The Great Lakes Water Quality Centennial Study – Phase I Report

A report submitted to the
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by the Health Professionals Advisory Board
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Project Leads

Joan Rose, MS, PhD, Professor and Homer Nowlin Chair in Water Research, College of Agriculture and Natural Resources, Michigan State University

Thomas Edge, MSc, PhD, Adjunct Professor in the Department of Biology, Faculty of Science, McMaster University

Great Lakes Work Group Members

David Buckeridge, MD, MSc, PhD, Professor in the Department of Epidemiology, Biostatistics and Occupational Health, Faculty of Medicine, McGill University

Laurie Chan, MPhil, PhD, Professor and Canada Research Chair in Toxicology and Environmental Health, University of Ottawa

Matthew Dellinger, MS, PhD, Assistant Professor, Division of Epidemiology, Institute for Health and Equity, Medical College of Wisconsin

Ruth Etzel, MD, PhD, Professor of Epidemiology, Zilber School of Public Health, University of Wisconsin-Milwaukee and Adjunct Professor of Pediatrics, Medical College of Wisconsin

Elaine Faustman, PhD, HPAB co-chair and Professor of Environmental and Occupational Health Sciences, School of Public Health, University of Washington

Seth Foldy, MD, MPH, FAAFP, Director of Epidemiology, Preparedness and Informatics at Denver Public Health and Visiting Professor of Family Medicine at the University of Colorado

Sharon Nappier, MSPH, PhD, Office of Water, Office of Science & Technology, US Environmental Protection Agency, Washington, DC

Workshop reviewer participants:

Janis Thomas and Ryan Newton

IJC Advisors

Jennifer Boehme, International Joint Commission, Windsor, Ontario

Ryan C. Graydon, Ohio Sea Grant Fellow (2018-2020), Windsor, Ontario

Cover image: Sewage discharge into Milwaukee, Wisconsin harbor, by SouthernWI via Flickr.

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Acronyms and Abbreviations

AOCs	Areas of Concern
BAV	beach action value
CFU	colony forming units
CSOs	combined sewer overflows
HPAB	Health Professionals Advisory Board
IJC	International Joint Commission
MPN	most probable number
MST	microbial source tracking
NPDES	(US) National Pollutant Discharge Elimination System
PCR	polymerase chain reaction
qPCR	quantitative polymerase chain reaction
USDA	US Department of Agriculture
USEPA	US Environmental Protection Agency
WWTP	wastewater treatment plant

Forward

There are a number of adages that bring attention to our goal to protect the water quality of the beautiful Great Lakes. New advances in technology mean that we are now less limited to 'looking under the light post' and that we can better detect changes in our environment 'you can't manage what you can't measure.' Monitoring and data have always been at the heart of the *Great Lakes Water Quality Agreement*. The International Joint Commission's 1913 study was the most advanced, expansive and comprehensive study ever undertaken in its day, and still today should be heralded as an outstanding plan that resulted in extensive binational collaboration and significant new knowledge and recommendations. In fact, when one examines transboundary agreements around the world, the Great Lakes Water Quality Agreement is a model to live up to. This region has led the way in using new techniques and instrumentation to understand the sources, fate and risk of contaminants in water. In particular, microbial source tracking is one of these new techniques that has been advanced by scientists in the Great Lakes to identify sources of fecal pollution and further understand and monitor our water quality.

The Health Professionals Advisory Board Centennial Study Report and associated experts' workshop was completed in 2019. However, we have since entered a new era of unprecedented global concern for our health. Coronavirus disease of 2019 (COVID-19) has changed our lives, how we work, how we learn and how we play. It is clear that while wastewater has always been viewed as a source of contaminants to our surface waters, equally—and more importantly—wastewater treatment is seen as a critical public health and essential service. SARS-CoV-2, the root cause of COVID-19, is found in feces and sewage, so the monitoring of this virus in wastewater is being investigated as a way to examine the disease prevalence in communities and provide an early warning alert for medical professionals. The levels in wastewater have been detected as high as 10 million virus particles per liter. Ultimately, the virus can be expected to be detected in the waters of the Great Lakes, making its way by inefficient wastewater treatment, combined sewer overflows and untreated sewage releases and spills. While waterborne transmission of COVID-19 is believed to be a very low concern (due to the relatively rapid die-off of the virus and its largely respiratory transmission), the virus fate will serve as an indicator of the impact of untreated wastewater discharges.

As the International Joint Commission moves forward to advance a Phase II Great Lakes Microbial Water Quality Project, the Health Professionals Advisory Board members see the potential for incorporating surveillance of SARS-CoV-2 as part of the comprehensive basinwide investigation of the extent of fecal pollution sources impacting the Great Lakes. This would be a natural extension of the need to collect sewage samples around the Great

Lakes to validate microbial source tracking methods in the region, and to investigate the prevalence of sewage contamination in nearshore waters.

Monitoring continues to be at the heart of the Great Lakes Water Quality Agreement and Health Professionals Advisory Board members believe that the IJC will continue to lead these efforts to investigate new approaches and new contaminants of concern that will assist in a large-scale and inclusive assessment. Monitoring is ultimately about our water quality and the protection of our health.

Joan B. Rose, Health Professionals Advisory Board member

February 2021

Executive Summary

The International Joint Commission (IJC) is responsible for regular reporting on the status of the Great Lakes and other boundary waters, as well as investigating the risk to ecosystems and human health that may result from current or future stressors. The Great Lakes are a dominant part of the physical and cultural heritage of North America. Shared by two countries and spanning a thousand miles across Canada and the United States, the shoreline is longer than the US East and Gulf coasts combined. The lakes also hold monumental environmental, cultural and economic value for both the region and our nations. First Nations and Tribes rely on native species, but habitats and ecosystems are changing with resulting effects impacting Indigenous peoples' access to resources for sustenance, support for ways of knowing and of life, and for their spiritual and other needs.

In 1913, the IJC conducted the first comprehensive, detailed monitoring study of the fecal-related pollution of the boundary waters of the Great Lakes and the potential link between disease and sewage pollution (International Joint Commission 1918). The 1913 study, that cost US$42,138 (at the time), to our knowledge is the largest fecal microbial water quality study in North America. The goals were to improve the understanding of bacteriological water quality across the basin and on how to address wastewater in the basin. The data from the study highlighted the public health risk of untreated sanitary sewer discharges to the Great Lakes when these waterways were also used as drinking water sources with no additional treatment. Typhoid deaths were tallied as part of the study. Analytical methods were in their infancy, and the most specific measure of fecal bacterial contamination was *Bacillus coli*, or what we now refer to as total coliform bacteria. The 1913 study also had important geographic omissions, namely that sampling was not done in Lake Michigan and near several important metropolitan areas, including: Duluth, Minnesota; Cleveland, Ohio; Hamilton, Ontario; and Toronto, Ontario.

Today, the Great Lakes basin still faces numerous water quality challenges. The lakes provide drinking water for an estimated 40 million in Canada and the United States (and water for food and beverage products for millions more). Modern drinking water treatment greatly reduces health risks for the majority, but the types and adequacy of protection may vary, and an unknown number may drink untreated lake water. Despite progress towards cleaner Great Lakes water over the last 100 years, public concern has arisen about increased incidence of nearshore sewage contamination and sources of releases (Environmental Commissioner of Ontario 2018; Great Lakes and St. Lawrence Collaborative 2020; Michigan Department of Environment, Great Lakes and Energy 2019; US Environmental Protection Agency 2016). Nearshore monitoring using modern tools such as microbial source tracking could inform management steps to address these issues. These tools advance applications of DNA technologies to allow identification of fecal pollution sources, that conventional tools based on *Escherichia coli* (*E. coli*) indicator bacteria cannot do.

Microbial source tracking advances have been particularly useful in improving the ability to detect sewage contamination. We also know that sewage contamination comes with concerns of other contaminants within the sewage, such as pharmaceuticals (Patz et al. 2008), antimicrobial-resistant microorganisms, microplastics, nutrients and toxic chemicals. Many sites along the shoreline require protection and restoration (including the Areas of Concern) and major investments in restoration have been made by federal, state and local governments, with the IJC and its Great Lakes Water Quality Agreement advisory boards continuing to lead the binational approach. Key questions have emerged as these restoration projects moved forward:

- Is nearshore water quality getting better or worse?
- Where is the pollution coming from?
- What are the public health risks associated with changing nearshore water quality?

This Health Professionals Advisory Board (HPAB) report addresses these questions by examining available data and literature on fecal contamination and fecal source identification, and proposes an updated binational centennial study to provide a framework for future efforts. The intent of the proposed framework is to help identify health risks and assist both countries prioritize cost-effective investment in improved restoration efforts associated with contaminated waters, increasing total maximum daily loads of contaminants, algal blooms, stormwater and wastewater treatment, and agricultural best management practices. The framework would also assist the binational Great Lakes community to move from a reactionary to preventive approach to beach and nearshore management.

Project goals for this investigation included:

i. Determine changes and trends in the concentration of fecal contaminants at the subset of sites of the 1913 study in the Great Lakes using available data, including consideration of Lake Michigan, that was not included in the original study but is anticipated for inclusion in a future synoptic reassessment survey.

ii. Based on literature describing current technologies (e.g., genomic indicators) and existing microbial source tracking data:

    a. Describe approaches for determining the contributions or relative levels of contamination from various sources—human fecal waste, agricultural animal fecal waste, domestic animals (pets) and wildlife (e.g., waterfowl)—at 20-40 sampling locations used in the 1913 study.

    b. Describe the public health risks for swimming and water consumption at these sites.

iii. Evaluate contemporary sampling and fecal source identification programs and data, including for Lake Michigan, to provide updated conclusions about the range, geographical origin and distribution of pollution from sources of human waste, and to identify fecal pollution hotspots around the Great Lakes.

The findings of the literature review indicate that since the 1913 study, the Great Lakes basin has changed in numerous ways:

1. Since the IJC 1913 study, the total population reported for 21 cities within the watershed has increased to over 9,300,000 residents, with additional, significant population spread out over larger metropolitan areas (Goal i).

2. More livestock (over 200 million) are present and concentrated in fewer areas (Goal i).

3. Nonpoint sources of runoff have become a more significant threat to water quality, as sewer, stormwater and septic system infrastructure has increased to support to increased suburban and population in outlying areas (urban sprawl). High failure rates of infrastructure such as sanitary sewer, stormwater and septic systems, as well as increased incidence combined sewer overflows (CSOs) are significant sources of fecal pollution transport to watersheds and the lakes. While CSOs continue, they will be addressed by rules that mandate fixes and will remain an intermittent problem due to climate change (Goal ii-a/Goal ii).

4. Better public health protection is becoming possible through advances in technologies such as microbial source tracking to attribute sources of fecal pollution and better target remedial actions (Goal ii-a).

5. Although infrastructure (including wastewater treatment, sanitary sewage and conveyance systems) was built to accommodate growing populations, upgrades and repairs are needed (Goal ii-b).

6. New threats to the Great Lakes emerged, including, for example, the spread of antimicrobial resistance, microplastics, nanomaterials and new pathogens in fecal pollution sources, harmful algal blooms, pharmaceuticals and climate change (Patz et al. 2008) (Goal ii-b).

7. It is possible to map fecal pollution hotspots and a future study should obtain the key data to support that analysis (Goal iii).

Today, over 100 years later, the lakes are more widely used for drinking water and recreation, increasing the potential to expose users to unsafe bacteria levels and waterborne pathogens, despite the advances in drinking water treatment technology and source control measures. However, we anticipate growing challenges because water recreational demands are increasing, there are more immune-compromised people vulnerable to waterborne pathogens, wastewater infrastructure is aging, agricultural and husbandry practices are changing, sewage releases are increasing, and extreme rain events and other manifestations of climate change are increasing.

To set the stage for another 100 years of action to support water quality in the Great Lakes, the **HPAB recommends that the IJC oversee a binational multiphase project addressing water quality across the Great Lakes basin over a five-year timeframe. The first phase of this project would be to establish a committee of federal, tribal, First Nations and the Métis Nation of Ontario, provincial, state and municipal agencies to oversee and coordinate a multiyear study of fecal pollution and its sources.**

The key goal during the first phase is to establish the committee to oversee the study design and review the public health applications of advances in DNA and other molecular and genomic technologies for assessing water quality in the Great Lakes. This includes microbial source tracking to evaluate the effectiveness of coastal restoration programs for identifying and remediating fecal pollution sources at the basin scale (including across international boundaries) as well as more locally and develop lake-by-lake health risk maps for assessing and protecting public health. The HPAB proposes that the structure of the committee would be similar to the Great Lakes-St. Lawrence River Adaptive Management Committee,[1] and would be overseen by the IJC. Subject matters experts for such a committee would include members provided by the governments of Canada and the United States ("the Parties"), rights holders and stakeholders in the basin, leadership of tribes, First Nations, and the Métis Nation of Ontario and/or their designee, and participants from provincial and state government agencies where many of the water quality monitoring capacity and responsibility exists.

There is a need to invest in sustaining source water for drinking, recreational water quality and economic vitality in the Great Lakes, given expanding human and livestock populations, aging infrastructure and climate and land use changes. A second phase of this work will be advanced, in collaboration with the IJC Great Lakes Water Quality Board to establish a binational surveillance network with key laboratories in the basin and move through a pilot microbial source tracking methods validation exercise project to harmonize applications of the methods across the basin. This project would include a subset of labs that would seek to harmonize molecular methods for surveillance of the SARS-CoV-2 virus at selected sewage treatment plants across the basin. A third project phase would be for the laboratory network to roll out a multiyear basinwide microbial source tracking study to identify fecal pollution sources and develop lake-by-lake health risk maps. A final phase would synthesize and communicate results and recommendations regarding fecal pollution sources and health risks to the Parties and stakeholders across the basin.

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[1] For information about the IJC's Great Lakes-St. Lawrence River Adaptive Management Committee, visit ijc.org/en/glam.

1.0 Introduction

The IJC is responsible for regular reporting on the status of the Great Lakes and other boundary waters, as well as investigating the risk to ecosystems that may result from current or future stressors (Canada and the United States, 2012). The Great Lakes constitute the largest freshwater ecosystem in the world. The basin is home to 3,500 species of plants and animals, and over 170 species of fish (Michigan Sea Grant 2020). These flora and fauna not only contribute to the environmental integrity, resilience and character of the region, they also support impressive Great Lakes tourism and recreation industries.

Viewed as a source of great pride among those who live in the region, the Great Lakes are a tourist draw to not only for North Americans but people from around the world. Residents and tourists alike spend nearly US$16 billion annually on boating trips and equipment in the Great Lakes and the region draws an impressive 37 million anglers, hunters, bird watchers and beach goers each year (Vaccaro and Read, 2011). The Great Lakes' beauty and ecological diversity mask their vulnerability to the cumulative effects of biological and chemical stresses. In reality, years of degradation from toxic contamination, destruction of coastal wetlands, nonpoint source pollution and invasive species have left the ecosystem at a tipping point (Bails, et al., 2005). Today, the Great Lakes contain 43 Areas of Concern (AOCs), places suffering extreme environmental degradation. Nonnative and invasive flora and fauna have further damaged ecosystem health. Sea lamprey, zebra mussels and quagga mussels are among the most well-known invasive species to date, and we also face the continued threat of Asian carp.

A changing climate also presents challenges for the Great Lakes ecosystem and its residents. Higher global temperatures are changing weather patterns and precipitation across the region. Diminishing duration and thickness of ice cover each winter and wider, more frequent variability in lake water levels are complicating planning and public and private infrastructure. This variability leads to fecal bacteria, from sewage releases along shorelines and septic systems, moving through watersheds (Verhougstraete et al. 2015). Many plants and animals important to Indigenous peoples are particularly vulnerable to climate change, including moose, wild rice and walleye, that place traditional agriculture, hunting and fishing harvests, and other economic and spiritual activities at risk. These changes affect Great Lakes ecology, economic value, and impact the lives and wellbeing of communities and populations around the basin. Changes in basin population, sewage treatment infrastructure, agricultural land use and practices and shoreline recreational use also influence the types and intensity of microbial contamination in the lakes.

The importance of clean Great Lakes water to human wellbeing has been a historic focus of the IJC with public health a prominent goal for maintaining water quality. Two critical human health and economic aspects of Great Lakes shoreline communities—drinking water and recreation—are impacted by fecal pollution from different sources of human and animal waste. The lakes provide drinking water for an estimated 40 million in the Canada the United Sates (and water for food and beverage products for millions more). Modern drinking water treatment greatly reduces health risks for the majority, but the types and adequacy of protection may vary, and an unknown number may drink untreated lake water.

Beaches and shallow waters of Great Lakes, known as the nearshore zone, provide significant recreational opportunities and are one of the most utilized areas in the region (US Environmental Protection Agency 1994). Recreation as an ecosystem service hinges on our continued expectations for clean water from an environment that is impacted by many stressors (Allan et al. 2013). The full benefits of achieving and maintaining a healthy nearshore zone are tied to improving many aspects of human wellbeing. The Great Lakes include 8,851 km (5,499.76 miles) of some of the world's greatest sandy beaches, but a growing trend of increasing beach closures has plagued many coastal communities (Chrzastowski et al. 1994; Folger et al. 1994; Natural Resources Defense Council 2011). Nationally, tourism has become a primary factor driving economic activity, job creation, wealth and investment (Houston 2008) and the economic value gained from Great Lakes beach tourism is visible in the foregone benefits of beach closures. Song et al. (2010) estimated closing all Lake Michigan beaches located in the state of Michigan would result in an economic loss of US$2.7 billion. Another Great Lakes basin study estimated beach closures cost the surrounding community nearly US$228,000 per event (Murray et al. 2001). The Brookings Institution (2007) suggested a 20 percent reduction in Great Lakes beach closures would result in an economic benefit of at least US$130 million per year, or at least US $2 billion in present day dollars. Therefore, Great Lakes beaches and nearshore environments are not only a treasured natural resource but also a vital economic driver for the surrounding communities and require protection against further degradation.

As early as 1913, the IJC conducted a detailed monitoring study of the fecal-related pollution of the boundary waters of the Great Lakes and the potential link between disease and sewage pollution (International Joint Commission 1918). The question of whether nearshore fecal bacterial/microbial water quality is getting better or worse is fundamental to maintaining the Great Lakes for recreational use and as a source of drinking water under the general objectives of the Great Lakes Water Quality Agreement. Public health is a prominent driver for maintaining and improving water quality; this project report provides the HPAB with an assessment of the state of knowledge on fecal contamination in the Great Lakes and examines how a basinwide, binational fecal pollution/microbial water quality reassessment might be carried out.

The 1913 IJC study looked at the relationship between fecal pollution and disease from using contaminated water as a drinking water source. Today, exposure occurs primarily through recreation and monitoring has focused on protecting beach users. An unknown number of people may use untreated or undertreated lake water for drinking as well, primarily in Indigenous or rural populations.

Monitoring tools are better today: we can enumerate more specific bacteria species (*E. coli* rather than total coliforms) and we can also use DNA-based technology known as microbial source tracking (MST) to identify fecal pollution sources of water quality impairment such as humans, cattle, pets and geese. These methods, combined with other tools that provide information on various pollution pathways (e.g., wastewater treatment plants (WWTPs), CSOs, septic systems, stormwater, direct deposition), allow public health officials to develop strategies to mitigate the pollution with targeted management actions.

1.1 Project overview

The purpose of this project was to use existing data to analyze fecal bacteria water quality changes and trends across the basin as observed within the last 10 years for comparison with those presented by the 1913 IJC study. The project also identified science and environmental management gaps related to fecal bacteria and fecal pollution sources that could inform investment in a basinwide microbial water quality reassessment. Project goals and objectives for a literature review and expert workshop included:

i. Determine changes and trends in the concentration of fecal contaminants at the subset of sites of the 1913 study in the Great Lakes using available data, including consideration of Lake Michigan, that was not included in the original study but is anticipated for inclusion in a future synoptic reassessment survey.

ii. Based on literature describing current technologies (e.g., genomic indicators) and existing microbial source tracking data:

    a. Describe approaches for determining the contributions or relative levels of contamination from various sources—human fecal waste, agricultural animal fecal waste, domestic animals (pets) and wildlife (e.g., waterfowl)—at 20-40 sampling locations used in the 1913 study.

    b. Describe the public health risks for swimming and water consumption at these sites.

iii. Evaluate contemporary sampling and fecal source identification programs and data, including for Lake Michigan, to provide updated conclusions about the range, geographical origin and distribution of pollution from sources of human waste, and to identify fecal pollution hotspots around the Great Lakes.

1.2 Project tasks

The project work group developed a work plan to describe the tasks, deliverables and schedule for the project. The tasks conducted to complete the project included:

- Reviewing the 1913 IJC study report and appendices. A total of 35 sampling locations used in the study were selected to span the geographical extent of the Great Lakes, including both lake and connecting channel areas (e.g., St. Marys River, St. Clair River, Lake St. Clair, Detroit River, Niagara River, St. Lawrence River) and the associated sampling information and biological (coliform) measurements were compiled. Information on the Great Lakes watershed conditions around 1913, such as human population sizes, were also compiled.
- Compiling and analyzing enumeration data for fecal coliform, E. coli and enterococci at locations in the Great Lakes from approximately 2004-2018. Additional data compiled

also includes information describing fecal bacteria conditions in the Great Lakes, including beach closing data. Data describing current watershed characteristics and conditions were also compiled. These data were used to characterize current fecal bacterial conditions in the Great Lakes and to compare contemporary conditions to conditions in and around 1913.

- Literature and data review for MST studies in the Great Lakes basin. These publications and data were used to assess the MST methods, markers and techniques used in Great Lakes research. They were also used to describe potential sources and pollution pathways.
- Hosting and facilitating a workshop of experts to discuss the analyses conducted for the project and to develop recommendations for a future basinwide, binational fecal bacterial/microbial water quality reassessment.

This report provides: an assessment of the 1913 conditions, as described in the 1918 report; a comparison to current fecal bacterial conditions across all of the Great Lakes, based on data from the last 10-15 years including both enumeration and MST methods; an assessment of sources and pollution pathways from published studies; a description of an expert workshop including a summary of findings and recommendations for improving bacterial monitoring and conditions basinwide; and an overall project summary. This report describes each of these tasks and the major findings.

2.0 The 1913 Great Lakes Transboundary Water Pollution Study

The IJC initiated a comprehensive, first-of-its-kind study of transboundary fecal bacterial contamination in the Great Lakes in 1913. The HPAB members believe that this study remains the largest fecal microbial water quality study, in terms of its spatial extent and number of samples collected, in North America. Prior to describing the study, we present some information on what the Great Lakes watershed was like a century ago for context. Note that this is not a comprehensive or detailed historical characterization of Canada or the United States during this period, but is intended to provide a sense of the state of the Great Lakes at that time.

2.1 The Great Lakes basin in 1913

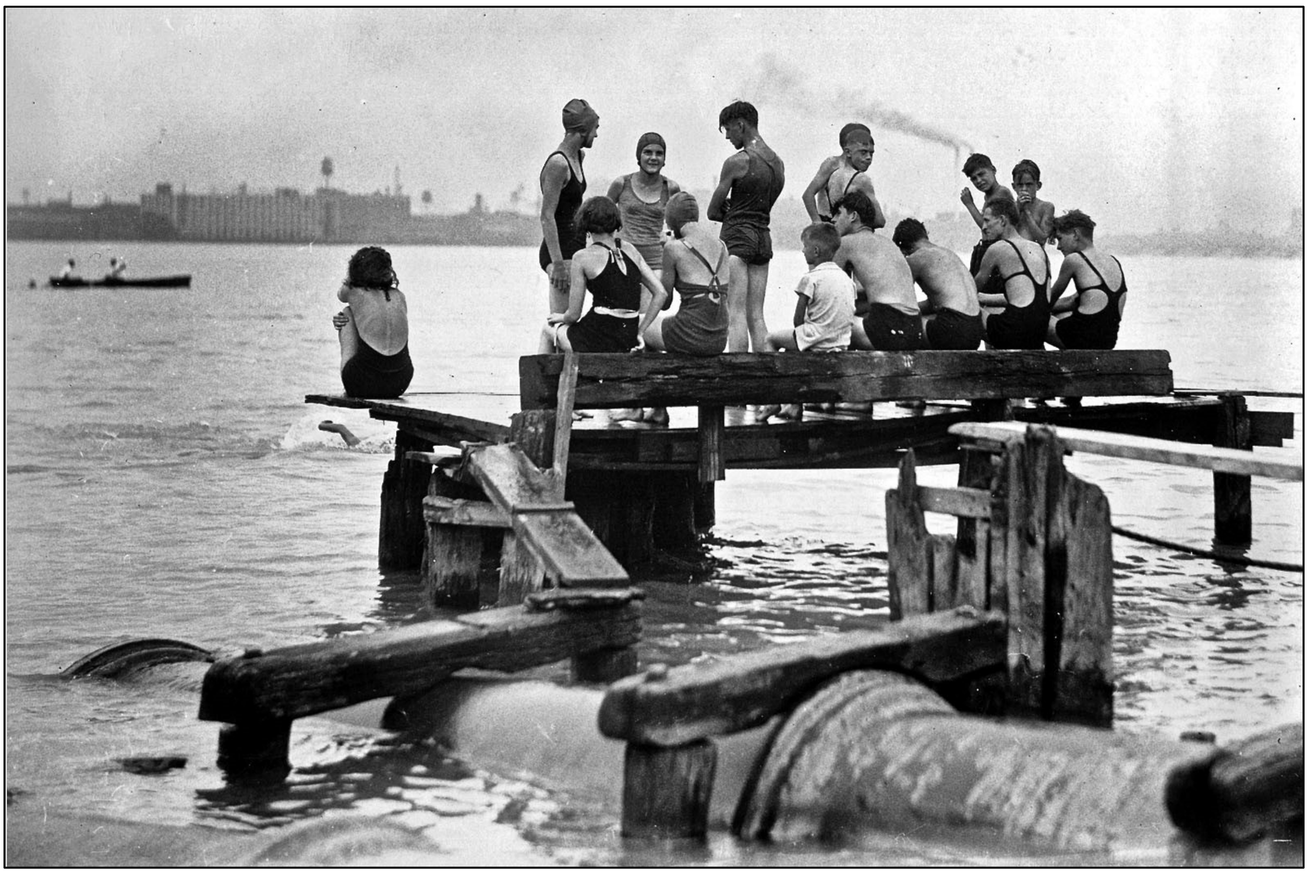
At the time of the 1913 IJC water pollution study, the Great Lakes basin was on the cusp of the population explosion that peaked midcentury in the United States and continues through today in Canada. Approximately seven million people lived along boundary waters of the Great Lakes. There were only eight cities with populations greater than 100,000 in 1910-1911 and of those Toronto was the only one in Canada (**Table 2-1** below). Buffalo was a larger city (population 423,715) than Toronto (population 327,753) in 1911.

Table 2-1: Population of major cities in the Great Lakes basin in 1910-1911.

City*	Great Lake/ Connecting Channel	1910/1911 Population**,†
Duluth, MN	Lake Superior	78,466
Thunder Bay, ON‡	Lake Superior	27,719
Sault Ste. Marie, ON	Lake Superior	10,984
Sault Ste. Marie, MI	Lake Superior	12,615
Green Bay, WI	Lake Michigan	25,236
Milwaukee, WI	Lake Michigan	373,857
Chicago, IL	Lake Michigan	2,185,283
Gary, IN	Lake Michigan	16,802
Muskegon, MI	Lake Michigan	24,062
Traverse City, MI	Lake Michigan	12,115
Saginaw, MI	Lake Huron	50,510
Sarnia, ON	St. Clair River	9,947
Detroit, MI	Detroit River	465,766
Windsor, ON	Detroit River	17,829
Toledo, OH	Lake Erie	168,497
Cleveland, OH	Lake Erie	560,663
Buffalo, NY	Niagara River	423,715
Rochester, NY	Lake Ontario	218,149
Kingston, ON	Lake Ontario	18,874
Toronto, ON	Lake Ontario	327,753
Hamilton, ON	Lake Ontario	81,959

* US cities populations are from 1910. Canadian city populations are from 1911.
** US cities population data source: worldpopulationreview.com that cites the US Census as its source.
† Canadian cities population data source: Table XXV in Appendix of 1918 IJC Transboundary Water Pollution Study (International Joint Commission 1918)
‡ In 1910, the contemporary Thunder Bay area was two municipal areas: Port Arthur and Fort Williams. The population of both cities were added together and reported in the table. This was done to facilitate comparisons to current day populations.

Many cities were in the process of building sewers at the time of the IJC study. A section of the 1918 IJC report details the sanitary sewer system plans for several communities in the Great Lakes. These sewer systems typically delivered the sanitary sewage waste directly to the nearest waterway with little or no treatment. Conventional wastewater treatment processes were in their infancy at the time of the 1913 study. For example, the activated sludge process had just been developed in 1912 in England (Metcalf and Eddy, 1915). Deaths due to typhoid were a major concern at this time. The link between fecal contamination from sanitary sewer discharges to rivers and streams and incidence of disease was not well known, as evidenced by the below photograph from 1925 showing a group of young people swimming by a sewer outfall in the Detroit River (IJC, personal communication, email from Jennifer Boehme to Carrie Turner, May 6, 2019).



Historical photograph of swimmers by a sewer outfall in the Detroit River in 1925. Photo credit: Tom Phare, Windsor then Windsor now, available from windsorthenwindsornow.wordpress.com/2011/02/25/the-good-old-days-swimming-in-the-poopy-detroit-river/.

Economically, the industrial revolution was underway. For example, the first Ford Model-T cars started rolling off the first moving assembly line in 1913. The industrial activity was creating a demand for iron ore, coal and other raw materials that the shipping routes on the Great Lakes were well suited to fill (**Figure 2-1** below).

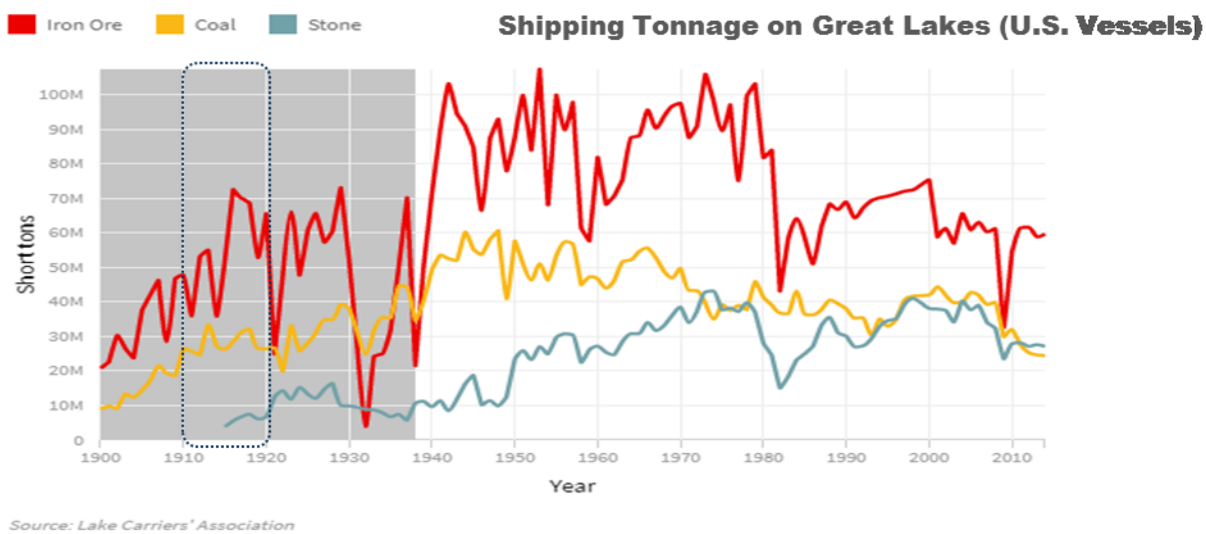


Figure 2-1: Shipping tonnage on the Great Lakes (US vessels) by year, 1900-2012. Data from Lake Carrier's Association as published by WBEZ, available at: wbez.org/stories/come-hell-or-high-water-can-great-lakes-shipping-make-a-resurgence/bf2c3960-2de7-4ece-ac7c-96ce07fa2866.

Freight shipping on the Great Lakes experienced rapid growth between 1910 and 1920. Iron ore tonnage shipped on the Great Lakes increased from less than 50 million tons to over 70 million tons by mid-decade. Less dramatic but still significant increases in coal shipping also occurred over the same time. Note that the amounts shipped today are similar to the amounts shipped in the 1910 decade for iron ore and coal. Vessels dumped their raw sewage directly into the lakes and rivers. There were far less poultry and far more ovine (sheep) and equine (horses) livestock compared to modern times, and livestock were dispersed over larger geographic areas but at lower densities.

2.2 The 1913 IJC water pollution study description

In 1912, the IJC was charged with determining the extent of fecal contamination in the parts of the Great Lakes that served as a shared boundary between Canada and the United States. The study objectives were to determine: 1) the extent and means that boundary waters are polluted; and 2) how cross-boundary pollution could be prevented and/or remedied. Lake Michigan was not included in the study.

2.2.1 1913 IJC study design

The study design was informed by public comments and a panel of experts, including public health officials, scientists, engineers, and state and provincial representatives. The study cost was

US$42,138.18 (1912 US dollars), that is equivalent to US$1,090,843.81 today (2018 US dollars), based on an average inflation rate of 3.01 percent over that 106-year period.[1]

An extensive sampling program was conducted over seven months in 1913, with a particular focus on areas where cross-boundary pollution was suspected, and nearly 1,500 locations were sampled. Each location was sampled multiple times over 10-30 days. Over 19,000 samples were collected in seven months. Areas near urban areas were sampled and provided information on the impacts of urban sanitary sewage discharges. Similarly, shipping channels were sampled to characterize impacts of sanitary discharges from ships.

A variety of sampling strategies were used to conduct the fecal pollution monitoring (**Figure 2-2** below). In the connecting channels, transects across the river were favored so that contamination from each side of the river could be characterized. In the lakes themselves, sampling was clustered around key areas, such as major tributary inputs. Both nearshore and offshore sampling were done in the lakes. Samples were also collected at depth in some locations. Note in the figure that the black numbers are the station identifier and the red numbers are the average concentration over the sampling period.

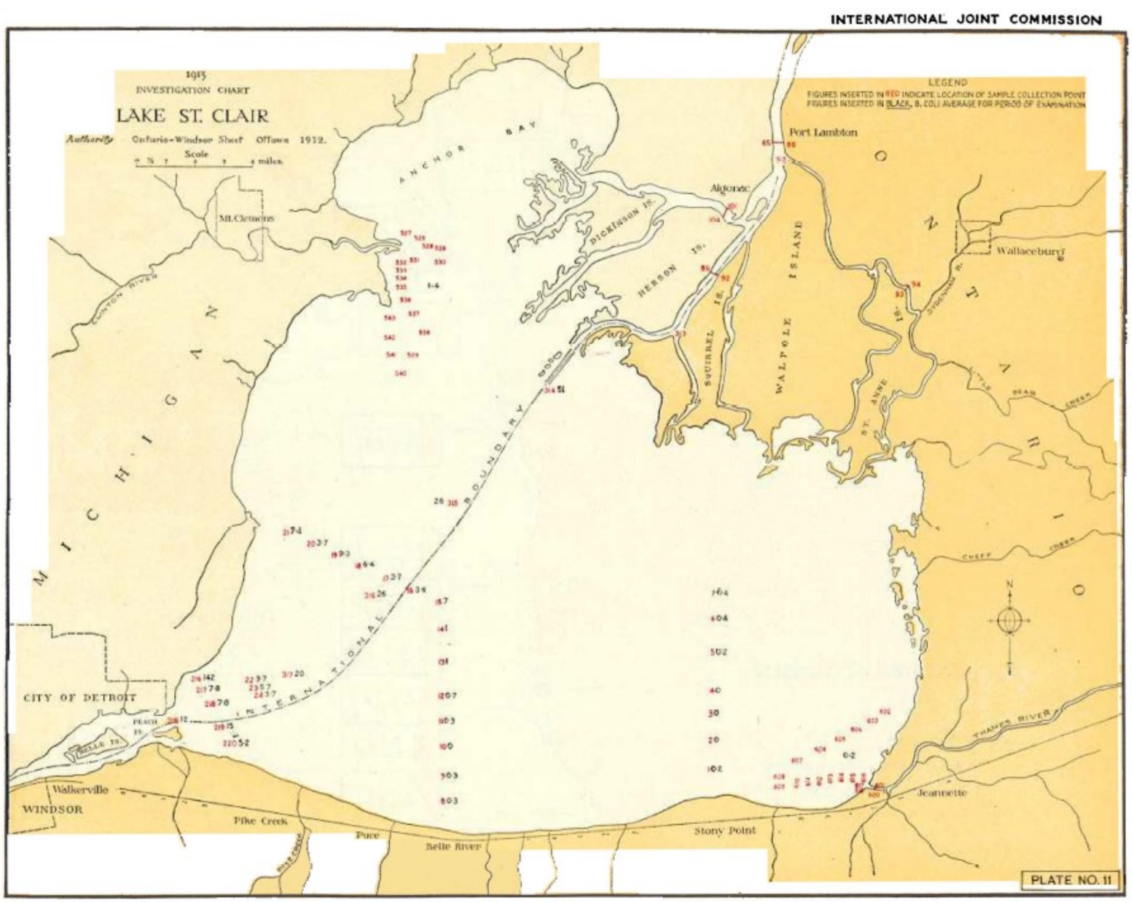


Figure 2-2: Example of IJC 1913 study sampling strategy in lakes and connecting channels.

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[1] Calculations for dollar values derived using in2013dollars.com/.

Samples were analyzed using the most advanced methods available at the time. Three bacterial analyses were conducted:

- Total bacteria incubated at 18-22°C
- Total bacteria incubated at 37°C
- *Bacillus coli* (*B. coli*) by lactose fermentation at 37°C (Phelps method)

The *B. coli* method is a measure of total coliform using the Phelps analytical method developed in 1908. This is a most probable number method, though the report authors note that it considerably underestimates the number of *B. coli*, but was used for its convenience. At the time of the study, *B. coli* was thought to be a type of bacteria that lives in the colon of mammals, so it was a useful measure of fecal contamination. However, we now see *B. coli* as representing a range of bacterial species similar to those in the total coliform group of bacteria. Seventeen labs across the basin were utilized for the analytical component of the study.

As part of the study, IJC researchers also compiled information related to health risks, including water supply sources, drinking water intake locations relative to sanitary sewer discharges, sanitary sewer system specifications and outlet locations, and rates of disease, specifically typhoid mortality.

2.2.2 1913 IJC study results

The 1918 report appendix contains the raw data from the nearly-19,000 samples collected. The report itself summarizes the maximum and average results from the three analytical methods. In general, offshore samples and samples taken at depth tended to have very low concentrations. Nearshore samples collected away from urban areas also tended to have low levels of fecal bacteria. Nearshore lake and river samples from urban areas tended to have the highest bacteria levels. The far shore lake and midstream connecting channel samples tended to have lower bacteria levels than corresponding nearshore samples, suggesting that transboundary transport of fecal pollution was sufficiently diluted or was not a significant process.

The study authors identified key zones of pollution (**Figure 2-3** below) and concluded that the connecting channels were “grossly polluted.” The key zones of pollution in Figure 2-3 tend to be mostly in the connecting channels and immediately downstream of the connecting channels.

Figure 2-3: "Zones of Pollution" identified in the 1913 IJC study.

The authors also developed a method to categorize the sites based on the *B. coli* results using a scale of 1 to 5. A site ranked as a 5, or grossly polluted, if the *B. coli* result was greater than 50 counts/100 ml. However, there were no "standards" in the conventional sense of today's water quality standards to compare to the scale or degree of contamination. The authors concluded that ship discharges were rarely significant, but that untreated sanitary sewage was the greatest factor in the level of pollution that they measured. To combat this, they recommended that treatment of city drinking water be increased to better protect the public.

2.2.3 1913 IJC study data subset

The 1913 dataset was too voluminous to fully digitize within this centennial study assessment. Therefore, a subset of locations that were representative of the Great Lakes, not just the most polluted sections, were identified and summarized for this project.

To identify 30-40 locations out of 1,500 possible locations, the following criteria were applied to the 1913 sampling locations to narrow down the list of potential locations:

- Is the sampling location in a current AOC, especially if it has a beach closing Beneficial Use Impairment? If an area is currently impaired, what can be learned by looking at the data from that location collected in 1913?
- Is the sampling location part of a river transect, especially a paired river transect? Transects were generally used in the connecting channels and provided information regarding the lateral mixing of fecal contamination, as well as potentially the country of origin.
- Is the sampling location a nearshore location, especially if it is near a current beach that is likely monitored today? Nearshore areas are typically where recreation activities and potential exposure to contamination from urban sewage occur. Also, offshore lake data generally had very low concentrations, well below the EPA recreational water quality criteria (US Environmental Protection Agency 2012), and are not sampled as frequently today as nearshore locations are.
- Does the location have a relatively high B. coli result? Those locations were given more consideration as they pinpoint fecal-impacted locations.

Table 2-2 (below on pages 13 and 14) provides a summary of the selected subset of locations with respect to the criteria listed above. Most of the high-concentration samples were in the connecting channels (**Figure 2-3** above), so the selected subset has a relatively high number of those locations (**Table 2-2**). Location information, sampling details and analytical results are summarized in **Table 2-3** (below on pages 15 and 16).

The subset of 1913 locations is shown on the map in **Figure 2-4** (below on page 17). The blue dots are the 1913 subset of sampling locations with their station identifier labeled, that can be cross-referenced to the entries in **Table 2-2**. The stars are the AOC locations.

It is notable that a few areas were not targeted for sampling in 1913, including the Duluth, Minnesota area in western Lake Superior; Saginaw Bay in Lake Huron; the Cleveland, Ohio area in Lake Erie; and the Hamilton and Toronto, Ontario metropolitan areas in western Lake Ontario. These areas may have been left out because they were not close to the international boundary (the white line bisecting the map in **Figure 2-4**).

Table 2-2: Basis of selection of 1913 sampling locations subset for water quality centennial study.

#	Geographic Area	Waterbody Type	1913 Sampling Point No.	Current AOC?	Beach Closing Beneficial Use Impairment?	River Transect?	Paired Transect?	High Concentration?	Basis for Selection
1	Lake Superior	Lake	39	Yes	Yes	..	..	Yes	Highest concentration along nearshore, Lake Superior dataset.
2	St. Marys River	Connecting Channel	28	Yes	Removed 2016	Yes	Yes	Yes	Opportunity for transect location with municipality on either side, capture impacts of municipal discharges.
3	St. Marys River	Connecting Channel	34	Yes	Removed 2016	Yes	Yes	Yes	Opportunity for transect location with municipality on either side, capture impacts of municipal discharges.
4	St. Marys River	Connecting Channel	26	Yes	Removed 2016	..	..	Yes	Levels described in report as being due almost entirely to navigation.
5	Lake Huron Lower End	Lake	167	..	..	..	..	..	Wanted a lake location, this one could overlap with contemporary monitoring due to proximity to Gratiot Beach.
6	Lake Huron Lower End	Lake -> River	44	Yes	Removed 2017	Yes	..	..	Characterize water quality exiting Lake Huron.
7	St. Clair River	Connecting Channel	172	Yes	Removed 2017	Yes	Yes	Yes	Opportunity for transect location with municipality on either side, capture impacts of municipal discharges.
8	St. Clair River	Connecting Channel	176	Yes	Removed 2017	Yes	Yes	..	Opportunity for transect location with municipality on either side, capture impacts of municipal discharges.
9	St. Clair River	Connecting Channel	85	Yes	Removed 2017	Yes	Yes	Yes	Characterize water quality leaving St. Clair River, downstream of current-day Algonac State Park (MI) so may have contemporary monitoring data.
10	St. Clair River	Connecting Channel	88	Yes	Removed 2017	Yes	Yes	..	Characterize water quality leaving St. Clair River, downstream of current-day Brander Park (ON) so may have contemporary monitoring data.
11	Lake St. Clair	Connecting Channel	543	Yes	Yes	..	..	..	Located around current-day Lake St. Clair Metropark and outlet of Clinton River (MI) so likely to have contemporary monitoring data.
12	Lake St. Clair	Connecting Channel	216	..	..	..	Yes	..	Characterize water quality entering Detroit River, very close to upper boundary of Detroit River AOC.
13	Lake St. Clair	Connecting Channel	220	..	..	..	Yes	..	Characterize water quality entering Detroit River, very close to upper boundary of Detroit River AOC.
14	Detroit River – Upper	Connecting Channel	227	Yes	Yes	Yes	Yes	Yes	Opportunity for transect location with municipality on either side. Upstream of Rouge River inputs and downriver communities' water intakes.
15	Detroit River – Upper	Connecting Channel	231	Yes	Yes	Yes	Yes	Yes	Opportunity for transect location with municipality on either side. Downstream end of Riverside Park, may have contemporary monitoring data.
16	Detroit River – Lower	Connecting Channel	243	Yes	Yes	..	..	Yes	Downstream of Rouge River inputs. One of highest concentrations in Detroit River.
17	Detroit River – Lower	Connecting Channel	263	Yes	Yes	..	..	Yes	Downstream of River Canard. Fairly high concentration for Canadian side of the Detroit River.
18	Detroit River – Lower	Connecting Channel	264	Yes	Yes	Yes	Yes	Yes	Transect location immediately downstream of urban inputs along Detroit River.
19	Detroit River – Lower	Connecting Channel	273	Yes	Yes	Yes	Yes	Yes	Transect location immediately downstream of urban inputs along Detroit River.
20	Lake Erie-Western End	Lake	122	Yes	Yes	..	..	Yes	Characterize water quality leaving Detroit River. Location is also just upstream of present-day Lake Erie Metropark (MI) so may have contemporary monitoring data.
21	Lake Erie-Western End	Lake	328	Yes	..	..	..	Yes	Location is within Maumee River AOC, near Maumee Bay State Park (OH) so may have contemporary monitoring data.
22	Lake Erie-Eastern End	Lake	1	..	..	..	Yes	..	Wanted a Lake Erie location, near (US) present-day Crystal Beach (ON) so may have contemporary monitoring data.

#	Geographic Area	Waterbody Type	1913 Sampling Point No.	Current AOC?	Beach Closing Beneficial Use Impairment?	River Transect?	Paired Transect?	High Concentration?	Basis for Selection
23	Lake Erie-Eastern End	Lake	16	..	..	..	Yes	..	Wanted a Lake Erie location, near (US) present-day Lake Erie Beach (NY) so may have contemporary monitoring data.
24	Upper Niagara River	Connecting Channel	50X	Yes	..	Yes	Yes	Yes	Characterize water quality at start of Niagara River. Opportunity for transect location with municipality on either side.
25	Upper Niagara River	Connecting Channel	50S	Yes	..	Yes	Yes	..	Characterize water quality at start of Niagara River. Opportunity for transect location with municipality on either side.
26	Niagara River	Connecting Channel	61	Yes	..	..	..	Yes	One of highest concentrations in Niagara River. Will capture effects of urban loads to Scajaquada Creek.
27	Niagara River	Connecting Channel	78	Yes	..	..	..	Yes	Characterize water quality immediately downstream of Niagara Falls area.
28	Lower Niagara River	Connecting Channel	157	Yes	..	Yes	Yes	Yes	Transect location immediately downstream of urban area on both sides of the river. River is noted as uniformly mixed after the Falls.
29	Lower Niagara River	Connecting Channel	159	Yes	..	Yes	Yes	Yes	Transect location immediately downstream of urban area on both sides of the river. River is noted as uniformly mixed after the Falls.
30	Lake Ontario – Western End	Lake	170	..	..	..	..	Yes	Characterize water quality into Lake Ontario. Near AOC Queens Royal Beach.
31	Niagara River	Connecting Channel	145	Yes	..	..	..	..	Characterize near shore conditions downstream of Tonawanda Creek/Erie Canal confluence near Tonawanda.
32	Lake Ontario – Eastern End	Lake	74	..	..	..	..	..	Characterize water quality leaving Lake Ontario.
33	St. Lawrence River	Connecting Channel	231	No	..	..	..	Yes	Characterize water quality in St. Lawrence River. Near Arrowhead Beach Park so may have contemporary monitoring data.
34	St. Lawrence River	Connecting Channel	270	No	..	..	..	Yes	Just upstream of start of St. Lawrence AOC near Massena (NY).

Table 2-3: Sampling information and data for 1913 sampling locations subset for water quality centennial study.

#	Geographic Area	Waterbody Type	Latitude (dec. deg.)	Longitude (dec. deg.)	Start Sample Date	End Sample Date	Number of Samples Taken	MAXIMUM			AVERAGE		
								Bacterial Counts per CC on Agar		B. coli Smallest Volume Showing Reaction (ml)	Bacterial Counts per CC on Agar		B. coli (mpn / 100 ml)
								18 – 22°C	37°C		18 – 22°C	37°C	
1	Lake Superior	Lake	48.450593	-89.169079	7/28/1913	8/18/1913	15	210	60	1	84	27	84
2	St. Marys River	Connecting Channel	46.500903	-84.307472	6/28/1913	7/16/1913	15	300	80	0.1	109	26	640
3	St. Marys River	Connecting Channel	46.493487	-84.313142	6/28/1913	7/16/1913	15	600	18	1	108	7	56
4	St. Marys River	Connecting Channel	46.514472	-84.368166	6/28/1913	7/16/1913	15	370	22	0.1	52	8	262
5	Lake Huron Lower End	Lake	43.03144	-82.428238	7/3/1913	8/7/1913	26	..	6,400	10	..	255	3
6	Lake Huron Lower End	Lake -> River	46.369446	-84.207568	7/29/1913	8/22/1913	18	62	28	1	13	8	91
7	St. Clair River	Connecting Channel	42.96517	-82.421061	7/13/1913	8/7/1913	21	..	550	0.01	..	115	2,405
8	St. Clair River	Connecting Channel	42.965108	-82.413757	7/13/1913	8/7/1913	21	..	110	0.1	..	26	193
9	St. Clair River	Connecting Channel	42.644223	-82.511132	7/28/1913	8/16/1913	15	2,000	3,200	0.1	524	522	299
10	St. Clair River	Connecting Channel	42.644258	-82.506413	7/28/1913	8/16/1913	15	195	110	1	49	25	15
11	Lake St. Clair	Connecting Channel	42.557757	-82.77612	10/6/1913	10/6/1913	18	40	33	25	6	6	1.4
12	Lake St. Clair	Connecting Channel	42.37621	-82.911947	5/23/1913	7/7/1913	23	..	110	0.1	..	47	142
13	Lake St. Clair	Connecting Channel	42.343061	-82.889517	5/23/1913	7/7/1913	23	..	181	10	..	34	5.2
14	Detroit River – Upper	Connecting Channel	42.31933	-83.065048	5/23/1913	7/7/1913	25	..	17,200	0.001	..	21,160	17,125
15	Detroit River – Upper	Connecting Channel	42.315084	-83.063006	5/23/1913	7/7/1913	25	..	1,160	0.01	..	472	5,050
16	Detroit River – Lower	Connecting Channel	42.204153	-83.144656	6/18/1913	7/31/1913	22	..	213,000	0.001	..	38,104	25,150
17	Detroit River – Lower	Connecting Channel	42.139076	-83.117142	7/3/1913	7/31/1913	22	..	1,100	0.01	..	155	2,223
18	Detroit River – Lower	Connecting Channel	42.071623	-83.18844	7/21/1913	7/31/1913	10	..	35,000	0.001	..	23,804	24,400
19	Detroit River – Lower	Connecting Channel	42.071978	-83.120013	7/21/1913	7/31/1913	10	..	280	0.1	..	137	460
20	Lake Erie-Western End	Lake	42.051974	-83.18039	9/6/1913	9/25/1913	15	120,000	90,000	0.01	29,214	12,035	3,693
21	Lake Erie-Western End	Lake	41.697499	-83.461499	8/1/1913	8/16/1913	15	..	910	0.01	..	341	2,620
22	Lake Erie-Eastern End	Lake	42.827376	-79.097555	5/26/1913	6/17/1913	14	24	17	0	5	3	0
23	Lake Erie-Eastern End	Lake	42.704218	-79.059236	5/26/1913	6/17/1913	15	516	58	1	54	10	16

#	Geographic Area	Waterbody Type	Latitude (dec. deg.)	Longitude (dec. deg.)	Start Sample Date	End Sample Date	Number of Samples Taken	MAXIMUM			AVERAGE		
								Bacterial Counts per CC on Agar		B. coli Smallest Volume Showing Reaction (ml)	Bacterial Counts per CC on Agar		B. coli (mpn / 100 ml)
								18 – 22°C	37°C		18 – 22°C	37°C	
24	Upper Niagara River	Connecting Channel	42.910405	-78.902524	6/14/1913	6/18/1913	4	20,000	4,400	0.01	5,470	1,303	3,025
25	Upper Niagara River	Connecting Channel	42.910325	-78.908097	6/14/1913	6/18/1913	4	73	10	25	39	8	2.5
26	Niagara River	Connecting Channel	42.944251	-78.912359	6/14/1913	6/18/1913	15	8,240	2,400	0.001	3,092	1,132	51,400
27	Niagara River	Connecting Channel	43.085503	-79.070424	5/30/1913	6/10/1913	10	800	1,130	0.1	440	222	1,630
28	Lower Niagara River	Connecting Channel	43.17978	-79.049611	8/1/1913	8/9/1913	7	..	5,960	0.01	..	3,640	6,142
29	Lower Niagara River	Connecting Channel	43.179597	-79.054398	8/1/1913	8/9/1913	7	..	4,170	0.01	..	2,800	4,857
30	Lake Ontario – Western End	Lake	43.267718	-79.066491	8/4/1913	8/21/1913	15	..	3,400	0.01	..	2,020	6,400
31	Niagara River	Connecting Channel	43.046515	-78.893434	6/25/1913	7/15/1913	15	..	6,200	0.001	..	2,477	21,466
32	Lake Ontario – Eastern End	Lake	44.196674	-76.553888	8/9/1913	9/3/1913	13	..	58	10	..	20	1.5
33	St. Lawrence River	Connecting Channel	42.315084	-83.063006	4/15/1913	5/4/1913	15	66	500	1	31	54	39
34	St. Lawrence River	Connecting Channel	44.928229	-75.100317	8/1/1913	8/27/1913	60	..	7,400	0.1	..	1,967	183

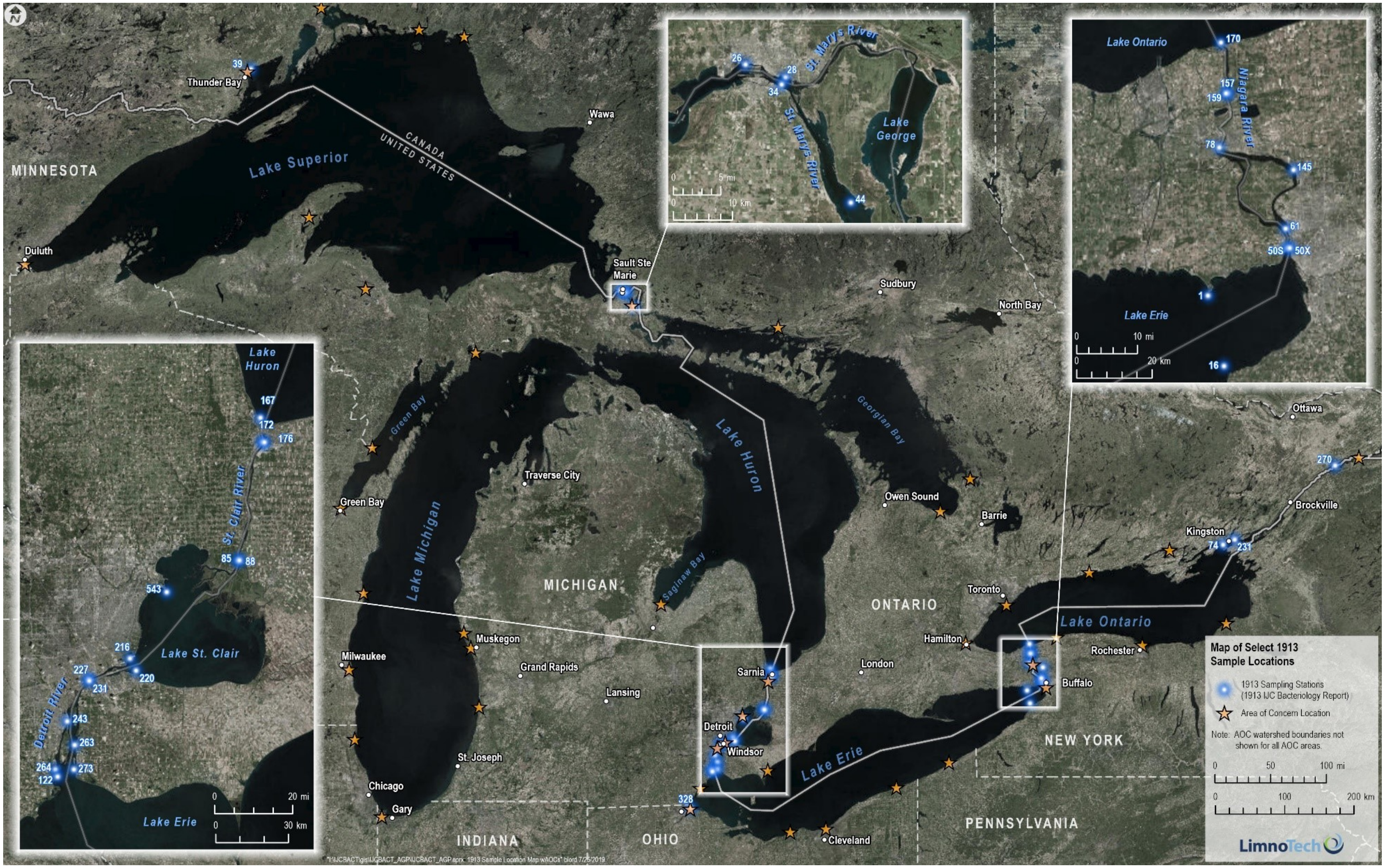

Figure 2-4: 1913 study sample location subset map. The blue dots are the 1913 subset of sampling locations with their station identifier labeled, the stars are AOC locations, and the white lines indicate the international boundary between Canada and the United States.

3.0 Contemporary (2008-2018) Data Compilation

Current data on fecal bacteria and their impacts on recreation were compiled for the purposes of:

- Characterizing conditions within each Great Lake and connecting channel;
- Evaluating recent trends (approximately 10-15 years) in fecal bacteria levels in each Great Lake; and
- Identifying gaps in understanding and data for the purposes of envisioning the next centennial water quality study.

Unlike in the 1913 study, this data compilation effort included Lake Michigan as well as beaches throughout each of the Great Lakes, including the areas not sampled in the 1913 study: Duluth, Minnesota; Saginaw, Michigan; Cleveland, Ohio; Hamilton, Ontario; and Toronto, Ontario.

Contemporary fecal bacteria/microbial analyses in the Great Lakes predominantly use *E. coli* (a more specific indicator of fecal contamination than total coliform) that was reported in the 1913 study as *B. coli*. Other fecal markers include fecal coliform and enterococci. *E. coli* was used as the marker of choice for this project because it is recommended by the US Environmental Protection Agency (USEPA) and Health Canada as a freshwater fecal indicator bacteria (Health Canada 2012; US Environmental Protection Agency 2012), analytical methods are well-established (American Public Health Association 1998; US Environmental Protection Agency 1985; US Environmental Protection Agency 2006), and many Great Lake locations have been monitoring it for years such that changes in conditions over time can be assessed.

3.1 Data compilation

Using a list of data providers provided by the IJC as a starting point, and supplementing with data available on US state and municipal websites, *E. coli* data from the Great Lakes were compiled (**Table 3-1** below). Where readily available, fecal coliform and enterococci enumeration data were also compiled, as well as meteorological data. Enumeration data were obtained for 1,869 locations across the Great Lakes, predominantly in nearshore beach locations. This limited the ability to assess transboundary transport in the contemporary data. Over 300,000 *E. coli* observations were compiled.

Table 3-1: Data sources for contemporary fecal bacteria data in the Great Lakes.

Data Source	Method of Accessing Data
Chicago Park District	Data file provided by Carol Kim
City of Racine, Wisconsin	Directed to Wisconsin Beach Guard website
Hamilton (ON) Beach Monitoring	Data digitized by hand from website hamilton.ca/parks-recreation/parks-trails-and-beaches/beach-water-quality-in-hamilton
Illinois Beach Guard	Downloaded from website idph.state.il.us/envhealth/ilbeaches/public/
Indiana Beach Guard	Downloaded from website extranet.idem.in.gov/beachguard/
Michigan Beach Guard	Downloaded from website deq.state.mi.us/beach/
Minnesota Beach Guard	Data copied and digitized by hand from website mnbeaches.org/gmap/dataviewer.html
National Oceanic and Atmospheric Administration Great Lakes Environmental Research Laboratory	Directed to Michigan Beach Guard
New York Beach Monitoring	Data copied and digitized by hand from website ny.healthinspections.us/ny_beaches/
Northeast Ohio Regional Sewer District	Data file provided by Eric Soehnlen
Ohio Beach Guard	Downloaded from website publicapps.odh.ohio.gov/beachguardpublic/
Toronto SwimSafe	Data digitized by hand from website app.toronto.ca/tpha/beaches.html
Water Quality Portal (USEPA/US Geological Survey)	Downloaded data via query from website waterqualitydata.us/
Windsor-Essex County	Data digitized by hand from website wechu.org/your-environment/beaches-pools-and-spas/beaches
Wisconsin Beach Guard	Data copied and digitized by hand from reports on website https://dnr.wisconsin.gov/topic/Beaches/Monitoring.html

It is important to note that the sampling protocols vary: some beaches are only sampled in June, July, and August, while others are sampled from May through October; some beaches are sampled once a week, some twice a week, some daily. As a result, data density varies by beach. Analytical methods also vary: some beach results are reported in plate count colony forming units (CFU/100 ml), while others report most probable number (MPN/100 ml) because an MPN method like Colilert is used for analysis.[1] For the purposes of the analyses for this project, CFU and MPN results were considered equivalent measures of bacteria concentrations.

[1] More information about Colilert can be accessed at: idexx.com/en/water/water-products-services/colilert.

The map in **Figure 3-1** below shows all the locations where quantitative *E. coli* data were obtained. The 1913 subset of locations are also shown on the map for reference. Note that there are few locations with both a 1913 subset location total coliform and current quantitative *E. coli* data.

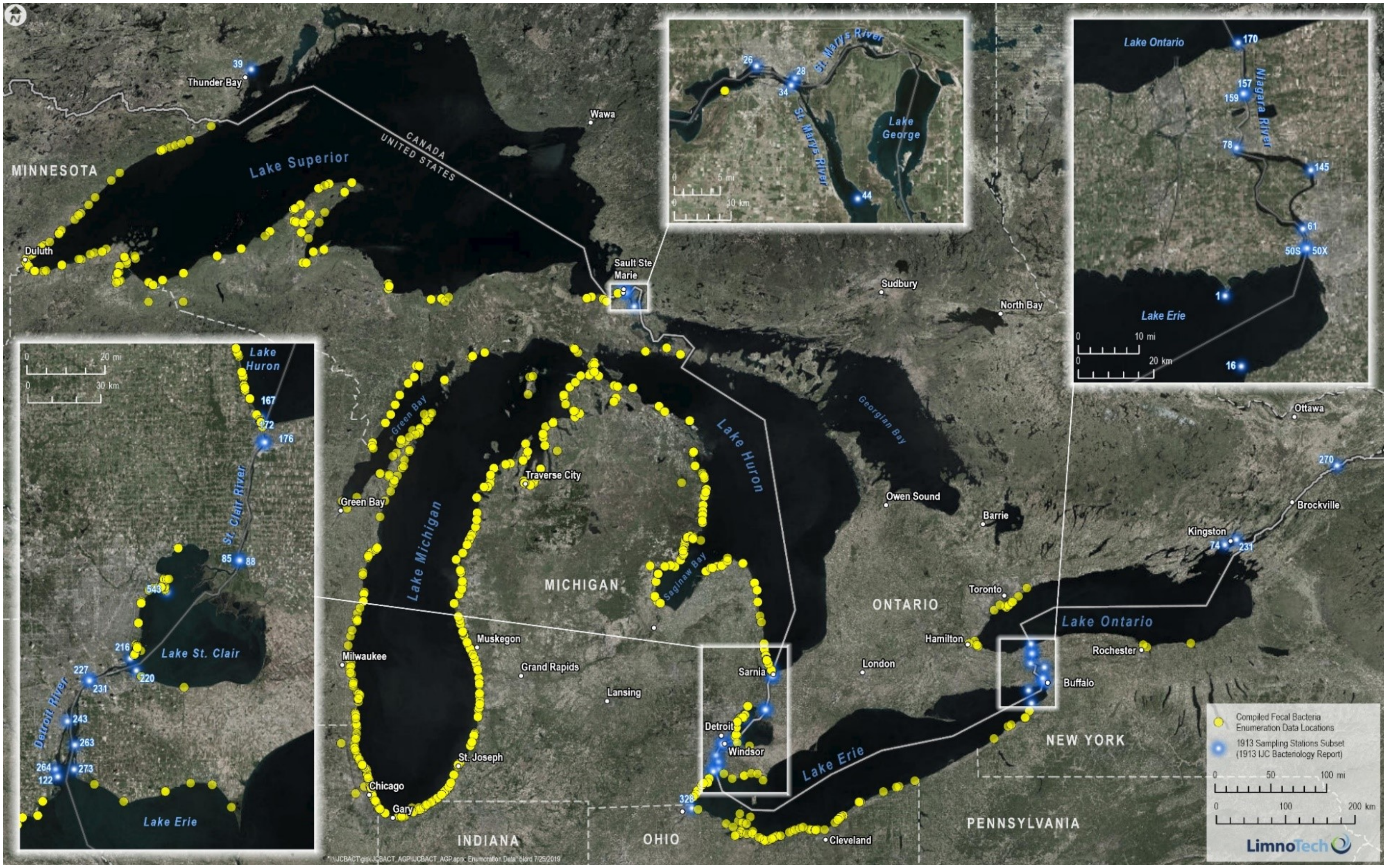

Figure 3-1: Locations of compiled *E. coli* enumeration data (yellow dots).

Figure 3-1 also shows that while beaches are monitored locally in Canada (by local health units) the data are not readily available online or in a central database. It was challenging to get *E. coli* data from Ontario sources, though data posted on websites for Toronto, Hamilton, and Windsor-Essex County were digitized by hand. The lack of readily available enumeration data from Canada and the differences between current sampling locations and 1913 sampling locations presented a quandary with respect to linking back to 1913 data and assessing each lake's water quality.

3.1.1 Beach closing data

An alternative dataset, beach closing data, were obtained from the SwimGuide website[2] for a subset of locations (**Figure 3-2** below on page 22). Most, but not all, states use 235 CFU/100 ml (number of *E. coli* measured as colony forming units), that is the USEPA's beach action value (BAV), as the basis for closing beaches. The appeal of this data type is that data could be obtained for both sides of the Great Lakes. There are over 1,500 beaches in the Great Lakes, so a subset of beaches for compiling data was identified based on several criteria:

- Is it close to a 1913 sampling location compiled for this project?
- Is it in an area that did not have *E. coli* enumeration data readily available?
- Is it at an area that was part of a microbial source tracking study, in case there is a connection between these two datasets?
- Is it known as a 'popular' beach and thus at a potentially higher risk for illness due to the higher number of people recreating at the site?

Annual beach closing frequency data spanning 2011-2018 for 111 beaches were compiled based on these criteria. Note that there are several thousand beaches in the Great Lakes and potentially many more that fit these criteria. The subset of beaches used in this analysis represent broad geographic extent, balanced binational coverage and a variety of land uses sufficient for conducting the analyses described in this report.

However, there are challenges with these data, namely that different beach managers use different criteria for closing beaches (**Table 3-2** below on page 23), making it difficult to draw conclusions on whether a beach that is closed more often than another beach is closed because that beach is actually more contaminated or that it has a more stringent criterion or set of criteria. In addition, some entities are using indicators other than *E. coli*, such as enterococci (Chicago area), and some managers are making beach closing decisions not only based on *E. coli* levels but also on conditions such as the presence of harmful algal blooms (e.g., Cleveland area beaches on Lake Erie).

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[2] More information about SwimGuide can be accessed at: theswimguide.org.

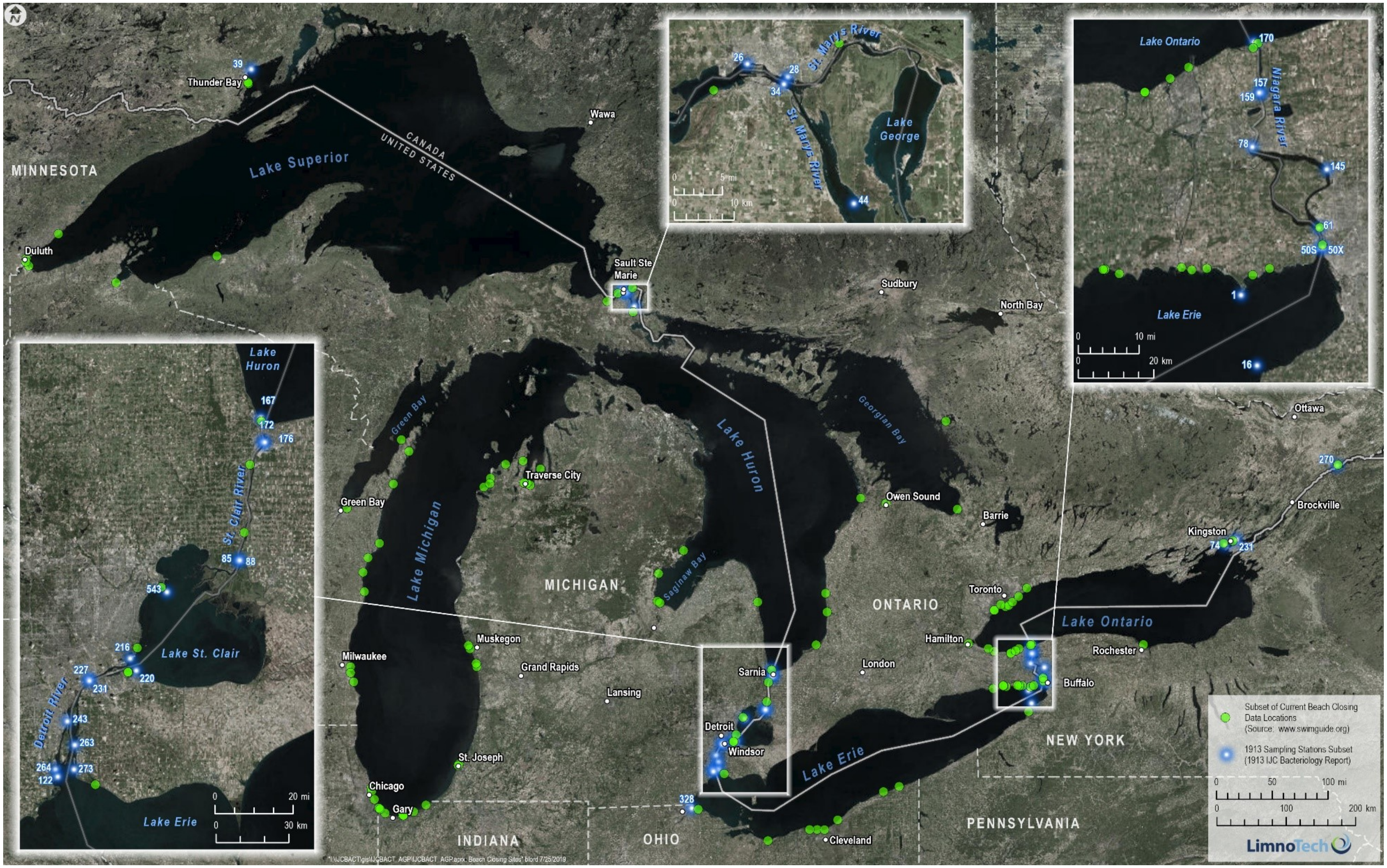

Figure 3-2: Subset of locations with beach closing data (green dots).

Table 3-2: Summary of beach closing criteria.

State/ Province	Criteria (# of E.coli /100 ml)	Criteria Type	Additional Notes
Illinois*	235	Single sample maximum	Chicago area beaches using enterococci for beach closing decisions (104/100 ml).
Indiana*	235	Single sample maximum	
Michigan*	300	Geometric mean maximum**	
Minnesota*	235	Single sample maximum	
New York*	235	Single sample maximum	
Ohio	235	Single sample maximum	Several beaches noted as using presence of harmful algal blooms as a basis for closing.
Ontario*	400	Single sample maximum	Ontario did not have a single maximum value prior to 2018. In 2018, Ontario changed from a geometric mean of ≤ 100/100 mL, to a geometric mean of ≤ 200/100 mL and/or a ≤ 400/100 mL maximum single-sample value.
Pennsylvania	235	Single sample maximum	
Wisconsin*	235	Single sample maximum	

* These states/provinces include a 30-day geometric mean criterion as well in assessing water quality at their beaches. Ontario changed their 30-day geometric mean criterion in 2017.

** For a given sampling "event," three samples spanning the geographic extent of the sampling location are collected and the geometric mean of the three samples is compared to the maximum criterion shown.

These data were reviewed for both the frequency of beach closings as well as their trend over the last eight years (2011-2018), when the data were consistently available.

3.2 Data analysis of contemporary lake fecal bacterial levels

Enumeration data collected over the last 10-15 years were analyzed to assess lake water quality with a focus on beach conditions because this is a key potential route of exposure. The enumeration data were analyzed with two direct measures. The first of these is the 95th percentile concentration. This was a human health indicator for illness risk from recreational water contact recommended by the HPAB in a 2014 report (International Joint Commission Health Professionals Advisory Board 2014). The second direct measure is the percent of values greater than 235 *E.coli*/100 ml, that is the BAV developed by the USEPA as part of its Recreational Water Quality Criteria in 2012 (US Environmental Protection Agency 2012). The value in doing this assessment is that all of the data were compared to the same criterion value, making a consistent comparison basis of beaches in different states and countries.

3.2.1 95th percentile E. coli concentration by beach (2018 data)

Figure 3-3 (below) shows the 95th percentile *E. coli* concentration from 2018, the most recent season of monitoring. Dark green circles represent locations where the 95th percentile concentration was less than 235 CFU/100 ml that corresponds to good beach quality. The highest concentrations tend to be in the Lake Erie watershed.

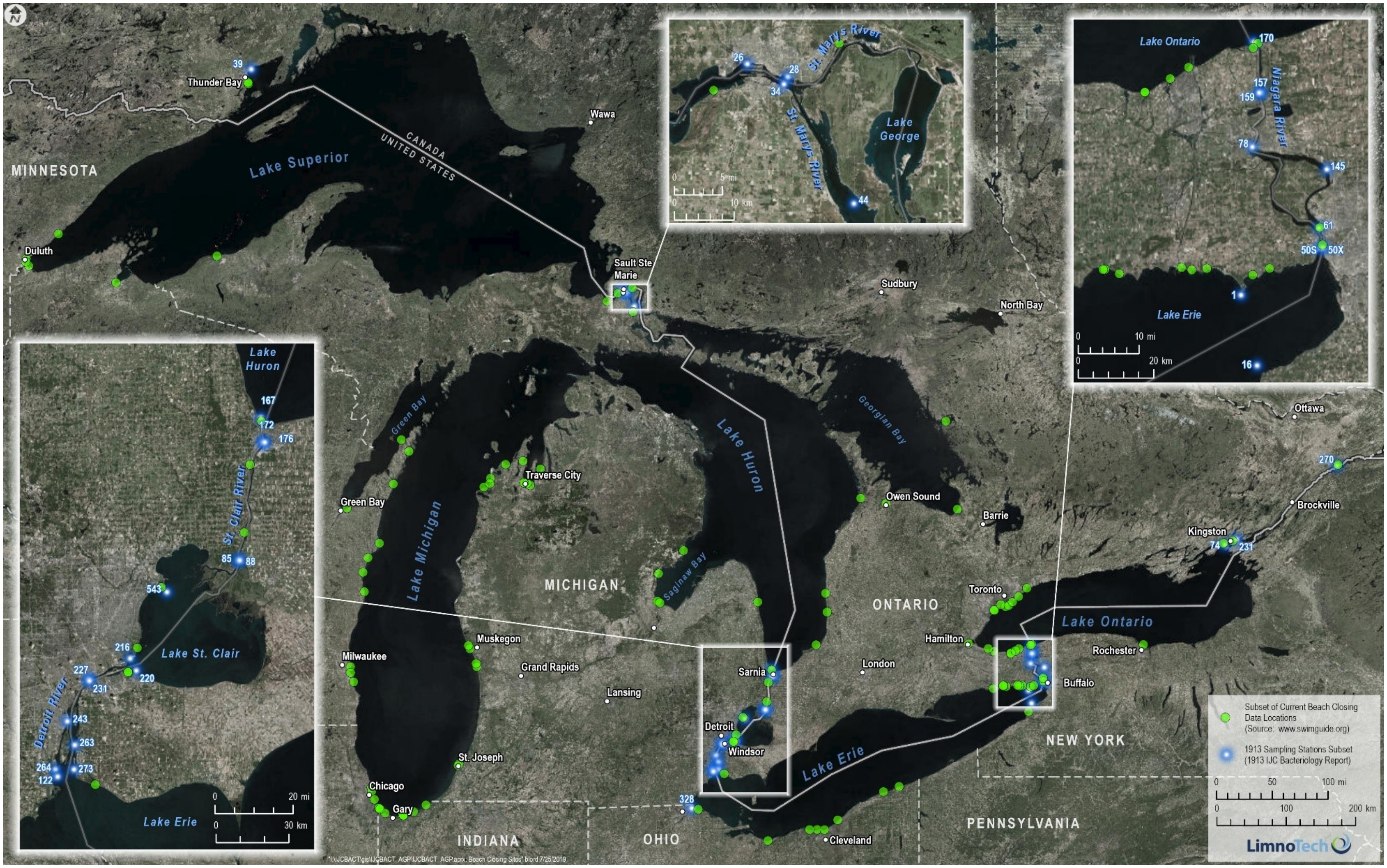

Figure 3-3: 95th percentile *E. coli* concentration by beach, 2018 data. Dark green circles represent locations where the 95th percentile concentration was less than 235 CFU/100 ml.

3.2.2 Percent of 2018 E. coli data greater than 235 E. coli/100 ml

For this analysis, the percent of observations exceeding 235 *E.coli*/100 ml, the USEPA BAV, were calculated for each beach using 2018 *E. coli* data (**Figure 3-4** below). Light and dark green locations are beaches where fewer than 10 percent of the *E. coli* measurements were higher than 235 *E.coli*/100 ml. Each lake had beaches with at least 25 percent of the values exceeding the BAV (orange and red dots), except Lake Ontario that had a limited dataset. Beaches located near large urban areas tended to have the highest percentages of *E. coli* observations above the BAV.

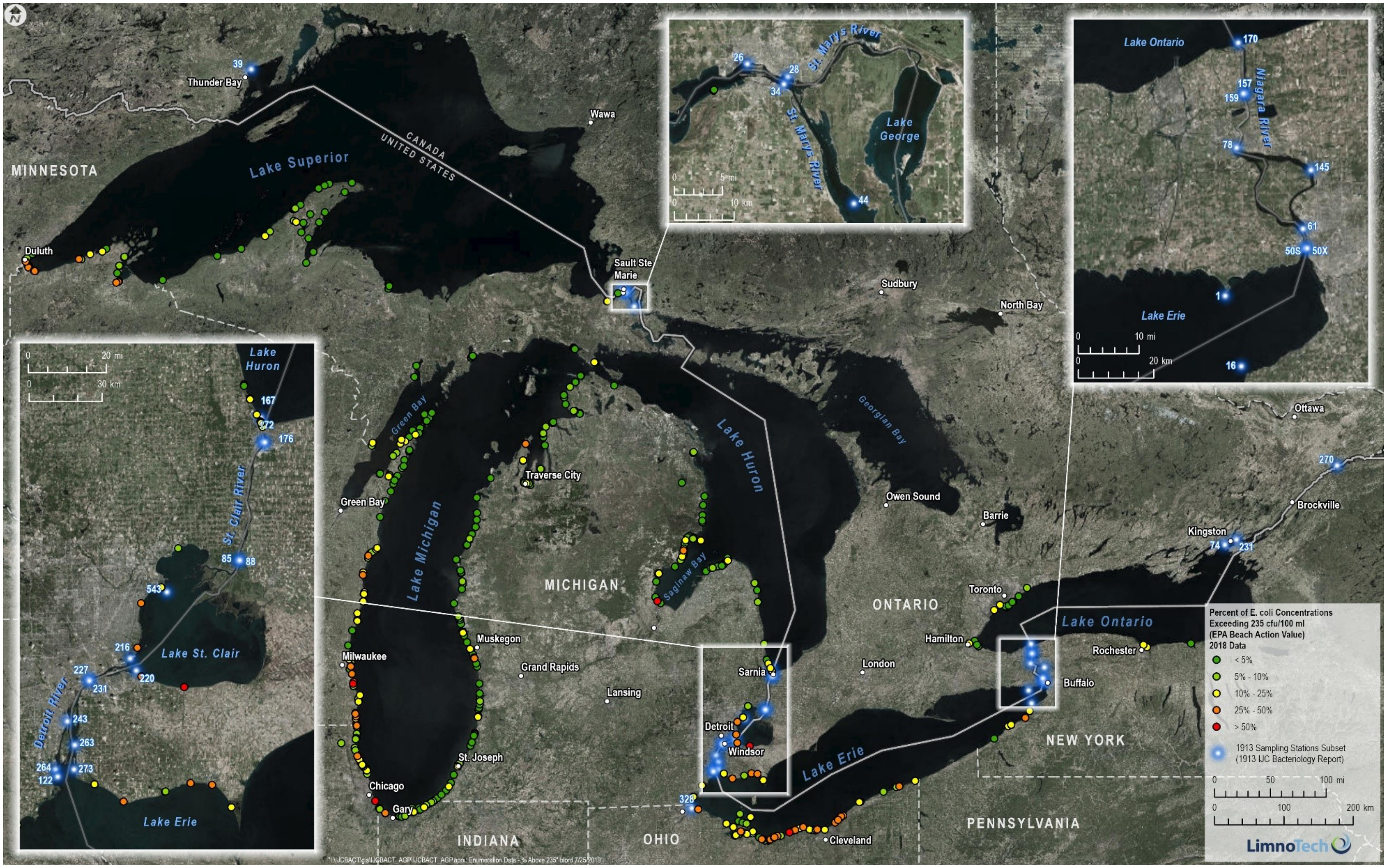

Figure 3-4: Percent of 2018 *E. coli* data exceeding USEPA BAV (235 *E. coli*/100 ml). Light and dark green locations are beaches where fewer than 10 percent of the *E. coli* measurements exceed BAV. Orange and red locations have 25 percent or greater of the measurements exceed BAV.

3.2.3 Time trend analysis by lake: 2004-2018

Figure 3-3 and **Figure 3-4** (above) present a snapshot of conditions in 2018 using readily available data that focuses on the US side of the lakes. However, understanding how conditions are trending over time in each Great Lake is of interest for several reasons:

- Answering the general question, “Are the lakes getting cleaner and safer for the public?”
- Understanding differences between lakes to inform the sampling strategy for the next centennial water quality study; and
- Determining where to target additional resources.

The data for the beaches in each Great Lake, as well as Lake St. Clair, were separated into three periods: 2004-2008, 2009-2013, and 2014-2018. The five-year aggregation was intended to smooth out year-to-year differences in meteorological conditions, sampling variability and other short-term effects that could mask the general trend. Variability between beaches was also reduced by limiting the dataset to data from samples collected from June through August when nearly all beaches are sampled. Finally, only the beaches that had data within each five-year period were used to calculate the time trend for each Great Lake.

As noted previously, the 95^{th} percentile *E. coli* concentration has been recommended as a human health indicator for illness risk from recreational water contact (International Joint Commission Health Professionals Advisory Board 2014). The 95^{th} percentile concentration for each five-year period was calculated for each beach in each Great Lake. The median of this dataset was used to determine the general trend in each lake. Results are shown in **Figure 3-5** (below on page 29). Individual beach 95^{th} percentile concentrations are shown as the blue circles, while the median is shown as the dashed symbol and line. A decreasing trend line indicates an improvement in lakewide water quality. USEPA’s BAV (235 *E. coli*/100 ml) is also indicated on each figure.

As a companion to the analysis summarized in **Figure 3-5**, the percent of beaches where the 95^{th} percentile exceeded 235 *E. coli*/100 ml was tallied for all of the beaches for each time period. Results are shown in **Table 3-3** (below on page 30). In this analysis, a lower percentage corresponds to better water quality conditions.

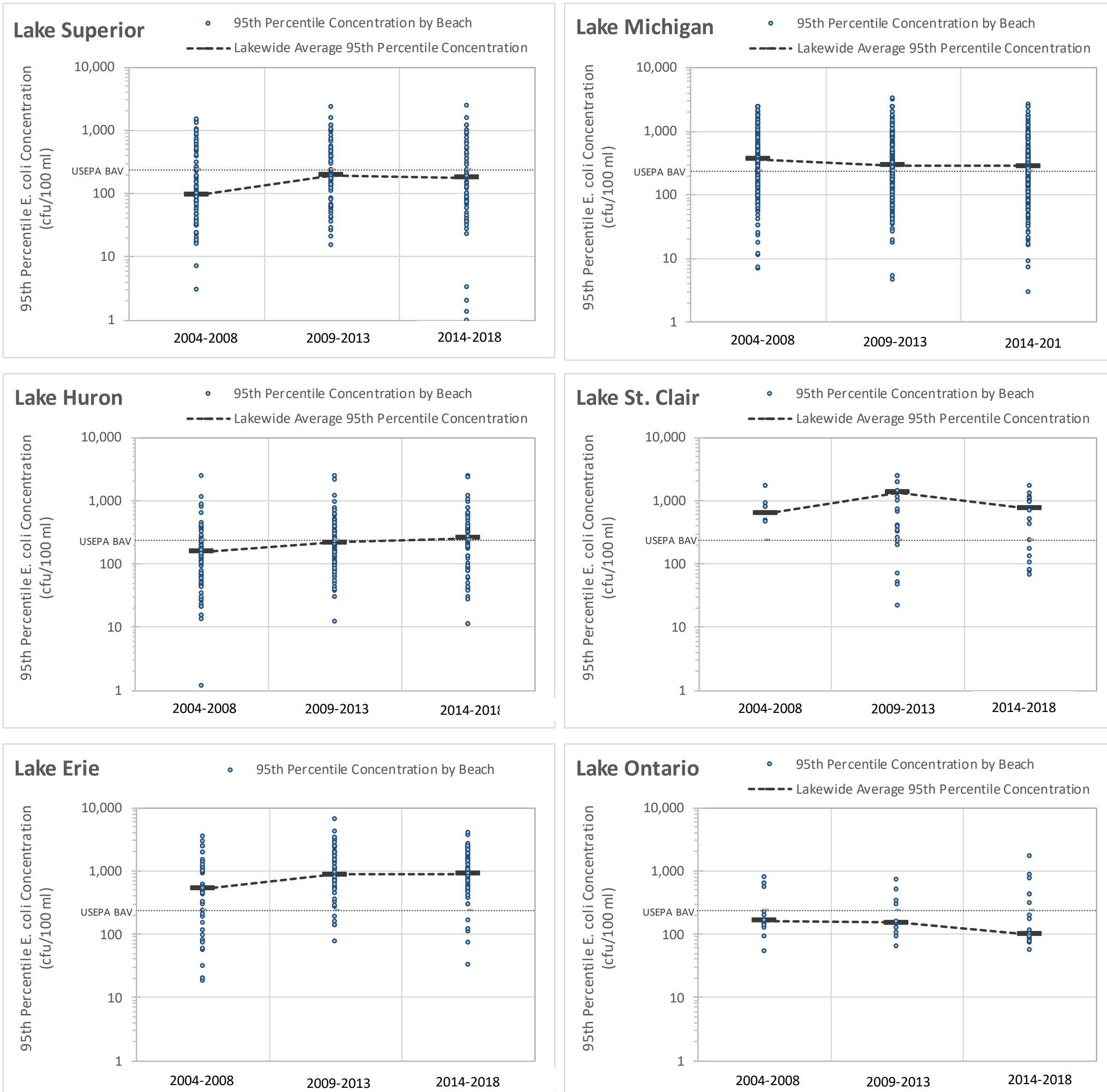

Figure 3-5: Time trend analysis by lake using 95th percentile *E. coli* concentration (June-August data only). Blue circles are individual beach 95th percentile concentrations. Median value indicated by dashed symbol and line.

Table 3-3: Percent of beaches, by lake, with 95th percentile *E. coli* concentration above USEPA BAV (235 *E. coli*/100 ml).

Lake	Number of Beaches Analyzed	Percent of Beaches where 95th Percentile Concentration Exceeds 235 *E.coli*/100 ml		
		2004-2008	2009-2013	2014-2018
Lake Superior	117	26%	43%	36%
Lake Michigan	356	61%	60%	57%
Lake Huron	101	23%	38%	53%
Lake Erie	88	71%	92%	94%
Lake Ontario	18	27%	36%	33%
Lake St. Clair	23	100%	71%	67%

Water quality in Lake Michigan appears to be slowly improving based on the direction of the trend line shown in **Figure 3-5** and the results in **Table 3-3**. The trend in 95th percentile concentrations lakewide is approaching the USEPA BAV. Water quality in Lake Ontario also appears to be improving over the last 10 years, and lakewide 95th percentile concentrations are below the USEPA BAV.

However, water quality for the United States side of Lake Huron appears to be worsening, based on a steady increase in concentrations in **Figure 3-5** and in the percent of beaches above the USEPA BAV in **Table 3-3**. The Lake Superior dataset showed a worsening of water quality from 2004-2008 and 2009-2013; however, the trend appears to have been stable over the last 10 years. Lakewide concentrations for all three periods are below the USEPA BAV.

The highest overall concentrations were in Lake Erie, the smallest of the Great Lakes, and in Lake St. Clair, that is much smaller than Lake Erie. Lakewide concentrations are well above the USEPA BAV for all three five-year periods in both lakes. However, the trend over the last 10 years appears to be stable in Lake Erie and improving in Lake St. Clair. The results in **Table 3-3** provide further evidence that Lake St. Clair water quality is improving while Lake Erie appears to have been fairly stable over the last 10 years.

Table 3-4 (below) presents a summary of the time trend analysis for each lake. Note that these characterizations reflect modest differences between each five-year period. The last two columns present the corresponding assessment of Beach Advisories sub-indicator in the IJC first triennial assessment of progress report on Great Lakes water quality (International Joint Commission 2017). The results of the bacterial concentration trend described in this report is generally consistent with the triennial assessment results in that Lake Erie is deemed to be in the worst condition, and Lake Superior, Lake Michigan and Lake Ontario are generally in "good" condition. However, the analysis presented in this report identified modest changes (e.g., 4 percent reduction in the number of beaches where the 95th percentile concentration exceeds USEPA's BAV) in Lakes Michigan, Huron and Ontario. The IJC's triennial assessment reports the trend in each of these lakes as "unchanging." This may be due to differences in the data periods used for each analysis and/or the basis used to assign the trend.

Table 3-4: Summary of US Great lakes bacterial trend analysis.

Lake	Water Quality Trend*	Lakewide Concentration Trend vs. USEPA BAV (235/100 ml, *E. coli*)		2017 IJC Triennial Assessment	
		Trend**	Status**	Trend	Status
Lake Superior	⟷ (Stable)	Lower than BAV	(Good)	Unchanging	Good
Lake Michigan	↑ (Improving)	Near BAV, trending lower	(Good)	Unchanging	Good
Lake Huron	↓ (Worsening)	Near BAV, trending higher	(Fair)	Unchanging	Good
Lake Erie	⟷ (Stable)	Higher than BAV	(Poor)	Deteriorating	Poor
Lake Ontario	↑ (Improving)	Lower than BAV	(Good)	Unchanging	Fair to Good
Lake St. Clair	↑ (Improving)	Higher than BAV	(Poor)	Not assessed	Not assessed

* Environment and Climate Change Canada and US Environmental Protection Agency, 2017.

** Designation assigned by authors based on analysis of information in **Figures 3-2** and **3-3** of this report.

3.3 Analysis of contemporary beach closing data in the Great Lakes

Due to the difficulty in obtaining *E. coli* enumeration data from Ontario, beach closing data were used as a proxy for fecal bacterial contamination. Beach closing data are more readily available for both sides of the lakes. Annual beach closing frequency data spanning 2011-2018 for 111 beaches were compiled, as described previously.

3.3.1 Frequency of 2011-2018 beach data below management criteria[3]

For the eight-year period of data (2011-2018), the average percent of time that a beach was open is shown in **Figure 3-6** (below on page 32) for the subset of beaches (111) used for this project. The general interpretation is that the less often a beach is open (e.g., red circles), the more likely it has occurrences of elevated *E. coli* levels. However, this interpretation must be qualified by the caveats regarding the closing criteria changing from location to location and that some beach managers include factors other than *E. coli* levels in making a beach closing decision.

The results from this analysis are similar to one of the findings from the 1913 study (**Figure 2-3** on page 11) that is that the connecting channels and lake areas immediately downstream of the connecting channels tend to have higher frequencies of beach closings (red and orange circles). Another observation from **Figure 3-6** is that beaches near urban areas tend to have higher closure rates, consistent with the analysis of data exceeding 235 *E. coli*/100 ml (**Figure 3-4** above on page 27).

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[3] Beach closing criteria vary by state and province. Refer to **Table 3-2** (above on page 23).

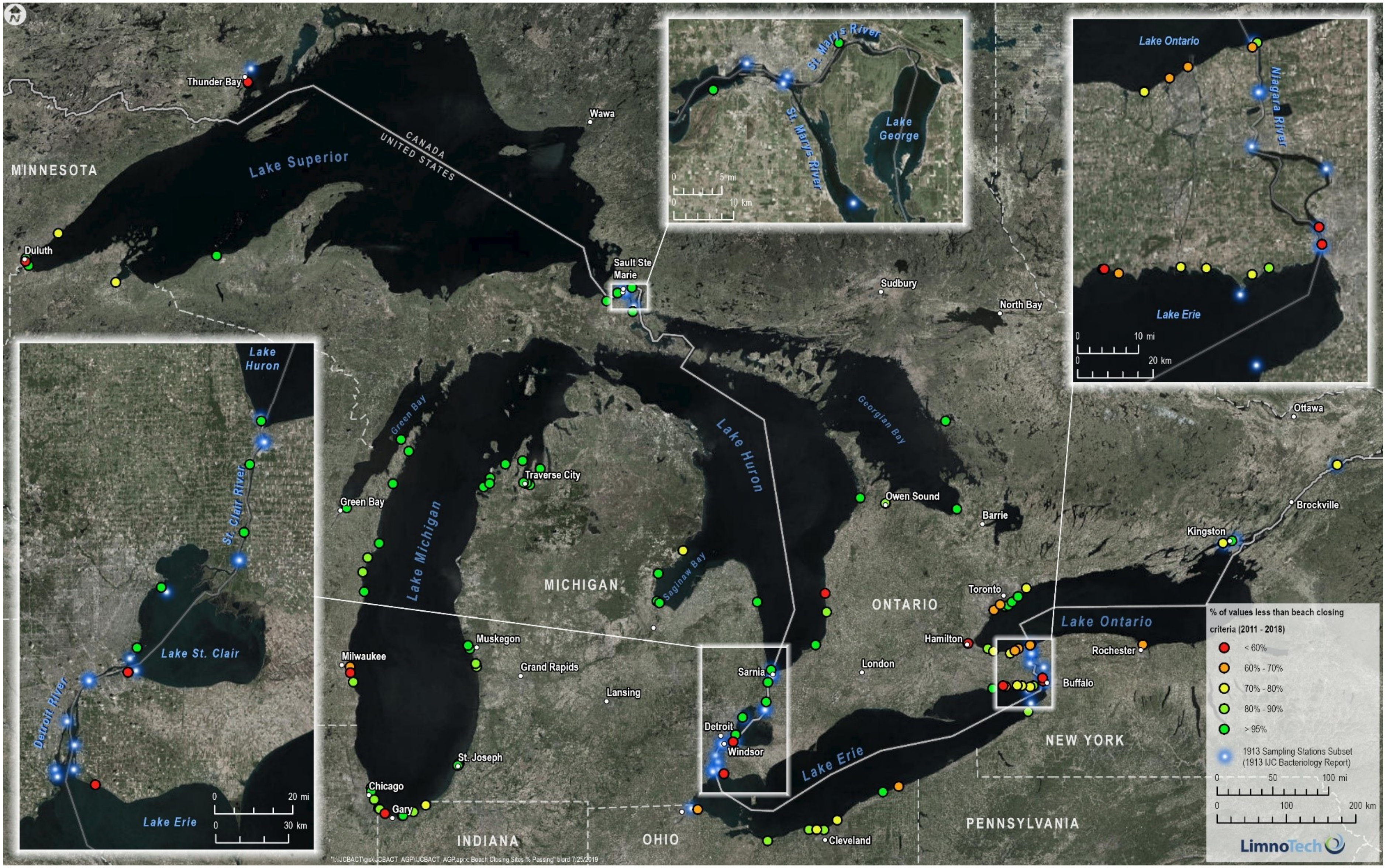

Figure 3-6: Percent of 2011-2018 data below state or provincial beach closing criteria.

Figure 3-7 (below on page 34) presents the same analysis but using only the 2018 data instead of the eight-year average results shown in **Figure 3-6** (above). The 2018 dataset compares favorably to the eight-year average results in several geographic areas, including Milwaukee. Data for three beaches in the Milwaukee area were compiled in the beach closing dataset. Milwaukee has more than three beaches, but these three (McKinley Beach, South Shore Park, and Grant Park) were selected to represent conditions over the geographical extent and local features of the Milwaukee area. In **Figure 3-6** (above), the eight-year average has a somewhat high frequency of failing the beach closing criteria at two of these beaches. The eight-year average may be influenced by years with worse weather than what occurred in 2018. However, it is also important to consider that conditions have not been static over that eight-year period. For example, Milwaukee made significant investments to reduce the frequency and volume of CSO discharges and address stormwater runoff through green infrastructure.[4] The improvement in the 2018 data relative to the eight-year average data may be reflecting these investments along with year-over-year differences in precipitation and other environmental factors.

The year-by-year results at each of the three Milwaukee beaches are shown graphically in **Figure 3-7**. In these plots, the closer the line is to 100 percent, the better the overall water quality. The graphs are also instructive because it is tempting to misinterpret one good year as evidence of a success story or one bad year as evidence of a problem. These graphs show that no single year or location tells the whole story. For example, 2015 was the worst year at McKinley Beach but the best year at Grant Park. As the next section will illustrate, beach water quality tends to be highly localized and pollution appears to be driven primarily by nearby sources. It may be that in 2015, McKinley Beach was impacted by a local project or source that affected only that beach and/or only that year. However, the trend in more recent years at McKinley Beach and South Shore Park is generally improving, while the conditions at Grant Park Beach, where the beach data have a high rate of compliance with beach standards (greater than or equal to 80 percent) each year, are stable. More monitoring and analysis of data from other area beaches would be needed for confirmation of this pattern.

[4] More information about Milwaukee's CSO impacted waters is available at: mmsd.com/about-us/weather-center/cso-impacted-waters.

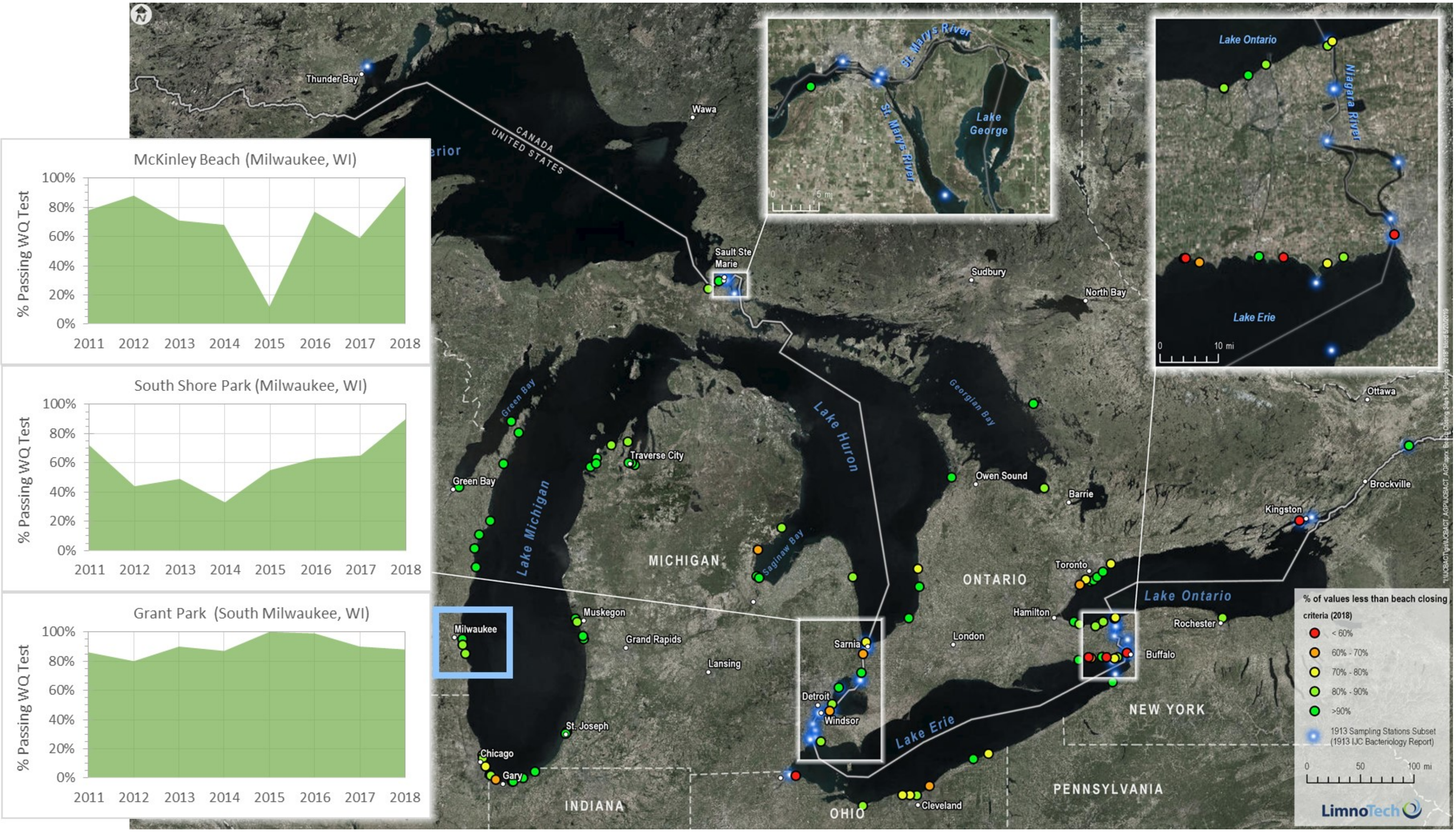

Figure 3-7: Percent of 2018 data below state or provincial beach closing criteria with inset of Milwaukee-area time series for three beaches.

3.3.2 Beach closing time trends by lake

As with the lake time trend analysis conducted with the *E. coli* enumeration data, the beach closing data for the subset of beaches compiled were aggregated by lake to evaluate trends over time. The averages of the beach data in each lake for each year from 2011-2018 are shown in **Figure 3-8**. Results show that beaches are open most of the time in Lakes Superior, Michigan and Huron (greater than 80 percent of the time), with moderately less time open in Lake Ontario and Lake Erie beaches (60-80 percent of the time). This provides supporting evidence for the *E. coli* trends and average levels shown previously.

Figure 3-8: Lakewide average percent of data less than beach closing criteria. N = the number of beaches included.

3.3.3 Relationship between predominant land use and beach closing data

For this analysis, four beaches in predominantly urban areas, four beaches in predominantly rural areas, and four beaches in predominantly undeveloped areas, such as national and state parks, were randomly selected. Each urban beach and rural beach is on a different Great Lake to get broad representation across the lakes (**Figure 3-9** below). Only three of the lakes had a suitable undeveloped beach. For each beach type, the data were aggregated and the annual geometric mean *E. coli* concentration was calculated for each year for the last ten years. Results are shown in the upper right of **Figure 3-9**, where orange is the urban beach average, green is the rural beach average, and purple is the undeveloped beach average. Three takeaways from this analysis include:

- The urban beaches had higher overall concentrations than rural or undeveloped beaches.
- The trend by year for this random subsample of beaches looks favorable (downward), especially for the urban beaches and undeveloped beaches.
- All of the beach types in recent years have had average concentrations less than the USEPA recommended 30-day geometric mean criterion of 126 CFU/100 ml. Keep in mind, however, that we averaged all of the data to generate an annual average and compared it to a 30-day criterion, so the results might be biased low, but the 30-day criterion provides useful context for assessing the magnitude of the annual concentrations.

Within each category, the concentrations were quite different at each of the beaches (**Figure 3-10** below on page 38). The same trends as the aggregated data are evident here, though there are urban beaches that do exceed the USEPA 30-day geometric mean criteria. The graphs in **Figure 3-10** show variability and trends from 2008-2018 with some key beaches consistently of poor quality.

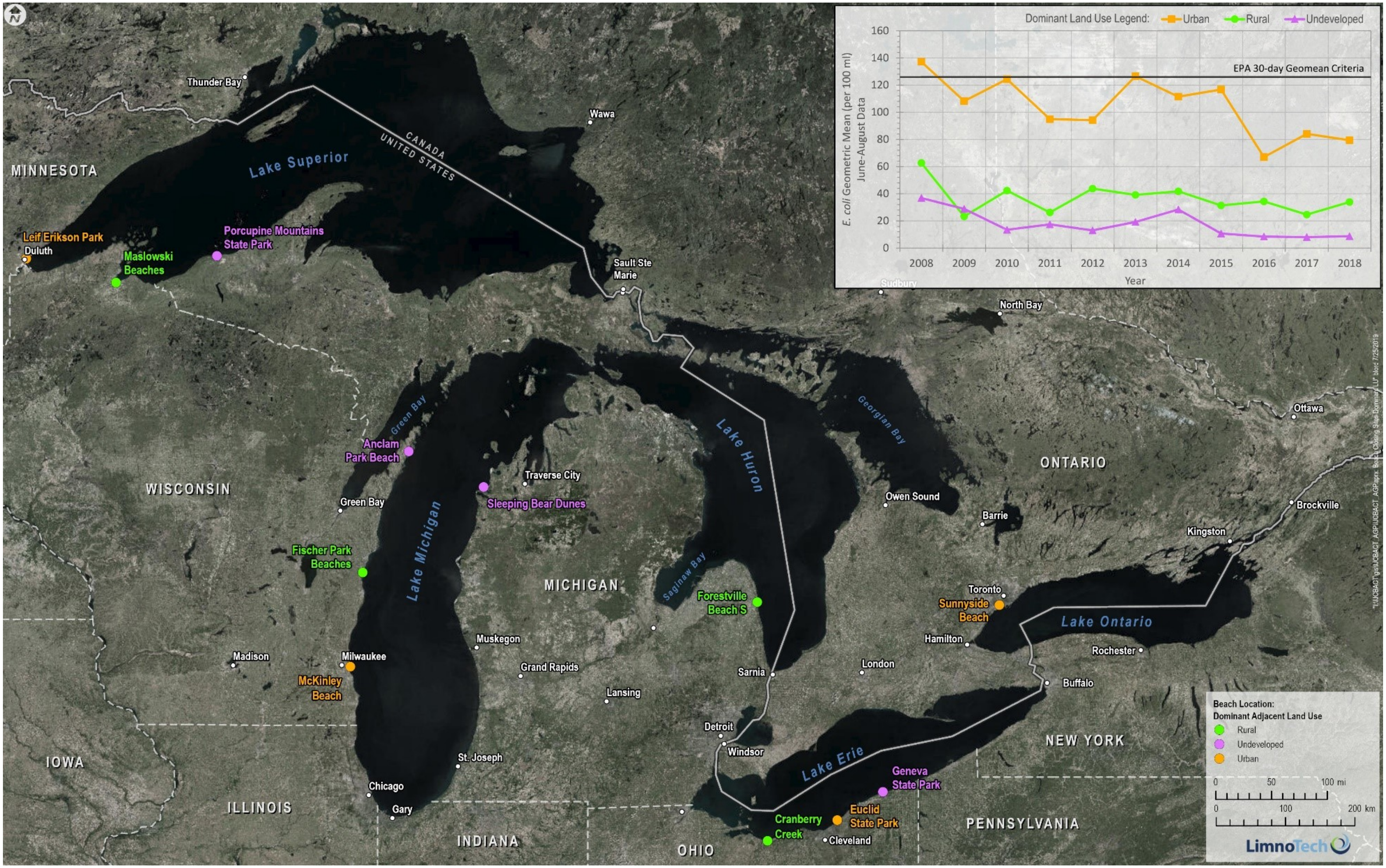

Figure 3-9: Relationship between predominant land use and beach water quality. Orange is the urban beach average, green is the rural beach average, and purple is the undeveloped beach average.

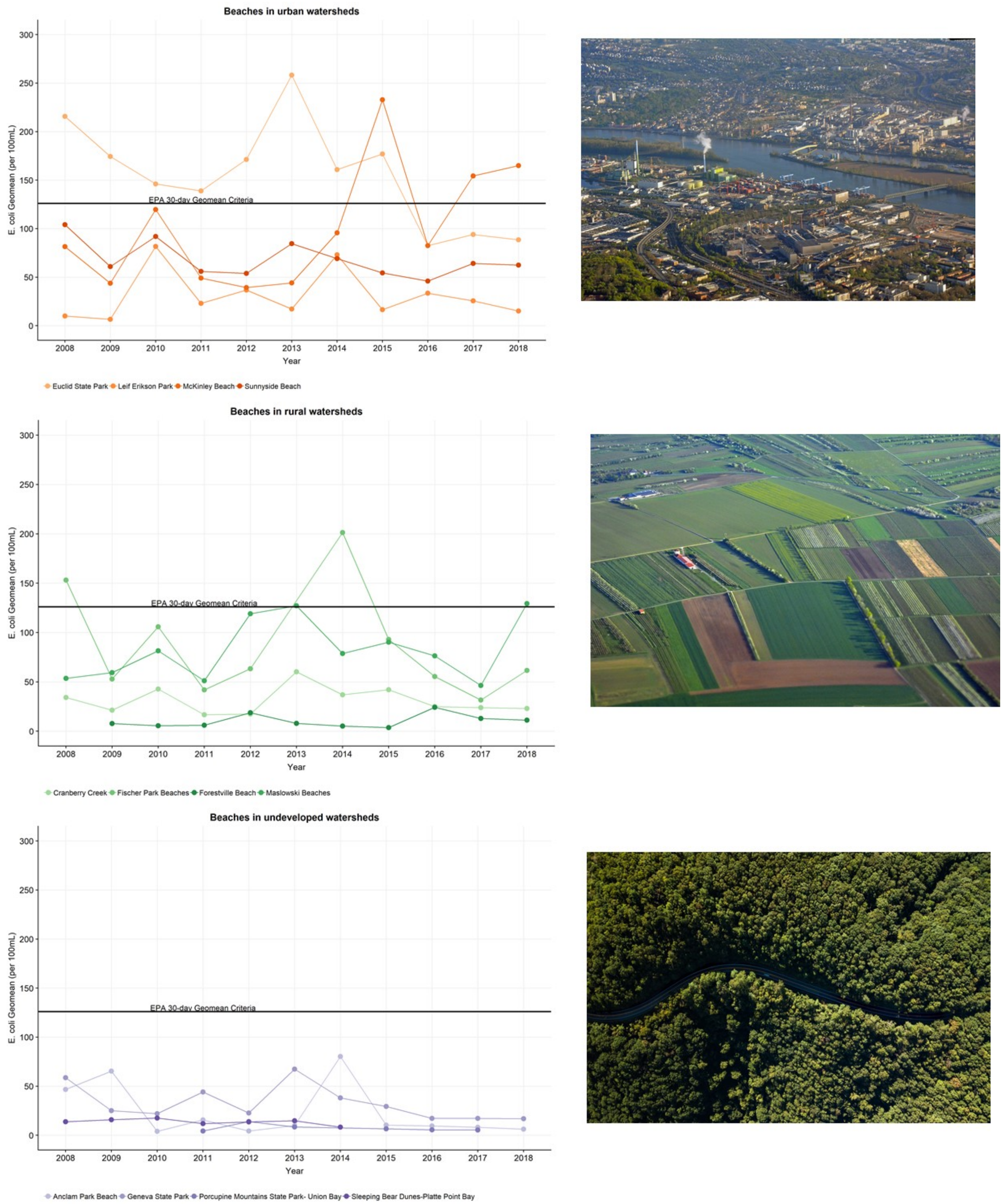

Figure 3-10: Annual geometric mean *E. coli* concentrations by beach, grouped by predominated watershed land use (urban, rural, undeveloped).

3.4 Comparison of 1913 and 2018 conditions

The 1913 study and contemporary data are challenging to compare because of differences in sampling locations and analytical measures. The 1913 study sites are mostly in the connecting channels and near potential transboundary pollution sources, while the contemporary data are primarily from recreational beaches that are predominantly on the lakes rather than on connecting channels. The bacteria measures and methods in 1913 were *B. coli* or total coliform, whereas contemporary methods are *E. coli* and enterococci. Instead, comparisons of 1913 and 2018 conditions are based on watershed characteristics that comparable data between eras could be evaluated.

3.4.1 City population comparison

There is no basinwide population data for 1913. Therefore, population for major cities in the basin were compiled from several data sources and compared graphically (**Figure 3-11** below). Data from 1910 and 2017 for US cities were obtained from the US Census Bureau.[5] The 1918 IJC study report included tables of population in 1911 for the Canadian cities in Appendix XXV (International Joint Commission 1918). Data for Canadian city population in 2016 were obtained from Statistics Canada.[6] **Table 3-5** presents a comparison of 1910/1911 and 2016/2017 city data for each of the cities in **Figure 3-11**. Note that these values are the city populations only and do not include the larger metropolitan area.

[5] US census data obtained via third-party website, accessed at worldpopulationreview.com.
[6] Canadian city population data accessed at: statcan.gc.ca/census-recensement/index-eng.cfm?MM=1.

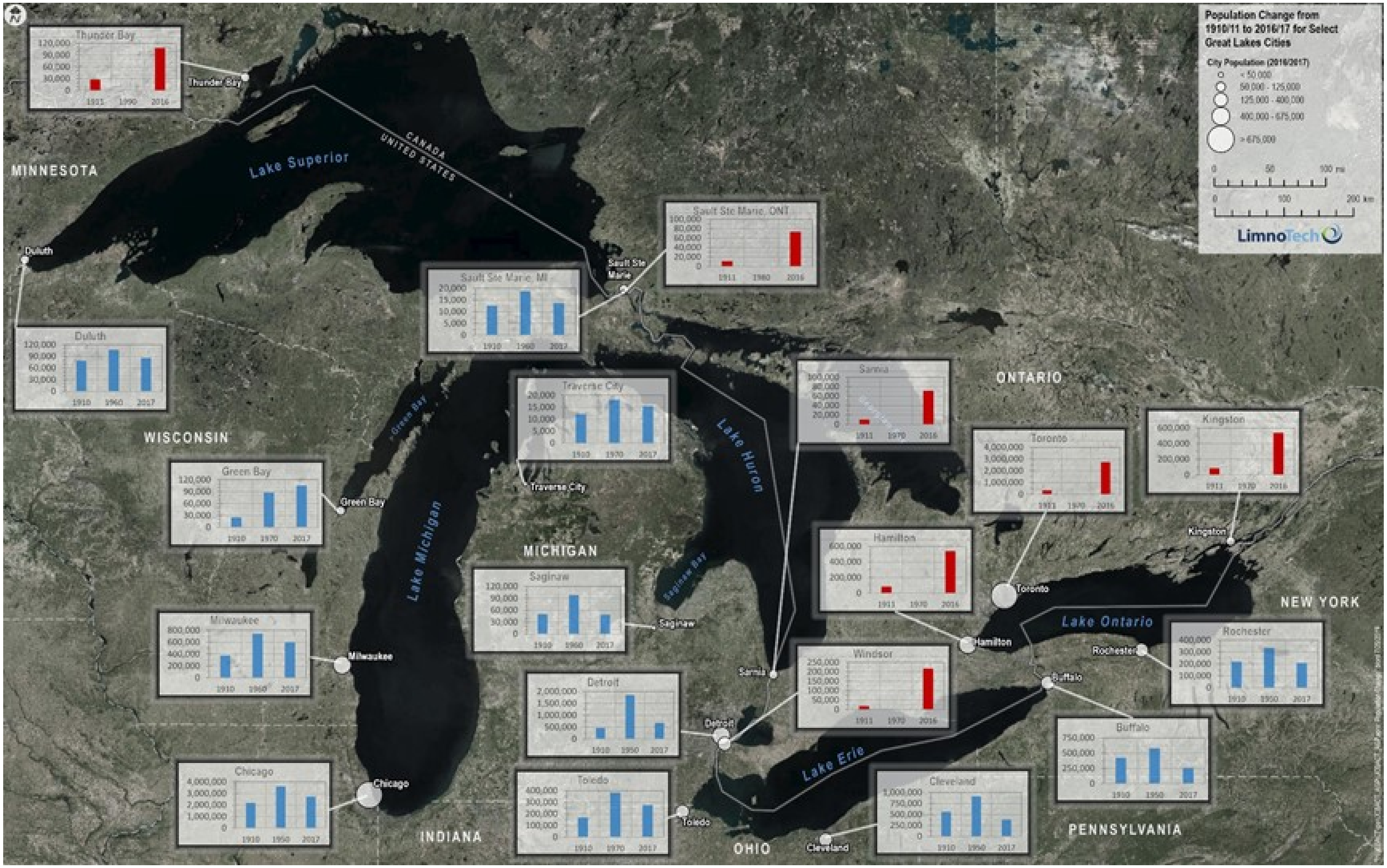

Figure 3-11: Population in Great Lakes cities in 1910/1911 and 2016/2017. Maxima or mid-century values are also shown for comparison for US cities.

Table 3-5: City populations in 1910/1911 and 2016/2017 in Great Lakes cities.

City	Great Lake/Connecting Channel	1910/1911 Population	Peak City Population		2016/2017 Population
			Population	Year	
Duluth, MN	Lake Superior	78,466	106,884	1960	86,066
Thunder Bay, ON4	Lake Superior	27,719	..	..	107,909
Sault Ste. Marie, ON	Lake Superior	10,984	..	..	73,368
Sault Ste. Marie, MI	Lake Superior	12,615	18,722	1960	13,631
Green Bay, WI	Lake Michigan	25,236	87,809	1970	105,116
Milwaukee, WI	Lake Michigan	373,857	741,324	1960	595,351
Chicago, IL	Lake Michigan	2,185,283	3,620,962	1950	2,716450
Gary, IN	Lake Michigan	16,802	178,320	1960	76,008
Muskegon, MI	Lake Michigan	24,062	48,429	1950	38,131
Traverse City, MI	Lake Michigan	12,115	18,048	1970	15,515
Saginaw, MI	Lake Huron	50,510	98,265	1960	48,677
Sarnia, ON	St. Clair River	9,947	..	..	71,594
Detroit, MI	Detroit River	465,766	1,849,568	1950	673,104
Windsor, ON	Detroit River	17,829	..	..	217,188
Toledo, OH	Lake Erie	168,497	383,062	1970	276,941
Cleveland, OH	Lake Erie	560,663	914,808	1950	385,525
Buffalo, NY	Niagara River	423,715	580,132	1950	258,612
Rochester, NY	Lake Ontario	218,149	332,488	1950	208,046
Kingston, ON	Lake Ontario	18,874	..	..	123,798
Toronto, ON	Lake Ontario	327,753	..	..	2,731,571
Hamilton, ON	Lake Ontario	81,959	..	..	536,917

Canada has experienced significant growth since 1911, with many cities increasing in population by five- to ten-fold. Population peaked mid-century for most cities in the United States, as shown in **Table 3-5** above. Some US cities have smaller populations in 2017 than in 1911, including Buffalo, Cleveland, and Saginaw. These demographic statistics reflect the larger economic history in both countries and migration patterns that have occurred over the last 100 years. These factors are discussed in the context of potential pollution sources in the next section.

3.4.2 Agriculture (livestock counts) comparison

Agriculture, particularly livestock such as cattle, has been identified as a potential fecal bacteria pollution source to local creeks, streams, and rivers, that can then impact recreational beaches on the Great Lakes. Canada and the United States have been collecting agricultural census data for over 150 years. These datasets were reviewed to compare livestock counts and distribution in 1910 and 2017. This comparison can capture changes in land use over this period (land use data are not available for 1913), changes in agricultural practices, changes in consumer preferences, and potential importance of agriculture to the economy of the Great Lakes region. Livestock data were compiled for cattle (dairy and beef), swine (pigs), poultry (chicken, turkeys, ducks and geese), ovine (sheep), and equine animals (horses, mules, burros and donkeys).

Due to the 107-year range between agricultural censuses for our study, changes in county boundaries and county boundaries not aligning with the Great Lakes basin boundaries, numerous limitations to our comparisons apply. For both the US Department of Agriculture (USDA) and Canada's census of agriculture data collection, there have been several data changes to each census, such as changes to the definitions and inclusion criteria of animals to be counted in the livestock categories (e.g., cattle, poultry, equine). For example, for the 2017 USDA Census of Agriculture, hogs and pigs used or to be used for breeding, ewes one year old or older, the number of hair sheep or wool-hair crosses, and the inventory of owned horses and ponies were all deleted and not collected for this census. Thus, the actual number of animals on each farm were not counted and consequently the census is an underestimate. This is likely due to the goal of the USDA census of agriculture "to account for any place from which $1,000 or more of agricultural products were produce and sold, or normally would have been sold, during the census year" and methods of mailing the census to "agricultural operations that potentially meet the farm definition" (US Department of Agriculture 2017b). The underestimate of livestock by the census of agriculture is a conclusion of another study of animal feeding operations in the Maumee River basin (Environmental Working Group and Environmental Law and Policy Center, 2019). Using livestock numbers from animal feeding operation permits as well as satellite imagery to identify non-permitted animal feeding operation facilities and industry standards for animal space to estimate livestock counts, magnitudes more animals were counted in this study compared to the census.

Additionally, watershed-specific estimates of livestock are not available for either census period, so additional processing of the available data was conducted to estimate the number of livestock within the Great Lakes basin. Considering these limitations, the following methods employed by LimnoTech for livestock estimates by county in 1910 and 2017 are described for each data source.

County level data for livestock in 1910 in the U.S. were obtained from an archived USDA census publication (US Department of Agriculture 1910). The data in these tables were digitized and using geographic information systems, the livestock counts for each county were distributed within the Great Lakes watershed. For counties that straddle the watershed boundary, the livestock counts were adjusted based on the proportion of the county area within the Great Lakes basin to total county area.

Nationwide data were available for Canada in 1910 (Statistics Canada 1999). To generate Great Lakes estimates, the data were processed as follows:

- The livestock were distributed using the percent of Canada's farms located in Ontario (about 31 percent).
- The percent of farms in Ontario that are within the Great Lakes watershed (85 percent) was estimated based on current cropland and pastureland use data.

- The livestock were distributed into individual counties based on percent of agricultural area in the county within the Great Lakes watershed to the total county agricultural area.

County-level livestock data for 2017 in Canada were obtained from the Ontario Ministry of Agriculture, Food and Rural Affairs (2021). County-level livestock data for 2017 in the United States were obtained from the USDA (2017a). As with 1910 data, the number of livestock within the Great Lakes watershed were estimated by distributing the livestock counts within each county based on the proportion of county area within the Great Lakes watershed to total county area.

Maps showing the estimated distribution of all livestock in 1910 and 2017 are shown in **Figures 3-12** and **3-13**, respectively (page 44). Corresponding maps for bovine (cattle) are shown in **Figures 3-14** and **3-15** (page 45); swine (pigs) in **Figures 3-16** and **3-17** (page 46); poultry in **Figures 3-18** and **3-19** (page 47); ovine (sheep) in **Figures 3-20** and **3-21** (page 48); and equine (horses, mules, burros, donkeys) in **Figures 3-22** and **3-32** (page 49). The counties shown on these figures are current, and it is important to note that county boundaries, particularly in northern Ontario, changed somewhat between 1910 and 2017.

Inspection of these maps shows several differences between the 1910 and 2017 censuses of agriculture, including a dramatic increase in the number of poultry in 2017 particularly in Ontario, and a significant decrease in the number of ovine and equine in 2017 compared to 1910 across the Great Lakes watershed. A consistent trend across all types of livestock from 1910 to 2017 is the concentration of livestock into smaller areas but with higher densities. For example, the number of cows has stayed relatively similar between the 1910 and 2017 censuses of agriculture. However, our results indicate there are many counties with fewer cattle in 2017 than in 1910, and there are a few counties where the cattle density has greatly increased, as evidenced by the dark blue counties in the 2017 map versus none in the 1910 map. Notably, plotting livestock numbers by county and shading the values accordingly can create density artifacts due to variable county sizes. For example, large counties and small counties with the same numbers of animals will have the same color, even though the actual density per unit geographic area may be less in the large county.

Additional discussion of livestock impacts on water quality is provided in the next chapter.

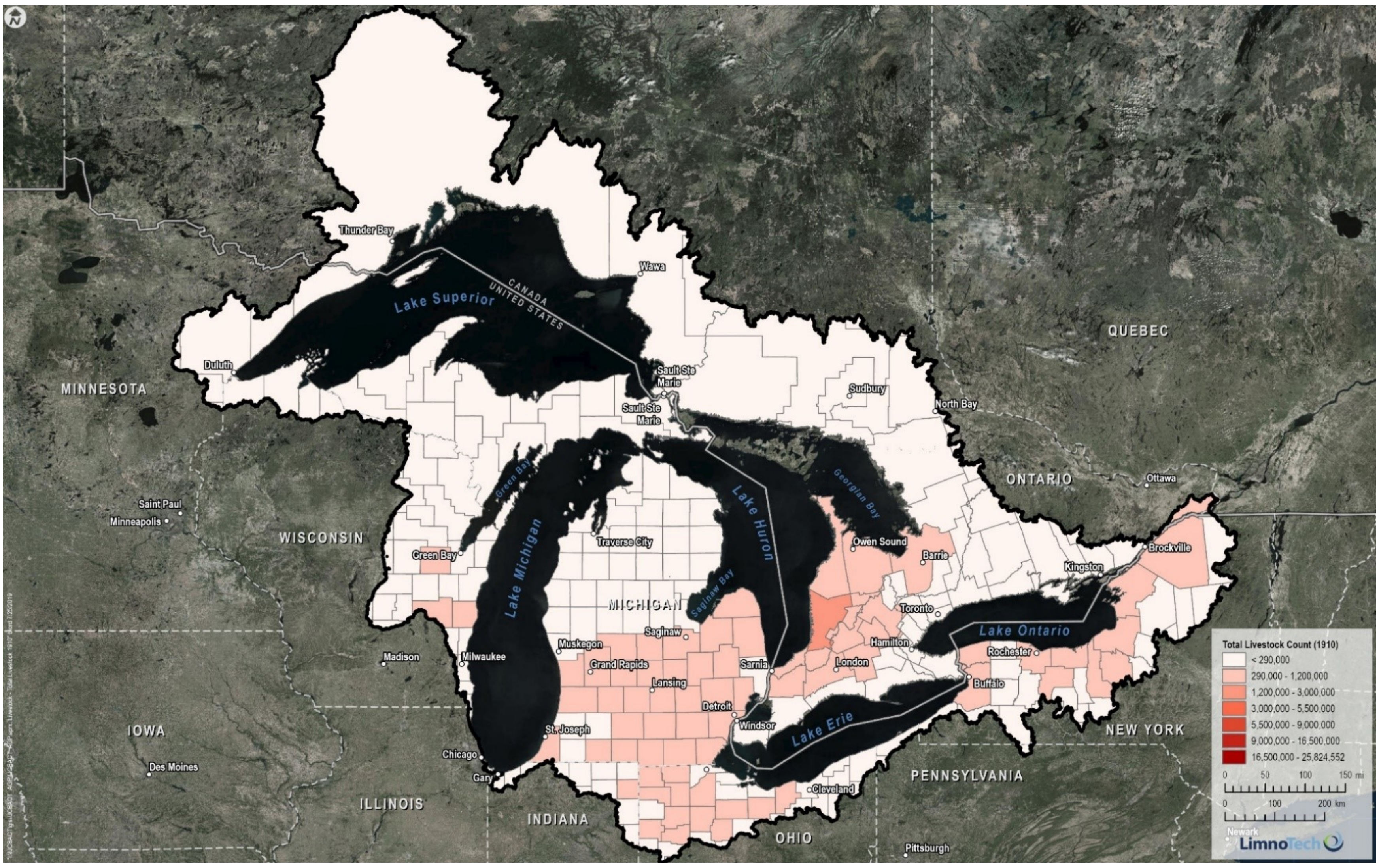

Figure 3-12: 1910, estimated number of livestock, all species, in the Great Lakes watershed in Canada and the United States. Data for counties in the United States are from the 1910 USDA census of agriculture that were reported at the county level. For counties in Ontario, data are from Statistics Canada 1910 agriculture statistics that were reported at the country level. Distribution of agriculture in Ontario was based on the proportion of reported farmland in each county. Current county boundaries are displayed. Importantly, the censuses were not comprehensive of all farms and animals, but only those farms that met minimum production and economic value thresholds.

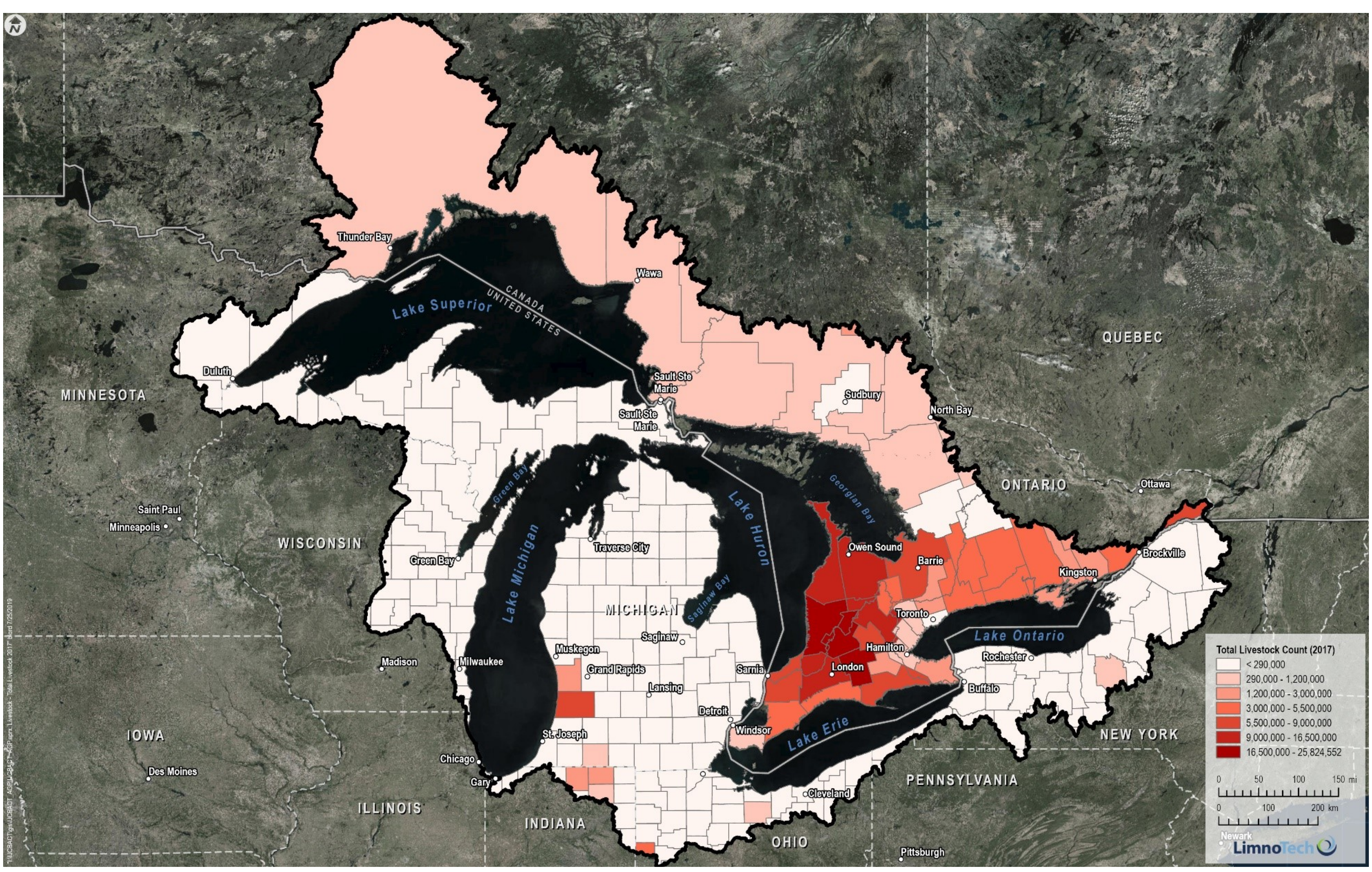

Figure 3-13: 2017, estimated number of livestock, all species, counts in the Great Lakes watershed, in Canada and the United States. Data for counties in the United States are from the 2017 USDA census of agriculture that were reported at the county level. For counties in Ontario, data are from the Statistics Canada 2017 census of agriculture that were reported at the provincial level. Distribution of agriculture in Ontario was based on the proportion of reported farmland and industries in each county. Importantly, the censuses were not comprehensive of all farms and animals, but only those farms that met minimum production and economic value thresholds.

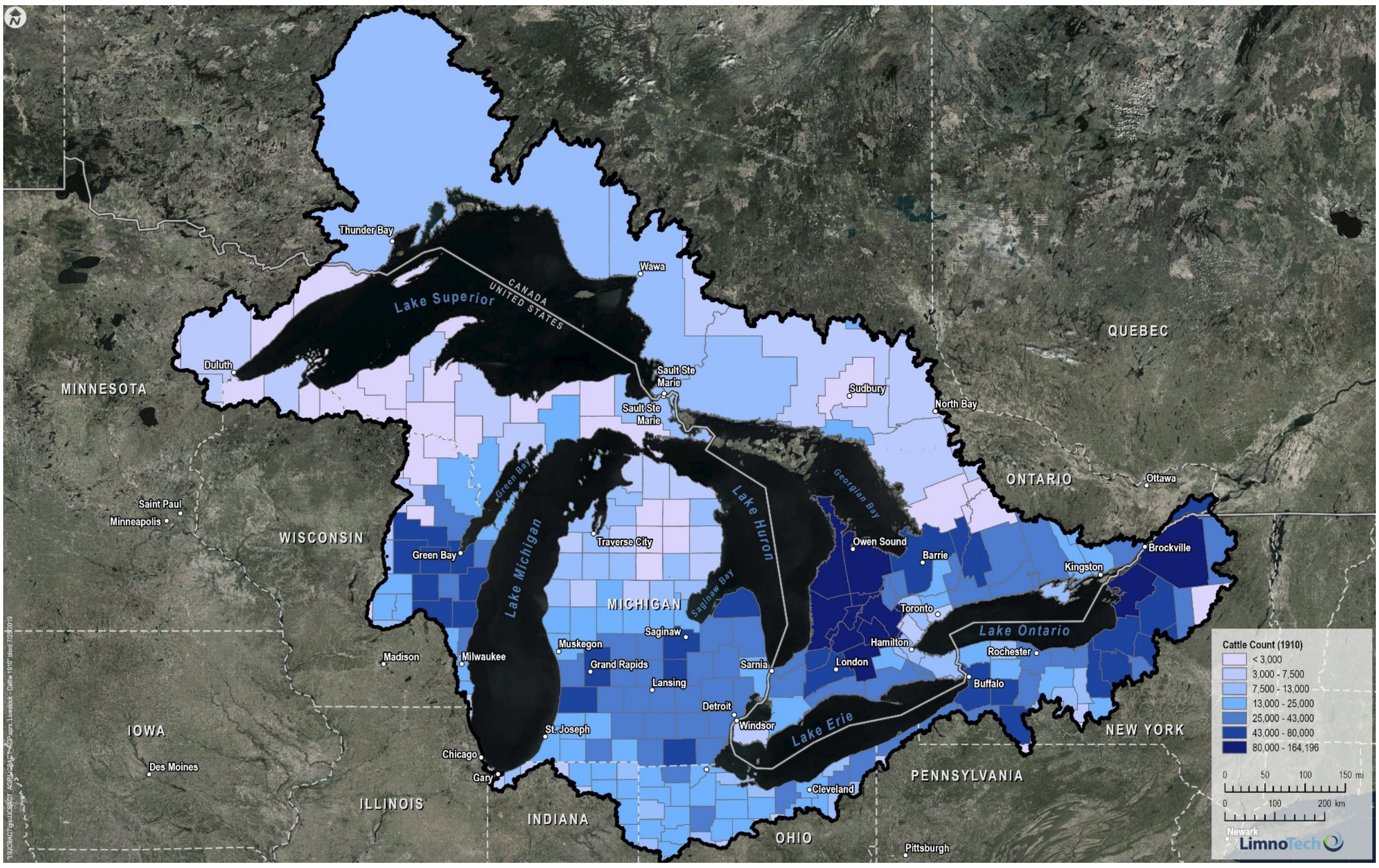

Figure 3-14: 1910, estimated number of bovine (cattle) livestock in the Great Lakes watershed in Canada and the United States. Data for counties in the United States are from the 1910 USDA census of agriculture that were reported at the county level. For counties in Ontario, data are from Statistics Canada 1910 agriculture statistics that were reported at the country level. Distribution of agriculture in Ontario was based on the proportion of reported farmland in each county. Current county boundaries are displayed. Importantly, the censuses were not comprehensive of all farms and animals, but only those farms that met minimum production and economic value thresholds.

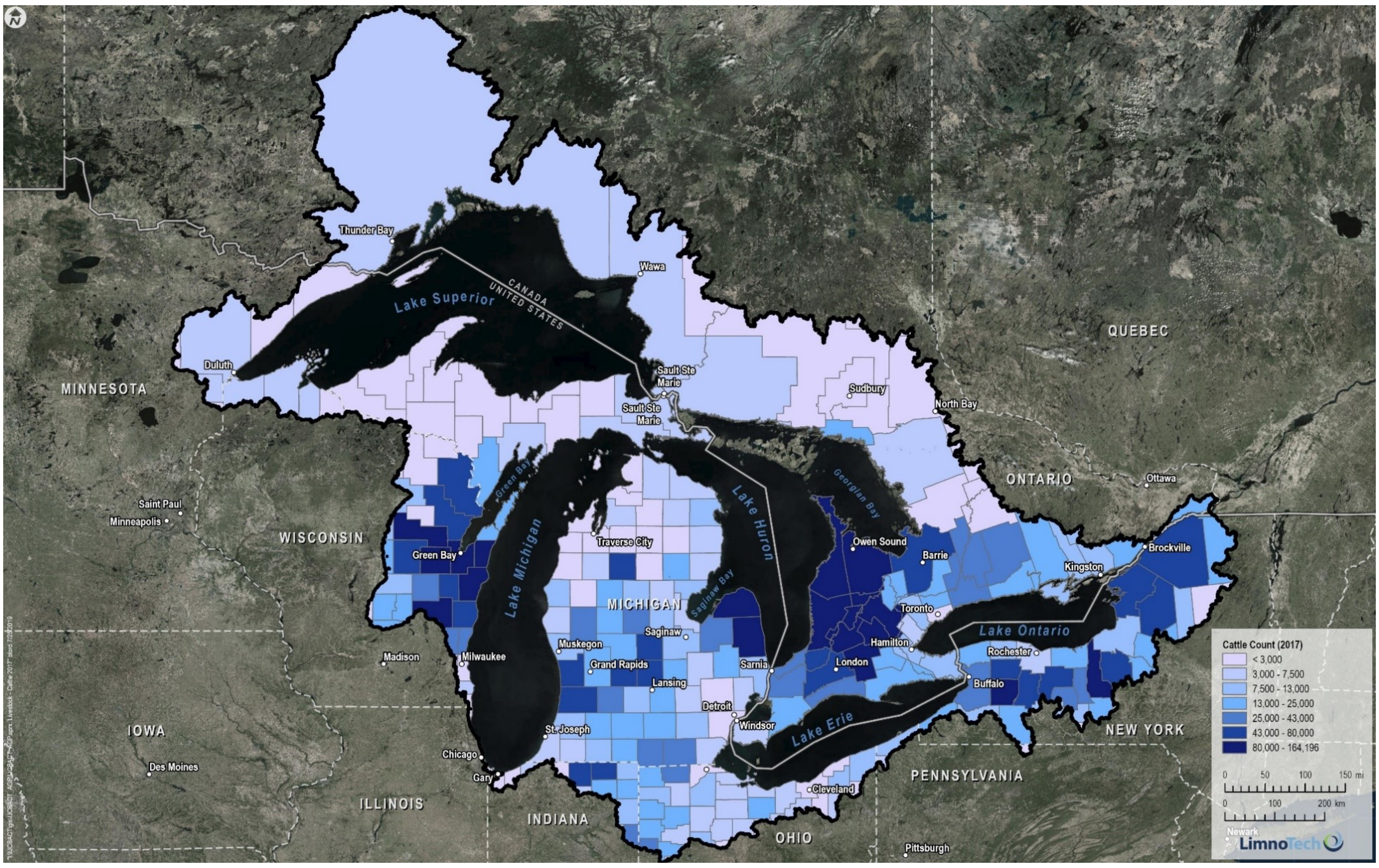

Figure 3-15: 2017, estimated number of bovine (cattle) livestock in the Great Lakes watershed in Canada and the United States. Data for counties in the United States are from the 2017 USDA census of agriculture that were reported at the county level. For counties in Ontario, data are from the Statistics Canada 2017 census of agriculture that were reported at the provincial level. Distribution of agriculture in Ontario was based on the proportion of reported farmland and industries in each county. Importantly, the censuses were not comprehensive of all farms and animals, but only those farms that met minimum production and economic value thresholds.

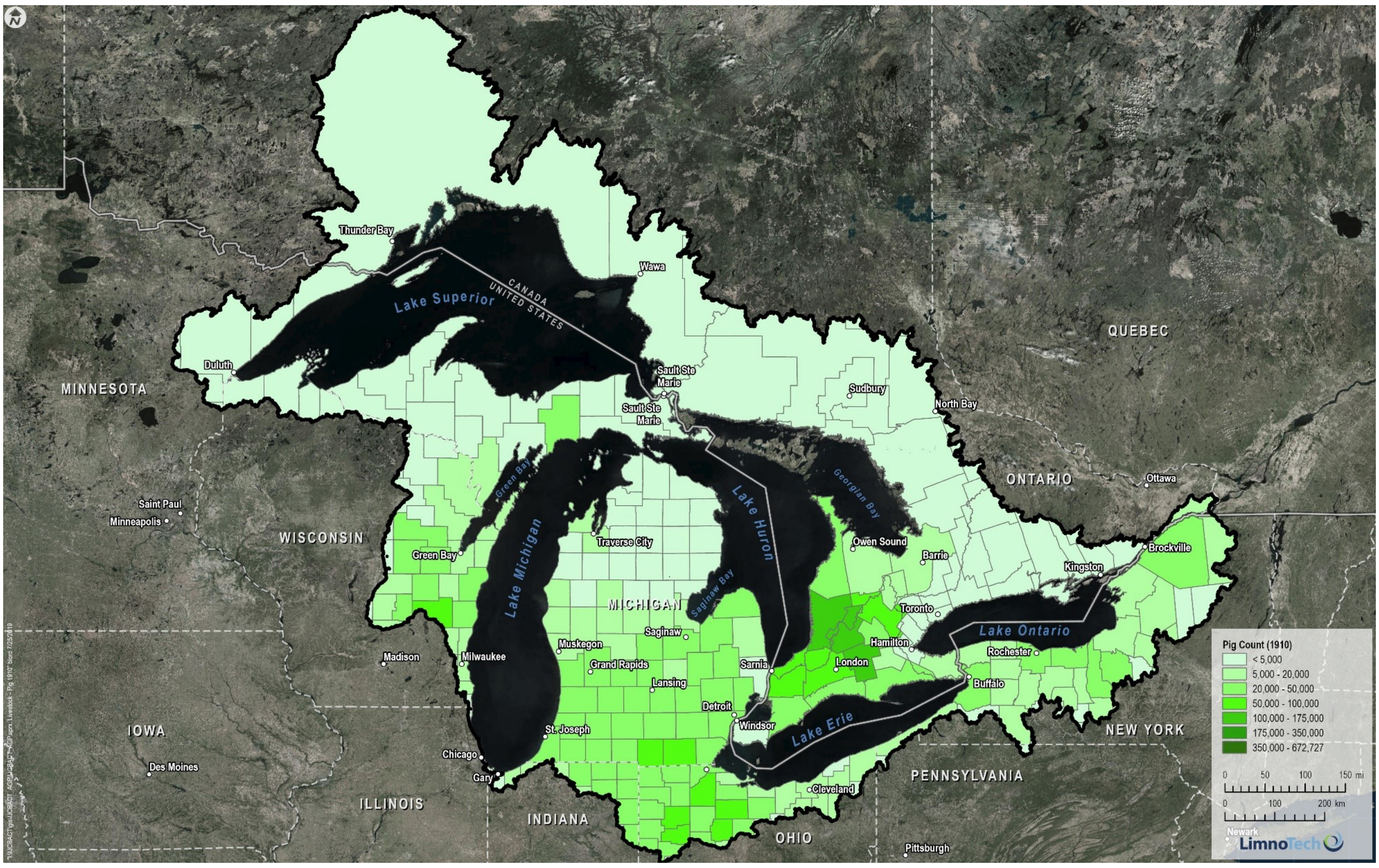

Figure 3-16: 1910, estimated number of swine (pigs) in the Great Lakes watershed in Canada and the United States. Data for counties in the United States are from the 1910 USDA census of agriculture that were reported at the county level. For counties in Ontario, data are from Statistics Canada 1910 agriculture statistics that were reported at the country level. Distribution of agriculture in Ontario was based on the proportion of reported farmland in each county. Current county boundaries are displayed. Importantly, the censuses were not comprehensive of all farms and animals, but only those farms that met minimum production and economic value thresholds.

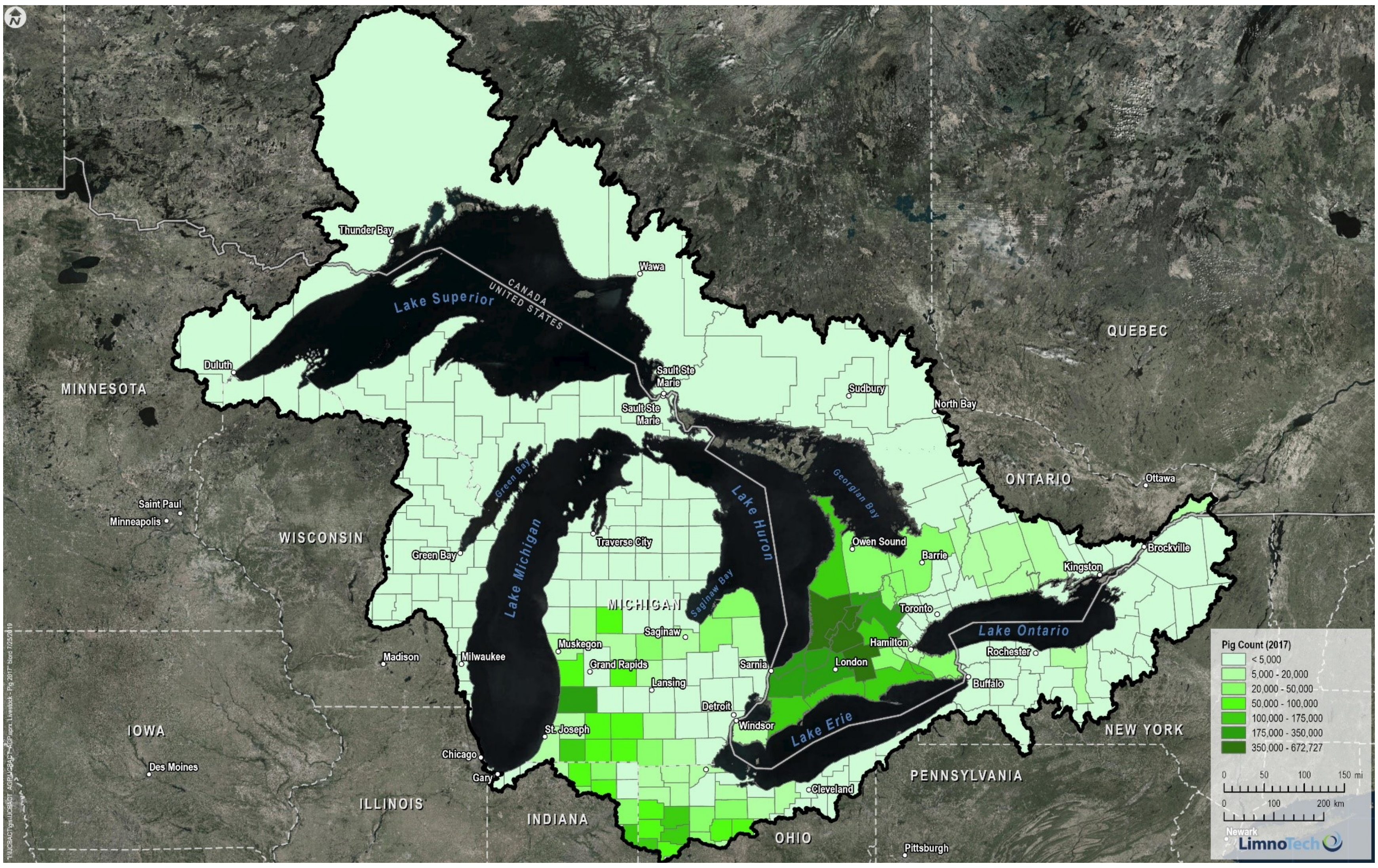

Figure 3-17: 2017, estimated number of swine (pigs) in the Great Lakes watershed in Canada and the United States. Data for counties in the United States are from the 2017 USDA census of agriculture that were reported at the county level. For counties in Ontario, data are from the Statistics Canada 2017 census of agriculture that were reported at the provincial level. Distribution of agriculture in Ontario was based on the proportion of reported farmland and industries in each county. Importantly, the censuses were not comprehensive of all farms and animals, but only those farms that met minimum production and economic value thresholds.

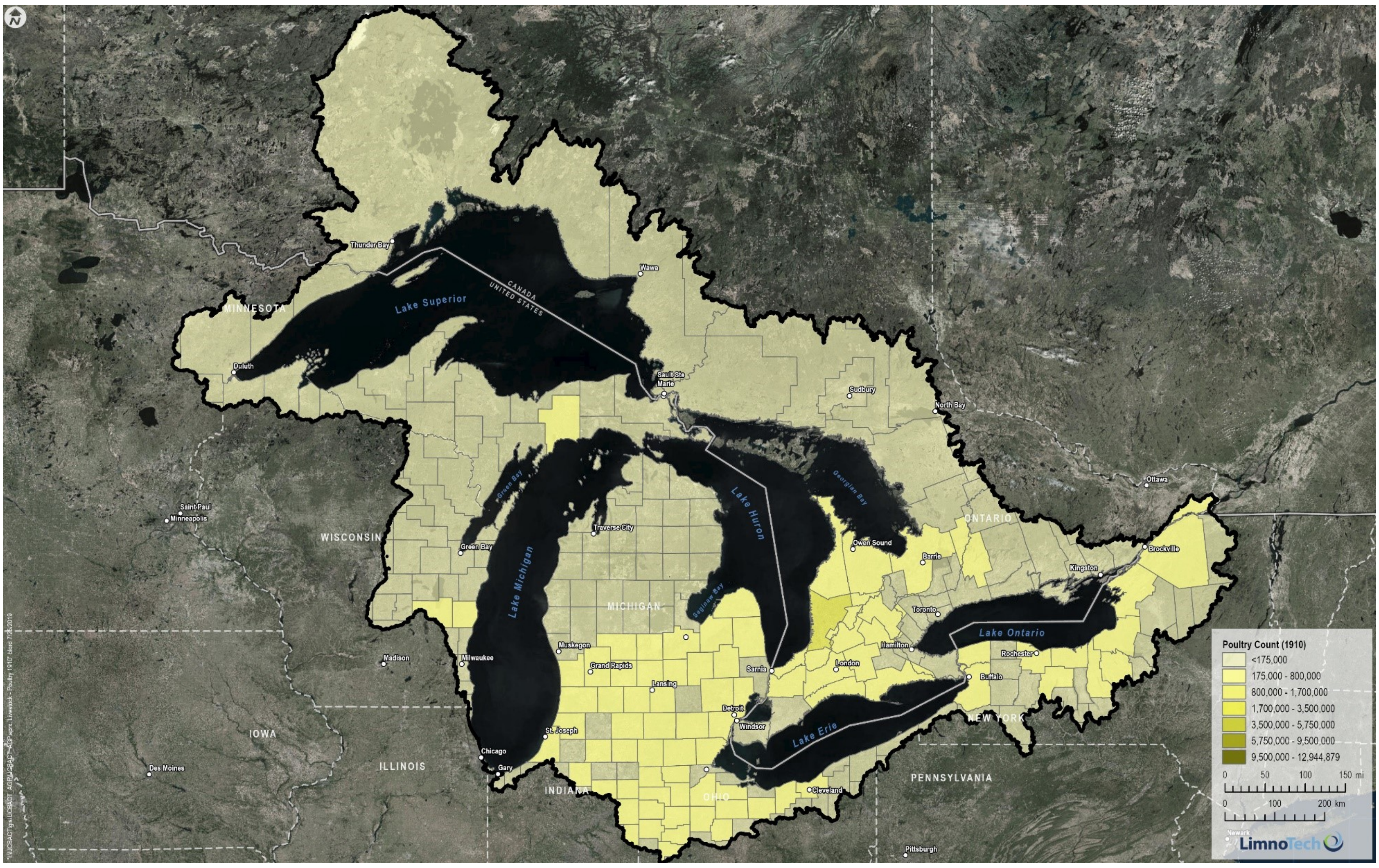

Figure 3-18: 1910, estimated number of poultry in the Great Lakes watershed in Canada and the United States. Data for counties in the United States are from the 1910 USDA census of agriculture that were reported at the county level. For counties in Ontario, data are from Statistics Canada 1910 agriculture statistics that were reported at the country level. Distribution of agriculture in Ontario was based on the proportion of reported farmland in each county. Current county boundaries are displayed. Importantly, the censuses were not comprehensive of all farms and animals, but only those farms that met minimum production and economic value thresholds.

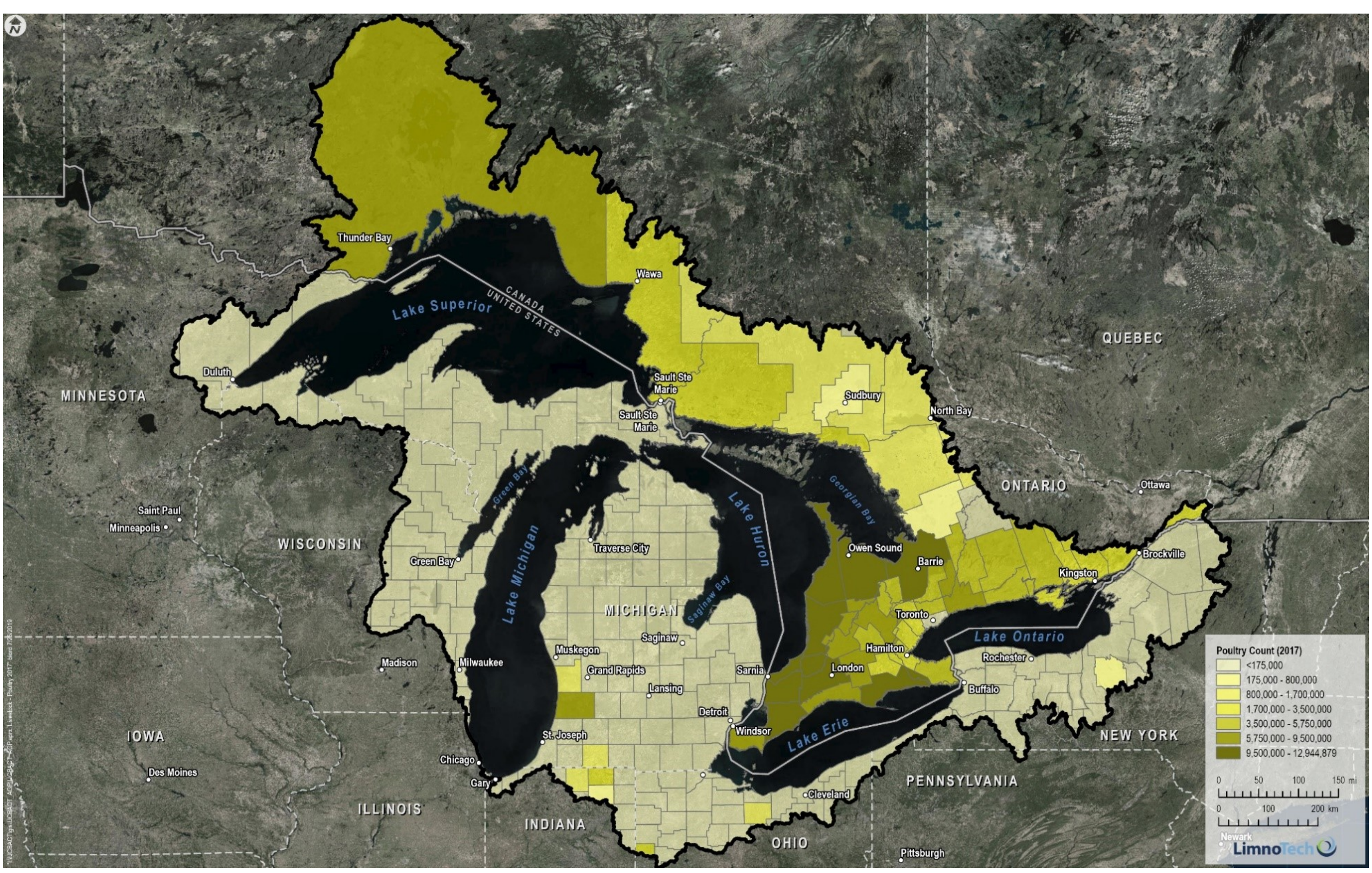

Figure 3-19: 2017, estimated number of poultry in the Great Lakes watershed in Canada and the United States. Data for counties in the United States are from the 2017 USDA census of agriculture that were reported at the county level. For counties in Ontario, data are from the Statistics Canada 2017 census of agriculture that were reported at the provincial level. Distribution of agriculture in Ontario was based on the proportion of reported farmland and industries in each county. Importantly, the censuses were not comprehensive of all farms and animals, but only those farms that met minimum production and economic value thresholds.

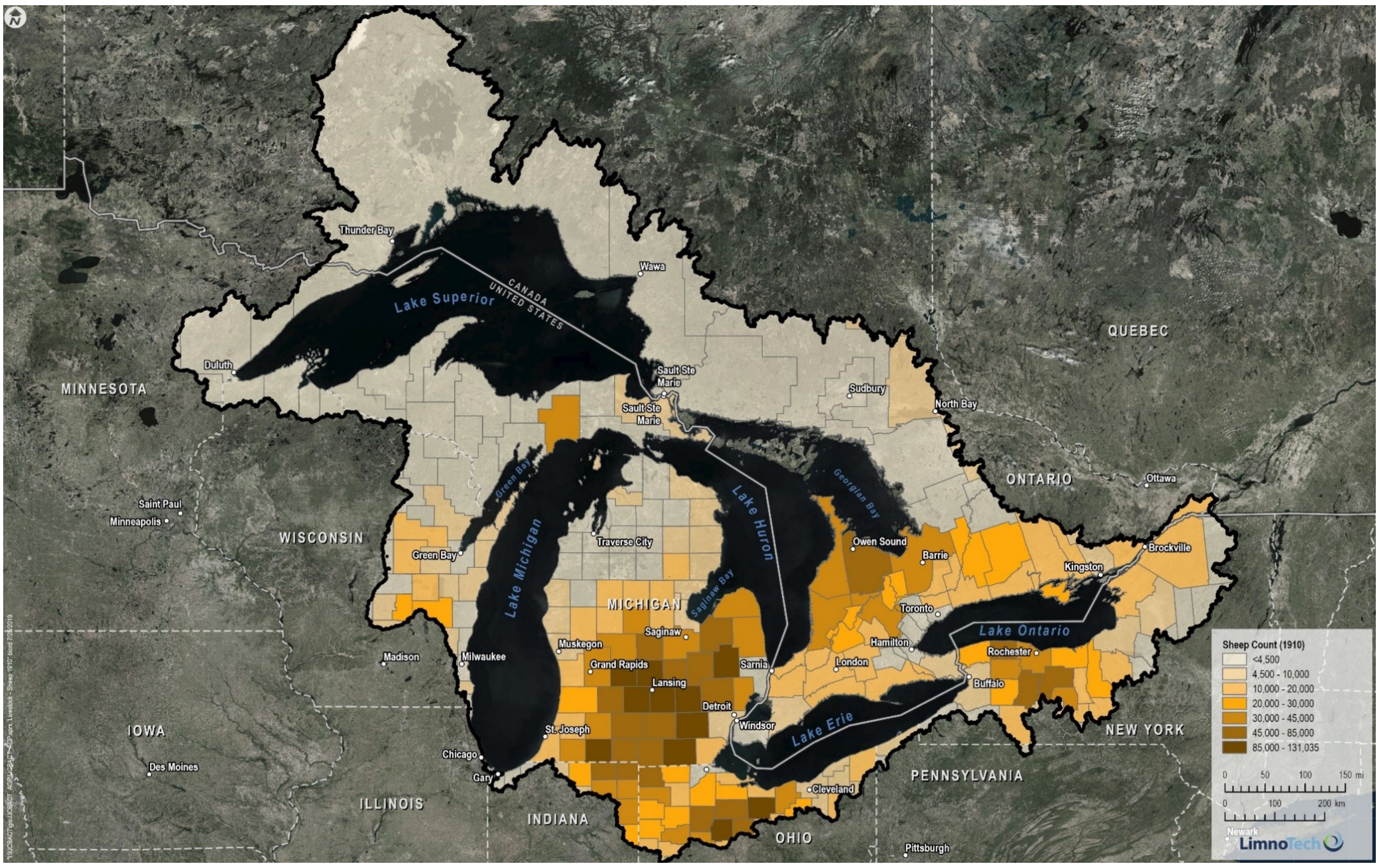

Figure 3-20: 1910, estimated number of ovine (sheep) in the Great Lakes watershed in Canada and the United States. Data for counties in the United States are from the 1910 USDA census of agriculture that were reported at the county level. For counties in Ontario, data are from Statistics Canada 1910 agriculture statistics that were reported at the country level. Distribution of agriculture in Ontario was based on the proportion of reported farmland in each county. Current county boundaries are displayed. Importantly, the censuses were not comprehensive of all farms and animals, but only those farms that met minimum production and economic value thresholds.

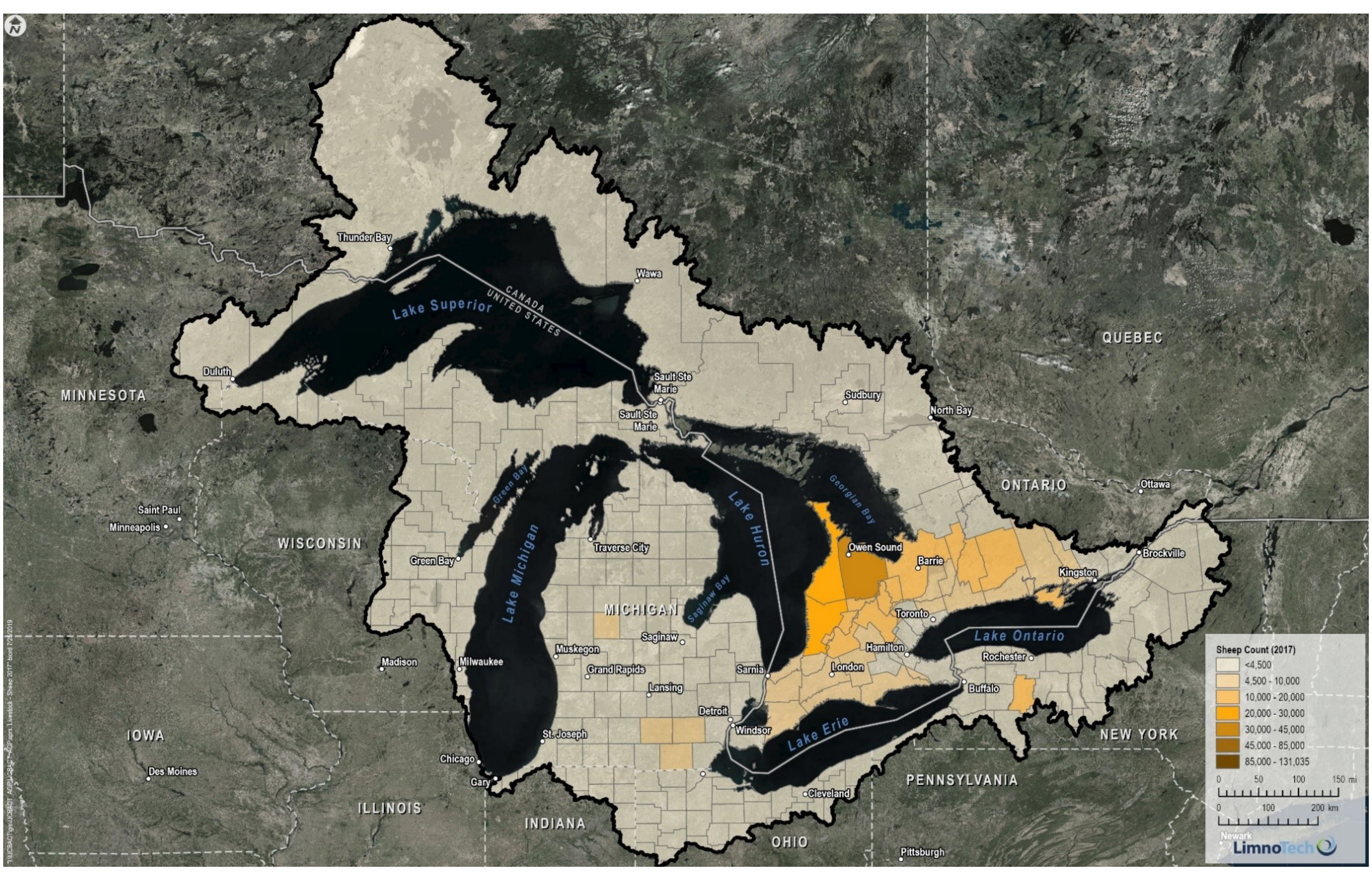

Figure 3-21: 2017, estimated number of ovine (sheep) in the Great Lakes watershed in Canada and the United States. Data for counties in the United States are from the 2017 USDA census of agriculture that were reported at the county level. For counties in Ontario, data are from the Statistics Canada 2017 census of agriculture that were reported at the provincial level. Distribution of agriculture in Ontario was based on the proportion of reported farmland and industries in each county. Importantly, the censuses were not comprehensive of all farms and animals, but only those farms that met minimum production and economic value thresholds.

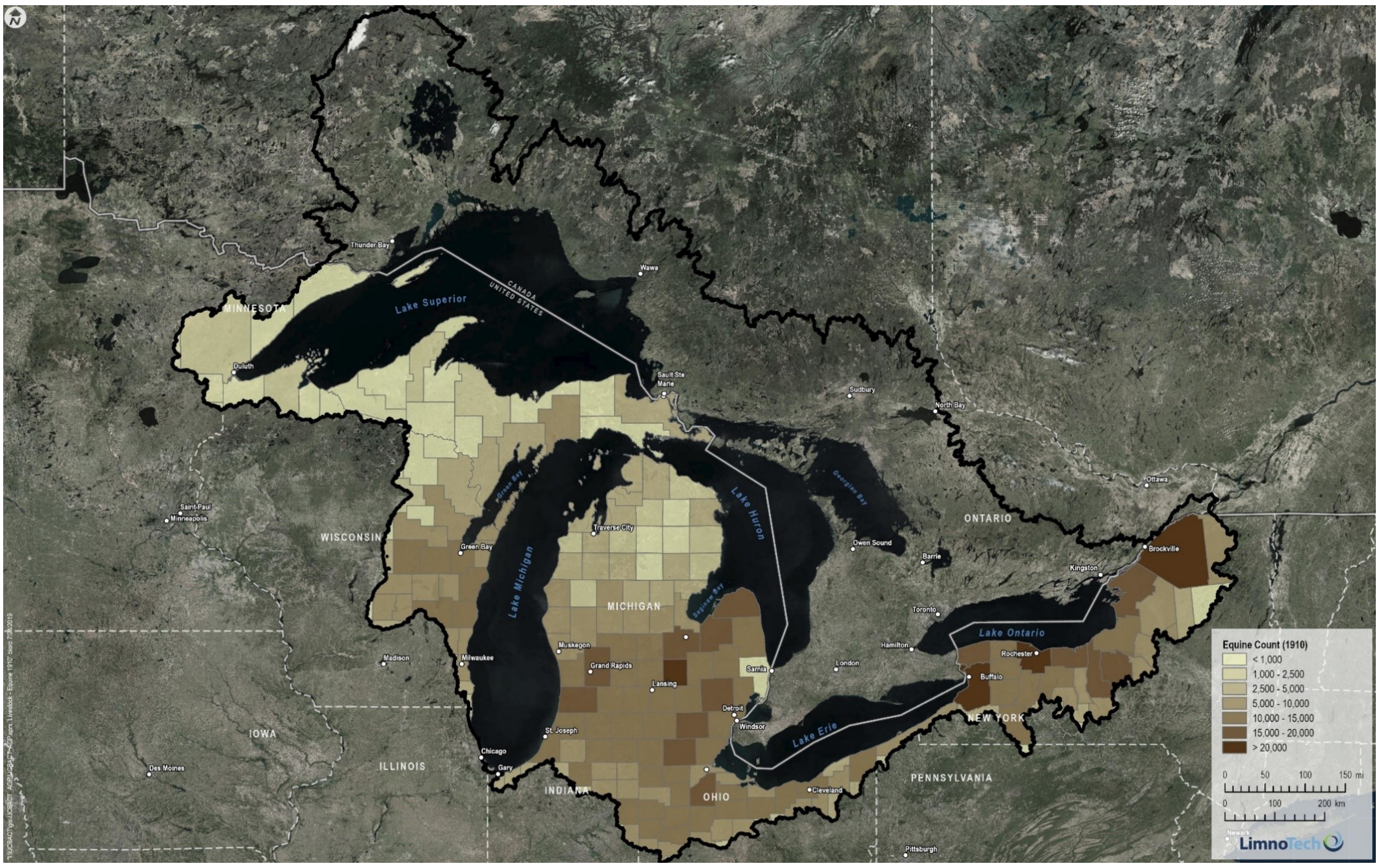

Figure 3-22: 1910, estimated number of equine (horses, mules, burros, donkeys) in the Great lakes watershed in the United States. Data for counties in the United States are from the 1910 USDA census of agriculture that were reported at the county level. Data for Canada were not available. Current county boundaries are displayed. Importantly, the censuses were not comprehensive of all farms and animals, but only those farms that met minimum production and economic value thresholds.

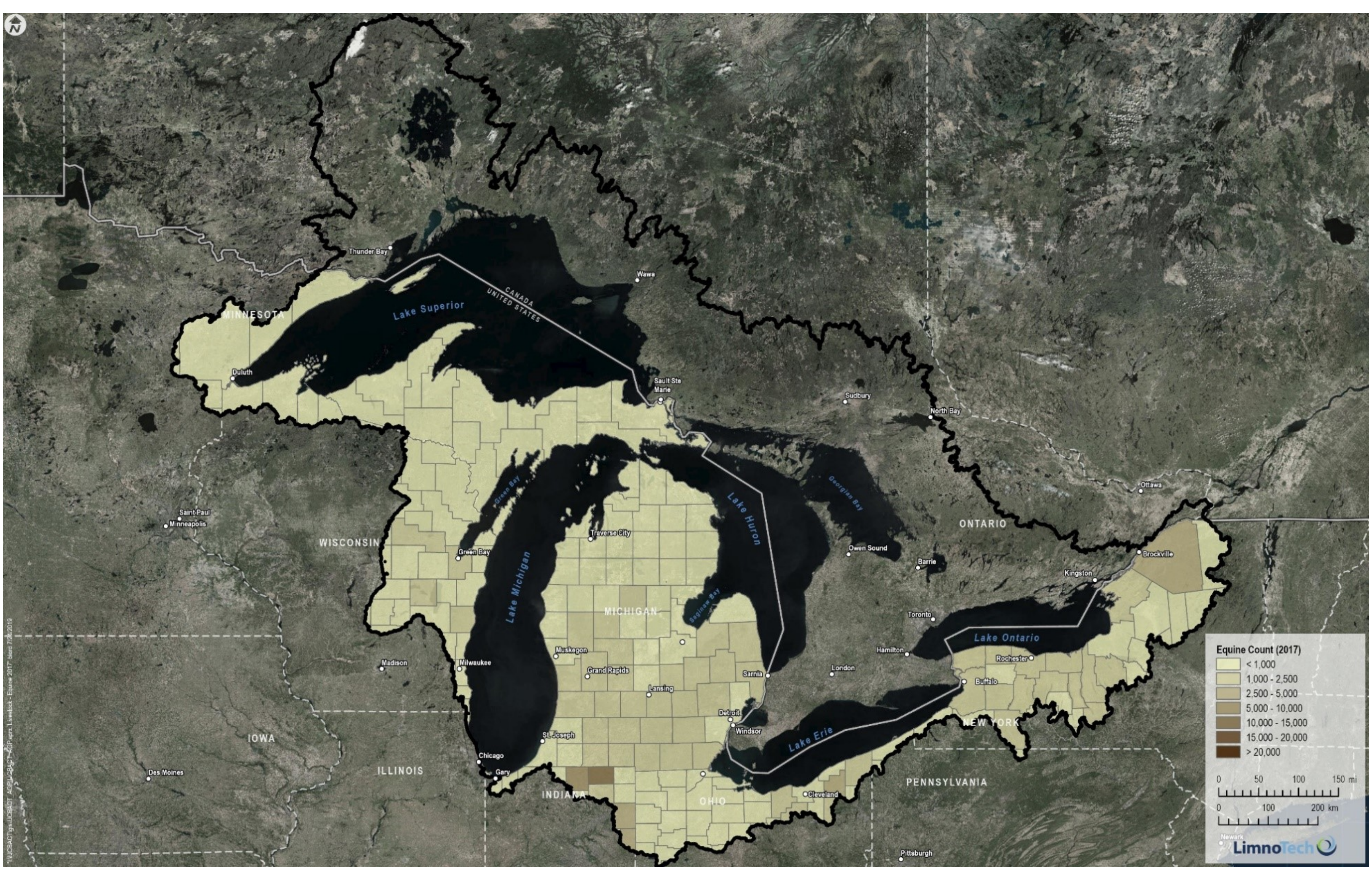

Figure 3-23: 2017, estimated number of equine (horses, mules, burros, donkeys) in the Great Lakes watershed in the United States. Data for counties in the United States are from the 2017 USDA census of agriculture that were reported at the county level. Data for Canada were not available. Importantly, the censuses were not comprehensive of all farms and animals, but only those farms that met minimum production and economic value thresholds.

3.4.3 1913 vs. 2018 summary

In addition to population and livestock counts, there are other statistics and descriptions that illustrate how conditions in the Great Lakes have changed from 1913 to today. **Table 3-6** below presents a summary of factors comparing 1913 and 2018, with additional detail following the table.

Table 3-6: Comparisons of other factors describing conditions in the Great Lakes watershed in 1913 and 2018.

Factor	1913	2018
Life expectancy (US)	50.3 (Male)* 55.0 (Female)*	76.2 (Male)** 81.1 (Female)**
Sewage disposal in cities	Sewage routed directly to waterway, with little to no treatment prior to discharge	Sewage routed to wastewater treatment plant for treatment including disinfection, intermittent discharge of untreated sewage through combined storm sewer and sanitary sewer overflows as a last resort.
Health indicator	Typhoid mortality	Gastrointestinal illness
Fecal bacteria indicator	*B. coli* (total coliform)	*E. coli*
Water quality standards	None	USEPA Recreational Water Quality Criteria; Health Canada Recreational Water Quality Guidelines; Ontario Public Health Standards, US State water quality standards
Agriculture	Family farms	More industrialization (confined animal feeding operations, etc.)
Agriculture equipment	Horses, mules and donkeys	Tractors, combines and other machinery
Population	Growth in cities	Cities declining, metropolitan areas increasing
Recreational opportunities	Limited	More beaches, more secondary contact recreational activities
Likely fecal sources	Humans Livestock	Humans Pets Livestock Birds

* Source of life expectancy data for 1913 from Berkeley University accessed at: demog.berkeley.edu/~andrew/1918/figure2.html.

** Source of life expectancy data for 2018 from the US Centers for Disease Control and Prevention National Center for Health Statistics National vital Statistics Reports, Volume 68, Number 4, United States Life Tables, 2016, accessed at: cdc.gov/nchs/data/nvsr/nvsr68/nvsr68_04-508.pdf.

Life expectancy increased dramatically by nearly 50 percent for both men and women. A large part of this can likely be credited to improvements in public health policy and research and decreases in infant mortality.

Sewage disposal was identified as a key source of pollution in the 1913 study. There was little to no sewage treatment at that time. Today, wastewater treatment is fairly advanced, especially in larger communities. Primary treatment, secondary treatment and disinfection are standard practice now. The United States also has the National Pollution Discharge Elimination System (NPDES) program to regulate discharges to waterways, including specifications for water quality requirements that must be met prior to discharge.[7] Most, if not all, wastewater treatment plants that discharge to a surface water in the Great Lakes have a fecal bacteria limit in their NPDES permit. Canada regulates wastewater discharges through its Wastewater Systems Effluent Regulations.[8]

The Stickney Wastewater Treatment Plant in Cicero, Illinois, USA. Picture by the US Army Corps of Engineers Chicago District via Flickr.

For comparing human health with respect to fecal bacteria exposure, there are three important differences between 1913 and 2018:

- ***Health endpoints:*** Health endpoints today, gastrointestinal illness (US Environmental Protection Agency 1986; US Environmental Protection Agency 2012), are not nearly as severe as what was used in the 1913 study (typhoid mortality).

[7] More information about the US NPDES program is available at: epa.gov/npdes/about-npdes.
[8] More information about the Canadian Wastewater Systems Effluent Regulations is available at: laws-lois.justice.gc.ca/eng/regulations/SOR-2012-139/FullText.html.

- ***Fecal indicators:*** Better indicators of fecal bacteria/microbial pollution are available now than in 1913. *E. coli* is a more specific indicator of fecal pollution than total coliform (US Environmental Protection Agency 1986). There are also better analytical methods now than in 1913. These two factors allow water resource managers and regulators to better understand the risk to lake users and to develop management strategies based on fecal pollution sources.
- ***Water quality standards***: There were no water quality standards in 1913. Now both Ontario and the United States have bacteria standards to protect the lakes and lake users. These standards now provide managers and regulators with both a target for acceptable lake conditions as well as a basis to evaluate progress.

In 1910, there were virtually no tractors in use. Farms were family-owned and relied on horses, mules and donkeys for power to plow fields. By 1960, tractors had completely displaced horses and mules in farming.[9] With more industrialization of agriculture over the last 100 years, there are now mega-farms and confined animal feeding operations that have high numbers of livestock concentrated in a relatively small area. The manure generated by this large number of animals is also concentrated in a relatively small location. For example, Hurricane Florence wrought havoc on the industrial-scale pig operations in North Carolina in 2018, resulting in major fecal pollution in the rivers as a result.[10]

People moving from cities to the suburbs presents a strain on infrastructure such as delivering drinking water and collecting wastewater. Much of this infrastructure is approaching the end of its useful life as many of the water and wastewater pipes were laid in the early to mid-20th century with a life span of 75-100 years (American Society of Civil Engineers 2017). In addition, the American Society of Civil Engineers estimated that demand on wastewater treatment systems will grow by more than 23 percent in the next 20 years due to new users connecting to new or existing centralized treatment systems. Aging infrastructure and increased demand could be drivers behind utility regionalization, that allows for better efficiencies in treatment of drinking water and wastewater that offset the challenges of larger distribution and collection systems. For example, the Great Lakes Water Authority, that was formed in 2016, services eight counties or 40 percent of Michigan's population with drinking water and 30 percent of Michigan's population with wastewater collection and treatment.[11] From a recreational water management perspective, regional water and wastewater utilities centralize treatment and can allow for more resources to be put into treatment, resulting in higher quality of the treated effluent discharged to the environment and potentially offers the advantage of more flexibility in managing flows to limit the discharges of untreated or partially treated sanitary sewage.

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[9] More information about the history of tractors is available at: eh.net/encyclopedia/economic-history-of-tractors-in-the-united-states/.
[10] Details are available at: nytimes.com/2018/09/19/climate/florence-hog-farms.html.
[11] More information about the Great Lakes Water Authority is available at: glwater.org.

4.0 Identifying Sources of Fecal Contamination with Microbial Source Tracking (MST) Methods

Despite all of the advances in human health, sanitary sewage handling and fecal bacteria detection described in the previous section over the last 100-plus years, the data analyses of contemporary *E. coli* enumeration and beach closing data indicate that work remains to ensure that beach and overall water quality fecal bacteria levels are safe for human recreation. This section presents a summary of more advanced analytical MST methods for determining sources (hosts) of fecal bacteria contamination, their use in the Great Lakes, and a discussion describing tools that have been used to identify pollution pathways that deliver fecal bacteria to the lakes and rivers. Taken together, these tools allow resource managers to move from pollution response (e.g., *E. coli* enumeration data) to pollution prevention (**Figure 4-1**), leading to more effective management and monitoring strategies to safeguard the recreational water quality conditions in the Great Lakes.

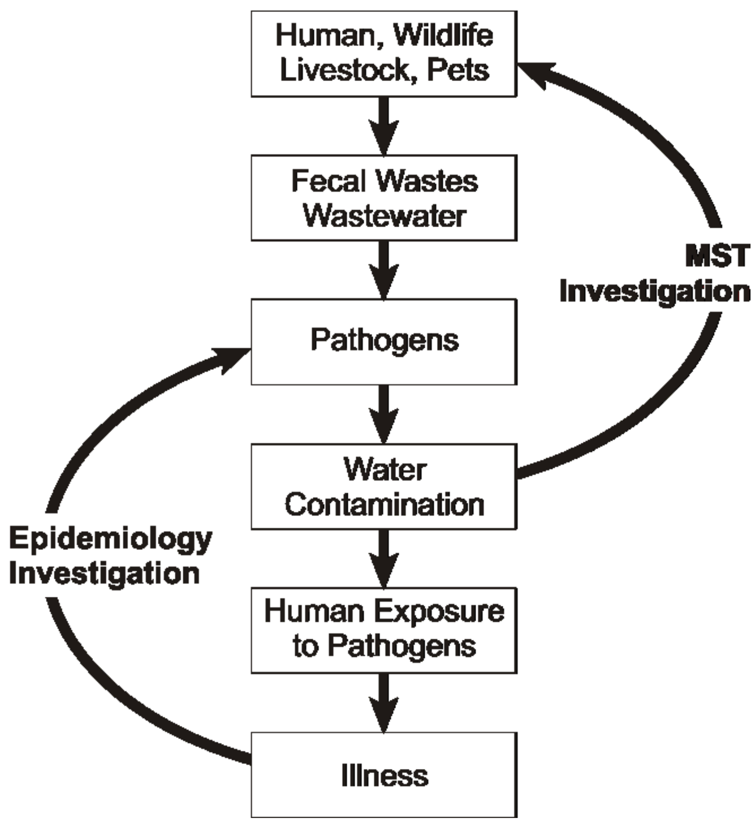

Figure 4-1: Charting the advancement of pollution response to pollution prevention. Figure by Tom Edge, McMaster University and HPAB member.

4.1 MST methods, assays and markers

4.1.1 MST method overview

MST is used to determine the sources of fecal contamination and may include a combination of microbiological, genotypic, phenotypic and/or chemical based methods (Scott et al. 2002). Early MST studies were primarily dominated by library-dependent methods that relied on biochemical or antibiotic resistance-based typing of cultured isolates like *E. coli*. These isolates (fingerprints) are compared to isolates from known fecal sources (Boehm et al. 2013). Examples of these included repetitive sequence-based polymerase chain reaction (PCR), pulse-field gel electrophoresis and ribotyping methods (genotypic), as well as antibiotic resistance analysis (phenotypic) methods (Korajkic et al. 2016). While some of these methods are still used today (e.g., Staley and Edge, 2016), most research has moved to library-independent methods such as quantitative PCR (qPCR). Indeed, MST research over the last decade has primarily focused on developing qPCR assays and more recently community analysis methods (e.g., DNA microarrays; Phylochip and high-throughput DNA sequencing; Illumina).

While not exhaustive, the following is a list of microbial source tools that may be used alone or in combination with others:

- Quantitative real-time PCR
- Digital PCR
- Next generation sequencing (e.g., Illumina)
- eDNA
- Microarray (e.g., PhyloChip)
- Antibiotic resistance profiling
- End-point PCR
- Ribotyping
- Immunological methods
- Chemical detection
- Canine scent detection
- Selective bacterial culturing
- Terminal restriction fragment length polymorphism

For example, canine scent tracking may be useful when selecting sampling sites that DNA-based assays can confirm and quantify the waste contamination (Van De Werfhorst et al. 2014).With all these methods there is a tradeoff with respect to cost, specificity and sensitivity, and the selection of the method(s) is specific to a user's set of objectives. Most current studies use quantitative or digital PCR to discriminate between different sources of fecal contamination, but selecting the appropriate assays requires careful consideration. This includes identifying the appropriate assay(s) for the sequence or gene target for the host-associated microorganism (Ahmed et al. 2019). There may be several potentially suitable assays for a range of hosts, including humans, ruminants, pigs, chickens and dogs. **Table 4-1** below presents an example of the wide range of targets used (to a varying extent) in identifying human sources. Only a few have been rigorously tested (Ebentier et al. 2013), and only one (HF183) has been validated for microbial source tracking by the USEPA as Method 1696 (US Environmental Protection Agency 2019).

Table 4-1: MST method assay components for human source identification.

Human	Subset of targets
Organism	*Bacteroides, Bacteroides*-like, *Enterococcus, Clostridium, Methanobrevibacter, Lachnospiraceae, Bifidobacterium*
Target	16S rDNA , Enterococcus surface protein, nifH, T antigen, NADH dehydrogenase subunit 5, cytochrome b, Coliphages, α-1-6 mannanase, viral genome, hypothetical protein
Markers	HF183, HuBac, BacHum-UCD, HB, BacH, Lachno2, HumanBac1, BacHuman, Buni, Bfrag, HF132, Bvulg, Pcopr, Bsteri, Btheta, HumM2, HumM3, YHF, BFD, esp, nifH, HadV, crAssphage, Lachno3, BacV6-21, PMMoV

One of the largest validation studies was performed by Boehm and colleagues (2013) that examined 41 MST methods across 27 unique laboratories. The authors specifically examined two of the most critical performance metrics: specificity and sensitivity. In general, the preferred assay should have both high source specificity (limited false positives) as well as high source sensitivity (limited false negatives) (Mayer et al. 2018). Although there is no benchmark criterion, host specificity markers that are greater than 80 percent specific are considered useful, but only those over 90 percent specific are considered excellent (Ahmed et al. 2019; Boehm et al. 2013). Viruses—e.g., human adenovirus (HadV), human polyomaviruses (HpyV)—tend to be more specific than bacterial markers though they often lack sensitivity due to being present at low levels. Other limitations that should be evaluated include the persistence of the marker, the ecology of the location including any potential inhibitors, and the overall reproducibility and transparency.

Given that the most thoroughly vetted markers (e.g., HF183) can have drawbacks, it may be necessary to use multiple markers (both bacterial and viral) to identify any one source (Harwood et al. 2014). In general, whenever a marker is identified and proposed for use in MST studies, a series of evaluations should be completed to determine its appropriateness and usability (Ahmed et al. 2019).

4.1.2 MST Great Lakes summary

A literature review of peer-reviewed journal articles was conducted to assess the extent of MST method application in the Great Lakes. Studies dating back to 2000 were tallied in **Table 4-2** below. Raw data were obtained for five of the studies (Dila et al. 2018; Ishii et al. 2007; McLellan et al. 2018; Olds et al. 2018; Verhougstraete et al. 2015) and provided as a deliverable as part of this project. **Figure 4-2** (page 60) provides a geographical view of the studies listed in **Table 4-2**.

Table 4-2: Summary of select research studies in the Great Lakes using MST methods.

Study	Great Lake/ Connecting Channel	City/County	State/ Province	Beach Location	Tributary Location	Source Location(s)	Latitude	Longitude	Year of Data Collection
Alm et al. 2018	Lake Michigan	Grand Haven	Michigan	North Beach		Municipal landfill runoff; wastewater lagoons	43.0828	-86.2545	2013
				Grand Haven City Beach			43.051877	-86.245294	
Bower et al. 2005	Lake Michigan	Milwaukee	Wisconsin	South Shore Beach		Cow feedlots; sanitary sewer overflow	42.995052	-87.881447	2004
		Milwaukee		McKinley Beach			43.053287	-87.881807	
		South Milwaukee		Grant Park Beach			42.908804	-87.84135	
		Manitowoc		Red Arrow Beach			44.076064	-87.655735	
		Sheboygan		Deland Park Beach			43.759168	-87.70238	
		Two Rivers		Point Beach			44.210742	-87.507223	
		Door County		Clay Banks Beach			44.759302	-87.327711	
		Door County		Nicolet Beach			45.165536	-87.223493	
		Door County		Anclam Park Beach			45.058648	-87.124176	
		Milwaukee County			Lake Michigan		43.373762	-84.752228	
		Milwaukee County			Kinnickinnic River		43.013819	-87.903828	
Byappanahalli et al. 2018	Lake Michigan	Frankfort	Michigan	Platte Point Beach			44.731834	-86.152879	2014
							44.731996	-86.15348	
							44.731592	-86.152217	
		Empire		Esch Road Beach			44.763225	-86.076119	
							44.762789	-86.076297	
							44.763675	-86.075959	
		Frankfort			Platte River		44.731442	-86.155157	
							44.731194	-86.15568	
							44.731621	-86.154561	
		Empire			Otter Creek		44.761441	-86.076789	
							44.761715	-86.076541	
							44.761104	-86.076878	
Corsi et al. 2014	Lake Michigan	Milwaukee	Wisconsin		Cedar Creek		43.290758	-87.950596	2007-2008
					Underwood Creek		43.059187	-88.033056	
					Milwaukee River		43.025355	-87.895768	
Corsi et al. 2016	Lake Michigan	Manitowoc	Wisconsin	Red Arrow Beach			44.076064	-87.655735	2010
		Door County		Clay Banks Beach			44.759302	-87.327711	
		Two Rivers		Point Beach			44.210742	-87.507223	
Dila et al. 2018	Detroit River	Detroit	Michigan		Rouge River		42.275027	-83.110088	2011-2013
	Lake St. Clair	Mt. Clemens	Michigan		Clinton River		42.560816	-82.845556	
	Lake Michigan	Milwaukee County	Wisconsin		Milwaukee River		43.025355	-87.895768	
	Lake Erie	Monroe	Michigan		Raisin River		41.89181	-83.335954	
	Lake Erie	Waterville	Ohio		Maumee River		41.693882	-83.467604	
	Lake Erie	Woodville	Ohio		Portage River		41.449466	-83.358399	
	Lake Michigan	Manitowoc	Wisconsin		Manitowoc River		44.092044	-87.651808	
	Lake Michigan	Marinette	Wisconsin		Menominee River		45.0947	-87.591735	
Edge and Hill, 2007	Lake Ontario	Hamilton	Ontario	Bayfront Park Beach		Beach sand; WWTP effluent; CSO storage tanks; gull droppings; Canada geese droppings; mallard duck droppings; dog droppings; cat droppings	43.271722	-79.874489	2004
Edge and Schellhorn, 2012	Lake Ontario	Niagara-on-the-Lake	Ontario	Queens Royal Beach		Stormwater runoff; Lake Erie agricultural drains; Lake Ontario agricultural drains; WWTP effluent; WWTP influent	43.2577	-79.0685	2010-2011
	Lake Erie	Fort Erie		Nickel Beach			42.875555	-79.239074	2010
	Lake Ontario			Nelles Park Beach			43.199	-79.542	2010
	Lake Erie			Lorraine Road Beach			42.871333	-79.21445	2010-2011
	Lake Erie	Wainfleet		Long Beach Conservation West Beach			42.87208	-79.425402	2010
							42.872284	-79.421196	2010-2011
	Lake Erie	Wainfleet		Long Beach			42.864657	-79.386902	2010-2011
	Lake Ontario			Lakeside Beach			43.2045	-79.265907	2010-2011
	Lake Ontario			Garden City Beach			43.224001	-79.222	2010-2011
	Lake Ontario	Winona		Fifty Point Conservation Area Beach			43.22495	-79.619	2010-2011
	Lake Erie	Fort Erie		Crystal Beach			42.862481	-79.069425	2010-2011
	Lake Ontario			Charles Daly West Beach			43.1807	-79.326	2010
							43.1813	-79.3265	2010
	Lake Erie	Fort Erie		Humberstone Centennial Park Beach			42.873874	-79.17856	2010
	Lake Erie	Fort Erie		Bernard Ave. Beach			42.874015	-79.029227	2010
	Niagara River			15 sites on the river			42.903536	-78.908852	2011

Study	Great Lake/ Connectin g Channel	City/County	State/ Province	Beach Location	Tributary Location	Source Location(s)	Latitude	Longitude	Year of Data Collection
Edge et al. 2018	Lake Ontario	Toronto	Ontario	Bluffer's Park Beach		Beach sand; stormwater runoff; groundwater; WWTP effluent; bird droppings	43.714082	-79.226	2005-2007
Eichmiller et al. 2013	Lake Superior	Duluth	Minnesota		Duluth-Superior Harbor lake water	Duluth-Superior Harbor lake sand and sediment; WWTP effluent; WWTP influent	47.226944	-91.900556	2010-2011
Fisher et al. 2015	Lake Michigan	Milwaukee	Wisconsin		Lake Michigan outside harbor	Sanitary sewage' stormwater runoff	43.373762	-84.752228	2010-2012
		Milwaukee			Kinnickinnic River		43.013819	-87.903828	
		Marinette			Menominee River		45.0947	-87.591735	
		Milwaukee			Milwaukee River		43.025355	-87.895768	
Francy et al. 2006	Lake Erie	Cleveland	Ohio	Edgewater Beach		Shallow groundwater; beach sediment; bird droppings; WWTP-secondary treatment; stormwater runoff	41.489371	-81.74064	2005
		Ashtabula		Lakeshore Beach			41.90828	-80.773999	
Haack et al. 2003	Lake Michigan	Traverse City	Michigan	West End Beach		Groundwater; beach sediment; floating detritus; gull droppings; geese droppings; duck droppings; bird droppings	44.77007	-85.63513	2000
		Traverse City		Clinch Beach			44.76577	-85.61905	
		Traverse City		Bryant Park Beach			44.76682	-85.59602	
		Elk Rapids		Yuba Beach			44.822775	-85.465003	
		Suttons Bay		Suttons Bay Beach			44.970569	-85.647357	
		Traverse City			Boardman River		44.76485	-85.612789	
Haack et al. 2009	Lake Erie	Ann Arbor	Michigan		Huron River		42.288711	-83.740207	2001
		Adrian			River Raisin		41.884963	-83.970832	
Ishii et al. 2007	Lake Superior	Duluth	Minnesota	Duluth Boat Club Beach		Beach sediment; beach sand; WWTP effluent; geese droppings; gull droppings	46.768873	-92.089849	2004-2005
Lee et al. 2014	Lake Erie	Kitchener	Ontario		Grand River	WWTP effluent	43.475071	-80.475576	2013
					Conestogo River		43.538316	-80.486737	
					Canagagigue Creek		43.573554	-80.490734	
Liu et al. 2006	Lake Michigan	Michigan City	Indiana	Central Ave. Beach			41.704581	-86.951939	2004
				Mt. Baldy Beach			41.712975	-86.925589	
					Kintzele Ditch		41.707403	-86.941574	
					Trail Creek		41.724627	-86.909123	
McLellan et al. 2007	Lake Michigan	Milwaukee	Wisconsin		Milwaukee River		43.049727	-87.90978	2004
		Milwaukee			Menominee River		43.042536	-87.982931	
		Milwaukee			Kinnickinnic River		43.006534	-87.914033	
					Milwaukee Harbor		43.025973	-87.888983	
					Lake Michigan outside harbor		43.026511	-87.876035	
McLellan et al. 2018	Lake Michigan	Milwaukee	Wisconsin		Lake Michigan outside harbor	WWTP influent	43.026511	-87.876035	2009-2011
Napier et al. 2018	Lake Michigan	Portage	Indiana	West Beach			41.628091	-87.196369	2003
	Lake Michigan	Michigan City	Indiana	Washington Park Beach			41.72867	-86.90445	2004
	Lake Michigan	St. Joseph	Michigan	Silver Beach			42.11109	-86.48805	2004
	Lake Erie	Cleveland	Ohio	Huntington Beach			41.490917	-81.934072	2003
Nevers et al. 2018	Lake Michigan	Hammond	Indiana	Hammond East Beach			41.69698	-87.51126	2015
				Hammond West Beach			41.69955	-87.51374	
					Grand Calumet River		41.644787	-87.559178	
		Chesterton - Indiana Dunes National Lakeshore		Whihala Beach			41.68921	-87.50005	
				Jeorse Park Beach			41.64936	-87.43324	
Newton et al. 2013	Lake Michigan	Milwaukee	Wisconsin		Lake Michigan outside harbor	WWTP influent; stormwater runoff	43.026511	-87.876035	2005, 2007-2009, 2011
					Milwaukee Harbor		43.025973	-87.888983	
Olds et al. 2018	Lake Michigan	Milwaukee	Wisconsin		Milwaukee River		43.045697	-87.913423	2014-2015
		Milwaukee			Kinnickinnic River		43.00842	-87.908432	
		Milwaukee			Menominee River		43.032827	-87.933057	

Study	Great Lake/ Connecting Channel	City/County	State/ Province	Beach Location	Tributary Location	Source Location(s)	Latitude	Longitude	Year of Data Collection
Oster et al. 2014	Lake Michigan	Sheboygan	Wisconsin	Deland Park Beach			43.759168	-87.70238	2012
	Lake Michigan	East Chicago	Indiana	Jeorse Park Beach			41.64936	-87.43324	
	Lake Michigan	Chesterton- Indiana Dunes National Lakeshore	Indiana	Portage Lakefront Beach			41.63063	-87.181633	
	Lake Michigan	Maple City - Sleeping Bear Dunes National Lakeshore	Michigan	Esch Road Beach			44.76304	-86.07643	
	Lake Superior	Brimley	Michigan	Brimley State Park Beach			46.41637	-84.55804	
	Lake Huron	Bay City	Michigan	Bay City Rec. Area Beach			43.67138	-83.90676	
	Lake Erie	Oregon	Ohio	Maumee Bay State Park Beach			41.6858	-83.3781	
Oun et al. 2017	Lake Huron	Saginaw Bay	Michigan	Singing Bridge Beach		Beach sediment	44.14288	-83.56688	2011
				Whites Beach			43.92871	-83.89031	
					Whitney Drain		44.160498	-83.585939	
Ram et al. 2007	Lake Erie	Ann Arbor	Michigan			Stormwater runoff; raccoon droppings; Canada geese droppings; dog droppings; cat droppings			2005
Ram et al. 2018	Detroit River	Detroit	Michigan	Belle Isle Beach			42.345321	-82.978235	~2017
	Lake St. Clair	Windsor	Ontario	Sand Point Beach			42.338888	-82.91966	
Ran et al. 2013	Lake Superior	Duluth	Minnesota			Beach sand, beach sediment	46.768873	-92.089849	2011
		Proctor					46.723054	-92.182442	
Sauer et al. 2011	Lake Michigan	Milwaukee	Wisconsin		Kinnickinnic River	Stormwater runoff; WWTP influent	42.990897	-87.95829	2008-2009
					Underwood Creek		43.043181	-88.056132	
					Honey Creek		43.038826	-88.012505	
Staley and Edge, 2016	Lake Ontario	Toronto	Ontario	Sunnyside Beach		Beach sand pore water	43.6375	-79.4557	2014
					Humber River		43.631618	-79.471188	
Staley et al. 2016	Lake Ontario	Toronto	Ontario		Humber River	Stormwater runoff; WWTP influent; WWTP effluent	43.632672	-79.472839	2014
Staley et al. 2018a	Lake Ontario	Toronto	Ontario	Rouge Beach		Beach sand pore water; stormwater runoff	43.7925	-79.119	2016
					Rouge River		43.794737	-79.11542	
Staley et al. 2018b	Lake Ontario	Etobicoke	Ontario	Marie Curtis Beach			43.585691	-79.540479	2013
					Etobicoke Creek		43.584801	-79.541257	
Templar et al. 2016	Lake Michigan	Milwaukee	Wisconsin		Kinnickinnic River		43.002857	-87.912101	2013
		Milwaukee			Menominee River		43.032617	-87.944649	
		Milwaukee			Milwaukee River		43.042997	-87.91324	
Verhougstraete et al. 2015	Lake Huron	Au Gres	Michigan		Au Gres River		44.028256	-83.68257	2010
	Lake Huron	Oscoda			Au Sable River		44.406512	-83.319044	
	Lake Michigan	Allendale			Bass River		42.98657	-86.031499	
	Lake Michigan	Muskegon			Bear Creek		43.278017	-86.2395	
	Lake Michigan	Petoskey			Bear River		45.375035	-84.960159	
	Lake Michigan	Peshawbestown			Belangers Creek		45.011358	-85.612597	
	St. Clair River	Marine City			Belle River		42.707149	-82.497078	
	Lake Michigan	Frankfort			Betsie River		44.629308	-86.244605	
	Lake Michigan	Ludington			Big Sable River		44.030272	-86.506596	
	Lake St. Clair	Clinton Township			Black Creek		41.926101	-84.121252	
	Lake Michigan	South Haven			Black River		42.40205	-86.284137	
	St. Clair River	Port Huron			Black River		42.972927	-82.419332	
	Lake Michigan	Traverse City			Boardman River		44.764843	-85.612735	
	Lake Michigan	Boyne City			Boyne River		45.21439	-85.014838	
	Lake Michigan	Byron Center			Buck Creek		42.910286	-85.778113	
	Lake Huron				Carp River		46.025186	-84.693018	
	Lake Huron	Saginaw			Cass River		43.378973	-83.983747	
	Lake Huron	Cheboygan			Cheboygan River		45.656329	-84.464645	
	Lake St. Clair	Harrison Township			Clinton River		42.594808	-82.775994	
	Lake Michigan	Glen Arbor			Crystal River		44.917918	-85.971158	
	Lake Michigan	Elk Rapids			Elk-Torch River		44.900764	-85.417303	
	Lake Huron				Flint River		43.337032	-84.070288	
	Lake Michigan	Whitehall			Flower Creek		43.468854	-86.460184	
	Lake Michigan	Grand Haven			Grand River		43.057549	-86.249847	
	Lake St. Clair				Harrington Drain		42.590802	-82.904134	
	Lake Erie	Flat Rock			Huron River		42.094245	-83.294931	
	Lake Michigan				Jordan River		45.153417	-85.130558	
	Lake Michigan	Saugatuck			Kalamazoo River		42.676139	-86.213354	
	Lake Michigan				Lincoln River		43.984351	-86.471594	

Study	Great Lake/ Connecting Channel	City/County	State/ Province	Beach Location	Tributary Location	Source Location(s)	Latitude	Longitude	Year of Data Collection
Verhougstraete et al. 2015 con't	Lake Michigan		Michigan		Little Manistee River		44.209811	-86.276619	2010
	Lake Michigan				Little Pigeon Creek		42.962656	-86.218169	
	Lake Huron				Little Trout River		45.36763	-83.669891	
	Lake Huron				Long Lake Creek		45.158392	-83.346815	
	Lake Michigan				Macatawa River		42.773858	-86.21097	
	Lake Michigan				Manistee River		44.249953	-86.343421	
	Lake Huron				Marsh Creek		43.349298	-84.107814	
	Lake Michigan				Mitchell Creek		44.750217	-85.559491	
	Lake Michigan				Monroe Creek		45.179271	-85.161742	
	Lake Michigan				Muskegon River		43.227814	-86.340084	
	Lake Michigan				North Branch Black River		42.432617	-86.234371	
	Lake Huron				Ocqueoc River		45.489896	-84.073411	
	Lake Michigan				Paw River		42.114433	-86.470041	
	Lake Michigan				Pere Marquette River		43.95229	-86.45933	
	Lake Huron				Pigeon River		43.945754	-83.279956	
	Lake Michigan				Pine Creek		44.261088	-86.076781	
	Lake Michigan				Pine River		44.228553	-85.910231	
	Lake Michigan	Frankfort			Platte River		44.679397	-86.059387	
	Lake Erie				Raisin River		41.89269	-83.338003	
	Lake Huron				Rifle River		43.993059	-83.822168	
	Detroit River				River Rouge		42.275338	-83.110937	
	Lake Michigan				Rush Creek		42.9109	-85.781307	
	Lake Michigan				Sand Creek		42.946018	-85.851608	
	Lake Erie				Sandy Creek		41.92806	-83.338259	
	Lake Huron				Shiawassee River		43.385908	-83.967005	
	Lake Erie				Silver Creek		42.040519	-83.203682	
	Lake Michigan				South Branch Black River		42.41783	-86.250304	
	Lake Michigan	St. Joseph			St. Joseph River		42.114378	-86.488538	
	Lake Michigan	Stony Lake			Stony Lake Outlet		43.559428	-86.497126	
	Lake Erie	Monroe			Swan Creek		41.976358	-83.246442	
	Lake Huron	Tawas City			Tawas River		44.258563	-83.526185	
	Lake Huron	Alpena			Thunder Bay River		45.061207	-83.425593	
	Lake Huron	Saginaw			Tittabawassee River		43.384527	-83.978299	
	Lake Huron	Rogers City			Trout River		45.429145	-83.827159	
	Lake Michigan	Whitehall			White River		43.374509	-86.425948	
Whitman and Nevers, 2003	Lake Michigan	Chicago	Illinois	63rd Street Beach		Beach sand; gull droppings	41.782949	-87.572224	2000
Wu et al. 2018	Lake Michigan	Williamston	Michigan		Sloan Creek	Bovine feces	42.694224	-84.386198	2015
					Button Drain		42.654497	-84.400567	

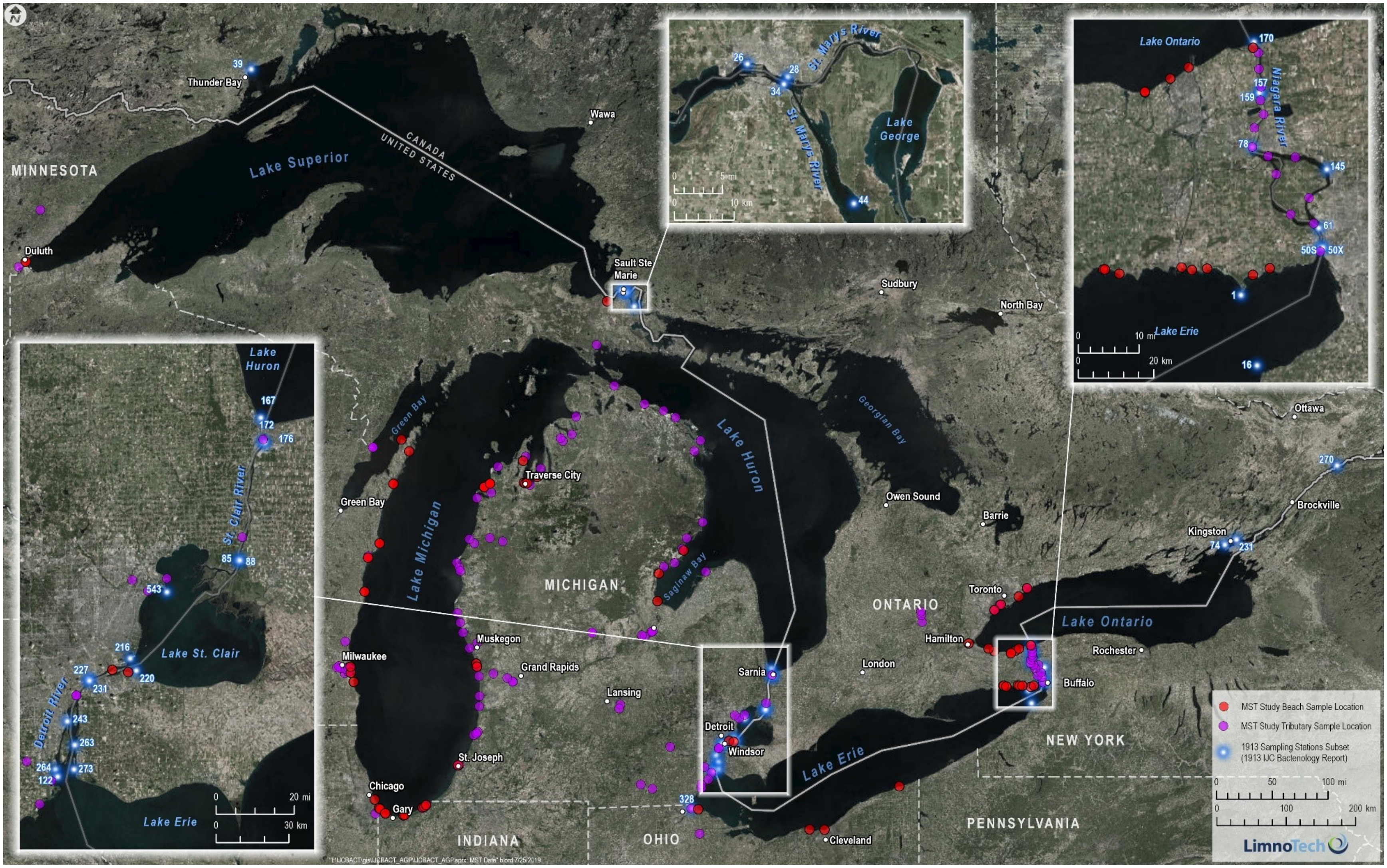

Figure 4-2: Locations of MST-related Studies in the Great Lakes. Red dots are beaches that have been sampled, while purple dots are watershed areas, mostly tributaries.

MST is an effective technique for identifying fecal sources (hosts) of water contamination, but the Great Lakes studies have tended to fall into three study categories:

- ***Characterize watershed contributors:*** This is the classic use of MST to identify fecal sources and their origin through targeted sampling of different pathways (discussed in the next section). Research done in Milwaukee by McLellan and colleagues (2007), Newton and colleagues (2013), Fisher and colleagues (2015), and Templar and colleagues (2016) are examples of this type of application of MST methods.
- ***Evaluate method performance:*** Since MST methods are relatively new, having been developed in the last 15-20 years, several studies in the Great Lakes (Bower et al. 2005; Ram et al. 2007; Staley et al. 2016) and more broadly (Boehm et al. 2013; Cimenti et al. 2009) have focused on method performance, persistence and prevalence, including comparisons for various hosts with respect to sensitivity and specificity.
- ***Translate markers into health risks:*** Current regulatory guidance for protecting human health were developed by relating illness rates to enumeration levels of *E. coli* or enterococci (for freshwater). Translating MST results using qPCR to a corresponding health risk is an active area of study (Byappanahalli et al. 2018; Edge and Schellhorn, 2012; Napier et al. 2018). Byappanahalli and colleagues (2018), for example, demonstrated through sampling in Lake Michigan and several tributaries that qPCR and culture-based enumeration methods were correlated. Quantitative PCR offers quicker results, that provides more timely information to the public, but qPCR-enterococci results yielded fewer beach advisories.

MST studies in the Great Lakes have considered a number of sources/hosts, but humans, birds (gulls/geese), ruminants (cows) and pets (dogs) are the most frequently analyzed and most frequently detected hosts. A summary of the sources included in each Great Lakes study is shown in **Table 4-3** below. Of the 37 studies compiled for the Great Lakes watershed, most (33 studies) included at least one human marker (see **Table 4-1** on page 56). "HF183" was the dominant marker from the genus *Bacteriodes*, but other markers specific to the genus (*B. theta*) have been successfully used to distinguish locations with a high number of septic systems (Verhougstraete et al. 2015). Further, the bacterial family, *Lachnospiraceae* (Lachno) is often used in combination with the *Bacteroidaceae* that may provide additional confidence in the results (Olds et al. 2018; Templar et al. 2016).

Table 4-3: Sources and/or hosts analyzed by MST methods in selected Great Lakes studies.

Study	Human	Birds	Ruminants (Cows)	Pets	Non-specific/ Other
Alm et al. 2018	X	X			
Bower et al. 2005	X		X		
Byappanahalli et al. 2018					X
Corsi et al. 2014	X		X		
Corsi et al. 2016	X		X		X
Dila et al. 2018	X		X		
Edge and Hill, 2007	X	X		X	
Edge and Schellhorn, 2012	X				
Edge et al. 2018	X	X			
Eichmiller et al. 2013	X				X
Fisher et al. 2015	X				
Francy et al. 2006	X	X			
Haack et al. 2003	X	X			
Haack et al. 2009	X		X		
Ishii et al. 2007	X	X	X	X	X
Lee et al. 2014	X		X		
Liu et al. 2006	X				
McLellan et al. 2007	X	X	X		
McLellan et al. 2018	X		X		
Napier et al. 2018	X				
Nevers et al. 2018	X	X		X	
Newton et al. 2013	X				
Olds et al. 2018	X				
Oster et al. 2014					X
Oun et al. 2017	X		X		
Ram et al. 2007	X	X		X	X
Ram et al. 2018	X	X	X	X	
Ran et al. 2013					X
Sauer et al. 2011	X				X
Staley and Edge, 2016	X	X	X	X	
Staley et al. 2016	X	X	X	X	
Staley et al. 2018a	X	X			
Staley et al. 2018b	X	X	X	X	X
Templar et al. 2016	X				
Verhougstraete et al. 2015	X				
Whitman and Nevers, 2003		X			
Wu et al. 2018	X		X		

Other well-studied sources included birds (14 studies), cows (15 studies) and pets (8 studies). Most of the bird studies in the Great Lakes used Gull, such as “Gull2” or “Gull4” markers (Alm et al. 2018; Nevers et al. 2018; Staley et al. 2016, 2018a), but other bird markers are also available, such as the Canada goose marker “CGO” (Fremaux et al. 2010) and general bird marker “GFD” (Green et al. 2012). Several ruminant (cow) markers have been used in the Great Lakes, including “BoBac,” “BacBovine,” “CowM2” and “CF128” (Bower et al. 2005; Lee et al. 2014; Oun et al. 2017; Staley et al. 2016; Wu et al. 2018). Like birds, other ruminant markers are also being used outside the Great Lakes (e.g., “BacCow,” “BacR,” “Rum2Bac”). While most of the recent Great Lakes pet studies used dog-specific markers such as “DogBact” (Nevers et al. 2018), Edge and Hill (2007) used antimicrobial resistance and rep-PCR DNA fingerprinting analyses to look at a wide range of sources including both dogs and cats. Researchers outside the Great Lakes are using other dog-specific markers (Green et al. 2014). Nonspecific markers such as “Genbac” (Alm et al. 2018; Staley et al. 2016) and/or other hosts were used in eight Great Lakes studies.

Pollution pathways most frequently cited in the Great Lakes studies for delivering fecal bacteria from the identified sources/hosts include sanitary sewage as well as CSOs and sanitary sewer overflows, stormwater runoff, treated wastewater, home septic systems, agriculture runoff and localized beach sources, such as sand and sediment. Each of these hosts/pollution pathways is described in the next section.

4.2 Human source potential pollution pathways

4.2.1 Population characteristics

People have been moving out of cities and into suburbs, commonly referred to as 'urban sprawl.' Baustian and colleagues (2014) illustrated this migration in the Lake St. Clair region. For a basinwide assessment for this project, a comparison of city and metropolitan populations for the major cities in the Great Lakes watershed was compiled (**Figure 4-3** below on page 65). City population in 1910/1911 is shown for reference. Metropolitan population data in 2017 for US cities were obtained from the US Census Bureau.[1] Data for Canada metropolitan area population areas in 2016 were obtained from Statistics Canada.[2] The difference between the size of the bars in the graphs in **Figure 4-3** generally serves as an indicator of the degree of sprawl for most, but not all cities (e.g., the Traverse City metropolitan area was defined as the seven surrounding counties, that are mostly rural in character). Urban sprawl has several potential impacts related to bacteria contamination:

- The stress on sewer utilities to extend service to these outlying areas, resulting in more pipes to maintain. Often the sanitary flow from these suburban and outlying areas have to be routed through the combined sewer system to reach the wastewater treatment plant for treatment and discharge.
- Urban sprawl increases imperviousness that results in increased runoff. Stormwater runoff typically has fecal bacteria levels well above the 'safe' recreation thresholds (e.g., USEPA BAV, etc.).
- Sewage exfiltration from pipes in poor condition can threaten drinking water source water and distribution networks.

Each of these impacts represents a potential pollution pathway to expose the public to human-originated fecal bacteria.

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[1] US census data obtained via third-party website, accessed at opendatanetwork.com.
[2] Canadian city population data accessed at: statcan.gc.ca/census-recensement/index-eng.cfm?MM=1.

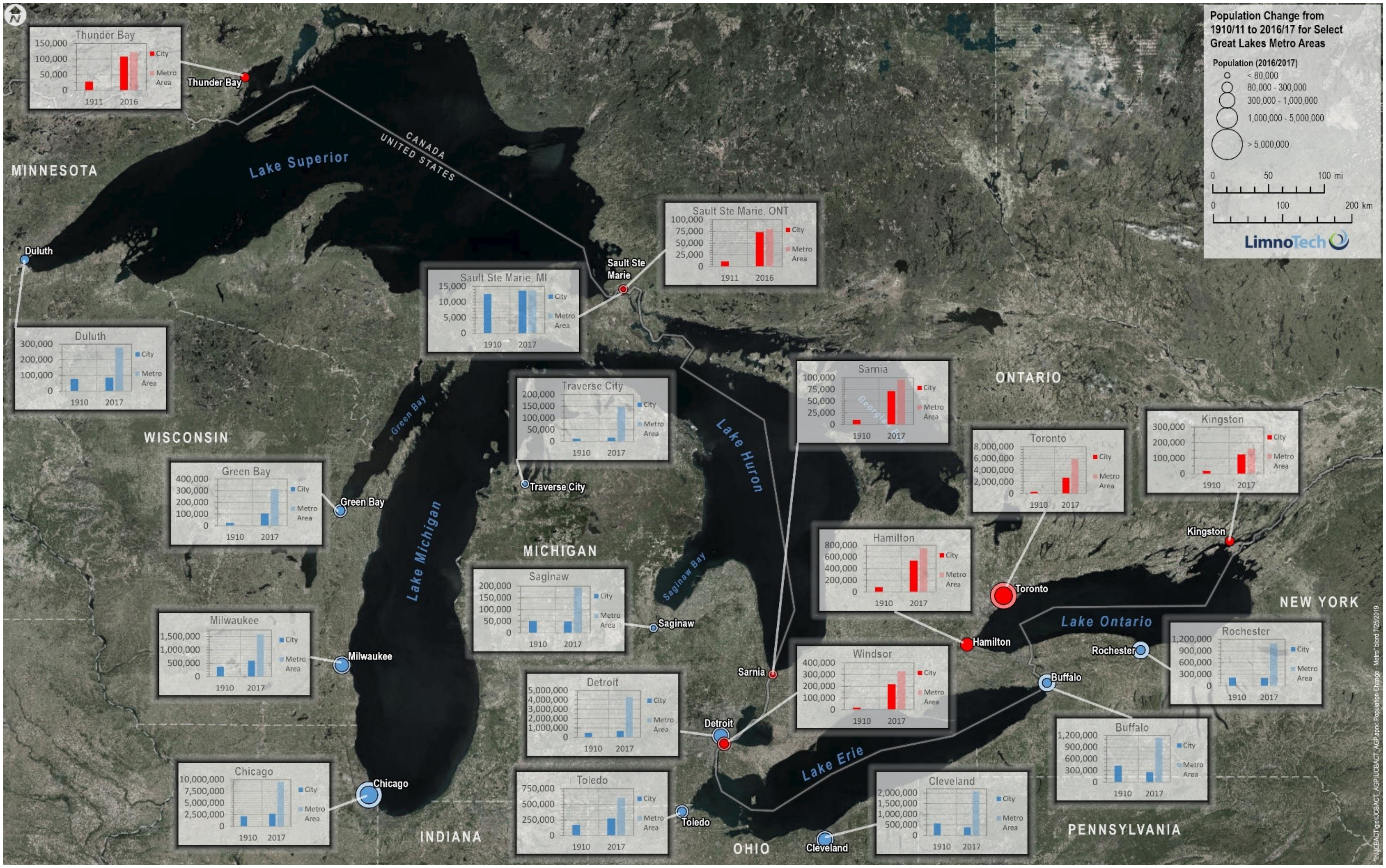

Figure 4-3: Comparison of populations of major cities and metropolitan areas in the Great Lakes basin, 1910/11 to 2016/17.

4.2.2 Combined sewer overflows

There are 184 US communities in the Great Lakes basin with combined sewer systems (US Environmental Protection Agency 2016). Canada has 24 communities with combined sewer systems in the Great Lakes basin (EcoJustice 2009). In a combined sewer system, both sanitary sewage and stormwater runoff are routed to the same collection system. During dry weather or small storms that produce little stormwater runoff, the entire flow in the collection system is routed to the wastewater treatment plant for treatment. CSOs are relief points in the combined sewer system that discharge a mixture of untreated sanitary sewage and stormwater directly to the waterway when the collection system capacity is exceeded. This practice prevents basement backups and other adverse impacts on the sewer system or wastewater treatment process.

Figure 4-4 (below on page 67) shows a map of 168 CSO communities within the Great Lakes basin where overflow volume statistics were available. The CSO community dots are sized by reported volume, though the year of the reported data varies. The orange dots are the reported volumes from 2014 from the USEPA Great Lakes CSO Report to Congress (US Environmental Protection Agency 2016). There were a couple of communities in northern Indiana that did not report volume in 2014, so the volume reported in 2005, that was taken from the USEPA's Lake Michigan CSO Report (US Environmental Protection Agency 2007) were used. Purple dots are the reported volumes from 2007 (EcoJustice 2009). The EcoJustice source was also used in the Great Lakes Environmental Assessment and Mapping project.[3]

Communities are implementing long-term control plans that have or will reduce CSOs to less than ten occurrences, many much fewer than that, in a typical year. CSO discharges will become increasingly rare events associated with large rain events as the long-term control plans are fully implemented. Milwaukee, Wisconsin has done several MST studies to evaluate CSO impacts on beaches:

- Bowers and colleagues (2005) measured human-specific *Bacteroides* species as far as 2 kilometers (1.25 miles) off-shore near Milwaukee, Wisconsin during CSO events. In contrast, cow-specific *Bacteroides* species were detected only near the river outflow.
- McLellan and colleagues (2007), working in same area, found that *E. coli* levels were less than 1-5 CFU/100 ml at locations 2-5 km (1.25-3.1 miles) beyond the harbor, and determined that the observed decrease was due to both dilution and die-off. However, work by Newton and colleagues (2013) found that the urban footprint, based on two human fecal indicators, extended at least 8 km (~5 miles) offshore.
- Sauer and colleagues (2011) found no correlation between human *Bacteroides* species, a human MST marker, and *E. coli* levels or *Enterococci* species levels. She found instances where the *E. coli* data had high levels but low or no evidence of sewage, and vice versa. The ratio of human *Bacteroides* to total *Bacteroides* species was used as an indicator of sewage in this analysis.

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[3] More information about the Great Lakes Environmental Assessment and Mapping project is available at: graham.umich.edu/activity/33677.

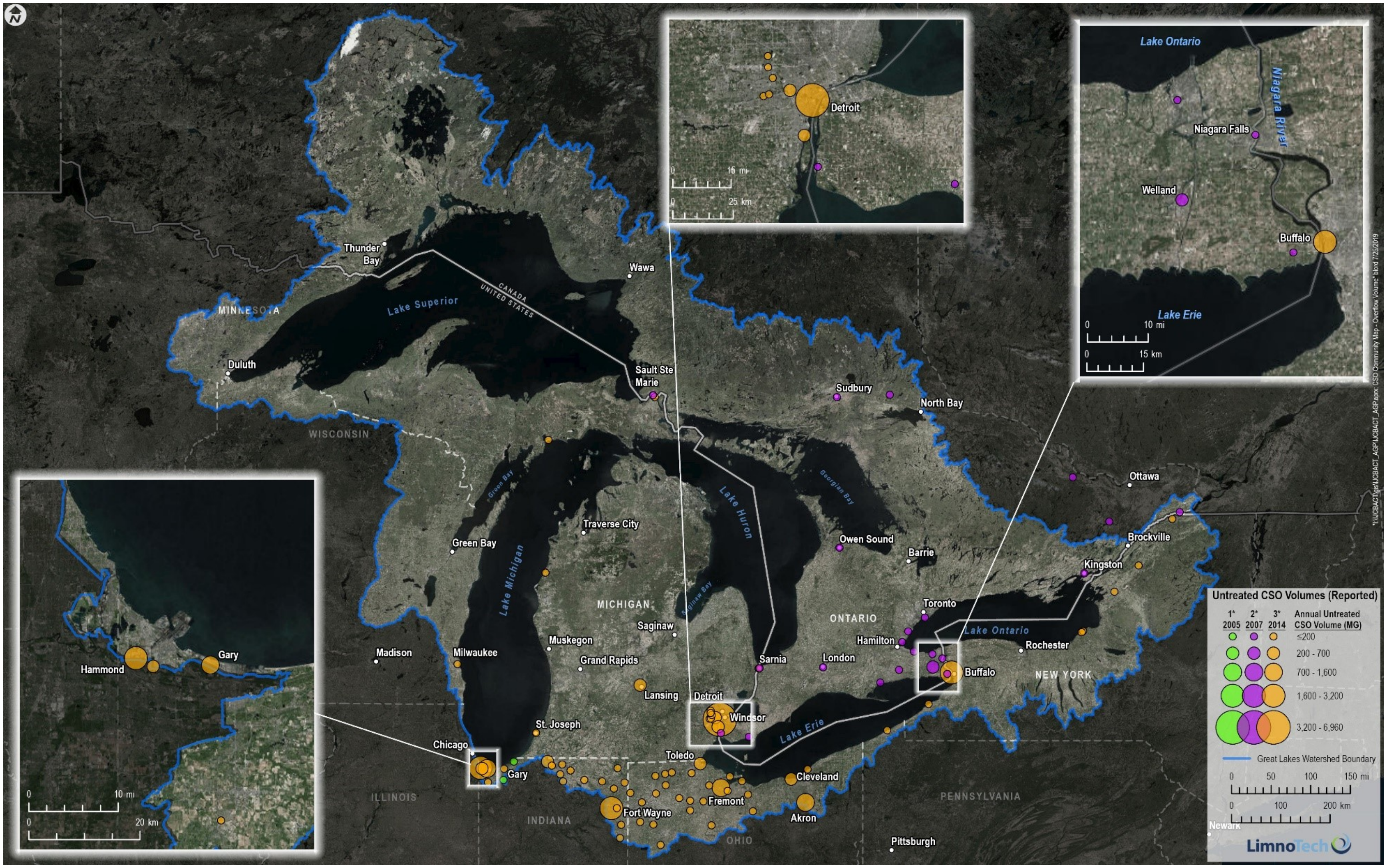

Figure 4-4: Combined sewer overflow (CSO) communities and volumes in the Great Lakes.

4.2.3 Stormwater

Many communities have municipal separate storm sewer systems that collect surface runoff (e.g., stormwater) and route it directly to local waterways. Unlike CSOs that are limited to 170 communities and relatively large storms, stormwater runoff occurs in every community and for all but the smallest rainfall events. Stormwater runoff from urban areas has two qualities that can affect bacteria contamination: erosion and water quality.

Stormwater has the power to reshape the landscape, exposing infrastructure pipes. It can also move stream channels and create connections between wastewater and stormwater infrastructure and surface waterways (see photograph to the right). All these factors can potentially create new pathways and/or accelerate pollutant delivery pathways.

In addition, stormwater contains fecal bacteria deposited on the surface. Wildlife, particularly raccoons, use the stormwater pipe network to travel from one point to another. Ram and colleagues (2007) found raccoons and pets were the primary sources of fecal contamination in two storm sewers basins in Ann Arbor, Michigan. Typical *E. coli* levels measured in stormwater exceed 1,000 CFU/100 ml, well above beach closing or water quality standard criteria to protect recreational users.

Illicit connections of sanitary lines to stormwater pipes are common enough that detecting and eliminating them is one of the six minimum control measures required under the US NPDES program for municipal separate storm sewer system permits. McLellan (2007) found no significant difference (p-value less than 0.05) in the frequency of antibiotic resistance traits between sewage-impacted water (e.g., CSO) and stormwater. One explanation is that illicit connections are delivering human sewage to the stormwater system. Also, a multiple line of evidence approach was used to identify cross-connections in stormwater pipes in the Toronto, Ontario area by Staley et al. (2016).

4.2.4 Septic systems

Homes typically in rural and unsewered urban areas rely on septic systems to treat their wastewater. When these systems fail to work properly or site conditions limit their effectiveness, the fecal bacteria from their systems can be a source of contamination to local waterways (see photograph below). Failure rates can exceed 50 percent in some areas, as the data compiled by the Ohio Department of Health indicate (**Figure 4-5** below on page 69). Verhougstraete and colleagues (2015) conducted a comprehensive study of watersheds in Michigan for septic system impacts and identified *B. theta* as a useful microbial indicator for septic systems.

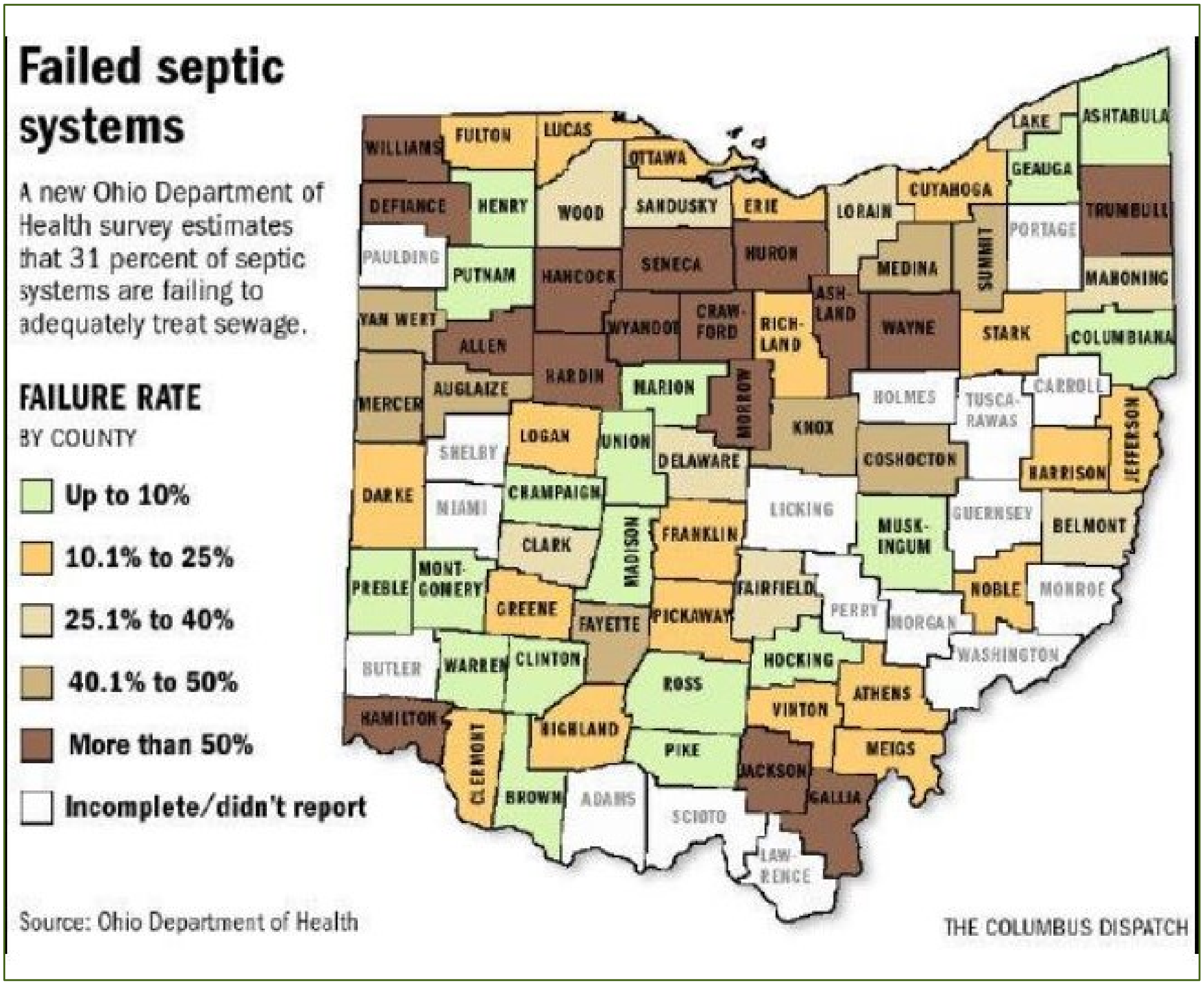

Figure 4-5: Septic system failure rates reported in Ohio counties, 2013. Figure by the Columbus Dispatch, accessed at: dispatch.com/article/20130210/NEWS/302109782.

4.3 Nonhuman source potential pollution pathways

4.3.1 Livestock source potential pollution pathways

The current data from by Great Lakes watershed show a total of over 5,150,000 cattle (cows), 6,075,000 swine (pigs), 229,639,000 poultry and 457,000 ovine (sheep). Cattle have been the focus of several MST studies in the Great Lakes (Bower et al. 2005; Corsi et al. 2014; Corsi et al. 2016; Dila et al. 2018; Haack et al. 2009; Ishii et al. 2007; Lee et al. 2014; McLellan et al. 2007; McLellan et al. 2018; Oun et al. 2017; Ram et al. 2018; Staley et al. 2016; Staley et al. 2018b; Wu et al. 2018). The number of cattle (cows) in the Great Lakes is fairly similar to the number in 1910 shown in **Figure 4-6** (below on page 71), but today they are mostly located in Wisconsin, southwest Michigan, the "thumb" of Michigan (the land east of Bay City between Saginaw Bay and the St. Clair River) and southwestern Ontario. Similar figures are shown for swine (pigs)

(**Figure 4-7**, page 71), poultry (**Figure 4-8**, page 72), and ovine (sheep) (**Figure 4-9**, page 72). From the literature review of studies in the Great Lakes, only one has included markers for swine, poultry and ovine (Ishii et al. 2007) and this study was in the Lake Superior watershed that has relatively low counts of these livestock compared to the other Great Lakes' watersheds. Based on these figures, more attention to livestock as sources in the other lakes may be warranted. Lake Erie has the most poultry and pigs in its watershed compared to the other lake watersheds. Both Lake Huron and Lake Ontario watersheds also have high numbers of poultry. The Lake Michigan watershed has the highest number of cattle. Sheep do not appear to be as important as a potential fecal bacteria source as cattle, pigs, and poultry.

Figure 4-6: Estimated number of cattle (cows) in each Great Lake watershed in 1910 and 2017 in the United States (top) and Ontario (bottom). Data for the United States are from the 1910 and 2017 USDA census of agriculture that were reported at the county level. For Ontario, 1910 data are from Statistics Canada agriculture statistics that were reported at the country level, and 2017 data are from the Statistics Canada census of agriculture that were reported at the provincial level. Distribution of agriculture in Ontario was based on the proportion of reported farmland in each county. Distribution of agriculture in each watershed was based on the proportion of the watershed in each county. Importantly, the censuses were not comprehensive of all farms and animals but only those farms that met minimum production and economic value thresholds.

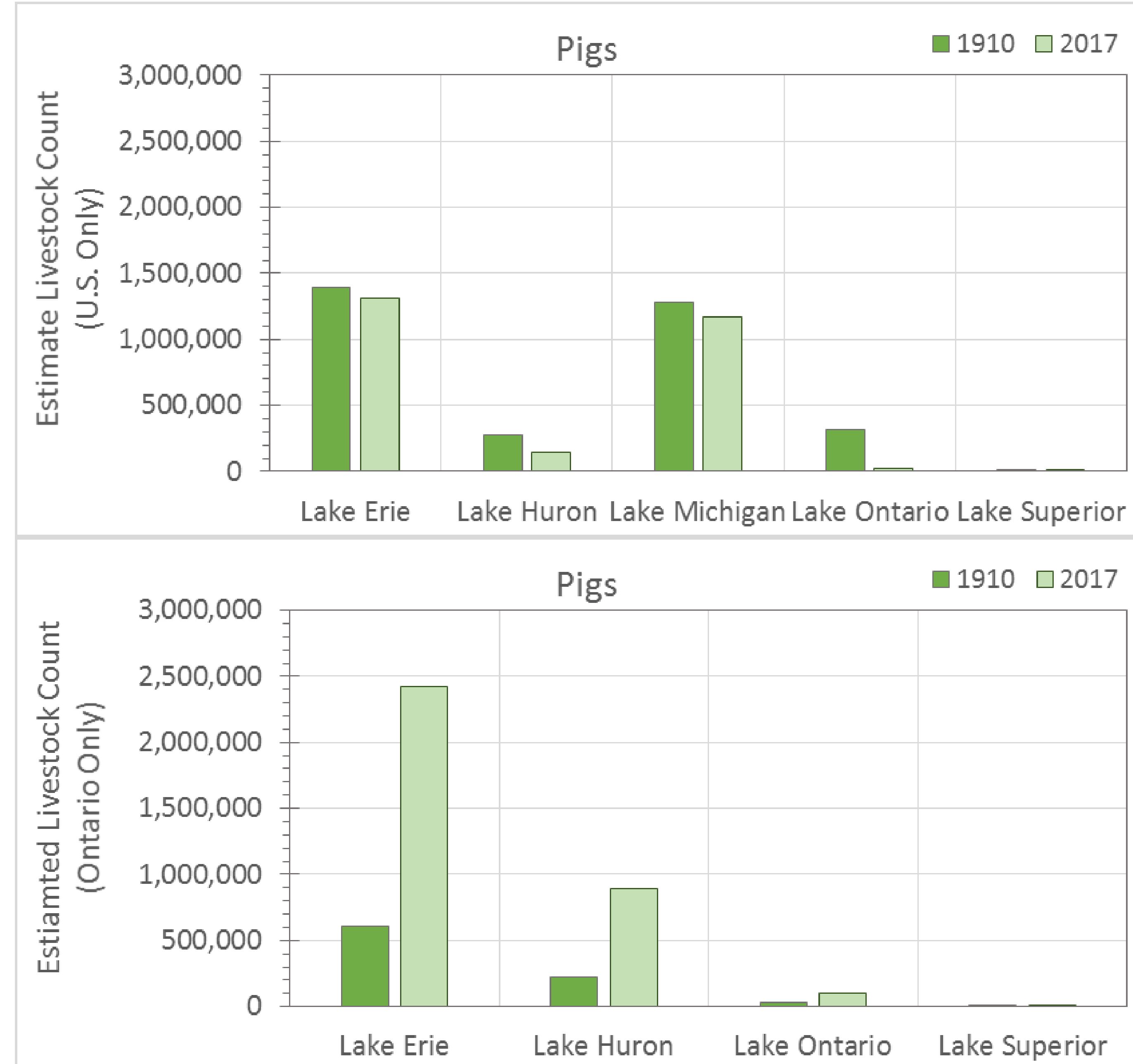

Figure 4-7: Estimated number of swine (pigs) in each Great Lake watershed in 1910 and 2017 in the United States (top) and Ontario (bottom). Data for the United States are from the 1910 and 2017 USDA census of agriculture that were reported at the county level. For Ontario, 1910 data are from Statistics Canada agriculture statistics that were reported at the country level, and 2017 data are from the Statistics Canada census of agriculture that were reported at the provincial level. Distribution of agriculture in Ontario was based on the proportion of reported farmland in each county. Distribution of agriculture in each watershed was based on the proportion of the watershed in each county. Importantly, the censuses were not comprehensive of all farms and animals but only those farms that met minimum production and economic value thresholds.

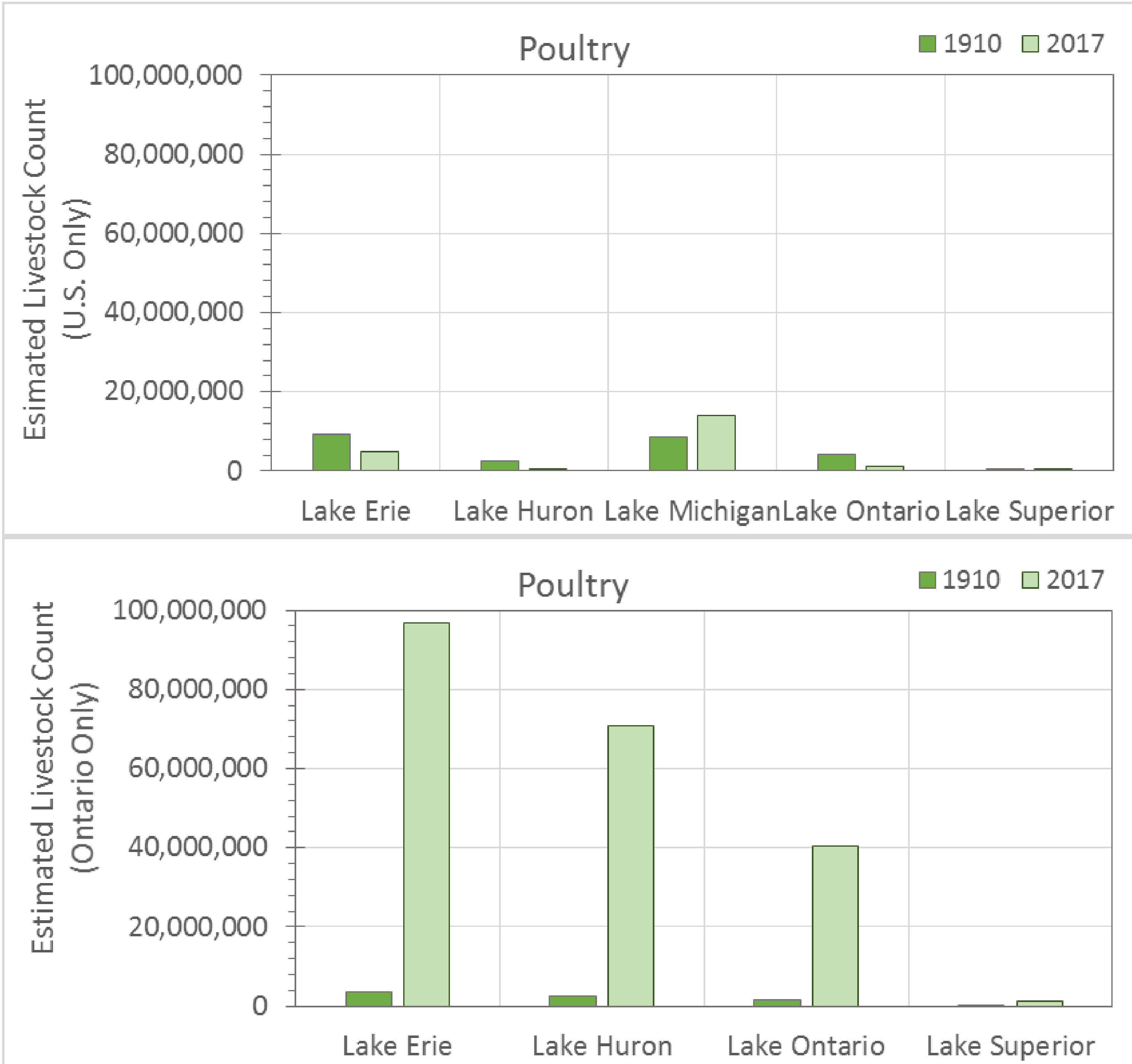

Figure 4-8: Estimated number of poultry in each Great Lake watershed in 1910 and 2017 in the United States (top) and Ontario (bottom). Data for the United States are from the 1910 and 2017 USDA census of agriculture that were reported at the county level. For Ontario, 1910 data are from Statistics Canada agriculture statistics that were reported at the country level, and 2017 data are from the Statistics Canada census of agriculture that were reported at the provincial level. Distribution of agriculture in Ontario was based on the proportion of reported farmland in each county. Distribution of agriculture in each watershed was based on the proportion of the watershed in each county. Importantly, the censuses were not comprehensive of all farms and animals but only those farms that met minimum production and economic value thresholds.

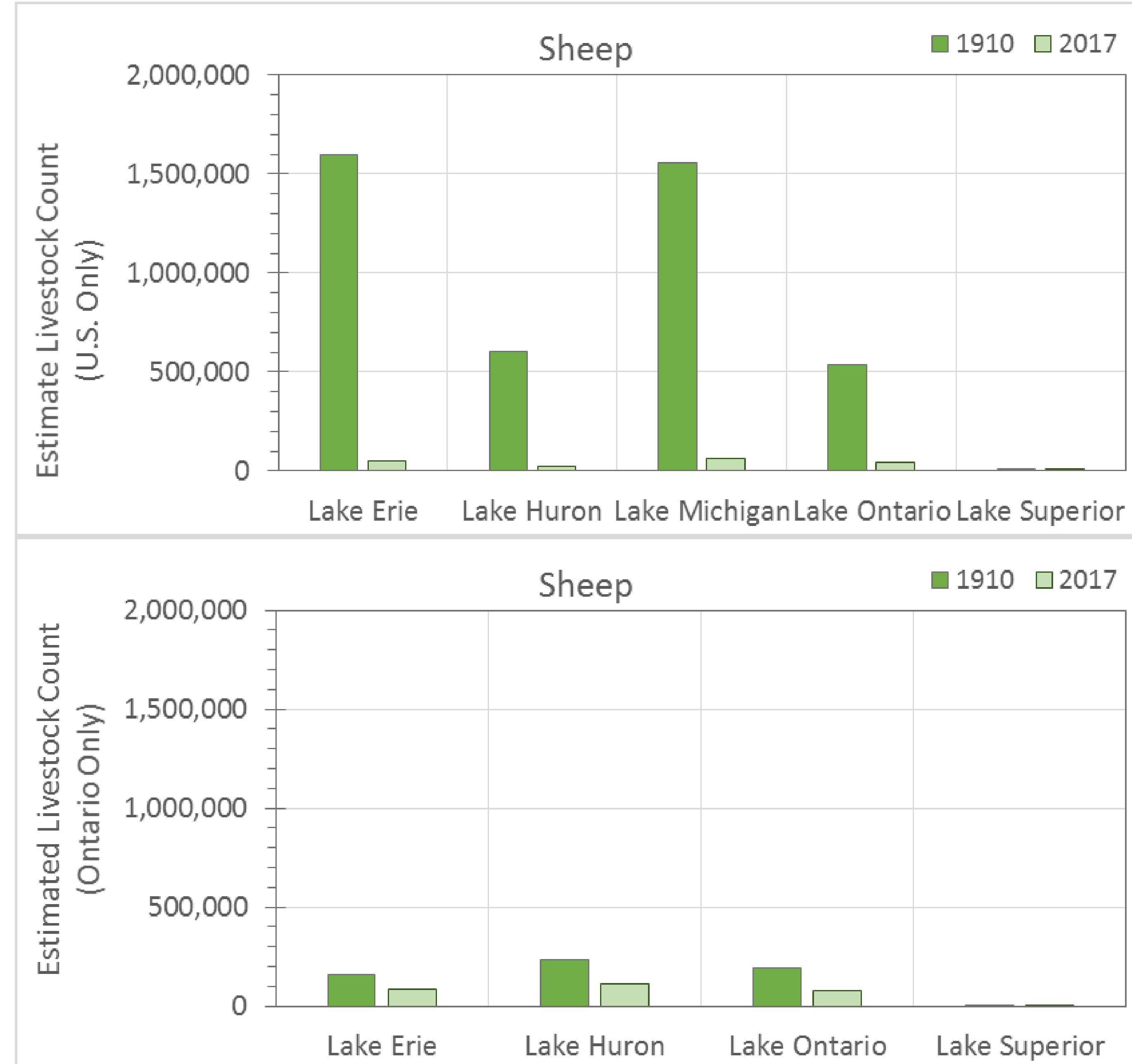

Figure 4-9: Estimated number of ovine (sheep) in each Great Lake watershed in 1910 and 2017 in the United States (top) and Ontario (bottom). Data for the United States are from the 1910 and 2017 USDA census of agriculture that were reported at the county level. For Ontario, 1910 data are from Statistics Canada agriculture statistics that were reported at the country level, and 2017 data are from the Statistics Canada census of agriculture that were reported at the provincial level. Distribution of agriculture in Ontario was based on the proportion of reported farmland in each county. Distribution of agriculture in each watershed was based on the proportion of the watershed in each county. Importantly, the censuses were not comprehensive of all farms and animals but only those farms that met minimum production and economic value thresholds.

4.3.2 Gulls and geese

Gulls and geese have been identified as important sources of fecal contamination at beaches in several MST studies in the Great Lakes (Alm et al. 2018; Edge and Hill, 2007). Edge and Hill (2007) showed that in Hamilton, Ontario the sand and nearshore elevated levels of *E. coli* were predominantly due to geese and gull droppings. Further away from shore, bird contamination decreased and wastewater contamination increased. Not only do gulls and geese directly deposit fecal material on beaches and beach waters, they also transport fecal matter from other hosts to waterways (Alm et al. 2018). This can confound interpretation of MST data for identifying sources and pollution pathways. Their populations are also increasing, potentially exacerbating the challenge of managing their impacts on water quality. Over the last 50 years, Canada geese, especially, have made a comeback (**Figure 4-10**), increasing in number by thirty-fold.

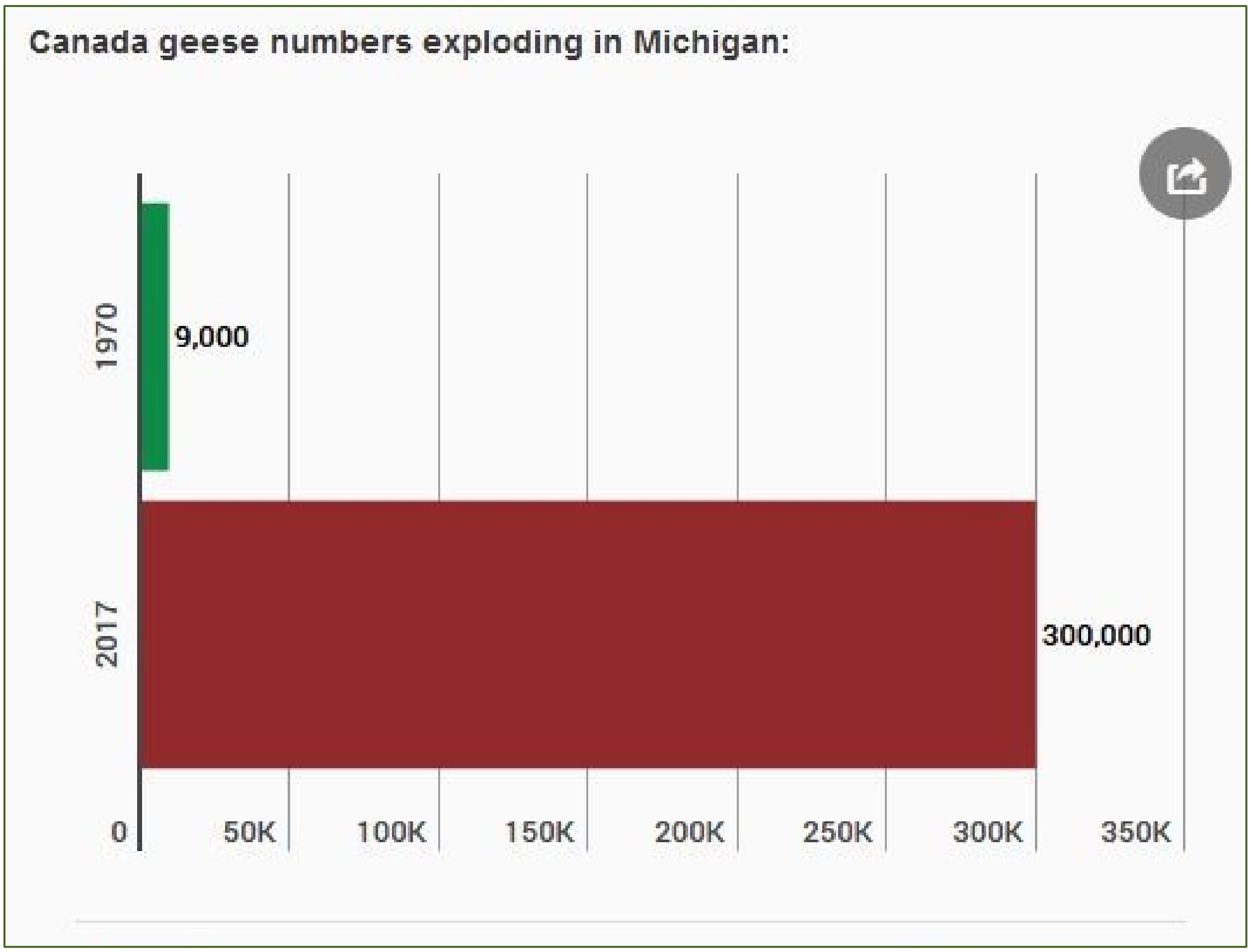

Figure 4-10: Canada geese populations in Michigan, 1970 and 2017. Figure by the Detroit Free Press, accessed at: freep.com/story/news/local/michigan/2017/11/07/how-much-poop-can-one-canada-goose-poop-one-day-read/830375001/.

4.3.3 Local reservoirs

Fecal coliform levels at beaches can be impacted by *E. coli* sequestered in local media, including:

- Foreshore sand
- Shallow groundwater
- Sediment
- Detritus/vegetation
- Soil

Whitman and Nevers (2003) identified foreshore sand as a source of *E. coli* in Lake Michigan beaches near Chicago, Illinois. Ran and colleagues (2013) found that enterococci can persist in watershed soils for a prolonged time after being introduced. Edge and Hill (2007) found that elevated *E. coli* levels in the water (in Hamilton, Ontario) were more similar to foreshore sand isolates than bird or wastewater isolates out to 150 meters offshore. Haack and colleagues (2003), working in Traverse City, Michigan, found that detritus harbored more bacteria than the coarse sand comprising much of the beach sand. Francy and colleagues (2006) hypothesized that shallow groundwater and wave interactions may be a mechanism for *E. coli* storage in foreshore sand based on work at several Lake Erie beaches.

However, some research has also indicated that the bacteria in these local environmental media originate elsewhere in the watershed. Eichmiller and colleagues (2013) found that sand and sediment may act as reservoirs for upland watershed sources, such as final effluent from wastewater treatment plants). Francy and colleagues (2006) also suggested that bird feces infiltration through sand may be concentrating *E. coli* in shallow groundwater. Oun and colleagues (2017) found that *B. theta*, a human source MST marker associated with septic systems, and "BoBac," a cattle MST marker, were elevated in sediment samples compared to overlying water samples at two beaches in Saginaw Bay, Lake Huron.

Whitman and colleagues (2006) suggested modeling of bacteria flux should consider entire "beachshed" interactions, based on the study that showed that *E. coli* may be stored in forest soils, sediments, surrounding springs, bank seeps, stream margins and pools, foreshore sand and lake water.

4.4 Other tools

MST analysis provides a significant advancement over traditional enumeration methods because techniques such as qPCR provide quantitative data ***and*** information about sources or hosts of the fecal material. Some MST studies are designed to sample not only beaches and waterways but also potential pathways of pollution, such as stormwater outfalls, wastewater and combined sewer overflow outfalls. However, there are other tools that can be used in concert with, or to supplement, MST studies that can provide additional confirmation of potential pathways, including:

- Sanitary surveys
- Models, including watershed, hydrodynamic and water quality models
- Surveillance
- Epidemiology studies
- Non-bacterial communities
- Anthropogenic chemical markers

Several example applications of other tools were included in the studies compiled in the literature review of MST studies to illustrate their use. Liu and colleagues (2006) developed a finite-element model of surf-zone hydrodynamics, temperature and *E. coli* and *Enterococci* species. They modeled inactivation in surf zone as a function of sunlight, temperature and sedimentation instead of traditional first-order inactivation formulation.

Fisher and colleagues (2015), building on work by Newton and colleagues (2013), developed an "urban microbial signature" for sewage and stormwater using non-fecal bacteria. *Arcobacter* and *Tricoccus* species were high in sewage but low in stormwater. *Acinetobacter*, *Aeromonas*, and *Pseudomonas* species were dominant and associated with pipe infrastructure rather than freshwater. The ability to detect these in local waterways is easier during wet weather.

Staley and colleagues (2016) used both MST and chemical source tracking to identify evidence of sewage in stormwater. They recommend a multiple line of evidence approach to identify and remediate sewage sources.

Napier and colleagues (2018) looked at the relationship between manmade chemicals, fecal levels and swimmer illnesses at several freshwater and marine beaches. Bisphenol A and cholesterol were associated with two percent and one percent increased risks (respectively) of gastrointestinal illnesses and diarrhea. No other chemicals were consistently associated with increased risk of illness.

4.4.1 Land use

A potentially rudimentary tool to identify pollution sources and pathways is current land use. Example maps spanning the Great Lakes are shown by hydrologic unit code level 8 for four land uses: urban (**Figure 4-11**, page 77), cropland (**Figure 4-12**, page 77), forest (**Figure 4-13**, page 78), and wetland (**Figure 4-14**, page 78). The data are based on 2010 Landsat satellite imagery at a 30-meter resolution and were obtained from Commission for Environmental Cooperation.[4] The dataset includes data for both Canada and the United States, making the analysis comparable across the basin. The bars show the relative magnitude of the indicated land use. These bars tend to be high for large watersheds and watersheds with a high amount of the indicated land use. For example, based on the urban map (**Figure 4-11** below on page 77), one might expect that

[4] Data sourced from the Commission for Environmental Cooperation, accessed at: cec.org/tools-and-resources/map-files/land-cover-2010-landsat-30m.

samples collected in or near the Lake St. Clair/Detroit River/western Lake Erie portion of the watershed would have human sources present.

Land use could also be useful for determining sampling locations for a centennial study at the Great Lakes basin level. For example, areas with a high degree of development could roughly correlate to human sources (**Figure 4-11** below on page 77). Similar strategies could be used for agriculture/cropland land use for livestock sources (**Figure 4-12** below on page 77), forested and wetlands land uses (**Figures 4-13 and 4-14**, below on page 78) for wildlife sources or areas where water quality may be reasonably expected to be better than areas near urban and rural land use (see **Figure 3-9** above on page 37).

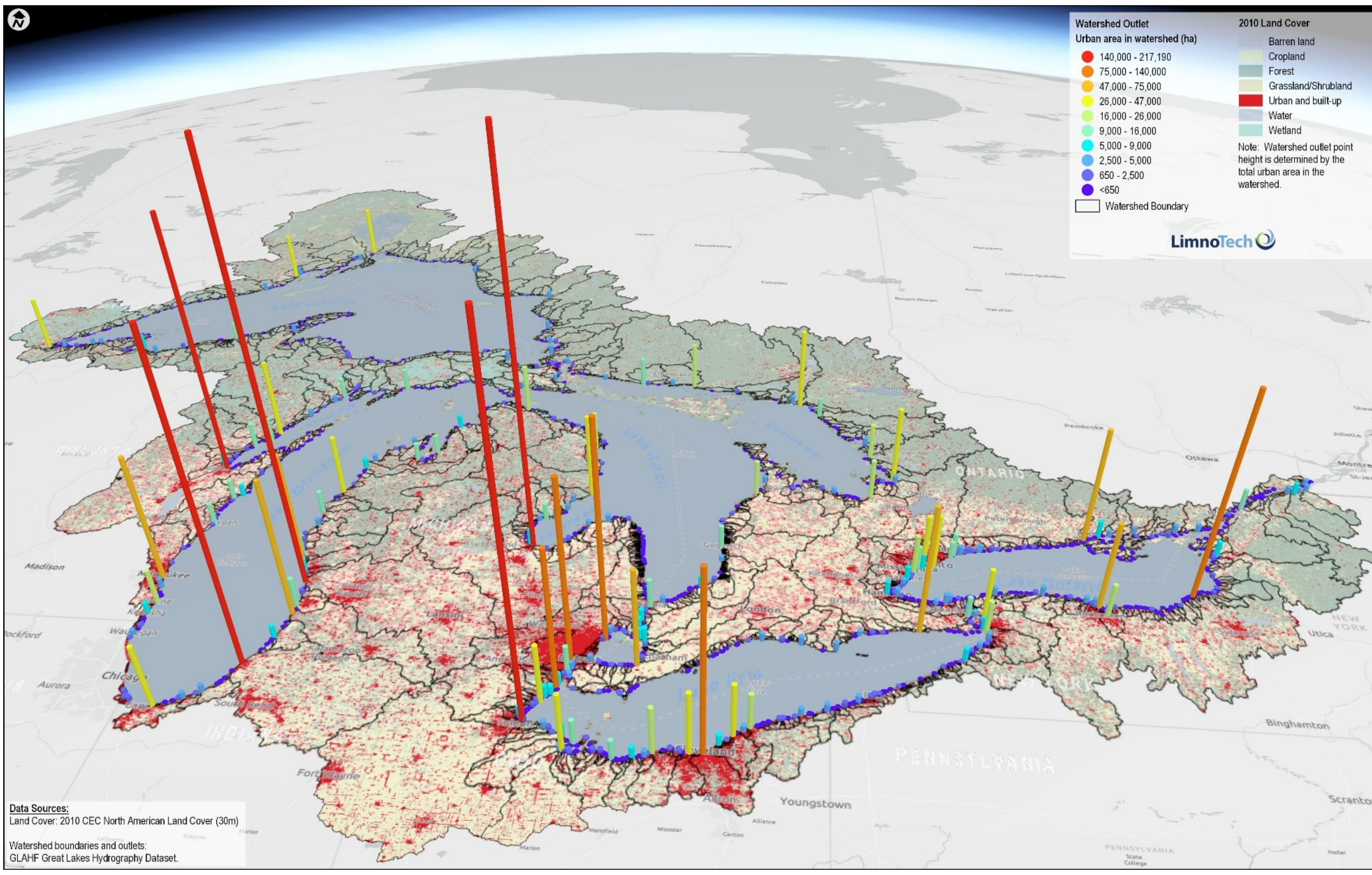

Figure 4-11: 2010 urban land use in the Great Lakes watershed. Data sourced from the Commission for Environmental Cooperation.

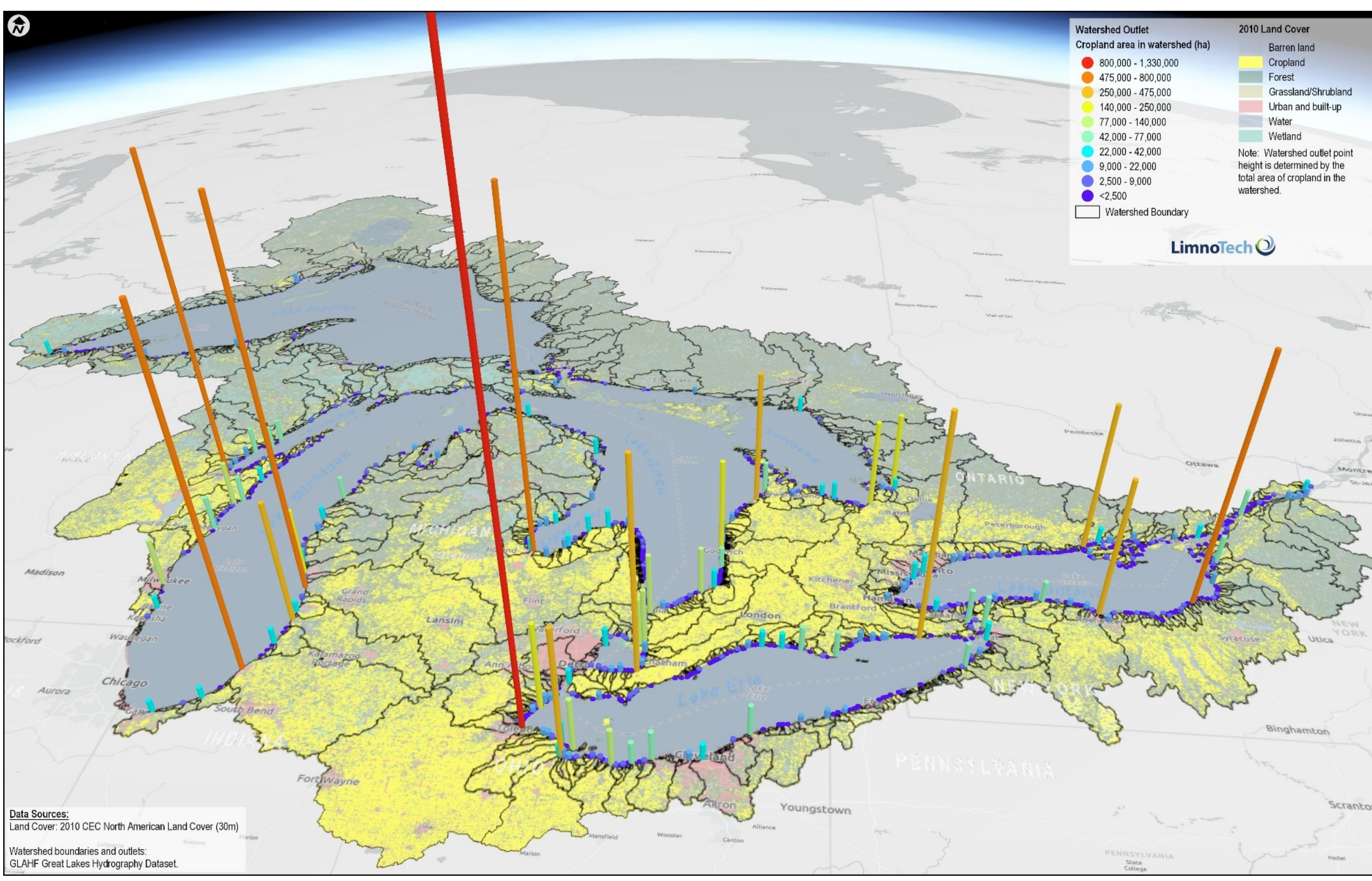

Figure 4-12: 2010 agricultural (cropland) land use in the Great Lakes watershed. Data sourced from the Commission for Environmental Cooperation.

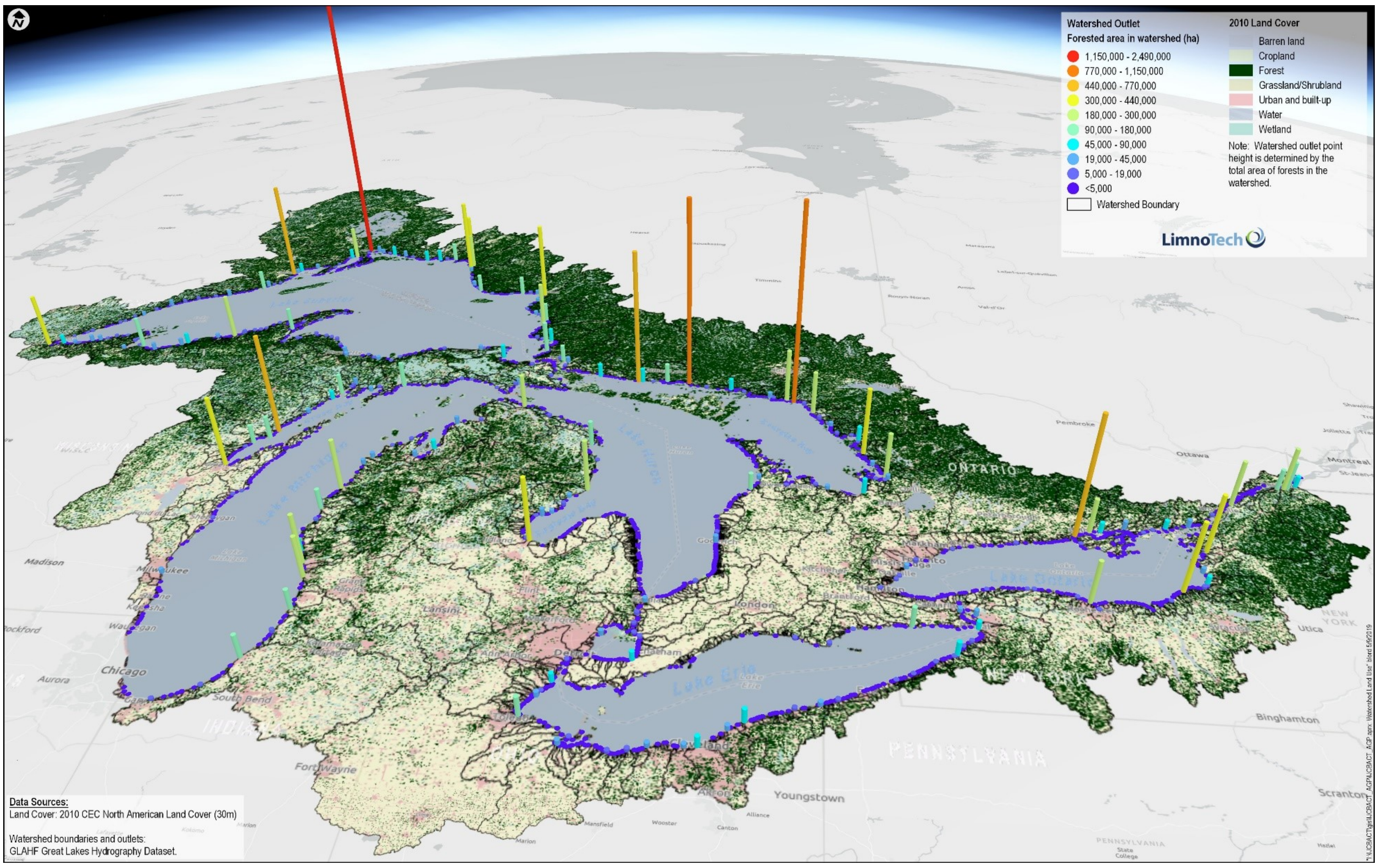

Figure 4-13: 2010 forested land use in the Great Lakes watershed. Data sourced from the Commission for Environmental Cooperation.

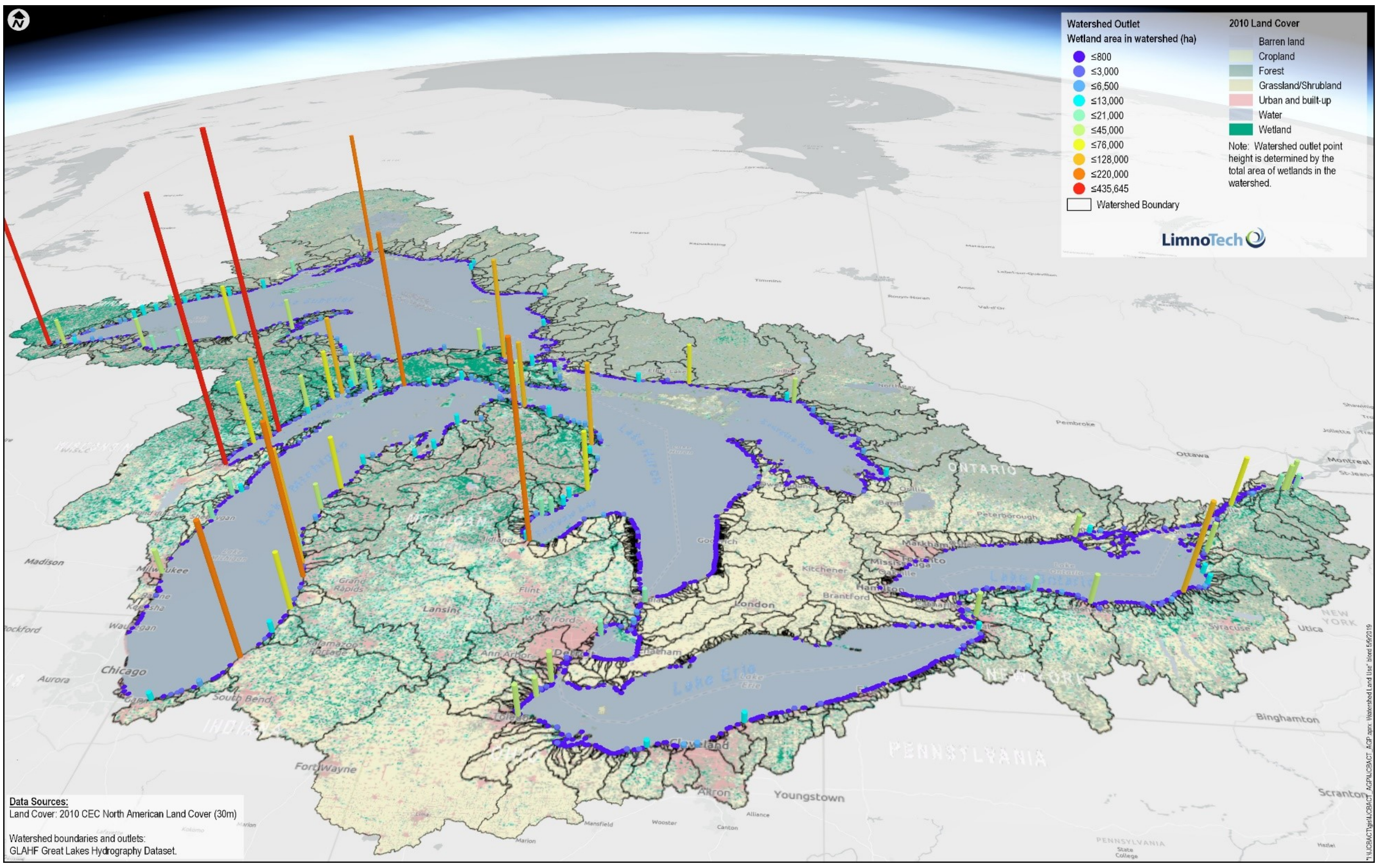

Figure 4-14: 2010 wetlands land use in the Great Lakes watershed. Data sourced from the Commission for Environmental Cooperation.

5.0 Implementing Management Strategies

By identifying sources/hosts and investigating pollution pathways for these sources, MST and other methods have led to better management of beaches in the Great Lakes.

Edge and colleagues (2018) used MST methods and surveillance techniques to identify sources of contamination at a beach in Toronto, Ontario, and determined the contamination originated from a combination of gulls, geese and wildlife. Subsequently, remediation actions were implemented to direct runoff away from beach water, and beach closing frequency improved from greater than 80 percent to less than 20 percent.

Nevers and colleagues (2018) found that the predominant source of *E. coli* at coastal beaches near Grand Calumet River in Lake Michigan were birds. Using a short-term management solution of using dogs to chase away the gulls (see below photograph), *E. coli* levels and beach closings dropped. Levels rebounded after the program stopped. Their point was that small-scale projects in AOCs can yield improvements while large-scale restoration efforts are conducted.

The photograph below is from an effort to reduce bacterial contamination at beaches in northwest Ohio, including Lake Erie and inland lakes. The leash requirement was changed to allow dogs to run off-leash to keep geese and gulls from contaminating the beach areas. This was piloted in early 2018. However, results regarding the effect of this rule change on water quality have not been published as of January 2021.

Using dogs to disrupt wild fowl congregation and shoreline defecation. Photo credit: Wide Open Pets, accessed at: wideopenpets.com/ohio-state-parks-requesting-dogs-to-keep-geese-off-beach/.

6.0 Expert Workshop Discussion and Recommendations

6.1 Overview

The IJC HPAB led a workshop of Great Lakes experts in public health, epidemiology and fecal bacteria water quality. The workshop was held at LimnoTech's Ann Arbor, Michigan office on May 21, 2019 from 8:30 a.m. to 5:00 p.m.

6.1.1 Objectives

The objectives for the workshop included:

- determine desirability and feasibility of conducting a basin-wide microbial pollution reassessment,
- identify locations and types of measurements that would be included in a basin-wide reassessment, and
- identify gaps in current knowledge about measures and sources of microbial pollution.

6.1.2 Agenda

The workshop began promptly at 8:30 and had three major components:

1. Morning:
    - introduction and context for the workshop by Joan Rose and Tom Edge, the US and Canadian leads for the Centennial Study from HPAB, respectively
    - presentation of project data and analyses

2. Afternoon: Small group breakout to discuss data gaps and develop a recommended scope for the next centennial study

3. Late afternoon: Reconvene as a large group to:

    - summarize outcomes, findings and recommendations
    - identify next steps

The workshop adjourned at 5:00 p.m.

6.1.3 Attendees

Attendees included public health managers, academic researchers, students, visiting professors and IJC staff. **Error! Reference source not found.** below lists the attendees and their affiliation. The workshop was facilitated by LimnoTech staff, including John Bratton, Carrie Turner and Jennifer Daley.

Table 6-1: Expert workshop attendees and their affiliations.

Name	Affiliation
Anne-Marie Abbey*	Ontario Ministry of the Environment, Conservation and Parks
Paul Allen	IJC
Jennifer Boehme	IJC
Shannon Briggs	Michigan Department of Environment, Great Lakes, and Energy
David Burden	IJC
Subbarao Chaganti*	University of Windsor
Erin Dreelin	Michigan State University
Tom Edge	McMaster University
Lisa Fogarty	US Geological Survey
Ryan Graydon	IJC
Marc Habash	University of Guelph
Natasha Isaacs	US Geological Survey
Molly Lane	Annis Water Resource Institute – Grand Valley State University
Phanikumar Mantha	Michigan State University
Bernard Mayer	Haliburton Kawartha Health Unit
Gertjan Medema	Michigan State University
Ryan Newton	University of Wisconsin-Milwaukee
Susan Peters	Michigan Department of Health and Human Services
Richard Rediskey	Annis Water Resource Institute – Grand Valley State University
Joan Rose	Michigan State University
Tami Sivy	Saginaw Valley State University
Craig Stow	National Oceanic and Atmospheric Administration Great Lakes Environmental Research Laboratory
Carmen Thiel	University of Wisconsin Oshkosh
Jan Thomas*	Ontario Ministry of the Environment, Conservation and Parks
Mark Weir*	Ohio State University
Richard Whitman	US Geological Survey (emeritus)

* Participated remotely by telephone

6.2 Discussion

The discussion among the workshop participants was spirited and expansive and is presented here in roughly chronological order in bulleted form from notes taken by the workshop facilitators.

6.2.1 Morning session discussion notes

Major points from the discussion of the project and data analyses included:

- Should we use the 1913 study as inspiration and to signify the value in a large-scale study? We need to ask, "What are the new key questions?" and figure out the new yardstick. Back then, they did not look at sources—it was a huge sewage problem.
- We have to realize that there has been major change since then, and comparing apples to oranges would not make sense, as we would have to understand trophic status, turbidity, hydrology etc. We cannot evaluate causation and trends without knowing other factors—chemical, biological etc.
- An example was that they looked at a beach in Windsor that they monitored for *E. coli* and MST markers. Often, even if the *E. coli* was not high, there were high pathogens. So, *E. coli* is not always a great indicator of health risk.
- Mainly, we need to know our new yardstick for pollution and risk—if not point sources, how to we design a study?
    - Risk Management study?
- Are we focusing on just beaches/recreation or also drinking water? Remember, the Milwaukee 1993 cryptosporidiosis outbreak and other recent human health events did happen—while in 1913, drinking water was major problem, it is still important today.
    - For example—after Milwaukee they extended intakes out into the lake, improved barriers etc.

6.2.2 Afternoon session discussion notes

<u>*Summary from each small group discussion:*</u>

Group 1:

- A binational health risk map would be beneficial, starting with sources/hazards:
    - Identify potential human sewage sources
    - Forecast capabilities based on population projections? Need to include existing data to forecast. EPA has beach attendance data, Canada–not sure
- Use sanitary surveys, MST methods and multiple items to identify priority areas
- Validate and harmonize MST methods
- Thoughts regarding next basin-wide survey:
    - Binational focus is important
    - Need something manageable—focus on connecting channels?

    - Basinwide survey would require IJC; no one else could do it. Benefit of basinwide survey would be to identify key exposure areas from data.
    - Formulate a study that could be communicated to the governments that would lead to recommendations and is something that the public can digest. Governments and the public are the stakeholders.
- Timeline:
    - Do human health risk map in the next three years while getting the labs on board for MST method harmonization.
    - Do source assessment with MST in the next six to nine years
    - Use this information for prevention and remediation and refining health risk maps.
- Gaps:
    - Epi data—in hot spots only? Hard to tease out waterborne pathway, lots of limits. (Could targeted monitoring be used for example using NORIS Armaturen Burkenstein GmbH & Co. KG automated systems that house various sensors and samplers etc.; N for beach exposures)
    - Swash zone (area where waves break onto the beach) sampling is needed—health risk gap
    - Connecting channels lack data
    - Go lake-by-lake due to differences between lakes

Group 2:

- Goal is identify and reduce risk for "DRINK SWIM FISH"
- Decadal assessments with focus on hot spots—use hydrodynamic models to inform monitoring strategies
- Discussion—determine persistence of different markers? Need a longer term six to nine-year outlook–evaluate technologies? Real-time monitoring at that point?

Group 3:

- Highlight success stories and identify gaps
    - USEPA is full of Great Lakes Restoration Initiative success stories
- Look at hot spots
- Federal agencies are under pressure to help states
- Tie to economic development:
    - Water is worth $1
    - Clean water is worth $3
- If we embark on basin scale, have a bank of samples and archive
- Where are qPCR labs?

Larger group discussion:

- Standardize methods? Risk map – suspected contributors – How do we connect maps with temporal component? Heat maps time and space?
- Tiered approach – can we get multiple groups involved? Who would partners be? Lake-specific to begin? Inclusion of regions near tribes/First Nations communities. Coordinate recommendations with a phased approach
- Compliance monitoring and/or diagnostics monitoring? Process monitoring to better understand system? Use models to inform where to monitor and vice versa.
- Do we have a mechanism to bring folks together? How do we get the right people talking?

General Notes from Recommendations made by each person.

- General support of heat mapping of at-risk areas – local people can look at remediation
- Also harmonizing MST methods
- Modelling and mapping – population density, predictions, exposure, livestock—can we describe processes in model?
- Can we use layers to enhance decisions? Overlay difference maps – more computational and geographic information system layers connecting everything together
- Validation studies
- Access to data
- Be clear about intent, for example, is this specifically recreational or drinking water? Both?
- Good idea to continue reviewing existing data and have a top-down approach to obtain the data. Also, would be great to have baseline risk maps and info to inform economics, stakeholders, policies, etc. Can we do spatial and temporal heat maps?
- What about taking on one lake first? E.g., Lake Huron
- Harmonizing and refining maps – IJC to define what this study might be?
- Binational validation MST study? Sample and archive, multi-level approaches?
- What about predicting what's coming ahead?
- Data repository?

6.2.3 Next steps

The next steps identified by the participants included:

- Defining a timeline for each of the recommendations in approximately 3-5-year time frames, and
- incorporating the recommendations into the IJC strategic planning process.

The workshop adjourned at 5:00 pm.

6.3 Workshop findings

After the small group breakout, the participants reconvened into a single group. A spokesperson from each group presented their group's discussion (summarized above). A round-robin approach was used to solicit specific findings, suggestions and/or recommendations, and to ensure everyone had an opportunity to express their opinion. These findings were compiled into overarching categories to serve as workshop findings.

6.3.1 Findings

The workshop findings fell into six major categories, with specific characteristics or additional considerations included as sub-bullets.

1. Mapping health risks and benefits: More comprehensive mapping across the lakes and transboundary is needed to better reflect the amount of study and monitoring being conducted in the Great Lakes.
    - Content that could be included:
        - health hazard risk
        - exposure
        - runoff
        - population
        - livestock density
    - Desired characteristics of a mapping tool(s)
        - Interactive
        - dynamic
        - include potential sources based on watershed characteristics and/or MST study results
        - display hot spots of high bacteria and/or pathogens (heat map?)
    - Uses of such a mapping tool:
        - public communication
        - inform modeling and monitoring
        - economics
        - policy development
        - additional study

2. Method validation and harmonization: A binational study would be more effective if the same MST methods were used throughout, aka 'harmonization,' and multiple methods were used for source/host identification, aka 'validation.'

3. Data and sample management needs include:
    - Central repository for all relevant data
    - May require a top-down approach to
        - mandate data sharing
        - define what methods to use and how to interpret
        - decisions about data
        - open and accessible

- Using sensor technology and/or other advancements in real time monitoring
- Banking samples for future use/analysis with improved methods
- Pair up with other measures (turbidity, chemical markers)
- Shorten the time between sampling and notification
- Support process-level understanding to develop better models: we need predictive tools to be ready for what is coming at us, not just tools for assessment of today.

4. Phased/tiered approach for addressing the next centennial study:
   - Process:
     - compile and review existing data (*E. coli,* MST, pathogens) and sanitary survey information
     - develop MST monitoring (source and mechanism, stakeholder engagement) strategy
     - sample to establish long-term trends
     - can the 1913 total coliform levels be related to gastrointestinal illness?
   - Geography options/priorities
     - lake-by-lake
     - connecting channels
     - areas of concern
     - Tribal/First Nations regions

5. Defined endpoints/intents
   - Characterize economic benefit – investment, blue accounting
   - Describe health benefits – recreation, drinking water, fishing, boating
   - Add predictive capabilities
   - Success stories on one or more of these endpoints

6. More collaboration needed:
   - meetings
   - listservs
   - federal agencies
   - federal coordination with states, states coordination with local entities

6.3.2 Recommendations

After the workshop, the findings from the workshop group discussion were rolled up by the HPAB leaders into the following recommendations:

- The IJC oversee a binational plan for a decadal study of fecal pollution and its sources across the Great Lakes basin.
- A binational committee of federal, provincial, and state agencies to coordinate the study potentially using the US Great Lakes Restoration Initiative, Canadian Great Lakes Protection Initiative or other means.
- A Decadal 'Centennial' Study framework and consortia to guide decisions on the study, data gathering, storing, sharing and applications of the data.

- A study to identify and diagnose hotspots of microbial pollution and health risks.
- Set up a Lake Huron basin case study of microbial pollution and its sources and outlets including the St. Clair River, Lake St. Clair and Detroit River corridor.
- Coordinate a validation study of microbial source tracking methods for human and animal fecal pollution sources across the basin, with the aim to binationally harmonize methods. Improved source information would be applied to updating the health risk maps in section 6.2.2.
- After Lake Huron, develop lake-by-lake maps of health risk (historical, current and future) using existing microbial source tracking data and sanitary survey information to identify known sources. Incorporate strong risk communication to support public information for these products.
- A large-scale longitudinal study for understanding microbial pollution processes to improve risk management decision making from watersheds to basin levels.

7.0 Discussion

The IJC study in 1913 highlighted the public health risk of untreated sanitary sewer discharges to the Great Lakes when these waterways were also used as drinking water sources with no additional treatment. Typhoid deaths were tallied as part of the study. Analytical methods were in their infancy, and the most specific measure of fecal coliform contamination was *B. coli*, or total coliform. The 1913 study had important geographic omissions, namely that sampling was not done in Lake Michigan and avoided several metropolitan areas, including Duluth, Minnesota, Cleveland, Ohio, and Hamilton and Toronto, Ontario.

Since the 1913 study, the Great Lakes watershed has changed in numerous ways:

- Since the IJC 1913 study, the total population reported for 21 cities within the watershed has increased to over 9,300,000 residents, with additional, significant population spread out over larger metropolitan areas;
- More livestock (over 200 million) are present and concentrated in fewer areas;
- Nonpoint sources of runoff have become a significant threat to water quality as sewer and septic system infrastructure has increased to support to increased suburban and population in outlying areas (urban sprawl). High failure rates of septic systems, stormwater runoff and combined sewer overflows are significant sources of *E. coli* transport from watersheds to the lakes;
- More infrastructure has been built but is need of repair and upgrades to support the growing population that includes wastewater treatment of sanitary sewage, treatment for drinking water supply and distribution, best management practices and other controls to reduce flooding;
- Better public health protection and water quality assessment through technology and regulation are available; and,
- Emergence of new threats to the Great Lakes, include for example harmful algal blooms, pharmaceuticals and climate change (Patz et al. 2008).

Over the last 100 years, sanitary sewage collection and treatment systems have greatly reduced the amount of raw sewage discharged into the lakes, though drinking water-related problems do occur. At the time of this report's publication, the HPAB is currently examining the link between waterborne acute gastrointestinal illness and climate and environmental risk factors by exploring these relationships in two American and two Canadian cities using Great Lakes as a drinking water source. Climate change is expected to impact several factors including changes in high intensity precipitation and flooding events that could be linked to gastrointestinal illness and other diseases and would impact existing drinking water treatment capacity, giving some urgency to assessing our capacity to detect and monitor this relationship. Understanding interactions of meteorological conditions and source-water quality with acute gastrointestinal illness incidence can support health protection recommendations that address the integrated ecology, but jurisdictionally-divided geography, of the Great Lakes. Such understanding also lays a foundation for coordinated testing and potential interventions to address vulnerabilities in drinking water systems.

In addition, many of the beaches in the Great Lakes still experience high fecal bacteria levels from time to time, and additional work is needed to improve public health from fecal-related exposures. There are ongoing monitoring for fecal pollution using current methods in both Canada and the United States. However, data accessibility for recreational monitoring remains a barrier to binational assessment of recreational waters, as noted by the results of the data inventory attempted for this report. Challenges to environmental and health data accessibility have been previously noted by the HPAB (Bassil et al. 2015; International Joint Commission Health Professionals Advisory Board 2013), and additional attention from both governments will be needed to address these challenges. There are now widespread concerns about fecal pollution sources such as combined sewer overflows, livestock operations and nonpoint sources such as stormwater runoff, septic systems, and gull and Canada geese droppings.

Enumeration methods for fecal bacteria are more specific and sensitive for fecal coliforms than the 1913 methods. Much research has been conducted relating fecal bacteria levels, specifically *E. coli* and enterococci, to gastrointestinal illness in freshwater recreational users. Today's technology also includes DNA-based analytical methods, or MST, that can help pinpoint fecal pollution sources (such as humans, cows, pets, birds, etc.) that are contributing to fecal bacteria contamination in the lakes and local waterways. These methods, that are still being refined, can be used in concert with other tools to then determine the pathways that deliver fecal pollution from these sources to the Great Lakes. With these tools in hand, it is possible to move from a reactionary mode of beach management to a proactive pollution prevention approach.

The potential exists for using MST methods in a sampling effort on the scale of the 1913 study to develop a binational understanding on reducing fecal pollution (e.g., bacteria, protozoa, viruses, etc.), improving water quality and more effectively addressing sources of fecal pollution like sewage, manure and waterfowl droppings to the Great Lakes, especially in fecal pollution hotspots that receive a high degree of public recreation In addition, such a study would document the changes and improvements to the Great Lakes in the last 100 years or so.

The workshop of Great Lakes experts in March 2019 examined the questions of the desirability and feasibility of conducting a basinwide microbial pollution reassessment, sought to identify locations and types of measurements that would be included in a basinwide reassessment, and identify gaps in current knowledge about measures and sources of microbial pollution. This workshop resulted in the following findings:

- A basinwide survey is feasible using new MST methods to better identify fecal pollution sources causing water quality impairments, and laboratory capacity on both sides of the border is sufficient.
- There is a need to address fecal pollution and MST monitoring gaps beyond Areas of Concern and include areas such as waters near indigenous lands.
- Extreme event-driven impacts and associated nonpoint source impacts from microbial pollution via stormwater should be better characterized for risk management.

- Moving forward, a reassessment should use fecal pollution and MST monitoring to evaluate the effectiveness of the numerous coastal restoration programs for remediating fecal pollution sources at the basin scale and develop health risk maps for select regions.

Our reassessment supports a large-scale, binational and longitudinal study for understanding microbial pollution processes to improve risk management decision making from watersheds to basin levels. The workshop produced the following recommendations for a path forward:

- The IJC oversee a binational plan for a decadal study of fecal pollution and its sources across the Great Lakes basin.
- A binational committee of federal, provincial, state and municipal agencies to coordinate the study potentially using the US Great Lakes Restoration Initiative, Canadian Great Lakes Protection Initiative or other means.
- A 'Spirit of 1913' Study framework and consortia to guide decisions on the study, data gathering, storing, sharing and applications of the data.
- A study to identify and diagnose hotspots of microbial pollution and health risks, including considerations of Tribes and First Nations communities.
- Pilot the concept with a Lake Huron basin case study of microbial pollution and its sources and outlets including the St. Clair River, Lake St. Clair and Detroit River corridor.
- Coordination of a validation study of MST methods for human and animal fecal pollution sources across the basin, with the aim to binationally harmonize methods. Improved source information would be applied to updating the health risk maps.
- After the Lake Huron pilot, develop lake-by-lake maps of health risk (historical, current, future) using existing microbial source tracking data and sanitary survey information to identify known sources. Incorporate strong risk communication to support public information for these products.

This effort would also provide a case study opportunity to examine needed processes to address ongoing challenges to binational data accessibility for recreational waters.

Concerns about the connection between sewage pollution and human disease triggered the IJC study of transboundary contamination across the Great Lakes in 1913, one of the largest-ever studies of its kind. Today, over 100 years later, the lakes are still used for drinking water and recreation, that have the potential to expose the users to unsafe bacteria levels, despite the advances in treatment technology and source control measures. There is a need to invest in sustaining recreational water quality and economic vitality in the Great Lakes, given expanding populations, aging infrastructure, and climate and land use changes.

8.0 Conclusions and Recommendation

The International Joint Commission (IJC) is responsible for regular reporting on the status of the Great Lakes and other boundary waters, as well as investigating the risk to ecosystems and human health that may result from current or future stressors. The Great Lakes are a dominant part of the physical and cultural heritage of North America. Shared by two countries and spanning a thousand miles across Canada and the United States, the shoreline is longer than the US East and Gulf coasts combined. The lakes also hold monumental environmental, cultural and economic value for both the region and our nations. First Nations and Tribes rely on native species, but habitats and ecosystems are changing with resulting effects impacting Indigenous peoples' access to resources for sustenance, support for ways of knowing and of life, and for their spiritual and other needs.

In 1913, the IJC conducted the first comprehensive, detailed monitoring study of the fecal-related pollution of the boundary waters of the Great Lakes and the potential link between disease and sewage pollution (International Joint Commission 1918). The 1913 study, that cost US$42,138 (at the time), to our knowledge is the largest fecal microbial water quality study in North America. The goals were to improve the understanding of bacteriological water quality across the basin and on how to address wastewater in the basin. The data from the study highlighted the public health risk of untreated sanitary sewer discharges to the Great Lakes when these waterways were also used as drinking water sources with no additional treatment. Typhoid deaths were tallied as part of the study. Analytical methods were in their infancy, and the most specific measure of fecal bacterial contamination was *Bacillus coli*, or what we now refer to as total coliform bacteria. The 1913 study also had important geographic omissions, namely that sampling was not done in Lake Michigan and near several important metropolitan areas, including: Duluth, Minnesota; Cleveland, Ohio; Hamilton, Ontario; and Toronto, Ontario.

Today, the Great Lakes basin still faces numerous water quality challenges. The lakes provide drinking water for an estimated 40 million in Canada and the United States (and water for food and beverage products for millions more). Modern drinking water treatment greatly reduces health risks for the majority, but the types and adequacy of protection may vary, and an unknown number may drink untreated lake water. Despite progress towards cleaner Great Lakes water over the last 100 years, public concern has arisen about increased incidence of nearshore sewage contamination and sources of releases (Environmental Commissioner of Ontario 2018; Great Lakes and St. Lawrence Collaborative 2020; Michigan Department of Environment, Great Lakes and Energy 2019; US Environmental Protection Agency 2016). Nearshore monitoring using modern tools such as microbial source tracking could inform management steps to address these issues. These tools advance applications of DNA technologies to allow identification of fecal pollution sources, that conventional tools based on *Escherichia coli* (*E. coli*) indicator bacteria cannot do.

Microbial source tracking advances have been particularly useful in improving the ability to detect sewage contamination. We also know that sewage contamination comes with concerns of other contaminants within the sewage, such as pharmaceuticals (Patz et al. 2008), antimicrobial-resistant microorganisms, microplastics, nutrients and toxic chemicals. Many sites along the shoreline require protection and restoration (including the Areas of Concern) and major investments in restoration have been made by federal, state and local governments, with the IJC and its Great Lakes Water Quality Agreement advisory boards continuing to lead the binational approach. Key questions have emerged as these restoration projects moved forward:

- Is nearshore water quality getting better or worse?
- Where is the pollution coming from?
- What are the public health risks associated with changing nearshore water quality?

This Health Professionals Advisory Board (HPAB) report addresses these questions by examining available data and literature on fecal contamination and fecal source identification, and proposes an updated binational centennial study to provide a framework for future efforts. The intent of the proposed framework is to help identify health risks and assist both countries prioritize cost-effective investment in improved restoration efforts associated with contaminated waters, increasing total maximum daily loads of contaminants, algal blooms, stormwater and wastewater treatment, and agricultural best management practices. The framework would also assist the binational Great Lakes community to move from a reactionary to preventive approach to beach and nearshore management.

Project goals for this investigation included:

i. Determine changes and trends in the concentration of fecal contaminants at the subset of sites of the 1913 study in the Great Lakes using available data, including consideration of Lake Michigan, that was not included in the original study but is anticipated for inclusion in a future synoptic reassessment survey.

ii. Based on literature describing current technologies (e.g., genomic indicators) and existing microbial source tracking data:

    a. Describe approaches for determining the contributions or relative levels of contamination from various sources—human fecal waste, agricultural animal fecal waste, domestic animals (pets) and wildlife (e.g., waterfowl)—at 20-40 sampling locations used in the 1913 study.

    b. Describe the public health risks for swimming and water consumption at these sites.

iii. Evaluate contemporary sampling and fecal source identification programs and data, including for Lake Michigan, to provide updated conclusions about the range, geographical origin and distribution of pollution from sources of human waste, and to identify fecal pollution hotspots around the Great Lakes.

The findings of the literature review indicate that since the 1913 study, the Great Lakes basin has changed in numerous ways:

1. Since the IJC 1913 study, the total population reported for 21 cities within the watershed has increased to over 9,300,000 residents, with additional, significant population spread out over larger metropolitan areas (Goal i).

2. More livestock (over 200 million) are present and concentrated in fewer areas (Goal i).

3. Nonpoint sources of runoff have become a more significant threat to water quality, as sewer, stormwater and septic system infrastructure has increased to support to increased suburban and population in outlying areas (urban sprawl). High failure rates of infrastructure such as sanitary sewer, stormwater and septic systems, as well as increased incidence combined sewer overflows (CSOs) are significant sources of fecal pollution transport to watersheds and the lakes. While CSOs continue, they will be addressed by rules that mandate fixes and will remain an intermittent problem due to climate change (Goal ii-a/Goal ii).

4. Better public health protection is becoming possible through advances in technologies such as microbial source tracking to attribute sources of fecal pollution and better target remedial actions (Goal ii-a).

5. Although infrastructure (including wastewater treatment, sanitary sewage and conveyance systems) was built to accommodate growing populations, upgrades and repairs are needed (Goal ii-b).

6. New threats to the Great Lakes emerged, including, for example, the spread of antimicrobial resistance, microplastics, nanomaterials and new pathogens in fecal pollution sources, harmful algal blooms, pharmaceuticals and climate change (Patz et al. 2008) (Goal ii-b).

7. It is possible to map fecal pollution hotspots and a future study should obtain the key data to support that analysis (Goal iii).

Today, over 100 years later, the lakes are more widely used for drinking water and recreation, increasing the potential to expose users to unsafe bacteria levels and waterborne pathogens, despite the advances in drinking water treatment technology and source control measures. However, we anticipate growing challenges because water recreational demands are increasing, there are more immune-compromised people vulnerable to waterborne pathogens, wastewater infrastructure is aging, agricultural and husbandry practices are changing, sewage releases are increasing, and extreme rain events and other manifestations of climate change are increasing.

To set the stage for another 100 years of action to support water quality in the Great Lakes, the **HPAB recommends that the IJC oversee a binational multiphase project addressing water quality across the Great Lakes basin over a five-year timeframe. The first phase of this project would be to establish a committee of federal, tribal, First Nations and the Métis Nation of Ontario, provincial, state and municipal agencies to oversee and coordinate a multiyear study of fecal pollution and its sources.**

The key goal during the first phase is to establish the committee to oversee the study design and review the public health applications of advances in DNA and other molecular and genomic technologies for assessing water quality in the Great Lakes. This includes microbial source tracking to evaluate the effectiveness of coastal restoration programs for identifying and remediating fecal pollution sources at the basin scale (including across international boundaries) as well as more locally and develop lake-by-lake health risk maps for assessing and protecting public health. The HPAB proposes that the structure of the committee would be similar to the Great Lakes-St. Lawrence River Adaptive Management Committee,[1] and would be overseen by the IJC. Subject matters experts for such a committee would include members provided by the governments of Canada and the United States ("the Parties"), rights holders and stakeholders in the basin, leadership of tribes, First Nations, and the Métis Nation of Ontario and/or their designee, and participants from provincial and state government agencies where many of the water quality monitoring capacity and responsibility exists.

There is a need to invest in sustaining source water for drinking, recreational water quality and economic vitality in the Great Lakes, given expanding human and livestock populations, aging infrastructure and climate and land use changes. A second phase of this work will be advanced, in collaboration with the IJC Great Lakes Water Quality Board to establish a binational surveillance network with key laboratories in the basin and move through a pilot microbial source tracking methods validation exercise project to harmonize applications of the methods across the basin. This project would include a subset of labs that would seek to harmonize molecular methods for surveillance of the SARS-CoV-2 virus at selected sewage treatment plants across the basin. A third project phase would be for the laboratory network to roll out a multiyear basinwide microbial source tracking study to identify fecal pollution sources and develop lake-by-lake health risk maps. A final phase would synthesize and communicate results and recommendations regarding fecal pollution sources and health risks to the Parties and stakeholders across the basin.

[1] For information about the IJC's Great Lakes-St. Lawrence River Adaptive Management Committee, visit ijc.org/en/glam.

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