PRIORITIZING CLIMATE SCIENCE KNOWLEDGE GAPS IN THE GREAT LAKES WATER QUALITY AGREEMENT

ONTARIO CLIMATE CONSORTIUM

Supported by Toronto and Region Conservation Authority

Prepared for:

Environment and Climate Change Canada

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Executive Summary

In 2015, the Ontario Climate Consortium (OCC) published a report titled, “State of Climate Change Science in the Great Lakes basin: A Focus on Climatological, Hydrological and Ecological Effects”, for Annex 9, Climate Change Impacts, of the Great Lakes Water Quality Agreement (GLWQA). This report synthesized available science of climate change and summarized 43 climate science knowledge gaps that could be potential priorities for research within the Great Lakes basin. Using these as a foundation, several Annex engagements were undertaken in 2017 and 2018, namely:

- An online survey to obtain preliminary input on the validity and level of work related to the knowledge gaps (early 2017);
- An interactive webinar to review all preliminary results and seek input on suggested priorities for moving forward (late 2017); and
- A series of telephone interviews with Annex co-leads and members to obtain targeted input and to refine climate science knowledge gaps in relation to the specific Annex (early 2018).

The aim of this report is to document all results and analyses completed to date and to produce refined, vetted priorities of climate science knowledge gaps across the GLWQA. Based on all engagements with Annexes to date, priorities were assigned as preliminary in 2017, and then further marked as “final” in early 2018 based on how important a particular knowledge gap was stated to be for a particular Annex and the level of work occurring to address the gap (low, medium, or high). The 2017-2019 Great Lakes binational priorities for science and action were used as one component of analysis to identify:

- **Short-Term Priority Gaps**: Fifteen of the total 43 knowledge gaps are directly relevant to Annexes currently and within the next two years (short-term priorities); and
- **Long-Term Priority Gaps**: The remaining 28 knowledge gaps are still assigned priorities along with potentially relevant Annexes whose objectives may align as future work plans are developed.

This report also provides a framework for Annex 9 to consider, in order to begin tackling some of the short-term, broad-reaching climate science knowledge gaps. This framework is illustrated on the following page (Figure E-1).

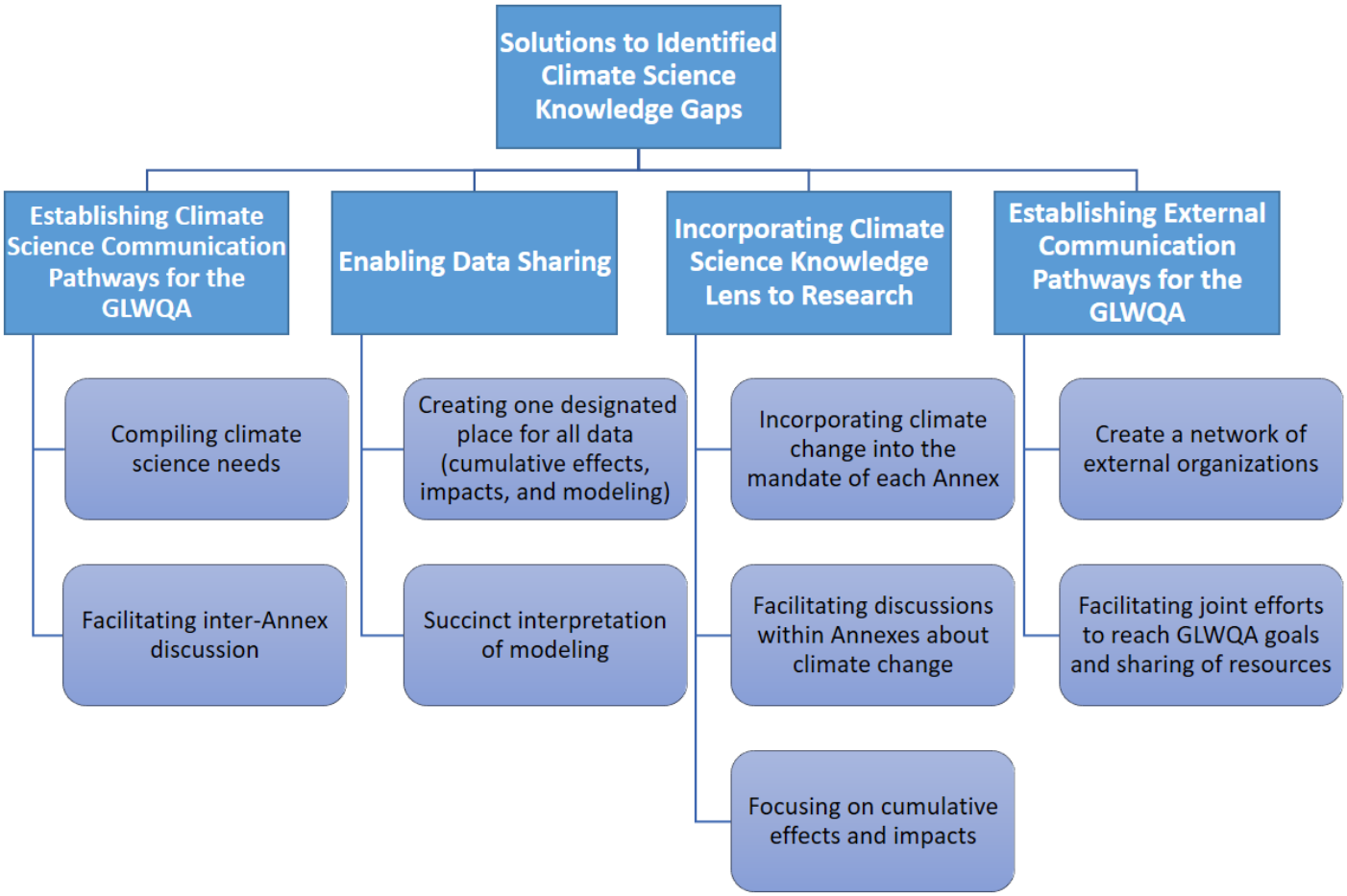

Figure E-1: A Framework for Moving Forward on Addressing Climate Science Knowledge Gaps in the Great Lakes basin.

The four main recommendations and sub-goals for Annex 9 are as follows:

1. Establishing climate science communication pathways;
    a. Compiling climate science needs (e.g., a report that summarizes all the climate science needs within the GLWQA. This report aims to complete this sub-goal).
    b. Facilitating inter-Annex discussions (e.g., identifying overlapping climate science needs to help facilitate inter-Annex discussions on work to be completed).
2. Enabling data sharing;
    a. Creating one designated place for data (e.g., a website or report where all available Great Lakes basin data sets and models, as well as an index of current data and modeling portals, to inform relevant Annexes for useful information).

   b. Succinct interpretation of modeling (e.g., summaries attached to data sets or models that highlight climate change trends change would help to bridge the gap between modeling and data analysis to policy-making).
   c. Incorporating climate science knowledge lens to research; and
3. Including climate change mandates into the GLWQA for each Annex (e.g., incorporating actionable climate change items into the mandates of every Annex will help move climate science to the foreground, and will help with inter-Annex discussions).
   a. Facilitating discussions within Annexes about climate change (e.g., Annex 9 could act as a climate change contact that Annexes could contact for guidance on incorporating climate science outside their own scope).
   b. Focusing on cumulative effects and impacts (e.g., the impacts of climate change on water chemistry, the impacts of changing water levels on fish populations and invasive species, etc. There are many unknowns on climate change, therefore focus should be given to this subject, to benefit all Annexes).
4. Establishing external communication pathways
   a. Create a network of external organizations (e.g., municipal, provincial, state, and federal governments, non-governmental organizations, the private sector, universities, and other stakeholders to build a network of parties with similar interests to protect the waters of the Great Lakes).
   b. Facilitate Joint Efforts to Reach GLWQA Goals and Sharing of Resources (e.g., knowledge sharing, resource sharing, and combined monitoring efforts, all of which would be made possible with increased communication).

These are scoped in finer detail in this report, along with summaries of specific Annex work, climate change initiatives, and research to help in filling some of the short-term and long-term climate science knowledge gaps within the GLWQA.

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Acknowledgments

This report was made possible through Environment and Climate Change Canada. It was written based on the expert testimony of individuals who work to fulfill the mandates of each Annex of the Great Lakes Water Quality Agreement. These individuals include Annex co-leads, individuals who work for governmental organizations in Canada and the U.S., as well as many others who are key contributors to each Annex. With that said, information gathered and presented in this report does not necessarily reflect the official stance of Annexes but rather the valuable opinions of key stakeholders in the accomplishment of the commitments of the Great Lakes Water Quality Agreement.

Suggested Citation

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Acronyms

AIS	Aquatic Invasive Species
AOC	Area of Concern
BUI	Beneficial Use Impairments
CMCs	Chemicals of Mutual Concern
CO2	Carbon Dioxide
DFO	Department of Fisheries and Oceans
DOC	Dissolved Organic Carbon
ECCC	Environment and Climate Change Canada
EPA	United States Environmental Protection Agency
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GLAHF	Great Lakes Aquatic Habitat Framework
GLB	Great Lakes Basin
GLC	Great Lakes Commission
GLISA	Great Lakes Integrated Sciences and Assessment
GLWQA	Canada-United States Great Lakes Water Quality Agreement
HBCD	Hexabromocyclododecane
IJC	International Joint Commission
IPCC	Intergovernmental Panel on Climate Change
LAMPS	Lakewide Action and Management Plans
LC-PFCA	Long-chain Perfluorinated Carboxylic Acids
MNRF	Ontario Ministry of Natural Resources and Forestry
MOECC	Ontario Ministry of Environment and Climate Change
NCP	Northern Contaminants Program
NOAA	United States National Oceanic and Atmospheric Administration
NRCAN	Natural Resources Canada
OCC	Ontario Climate Consortium
PAH	Polycyclic Aromatic Hydrocarbons
PBDE	Polybrominated Diphenyl Ethers
PCB	Polychlorinated Biphenyls
PFOA	Perfluorooctanoic Acid
PFOS	Perfluorooctane Sulfonate
RAP	Remedial Action Plans
RCM	Regional Climate Model
SCCP	Short-Chain Chlorinated Paraffins
tDOM	Terrestrial Dissolved Organic Matter
TEK	Traditional Ecological Knowledge

1.0 Introduction

1.1 Great Lakes Basin and its Governance

The Great Lakes are an extremely important natural resource to both Canada and the United States (U.S.), providing economic, ecological, and recreational benefits to the people residing in their surrounding areas. They cover an area of 244,000 km2 and contain 23,000 km3 of water (Breffle et al. 2013). More than forty-million people reside in the Great Lakes basin, an area that spans eight states and two provinces (Figure 1), who rely on the Great Lakes for drinking water, manufacturing, forestry, agriculture, and shipping industries (EPA, 2017a; Government of Ontario, 2016). The Great Lakes also sustain over 4,000 species of plants, fish, and wildlife, making it a significant reservoir for biodiversity in Canada and the U.S. (Government of Ontario, 2016).

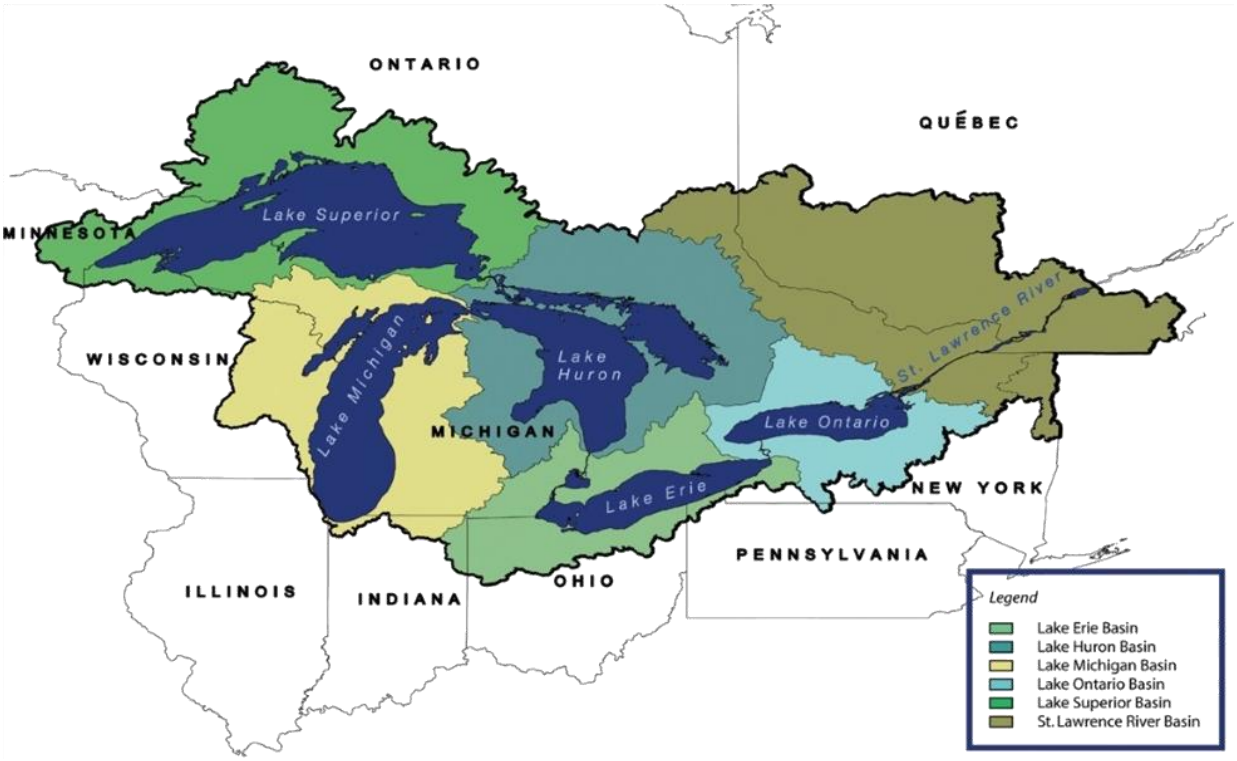

Figure 1: Map of the Great Lakes basin, with individual lake catchment areas.

In order to protect the Great Lakes, Canada and the U.S. formed a joint agreement called the Great Lakes Water Quality Agreement (GLWQA) in 1972; since then, the report has been updated several times, the most recent update being in 2012. The GLWQA includes 10 Annexes which address different issues related to

water quality of the Great Lakes, each having their own responsibilities and commitments to help in the restoration and protection of the waters. The 10 Annexes are:

1. Areas of Concern;
2. Lakewide Management;
3. Chemicals of Mutual Concern;
4. Nutrients;
5. Discharge from Vessels;
6. Aquatic Invasive Species;
7. Habitat and Species;
8. Groundwater;
9. Climate Change Impacts; and,
10. Science.

1.2 Purpose

The purpose of this report is to document all results and analyses completed to date and to produce refined, vetted priorities of climate science knowledge gaps across the GLWQA. In addition, it is meant to leverage information obtained across Annex engagements to identify a potential framework to address high priority knowledge gaps and improve the climate change science and information needs as part of the GLWQA. In doing so, this scope of work has supported the following objectives:

- Assessing and improving Annex members' awareness of current climate science knowledge gaps and research needs;
- Prioritizing knowledge gaps, along with a framework for moving forward, based on a consensus-driven approach through a series of engagements with other Annex members; and
- Providing information that can potentially inform and/or support future work plans under the Great Lakes Water Quality Agreement based on the knowledge gaps, and any new research that has been released since the publication of the State of the Climate Change Science Report in 2015.

2.0 Methodology and Development of Knowledge Gaps

In 2015, the Ontario Climate Consortium produced a report titled, "State of Climate Change Science in the Great Lakes basin: A Focus on Climatological, Hydrological and Ecological Effects". The objective of the initial report (McDermid et al., 2015) was to review the observed and projected impacts of climate change in the Great Lakes basin and provide authentic information on climate change impacts, scenario planning and use of climate data for decision makers. This report synthesized available science on observed and projected impacts of climate change and summarized 43 climate science knowledge gaps that could be potential priorities for research.

As defined in McDermid et al. (2015), a climate science knowledge gap is a brief description of an identified deficiency in the scientific understanding of a particular theme as it pertains to climate change (e.g., water levels and surface hydrology) in the Great Lakes basin. In total, 43 knowledge gaps were identified from an analysis of literature review and through engaging over 85 subject matter experts on their perceived scientific needs using a symposium format. More specifically, ideas that were identified as having low agreement in scientific evidence or limited agreement (as opposed to high agreement or robust evidence) were included and identified as climate science knowledge gaps (refer to Appendix B for a full summary). Using these as a foundation, Annex engagements were undertaken in 2017 and 2018. Namely:

1. An online survey designed for Annexes within the GLWQA, to assess the state of the climate science knowledge gaps named in the 2015 report. This survey specifically asked the following questions:
    a. Is addressing the gap essential to fulfilling your Annex's objectives?
    b. Have you undertaken any work that partially or completely addresses the gap?
    c. Do you have plans to undertake work to address the gaps by 2019?
    d. Are you aware of other work being conducted and/or planned to partially or completely address gaps?
2. A webinar on November 20th, 2017, to review all preliminary results compiled via the survey, and to seek input from attendees on suggested research priorities moving forward. During the webinar, participants expressed interest in having more targeted knowledge gaps for each specific Annex, followed by phone calls with people from those specific Annexes for more discussion.
3. A second round of phone interviews among Annexes in the GLWQA took place between December 2017 and February 2018. These phone calls mostly involved Annex co-leads and key partners, where knowledge gaps were tied to specific GLWQA statements and/or 2017-2019 priorities as proposed discussion ideas. These discussions lasted approximately one hour each and information was gathered based on the following:
    a. What is the current scope of the work of your Annex?
    b. Are the listed gaps relevant to your Annex (e.g., how, why)?
    c. What can Annex 9 do to support the work of your Annex?
4. Reporting on results and analysis completed to date. Specifically, all phone call transcripts were recorded and reviewed, and the knowledge gaps were refined and updated based on the most recent input and information available.

Figure 2 below illustrates the overarching methodology followed to produce the information contained in this report, and relevant knowledge gaps for each Annex along with additional analyses are provided in Appendix C.

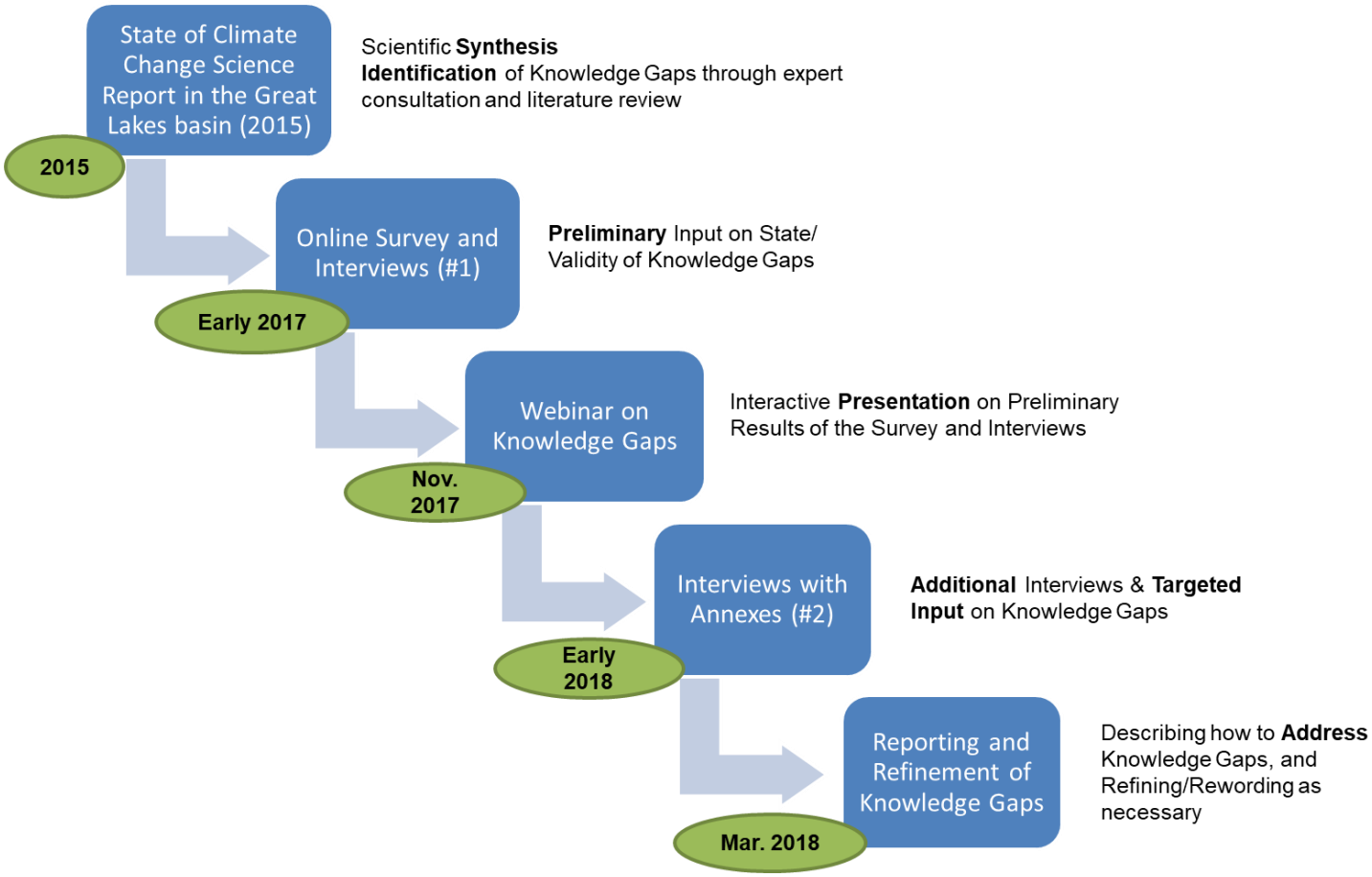

Figure 2: Methodology followed to Identify, Prioritize and Refine Climate Science Knowledge Gaps for Annexes within the GLWQA.

The priority of a knowledge gap is a term used in this report based on analyses conducted (refer to Appendix A for a comprehensive Glossary of terms). The priority of a particular knowledge gap is rated 'low', 'medium', or 'high' based on the importance of the gap in filling Annex objectives and the level of work needed to address the gap. Specifically:

- **Low Priority (coloured green)**: Knowledge gap is considered less important or the gap is considered important but already has significant amount of work taking place to fill the gap.
- **Medium Priority (coloured yellow)**: Knowledge gap is considered somewhat important and work taking place is low, or the difference between importance and work taking place falls between low and high priorities.

- **High Priority (coloured red)**: Knowledge gap is considered highly important but the amount of work taking place is low.

In addition to the priority ratings that knowledge gaps were given, they were also organized into short-term and long-term priorities. Short-term priority gaps refer to knowledge gaps that are within a specific Annex's current work and/or within their 2017-2019 commitments of the GLWQA. Long-term priority gaps refer to the gaps that are still assigned priorities along with potentially relevant Annexes whose objectives may align as future work plans are developed (i.e. there are no commitments to filling these gaps for the 2017-2019 mark). Sections 3.0 and 4.0 provide analysis results for short-term priority knowledge gaps and long-term priority knowledge gaps, respectively.

3.0 Short-Term Priority Knowledge Gaps

As mentioned previously, short-term priority knowledge gaps have been defined as those with specific relevance to one or more 2017-2019 Great Lakes binational priorities for science and action. If a particular knowledge gap was identified to be relevant, it was then brought forward to the specific Annex for validation and/or revision to produce a priority ranking of high, medium, or low. In this manner, these knowledge gaps reflect existing priorities and/or work being undertaken by an Annex and can be considered as "short-term" needs. Of the total 43 knowledge gaps identified in McDermid et al. (2015), 15 have been identified as short-term priorities. Table 1 summarizes short-term priority knowledge gaps by research theme, the results from the survey and interviews, the preliminary priority rating and the specific Annex(es) of which they have been flagged, and the adjusted priority ranking after the phone call interviews with the Annex(es) that confirmed the final priority rankings.

Although many climate science knowledge gaps were identified in 2015 to be relevant within the GLWQA, only some specific gaps have been labelled as high priority in which more attention should be given. The results summarized in Table 1 illustrate that there are five high priority knowledge gaps, which are linked to existing science and action priorities. Of these five, the most common research theme is Chemical Effects, which contains three high priority knowledge gaps.

It is also important to consider the number of relevant Annexes for each knowledge gap. For example, Gap 14.1, (Limited cumulative effects assessments that examine multiple environmental stressors), is considered to be of high priority for three of the ten Annexes in the GLWQA. In other words, addressing this knowledge gap could facilitate and support multiple Annexes as they build and develop management strategies and accomplish their own objectives (i.e., as climate change science informs the relevant components of their priorities). As scientific research has progressed, significant information has emerged in relation to specific and/or niche aspects of climate change and its impacts. However, cumulative impacts and the inter-dependencies between multiple stressors and their implications remains challenging but of high interest.

Thus, a targeted focus among the research community could benefit priorities and decisions relevant within the GLWQA.

Table 1: Short-Term Knowledge Gaps and their Associated Priorities across the GLWQA.

Theme	Knowledge Gap		Preliminary Results completed in 2017 via survey and select follow-up discussions							Final Results validated and refined in early 2018	
			Q1. Essential to Annex Objectives (%)	Q2. Currently working on the Gap (%)	Q3. Planning Future work to Address Gap by 2019 (%)	Q4. Aware of other work ongoing to Address Gap (%)	Work Taking Place (%)	Essential to Annex vs. Work Taking Place	Preliminary Priority[1]	Stated as Relevant by Annex (if any)	Final Priority[2]
Water Levels and Surface hydrology	3.1	There are uncertainties in the relative roles of precipitation, runoff, evaporation and evapotranspiration in water level modeling.	56%	25%	8%	33%	33%	22.3	Low	Annex 10 - Low	Low
Wetlands	6.1	There has been a lack of detailed research on the vulnerability of wetlands, such as patterns of wetland drying.	50%	8%	0%	10%	10%	40	Medium	Annex 7 - Medium	Medium
Groundwater	7.1	Groundwater recharge and discharge rates and patterns are not well understood in the Great Lakes basin.	63%	17%	10%	20%	20%	42.5	Medium	Annex 8 - Medium	Medium
Chemical Effects	9.1	Projections of changes in lake and river chemistry are limited (such as oxygen, carbon, nitrogen and phosphorous levels).	70%	8%	9%	9%	9%	60.9	High	Annex 2 - High Annex 3 - High	High
	9.4	Projections of changes in chemical uses and applications are limited.	50%	0%	0%	0%	0%	50	High	Annex 3 - High	High
	9.5	Knowledge and data of climate change and its direct effects on chemical exposure, fate and transport are limited.	60%	0%	8%	0%	8%	51.7	High	Annex 3 - High	High
Species Ranges and Ecosystem Shifts	10.1	Expanding ecological modeling beyond species-level responses to climate change could help address multi-species interactions and ecosystem changes.	56%	0%	0%	30%	30%	25.6	Low	Annex 2 - Low Annex 6 - Low	Low
	10.2	The consideration of impacts of climate change on the local scale, including micro-climate niches is limited.	67%	18%	0%	11%	18%	48.5	Medium	Annex 2 - Medium Annex 6 - Medium	Medium
Invasive species, parasites and pathogens	12.1	Limited integrated research on climate change and invasive species identify and investigate invasive species that may expand into the Great Lakes basin.	56%	18%	0%	10%	18%	37.4	Medium	Annex 2 - Medium Annex 5 - Medium Annex 6 - Medium	Medium

Theme	Knowledge Gap		Preliminary Results completed in 2017 via survey and select follow-up discussions							Final Results validated and refined in early 2018	
			Q1. Essential to Annex Objectives (%)	Q2. Currently working on the Gap (%)	Q3. Planning Future work to Address Gap by 2019 (%)	Q4. Aware of other work ongoing to Address Gap (%)	Work Taking Place (%)	Essential to Annex vs. Work Taking Place	Preliminary Priority[1]	Stated as Relevant by Annex (if any)	Final Priority[2]
	12.2	Limited research on aquatic, tree and wildlife parasites and pathogens that may expand into the Basin.	44%	9%	10%	10%	10%	34.4	Medium	Annex 2 - Medium Annex 5 - Medium	Medium
Cumulative Effects, integration and land use	13.1	Further integration of the cumulative effects of other environmental stressors into climate change impact analyses would be beneficial.	78%	9%	0%	0%	9%	68.7	High	Annex 8 - High	High
Community and Human Effects	14.1	Cumulative effects assessments that examine multiple environmental stressors have been limited (e.g., cumulative human impacts including social, cultural, economic, health, built and political systems).	56%	0%	0%	0%	0%	55.6	High	Annex 2 - High Annex 3 - High Annex 5 - High	High
	14.2	Dissemination of climate information to resource users, decision makers and practitioners could be improved.	67%	36%	40%	20%	40%	26.7	Low	Annex 6 - Low Annex 7 - Low Annex 10 - Low	Low
Use of climate science for adaptive management	15.1	The development and promotion of tools that increase accessibility and effective use of climate change science would help the use of this information in evidence-based adaptive management.	78%	36%	20%	20%	36%	41.4	Medium	Annex 6 - Medium Annex 8 - Medium	Medium
	15.2	Leadership on evidence-based adaptive management and dialogue between researchers and decision makers is limited.	78%	55%	20%	30%	55%	23.3	Low	Annex 2 - Low	Low

More generally, it is recommended that all of the identified "high" priority short-term knowledge gaps stated above should be considered, and may be of particular interest for Annex 9 to move forward, using the proposed framework described in Section 5.0. These are extracted from Table 1 for ease of reading (see Table 2).

Table 2: High Priority, Short-Term Climate Science Knowledge Gaps and their relevant Annexes.

High Priority, Short-Term Climate Science Knowledge Gap	Relevant Annexes
Gap 9.1: Modeled future projections of lake and river chemistry components (such as oxygen, carbon, nitrogen and phosphorous levels) are limited.	2, 3
Gap 9.4: Lack of future projections of chemical uses, applications, and releases (i.e., socio-economic influences such as pesticides, phosphorous, or others used in agricultural applications).	3
Gap 9.5: Lack of knowledge on the impacts climate change has on the Great Lakes basin's chemical exposure, fate, and transportation (i.e., ecosystem responses under future climate and chemical conditions are not well known).	3
Gap 13.1: Lack of understanding of cumulative effects of environmental stressors into climate change impact projections in the Great Lakes (e.g., groundwater).	8
Gap 14.1: Lack of cumulative effects assessments that examine multiple environmental stressors (e.g., social, cultural, economic, health, built and political systems).	2, 3, 5

4.0 Long-Term Priority Knowledge Gaps

As mentioned earlier, 43 knowledge gaps were identified in the State of the Climate Change Science report in 2015, and 15 were identified to be short-term priorities accordingly in Section 3.0. The remaining 28 climate science knowledge gaps are listed below (Table 3) and have been assigned a priority level for the Great Lakes basin overall (high, medium, or low) but are not necessarily attributable to a particular Annex. It should be emphasized that while these knowledge gaps have not been attributed to a particular Annex priority or GLWQA statement, it does not necessarily mean that these should not be addressed in some capacity. Of these 28 long term knowledge gaps, two are listed as high priority (red), 13 are listed as medium priority (yellow), and 13 are listed as low priority (green).

Table 3: Long-Term Knowledge Gaps and their Associated Priorities across the GLWQA.

Theme	Gap		Preliminary Results completed in 2017							Final Results validated and refined in early 2018		
			Q1. Essential to Annex Objectives (%)	Q2. Currently working on the Gap (%)	Q3. Planning Future work to Address Gap by 2019 (%)	Q4. Aware of other work ongoing to Address Gap (%)	Work Taking Place (%)	Essential to Annex vs. Work Taking Place	Preliminary Priority[1]	Stated as Relevant by Annex (if any)	Final Priority[2]	Potential Relevance in Future (e.g., as Priorities are Updated)
Climate Modeling in the Great Lakes basin	1.1	The ability to model processes and feedbacks between the earth's surface and atmospheric systems at local scales across the Great Lakes basin is limited.	56%	17%	8%	42%	42%	**13.9**	Low	N/A	Low	None Identified
	1.2	The application and advancement of dynamical downscaling is limited in the Great Lakes basin. There is a lack of integration of emerging model scenarios into research, needed to ensure future findings build on existing knowledge base.	56%	33%	25%	33%	33%	**22.3**	Low	N/A	Low	Annex 2 Annex 6
	1.3	A retrospective analysis (such as hind casting) is needed to validate model performance.	44%	9%	9%	18%	18%	**26.2**	Low	N/A	Low	Annex 4 Annex 6 Annex 7
	1.4	The coverage and quality of information from climate and weather observations networks has not been assessed for its ability to support adaptive management and the development of climate change and impact information.	56%	27%	27%	36%	36%	**19.2**	Low	N/A	Low	Annex 1 Annex 5 Annex 7 Annex 8
	1.5	The limitations and assumptions used in non-climatological research and other applications has not been well communicated (e.g., downscaling, GCM selection, emission scenarios).	44%	33%	36%	27%	36%	**8**	Low	N/A	Low	Annex 4 Annex 6 Annex 7 Annex 8
Water Temperature	2.1	Consideration of the spatial dynamics of lakes has not been incorporated into water temperature modeling.	33%	0%	0%	18%	18%	**15.1**	Low	N/A	Low	Annex 4 Annex 8

Theme	Gap		Preliminary Results completed in 2017							Final Results validated and refined in early 2018		
			Q1. Essential to Annex Objectives (%)	Q2. Currently working on the Gap (%)	Q3. Planning Future work to Address Gap by 2019 (%)	Q4. Aware of other work ongoing to Address Gap (%)	Work Taking Place (%)	Essential to Annex vs. Work Taking Place	Preliminary Priority[1]	Stated as Relevant by Annex (if any)	Final Priority[2]	Potential Relevance in Future (e.g., as Priorities are Updated)
	2.2	There is limited monitoring and modeling of lake thermal profiles and surface-temperature based analyses. Changes due to climate change have not been incorporated into ice models.	33%	0%	0%	18%	18%	**15.1**	Low	N/A	Low	Annex 6 Annex 7
Lakes	4.1	There is a lack of clarity in the understanding of multiple factors (including hydroclimatic factors) influencing water level projections for the Great Lakes.	67%	33%	10%	27%	33%	**33.4**	Medium	N/A	Medium	Annex 5 Annex 7
	4.2	The diversity of inland lake types and the impacts of climate change on those lakes have not been well characterized.	40%	8%	0%	0%	8%	**31.7**	Medium	N/A	Medium	Annex 4 Annex 7 Annex 8
Rivers	5.1	There is a lack of clarity in the understanding of multiple factors (including hydroclimatic factors) influencing water level projections for rivers.	63%	18%	0%	10%	18%	**44.3**	Medium	N/A	Medium	Annex 7 Annex 8
	5.2	The diversity of river thermal regimes/habitats and the impacts of climate change on those rivers have not been well characterized.	63%	9%	0%	20%	20%	**42.5**	Medium	N/A	Medium	Annex 6 Annex 7
Wetlands	6.2	There is limited understanding of how climate impacts the water budgets of wetlands.	50%	8%	0%	10%	10%	**40**	Medium	N/A	Medium	Annex 7 Annex 8
	6.3	Wetland monitoring has not been geared to evaluate impacts of projected changes in water levels.	33%	0%	11%	0%	11%	**22.2**	Low	N/A	Low	Annex 7 Annex 10

Theme	Gap		Preliminary Results completed in 2017							Final Results validated and refined in early 2018		
			Q1. Essential to Annex Objectives (%)	Q2. Currently working on the Gap (%)	Q3. Planning Future work to Address Gap by 2019 (%)	Q4. Aware of other work ongoing to Address Gap (%)	Work Taking Place (%)	Essential to Annex vs. Work Taking Place	Preliminary Priority[1]	Stated as Relevant by Annex (if any)	Final Priority[2]	Potential Relevance in Future (e.g., as Priorities are Updated)
Groundwater	7.2	An inventory of groundwater resources has not been completed for the basin.	50%	8%	0%	20%	20%	**30**	Medium	N/A	Medium	Annex 7 Annex 8 Annex 10
	7.3	There is limited understanding of the magnitude/direction of groundwater changes.	63%	17%	10%	10%	17%	**45.8**	Medium	N/A	Medium	Annex 7 Annex 8
Precipitation and Extreme events	8.1	Research identifying indicators for extreme weather events related to flooding and drought risks is limited.	56%	42%	17%	42%	42%	**13.9**	Low	N/A	Low	Annex 2 Annex 4 Annex 5 Annex 6 Annex 7 Annex 8
	8.2	Precipitation projections have limited resolution and could better characterize precipitation cycle feedbacks.	56%	25%	17%	18%	25%	**30.6**	Medium	N/A	Medium	Annex 8
	8.3	The consequences of altered disturbance regimes, such as fire and drought are not well documented.	56%	8%	9%	18%	18%	**37.4**	Medium	N/A	Medium	Annex 4 Annex 5 Annex 7 Annex 8
Chemical Effects	9.2	Carbon dioxide fertilization effects have not been incorporated into carbon cycle modeling.	44%	0%	0%	0%	0%	**44.4**	Medium	N/A	Medium	None Identified
	9.3	The changes in pesticides/biocide uses and applications, with pathogen, parasite and invasive species changes have not been factored into models of chemical effects.	60%	8%	0%	9%	9%	**50.9**	High	N/A	High	Annex 3 Annex 6 Annex 8 Annex 10

Theme	Gap		Preliminary Results completed in 2017							Final Results validated and refined in early 2018		
			Q1. Essential to Annex Objectives (%)	Q2. Currently working on the Gap (%)	Q3. Planning Future work to Address Gap by 2019 (%)	Q4. Aware of other work ongoing to Address Gap (%)	Work Taking Place (%)	Essential to Annex vs. Work Taking Place	Preliminary Priority[1]	Stated as Relevant by Annex (if any)	Final Priority[2]	Potential Relevance in Future (e.g., as Priorities are Updated)
	9.6	Monitoring is not geared up to conduct rigorous chemical and pesticide monitoring and testing, including a carbonate chemistry and acidification.	50%	9%	10%	9%	10%	**40**	Medium	N/A	Medium	Annex 3 Annex 4 Annex 6 Annex 8 Annex 10
Species Ranges and Ecosystem Shifts	10.3	Research is limited on the impacts of climate change on coastal ecosystems.	56%	0%	0%	10%	10%	**45.6**	Medium	N/A	Medium	Annex 2 Annex 7 Annex 10
	10.4	Monitoring of species and community-level changes is necessary to refine hybrid models, which could lead to a better understanding of the reconfiguration of ecosystems and inform changes in chemical and pesticide use.	44%	9%	0%	10%	10%	**34.4**	Medium	N/A	Medium	Annex 6 Annex 10
Genetic and Phenological Changes	11.1	There is a gap in research identifying and examining the genetics of fitness-related traits that will impact adaptation of species to climate change.	25%	0%	0%	0%	0%	**25**	Low	N/A	Low	Annex 6 Annex 10
	11.2	Research in genetic matching to identify genotypes best suited to future climates is limited.	25%	0%	0%	0%	0%	**25**	Low	N/A	Low	Annex 6
	11.3	Research of the political, ethical, operational and scientific aspects of the assisted migration of species is limited.	38%	0%	0%	10%	10%	**27.5**	Low	N/A	Low	Annex 6
	11.4	Research investigating asynchronies resulting from phenological changes in species and ecosystems is limited.	38%	0%	0%	10%	10%	**27.5**	Low	N/A	Low	Annex 10

Theme	Gap		Preliminary Results completed in 2017							Final Results validated and refined in early 2018		
			Q1. Essential to Annex Objectives (%)	Q2. Currently working on the Gap (%)	Q3. Planning Future work to Address Gap by 2019 (%)	Q4. Aware of other work ongoing to Address Gap (%)	Work Taking Place (%)	Essential to Annex vs. Work Taking Place	Preliminary Priority[1]	Stated as Relevant by Annex (if any)	Final Priority[2]	Potential Relevance in Future (e.g., as Priorities are Updated)
Cumulative Effects, integration and land use	13.2	The integration of the impacts of land-use management decisions into climate change modeling is limited.	78%	9%	0%	10%	10%	**67.8**	High	N/A	High	Annex 1 Annex 2 Annex 4 Annex 5 Annex 7 Annex 8

[1]Current priorities were rated using a percentile approach in Excel and is based on knowledge gaps' importance to Annex Objectives and the level of work taking place to address the knowledge gap. Appendix A describes all priority ratings in greater detail.

[2]Future priorities were not changed based on initial input received in 2017, and potentially relevant Annexes have been proposed by the Ontario Climate Consortium as an attempt of how climate change may inform and/or support priorities of Annexes in the future.

It should be noted that Final Priority ratings included in Table 3 were not identified by the potentially relevant Annexes listed in the final column on the right. Rather, OCC proposed these Annexes based on potential relevance of a particular knowledge gap and the work of an Annex. As Annex priorities and commitments shift or are updated, these proposed linkages should be revisited and updated. Table 4 provides an example of some of the rationales used to identify potentially relevant Annexes to the long term knowledge gaps (refer to Appendix C for additional Annex specific analyses and details). The specific knowledge gaps included in Table 4 are consistent with those summarized in Table 3; they have simply been re-formatted and re-framed to demonstrate the rational links being made.

Table 4: Identifying Potentially Relevant Annexes for Long Term Knowledge Gaps

Annex	Rationale and/or Assumption	Relevant Gap(s)
1	Annex 1 focuses on the Areas of Concern (AOC) in the Great Lakes, and thus increased information on how climate change impacts the state of these areas and how they are used could be useful in determining future AOCs and AOCs in recovery.	Gaps 1.4, 13.2
2	Annex 2 is charged with Lakewide Management. Downscaled modeling and cumulative effects analysis as well as increased information on environmental impacts could be used to better incorporate data and used to implement policy.	Gaps 1.2, 8.1, 10.3, 13.2
3	Annex 3, which is focused on Chemicals of Mutual Concern, may benefit from information and understanding of gaps 9.3 and 9.6, which seek to better understand the chemical effects in the Great Lakes.	Gaps 9.3, 9.6
4	Annex 4 focuses on nutrient concentrations in the Great Lakes. Increased information on nutrient loading, changes in nutrient levels caused by extreme events, human activity, as well as information on water chemistry and how it pertains to nutrients are important to the scope of Annex 4's work.	Gaps, 1.3, 1.5, 2.1, 8.1, 8.3, 9.6, and 13.2
5	Annex 5, which is tasked with preventing and controlling vessel discharge, could benefit from access to climate change information as it pertains to weather observations as any changes could drastically change shipping lanes, spread of invasive species, and many associated cumulative effects.	Gaps 1.4, 4.1, 8.1, 8.3, 13.2
6	Annex 6, which is focused on aquatic invasive species, may benefit from a number of the long term knowledge gaps that relate to invasive species as well as those concerned with increasing clarity of climate science.	Gaps 1.2, 1.3, 1.5, 2.2, 2.5, 8.1, 9.3, 9.6, 10.4, 11.1, 11.2, and 11.3

Annex	Rationale and/or Assumption	Relevant Gap(s)
7	Annex 7 focuses on protecting, maintaining, restoring and enhancing the resilience of native species and their habitats, as well as enhancing essential ecosystem services. Because of this non-Annex specific climate science information about native species as well as clarity of climate science could contribute to the scope of their work.	Gaps 1.3, 1.4, 1.5, 2.2, 4.1, 4.2, 5.1, 5.2, 6.2, 6.3, 7.2, 8.1, 8.3, 10.3, and 13.2
8	Annex 8 may also have a need for increased modeling and understanding of current climate science modeling as it pertains to ground water. This coupled with increased information on water in the Great Lakes basin as well as cumulative effects all have the potential to pertain to the work conducted by Annex 8.	Gaps, 1.4, 1.5, 2.1, 4.2, 5.1, 6.2, 7.2, 7.3, 8.1, 8.2, 8.3, 9.3, 9.6, and 13.2
10	Annex 10 is responsible for the coordination, integration, synthesis, and assessment of science activities in the Great Lakes basin. Because of this, the additional collection of data and information as it pertains to other Annexes is also a concern of Annex 10.	Gaps 6.3, 7.2, 9.3, 9.6, 10.3, 10.4, 11.1, and 11.4

More generally, one potential solution to the long term knowledge gaps could be the implementation of policy changes to allow for ease of information sharing and communication between Annexes. This is explored further in Section 5.0

5.0 A Framework for Moving Forward

Of the 43 total knowledge gaps identified in the State of Climate Change Science report, 15 were flagged as relevant to specific Annex priorities (short-term priorities) and 28 were provided a condition rating, but not necessarily attributed to a specific Annex (long-term priorities). Thus, it is recommended that the short-term knowledge gaps be addressed and considered first in comparison to long-term knowledge gaps. As a secondary step, the remaining long-term knowledge gaps should be investigated, as needed.

Given the high number of short-term knowledge gaps, the following is proposed as a more manageable approach to reduce gaps across multiple research themes at once and to improve efficiency, and to eventually prioritize the longer-term knowledge gaps. Although many of the knowledge gaps are multidisciplinary, they can be subdivided into four overarching challenges that should be addressed:

1. A lack of clarity, characterization, and understanding of data and climate science knowledge;
2. The need to integrate a climate science lens in research;
3. A lack of available data and research; and
4. A need for improved and accessible modeling.

A framework (see Figure 3) below provides a visual representation of the four main challenges Annex 9 could consider addressing, along with potential steps to begin to solve these underlying issues.

It is suggested that once these four main challenges have been addressed, Annexes will have the opportunity to collaborate, and provide one another with additional value and support as they continue their work and set priorities and work plans in the future. Similarly, this could support and provide all Annexes with tools to begin working towards understanding and/or assisting in filling their respective knowledge gaps. In the framework below (Figure 3), more detailed discussion of each component (or box) follows for consideration. The first four components are proposed as main goals for Annex 9 to consider in moving forward, and the following are actionable steps that could be taken to accomplish these goals.

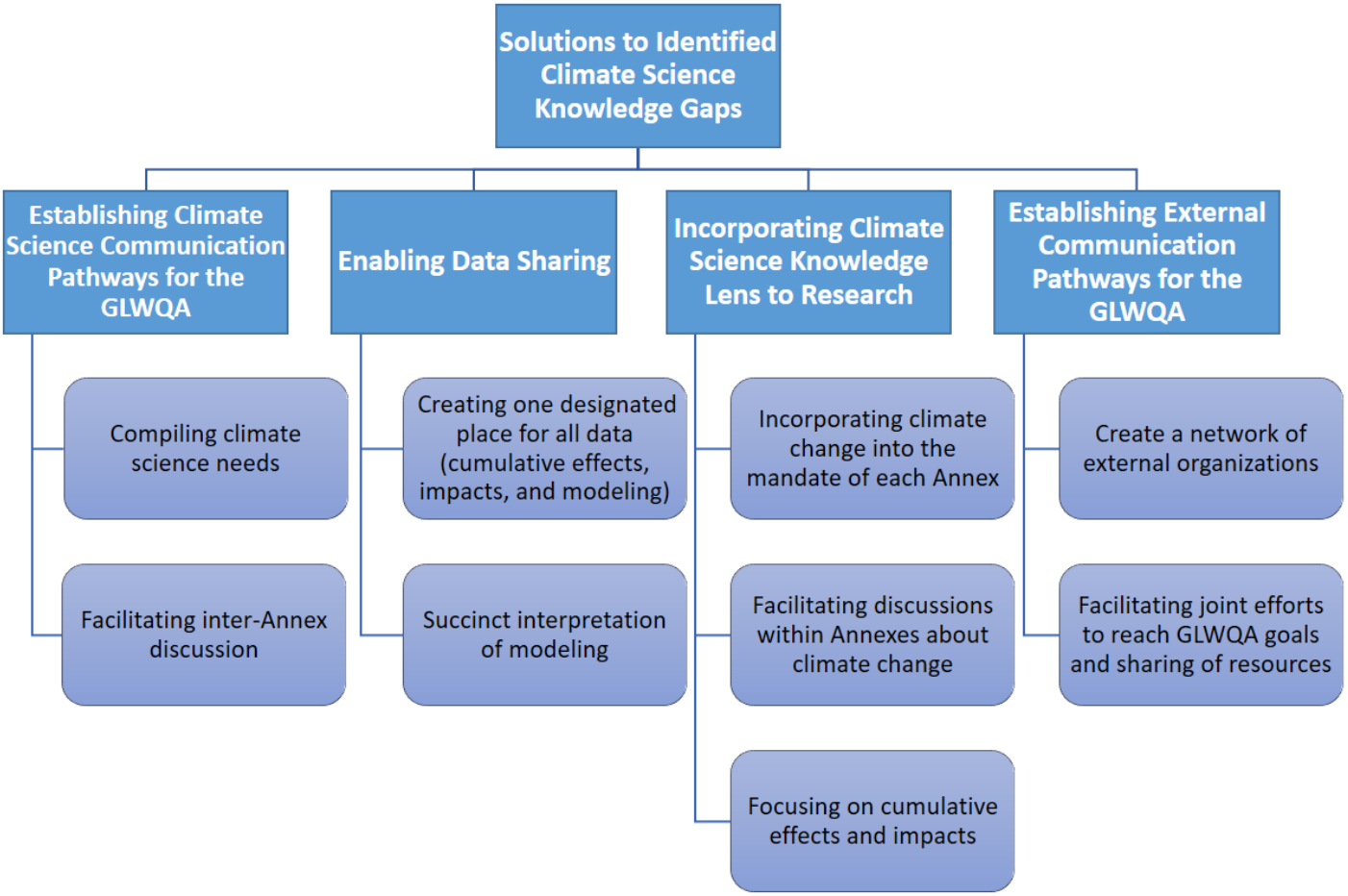

Figure 3: A Framework for Moving Forward on Addressing Climate Science Knowledge Gaps in the Great Lakes basin.

5.1 Establishing Climate Science Communication Pathways

To address the first issue of a lack of clarity of climate science knowledge, such as Gap 4.1, communication must be increased, and communication pathways must be developed. As was mentioned during the interview stage with Annex 10, understanding and implementing climate science knowledge and information is difficult. For example, when creating the State of the Great Lakes 2017 report, changing temperatures cannot be characterized as “good” or “bad” in a similar manner to other themes (e.g. lake levels, toxic chemicals, drinking water, etc.). This is reaffirmed by Melillo (2014) who described that with increasing knowledge and research in the field of climate science, there is an increasing need for accessible climate science information

that can be used for various fields of study, as well as for policy makers. To that regard, merely producing data and increasing amounts of information does not contribute to the incorporation of or clarity of climate science (Clark et al, 2016). Increased communication however, has been found to lead to the development of credible and accessible climate science information (Buizer et al. 2016; Wall et al., 2017). To increase clarity of climate science knowledge in the GLWQA, there is a need for increased communication and information sharing across multiple stakeholders, levels of government, and researchers, internally and externally. One specific example of this could be to create policy groups to better link the research carried out under identified knowledge gaps to the decision making processes.

In most second-stage Annex interviews, a lack of efficient communication between Annexes was mentioned as a barrier to filling knowledge gaps. Cases with clear communication pretenses, such as Annex 2 coordinating the intensive field year with Annex 3, gave the impression of being mutually beneficial. However, in many cases comments were made that relevant work to address knowledge gaps may be ongoing or planned by different Annexes. This shows the need for clearly defined communication pathways between Annexes to foster mutually beneficial knowledge sharing and collaboration. Two ideas for improving communication within the GLWQA's Annexes include: 1) creating a compilation of Annex official climate science needs for the Great Lakes basin and 2) creating specific pathways for communication among Annexes such as forums and data sharing platforms.

Compiling Climate Science Needs

The completion of this report establishes a significant step in addressing this particular component of the proposed framework. More specifically, this report has provided a compilation of climate science needs. It can provide an accessible, singular source of climate science needs from a wide range of experts. Lastly, this report can inform future GLWQA policy updates, Annex objectives, Annex collaborations, university research, and government funding.

Facilitating Inter-Annex Discussion

In order to solidify Annex climate science research needs moving forward and working towards addressing them, inter-Annex discussion should be facilitated. After each Annex submits their climate science needs report, Annex 9 could find overlap and linkages between different needs. After identifying linkages, Annex 9 could then connect Annexes who had similar/overlapping climate science needs, and facilitate the initial discussions between them. Such inter-Annex discussions could work towards incorporating research needs into existing initiatives of other Annexes and provide an opportunity to share resources on the subject. Collaboration in this manner may even expand beyond the climate science needs and lead to more effective pooling of Annex resources.

Annex 9 could further work to make sure the official climate change science needs of the Annexes, along with other climate change science information, is spread to external partners, including universities, policy makers, and non-governmental organizations. This would align climate change priorities of all parties involved in the Great Lakes basin and fosters increased communication and collaboration.

5.2 Enabling Data Sharing

Annex 9 is in a position to be able to provide modeling and climate science data to all Annexes. The creation of a central data and modeling location and facilitating discussion of data needs and interpretation between the Annexes, are two ways in which Annex 9 could improve data sharing and communication in the Great Lakes basin.

Increased communication, including the development of strong communication pathways and the translation of useful climate science information, is important in coproducing effective climate science and enabling data sharing (Wall et al., 2017). Knowledge coproduction refers to a collaborative approach to the production of knowledge, wherein multiple parties contribute to the end result. This allows for science to be more readily accepted and applied as there is a better understanding of the process by which it was obtained. Furthermore, by having multiple parties coproduce knowledge, that knowledge is more likely to fit the individual needs of each party and be integrated when moving forward (Wall et al., 2017; Jasanoff, 2004). To address any high priority knowledge gaps, it is anticipated that a collaborative approach is needed to incorporate a climate science lens in research basin wide. By incorporating a climate science lens in the coproduction of research throughout the GLWQA, there would be an increase in available data and research that is most relevant, cross-cutting, and needed among Annexes.

In 2018, the Great Lakes Science Advisory Board commissioned a report titled, “Information Coordination and Flow in the Great Lakes basin” to not only propose key policy changes to be made within the GLWQA, but also outlines potential barriers to data and information flow between key stakeholders. Of these barriers, those categorized under a lack of data sharing and integration can be linked to the overarching challenges of addressing climate science knowledge gaps. The Great Lakes Science Advisory Board et al. (2018) propose that the limiting factors in enabling proper communication and data sharing throughout the Great Lakes basin are:

- A lack of policies that require sharing data collected with public funding;
- A lack of data sharing policies and agreements among relevant monitoring programs;
- Policies that prevent sharing of sensitive data; and
- A lack of policies that facilitate sharing of sensitive data.

Given that these are limiting factors specific to GLWQA policy; it is recommended that consideration be given to them in the following actions as they should be addressed to enable proper communication and data sharing.

Creating One Designated Place for All Data (Cumulative Effects, Impacts, and Modeling)

A central location with access to all available Great Lakes basin data sets and models as well as an index of current data and modeling portals would be an effective way to get as much information to the right parties as possible. Each Annex could use the completed data from any other Annex to inform their own work and to be informed on the current work being done in other Annexes, with the ability to contact the Annex for partial data or inquiries. The goal would be to create transparency between Annexes, to share all useful climate science data and information.

Succinct Interpretation of Modeling

If modelers and data analysts could create succinct interpretation of their respective data sets or models, this would greatly help with their application and use. Summaries attached to data sets that highlight trends in the data and how they fit into the narrative of climate change would aid in the transition towards assessing potential management implications and potential adaptive measures. These interpretations could be extremely beneficial to Annexes, as this would make it easier for the analysis of relevant data, without reaching out externally for data analysis. Of course, this could translate to public usage as well, allowing researchers, managers, and policy makers alike to access a brief synopsis that informs them of what data could mean for their own research purposes.

5.3 Incorporating A Climate Science Knowledge Lens to Research

While many Annexes know the importance of incorporating climate change science and its impacts into their work, they are limited by their Annex-specific priorities under the GLWQA, more urgent water quality issues, and project timelines. This drives the importance of incorporating specific climate change considerations into each Annex's long-term priorities and commitments in the GLWQA. Furthermore, as the quality of the waters of the Great Lakes basin improves with management, more focus will be placed on combating longer-term processes, and climate change may be one of the most important of these.

Incorporating Climate Change into the Mandate of Each Annex

Incorporating explicit and actionable climate change items into the mandates of every Annex will move climate science to the foreground. This step is crucial in validating work by the Annexes to address one of the larger upcoming threats to the Great Lakes basin, and allows the Annexes to dedicate more time to the subject. Having language that emphasizes the potential of climate change implications in all work conducted by the Annexes and the inclusion of climate change sections when relevant in reports will further aid in the development of adaptation strategies. Making such statements actionable is also important, as current non-actionable climate change phrasing in some Annexes greatly limits their ability to incorporate climate change in their work, given the urgency of other commitments. However, beyond specific actionable phrasing, generally keeping climate change effects in mind when choosing which data to collect during sampling, setting management priorities, etc. is necessary to shift the GLWQA to incorporate climate change into its entirety.

Facilitating Discussions within Annexes about Climate Change

Annex 9 could work as a knowledge hub for climate science. If Annex members have questions on how to incorporate climate change processes into the scope of their work, they could contact members of Annex 9, specifically if they wish to incorporate climate science outside their own scope; for example, Annex 3 incorporating climate science into specific chemicals of mutual concern.

Focusing on Cumulative Effects and Impacts

While increasing climate change discussions in individual Annex initiatives is positive, there are many unknowns associated with climate change when considering cumulative effects. The endless complexity of cumulative effects often leaves the entire subject untouched, but attempting to navigate how different climate change impacts effect one another will greatly influence climate science research.

5.4 Establishing External Communication Pathways

Emphasis has been put on the importance of internal, Annex-wide communication; however, communication with external parties is also of great value. From non-government organizations, government agencies, policy makers, to universities, etc. there is a significant amount of work being conducted to protect the waters of the Great Lakes basin. Effectively engaging these parties through networks and established communication pathways has the potential to contribute to the goals of the GLWQA.

Create a Network of External Organizations

Annex 9 could work to establish contacts in external organizations such as municipal, provincial, state, and federal governments, non-governmental organizations, the private sector, universities, and other stakeholders to build a network of parties with similar interests to protect the waters of the Great Lakes. This network database would be accessible by all Annexes and could be based on compiling existing Annex contacts and then be expanded upon. Identifying external parties to expand the network could be accomplished by simply contacting these organizations, which often have their own local networks, and to start the discussion of sharing these networks. Such a network would encourage knowledge sharing, priority setting, and would ensure information is spread through different levels of government, or different subjects regarding water quality and climate change, in order to increase its value. If Annex 9 were to facilitate discussion within this network, as well as to be a central hub for climate change science, this would increase its effectiveness, and keep the conversations flowing.

Facilitate Joint Efforts to Reach GLWQA Goals and Sharing of Resources

Beyond the spreading of information and building a network for discussion, actively facilitating collaboration within the network would be beneficial for the integration of climate change science into all aspects of the GLWQA. Aligning goals of the GLWQA with partners of universities, governments, and NGOs would reduce inefficiencies in overlap and make the most of limited climate science funding across the board. Such collaboration could take many forms,

such as knowledge sharing, resource sharing, and combined monitoring efforts, all of which would be made possible with increased communication. Annex 9 would play a role in identifying external parties, their climate science goals, and alignments between these goals and the goals of the GLWQA.

6.0 Lessons Learned

A wide variety of information was obtained as part of this process, and a number of emerging issues and lessons learned were identified and are included below.

Firstly, the knowledge gaps identified in the 2015 research report and included in the survey questions are very specific. While this was beneficial for some specific Annexes and for institutions carrying out related research, it was not as easy for stakeholders working in policy to understand the relevance of the research without clear linkages with their overall goals. Further engagement among the Annexes at the management and policy level could add value to these existing results.

Furthermore, it was identified several times that existing financial resources are limited in order to address some of the key gaps identified in this report. Based on information collected for this report, most of the funds are allocated to conduct predetermined basin management activities. However, one suggestion received was to either channel available resources towards the identified research gaps or to seek new funding opportunities to ensure these are not missed in the effective implementation and work being carried out under the GLWQA. For example, Annex 9 could support the identification of relevant funding opportunities to move climate change research and action forward related to high priority short term knowledge gaps. However, a lack of plans to address some of these gaps by 2019, demonstrates the need for potential new funding channels. Ultimately, to effectively fill many of the gaps identified through this work, high level political commitment is needed to ensure not only financial resources are sufficient but also buy-in to produce future work plans.

There seems to also be a growing consensus among members of the various Annexes that a coordinating unit could be valuable, particularly one that is ready to provide technical solutions and expert advice when it comes to climate-smart, sector specific planning and program implementation. Notably, some Annexes and their projects are in different points and steps in utilizing climate information. For instance, some Annexes are ahead of the curve and use climate models in their planning process while other annexes are more implementation focused and may not consider models or climate information explicitly in meeting their work objectives. However, through these discussions, it is clear that Annex 9 has a coordinating role to incorporate climate change and provide technical expertise where needed.

The body of climate change research on the array of research themes is rapidly growing. For instance, many survey responses identified numerous research studies being carried out by other network institutions. Growing research activity to address the knowledge gaps was also

recognized in the follow-up interviews. Coordination and compilation of select climate relevant research activities across the two national jurisdictions may be beneficial to achieve the overall objective of Annex 9, particularly in avoiding duplication of efforts and in the sharing of resources.

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Appendix 1: Glossary of Terms

Adaptation by Stealth – detailed in a review by Rasmussen et al. (2017); suggests that municipalities use various tactics and framings to introduce climate change policy and adaptation without the explicit framing of climate change.

Aquatic Invasive Species (AIS) – s any non-indigenous species, including its seeds, eggs, spores, or other biological material capable of propagating that species, that threatens or may threaten the diversity or abundance of aquatic native species, or the ecological stability, and thus water quality, or water quality of infested waters, or commercial, recreational, or other activities dependent on such waters (GLWQA, 2012).

Antifouling System – a coating, paint, surface treatment, surface or device that is used on a vessel to control or prevent attachment of unwanted organisms (GLWQA, 2012).

Ballast Water – water with its suspended matter taken on board a vessel to control trim, list, draught, stability or stresses of the ship (GLWQA, 2012).

Biofouling – the accumulation of aquatic organisms such as microorganisms, plants and animals on surfaces and structures immersed in or exposed to the aquatic environment (GLWQA, 2012).

Beneficial Use Impairment– a reduction in the chemical, physical or biological integrity of the Waters of the Great Lakes sufficient to cause any of the following: 1) restrictions on fish and wildlife consumption, 2) tainting of fish and wildlife flavor, 3) degradation of fish and wildlife populations, 4) fish tumors or other deformities, 5) bird or animal deformities or reproduction problems, 6) degradation of benthos, 7) restrictions on dredging activities, 8) eutrophication or undesirable algae, 9) restrictions on drinking water consumption or taste and odour problems, 10) beach closings, 11) degradation of aesthetics, 12) added costs to agriculture or industry, 13) degradation of phytoplankton and zooplankton populations, 14) and loss of fish wildlife habitat (GLWQA, 2012).

Discharge - includes, but is not limited to, any spilling, leaking, pumping, pouring, emitting or dumping; it does not include unavoidable direct discharges of oil from a properly functioning vessel engine (GLWQA, 2012).

Groundwater – Water originating as precipitation, runoff and snowmelt that infiltrates into the ground to the water table, where it is contained beneath the Earth's surface in

soil pore space and rock formation fracturing. This component encompasses groundwater flow paths (e.g., interstitial/interflow, artesian/springs, hydraulic connections to rivers/wetlands), storage (e.g., deep and shallow aquifers) and functional processes (e.g., recharge/discharge, baseflow contribution, infiltration and thermal regulation of surface water) (Tu et al., 2017).

Hazardous Polluting Substance – a substance subject to Canadian or United States national laws or regulations, any substance which, if introduced into marine or fresh waters is liable to create hazards to human health, to harm living resources and marine life, to damage amenities or to interfere with other legitimate uses of the waters, and includes but is not limited to substances subject to control by the International Convention for the Prevention of Pollution from Ships, 1973 as amended by the Protocol of 1978, and those substances subject to control by the International Convention on Liability and Compensation for Damage in Connection with the Carriage of Hazardous and Noxious Substances by Sea, 1996, when the latter comes into effect, the Canada Shipping Act, 2001, the Federal Water Pollution Control Act of 1972, as amended, the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), as amended, and the Oil Pollution Act (OPA) of 1990, as amended, but excluding Ballast Water, Oil, Garbage, and Sewage (GLWQA, 2012).

Hydrological Vulnerability Index – an index evaluating how vulnerable a region is to hydrological components and assigning the region a number corresponding to this vulnerability (flood, drought) (Mildrexler et al., 2016).

Hypoxic Zones – an area of decreased dissolved oxygen content, which makes it difficult for aquatic life to survive (Boesch, 2008).

Intensive Field Year – an initiative of Annex 10 which calls for intensive sampling and monitoring, followed by Annex 2 preparing the data for management use.

Knowledge Gap Priority – the priority of a knowledge gap is a term used in this report based either on prior analyses conducted or when stated to differ from original designation to a designation specific to an Annex, the new priority is based on phone call conversation and research for this report. The priority of a particular knowledge gap
is rated as ‘low, ‘medium’, or ‘high’ based on a gaps’ importance in filling GLWQA objectives and the level of work taking place to address the gap. Specifically:

1) *Low Priority*: Knowledge gap is considered less important or the gap is considered important but has significant amount of work taking place to fill the gap.

2) *Medium Priority:* Knowledge gap is considered somewhat important and working taking place is low, or the difference between importance and work taking place falls between green and red condition ratings.
3) *High Priority*: Knowledge gap is considered highly important but the amount of work taking place is low.

Lakewide Action and Management Plans – Under the Great Lakes Water Quality Agreement, the Governments of Canada and the United States have committed to develop five-year management plans for each of the Great Lakes. The LAMP is a world-recognized model for cooperation among governmental jurisdictions and their management agencies. It represents a shared understanding of the health of each lake and a means for coordinating and documenting management actions (Lake Huron Partnership Agencies, 2017).

Nearshore Framework – An integrated, systematic and collective approach for assessing nearshore health and identifying and communicating cumulative impacts and stresses, is needed to inform and promote action at all levels to restore and protect the ecological health of Great Lakes nearshore areas (Environment and Climate Change Canada & U.S. Environmental Protection Agency, 2016).

Northern Contaminants Program – a Canadian program in the Arctic undertaking contaminant research and outreach efforts.

Oligotrophic State – a condition in a lake or other water body in which high amounts of dissolved oxygen in the deeper regions are present and the overall condition of the water body contains low levels of plant nutrients (Toronto and Region Remedial Action Plan, 2015).

Phosphorus Loading – The loading of phosphorus from outside sources into a system, excess phosphorus from loading can cause major algal blooms that can disrupt ecosystems and cause outbreaks of toxic algae (Tu et al., 2017).

Terrestrial Dissolved Organic Matter – organic matter (from plants, animals, etc.) of very small size that inputs land-based carbon into aquatic ecosystems (Tu et al., 2017).

Appendix 2: B: Previously Identified Climate Science Knowledge Gaps (from McDermid et al., 2015)

Theme	Climate Science Knowledge Gap	
Climate Modeling in the Great Lakes basin	1.1	The ability to model processes and feedbacks between the earth's surface and atmospheric systems at local scales across the Great Lakes basin is limited.
	1.2	The application and advancement of dynamical downscaling is limited in the Great Lakes basin. There is a lack of integration of emerging model scenarios into research, needed to ensure future findings build on existing knowledge base.
	1.3	A retrospective analysis (such as hind casting) is needed to validate model performance.
	1.4	The coverage and quality of information from climate and weather observations networks has not been assessed for its ability to support adaptive management and the development of climate change and impact information.
	1.5	The limitations and assumptions used in non-climatological research and other applications has not been well communicated (e.g., downscaling, GCM selection, emission scenarios).
Water Temperature	2.1	Consideration of the spatial dynamics of lakes has not been incorporated into water temperature modeling.
	2.2	There is limited monitoring and modeling of lake thermal profiles and surface-temperature based analyses. Changes due to climate change have not been incorporated into ice models.
Water Levels and Surface hydrology	3.1	There are uncertainties in the relative roles of precipitation, runoff, evaporation and evapotranspiration in water level modeling.
Lakes	4.1	There is a lack of clarity in the understanding of multiple factors (including hydroclimatic factors) influencing water level projections for the Great Lakes.
	4.2	The diversity of inland lake types and the impacts of climate change on those lakes have not been well characterized.
Rivers	5.1	There is a lack of clarity in the understanding of multiple factors (including hydroclimatic factors) influencing water level projections for rivers.
	5.2	The diversity of river thermal regimes/habitats and the impacts of climate change on those rivers have not been well characterized.
Wetlands	6.1	There has been a lack of detailed research on the vulnerability of wetlands, such as patterns of wetland drying.
	6.2	There is limited understanding of how climate impacts the water budgets of wetlands.

Theme	Climate Science Knowledge Gap	
	6.3	Wetland monitoring has not been geared to evaluate impacts of projected changes in water levels.
Groundwater	7.1	Groundwater recharge and discharge rates and patterns are not well understood in the Great Lakes basin.
	7.2	An inventory of groundwater resources has not been completed for the basin.
	7.3	There is limited understanding of the magnitude/direction of groundwater changes.
Precipitation and Extreme events	8.1	Research identifying indicators for extreme weather events related to flooding and drought risks is limited.
	8.2	Precipitation projections have limited resolution and could better characterize precipitation cycle feedbacks.
	8.3	The consequences of altered disturbance regimes, such as fire and drought are not well documented.
Chemical Effects	9.1	Projections of changes in lake and river chemistry are limited (such as oxygen, carbon, nitrogen and phosphorous levels).
	9.2	Carbon dioxide fertilization effects have not been incorporated into carbon cycle modeling.
	9.3	The changes in pesticides/biocide uses and applications, with pathogen, parasite and invasive species changes have not been factored into models of chemical effects.
	9.4	Projections of changes in chemical uses and applications are limited.
	9.5	Knowledge and data of climate change and its direct effects on chemical exposure, fate and transport are limited.
	9.6	Monitoring is not geared up to conduct rigorous chemical and pesticide monitoring and testing, including a carbonate chemistry and acidification.
Species Ranges and Ecosystem Shifts	10.1	Expanding ecological modeling beyond species-level responses to climate change could help address multi-species interactions and ecosystem changes.
	10.2	The consideration of impacts of climate change on the local scale, including micro-climate niches is limited.
	10.3	Research is limited on the impacts of climate change on coastal ecosystems.
	10.4	Monitoring of species and community-level changes is necessary to refine hybrid models, which could lead to a better understanding of the reconfiguration of ecosystems and inform changes in chemical and pesticide use.
Genetic and Phenological Changes	11.1	There is a gap in research identifying and examining the genetics of fitness-related traits that will impact adaptation of species to climate change.
	11.2	Research in genetic matching to identify genotypes best suited to future climates is limited.
	11.3	Research of the political, ethical, operational and scientific aspects of the assisted migration of species is limited.
	11.4	Research investigating asynchronies resulting from phenological changes in species and ecosystems is limited.

Theme	Climate Science Knowledge Gap	
Invasive species, parasites and pathogens	12.1	Limited integrated research on climate change and invasive species identify and investigate invasive species that may expand into the Great Lakes basin.
	12.2	Limited research on aquatic, tree and wildlife parasites and pathogens that may expand into the Basin.
Cumulative Effects, integration and land use	13.1	Further integration of the cumulative effects of other environmental stressors into climate change impact analyses would be beneficial.
	13.2	The integration of the impacts of land-use management decisions into climate change modeling is limited.
Community and Human Effects	14.1	Cumulative effects assessments that examine multiple environmental stressors have been limited (e.g., cumulative human impacts including social, cultural, economic, health, built and political systems).
	14.2	Dissemination of climate information to resource users, decision makers and practitioners could be improved.
Use of climate science for adaptive management	15.1	The development and promotion of tools that increase accessibility and effective use of climate change science would help the use of this information in evidence-based adaptive management.
	15.2	Leadership on evidence-based adaptive management and dialogue between researchers and decision makers is limited.

Appendix 3: Relevant Climate Science Knowledge Gaps by Annex

(Available upon request).

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