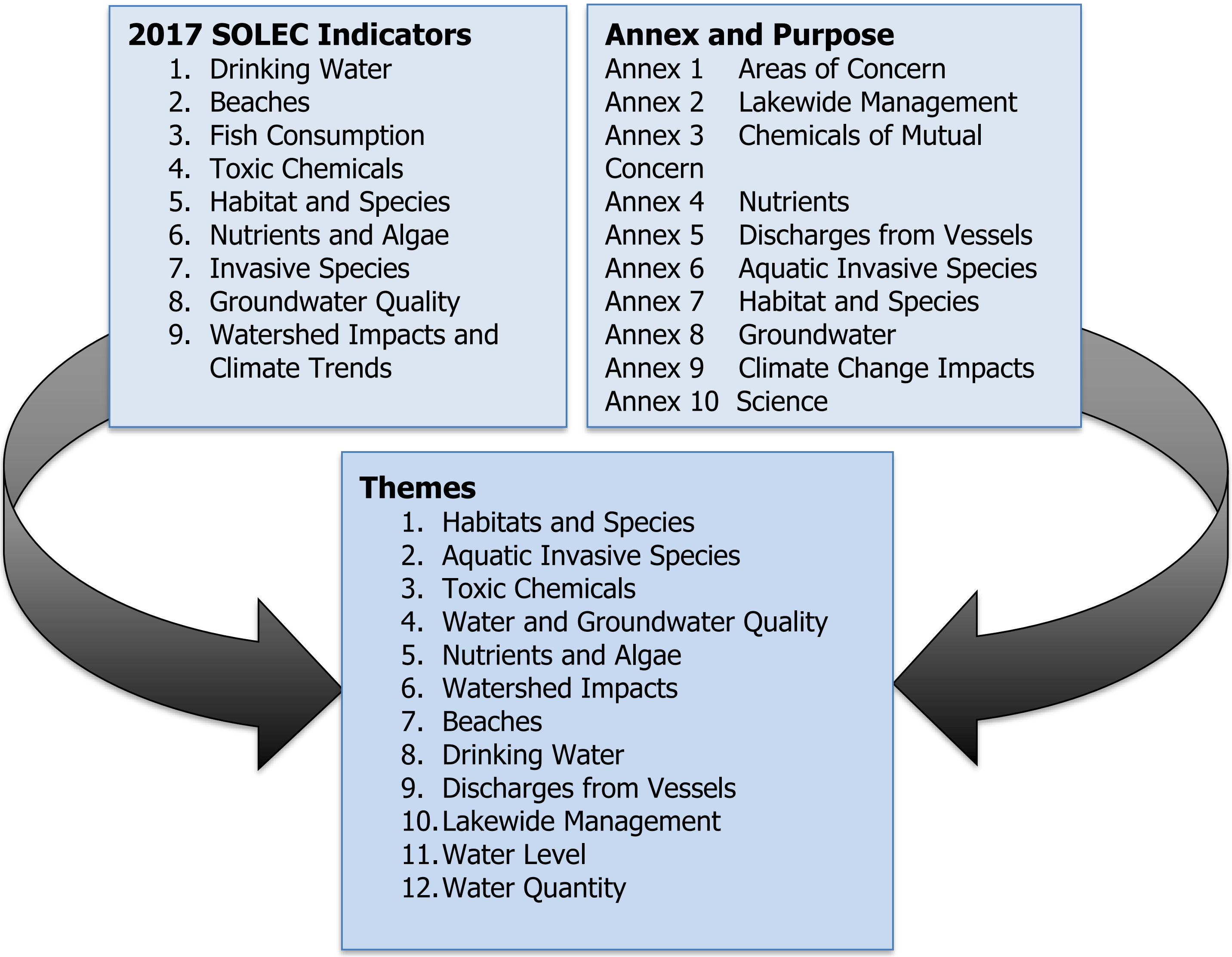

Figure 4: Thematic areas that reflect topics of potential research interest to meet GLWQA obligations

6.0 Results: Overview of Key Findings

Through the literature review, we were able to identify and compare several different components of the vulnerability assessments. Key components included the framework or approach for the vulnerability assessment; extent and use of stakeholder engagement; use of unique methods; recommended adaptation actions; and an analysis of, or recommendations for incorporating climate change into management and policy actions. Please refer to the Glossary of Terms for the defined use of 'stakeholder engagement' in this report.

An illustrative summary of our findings can be found in Figure 1. Refer to Appendix B for a description of each individual study included in the literature review. Overall, the most commonly applied framework for assessing vulnerability of the Great Lakes ecosystem was a top down approach (See Box 1). However, most often, the frameworks and approaches differed and the researchers often used a multidisciplinary approach that typically involved modeling (climate models, biophysical models, and/or both); primary research (field work); secondary research (literature reviews); development of, or application of existing indicators; and/or stakeholder engagement.

Nearly half (45%) of the vulnerability assessments reviewed relied on or used stakeholder engagement for a variety of purposes, such as to identify vulnerable components of a system or an entire system itself; to determine the overall vulnerability scores/ratings; or provided input into the scope or approach of the studies. Over half of the literature used unique methods when performing vulnerability assessments. Almost three quarters of the literature suggested adaptation actions and changes to management and/or policies. A unique method is defined as a method that stands alone from each of the other studies and were not repeatedly applied. These findings suggest that researchers are still discovering new ways to research vulnerability in the GLB, and while some adaptation actions are taking place, more are necessary to reduce the magnitude of climate impacts. The geographic scope/location of the studies are diverse. Of the 22 studies reviewed, an equal amount of 10 studies were located in the U.S., 10 in Canada and two studies were binational (U.S. and Canada) (Figure 5).

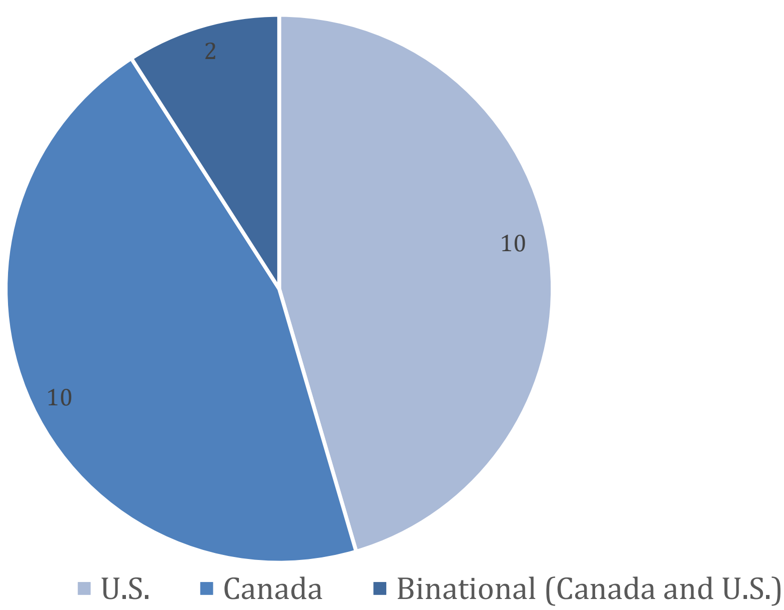

Figure 5: Geographic study areas by country

The studies also ranged at the provincial and state scale. Figure 6 shows the number of studies by state and province.

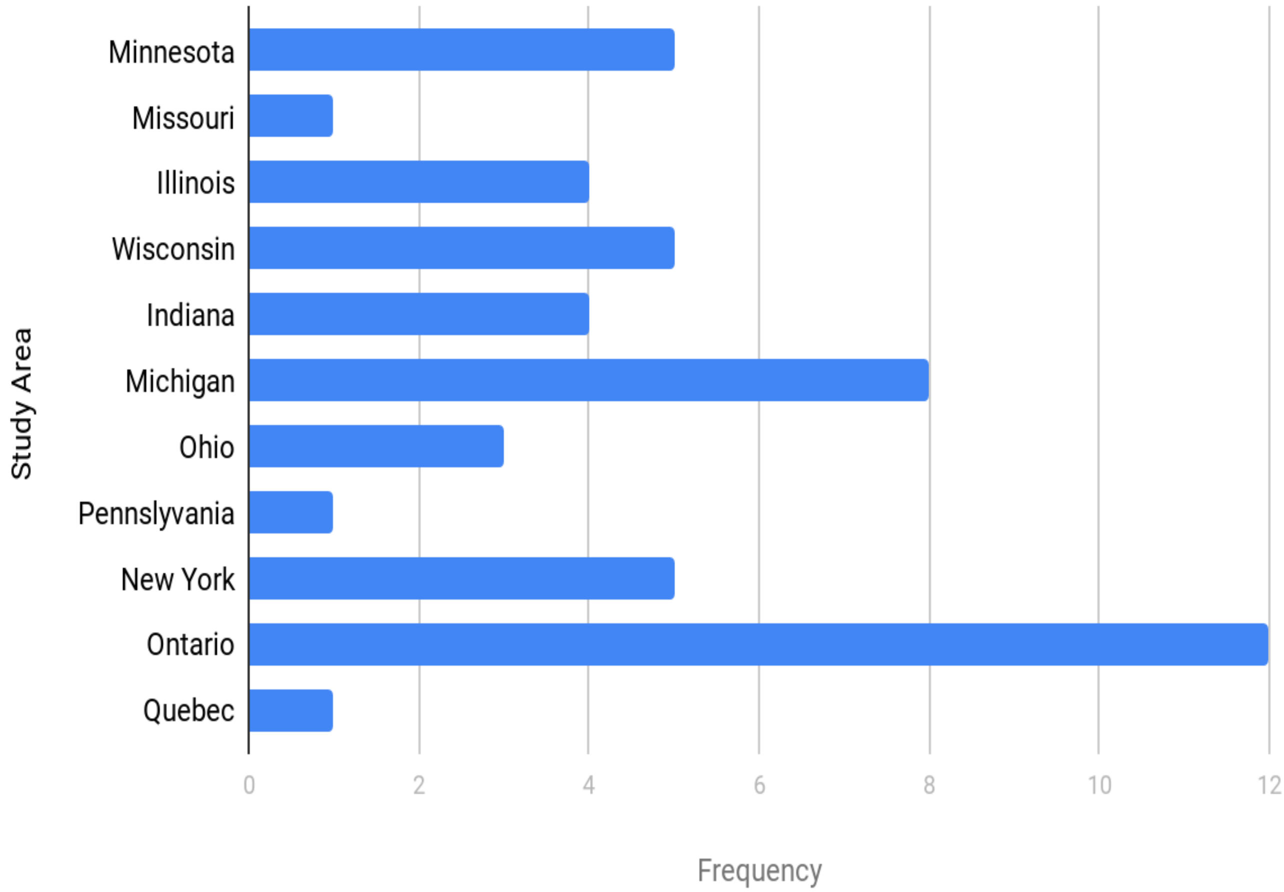

Figure 6: Geographic study areas by state (U.S.) and province (Canada); west to east

Lastly, the water body scales varied considerably; see Table 2.

Table 2: Scales of ecosystems by project name

Project Name	Water Body
Great Lakes water levels	All Great Lakes
Central Hardwoods ecosystem vulnerability assessment and synthesis	Groundwater of GLB
Assessment of suitable habitat for *Phragmites* australis in the Great Lakes coastal zone	Basin-wide, and upper lakes (Lake Superior, Lake Michigan, and Lake Huron) and lower lakes (Lake St. Clair, Lake Erie, Lake Ontario)
Ontario adaptive capacity and climate change assessment	Great Lakes Basin, and other major lakes and tributaries in Ontario
CCVA for aquatic ecosystems in the Clay Belt of Northeastern Ontario	Wetland, stream, and lake ecosystems in the Clay Belt
Great Lakes Basin inland aquatic ecosystems vulnerability assessment	Wetland, stream, and lake ecosystems of each lake basin (Lake Superior, Lake Huron, Lake Erie, Lake Ontario, and the Upper St. Lawrence River.
Lake Simcoe and the wetlands and streams within the watershed	Wetlands and streams in the Lake Simcoe watershed
Climate Change as a long-term stressor for the fisheries in the Great Lakes	All Great Lakes
Future proofing management strategies in the Lake Simcoe watershed	Black River, a tributary of Lake Simcoe
Minnesota Ecological Limits of Hydrologic Alteration study	Minnesota's Lake Superior tributaries (Three watersheds: Knife, Baptism and Poplar)

Vulnerability assessment of 400 species of greatest conservation need and game species in Michigan	Lake Michigan
Michigan Tribal Climate Change Vulnerability Assessment and Adaptation Planning	All GLs touching Michigan (all except for Lake Ontario)
Climate Change Vulnerability Assessment of Natural Features in Michigan's Coastal Zone - Phase 1: Assessing Rare Plants and Animals	Coastal zone (Lake Michigan)
Making of a Watershed-scale CCA Strategy	Lake Simcoe
Lake Simcoe Water Quality/Quantity VA	Lake Simcoe watershed and 18 subwatersheds in Lake Simcoe
GL Coastal Wetland VA	Coastal wetlands on Lake Ontario, Lake Erie, and Lake St. Clair
Binational VA of migratory birds	Great Lakes - St Lawrence Watershed
Climate Change Adaptive Capacity Assessment - Agriculture and Hydrology - Lake Simcoe Watershed	18 subwatersheds in Lake Simcoe
FishVis, Regional Vulnerability Assessment Decision Support Tool	Includes 369,215 kilometers (km) of streams, encompassing a range of thermal conditions, and covering the entire United States Great Lakes Basin, part of the Upper Mississippi River Basin to the west, and part of the Mid-Atlantic Basin to the east.
Natural Systems Vulnerability to Climate Change in Peel Region	Lake Ontario
North Atlantic Coast Comprehensive Study: Resilient Adaptation to Increasing Risk	Atlantic Ocean
Great Lakes Barrens CCVA	Lake Michigan and Lake Superior

6.1 Common Approaches and Frameworks

Most climate change vulnerability assessments that were reviewed followed a top-down approach (e.g. Chu, 2015; Chiotti and Lavender, 2008). In these top-down studies, research tended to concentrate on biophysical effects of climate change that can be quantified, such as water levels, nutrients, and habitat and species loss.

A number of vulnerability assessments reviewed adopted a multi-method adaptation framework approach to assess vulnerability of the Great Lakes ecosystems. Many used an integrated approach and a variety of tools and methods to gather information on historical and projected climate trends, including a combination of literature reviews, field surveys, species modelling, vulnerability indices, climate models, fieldwork, maps, and stakeholder knowledge and expertise (e.g. Mortsch et al. 2006). For example, Lemieux et al. (2014) applied a multi-method approach to assess vulnerabilities of natural and built systems to climate change and develop adaptation options for inclusion in a climate change adaptation strategy for the Lake Simcoe Watershed in Ontario, Canada (Figure 8). Their approach included workshops, face-to-face meetings, and an iterative Policy Delphi survey for helping identify and understand multi-sector climate change vulnerabilities in the watershed, and bringing climate change experts and decision-makers together to work on a proactive, science-based policy outcome. Scientists were elicited to explore the 'exposure' and 'sensitivity' aspects of vulnerability by integrating climate-model-scenario combinations with socio–ecological data.

The primary advantage of the framework used in Lemieux et al. (2014) is that it's highly transparent and can solicit both quantitative and qualitative information to support policy development and is flexible to accommodate a diversity of multi-stakeholder interests. The use of a multi-method adaptation framework (i.e., workshops, scientific vulnerability assessments, and a Policy Delphi survey (Box 2)) produced a wealth of recommendations to help develop the Lake Simcoe Climate Change Adaptation Strategy.

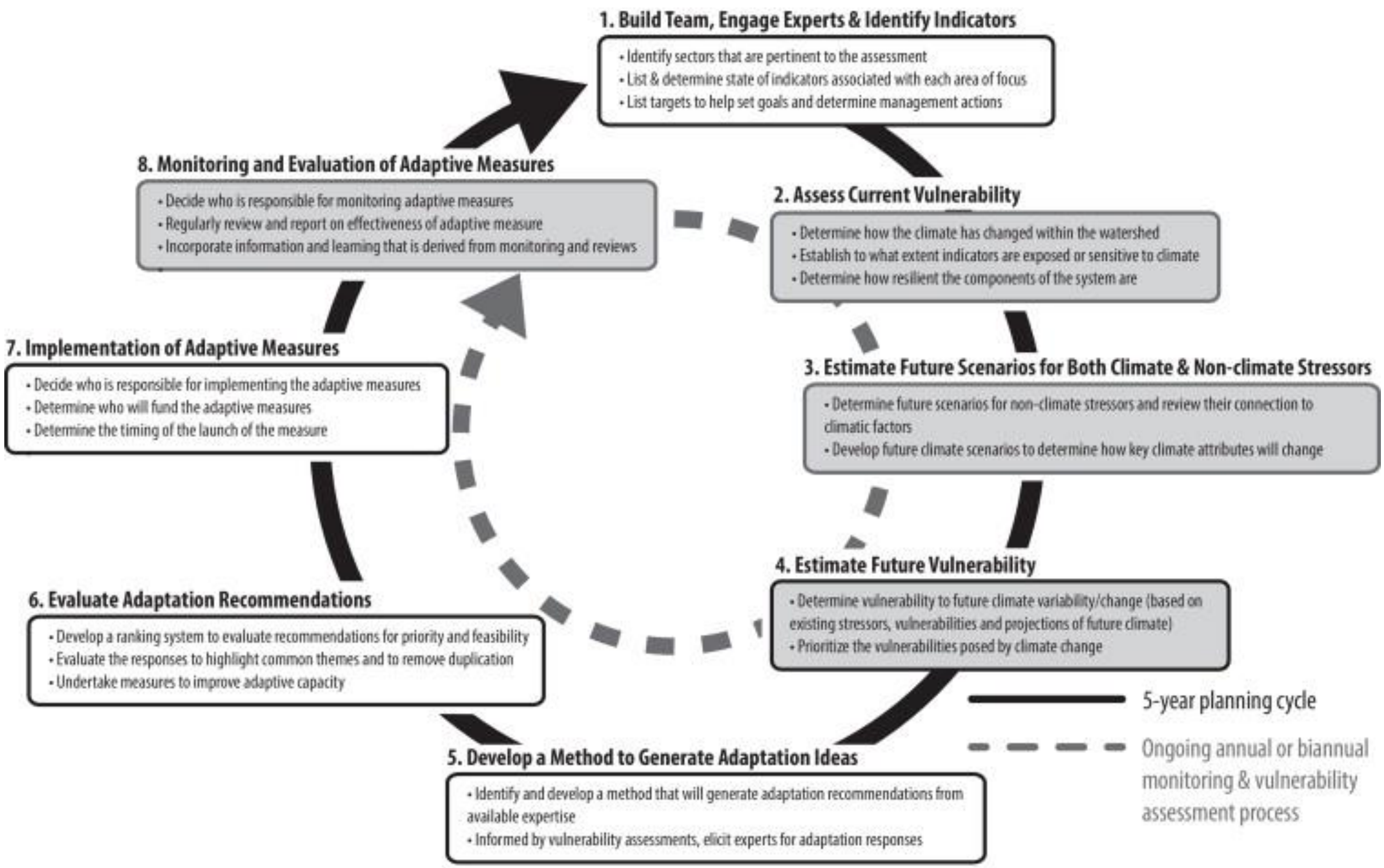

Figure 7: The adaptation framework used to inform development of the Lake Simcoe Climate Change Adaptation Strategy (Lemieux et al. 2014)

Box 1. Top-down, Bottom-up and Integrated Vulnerability Assessments

Vulnerability assessments are commonly distinguished as either following 'top-down' or bottom-up' approaches (Dessai and Hulme, 2004). Top-down vulnerability assessments are future-explicit and use tools for the purpose of establishing causative predictions. For example, using global climate models and downscaling approaches as inputs into biophysical models in order to predict impacts and vulnerabilities to inform climate change adaptation.

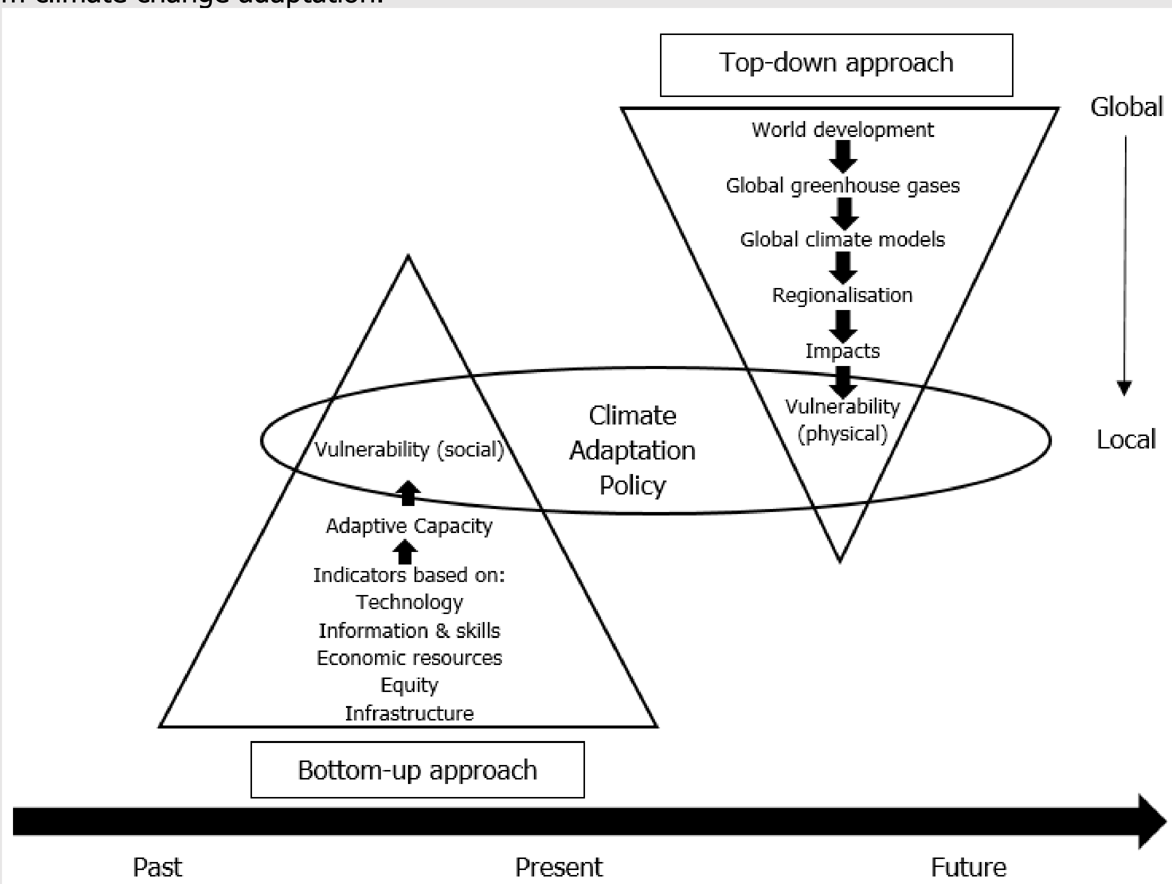

Figure 8: Top-down and bottom-up approaches in vulnerability assessments and climate adaptation policy (recreated from Dessai and Hulme, 2004)

Bottom-up vulnerability assessments emphasize social and economic well-being by focusing on past and present conditions to create an understanding of vulnerabilities, as well as future adaptation measures. Bottom-up approaches use scenario analysis or visioning processes with relevant stakeholders and end users to identify and understand social vulnerabilities. These can then be used to identify the best opportunities for adaptation to climate change. It is important to note that these approaches are complementary to each other, each providing useful information and perspectives on climate change vulnerability.

An integrated vulnerability assessment combines some or all aspects of the two approaches to create a more holistic view of vulnerability that is focused on both future impacts to the environment, but also social and economic concerns. Since both top-down and bottom-up vulnerability assessments include many different variables, integrated approaches can be conducted in many different ways.

Box 2. Using the Delphi Technique to develop Adaptation Options

Lemieux, C.J., P.A. Gray, A.G. Douglas, G. Nielsen, D. Pearson. 2014. From science to policy: The making of a watershed-scale climate change adaptation strategy. *Environmental Science & Policy,* 42: 123-137.

The Delphi technique is a widely used and accepted method for gathering data from respondents within their domain of expertise (Hsu and Sandford, 2007). The technique uses a series of questionnaires to collect data from a panel of selected subjects and develop a consensus of ideas. In contrast to other data gathering and analysis techniques, Delphi uses multiple iterations designed to develop a consensus of opinion concerning a specific topic. The Delphi procedure is iterative and allows individuals to respond anonymously, thus helping to advance innovative and transformational ideas that are often needed yet difficult to attain in the area of climate change adaptation.

Lemieux et al. (2014) employed the method to generate and refine a list of adaptation options that was ultimately used to inform the development of an adaptation strategy for the Lake Simcoe Watershed in Ontario, Canada. A survey containing 11 questions organized according to seven general management categories was provided to an expert panel. The ideas generated during workshop breakout sessions and through an online survey engine were used in the survey to identify adaptation options.

Examples of open-ended questions posed to an expert panel in the first round of a Delphi survey. Results were used to solicit climate change adaptation options (category):

- What barriers to adaptation can be eliminated by modifying existing legislation or policy at any level of government? If possible, please identify the statute or policy, the barrier, and recommended action(s) (Legislation and policy).
- What actions could help mitigate impacts and embrace opportunities associated with potential climate change in natural ecosystems and the built environment? (Management and operations).

For the second-round of the Delphi survey, a Likert-type scale was used to provide expressions of judgement on the perceived priority and feasibility of each adaptation option. On the basis of a review and prioritization of 85 identified options completed by workshop participants, the planning team drafted a final suite of 30 adaptation options to inform development of the climate change adaptation strategy. The 30 adaptation options were reorganized and prioritized into four themes, based on expert panel evaluations of the perceived priority of the adaptation option: (1) Engage People, (2) Reduce Threats, (3) Enhance Adaptive Capacity and (4) Improve Knowledge.

Overall, Lemieux et al. (2014) considered the iterative Delphi process to be important for engaging expertise, for sharing ideas about the effects of climate change unconstrained and for identifying and evaluating adaptation options that is supportive of complex decision-making.

Adaptive Management

Adaptive management is a learning-oriented process that incorporates flexibility and thus helps decision-makers manage for uncertainty (Gleeson et al. 2011). Chu and Fischer (2012) recognized the principles of adaptive management in their study which identified vulnerability indicators for wetland, stream, and lake ecosystems in the Clay Belt (a vast tract of fertile soil that spans from the Cochrane District in Ontario, and Abitibi County in Quebec) that can be used to quantify the sensitivity of each system to climate change, develop adaptation options, and inform an adaptive strategic planning process (Figure 9).

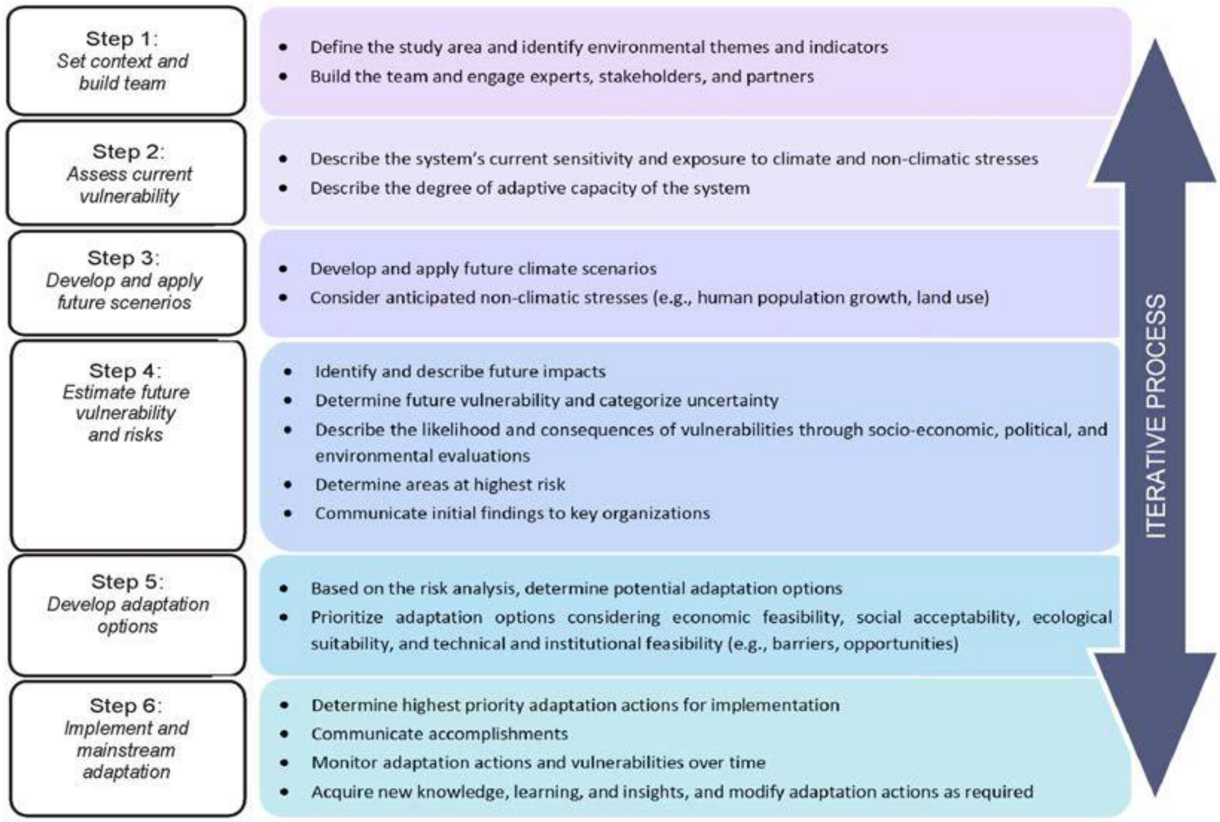

Figure 9: A conceptual framework that can be used by agencies to help determine organizational readiness to adapt to climate change, complete vulnerability analyses, and develop, implement, monitor, and adjust adaptation options as required (Source: Gleeson et al. 2010)

The overall methodology in Tu et al. (2017) also followed an adaptive management approach (see Figure 10), which was iterative and evidence based. The methodology was based on provincial guidance for conducting ecosystem-based climate change vulnerability assessments.

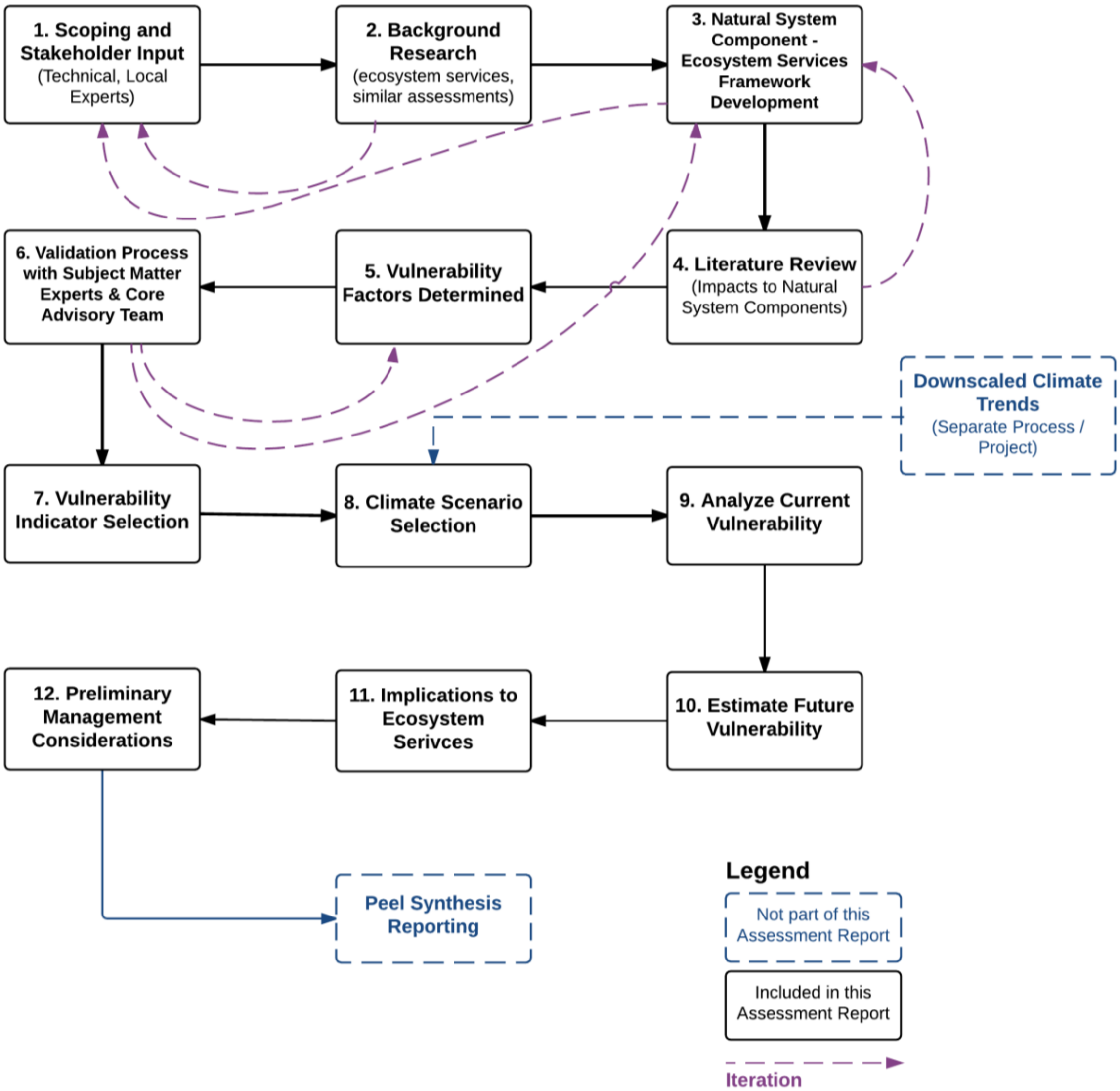

Figure 10: Overall methodological approach used in Tu et al. (2017) to assess the impacts of climate change on natural systems in the Region of Peel.

6.2 Themes

The 12 themes outlined in section 5.3 were connected with the 22 pieces of literature reviewed. Twenty of the 22 studies focused on more than one theme for their vulnerability assessments, with the exception of Stewart et al. (2016) (Habitats and Species only) and Rempel and Hornseth, (2017) (Habitats and Species only). Nineteen of the 22 reports reviewed explored the vulnerability of Habitats and Species, while the theme with the least focus was Toxic Chemicals at only three studies (Tu et al. 2017, Crossman et al. 2017, and Carlson Mazur et al., 2014). A review of the frequency of all the themes can be seen in Figure 11.

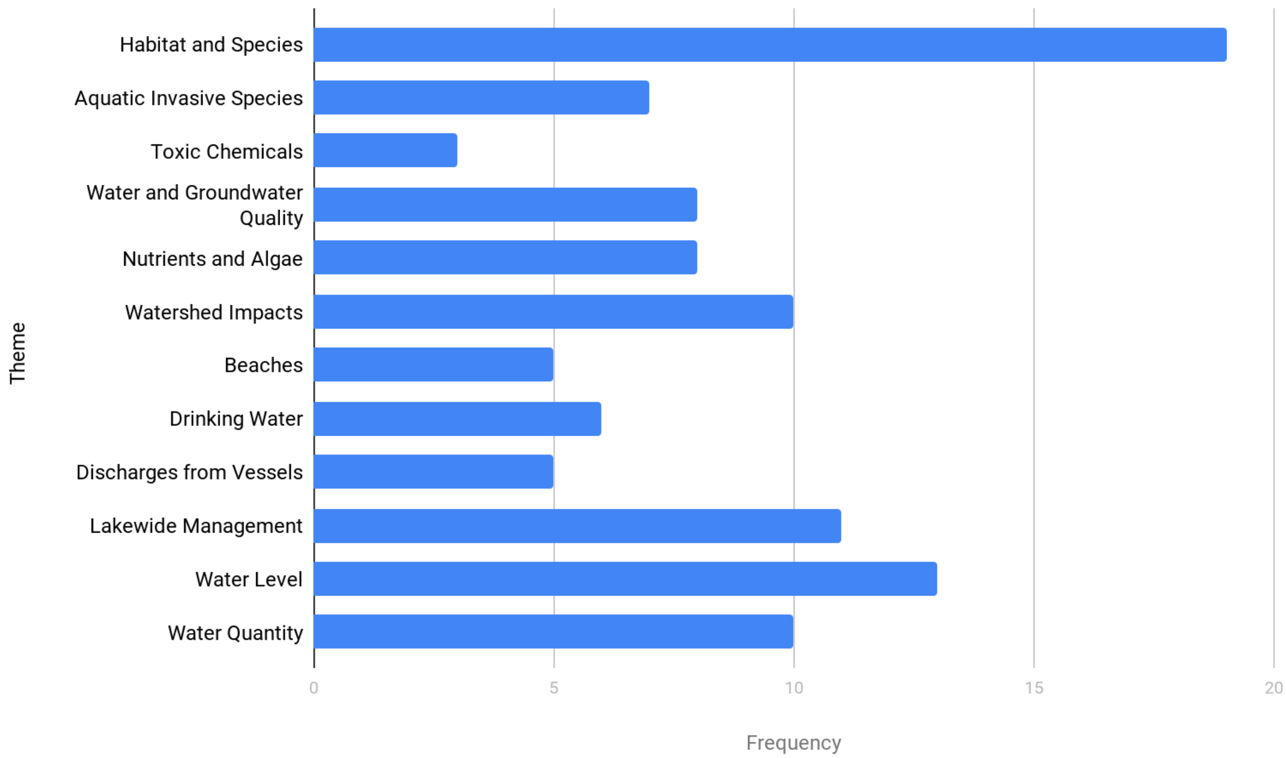

Figure 11: Frequency of Themes found in the Literature

A full list of themes present in the literature is found in Appendix E.

6.3 Tools and Methods

The studies employed a diverse array of tools and methods when conducting their vulnerability assessments. This section explores these in greater detail by assessing the indicators used, the vulnerability indices, climate data and models, other data and models (e.g. habitat models), and stakeholder engagement.

6.3.1 Indicators

Several studies on vulnerability assessments of the Great Lakes developed a set of indicators/sub-indicators or proposed the use of ecological indicators to measure current conditions and future changes in the hydrological system. For instance, Richard and Douglas, (2014) created a list of 85 potential indicators of adaptive capacity for the Agriculture and Hydrology sectors, and this list was rearranged by consulting with staff from the Ontario Ministry of the Environment (OME), Ontario Ministry of Agriculture and Food and Rural Affairs (OMAFRA), and Agriculture and Agri-Food Canada (AAFC). Further, data availability was discussed with OMAFRA, AAFC, Statistics Canada, Laurentian University, and the Lake Simcoe Region Conservation Authority.

Chu and Fisher, (2012) used five indicators to measure the potential effects of climate change on the wetland, stream, and lake ecosystems of the Clay Belt. Smallmouth bass were selected as an indicator species because of their northward expansion in Ontario and their negative effect on resident fish communities after colonization. Walleye were also selected because they are one of the most important fishery resources in the Clay Belt and changes in their habitat and productivity may have significant socioeconomic consequences.

The approach used in MacRitchie and Stainsby (2010) was similar to the one used by the Lake Simcoe Region Conservation Authority (LSRCA) in the Watershed Report Card where indicators were used to represent a number of commonly monitored parameters that indicate changes in the environment (Table 3). In MacRitchie and Stainsby (2010), nine indicators were used for water quality and quantity to assess the sensitivity of the 18 sub-watersheds in Lake Simcoe to changes in the hydrological cycle. The nine indicators (Table 3) were determined through a review of a compendium of reports prepared by the Lake Simcoe Science Advisory Committee (2008).

Table 3: Indicators used for Current Sensitivity Assessment for 18 sub-watersheds in Lake Simcoe (Reproduced from MacRitchie and Stainsby, 2010)

Water Quantity Indicator	Indicator Description
Water Use/Availability	Ratio of surface and groundwater withdrawals to mean annual streamflow.
Baseflow Index	Ratio of baseflow to mean annual streamflow.
Wetland Cover	Percentage of area occupied by wetlands in each subwatershed.
Groundwater Vulnerability	Percentage of area of high, medium and low groundwater vulnerability in each subwatershed.
Forest Cover	Percentage of area occupied by forest/woodland in each subwatershed.
Phosphorus Loading	Annual mass flux of P from subwatershed.
Variability of Streamflow	Ratio of the standard deviation of annual streamflow to mean annual streamflow.
Floodplain Area	Percentage of area occupied by floodplain.
Sewage Bypass	Volume of primary and secondary sewage bypass.

Overall, 16 studies applied the use of ecological or socio-ecological indicators as a measure of quantifying vulnerability.

6.3.2 Vulnerability indices

Approaches specifically designed to measure vulnerability of water resources include the Water Resources Vulnerability Index (WRVI) at the global scale (Raskin et al., 1997), the Index of Watershed Indicators (IWI; EPA 2002), the indicator of regional vulnerability of water resources to climate change in the contiguous United States, and the hydrological response model for land-use and climate change in southern Africa. While these approaches help to resolve the coupled effects of global- and regional- scale perturbations and have been used to identify hydrologically sensitive areas at intermediate regional scales, they often do not provide the fine-scale representation at the watershed scale in which local managers operate on a daily basis (Alessa et al. 2008). The Canadian Water Sustainability Index (CWSI) does provide a finer-scale consideration at the local level by implementing a Water Poverty Index for evaluating the well-being of Canadian communities with respect to freshwater, but it does not focus specifically on vulnerability because it emphasizes sustainability of agricultural areas of southern and central Canada (PRI, 2007).

In general, approaches used to quantify vulnerability differed among the literature and are reflective of a case-by-case basis when defining vulnerability. Table 4 provides a brief overview of the different approaches of the 18 of 22 studies that provided vulnerability scores and demonstrated the range of approaches available for assessing vulnerability. The dimensions of vulnerability (i.e. sensitivity, exposure, adaptive capacity) can be measured quantitatively ('top down') or characterized qualitatively ('bottom up'). For instance, Stewart et al. (2016) calculated vulnerability of lotic fish species in the U.S. GLB by calculating scores of vulnerability (loss of species) and opportunity (gain of species) for all stream reaches by evaluating changes in fish species occurrence from present-day to future climate conditions. Conversely, the Inter-Tribal Council of Michigan Inc. (2016) consulted nine federally-recognized Tribes in the State of Michigan to identify important natural resources and infrastructure across the respective reservations and treaty ceded territories, which may be vulnerable to projected changes in climate. Tribal members assigned a rating of extremely vulnerable, highly vulnerable, moderately vulnerable, and less vulnerable for individual species, whole freshwater systems, infrastructure, and cultural practices.

Table 4: Vulnerability indices and scoring used for assessments in the Great Lakes basin

Study	**Index Used**	**Process**
Mortsch et al. 2006	Developed a Hydrological Vulnerability Index (HVI)	Compared vulnerability of coastal wetland plants to climate-induced hydrologic change
Chu, 2015	Hydrological Vulnerability Index from Mortsch et al. (2006)	Used HVI to rank vulnerability of wetland-dependent bird species.
MacRitchie and Stainsby, 2010	Suggested calculation using formula from Fonataine and Steinermann, 2009: Vulnerability = $\frac{\text{(Exposure + Sensitivity)}}{\text{Adaptive Capacity}}$	A vulnerability score was not calculated, but a suggestion of how to calculate a score was provided.
Richard and Douglas, 2014	Calculated using formula from Fonataine and Steinermann, 2009: $$\text{Vulnerability} = \frac{\text{(Exposure + Sensitivity)}}{\text{Adaptive Capacity}}$$	Adaptive Capacity was scored as High (H), Medium, and Low, with values of 3, 2, and 1, respectively. Vulnerability for Agriculture was scored as: Low Vulnerability (0-3), Moderate Vulnerability (4-6), and High Vulnerability (7-9). Vulnerability for Hydrology was scored as: Low Vulnerability (13-15), Moderate Vulnerability (16-18), and High Vulnerability (19-21).
Herb et al. 2016	Threshold Indicator Taxon Analysis (TITAN)	TITAN was used to identify fish and invertebrate community thresholds
Stewart et al. 2016	Calculated by evaluating change between fish species occurrence from present-day to projected climate conditions	Vulnerability = loss of species Opportunity = gain of species
Lee et al. 2011	NaturServe Climate Change Vulnerability Index (CCVI)	Vulnerabilities were either Extremely Vulnerable (extremely likely to substantially decrease or disappear by 2050), Highly Vulnerable (likely to decrease significantly by 2050), Moderately Vulnerable (likely to decrease by 2050), Not Vulnerable/Presumed Stable (evidence does not show a change by 2050), Not Vulnerable/Increase Likely (likely to increase by 2050), or Insufficient Evidence (information = inadequate to calculate).
Hoving et al. 2013	NaturServe Climate Change Vulnerability Index (CCVI)	Exact process as Lee et al. 2011
Inter-Tribal Council of Michigan Inc. 2016	Participatory driven climate change vulnerability assessments. Calculated based on climate stress (temperature and moisture content), indirect climate exposure, and sensitivity, and adaptive capacity.	Participants assigned a rating of extremely, highly, moderately, or less vulnerable.
Rempel and Hornseth, 2017	NaturServe Climate Change Vulnerability Index (CCVI) combined with a species distribution model (SDM) if available. Climate Change Exposure Index (CCEI)	Same process as Lee et al. 2011, if SDM was available then a combination of results from the exposure/sensitivity/adaptive capacity section and modeling section is used. Severity of exposure to climate change in overwintering grounds

		was estimated using CCEI
Wisconsin Initiative on Climate Change Impacts, 2017	Group discussion	Panelists evaluated the intersection of potential climate change impacts and adaptive capacity of each community type to develop vulnerability ratings. Panelists ranked impacts as well as factors of adaptive capacity.
US Army Corps of Engineers, 2015	Based off adaptive capacity, exposure, frequency of storms, extent and impacts of predicted flooding, planning, and evacuation policies.	Indicators were weighed differently and contributed to the overall vulnerability of the coasts, evaluated at high, moderate, and low risk.
Chu and Fischer, 2012	Based off increased evapotranspiration from warmer temperatures, water loss associated with decreased precipitation, and groundwater inflow.	Vulnerability was defined as degraded quality or loss of wetland area due to drying that may result from increased evapotranspiration at warmer air temperatures, water loss associated with decreased precipitation, and/or groundwater inflow.
Chu, 2011	Wetland vulnerability indicator	Ranked the vulnerability of individual wetlands to projected increases in air temperature and decreases in precipitation and groundwater inflow based on projectors by the CGCM2 A2 scenario.
Brandt et al. 2013	Group discussion mixed with empirical data and projections	Vulnerability was ranked from low to high, and communities were rated by the potential impacts, adaptive capacity, vulnerability, evidence (data), and agreement (between 20 panel members)
Tu et al. 2017	Based off physical factors: depth ratio, aquifer maintenance, degree of connectivity, urban forest canopy, previous cover, rooting depth and strength, topography and grade, water taking and wastewater assimilation, soil quality, ice cover, snow cover; chemical factors such as nutrient availability and water chemistry; biological response factors such as species diversity, community range, flow variation, thermal gradient/regime	Vulnerability was scored as high, moderate, or low based on the conditions that the CAT agreed made the ecosystem service vulnerable.
Carlson Mazur et al. 2014	Based off projections of the suitability of the environment for *Phragmites* in 2050	From most vulnerable to least, the areas were ranked as most suitable, more suitable, suitable, unsuitable, more unsuitable, or most unsuitable
Lemieux et al. 2014		Expert knowledge was elicited to determine vulnerability of natural and built systems to climate change in Lake Simcoe. Experts assessed vulnerability by identifying the known and potential effects (i.e., exposure and sensitivity of climate change on social–ecological systems) and evaluating the adaptive capacity of these systems to respond.

Not all assessments went on to quantify exposure, sensitivity or adaptive capacity, but instead, employed methods to only estimate potential future impacts (e.g. Angel and Kunkel, 2010).

Box 3. Using NatureServe Climate Change Vulnerability Index (CCVI) in vulnerability assessments

The NatureServe Climate Change Vulnerability Index (CCVI) was used in three studies (Lee, Y. et al. 2011; Hoving et al., 2013; and Rempel and Hornseth. 2017) for calculating vulnerability of plant or animal species to climate change. The Index calculates vulnerability by combining information on exposure and sensitivity to produce a numerical sum, which is then converted to a categorical score (Extremely Vulnerable, Highly Vulnerable, Moderately Vulnerable, Less Vulnerable, and Insufficient Evidence) based on threshold values. For instance, Rempel and Hornseth (2017) used the NatureServe CCVI release 3.01 to assess vulnerability of three migratory bird species that have breeding grounds within the Great Lakes basin. The CCVI considered i) exposure of the species to climate change within the breeding range, ii) indirect climate exposure resulting from human responses to climate change, iii) sensitivity to climate exposure and adaptive capacity, iv) an exposure index for the overwintering grounds, v) modeled distributional changes (or changes in climate envelope) expected under specific climate change scenarios, and vi) documented responses (peer review) to climate change.

Overall, a variety of tools (Box 3) and approaches (Box 4) can be used in vulnerability assessments. The selection of approach is dependent on available knowledge and data; technical abilities; capacity, which includes people, time, and money; and information required by decision-makers in a particular situation (Nelitz et al. 2013).

Box 4. Using a multi-method approach to quantify vulnerability

The process used to determine vulnerability by the Wisconsin Initiative on Change Impacts, (2017) combined published literature, climate and species distribution models, and an expert panel to assess potential climate impacts, inherent adaptive capacity, and overall vulnerability of Great Lakes Barrens natural community in Wisconsin. The process closely follows the methods developed, tested, and used extensively by the USDA Forest Service, Northern Research Station for Forest Ecosystem Vulnerability Assessments for forests across the Great Lakes Region as well as Central Hardwoods and Central Appalachian regions (e.g., Janowiak et al., 2014).

Determining overall vulnerability

Following extensive group discussion in workshop setting, each expert panelist evaluated the intersection of potential impacts and adaptive capacity of the natural community to arrive at a vulnerability rating. The panel assessed impacts by considering a range of climate futures bracketed by two scenarios: a low change scenario (PCM B1) and a high change scenario (GFDL A1FI). Participants were provided with individual worksheets and asked to list which impacts they felt were most important to that community in addition to the major factors that would contribute to the adaptive capacity of the community. Panelists were directed to mark their rating in two-dimensional space on the individual worksheet and on a large group poster (Figure 12).

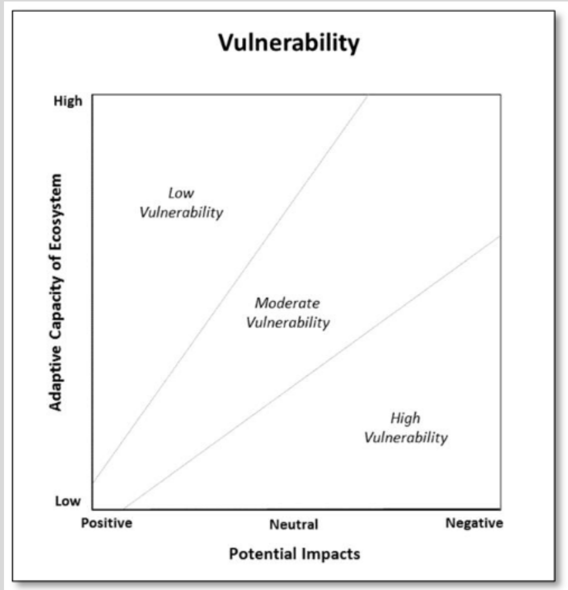

Figure 12: Vulnerability determination worksheet, with vulnerability determined by the intersection of potential impacts and adaptive capacity, after Swanston and Janowiak (2012)

The vulnerability worksheet required the participants to evaluate the degree of potential impacts related to climate change as well as the adaptive capacity of the system to tolerate those impacts. Participants bracketed the uncertainty related to the two climate scenarios by noting vulnerability separately under the low change scenario and high change scenario. Individual ratings were compared and discussed and used to arrive at a consensus group determination for each of the two climate scenarios. Lastly, panelists were also directed to give a confidence rating to each of their individual vulnerability determinations. Panelists were asked to evaluate the amount of evidence they felt was available to support their vulnerability determination and the level of agreement among the available evidence. Panelists evaluated confidence individually and as a group, in a similar fashion to the vulnerability determination.

6.3.3 Climate data and projections

The provision of observational and future climate conditions formed essential components of all 22 studies reviewed. Overall, data from observations and statistical records proved important for understanding ongoing trends and key processes within ecosystems. Historical and baseline climate information formed the basis of the studies' research on climate impacts and were applied for various specific purposes (e.g. as a reference for future climate projections, calibrating and validating models, and assessing historical impacts and trends). The majority of the studies used periods of 30 year durations, which is consistent with the WMO guidelines for climatological analysis.

Characterization of future conditions through the use of climate modeling was also essential to the assessment of impacts and adaptation planning. Global climate models (GCMs) are representations of climate based on biological, chemical and physical properties and are widely regarded as the best and most reliable tools to project future conditions (Picketts et al., 2012; IPCC, 2014). There remains some uncertainty as to how climate will change at regional scales

(Giorgi and Francisco, 2000) and as to how this will influence local hydrology and water quality. While climate models do not provide complete certainty of future conditions, they are a means of comparing past conditions to current and future state of the climate, therefore helping practitioners engage people in strategic discussions and decisions about potential future climates, targets and adaptive responses (Moss et al., 2010). Climate model scenarios have therefore been adopted as the best available tool for obtaining this information (Bates et al., 2008; Kundzewicz et al., 2007; Whitehead et al., 2009). When relying on future climate information, research authors need to select from a range of emission scenarios, global climate models, spatial and temporal downscaling and disaggregation techniques (McDermid et al. 2015). For example, Herb et al. (2016) used a series of models including hydrological simulation program (HSPF) hydrologic model, global climate change models (GCMs), LANDIS (a forest landscape simulation model), as well as statistical models to project climate changes from 2061-2080, as well as land cover change from 2050 to 2150.

Some studies used climate projections as inputs to hydrological or species distribution models. For example, in MacRitchie and Stainsby (2010), monthly temperature and precipitation projections from 10 climate models for the period 2071-2100 were used as input to a simple water balance model to determine potential impacts on the hydrologic cycle on the Lake Simcoe watershed. In Brandt et al. (2013), downscaled climate data was incorporated into hydrological models to better understand impacts on such variables as soil moisture, evapotranspiration, and streamflow. They were also incorporated into forest species distribution models and process models. To estimate possible future levels of the Great Lakes due to climate change, Angel and Kunkel (2010) applied the output of 565 model runs from 23 Global Climate Models to a lake-level model developed by the Great Lakes Environmental Research Laboratory (GLERL) called the Advanced Hydrologic Prediction System (AHPS). As input into the GLERL AHPS model, change functions were calculated for each of the 565 GCM simulations for all grid points near the basin. These change functions were introduced into the GLERL model to compute the expected water levels for each of three future periods (2005–2034, 2035–2064, and 2065–2094)[1]. Lemieux et al. (2014) referred to existing data and completed reports and publications where scientists employed or referenced a variety of climate model-scenario combinations to complete vulnerability assessments.

[1] Readers are encouraged to see papers by Lofgren et al. (2011) and Lofgren and Rouhana (2016) when considering methods for projecting lake water levels, particularly in context of the method employed by Angel and Kunkel (2010).

Box 5. Using a 'snapshot' approach to estimate future climate change

Crossman, J., M.N. Futter, S.K. Oni, P.G. Whitehead, L. Jin, D. Butterfield, H.M. Baulch and P.J. Dillon. 2013. Impacts of climate change on hydrology and water quality: future proofing management strategies in the Lake Simcoe watershed, Canada. *Journal of Great Lakes Research,* 39(1), 19-32.

Changes in future climate are often expressed as changes between future time horizons and a reference (or baseline) period. Examples of future time horizons are horizon 2050, which corresponds to the period 2041-2070 and horizon 2080, which corresponds to the years 2071-2100. Both future horizons and reference periods used in the studies are in 30-year periods. However, in Crossman et al. (2013), both long-term future time periods (2071-2100) and shorter 9-year 'snapshot' time periods were selected for study (2021–2029, 2031–2039, 2061–2069 and 2091–2099) (Figure 13).

Time periods	Date	Median annual temperature (°C)		Absolute change (°C)		Median annual precipitation (mm)		% Change	
		A1b	A2	A1b	A2	A1b	A2	A1b	A2
Baseline	2001–2009	7.95	6.68	n/a	n/a	913.37	916.47	n/a	n/a
Short-term	2021–2029	8.04	6.74	0.09	0.06	858.35	882.71	− 6.02	− 3.68
	2031–2039	8.21	7.30	0.26	0.62	877.05	875.53	− 3.98	− 4.47
	2061–2069	10.57	8.29	2.62	1.61	1014.24	885.18	11.04	− 3.41
	2091–2099	11.66	9.14	3.71	2.46	893.27	939.91	− 2.20	2.56
Long-term	2071–2100	9.86	9.08	1.91	2.4	888.97	970.51	− 2.67	5.90

Figure 13: Annual average values and % change in temperature and precipitation from the baseline through short and long term future climate periods, for A1b and A2 IPCC scenarios (Crossman et al. 2013)

The 'snapshot' approach may be particularly useful for research being undertaken to assist water resource managers. The research of Crossman et al. (2013), for example, was undertaken to support the Lake Simcoe Regional Conservation Authority (LSRCA) with managing the Lake Simcoe system into the future. In this study, the CGCM3 driven scenarios (A1b and A2) data were downscaled using a Statistical Downscaling Model (SDSM4.2), to provide regionally representative temperature and precipitation data for the Simcoe catchment. The 'snapshot' climate periods supports decision-making over the next 10-20 years and therefore provides an analysis of the future effectiveness of management strategies on the Black River and Lake Simcoe, which was the focus of this particular research study.

6.3.4 Data and Other Models

Geographic Information Systems (GIS) based approaches and ArcGIS software were used in six studies for modelling habitats and/or species response to change. In Mortsch et al. (2006), historical air photos and wetland maps were used to interpret wetland vegetation cover change over time (Figure 14). Air photo analysis combined with field surveys that was undertaken in support of the current IJC Lake Ontario-St. Lawrence River (LOSLR) Study contributed extensively to understanding the relationships between Lake Ontario water level fluctuations and wetland plant, bird, and fish communities. Chu (2015) utilized ArcGIS software for spatial analyses of how wetland changes due to climate change may influence habitat availability and the distribution of wetland-dependent species.

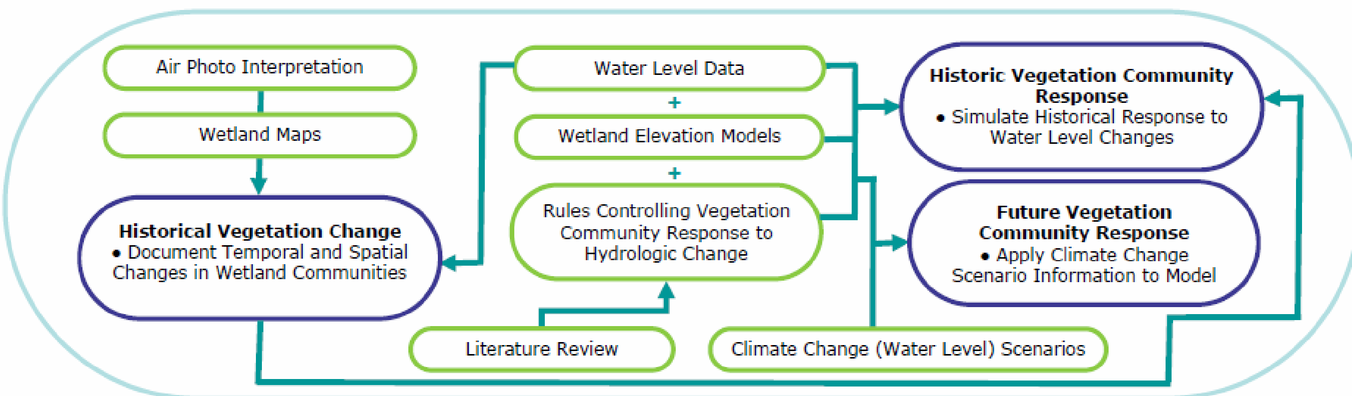

Figure 14: Flow diagram showing air photos and wetland maps in the approach used in Mortsch et al. (2006) to evaluate the vulnerability of wetland vegetation communities and potential response to climate-induced hydrological change.

Species distribution models, or SDM's, were frequently applied by studies to estimate future changes of habitat and species distribution. SDM's are a GIS method that uses core data to provide future estimates of habitat suitability and therefore the vulnerability of species to projected climate change (NatureServe, 2014). In their study on the invasive species *Phragmites australis* (common reed) distribution in the Great Lakes coastal zone, Carlson Mazur et al. (2014) listed several limitations to using SDM's. In the case of *Phragmites*, their niche area continues to expand, and therefore their boundary is not yet determined. However, ecological niche models assume conservation of the prior niche when a species invades a new area (Fitzpatrick and Weltzin, 2005). Although using a correlative model based on a fully realized niche to inform a vulnerability assessment may be preferred (Beaumont et al. 2009), the authors note that such data is rarely available. Therefore, they used the current distribution of *Phragmites* in its unrealized niche to predict suitable habitat.

Box. 6. North American CORDEX Program

NA-CORDEX is the North American component of the international CORDEX (Coordinated Regional Downscaling Experiment) program sponsored by the World Climate Research Program. The NA- CORDEX program provides global coordination of regional climate downscaling for improved regional climate change adaptation and impact assessment. Specifically, the program aims to produce multi-decadal downscaled simulations and data sets for North America using multiple statistical and dynamical downscaling models driven by an ensemble of global climate models (from the CMIP5 data set), according to the specifications of the International CORDEX Program. The purpose of the simulations and analyses is to "provide climate scenarios for use by impacts and adaptation researchers and decision-makers (e.g., water resource managers) to explore the potential effects of climate change on various human and natural systems". It will also allow exploration of the uncertainties regarding future regional climate change at resolutions relevant for impacts and adaptation planning.

Furthermore, it will provide the opportunity to determine the added value of high-resolution regional model simulations that arises in part by including processes missing in coarser resolution global climate models.

For more information on NA-CORDEX, please visit: https://na-cordex.org/

6.3.5 Stakeholder Engagement

Extensive discourse with stakeholders is important for the policy-making process, in order to enhance the quality of the content as well as the acceptance of the policy and its chances of successful implementation (Grothman, et al. 2014). The process of consultation and engagement of experts, organizations, community members and other stakeholders was applied frequently throughout the studies reviewed and was often cited as instrumental to project success and completion (e.g. Lemieux et al. 2014).

Of the 22 literature papers reviewed, 10 undertook stakeholder consultation or engagement. The approach, purpose, extent, timeframe and type of stakeholder consultation and engagement all varied widely across the studies. For instance, Mortsch et al. (2006) engaged stakeholders twice throughout the project to: 1) finalize research scope and integration of data and expertise, and 2) review preliminary results and to provide feedback on adaptation options/recommendations. Numerous government departments conducted field work for the project, to collect elevation, vegetation, water level, bathymetry, wetland fish and habitat, water levels, and marsh bird data. Others provided logistical support and assisted in the design of certain studies, and provided GIS support. Uniquely, a website was developed and dedicated for use as a communication tool among the stakeholders and with the Great Lakes Community in Mortsch et al. (2006).

Stakeholder knowledge was sought in discussions regarding potential climate change impacts, vulnerabilities and adaptation options. For example, the Wisconsin Initiative on Climate Change Impacts (2017) created an expert panel to assess potential climate impacts, inherent adaptive capacity, and overall vulnerability of 52 natural communities in Wisconsin. Ten one-day, in-person workshops were held across Wisconsin, each focusing on a different broad natural community group. For each workshop, they elicited input from a panel of experts representing a variety of land management and research organizations across Wisconsin. They sought teams of panelists who would be able to contribute a diversity of subject area expertise, knowledge of management history, and organizational perspectives. Most panelists had extensive knowledge about the ecology, management, and climate change impacts relevant to the natural communities that were the focus of a given workshop. Brandt et al. (2014) took a similar approach and partnered with a wide variety of researchers, which provided a thorough review of climate factors in the region. This improved projections of future climate changes, as well as potential impacts on a variety of vegetation types.

Resource manager engagement formed a key component of the study by Herb et al. (2016) that assessed the future vulnerability of streams in Lake Superior tributaries in Minnesota and identified management actions that if taken today, could maintain and enhance streams' natural resilience. Because the goal of this study was to inform and influence management decisions, the researchers consulted with a wide range of resource managers throughout the course of the project. Managers were identified by Minnesota Sea Grant staff and confirmed with the project leadership team. Stakeholder expertise included:

- Two core advisors;
- Scientists and researchers in the Lake Superior Basin;
- Conservation managers;
- Naturalists;
- Fisheries specialists;
- Coastal program specialists; and
- Watershed specialists.

Stakeholder knowledge and expertise also formed a significant part of the vulnerability assessment study on the impacts of climate change on natural systems in the Region of Peel by Tu et al. (2017). Two workshops were held at the start of the project (a broad stakeholder engagement workshop and a technical stakeholder workshop) and were cited as critical to defining the project scope and in conducting the vulnerability analysis. The first workshop launched the project and received input from a broad group of stakeholders on the importance of natural systems and what ecosystem services were most valued by participants living and/or working in Peel Region. The second workshop convened participants from the project team as well as technical staff from the Toronto Regional Conservation Authority and Credit Valley Conservation to identify the natural system components to be used in the assessment. Using the input from both workshops and a literature review, a framework that linked key ecosystem services to natural systems components was developed and reviewed by the project team and technical stakeholders. Tu et al. (2017) incorporated additional stakeholder knowledge and expertise through a combination of project meetings, formal subject matter expert interviews and focus-group workshops.

A select number of authors discussed the advantages and/or limitations to their stakeholder engagement approach. For example, the layered stakeholder approach adopted by Herb et al. (2016) observed key benefits to resource managers. For example, the one-on-one interviews provided the opportunity for open-ended observations about the connection between research and science. The formal and informal presentations of research – at the symposium and in the workshops – provided opportunities to learn and critique research. And finally, the interaction portion of the workshop provided informed feedback about how the research would provide managers critical information. The planning team in Lemieux et al. (2014) encountered difficulty in recruiting participants with expertise in agriculture and infrastructure to assess vulnerabilities in these sectors. This gap was filled through completion of a literature review of known and potential effects and prepared policy briefs that representatives from the agricultural sector and municipalities used to identify adaptation options. Further, Lemieux et al. (2014) found that engaging communities, stakeholders, and experts substantively early on and continuously were essential to ensure buy-in and to increase the likelihood that vulnerabilities and adaptation options identified were realistic and relevant to local social-ecological contexts.

6.4 Management and Policy: Mainstreaming Climate Change Adaptation

'Mainstreaming' is an increasingly important concept in policy making as various policy areas/sectors are affected by climate change. The objective of mainstreaming climate change adaptation is to ensure that the relevant policies take due account of the climatic changes with which they are concerned, increase resilience and optimize potential benefits and new opportunities (McCallum and Dworak, 2014). The primary benefit of integrating the management of climate change risks into existing policy is that it leads to "win-win" or "no-regrets" through policy that reduces vulnerability to climatic risks while addressing other priorities (Ford et al. 2007). Moreover, mainstreaming can lead to a holistic engagement, and results in a more efficient and effective use of financial and human resources rather than designing, implementing and managing climate policy separately from ongoing activities (Schipper and Pelling, 2006; Klein, 2001). Key characteristics of mainstreaming include (Nunan et al. 2012; UNDP-UNEP Poverty-Environment Initiative, 2013; TRCA, 2012):

- Being conducted as an intentional process;
- Targets having many outputs;
- Working at the intersection of science-based analysis and policy decision-making
- Requiring a multidisciplinary approach that includes economic, social, environmental and political disciplines;
- Taking place across multiple levels of an organization;
- Being flexible, responsive and adaptive over time; and
- Guiding implementation at the central and local levels of an organization.

The European Climate Adaptation Platform (Climate-ADAPT) has a list of available guidance documents, publications, and tools for the implementation of climate adaptation through mainstreaming. These resources vary in focus, from climate proofing investments (e.g., Agrawala et al., 2010), to the incorporation of climate change into environmental impact assessments (e.g., Hart et al., 2012). Lessons learned in mainstreaming for natural resource areas are also cited in the literature. For example, the World Wildlife Fund published a user manual for protected areas managers to build resistance and resilience to climate change in natural systems (Hansen et al. 2003). Through Climate-ADAPT, HABIT-CHANGE is a project implemented through the CENTRAL EUROPE Programme that explored opportunities to adapt management of large European conservation areas, like biosphere reserves, national parks, and nature parks, to climate change. The results of the project, which ran from 2010 to 2013, are described in a handbook that can be used as a reference for adaptation management in protected area. It also provides useful support for initiating the process of adaptation to climate change in the management of protected areas, as well as other fields of natural resource management (Wilke and Rannow, 2013).

Mainstreaming (to incorporate or integrate) our understanding of climate change impacts and risks into existing policies (e.g., legislation), management structures (e.g., networks), and processes (e.g., decision-making) can take place at different levels (international, national, sub-national, sectoral, and project level) and in different areas of decision-making (policy-making, planning, budgeting, implementation and monitoring) (Ford et al. 2007; TRCA, 2012; Burton and Lim, 2005; Patwardhan, 2006; GIZ, 2013). Grounded in the objectives of mainstreaming is to identify specific points of entry within the governance structure, policy cycle, and generic function, ranging from policy making to resource allocation and implementation of projects or activities on the ground (OECD, 2009). Table 5 provides examples of the activities undertaken at various stages of the policy cycle where climate change considerations can be incorporated.

Table 5: Policy roles and tasks in the policy cycle (Source: Wellstead and Stedman, 2015; Dalal-Clayton and Bass, 2009; British Columbia, 2016)

Policy cycle stage	Policy activities	Examples of mainstreaming
Agenda setting	• Identifying policy issues • Identifying policy options • Environmental scans • Consulting with the public	• Review, update and implement legislation, policies and programs to ensure preparation for and resilience to the impacts of climate change.
Policy formulation	• Appraising policy options • Collecting policy-related data • Collecting policy-related information • Conducting policy-related research • Negotiating with stakeholders • Preparing position papers	• Establish criteria for the consideration of climate change during the environmental assessment process. • Develop water resource management strategy that considers climate change impacts on water quality and quantity.
Decision-making	• Compare policy options • Decision matrices • High-level briefing • Negotiating with central agencies • Department planning	• Require revisions to planning processes that ensure climate change is integrated early and systematically into decision-making procedures. • Improve ability to make durable decisions that consider climate change, and cumulative effects on key environmental, social and economic values.
Implementation	• Implementing or delivering policies or programs • Negotiating with program managers • Consulting with stakeholders • Legal analysis	• Inclusion of climate change into sector plans. • Work with stakeholders in climate sensitive sectors to assess risk and prioritize actions to successfully adapt to a changing climate.
Evaluation	• Policy evaluation skills (e.g., cost benefit analysis, risk assessment) • Risk-based tools and techniques • Evidence-based policy	• Conduct climate change risk and vulnerability assessments. • Embed climate change strategies into resource management policy and practices.

The impact of mainstreaming programs can manifest beyond policies and plans, and can strengthen organizational capacities and behavioral changes within institutions (Benson et al. 2014). The integration of climate change considerations at one decision-level (e.g., policy, budgetary and programmatic choices) might enable action at the ground setting (e.g., day-to-day operations and management) (OECD, 2009), therefore leading to an institutional culture that promotes empowerment and collaborative action (Gray, 2012).

In contrast to the opportunities of mainstreaming, a few key challenges with mainstreaming climate change can also be observed. In Ontario, the inadequate availability of, or access to (see ECO, 2015), relevant, regionally downscaled climate data is a key policy challenge for decision-makers, yet it is critical to in order to integrate adaptation. Limited information on the costs and benefits of adaptation measures can also impede an organization's ability or momentum to make the economic case for investing in adaptation. Efforts to review and adjust regulations and standards that reflect climate impacts within an agency can be challenged by the lack of specific information on the ways climate change can affect core institutional functions (OECD, 2009). Moreover, a general lack of incentives to incorporate climate change into existing structures and practices may be reflected in an unwillingness to adopt mainstreaming measures by staff within organizations. It is not expected, nor is it a requirement, that every member of the GLWQA become a climate expert. Instead, mainstreaming should offer a practical list of options; access to external climate change expertise; and enabling tools that members can utilize to undertake assessments themselves (e.g., vulnerability assessments).

Ultimately, for the GLWQA Annexes, mainstreaming has the potential to result in co-benefits that include more transparent decision-making; better cross-annex collaboration; increased awareness on climate risks; changed perceptions; efficient use of resources; and improved decision-making (Benson et al., 2014). Furthermore, driving climate change decisions through opportunities within existing policies, plans and programs helps to avoid trade-offs between climate change adaptation and the objectives of the Agreement.

6.4.1 Mainstreaming in the context of organizational readiness

Organizational readiness is crucial for any organization that is planning to proactively manage for the effects of climate change. The vulnerability of any organization is reflective (or a function) of its exposure and sensitivity to climate change, and is determined through its adaptive capacity. The forces that influence the ability of a system or organization to adapt are known as the drivers (or determinants) of adaptive capacity (Smit and Wandel, 2006).

Complementary to adaptive capacity is organizational readiness, which examines the factors that influence an organization's ability to manage for climate change (Figure 15). Adaptive capacity reflects the *potential* for adaptation, where adaptation is neither inevitable nor automatic, even where adaptive capacity is high (Ford and King, 2015). Organizational readiness on the other hand, captures the processes and conditions that determine the likelihood of capacity translating into actual adaptive actions. Organizational readiness deals with an alternative and complementary viewpoint to adaptive capacity, capturing real actions that have already been started to prepare for adaptation and to help inform if and when adaptive capacity will translate into action. In essence, it seeks to characterize whether a system or organization is prepared and ready to 'do adaptation' (Ford and King, 2015).

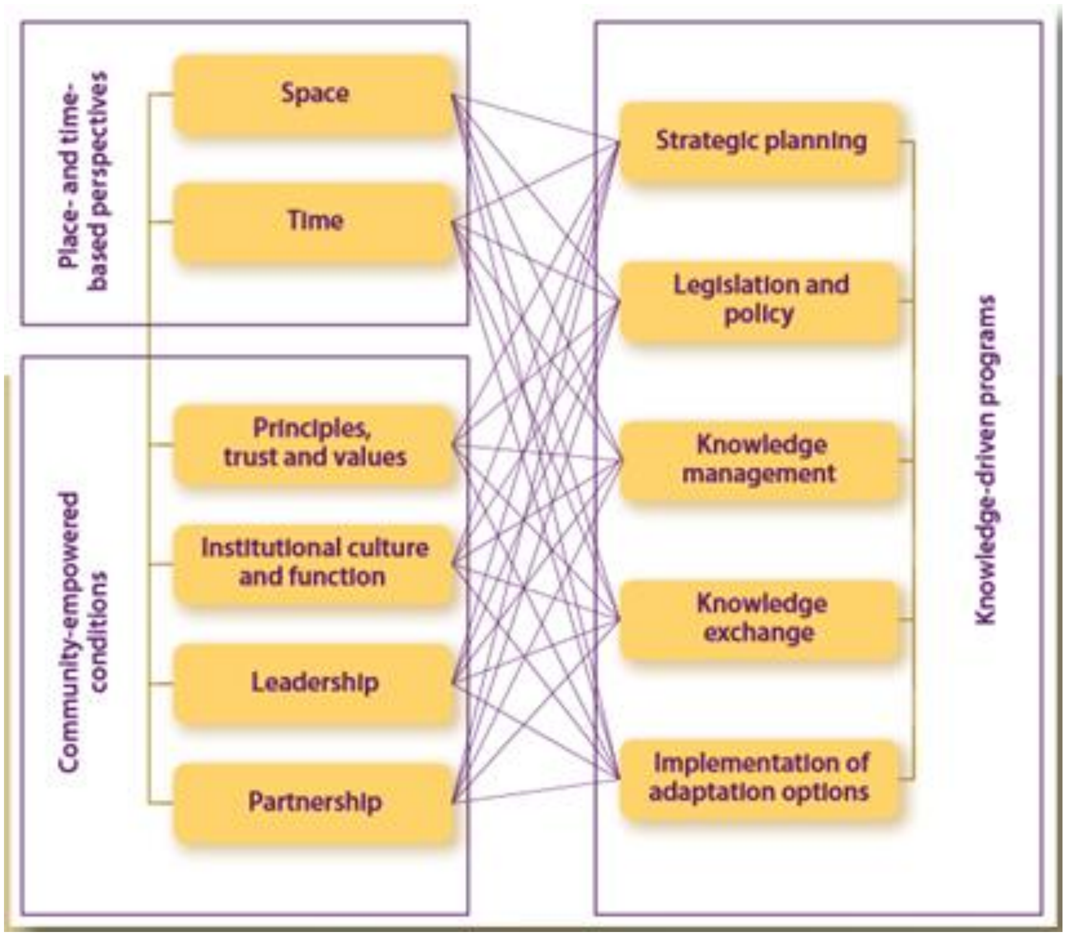

Figure 15: A framework to help organizations that are committed to mainstreaming climate change into decision-making programs assess their readiness to manage for climate change (Source: Gray, 2012)

The answer depends on the robustness of the unique combination of values, institutional culture, commitment to public engagement, financial and human assets, acquisition and use of data and information, know-how, and decision-making processes used by an agency to plan and manage a way forward (Gray, 2012).

In the context of mainstreaming, assessing organization-level readiness can determine the organization's commitment to change, in addition to their collective capability to do so. A high level of organizational readiness would indicate that organizational members are more likely to initiate change (e.g., institute new policies, procedures, or practices), exert greater effort and commitment, and display more cooperative behavior, which results in more effective implementation (Weiner, 2009).

An immediate challenge for mainstreaming climate change is finding the right environment, or organizational home. Barriers or limitations within organizations can be cause for delay in the adoption of climate change measures and/or implementation, or may be excluded from consideration as a whole. Barriers at the organizational level can present as:

- Incompetent leadership;
- A lack of political support;
- Limited to no public pressure;
- Lack of coordination and organizational cultures; and
- Competition of other objectives in the policy process (Uittenbroek et al., 2013).

In turn, barriers can affect the extent to which climate change is mainstreamed.

On the contrary, multiple opportunities can arise from organizational readiness. For instance, assessing the institutional culture and function of an organization can identify members who express championing behavior, also referred to as a 'climate champion'. Leveraging the motives and values of the champion can propel the initiation of the mainstreaming process (Weiner, 2009). Assessing readiness can also identify weaknesses, which can lead a more efficient overcoming of challenges and barriers. Furthermore, the process of assessing organizational readiness for climate change mainstreaming can be a powerful way to increase awareness of and urgency about incorporating climate change issues into programs, plans and policies; it helps people to see why a change is needed, important, and worthwhile (Weiner, 2009).

Table 6: Suggestions from the literature on incorporating climate change into policy actions, plans and management

Area of 'Organizational Readiness'	Example of mainstreaming climate change	Author
Policy and legislation	• Include a requirement for stormwater master planning in the Planning Act. • Develop realistic, sustainable strategic land use policies. • Review official plans, land use plans, infrastructure plans, bylaws, and associated policies to determine how well they account for and protect important natural assets.	Lemieux et al. 2014.
Strategic planning	• Develop and maintain comprehensive biodiversity survey to more thoroughly characterize baseline conditions, against which future change can be effectively detected, managed and mitigated.	Herb et al. 2016
	• Expansion of monitoring and research to consider the stresses of climate change to offer managers the best opportunity to keep the valuable Great Lakes fisheries sustainable in the face of continued human-driven changes.	Collingsworth et al., 2017
Valuation	• Consider tax breaks or payments for shoreline landowners who naturalize shores even if no wetland area is present. Shore land provides storm protection, ecological linkage, recreation trail options, water quality buffer, and space for wind generators. • Use bigger tax breaks and/or payments for conservation easements to reflect the value of ecological services, such as protection against more intense storms and filters of upstream eroded sediment to help protect lakes, carbon uptake, and fish nursery.	Mortsch et al. 2006
Spatial and temporal scales	• A network of monitoring stations should be established throughout the GLB wetlands to detect any changes in wetland extent and quality.	Chu, C. 2015.
	• Landscape-scale analyses are needed to help land managers target existing	Carlson Mazur et al.

	populations of *Phragmites* and identify areas most vulnerable to future invasions in order to limit spread, especially those areas being ecologically restored or those likely to experience the greatest change in regional climate.	2014
	• Protect, enhance or restore regional species diversity by increasing connectivity of natural areas, including forests, meadows, wetlands and watercourses. The focus should be on enhancing or expanding areas that currently function well and have low to moderate vulnerability to climate change.	Tu et al. 2017
Communication, education, and knowledge exchange	• Incorporate multiple sciences together to understand the impacts of climate change fully (e.g. social impacts and ecological impacts of climate change).	Collingsworth et al., 2017
	• Promote effective collaboration, cooperation and streamlined information sharing amongst regional Conservation Authorities, municipalities, and the Peel Community Climate Change Partnership, as well as with landowners, developers, businesses, non-governmental organizations, adjacent or upstream municipalities and the provincial and federal governments.	Tu et al. 2017
	• Raise public awareness by publishing success stories of local communities' adaptation and mitigation actions.	Mortsch et al. 2006
Principles	• Involve First Nations who bring traditional ecological understanding.	Mortsch et al. 2006.
	• Encourage stewardship groups to protect and rehabilitate aquatic habitat, riparian zones and wetlands.	Herb et al. 2016
Institutional culture and function	• Conduct assessment of readiness and capacity to respond by evaluating past damage of storms (e.g. infrastructure, evacuation plans, and strategies for cleanup), climate change, population increases, and existing barriers to comprehensive coastal storm risk management.	US Army of Corps of Engineers, 2015.
	• Provide regulator staff funding adequate for fast reviews of permits.	Mortsch et al. 2006.

Partnership	• Fisheries managers should collaborate with foresters and land use planners to establish thresholds for minimum forest cover using historical or "range of natural variation" benchmarks to improve the chances of maintaining flow regimes within the range of natural variation to which stream systems have adapted.	Herb et al. 2016
	• Management initiatives should be coordinated across Conservation Authorities and integrated into existing restoration, retrofit and stewardship programs (through riparian planting for shade and infiltration of runoff, for example).	Tu et al. 2017
	• Ensure community engagement and interagency cooperation and coordination.	Lemieux et al. 2014.
	• For species that are already experiencing population and habitat declines, conservation planning and research efforts should include a coordinated binational approach to ensure that conservation strategies are effective and suitable for those species that are most vulnerable to climate change.	Rempel and Hornseth. 2017
Program planning and design	• Review current natural system monitoring programs carried out by Conservation Authorities and municipalities to ensure they include a focus on climate change impacts. If necessary, revise programs so that they effectively track vulnerabilities, and establish an evaluation system to measure the success of adaptation efforts in achieving watershed resiliency. • Incorporate climate change into watershed planning more directly, including identifying and protecting important local connections between shallow groundwater and surface features.	Tu et al. 2017

6.5 Vulnerability Assessment Outputs

Vulnerability assessments outputs aim to provide information to direct adaptation measures, create methods and tools for future use, and increase resilience of an area. There were many different types of vulnerability assessment outputs that resulted from the research studies, from adaptation strategies for local conservation authorities (e.g. Lemieux et al. 2014), to a compendium of tools (See Table 7).

Table 7: Examples of research outputs

Author(s)	**Output**	**Description**
Herb et al. 2016	Management Decision Tool	The tool is an aid in deciding which types of management actions are appropriate in certain places given available information about current stream conditions and how they may change in the future. *Refer to section 2-10 of the report for an expanded overview of tool: http://files.dnr.state.mn.us/waters/lakesuperior/eloha/eloha_report.pdf*
Stewart et al. 2016	FishVis version 1.0, a companion Web-based decision support mapping application	A Web-based decision support mapping application termed "FishVis" was developed to provide a means to integrate, visualize, query, and download the results of projected climate-driven responses and help inform conservation planning efforts within the region. These geospatial tools and data can be used to identify baseline conditions and guide strategic conservation investments and restoration efforts. FishVis is currently accessible by following the publicly available Web link http://ccviewer.wim.usgs.gov/FishVis/
Mortsch et al. 2006	Hydrological Vulnerability Index (HVI)	A Hydrological Vulnerability Index (HVI) was developed and used to compare the vulnerability of coastal wetland plants to climate-induced hydrologic change. The HVI assigns a series of codes and hydrological vulnerability scores for selected habitat requirements, life history traits, and population parameters used to assess the hydrological vulnerability of selected wetland plants in Great Lakes coastal wetlands. The HVI developed by Mortsch et al. 2006 was used to rank wetland dependent bird species in Chu, 2015.

The most common output among the literature was a ranked list of vulnerability scores for species or habitat. For instance, Hoving et al. (2013) produced an index of climate change vulnerability scores for each species assessed and included a measure of confidence/uncertainty around the score. The CCVI scores provided in this report can be used by managers to help the prioritization of game management plans, or species recovery plans that require revision to include information on climate threats. The Inter-Tribal Council of Michigan Inc. (2016) also produced three large tables, ranking all vegetation species, wildlife species, and fish species that are at risk. These rankings range from extremely vulnerable, highly vulnerable, moderately vulnerable, and less vulnerable. Through this project, the Inter-Tribal Council of Michigan Inc. facilitated a tribal-led process of analyzing climate projections at mid-century, assessing resource vulnerabilities, and identifying planning resources and adaptation strategies across jurisdictional boundaries to benefit Tribes in Michigan as they face a changing climate.

By providing a measure of vulnerability and/or future potential impact, each study successfully increased awareness of climate change in the regions studied. In addition, the research helped to inform management actions and policies for resource managers and agencies and the associated hydrological or terrestrial ecosystems.

Authors also employed a variety of tables, maps, and figures to present the findings of their research. For instance, Chu, (2015) included maps showing levels of vulnerability of wetlands in each Great Lake. In addition, to a decision support tool, Herb et al. (2015) created outreach materials and held workshops in order to inform restoration and management actions among resource managers in Minnesota's Lake Superior tributaries.

Two studies informed or supported the development of local adaptation strategies and/or adaptive measures. For example, the results of the vulnerability assessment by Chu (2011) were completed using selected indicators in support of the Lake Simcoe Climate Change Strategy called for in the Lake Simcoe Protection Plan by the Expert Panel on Climate Change Adaptation (2009) and Ontario's Adaptation Strategy and Action Plan: 2011-2014. These results were used to develop adaptation strategies for each ecosystem and inform the adaptive strategic planning process. The results of the vulnerability assessment by Lemieux et al. (2014) was used to develop adaptation options for inclusion in a climate change adaptation strategy for the Lake Simcoe Watershed in Ontario, Canada.

6.5.1 Adaptations Actions

Fifteen of the 22 vulnerability assessments reviewed recommended or referred readers to where adaptation actions can be found in order to increase resiliency of the environment studied. Despite the majority of studies recommending adaptation actions, several of these were not necessarily comprehensive, and few included an evaluation of adaptive capacity. For example, Rempel and Hornseth (2017) suggested increasing cross-border collaboration to enhance the availability of resources needed to improve vulnerability assessments and development of conservation strategies. Many of the researchers suggested a similar, social approach to adaptation. The use of stakeholder engagement within or to develop adaptation strategies was suggested by Brandt. et al. (2013), Chiotti and Lavender (2008), Inter-Tribal Council of Michigan Inc. (2016), Lemieux et al. (2014), US Army Corps of Engineers (2015), and Tu et al. (2017). Examples of engagement included building new partnerships for information sharing to build data for adaptation strategies, and for public outreach and education to increase awareness and education among resource managers and the public about the impacts of climate change and ways to adapt on the individual or local level.

Science-based adaptation actions were suggested by most of the studies, with data collection, monitoring and surveillance, and general actions to protect and increase resiliency of the environment. The recommended adaptation actions suggested were based on the themes studied in a particular area, as well as to the potential impacts of climate change on that area. For example, Chu and Fischer (2012) suggested an increase in the monitoring of species in lakes, streams and wetlands, including invasive species; and monitoring baseline flows, temperatures and water levels. Some studies suggested ecosystem-based adaptation, such as Brandt. et al. (2013), who recommended urban forests and crop adjustments, and Collingsworth et al. (2017), who suggested more sustainable fisheries management.

Some recommended adaptation actions came in the form of mainstreaming adaptation to climate change into decision-making, and through the use of policies and programs that focus on decreasing vulnerability and increasing resilience by supporting adaptation actions, policy and management. For example, beyond stakeholder engagement, Chiotti and Lavender, (2008) considered mainstreaming as a strategy with policies and programs that deal with infrastructure renewal, low water programs, and growth strategies (e.g. the Clean Water Act) to be the most impactful. Similarly, many adaptation actions were suggested in the form of changes to management strategies and policy. For a more comprehensive review of recommended adaptation actions, please refer to Appendix D.

7.0 Observations and Recommendations

This section provides examples from the literature on 'lessons learned', which includes best practices, adaptation actions, limitations, and general lessons as reflected on by the authors. It's important to note that this section is not comprehensive and it is recommended that readers refer to original studies for a full list of 'lessons learned'.

7.1 Best Practices

Each of the 22 vulnerability assessments reviewed differed in terms of themes assessed, frameworks, outputs, and overall methods. Due to these differences, assessing for best practices is not possible. However, several of the authors included best practices in their reports, especially when addressing their respective barriers. Many of these best practices refer to how to effectively involve stakeholders in vulnerability assessments.

The planning team in Lemieux et al. (2014) encountered difficulty in recruiting participants with expertise in agriculture and infrastructure to assess vulnerabilities in these sectors. This gap was filled through completion of a literature review of known and potential effects and prepared policy briefs that representatives from the agricultural sector and municipalities used to identify adaptation options. Further, Lemieux et al. (2014) found that engaging communities, stakeholders, and experts substantively early on and continuously were essential to ensure buy-in and to increase the likelihood that vulnerabilities and adaptation options identified were realistic and relevant to local social-ecological contexts.

The layered stakeholder approach adopted by Herb et al. (2016) observed key benefits to resource managers. For example, the one-on-one interviews provided the opportunity for open-ended observations about the connection between research and science. The formal and informal presentations of research – at the symposium and in the workshops – provided opportunities to learn and critique research. And finally, the interaction portion of the workshop provided informed feedback about how the research would provide managers critical information.

The Inter-Tribal Council of Michigan Inc. (2016) also found communication to be key in the development of the vulnerability assessment. Tribal councils, community members, and cultural leaders encouraged knowledge sharing within the community. These communication efforts served as an educational experience about future climate projections and potential climate impacts. Furthermore, knowledge was shared with the Inter-Tribal Council of Michigan Inc. from nine Tribes, community members, and governments in order to complete this vulnerability assessment. This was a similar method between stakeholders involved with Hoving et al. (2013), Lee et al. (2011), and others.

7.2 Other Considerations

In addition to Best Practices, authors discussed other strengths and weaknesses associated with their studies, such as knowledge gaps and limitations; technical shortcomings; challenges with temporal and spatial scale; project timelines; and the overall approach or process taken. While not a comprehensive list, a few examples are provided, below.

In terms of reflection on overall approach, process and framework, Lemieux et al. (2014) recommends: carefully selecting idea generation strategies to match needs, expectations, and time; and when innovating, provide a flexible, enabling working environment. The primary advantage of the framework introduced in their study is noted in its high transparency, its ability to solicit both quantitative and qualitative information to support policy development, and in its flexibility to accommodate a diversity of multi-stakeholder interests. Specifically, the research to complete the Lake Simcoe watershed vulnerability assessments represented a significant capacity building exercise, by providing a more robust understanding of how climate change is affecting the watershed now, and how these effects may intensify over the next 30 years and beyond.

Lee et al. (2011) noted that additional factors might have biased or affected the results of their vulnerability assessment of rare and declining plants and animals in Michigan's coastal zone. For instance, the western Upper Peninsula and northern Lower Peninsula have not been surveyed as completely as the rest of the state. This may skew results of "temperature scope" and the "moisture metric scope" away from the categories for species that actually occur in the western UP but have not been recorded there. They also noted that the Great Lakes are known to affect local and regional climate/weather patterns, and a regional model for climate change accounting for the influence of the Great Lakes would allow for a more accurate assessment of the potential impacts to species occurring in the Coastal Zone of Michigan. The authors suggested that it would be beneficial to recalculate the Climate Change Vulnerability Index (CCVI) when finer-scale or better downscaled climate models are available for Michigan.

Rempel and Hornseth (2017) recorded findings on limitations with data and spatial and temporal scale restrictions. Notably, their study indicated current modeling efforts are in some cases restricted by jurisdictional boundaries; this impedes vulnerability assessments by necessitating extrapolations to complete the CCVI. For almost every climate exposure parameter considered they found gaps in data or modeling. In some cases models did not exist for Canada (e.g., Hamon moisture metric), and in other cases data was difficult to access because of broken web-links or issues with automated mapping. Best guess extrapolations were used where data was lacking in the Canadian watersheds. Rempel and Hornseth (2017) recommend improving ClimateWizard's packaged climate data to enable easy extraction of Canada and Central American GIS data which would eliminate this impediment[2].

Chu,)2011) observed several uncertainties in her study on the effects of climate change on the wetland, stream, and lake ecosystems of the Lake Simcoe Watershed, which require additional research given expected changes in climate, including:

- The amount of change that can be expected in wetland extent;
- Stream temperatures are more heterogeneous than the simplified approach used in the study;
- Coldwater species are not uniformly distributed within the sub-watersheds;
- The types of shifts in wetland plant composition that may occur;
- Whether birds will move to less optimal habitats or adapt to changing wetland conditions;
- The cumulative effects of other factors that influence wetland vulnerability such as infilling and draining;
- The predicted[3] temperature profiles represent the average thermal conditions in the lake;
- Other factors known to influence the spatial variability of water temperature (e.g. wind and lake morphometry) of Kempenfelt Bay were not included but should be;
- Other factors that influence the availability of suitable habitat for different species (e.g., substrate and prey availability) have not been included
- The direct influence of climate change on lake species has not been assessed; and
- Lower trophic level dynamics also may change with climate.

In their assessment of the vulnerability of populations infrastructure, and resources at risk throughout more than 31, 200 miles of the North Atlantic coastal region, the US Army of Corps of Engineers (2015) made recommendations, including: undertake additional technical and scientific analyses (to advance incorporation of resilience, risk, and uncertainty); risk communication and collaboration (Federal, State, Tribal, and local governments, NGOs,

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[2] Please note that the current version of ClimateWizard is based on older projections (CMIP3).

[3] UNITAR (2015) states that climate predictions are estimates of future natural conditions, while climate projections are estimates of future climates under the assumptions of future human related activities such as socioeconomic and technical developments. Here, Chu (2011) predicted temperature profiles based on data from 1980 - 2009. It is not projected because the temperature profiles were not estimated under the assumption of future human-related activities.

academia, private industry, and the public); and institutional and financing (coordination to overcome challenges associated with land-use policy and permitting actions).

Lee et al. (2011) suggested that vulnerability assessments should be viewed as a first step and as part of an iterative process - an observation made in other studies as well (e.g. Lemieux et al. 2011). The authors suggest "vulnerability assessments should be revisited and reassessed as better and more information about climate changes and species distribution, life history, ecology, genetics, and responses to climate change become available. Tools for assessing vulnerability such as the CCVI also continue to be developed and enhanced" (Lee et al. 2011: 35).

Finally, in Carlson Mazur et al. (2014), spatial and temporal limitations were noted as inherent to the data used to generate a map *Phragmites australis* (common reed) and environmental predictor datasets. The authors provide the example that error can be introduced into large geospatial datasets that, by necessity, are compiled over multiple years.

8.0 Case Study: The Arctic Water Resource Vulnerability Index, Alaska, U.S.

A case study on assessing vulnerability at the watershed scale is provided. The process used in the vulnerability index and applied in the Arctic may be of interest to those considering examining a suite of constituent physical and social scores rather than methods that calculate a total vulnerability score alone.

Alessa, L., A. Kliskey, R. Lammers, C. Arp, D. White, L. Hinzman, and R. Busey. 2008. The Arctic Water Resource Vulnerability Index: An integrated assessment tool for community resilience and vulnerability with respect to freshwater. *Environmental Management. 42 (3): 523-541.*

Freshwater is considered a critical resource for communities living in the Arctic. However, the Arctic presents a set of unique challenges when analyzing water quality and supply, such as the combination of very remote communities with poorly developed infrastructure and high energy costs, a rapidly changing climate, and a scarce amount of available liquid water for much of the year. Due to subsistence hunting and fishing, the vulnerability of water resources for communities in the Arctic are felt at the local scale of small watersheds. Climate change is expected to have significant effects on the hydrologic cycle in Arctic regions (Hinzman and others 2005; Serreze and others 2000), yet no current index exists to adequately assess resilience and vulnerability of Arctic communities to changes in water resources at the local scale (Alessa et al. 2008). To address this, the Arctic Water Resource Vulnerability Index (AWRVI) was developed by Alessa et al. (2008) and applied in three Alaskan communities and their associated watersheds of Eagle River, White Mountain, and Wales, respectively, spanning a range of latitudes, environmental settings, and levels of human development. The AWRVI was applied to assess the relative vulnerability–resilience of the communities and their respective watersheds to changes in their water resources from a variety of biophysical and socioeconomic processes.

The Arctic Water Resource Vulnerability Index (AWRVI)

The AWRVI is an index that characterizes vulnerability of a community and its watersheds as a function of two sub-indices: the surrounding physical conditions related to water supply and water quality, as well as the social conditions related to a community's social network and adaptive capacity. These sub-indices are characterized by a set of constituent indices and related indicators, which are further informed by the best available data for these indicators (e.g. publicly available data). Each component of the AWRVI was chosen through the Delphi Technique (See Box 1) by obtaining a consensus from water experts with experience in Arctic regions and using a series of questionnaires.

The physical sub-index rates the contribution to the vulnerability of a community from biophysical drivers and moderators of freshwater in the watershed. The sub-index is defined by indices that measure natural water supply, municipal supply, water quality, permafrost status, and subsistence habitat in a watershed. Specific indicators include:

- **To characterize natural supply:** measures of precipitation, surface water storage, and river runoff;
- **To characterize municipal supply:** yield from water sources, diversity of water sources, water treatment technology, hydraulic gradient, and infrastructure reliant on permafrost;
- **To characterize water quality:** amount of upstream development and number of streams with water quality data;
- **To characterize permafrost:** distribution of permafrost; and
- **To characterize subsistence habitats:** the proportion of a watershed with fish recruiting streams and level of forest cover.

regions and using a series of questionnaires.

The social sub-index rates the contribution to the vulnerability of a community from social moderators of freshwater in the watershed and is defined by indices that measure knowledge, economics, informational capacity, and sensitivity to change. Specific indicators include:

- **To characterize knowledge:** measures of traditional and western knowledge, residency time of people in community;
- **To characterize economics:** average household income;
- **To characterize informational capacity:** amount of land as a protected area; and
- **To characterize sensitivity to change:** importance of subsistence living, diversity of the social network, and the perception of water planning activities in the community.

Each indicator is assigned a score between 0 and 1 where the low end of the scale represents a high level of vulnerability to change in water resources and the high end of the scale represents a high level of resilience to change in water resources, with the mid part of the scale representing the threshold between vulnerability and resilience (i.e., highly vulnerable, moderately vulnerable, threshold, moderately resilient, highly resilient). All indicators are weighted equally in the final calculation to avoid the value judgements required for such weightings. The constituent indices, sub-indices, and overall index is calculated using a simple averaging technique based on the following generic formula:

AWRVI = [AWRVIphysical + AWRVIsocial]/2

Physical sub-index = (natural supply indicators + municipal supply indicators + water quality indicators + permafrost indicator + subsistence habitat indicators) / 5

Social sub-index = (knowledge indicators + economic indicator + information capacity indicator + sensitivity change indicators) / 4

When applied to the three communities, the index proved informative as it provided a relative ranking of the overall vulnerability of each community and watersheds, the results of which were corroborated by independent experts. Notably, the index components were further useful as a diagnostic tool to understand which parts of the social-ecological system was most vulnerable or most resilient to disturbance. Given the success of this methodology at the watershed scale in the Arctic, the approach should be considered for use when assessing watersheds in the GLB.

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Glossary of Terms

Vulnerability: "*The degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude and rate of climate change and the variation to which a* [social-ecological] *system is exposed, its sensitivity and its adaptive capacity"* (Parry et al. 2007).

Exposure: *"A measure of the magnitude and extent (i.e., spatial and temporal scales) of exposure to climate change impacts."* (Nelitz et al., 2013). "The presence of people, infrastructure, and/or environmental resources (receptors) in areas subject to potential [impacts of climate change]" (NACCS, 2015).

Sensitivity: *"A measure of how a system is likely to respond when exposed to a climate Induced stress"* (Nelitz et al., 2013).

Stakeholder Engagement: In this report, 'stakeholder engagement' refers to the process by which a study involves people who provide knowledge and/or expertise on a particular subject matter or topic, relevant to the research in focus.

Adaptive capacity: 'the ability of a system to adjust to climate change – including climate variability and extremes – to moderate potential damages, to take advantage of opportunities, or to cope with the consequences' (McCarthy, et al., 2001).

Vulnerability Assessment: A process for assessing, measuring, and/or characterizing the exposure, sensitivity, and adaptive capacity of a natural or human system to disturbance (from Nelitz et al., 2013).

Top-down: Vulnerability assessments that use tools to predict future impacts – i.e. global climate models and downscaling approaches as inputs into biophysical models to predict impacts and vulnerabilities to inform climate change adaptation.

Bottom-up: Bottom-up approaches focus on understanding society's vulnerability to past and present-day climate change and what causes them to be sensitive and exposed in the first place. Bottom-up approaches are participatory in nature and are conducted at local levels and are more focused on current vulnerability rather than future vulnerability as with top-down approaches (Kalisch, 2014).

Integrated approach: a combination of the top-down and bottom-up approaches.

Appendix A - List of useful tools and resources for conducting vulnerability assessments

Scanning the Conservation Horizon: A Guide to Climate Change Vulnerability Assessment (2011)

- Guidance document produced to provide resource managers some background information and approaches to conduct vulnerability assessments.
- www.habitat.noaa.gov/pdf/scanning_the_conservation_horizon.pdf

National Wildlife Federation and EcoAdapt – Restoring the Great Lakes' Coastal Future: Technical Guidance for the Design and Implementation of Climate-Smart Restoration Projects (2014)

- Guidance document that provides an overview of adaptation principles, guidance for climate-smart restoration projects in the Great Lakes, and reviews experience from seven case studies.
- www.nwf.org/~/media/PDFs/Global-Warming/Climate-Smart-Conservation/2014/Restoring-the-Great-Lakes-Coastal-Future-032114.pdf

Great Lakes Coastal Wetland Communities: Vulnerabilities to Climate Change and Response to Adaptation Strategies (2006)
- www.env.uwaterloo.ca/research/aird/aird_pub/Great_Lakes_Coastal_Wetlands_Report_2006.pdf

ClimateWizard
- Enables technical and non-technical audiences alike to access leading climate change information and visualize the impacts any-where on Earth.
- www.climatewizard.org/
- Please note that the current version of ClimateWizard is based on older projections (CMIP3) and should be updated.

The National Conservation Training Center
- Offers in-person vulnerability assessment training and an online, self-paced version of the same training.
- nctc.fws.gov/courses/programs/climate-change/training-resources.html

NatureServe's Climate Change Vulnerability Index
- Helps identify plant and animals that are particularly vulnerable to the effects of climate change.
- www.natureserve.org/conservation-tools/standards-methods/climate-change-vulnerability-index

Climate Change Vulnerability Index for Ecosystems and Habitats

- Focuses on species and uses a scoring system that integrates a species' predicted exposure to climate change within an assessment area and three sets of factors associated with climate change sensitivity, each supported by published studies.
- www.natureserve.org/conservation-tools/data-maps-tools/climate-change-vulnerability-index-ecosystems-and-habitats

Changing Climate, Changing Wildlife A Vulnerability Assessment of 400 Species of Greatest Conservation Need and Game Species in Michigan (2013)
- Presents the results of a NatureServe CCVI analysis on 400 species of fish and wildlife in Michigan.
- www.michigan.gov/documents/dnr/3564_Climate_Vulnerability_Division_Report_4.24.13_418644_7.

Climate Change Response Framework
- A six-step framework process that is a collaborative, cross-boundary approach among scientists, managers, and landowners to incorporate climate change considerations into natural resource management.
- https://www.forestadaptation.org/our-approach/framework-overview

Vulnerability determination worksheet:
- As used in: Wisconsin Initiative on Climate Change Impacts [WICCI]. 2017. Climate Change Vulnerability Assessment for Great Lakes Barrens in Wisconsin. Climate Vulnerability Assessments for Plant Communities of Wisconsin. Wisconsin Initiative on Climate Change Impacts, Madison, WI. Available at: https://www.wicci.wisc.edu/resources/Great_Lakes_Barrens_CCVA.pdf
- **Worksheet adapted from:** Swanston, C., and M.K. Janowiak. 2012. Forest adaptation resources: Climate change tools and approaches for land managers. General Technical Report NRS-87. Newtown Square, Pennsylvania. http://www.nrs.fs.fed.us/pubs/40543

Confidence rating worksheet:
- As used in: Wisconsin Initiative on Climate Change Impacts [WICCI]. 2017. Climate Change Vulnerability Assessment for Great Lakes Barrens in Wisconsin. Climate Vulnerability Assessments for Plant Communities of Wisconsin. Wisconsin Initiative on Climate Change Impacts, Madison, WI. Available at: https://www.wicci.wisc.edu/resources/Great_Lakes_Barrens_CCVA.pdf
- **Worksheet adapted from:** Mastrandrea, M.D., C.B. Field, T.F. Stocker, O. Edenhofer, K.L. Ebi, D.J. Frame, H. Held, Elmar Kriegler, K.J. Mach, P.R. Matschoss, G. -K. Plattner, G.W. Yohe, and F.W. Zwiers. 2010. Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties. Intergovernmental Panel on Climate Change (IPCC). Geneva, Switzerland.

Appendix B - Description of research topics by study

Project Name	Author (s)	Project Affiliation	Project Description
Great Lakes water levels	Angel and Kunkel. 2010	Institute of Natural Resource Sustainability, (University of Illinois), and the Desert Research Institute	This study examined the potential future response of Great Lakes water levels using 565 model simulations from 23 GCMs used in the fourth IPCC report and three emission scenarios (A2, A1B, and B1) as input into the AHPS Great Lakes hydrology model developed by the Great Lakes Environmental Research Laboratory (GLERL).
Central Hardwoods ecosystem vulnerability assessment and synthesis	Brandt et al., 2013	US Department of Agriculture (USDA) Forest Service	This assessment evaluates key ecosystem vulnerabilities to a range of future climate scenarios across the Central Hardwoods Region of Missouri, Illinois, and Indiana.
Assessment of suitable habitat for *Phragmites* australis in the Great Lakes coastal zone	Carlson Mazur et al., 2014	Bellarmine University, School of Environmental Studies, USGS Great Lakes Science Center	This study analyses current and predicted suitable coastal habitat of the invasive plant Phragmites australis (common reed) using boosted regression trees, a type of species distribution modeling. They also investigated differential influences of environmental variables in the upper lakes (Lakes Superior, Michigan, and Huron) and lower lakes (Lakes St. Clair, Erie, and Ontario).
Ontario adaptive capacity and climate change assessment	Chiotti and Lavender. 2008	Natural Resources Canada	This chapter presents an assessment of the most significant issues expected in Ontario as a result of climate change. Included in the chapter is: an overview of key current and future environmental, demographic and economic conditions that influence vulnerability to climate change; information known about climate sensitivities, impacts and adaptive capacity for three subregions of the province; and a synthesis of results across subregions, identifying potential areas of greatest concern.
CCVA for aquatic ecosystems in the Clay Belt of Northeastern Ontario	Chu and Fischer. 2012	Ontario Ministry of Natural Resources and Forestry	Based on a vulnerability and adaptation framework, the main objective of this study was to identify vulnerability indicators for wetland, stream, and lake ecosystems in the Clay Belt of northeastern Ontario.
Great Lakes Basin inland aquatic ecosystems vulnerability assessment	Chu, C. 2015.	Ontario Ministry of Natural Resources and Forestry	The objectives of this study were to assess the vulnerability of different indicators to inform the development of a climate change adaptation strategy for aquatic ecosystems within the GLB of Ontario.
Lake Simcoe and the wetlands and streams within the watershed	Chu. 2011	Ontario Ministry of Natural Resources and Forestry	The objectives of this study were to 1) use ecological indicators to assess the potential effects of climate change on wetlands and streams in the Lake Simcoe watershed and 2) apply those results to inform the development of a climate change adaptation strategy for aquatic ecosystems within the Lake Simcoe Watershed.
Climate Change as a long-term stressor for the	Collingsworth et al., 2017	Purdue University, U. S. Geological Survey (Great Lakes Science Center),	Using the Integrated Catchment Model (INCA-P) and the Canadian coupled ocean-atmosphere Global

fisheries in the Great Lakes		National Wildlife Federation, Michigan Department of Natural Resources, National Oceanic and Atmospheric Administration (NOAA), The Ohio State University, and Michigan State University	Climate Model 3 (CGCM3) this study aims to: 1) Identify the impact of climate change on hydrology and water quality of the Black River, a tributary of Lake Simcoe 2) Assess the implications of any changes for the future of Lake Simcoe, and 3) Evaluate the potential success of future management strategies under a changing climate.
Future proofing management strategies in the Lake Simcoe watershed	Crossman et al. 2013	University of Oxford, Trent University, Swedish University of Agricultural Science, State University of New York at Cortland, School of Environment and Sustainability and Global Institute for Water Security (University of Saskatchewan)	This study assesses the impacts of climate change on hydrology and water quality of the Black River, a tributary of Lake Simcoe, Canada, were assessed for the period 2001–2100.
Minnesota Ecological Limits of Hydrologic Alteration study	Herb et al. 2016	Natural Resources Research Institute (UMD), The Nature Conservancy, Minnesota Department of Natural Resources (Minnesota's Lake Superior Coastal Program), and Minnesota Sea Grant. Funds were provided by the Great Lakes Restoration Initiative and NOAA.	This study explored the relationships between water quantity and the health of fish and invertebrates in Minnesota's Lake Superior tributaries to determine how vulnerable these streams may be in the future.
Vulnerability assessment of 400 species of greatest conservation need and game species in Michigan	Hoving, C. L. et al., 2013	Michigan Department of Natural Resources	This study is an extension of Lee et al., 2011. This study assessed the vulnerability of 400 animal species to climate change using the Climate Change Vulnerability Index (CCVI) developed by NatureServe.
Michigan Tribal Climate Change Vulnerability Assessment and Adaptation Planning	Inter-Tribal Council of Michigan Inc. 2016.	Inter-Tribal Council of Michigan Inc.	The objective of this report was for Michigan Tribes to identify vulnerable regions (natural resources, infrastructure, plant, fish, wildlife species, natural features, public health) to climate change impacts, and from here to create policies and an adaptation strategy based on the results.
Climate Change Vulnerability Assessment of Natural Features in Michigan's Coastal Zone - Phase 1: Assessing Rare Plants and Animals	Lee, Y. et al. 2011	Michigan Natural Features Inventory, Michigan Coastal Management Program - Office of the Great Lakes, Michigan State University Extension	To assist in climate change adaptation efforts, the Michigan Natural Features Inventory (MNFI) in collaboration with the Michigan Coastal Management Program initiated a two-year project to assess the vulnerability of natural features in Michigan's coastal zone to climate change, focusing on rare plant and animal species and natural communities.

Making of a Watershed-scale CCA Strategy	Lemieux et al. 2014.	Wilfrid Laurier University, Ontario Ministry of Natural Resource, Ontario Centre for Climate Impacts and Adaptation Resources (OCCIAR), Laurentian University	This paper describes the approach, methods, and results of a multi-partner pilot project that was used to assess vulnerabilities of natural and built systems to climate change and develop adaptation options for inclusion in a climate change adaptation strategy for the Lake Simcoe Watershed in Ontario.
Lake Simcoe Water Quality/Quantity VA	MacRitchie and Stainsby. 2010	Ontario Ministry of the Environment	In this study, researchers assessed the impact of climate change on the hydrologic cycle in the Lake Simcoe watershed.
GL Coastal Wetland VA	Mortsch et al. 2006	Environment Canada, Fisheries and Oceans Canada, and the University of Waterloo	Researchers in this study undertook a collaborative research project to assess the vulnerability of selected wetlands on Lake Ontario (Presqu'ile Bay, Hay Bay, Lynde Creek, and South Bay wetlands), Lake Erie (Long Point, Turkey Point, Dunnville, and Rondeau wetlands), and Lake St. Clair (Mitchell's Bay) to climate change.
Binational VA of migratory birds	Rempel and Hornseth. 2017.	Ontario Ministry of Natural Resources and Forestry	This study explored tools and impediments to understanding and responding to the effects of climate change on vulnerability of migratory birds from a binational perspective.
Climate Change Adaptive Capacity Assessment - Agriculture and Hydrology - Lake Simcoe Watershed	Richard and Douglas. 2014	Ontario Centre for Climate Impacts and Adaptation Resources (OCCIAR)	This assessment was based off of a number of climate change vulnerability assessments conducted in 2010 in the Lake Simcoe Watershed. This report aims to build on the agriculture and hydrology themes, and assesses the adaptive capacity of agriculture, and water quality and quantity in the subwatershed of Lake Simcoe.
FishVis, Regional Vulnerability Assessment Decision Support Tool	Stewart et al. 2016	Michigan State University, Michigan Department of Natural Resources Institute of Fisheries Research, and the Wisconsin Department of Natural Resources	This report documents the approach and data used to predict and project fish species occurrence under present-day and future climate conditions for 13 lotic fish species in the United States Great Lakes Basin.
Natural Systems Vulnerability to Climate Change in Peel Region	Tu et al., 2017.	Toronto Conservation Authority and the Ontario Climate Consortium Secretariat	This vulnerability assessment studies the impacts of climate change on natural systems in the Region of Peel.
North Atlantic Coast Comprehensive Study: Resilient Adaptation to Increasing Risk	US Army of Corps of Engineers, 2015.	US Army Corps of Engineers and the National Research Council	This study assesses the vulnerability of populations infrastructure, and resources at risk throughout more than 31, 200 miles of the North Atlantic coastal region. The study is intended for communities to identify their flood risks, and plan and implement strategies in collaboration with others, to reduce that risk now and into the future.
Great Lakes Barrens CCVA	Wisconsin Initiative on Climate Change Impacts. 2017.	Wisconsin Department of Natural Resources	This assessment is one of 10 conducted by the Wisconsin Department of Natural Resources Natural Heritage Conservation Program used to evaluate the potential impacts of climate change on over 50 natural communities.

Appendix C - List of data and data sources by study

Author(s)	Data Sources
Angel and Kunkel. 2010	Potential future changes in climate over the Great Lakes region were derived from the latest set of global climate model simulations produced for the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) (IPCC, 2007a). Model data were obtained and information for the Great Lakes region extracted for the 20th and 21st centuries. In this study, simulations for three emission scenarios (Nakicenovic et al., 2000). Additional models are employed for channel routing (Hartmann, 1988), lake regulation (International St. Lawrence River Board of Control, 1963),diversions, and water consumption (International Great Lakes Diversions and Consumptive Uses Study Board, 1981). Croley (2005) describes AHPS in greater detail. AHPS has been used to make probabilistic hydrologic outlooks of the Great Lakes based on long-range outlooks of temperature and precipitation (GLERL, 2008) as well as several studies of climate change impacts (e.g., Lofgren et al., 2002; Croley and Lewis, 2006).
Brandt et al., 2013	Tree distribution data from the US Forest Service, Forest Inventory and Analysis, which can be found at: https://www.fia.fs.fed.us/tools-data/. Climate variables (daily temperatures, precipitation, wind speed, and solar radiation, soil moisture capacity for multiple soil layers, wilting point, percentage of rock, percentage of clay, percentage of sand, initial organic matter, and nitrogen contents) obtained from weather station observations were also used for model inputs.
Carlson Mazur et al., 2014	*Phragmites* occurrence data was obtained from a recent, basin-scale mapping effort performed from radar images collected between 2008-2010 within a 10-km inland buffer of the Great Lakes shoreline. Their response variable (*Phragmites* presence/absence) resulted from the mapping methodology of Bourgeau-Chavez et al. (2013). To produce the *Phragmites* map, Bourgeau-Chavez et al. (2013) relied primarily on the field-verified classification of radar data but, to reduce class confusion, also utilized manual editing guided by aerial imagery and a land cover- based filter constructed from the 2006 National Oceanic and Atmospheric Administration's Coastal Change Analysis Program (C-CAP) (NOAA 1995-present) and the 2009 United States Department of Agriculture's Cropland Data Layer (CDL) (USDA 2009). Existing geospatial data that spanned the entire study area were analyzed in a GIS (ESRI ArcGIS Desktop version 9.3 and 10.0) to determine the independent variables to include in our models. Variables were considered that either directly described environmental conditions pertinent to *Phragmites* distribution or that could act as surrogates where equivalent data were either unavailable or difficult to define in a spatially explicit manner. As implemented in the SDM, our environmental variables fell into one of six categories: topography, disturbance, ecoregion, soils, nutrients, and climate. All variables included native data taken directly from the source with the exception of the following derived variables: road density (RoadDens); proximity to agriculture (ProxAg), development (ProxDev), and land-cover change (ProxLCC); and topographic roughness (TopoRough).
Chiotti and Lavender. 2008	This article produced graphs and maps of Ontario with various climate change scenarios, using the GCM. The rest of the data used to produce this report consisted of literature of climate change adaptation articles.
Chu and Fischer. 2012	Land cover 2000 (OMNR 2000) was used to identify and map the wetlands within the Clay Belt in ArcGIS® 9.2 (Environmental Systems Research Institute Inc., Redlands, California, USA). The change in growing season (April to September) air temperatures and total precipitation from current conditions for the climate scenarios were spatially joined to the wetland polygons in ArcGIS. Area-weighted base flow index values were calculated for each of the wetland polygons, again using ArcGIS. Lakes greater than 0.1 km2 (n = 1,313) (to avoid including ponds in the analyses) were selected from the Ontario Provincial Hydrometric Network (OMNR 2010) using ArcGIS. Mean July and mean annual air temperatures were calculated using ArcGIS for each of the lakes for present and future conditions. These values were used to project maximum surface water temperatures and thermal habitat for smallmouth bass in the lakes.
Chu, C. 2015.	Current climate conditions were estimated using the 1971-2000 climate normals from McKenney et al. 2010. The ensemble estimates represented air temperature and precipitation changes predicted from the Canadian Coupled Global Climate Model 3 (CGCM-3), U.S. National Center for Atmospheric Research (NRCAR-3) model, Japanese Model for Interdisciplinary Research on Climate (MIROC32) and Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO) models, and has been endorsed by the Intergovernmental Panel on Climate Change (IPCC 2007, Lalonde et al. 2012). Maximum annual, mean July air temperature, growing season mean, and total precipitation in the growing season were used to project the changes in the indicators (McKenney et al. 2010; Lalonde et al. 2012).Mapped wetlands were acquired from the Ontario Ministry of Natural Resources and Forestry (OMNRF) Wetland unit layer within the Land Information Ontario (LIO) database (OMNR 2011). Used Hydrological Vulnerability Index (HVI) developed by Mortsh et al. (2006). American coot and pied-billed grebe data were acquired from the Ontario Breeding Bird Atlas of Bird Studies Canada, in which presence data are represented by -10 km x 10km grids (BSC 2008).

	The ensemble climate change model provided the maximum air temperatures used in the analyses. Streams, slopes, and Shreve values of the streams were acquired from the OMNRF's Integrated Hydrology (OMNR 2013). Cold, cool, and warm water habitat were defined as streams having MWAT's of <19°C, >19s25°C and >25°C, respectively based on a national synthesis of the life history characteristics of Canadian fishes (Coker et al. 2001). A provincial model developed by Lester et al. (2004) was used to estimate the changes in walleye biomass.
Chu. 2011	Temperature profile data (temperatures at 1 m depths) for the OMOE station K42 in Kempenfelt Bay (the deepest part of the lake) were used to complete the analysis. These temperature data spanned 1980 to 2009; end of summer (September 15th) temperatures were used to calculate the current mean temperature profile. That is, temperatures at each 1 m depth interval were averaged across the 1980 to 2009 period to produce a single temperature profile that represented the average end of summer temperature profile for K42. Mean September air temperature data from 1980 to 2009 were obtained from the Barrie Water Pollution Control Centre climate station and used to calculate water temperatures at the lake surface from air temperatures ($y= 0.63x + 8.28$, $r2 = 0.37$, $p = 0.001$). This equation was used to predict surface water temperatures under the CGCM2 A2 scenario for the 2011-2040, 2041-2070, and 2071-2100 periods. These surface water temperature values were entered into Equation 1 to predict future temperature profiles for Lake Simcoe.
Collingsworth et al., 2017	Previous literature.
Crossman et al. 2013	A list of key input parameters, and associated sources of data required for the calibration of INCA-P is available in Table 1. Two weather stations were used to obtain the time series of precipitation and temperature. The Baldwin station in the Black River catchment had only data from 1994 onward, so was supplemented with data (1992–1993) from the Udora station in the neighbouring Pefferlaw Brook catchment. Both weather stations are monitored by Environment Canada. A Water Survey Canada (WSC) gauging station near the river mouth supplied the flow data used in the modelling process.
Herb et al. 2016	Numerous data sources were compiled and considered for use in this project. The authors provide a companion to the report with the data, which can be found at: http://data.nrri.umn.edu/data/dataset/eloha.
Hoving, C. L. et al., 2013	The authors used the MNFI Natural Heritage Database, MNFI species abstracts, MNFI Rare Species Exploder, NatureServe Explorer, Michigan GAP data, and other references in literature (Michigan Breeding Bird Atlas, Michigan Fish Atlas).
Inter-Tribal Council of Michigan Inc. 2016.	There is no scientific data that was acquired for this report, however, data was collected by working with community members and cultural leaders to identify culturally and socio-economically important fish, wildlife, and plant species, natural features, cultural activities, human health risks, and infrastructure/community development resources.
Lee, Y. et al. 2011	Identification of endangered species: the Michigan Natural Features Inventory's (MNFI) Natural Heritage Database, MNFI's species abstracts, MNFI Rare Species Explorer, NatureServe Explorer, the Species of Greatest Conservation Need (SGCN) in Michigan's Wildlife Action Plan (WAP), other relevant literature and references (e.g. Michigan Breeding Bird Atlas, Michigan Fish Atlas).
Lemieux et al. 2014.	This project used a heterogeneous cross-section of 74 experts and policy-makers. The selection of participants followed broad guidelines set out by Smit et al. (2000) and others *e.g., Franca Doria et al. 2009).
MacRitchie and Stainsby. 2010	The monthly temperature and precipitation projections from the Canadian Global Climate Model (CGCM) version 3.1 using the A2 scenario has been used per the guidance received for this analysis. Monthly temperature and precipitation projections for the period 2071 - 2100 were used as input to a simple water balance model (McCabe and Markstrom, 2007) to determine potential impacts on the hydrologic cycle. The nine indicators used to evaluate the 18 subwatersheds in the Lake Simcoe watershed were determined through a review of a compendium of reports prepared by the Lake Simcoe Science Advisory Committee (2008). The sources of the data for the indicators included: 1. Louis Berger Group Inc., 2010. Estimation of the Phosphorus Loading to Lake Simcoe. Report prepared for Lake Simcoe Conservation Authority, September 2010; 2. South Georgian Bay-Lake Simcoe Source Protection Committee, 2010. Draft Proposed Assessment Report, Chapter 3: Water Budget and Water Quantity Assessment Chapter; 3. Data and GIS layers provided by the Lake Simcoe Region Conservation Authorities. Information and data about the quality and quantity of the Lake Simcoe water sector are available from recent reports such as: OMOE Lake Simcoe Water Quality Update, (Young et al. 2010) LSRCA, OMOE (2009) Report on the phosphorus loads to Lake Simcoe 2004–2007. Lake Simcoe Region Conservation Authority and Ontario Ministry of the Environment

	Joint Report
Mortsch et al. 2006	Field surveys were conducted of bird community response to hydrologic change and fish assemblage response to hydrologic and thermal changes. Air photo analysis and field work on understanding the relationships between Lake Ontario water level fluctuations and wetland plant, bird, and fish communities undertaken in support of the current IJC Lake Ontario-St. Lawrence River (LOSLR) Study contributed to this project (DesGranges et al. 2005; Doka et al. 2005; Wilcox et al. 2005).
Rempel and Hornseth. 2017.	Reviewed literature on species biology, population and range trends, and climate modeling.
Richard and Douglas. 2014	The authors obtained data from: the Agricultural Census 2011 (Statistics Canada, 2012), Subwatershed Plans (Lake Simcoe Region Conservation Authority available at http://lsrca.on.ca/reports/), Source Water Protection Assessment Reports for Lake Simcoe (available at http://www.ourwatershed.ca/documents/assessment_reports/approved_assessment_reports.php), Lake Simcoe Clean Up Fund (available at http://www.ourlakesimcoe.com/), Lake Simcoe.com, Municipal websites, and various reports (available at http://lsrca.on.ca/reports/) and data from the Lake Simcoe Region Conservation Authority.
Stewart et al. 2016	Data on fishes and environmental characteristics were compiled for 5,627 sites in the Great Lakes region and used to develop empirical models of species occurrence for 13 lotic fish species that represent the three ecological thermal guilds (cold, cool, and warm). Environmental characteristics were compiled for all stream reaches in the study area, and models and thermal thresholds were applied to predict present-day fish species occurrence for all reaches, most of which were unsampled. 1:100,000 scale National Hydrography Dataset Plus version 1 (NHDPlusV1) (USGS, 2010) served as the spatial framework to which all environmental and biological data were attributed.
Tu et al., 2017.	The data used for this report was collected through literature reviews, interviews and workshops with various stakeholders.
US Army of Corps of Engineers, 2015.	National (US) datasets of population, infrastructure, social vulnerability, factors of the population, and environmental and cultural sensitivities. Datasets of climate-related data that was incorporated into the SLOSH model (sea levels, winds, storm frequency, impacts of past flooding events, general circulation models - temperatures and precipitation, etc).
Wisconsin Initiative on Climate Change Impacts. 2017.	The Climate Change Tree Atlas from the WICCI Plants and Natural Communities working group website was used. More information can be found here: http://www.wicci.wisc.edu/resources/WICCI_Explanation_of_Tree_Atlas_model.pdf. A full review of how the vulnerability assessment was conducted can be found here: http://www.wicci.wisc.edu/resources/WI_Natural_Community_CCVA_Process.pdf.

Appendix D - Recommended adaptation actions by study

Author(s)	Recommended Adaptation Actions
Brandt et al., 2013	While the authors did not provide their own recommendations, they summarized where more information could be found for the readers (e.g. to learn more about species of concern, the authors suggest that the readers go to the Chicago Botanic Garden and Missouri Botanical Garden websites for more information on their current policies and strategies and to participate in the public consultation meetings. The authors also give management advice moving forward with the vulnerability assessment - education and public outreach are both vital to adaptation for the Central Hardwoods Region, as the public can be aware of future changes, and can adjust their crops, and create urban forests.
Chiotti and Lavender. 2008	Many recommendations that were in this report, such as: mainstream adaptation to climate change into decision-making through policies and programs that deal with infrastructure renewal, low water programs, and growth strategies (e.g. the Clean Water Act), develop and implement adaptation plans/strategies (similar to the plans recommended for First Nation communities and health infrastructure) that include: stakeholder engagement, monitoring and surveillance, education, and partnership building.
Chu and Fischer. 2012	Recommendations are made for for wetlands, streams, and lakes. **Wetlands** • Broad-scale data, not currently available for wetland types (e.g., bogs, fens, marshes etc.) throughout the Clay Belt, need to be collected to effectively determine the fate of wetlands as the climate changes. • A network of monitoring stations needs to be established in Clay Belt wetlands to support the detection of changes in wetland extent and quality. • Wetland species (e.g., waterfowl and amphibians) need to be monitored to determine the effect of changes in wetland extent on their distribution and populations. **Streams** • Currently, only two HYDAT (Water Survey of Canada) stations exist in Ecodistrict 3E-1. This network needs to be expanded to ensure that accurate baseline flows, and temperatures and water levels of streams are established and changes monitored. • Thirty-two of the 90 quaternary watersheds in the Clay Belt have no readily available stream fish data. A water quality monitoring network that includes a fish and benthic invertebrate inventory should be established for streams. • Data from hydropower environmental assessment reports could be compiled and used to help inform the development of a stream monitoring network throughout the Clay Belt. **Lakes** • Continued support of the broad-scale monitoring program is necessary to establish present conditions of lakes in the Clay Belt and monitor changes over time. Broad-scale sampling should be maintained and if possible expanded. Broad-scale sampling allows for the monitoring of water quality as well as zooplankton and fish populations. • A better understanding of the natural and anthropogenic processes driving invasive fish species expansions would help inform the management and/or control of those species.
Chu, C. 2015.	Recommendations for land use management and planning; habitat restoration, expansion and protection; invasive species eradication/management; water level regulation; human activities, and monitoring.
Chu. 2011	• Continue to prevent infilling and draining activities in wetlands • Continue to regulate surface and groundwater withdrawals to ensure wetland water budgets are maintained • Rehabilitate wetlands through large-scale projects such as restoring riparian buffers and flow through streams buried on agricultural lands or small-scale projects such as tree planting • Introduce or extend riparian buffers adjacent to streams to provide shading that reduces stream temperatures in response to climate-induced warming and to buffer the stream against deleterious runoff • In regulated streams, consider converting dams and storm water ponds to bottom-draw systems so cooler waters drain into downstream reaches • Consider limiting land-use (particularly activities that cause impervious surface cover) that can change fluvial and thermal regimes • Limit or regulate groundwater and surface water withdrawals to maintain flow and temperatures in the streams. • To adapting to the effects of climate change on suitable habitat for lake biota, also regulate surrounding land use, particularly discharges such as sewage effluent and phosphorus loadings that may compromise water quality • For coldwater fish species, adjust fishing regulations such as catch limits, slot size limits, season lengths, and protected areas

Collingsworth et al., 2017	Since adaptation research in fisheries of freshwater lakes is still new, the authors discuss the possible adaptation actions that could be used, and review the literature on it, such as ecosystem-based adaptation to fisheries management in the Great Lakes. The authors then emphasize the importance of incorporating the complicated nature of fisheries management in the Great Lakes region - including eight states, a Canadian province, and several tribal entities, two federal governments, and the binational Great Lakes Fishery Commission. The authors then go over municipal and public management documents that consider climate change in their documents (e.g. Ontario's provincial fish strategy, the Ohio Department of Natural Resources-Division of Wildlife's fisheries tactical plan, the Great Lakes Indian Fish and Wildlife Commission's multiple fisheries projects, the Michigan Department of Natural Resources' vulnerability assessment on 400 fish and wildlife species). The authors also stress the need for a link between ecological and social systems on broader fisheries management challenges.
Crossman et al. 2013	The authors include model management scenarios, which assess the effectiveness of mitigation measures in the Black River catchment during 2001–2009, were developed by Whitehead et al. (2011). Strategies for management included limiting sewage loads from treatment works to 35 kg P/year, as set out in the Lake Simcoe Phosphorus Reduction Strategy (2010), controlling TP loading from fertiliser and manure to within 16.7 kg P/ha/year, and implementing a set of sediment control measures, such as buffer strips and bank erosion controls.
Herb et al. 2016	The authors provide 17 adaptive management objectives focused on increasing resilience, such as maintaining and restoring riparian and instream connectivity, establishing ecological buffer zones around natural features, and encouraging stewardship groups to protect and rehabilitate aquatic habitat, riparian zones, and wetlands.
Inter-Tribal Council of Michigan Inc. 2016.	The report includes a Strategic Adaptation Planning section, where the authors provide recommended adaptation actions and adaptation strategies. The most fundamental adaptation actions include the concepts of resistance, resilience, and response. Adaptation strategies include modeling and monitoring to assess the impacts of climate change and reducing the risk of negative impacts. Data retrieved from monitoring can be used to plan and implement effective adaptation actions. Specific adaptation actions identified were land and water management for the benefit of communities, ecological communities, natural features, or infrastructure; new or modified policies, new or modified technologies, and community engagement and outreach.
Lemieux et al. 2014.	The authors used Policy-Delphi survey and Likert-type scale to support development of adaptation options. The 43 respondents to the first-round survey submitted more than 900 ideas on adaptation options based on the vulnerability assessment results. Options ranged from bulleted lists of action items to detailed descriptions in paragraph form. The planning team reviewed the 900+ ideas, eliminated redundancies using content analysis, and drafted 85 first-order priority options and 48 second-order priority options. On the basis of a review and prioritization of the 85 options completed by workshop participants, the planning team drafted a final suite of 30 options to inform development of the climate change adaptation strategy.
MacRitchie and Stainsby. 2010	The authors include recommendations for water conservation and management; protection/enhancement of groundwater recharge areas; reforestation; protection/enhancement of wetland areas; enhancement of phosphorus reduction strategies; enhancement of snow and ice monitoring; sewage treatment plant evaluation; water infrastructure development and management (e.g. low impact development).
Mortsch et al. 2006	The authors include recommendations for lake-wide water level regulation; evaluation of current wetland dyking effects; and land use planning. The main recommendation resulting from the review of planning needs and the current situation is development of a natural coastal corridor and Ten Planning Criteria.
Rempel and Hornseth. 2017.	The authors suggested increased cross-border collaboration to enhance the availability and resources needed to improve vulnerability assessments and development of conservation strategies.
Tu et al., 2017.	The authors do not discuss adaptation actions directly, however, they provide resources to improve adaptive capacity and they also provide management options.
US Army of Corps of Engineers, 2015.	The majority of this report discusses opportunities for climate change adaptation, including: improved land use, wise use of floodplains, responsible evacuation planning, strategic retreat, communities to plan for long-term, comprehensive and resilient risk management, building new partnerships, strengthening pre storm planning, collaboration among local, regional, Tribal, State and Federal entities, NGOs, academia, business, and industries.

Appendix E - Themes present in the literature

Project name	Author(s)	Theme(s) present
Great Lakes water levels	Angel and Kunkel. 2010	Drinking water, Lakewide Management, Water level, Water Quantity
Central Hardwoods ecosystem vulnerability assessment and synthesis	Brandt et al., 2013	Habitat and Species, Aquatic Invasive Species (non-aquatic invasives), Nutrients and Algae, Lakewide Management
Assessment of suitable habitat for Phragmites australis in the Great Lakes coastal zone	Carlson Mazur et al., 2014	Habitats and Species, Aquatic Invasive Species, Toxic Chemicals, Nutrients and Algae, Beaches, Discharges from Vessels, Lakewide Management, Water Quantity
Ontario adaptive capacity and climate change assessment	Chiotti and Lavender. 2008	Habitats and Species, Water and Groundwater Quality, Nutrients and Algae, Watershed Impacts, Drinking Water, Water Level, Water Quantity
CCVA for aquatic ecosystems in the Clay Belt of Northeastern Ontario	Chu and Fischer. 2012	Habitats and Species, Watershed Impacts,
Great Lakes Basin inland aquatic ecosystems vulnerability assessment	Chu, C. 2015.	Habitats and Species, Water and Groundwater Quality
Lake Simcoe and the wetlands and streams within the watershed	Chu. 2011	Habitats and Species, Water and Groundwater Quality, Nutrients and Algae, Watershed Impacts, Lakewide Management, Water Level, Water Quantity
Climate Change as a long-term stressor for the fisheries in the Great Lakes	Collingsworth et al., 2017	Habitats and Species, Aquatic Invasive Species, Nutrients and Algae, Lakewide Management, Water Level,
Future proofing management strategies in the Lake Simcoe watershed	Crossman et al. 2013	Habitats and Species, Aquatic Invasive Species, Toxic Chemicals, Water and Groundwater Quality, Nutrients and Algae, Drinking water & Discharges from Vessels (sewage treatment/stormwater run-off), Lakewide Management
Minnesota Ecological Limits of Hydrologic Alteration study	Herb et al. 2016	Habitats and Species, Watershed Impacts, Lakewide Management, Water Quantity
Vulnerability assessment of 400 species of greatest conservation need and game species in Michigan	Hoving, C. L. et al., 2013	Habitats and Species, Aquatic Invasive Species, Water Level, Water Quantity
Michigan Tribal Climate Change Vulnerability Assessment and Adaptation Planning	Inter-Tribal Council of Michigan Inc. 2016.	Habitats and Species, Aquatic Invasive Species, Watershed Impacts

Climate Change Vulnerability Assessment of Natural Features in Michigan's Coastal Zone - Phase 1: Assessing Rare Plants and Animals	Lee, Y. et al. 2011	Habitats and Species, Aquatic Invasive Species, Water Level, Water Quantity
Making of a Watershed-scale CCA Strategy	Lemieux et al. 2014.	Habitats and Species, Discharge from Vessels, Lakewide Management, Water Level
Lake Simcoe Water Quality/Quantity VA	MacRitchie and Stainsby. 2010	Habitats and Species, Water and Groundwater Quality, Nutrients and Algae, Watershed Impacts, Beaches, Water Level
GL Coastal Wetland VA	Mortsch et al. 2006	Habitats and Species, Aquatic Invasive Species, Watershed Impacts, Beaches, Discharges from Vessels, Lakewide Management, Water Level
Binational VA of migratory birds	Rempel and Hornseth. 2017.	Habitats and Species
Climate Change Adaptive Capacity Assessment - Agriculture and Hydrology - Lake Simcoe Watershed	Richard and Douglas. 2014	Water and Groundwater Quality, Watershed Impacts, Drinking Water, Water Level, Water Quantity
FishVis, Regional Vulnerability Assessment Decision Support Tool	Stewart et al. 2016	Habitats and Species
Natural Systems Vulnerability to Climate Change in Peel Region	Tu et al., 2017.	Habitats and Species, Aquatic Invasive Species, Toxic Chemicals, Water and Groundwater Quality, Nutrients and Algae, Watershed Impacts, Drinking Water & Discharge from Vessels & Lakewide Management (wastewater treatment effluent), Water Level, Water Quantity
North Atlantic Coast Comprehensive Study: Resilient Adaptation to Increasing Risk	US Army of Corps of Engineers, 2015.	Water and Groundwater Quality, Watershed Impacts, Beaches, Drinking Water, Water Level, Water Quantity
Great Lakes Barrens CCVA	Wisconsin Initiative on Climate Change Impacts. 2017.	Habitats and Species, Aquatic Invasive Species (non-aquatic invasives), Beaches, Lakewide Management, Water Level