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National Capital Region

Canadian Science Advisory Secretariat
Science Advisory Report 2024/008

NATIONAL AQUATIC INVASIVE SPECIES (AIS) RISK ASSESSMENT FOR ZEBRA MUSSEL (*DREISSENA POLYMORPHA*) AND QUAGGA MUSSEL (*DREISSENA ROSTRIFORMIS BUGENSIS*), APRIL 2022

Figure 1A. Distribution (1986-2021) of Zebra Mussel in North America (Wilcox et al. 2024)

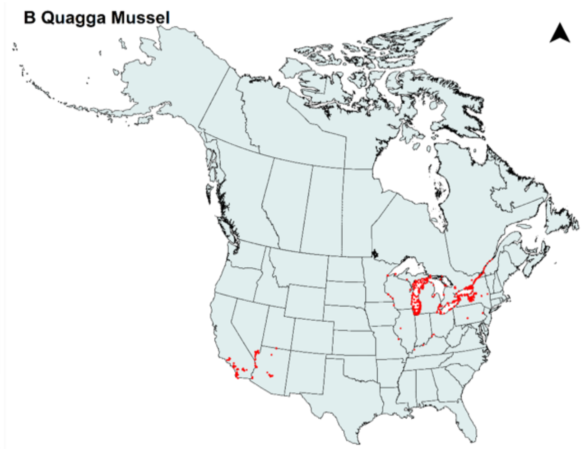

Figure 1B. Distribution (1989-2021) of Quagga Mussel in North America (Wilcox et al. 2024)

Context:

*Invasive species are important drivers of ecosystem change and threaten ecosystems globally. In freshwater ecosystems, two prominent dreissenid mussel species, Zebra Mussel (*Dreissena polymorpha*) and Quagga Mussel (*Dreissena rostriformis bugensis*), both native to the Ponto-Caspian region, have a long history of causing significant ecological and economic impacts in Europe and North America. Given the potential for these non-indigenous species to cause severe negative impacts on food webs and nutrient processing, an ecological risk assessment for these species was conducted in 2012 for freshwater ecosystems with an emphasis on the western Canadian provinces, Ontario, and Quebec (Therriault et al. 2013). Since then, dreissenid mussels have continued to expand their distribution in Canada. For example, Zebra Mussels were discovered in Lake Winnipeg in 2013 and subsequently spread into connected and adjacent waterbodies. Similarly, in 2017, Zebra Mussels were first reported in Lake Memphremagog, Quebec, confirming spread further eastward. Also, in early 2021, Zebra Mussel individuals were found in moss ball products associated with the aquarium trade across Canada increasing the potential for spread.*

Given the potential for these non-indigenous species to have substantial negative impacts on Canadian freshwater ecosystems as well as continued spread throughout Canada, Fisheries and Oceans Canada's (DFO) Aquatic Invasive Species Core Program requested DFO Science to update the 2012 ecological risk assessment. The new ecological risk assessment identifies freshwater watersheds at higher risk of invasion by Zebra and Quagga Mussels in Canada by expanding the coverage to all freshwater ecosystems across Canada and including newly available environmental and species distribution data. The new risk assessment provides science-based guidance to resource managers to inform management decisions and actions including early detection, response planning, and/or *regulatory and policy measures aimed at mitigating the potential spread and risk posed by Zebra and Quagga Mussels to Canadian freshwater ecosystems.*

This Science Advisory Report is from the National Peer Review of April 4 to 7, 2022 on the National Aquatic Invasive Species (AIS) Risk Assessment for Zebra and Quagga Mussels, 2022 Update. Additional publications from this meeting will be posted on the [Fisheries and Oceans Canada (DFO) Science Advisory Schedule](#) as they become available.

SUMMARY

- Since being introduced into the Laurentian Great Lakes region in the 1980s, Zebra (*Dreissena polymorpha*) and Quagga (*Dreissena rostriformis bugensis*) Mussels have spread throughout North America and have had significant ecological impacts to freshwater ecosystems. In Canada, Zebra Mussels have subsequently spread to certain waterbodies in Manitoba and southern Quebec, while Quagga Mussels have only spread within the Laurentian Great Lakes region.
- Compared to the 2012 risk assessment, this new assessment was conducted at a higher spatial resolution. It included all provinces and territories, new and updated environmental data and species occurrence information, and two different habitat suitability models. The ecological risk for both Zebra and Quagga Mussels was assessed by integrating metrics related to introduction, establishment, and ecological impact.
- This new assessment did not evaluate the risk to individual waterbodies. Rather, it provided an ecological risk assessment at 9,260 m x 9,260 m grid cell resolution across Canada. As a result, risk and impacts may differ at smaller spatial scales where conditions may be more or less favourable.
- Introduction was assessed based on a proxy of human activity (Human Footprint Index) and proximity to invaded waterbodies (connectivity metric).
- Establishment was assessed using two modeling approaches to characterize habitat suitability (Calcium-based model and MaxEnt-based model).
- Since Zebra and Quagga Mussel have significant and well documented negative ecological impacts, the impact to Canadian freshwater aquatic ecosystems was determined to be very high.
- For both Zebra and Quagga Mussel, all provinces and territories contain watersheds that have Moderate or High Ecological Risk. Higher ecological risk areas are distributed along the southern reaches of Canada ranging from Nova Scotia to southern Alberta and British Columbia.
- The ecological risk presented here represents current conditions. As Zebra and Quagga Mussel invasions continue and environmental drivers change, the risk to Canadian freshwater aquatic ecosystems may change and will need to be reassessed.
- Data limitations resulted in a number of uncertainties related to the characterisation of risk in this assessment. Improved and expanded geospatial data (e.g., environmental, species, and introduction vectors) will improve future risk assessments.

INTRODUCTION

In freshwater ecosystems, Zebra Mussel (*Dreissena polymorpha*) and Quagga Mussel (*D. rostriformis bugensis*) have caused significant ecological and economic impacts in Europe and

North America (Mackie and Claudi 2010, van der Velde et al. 2010). These mussels can negatively impact water quality and all major trophic levels and can spread by natural dispersal or human-mediated activities.

In 2012, DFO Science conducted an ecological risk assessment for three dreissenid mussel species in Canadian freshwater ecosystems that identified several high risk areas but did not fully assess the risk to sub-drainages in the Maritimes, Newfoundland and Labrador, and the Canadian Arctic (DFO 2013). Since 2012, Zebra and Quagga Mussels have continued to expand their distribution in Canada (Figure 1) necessitating a new assessment. This new risk assessment not only incorporates the expanded distribution of these species but also extends the geographic scope to include all freshwater ecosystems in Canada, including all provinces and territories. It was conducted at a higher spatial resolution (grid cells of 9,260 x 9,260 m), included additional environmental variables such as calcium concentrations and pH interpolated across Canada, and used two habitat suitability modelling approaches (a calcium-based model and MaxEnt-based model). This assessment, which includes both the likelihood and consequences of an invasion (i.e., expected impacts), identifies freshwater watersheds at higher ecological risk using new data and approaches to assess risk to improve managements' ability to inform, prevent, prioritize, and respond to dreissenid invasions in Canada.

It is important to note that while certain areas may be considered low risk, this does not mean no risk as both species have demonstrated the ability to be transported long distances and to remote locations and have very high ecological impacts in invaded systems. Further, to facilitate various decision-making processes, results are conveyed in different formats. Specifically, this assessment uses two different habitat models (for each species, presented both at the high resolution grid cell level and summarized at the sub-drainage basin using two metrics (the greatest Ecological Risk value for any area within the sub-drainage [Maximum] and the most common Ecological Risk value within the sub-drainage [Mode]). Depending on the specific decision and risk tolerance, the information in this assessment can be used to inform management actions, including early detection, response planning, and/or regulatory and policy measures aimed at mitigating potential risk posed by invasive Zebra and Quagga Mussel to Canadian freshwater ecosystems.

ASSESSMENT

In general, risk represents the product of the probability of an event occurring and the consequences of that event. In this assessment, Ecological Risk for Zebra and Quagga Mussel represents the likelihood of an invasion occurring and the consequences or expected impacts of that invasion for each spatial unit (grid cell) over an approximate period of about five to ten years (representing current climatic conditions). The likelihood of invasion represents the sequential steps in the invasion process where an organism must be entrained in an invasion vector, moved by that vector to a new location, survive transit, be released from the vector into a new ecosystem, encounter conditions amenable for survival and reproduction, and then spread from the initial introduction point. As such invasions are complex with many unknowns and uncertainties such that true probabilities around this sequence of events leading to a successful invasion are not known.

2012 DFO Risk Assessment Compared to a new 2022 DFO Risk Assessment

In 2012, DFO conducted an ecological risk assessment of three non-indigenous dreissenid mussels (Therriault et al. 2013) considering probabilities of survival (habitat suitability) and arrival at the Canadian sub-drainage scale. Compared to the 2012 risk assessment (Therriault et al. 2013), this new assessment was conducted at a higher spatial resolution (grid cells of

9260 x 9260 m) and included additional environmental variables such as updated calcium concentrations and pH interpolated across Canada (Wilcox et al. 2024). For modelling purposes, the extent of the study area included Canada and the continental United States. Additionally, this assessment excluded Dark False Mussel (*Mytilopsis leucophaeata*), a coastal marine or estuarine species included in the previous risk assessment.

It is important to note that results of this assessment are not directly comparable to the 2012 assessment as they are based on updated data and different modelling approaches. Further, there are differences in how certain components of invasion risk were determined. For example, in the 2012 assessment, connectivity as part of the estimation of potential propagule pressure was modelled as a simple function of whether a sub-drainage was adjacent to an invaded sub-drainage whereas here, connectivity was modelled as a geospatial function (see below) of proximity to invaded areas but does not explicitly incorporate connectivity of downstream flow from invaded lakes. Also, habitat suitability was modelled here using two different approaches (a calcium-based model and MaxEnt-based model) with each a refinement over the original assessment.

There were also some differences with respect to terminology. Since the true probabilities for each step in the invasion process that leads to successful establishment is unknown, proxies were used for these probabilities using available variables known to be related to invasion risk. While different proxies and data were used between the two assessments, ecological risk still represents the product of the potential for invasion and ecological impacts expected from an invasion. Further, low risk this does not mean no risk as both species have dispersed over great distances and demonstrated very high ecological impacts in invaded systems.

Risk Assessment Methodology

An ecological risk assessment was conducted to determine the risk posed by Zebra and Quagga Mussel to Canadian freshwaters. A summary of the data products are available in Wilcox et al. 2024 and can be downloaded from the Open Government data portal.

This risk assessment considered the probabilities of introduction (propagule pressure), establishment (habitat suitability), and ecological impacts to derive a metric of Ecological Risk for these two species. Areas that are currently invaded do not automatically translate to high risk in any risk assessment approach. Invasions are complex and can succeed even when the potential for introduction, establishment, or spread is lower, which could result in a lower overall risk score. The Ecological Risk posed by these species was assessed using two separate modelling approaches for establishment based on calcium concentrations and a Maximum Entropy-based (MaxEnt) habitat suitability model (Figure 2). Both models have different constraints and benefits and thus both were used as it is not possible to identify a “preferred” model given both Zebra and Quagga Mussel invasions are ongoing. Also, both species currently occupy areas that would be identified as Moderate or High Ecological Risk.

For both models, the Potential for Establishment was integrated with the Potential for Introduction to obtain the Potential for Invasion which was then combined with the Potential for Ecological Impacts using a heat matrix to determine the overall Ecological Risk which ranges from Low to High. A temperature threshold was applied to those parts of Canada that were considered too cold to support larval development in Zebra and Quagga Mussel populations. For more details regarding the methodology and results as well as the species specific intermediate data products (e.g., Calcium-based and MaxEnt-based suitability layers) see Wilcox et al. 2024.

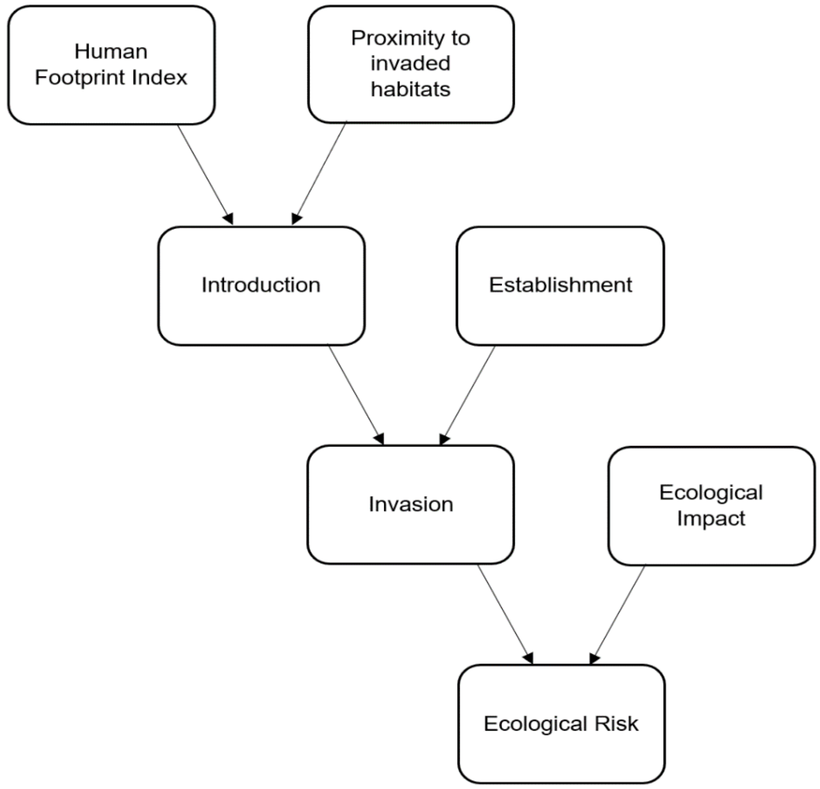

Figure 2. Conceptual flow diagram of the risk assessment process for Zebra and Quagga Mussel invasion into Canadian freshwaters. Two modelling approaches were used to determine suitable habitats for establishment: a calcium-based model and a MaxEnt-based model.

Potential for Introduction

For Zebra and Quagga Mussel to pose a risk to a Canadian ecosystem they first must be introduced to that system. The Potential for Introduction is related to both the ability of propagules to be moved from a source population and the proximity of that population (as both likelihood and survival is greatest over shorter distances). The primary vector for introduction of Zebra and Quagga Mussels is through human activities (e.g., movement of watercraft) with natural dispersal (e.g., downstream movement of larvae) contributing to the introduction. A metric of connectivity was developed based on the distance from the currently known distribution for each species and then scaled to reflect recreational boater activity (see Wilcox et al. 2024). This metric was then integrated with the Human Footprint Index (Venter et al. 2018) which is a relative index based on human population and activity as a means of accounting for geographic variability in the magnitude of boating activity (or other human-mediated movements). Maps of propagule pressure (Human Footprint Index) and proximity to invaded habitats (Connectivity Metric) for Zebra and Quagga Mussel are presented in Wilcox et al. 2024.

Zebra Mussel

The Potential for Introduction to Canadian freshwater ecosystems by Zebra Mussel is greatest in areas that are both proximate to the current known locations of Zebra Mussel and to more heavily populated areas in Canada. The areas with the highest Potential for Introduction include southern Ontario, Quebec, and south and central Manitoba where Zebra Mussel is known to have invaded. Saskatchewan and New Brunswick also show higher Potential for Introduction due to the proximity to invaded locations. Newfoundland and Labrador, northern British

Columbia, as well as Yukon and Northwest Territories show lower Potential for Introduction due to their distance from invaded systems.

Quagga Mussel

The Potential for Introduction to Canadian freshwater ecosystems by Quagga Mussel is greatest in southern Ontario and Quebec where they have invaded the Laurentian-Great Lakes system. Higher Potential for Introduction areas include parts of New Brunswick and Manitoba, as well as southern areas of Saskatchewan and Alberta. The Northwest Territories, Yukon, British Columbia, and northern areas of the Prairie provinces show lower Potential for Introduction due to their increased distance from currently known invaded systems.

Potential for Establishment

Generally, invasive species establish in ecosystems that are conducive to their survival and reproduction. In the case of Zebra and Quagga Mussels, calcium concentrations are a good indicator of Potential for Establishment (habitat suitability) given the requirement of dissolved calcium for shell development and growth (Whittier et al. 2008, Therriault et al. 2013) but other variables can be important as well. One method to incorporate additional variables is habitat suitability modelling that uses a suite of environmental variables in conjunction with the distribution of the species to determine the relative importance of those environmental variables to the current distribution and uses this relationship to predict habitat suitability across a landscape.

There are advantages and disadvantages to both modelling approaches. Habitat suitability modelling incorporates a range of environmental variables that influence the distribution of these invasive mussel species. However, it is based on the current known distribution and likely does not represent the full suite of suitable habitats that these mussels could invade. The calcium-based modelling approach uses only one environmental variable to determine Potential for Establishment but it is not constrained by whether the current distribution fully represents the suitable habitats that these mussels could invade. For this reason, both modelling approaches were used in this risk assessment. Maps of the Potential for Establishment of Zebra and Quagga Mussel based on both models (calcium-based and MaxEnt-based) are presented in Wilcox et al. 2024.

Temperature Threshold

The temperature thresholds applied to both habitat suitability models were set at 10°C for Zebra Mussel (Pollux et al. 2010) and 5°C for Quagga Mussel (Peyer et al. 2010), recognizing that Quagga Mussel is better adapted to living in deeper, cooler waters. Because water temperatures were unavailable at the national scale, air temperatures were used as a proxy for water temperature as these are assumed to be correlated (Stefan and Preud'homme 1993). Areas were denoted as below the temperature threshold if the mean temperature of the warmest quarter (BioClim 10) was lower than the species specific temperature threshold. Values for such areas were set to 0 for the Potential for Establishment in both modeling approaches.

Calcium-based Model

Zebra Mussel

For Zebra Mussel, the concentration of calcium across most of Canada is highly suitable (30 mg/L) for establishment. After accounting for areas with temperatures below the thermal threshold, areas of highly suitable habitat (Potential for Establishment) include western

Northwest Territories, Yukon, northern and central British Columbia, Alberta, as well as southern and central portions of Saskatchewan and Manitoba, southern Ontario, the Laurentian-Great Lakes and south of the St. Lawrence River in Quebec. The remainder of Canada, especially on the Canadian Shield, has lower suitability with some small patches of higher suitability through northern Ontario and the Maritime Provinces.

Quagga Mussel

For Quagga Mussel, the concentration of calcium across much of Canada is highly suitable (30 mg/L) for establishment. After accounting for areas with temperatures below the thermal threshold, areas of high suitability (Potential for Establishment) include Yukon, western Northwest Territories, northern and central British Columbia, Alberta, southern and central portions of Saskatchewan and Manitoba, as well as much of southern Ontario, the Laurentian-Great Lakes and south of the St. Lawrence River in Quebec. The other parts of Canada have lower habitat suitability, with the exception of small areas in northern Ontario and the Maritime Provinces which have higher suitability.

MaxEnt-based Model

Zebra Mussel

The MaxEnt-based model for Zebra Mussel provides a more restricted geographic area of highly suitable habitat (Potential for Establishment) compared to that of the calcium-based model and corresponds with the environmental conditions currently experienced by Zebra Mussels in its current known distribution within North America. As a result, the areas of highest suitability are located in the Laurentian-Great Lakes, southern Ontario, and Lake Winnipeg, which corresponds to the current distribution of the species in Canada. Other areas with patches of higher suitability include southeastern British Columbia, south of the St. Lawrence River in Quebec as well as the Maritime provinces, particularly New Brunswick. The rest of Canada shows lower habitat suitability.

Quagga Mussel

The MaxEnt-based model for Quagga Mussel provides a more restricted geographic area of highly suitable habitat (Potential for Establishment) compared to that of the calcium-based model and corresponds with the environmental conditions currently experienced by Quagga Mussel in its currently known distribution within North America. The areas of highest suitability in Canada are located in the Laurentian-Great Lakes and southern Ontario. Areas with patches of higher suitability include the Okanagan Valley in southern British Columbia and most of southern Alberta. The rest of Canada shows lower habitat suitability.

Potential for Invasion

The Potential for Invasion was determined based on the product of the Potential for Introduction and Potential for Establishment with both given equal weighting as the relative importance of each of these components are unknown. These conditional calculations were made for both the calcium-based and MaxEnt-based models with maps available in Wilcox et al. 2024.

Calcium-based Model

Zebra Mussel

The areas of highest Potential for Invasion include the southern and central portions of the Prairie provinces (including the Nelson River in Manitoba) as well as southeastern Ontario and south of the St. Lawrence River in Quebec along with some areas in northern Ontario and the

Maritime provinces. Areas of lower Potential for Invasion include Yukon, Northwest Territories and the remainder of Western Canada.

Quagga Mussel

Similar to Zebra Mussel, the Potential for Invasion for Quagga Mussel using the calcium-based modelling approach was also heavily influenced by the Potential for Establishment. The areas of highest Potential for Invasion include southeastern Ontario, southern and central portions of the Prairie provinces, south of the St. Lawrence River in Quebec, and several discrete areas in the Maritime provinces.

MaxEnt-based Habitat Suitability Model

Zebra Mussel

The Potential for Invasion for Zebra Mussel using the MaxEnt-based modelling approach generally mirrors the current known distribution of Zebra Mussel. As a result, areas with the highest predicted values for Potential for Invasion include the Laurentian-Great Lakes system, southern Ontario, the Lake Winnipeg area as well as south of the St. Lawrence River in Quebec and New Brunswick.

Quagga Mussel

Similar to Zebra Mussel, the Potential for Invasion for Quagga Mussel using the MaxEnt-based modelling approach generally mirrors the current known distribution of the species. As a result, areas with the highest Potential for Invasion were around the Laurentian-Great Lakes system and southern Ontario. The Potential for Invasion in the rest of Canada was predicted to be lower.

Potential for Ecological Impacts

To ensure consistency across models and species with respect to the criteria for determining expected ecological impacts, the approach of Therriault et al. (2013) modified from Therriault and Herborg (2008) was adopted. This approach identifies five categories for each impact, ranging from Very Low to Very High (Wilcox et al. 2024). Currently, there are no established metrics for either species that are available at the scale or resolution required to differentiate the geographic variability in ecological impacts. Given that Zebra and Quagga Mussel invasions have well-documented negative ecological impacts on the freshwater systems they are introduced to, the ecological impact for this risk assessment is expected to be Very High across Canada. The uncertainty is expected to be very low given that these impacts have been well documented in both North America and Europe.

Potential for Ecological Risk

The Ecological Risk posed by these invasive species was determined by combining the Potential for Ecological Impacts and Potential for Invasion for each modelling approach using a heat matrix. Ecological Risk for Zebra and Quagga Mussel are presented at the 9,260 m x 9,260 m grid cell resolution in Figures 3-6, while Ecological Risk by sub-drainage (Mode and Maximum) are presented in Appendices A and B. Detailed maps of Ecological Risk at regional extents using the grid cell resolution are presented in Wilcox et al. (2024). Given that Ecological Impacts are Very High across all of Canada the final determination of Ecological Risk represents differences in the Potential for Invasion. Thus, Low Risk areas have a lower Potential for Invasion than High Risk ones but this does not mean Zebra or Quagga Mussels would have less impacts should they invade.

Calcium-Based Model

Zebra Mussel

Using the calcium-based model, areas of High Ecological Risk for Zebra Mussel include the Laurentian-Great Lakes system and areas around Lake Winnipeg (Manitoba), which corresponds with the current known distribution of this species (Figure 3). Outside the current known distribution, some discrete areas of High Ecological Risk in New Brunswick , Saskatchewan and Alberta were predicted. The Provinces of Ontario, Alberta, Saskatchewan, Manitoba, Prince Edward Island, and New Brunswick showed predominately more Moderate Ecological Risk. There are also large areas of Moderate Ecological Risk in Quebec, British Columbia, and the Northwest Territories. The Northwest Territories, Nunavut, Labrador, northern regions of Quebec and mountainous areas in the Western provinces are below the temperature threshold and likely Very Low Ecological Risk.

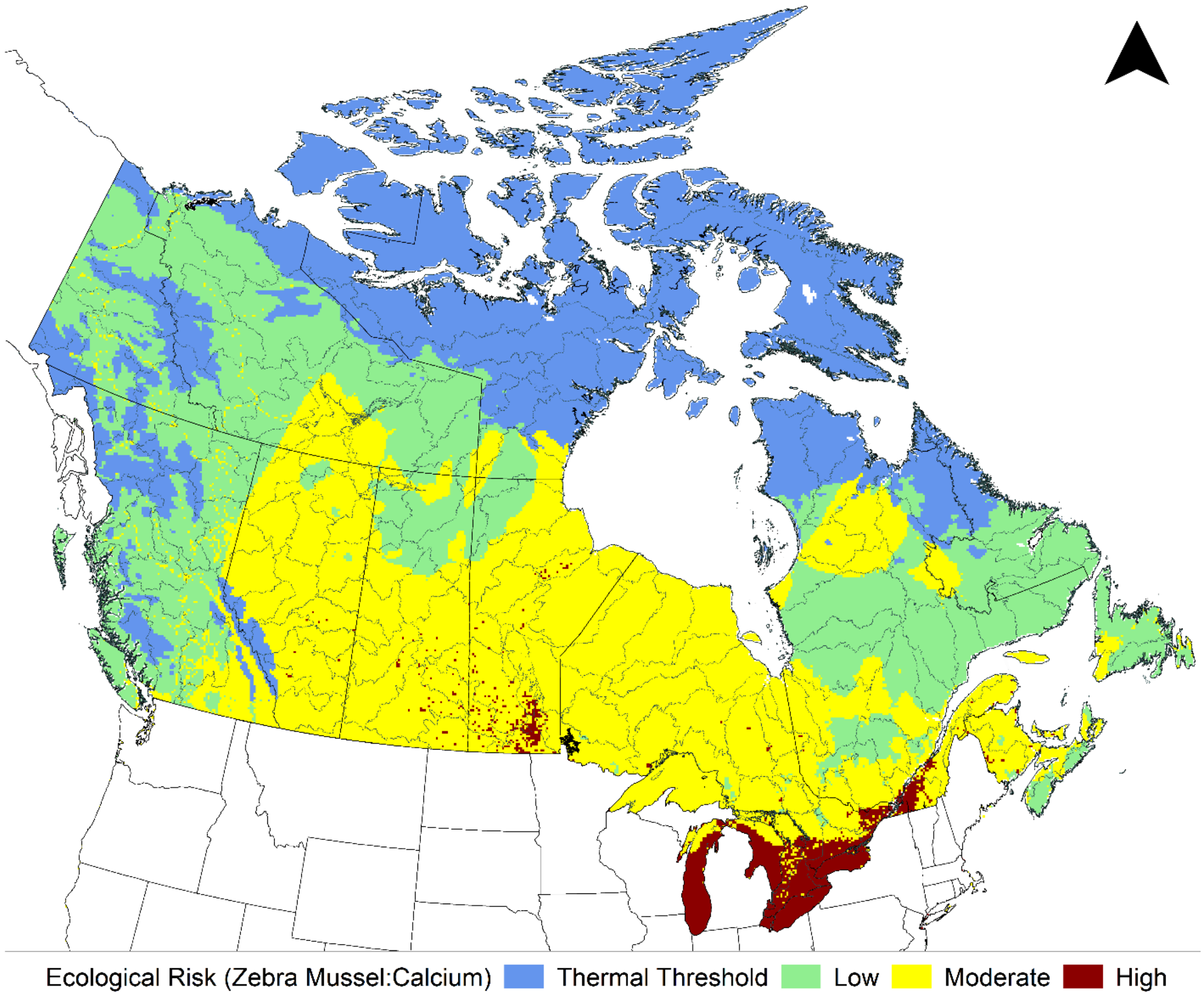

Figure 3. Zebra Mussel Ecological Risk in Canada using the calcium-based model. Risk is based on the Potential for Invasion and Ecological Impacts. Given that Ecological Impacts are Very High across all of Canada the final determination of Ecological Risk represents differences in the Potential for Invasion.

Quagga Mussel

Using the calcium-based model, the Ecological Risk for Quagga Mussel across Canada is generally Low (Figure 4). High Ecological Risk areas are located in the Laurentian-Great Lakes system corresponding to the current known distribution of the species. There was also discrete areas of High Risk in New Brunswick and Manitoba, particularly around Lake Winnipeg. Areas of Moderate Ecological Risk can be found in most of Ontario, southern and central Manitoba through the Nelson River, southern Alberta and Saskatchewan, south of the St. Lawrence Estuary in Quebec, as well as the Maritime provinces, particularly New Brunswick and Prince Edward Island. Unlike Zebra Mussel, areas of Very Low risk due to the temperature threshold are generally restricted to the Arctic Archipelago.

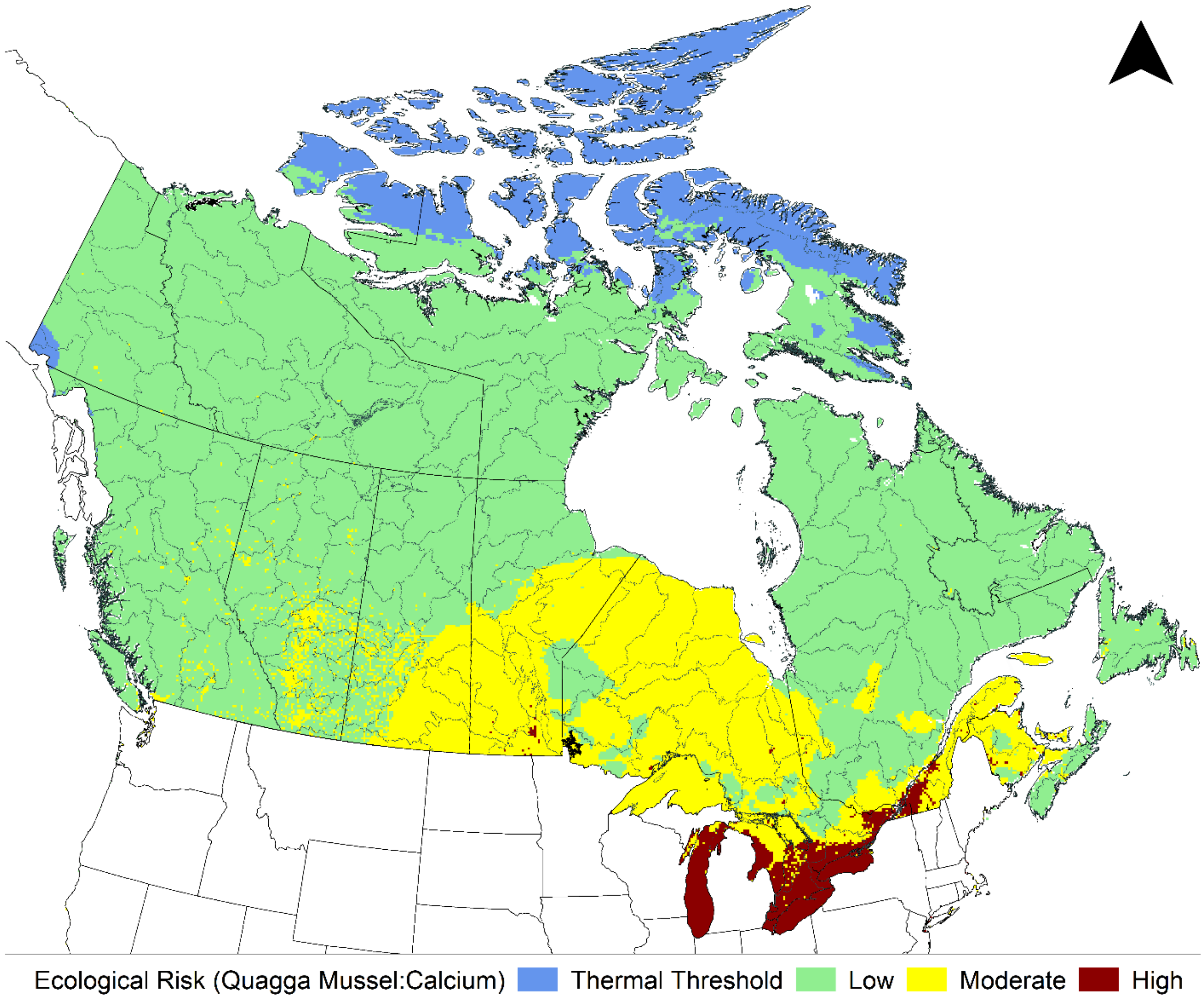

Figure 4. Quagga Mussel Ecological Risk in Canada using the calcium-based model. Risk is based on the Potential for Invasion and Ecological Impacts. Given that Ecological Impacts are Very High across all of Canada the final determination of Ecological Risk represents differences in the Potential for Invasion.

MaxEnt-Based Model Habitat Suitability Modelling

Zebra Mussel

Using the MaxEnt-based model, the Ecological Risk for Zebra Mussel was Moderate for most of Canada, including throughout most of Eastern Canada and the Prairie provinces (Figure 5). Areas of Low Risk included coastal and northern British Columbia, Yukon, Northwest Territories, northeastern Quebec and most of Labrador. High Risk areas included the Laurentian-Great Lakes area and around Lake Winnipeg, Manitoba which corresponds to the current known distribution of this species. Limitations of this approach are represented by the fact that the Red River, Lake Manitoba and Nelson River are not displayed as High Risk in the model output where Zebra Mussels are known to occur (Figure 5). Several discrete areas in New Brunswick, which are outside the current distribution of Zebra Mussel in Canada, also are High Risk. Labrador, the Northwest Territories, northern regions of Quebec, most of Nunavut and mountainous areas in the Western provinces are below the temperature threshold, and therefore, likely Very Low Ecological Risk.

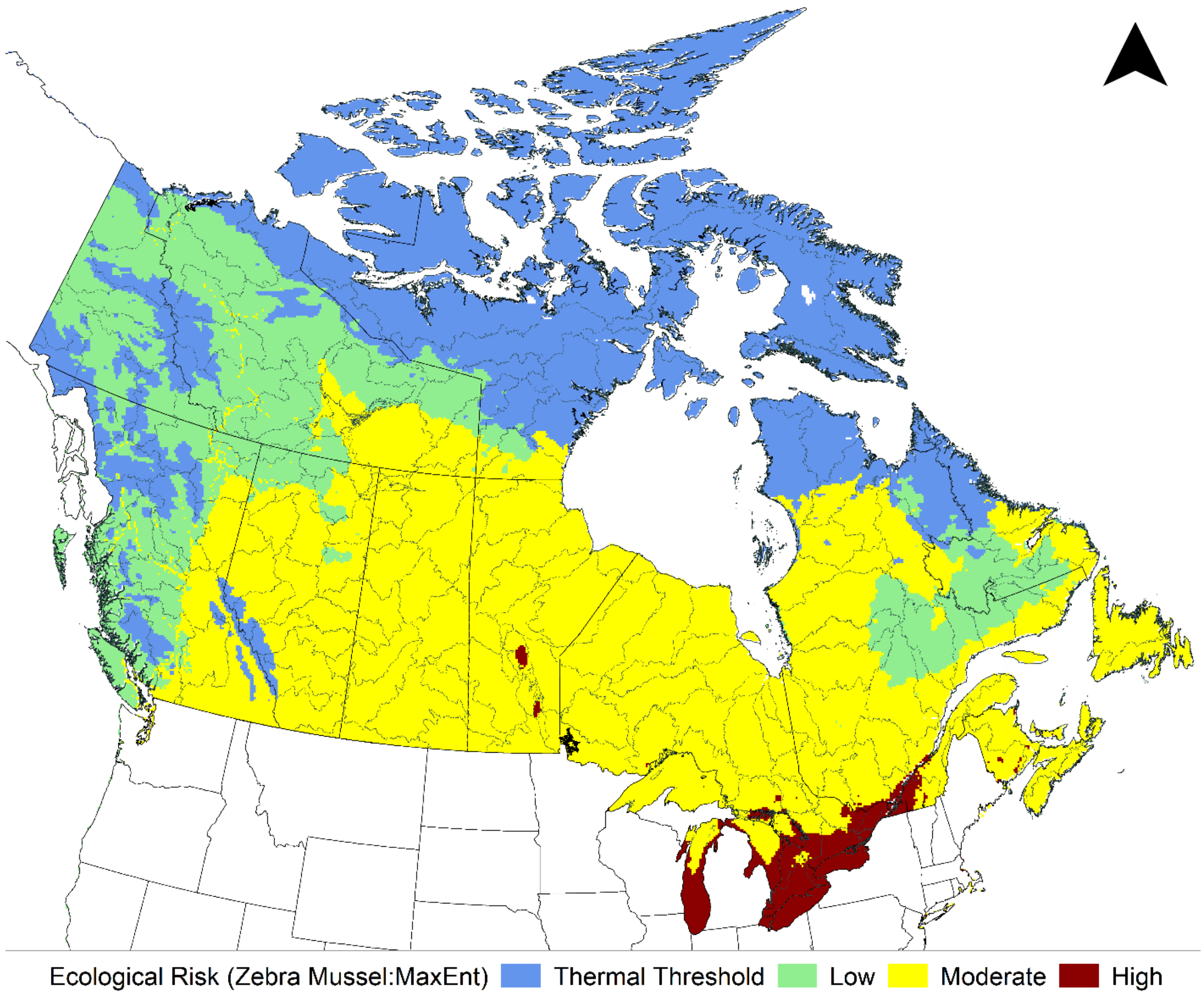

Figure 5. Zebra Mussel Ecological Risk in Canada using the MaxEnt-based habitat suitability model. Risk is based on the Potential for Invasion and Ecological Impacts. Given that Ecological Impacts are Very High across all of Canada the final determination of Ecological Risk represents differences in the Potential for Invasion.

Quagga Mussel

Due to the relatively low habitat suitability (Potential for Invasion) identified by the MaxEnt-based model and the constrained distribution of this species, the Ecological Risk for Quagga Mussel for most of Canada was Low (Figure 6). There are discrete areas of Moderate Risk in southern Alberta, southern British Columbia, Quebec, and New Brunswick. The Laurentian-Great Lakes system contains both Moderate and High Risk areas which corresponds to the current known distribution of this species.

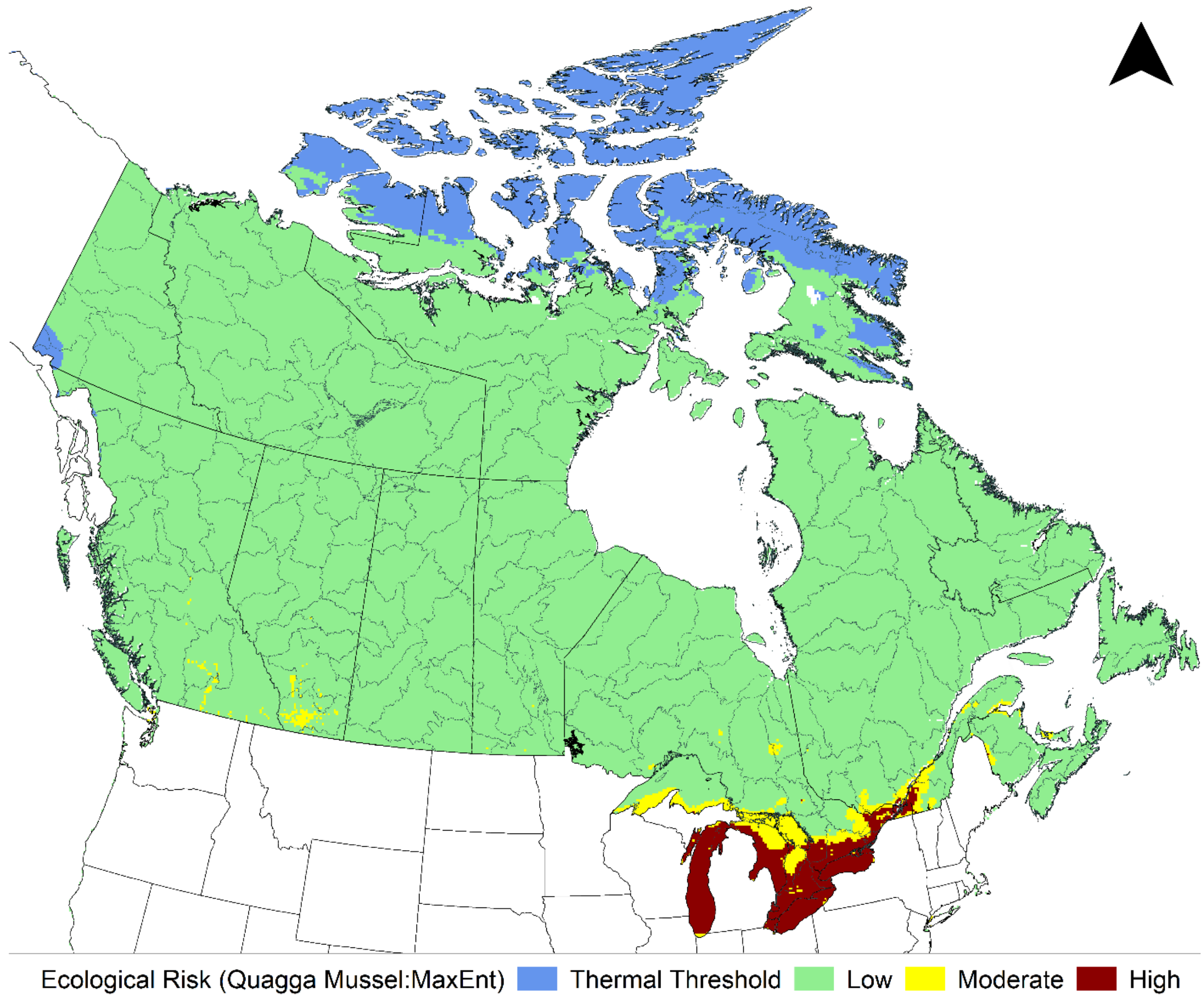

Figure 6. Quagga Mussel Ecological Risk in Canada using the MaxEnt-based habitat suitability model. Risk is based on the Potential for Invasion and Ecological Impacts. Given that Ecological Impacts are Very High across all of Canada the final determination of Ecological Risk represents differences in the Potential for Invasion.

Sources of Uncertainty

All models are inherently imperfect and rely on the data and assumptions used to develop them. Both habitat suitability models used in this assessment are no different and each has biases, strengths, and weaknesses. The calcium-based model used biological thresholds for the two species from the literature to identify suitable habitat across Canada. It assumes all habitats are suitable except for low calcium areas and that populations are not influenced by other environmental or biotic factors (e.g. food, oxygen, species interactions, etc.) and is not dependent on the species distribution. Areas predicted to be unsuitable are likely true but higher uncertainty exists for areas that are predicted to be suitable as the tendency in this approach is to overpredict suitable habitat. In contrast, the MaxEnt-based model relies on correlations between species occurrences and several environmental variables (e.g., calcium, pH, temperature, and precipitation). Because the invasion is still ongoing, the current distribution of the species (1989-2021) may not represent the fully realized suite of suitable habitats that these dreissenid mussels could invade. As such, MaxEnt-based models may underpredict habitat suitability. Areas predicted to be highly suitable are likely true but higher uncertainty exists when considering areas predicted to be less suitable.

Some regions such as the Arctic, in particular Nunavut, the Northwest Territories, Yukon, and Alaska were data-poor, resulting in a higher degree of uncertainty for calcium and pH interpolations. In addition, the results and predictions of the models are highly dependent on the scale used in the input data, in this case ~100 km^2. Prioritizing efforts to generate higher resolution environmental data would improve the resolution of future assessment while also creating data layers that could be used for similar assessments.

There is considerable variation in the literature reporting environmental tolerances of dreissenids due to the variability in observations over the widespread geographical footprint of these species and a number of laboratory studies that do not necessarily reflect actual field conditions. It is important to note that at the scale of this risk assessment there can be considerable intra-sub-drainage variability. This variability is the greatest source of uncertainty when projecting habitat suitability to the subdrainage spatial scale used in this risk assessment.

There may be other variables that were not included in this risk assessment that could influence distributions of Zebra and Quagga Mussels (e.g., lack of chlorophyll *a* spatial data layers) and including them in future risk assessments could improve predictions of habitat suitability and ecological risk. Similarly, future refinement of existing data inputs (e.g., *in-situ* water temperature vs. air temperature proxies) could improve model performance.

Given the frequency with which dreissenind mussels use overland transport to disperse (including long distance) and reach new environments, the Potential for Introduction may be underestimated. The Potential for Introduction calculated here used proxies for human activity and connectivity and did not include habitat use by humans (i.e. site attractiveness). Thus, a metric of attractiveness could improve future assessments and could serve as a way to prioritize early detection/monitoring locations, especially high-use areas that have suitable habitats.

Areas that are currently invaded do not automatically translate to high risk in any risk assessment approach. It is difficult to determine how each metric in the invasion process should be weighted without an understanding of the relative importance of each metric to the associated component and each component to the overall likelihood and impact of invasion. For example, the Human Footprint Index and connectivity metric were given equal weighting when calculating the Potential for Introduction, however it is unknown whether one metric contributes more to the probability of an introduction than the other.

Both Zebra and Quagga Mussel have had well demonstrated impacts on the ecosystems they invade. However, quantifying these impacts across Canada is difficult as the scale of these impacts will vary spatially and is dependent on many factors including those related to the size/extent of the invading mussel population and the characteristics of the receiving environment, including the presence of at-risk species. Future efforts should aim to establish appropriate indicators that can be applied at a high resolution and national extent to refine grid cell-specific ecological impacts.

CONCLUSIONS AND ADVICE

Since being introduced into the Laurentian Great Lakes region in the 1980s, Zebra (*Dreissena polymorpha*) and Quagga (*Dreissena rostriformis bugensis*) Mussels have spread throughout North America and have had significant ecological impacts to freshwater ecosystems. In Canada, Zebra Mussels have subsequently spread to certain waterbodies in Manitoba and southern Quebec, while Quagga Mussels have only spread within the Laurentian Great Lakes region (Figure 1A and 1B). Conducting an ecological risk assessment is an important management tool to be more efficient and effective to inform, prevent, prioritize, and respond to aquatic invasive species. As Zebra and Quagga Mussel invasions continue and environmental drivers change, the risk to Canadian freshwater aquatic ecosystems may also change overtime and will need to be reassessed. In addition, the new data inputs and analytical methods could improve future risk assessments.

The new assessment approach was conducted at a higher spatial resolution, using 9,260 m x 9,260 m grid cell resolution across Canada, unlike the subdrainage basin approach that was undertaken previously (DFO 2013). The new assessment also included all provinces and territories, new and updated environmental data and species occurrence information, and two different habitat suitability models. The ecological risk for both Zebra and Quagga Mussels was assessed by integrating metrics related to introduction and establishment, and ecological impact. Introduction was assessed based on a proxy of human activity (Human Footprint Index) and proximity to invaded waterbodies (connectivity metric). Establishment was assessed by two modeling approaches to characterize habitat suitability. Since Zebra and Quagga Mussels have significant and well documented negative ecological impacts, the impact to Canadian freshwater aquatic ecosystems was determined to be Very High.

This assessment used two different habitat models (calcium-based and MaxEnt-based) for each species, presented both at the high resolution grid cell level and summarized at the sub-drainage basin using two metrics (the greatest Ecological Risk value for any area within the sub-drainage [Maximum] and the most common Ecological Risk value within the sub-drainage [Mode]). Depending on the specific decision and risk tolerance, the information in this assessment can be used to inform management actions, including early detection, response planning, and/or regulatory and policy measures aimed at mitigating potential risk posed by invasive Zebra and Quagga Mussel to Canadian freshwater ecosystems.

The new assessment approach resulted in all provinces and territories containing watersheds that have Moderate or High Ecological Risk under at least one scenario for both Zebra and Quagga Mussel (Appendix A and B). Higher ecological risk areas are distributed along the southern reaches of Canada ranging from the Maritime provinces to southern British Columbia, with the largest areas of High risk occurring in the Laurentian Great Lakes, and south and central Manitoba (Figures 3-6).

Ecological Risk values are not absolute, and areas of Low Risk do not necessarily indicate that Zebra and Quagga Mussel cannot be introduced, establish, or impact those Canadian ecosystems, but rather indicates that the risk of ecological impacts related to invasion are lower relative to areas that are at higher risk (or already invaded). Both species have demonstrated the ability to be transported long distances and to remote locations. Additionally, the ecological risk assessment presented here represents current conditions (environmental and known distribution up to 2021) at the time of this report. Should a waterbody (lake, river, or stream) get invaded with Zebra or Quagga Mussel, it should be assumed that there is a very high risk of invasion to any connected, downstream waterbody due to natural dispersal as well as adjacent waterbodies through human activities.

As with both the 2012 and this new assessment, data limitations resulted in a number of uncertainties related to the characterisation of risk in this assessment. Additionally, it was noted that there were discrepancies between the known distribution of Zebra and Quagga Mussels (Figures 1A and 1B) and the ability of the model to identify those using the data inputs and data treatment parameters of the model (e.g., central Manitoba). Improved and expanded geospatial data (e.g., environmental, species, and introduction vectors) will improve future risk assessments. The information presented in this advice, builds on previous advice (DFO 2013) to further improve the efficiency and effectiveness of reducing the potential risk posed by invasive Zebra and Quagga Mussel to Canadian freshwater ecosystems.

OTHER CONSIDERATIONS

There is no indication that the invasion by Zebra and Quagga Mussel in North America is complete and that the current distribution represents the fully realized distribution of these two species. As a result, there is a need to refine the data inputs as the invasion continues to unfold including updated species occurrences and improved spatial and temporal coverage for environmental variables. This risk assessment will need to be updated regularly to reflect the new distribution of each dreissenid species which could change the Potential for Introduction by altering the metric of connectivity. It would also require the MaxEnt-based habitat suitability models be retrained using the new distribution, which could refine the input parameters to reflect more closely the full suite of habitats suitable for establishment.

A national database of geo-referenced environmental and water quality data and aquatic invasive species occurrences in Canadian aquatic ecosystems is needed. Such a database would be useful for predicting potential distribution of aquatic invasive species and also help to better understand climate variables and how they affect Canadian species and ecosystems.

Increased environmental, water quality, and invasive species monitoring is necessary to generate higher resolution environmental data that would improve the resolution of future assessments while also creating data layers that could be used for similar assessments for other species.

Geospatial data is needed for key vectors of introduction and spread including the transportation of watercraft and water-based equipment as well as the role of e-commerce and the transportation of aquatic organisms. Prior to the detection of Zebra Mussel associated with moss balls in Canada related to organisms in trade, this vector would have largely been missed.

Human-mediated transport of Zebra and Quagga Mussel, especially overland transport of watercraft and water-based equipment (both short and long distances) are likely the most significant vectors contributing to the redistribution of these species in North America. It is recommended that future assessments aim to refine connectivity metrics using finer scale information on watercraft movement, particularly with respect to invaded systems. Such a data set could be based on watercraft inspection data (such as those available for Alberta, Saskatchewan, and Manitoba) but would need to be available at a national scale.

Ecological impacts by Zebra and Quagga Mussels were determined to be Very High. While it is likely impacts are on the higher end of the scale, it is also likely that they vary spatially and could be context dependent at small spatial scales (i.e. waterbodies). Future work could include a full impact analysis where different types of impacts for dreissenid mussels are characterized spatially and would increase the potential for quantification of ecological impacts. Alternatively, a national scale assessment of general habitat vulnerability, identifying areas of greater sensitivity to disturbance such as an invasion could be employed to provide greater differentiation and potentially be used in conjunction with (or incorporate) current information on at-risk species distributions.

Currently, there are no independent data sets available to validate the weighting of each component in this risk assessment, nor the two models used for the Potential for Establishment. To improve future risk assessments, continual monitoring of species distribution expansions could yield occurrence data necessary to inform the relative importance of the various metrics, validate future models, and improve the accuracy of predictions.

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This Science Advisory Report is from the National Peer Review of April 4 to 7, 2022 on the National Aquatic Invasive Species (AIS) Risk Assessment for Zebra and Quagga Mussels, 2022 Update. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

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APPENDICES

Appendix A: Summary of Ecological Risk (mode and maximum) by sub-drainage for Zebra Mussel using the calcium-based and MaxEnt-based habitat suitability model.

For each of the two modeling approaches (calcium-based model and MaxEnt-based habitat suitability model) values for Ecological Risk for Zebra Mussel (Figure A1-2, Table A1) were assigned to each sub-drainage representing the mode (most common Ecological Risk value) and maximum risk values of grid cells within that sub-drainage. Sub-drainage designations (codes and names) from the Atlas of Canada (Natural Resources Canada 2016) can be found in Wilcox et al. 2024. Note that sub-drainage 020 (Great Lakes and St. Lawrence) includes both freshwater and marine habitats, however marine habitats are unsuitable for both species and thus the risk should be applied to only freshwater portions of this sub-drainage.

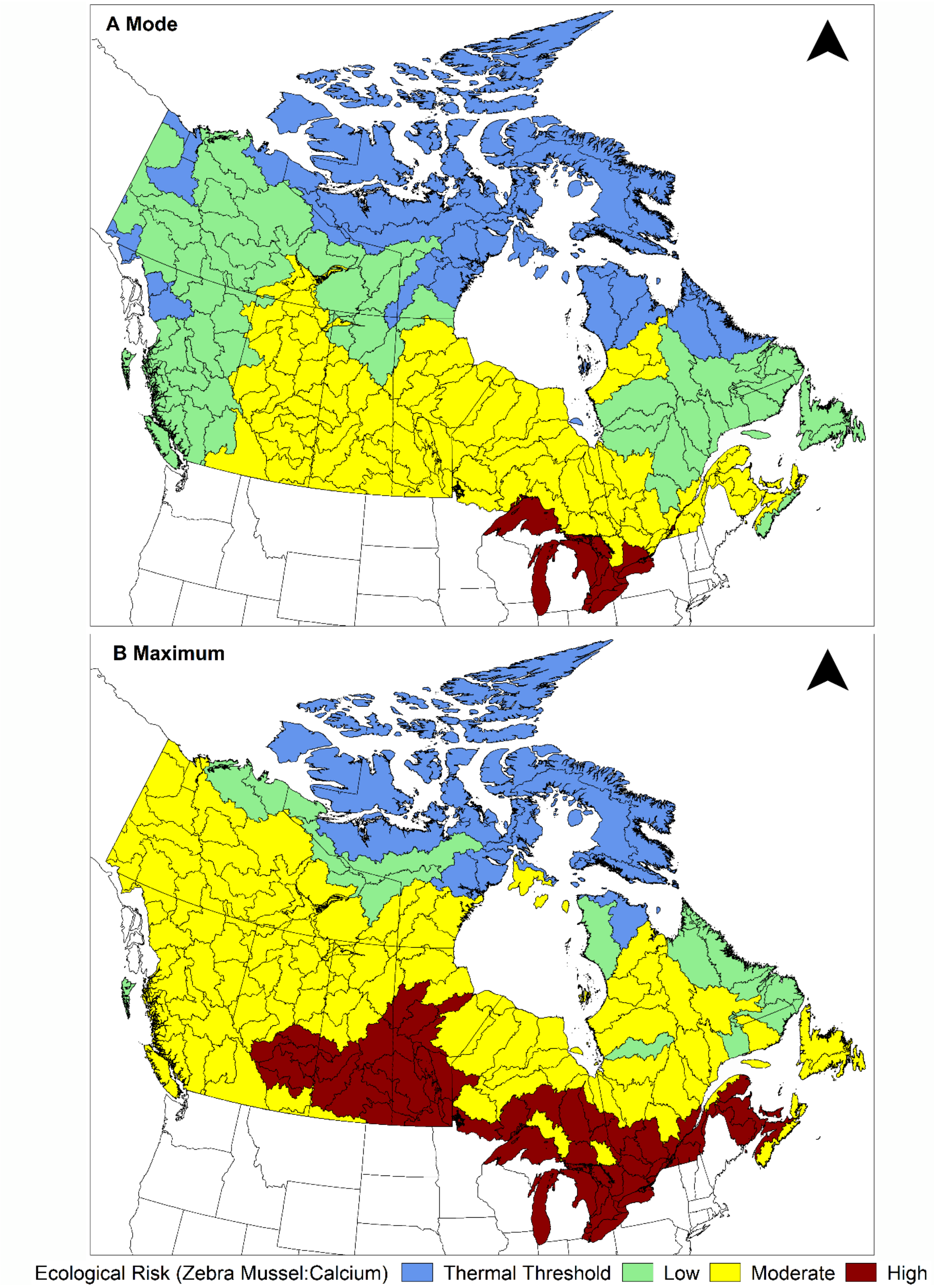

Figure A1. Mode (A) and maximum (B) Zebra Mussel Ecological Risk per Sub-drainage in Canada using the calcium-based model.

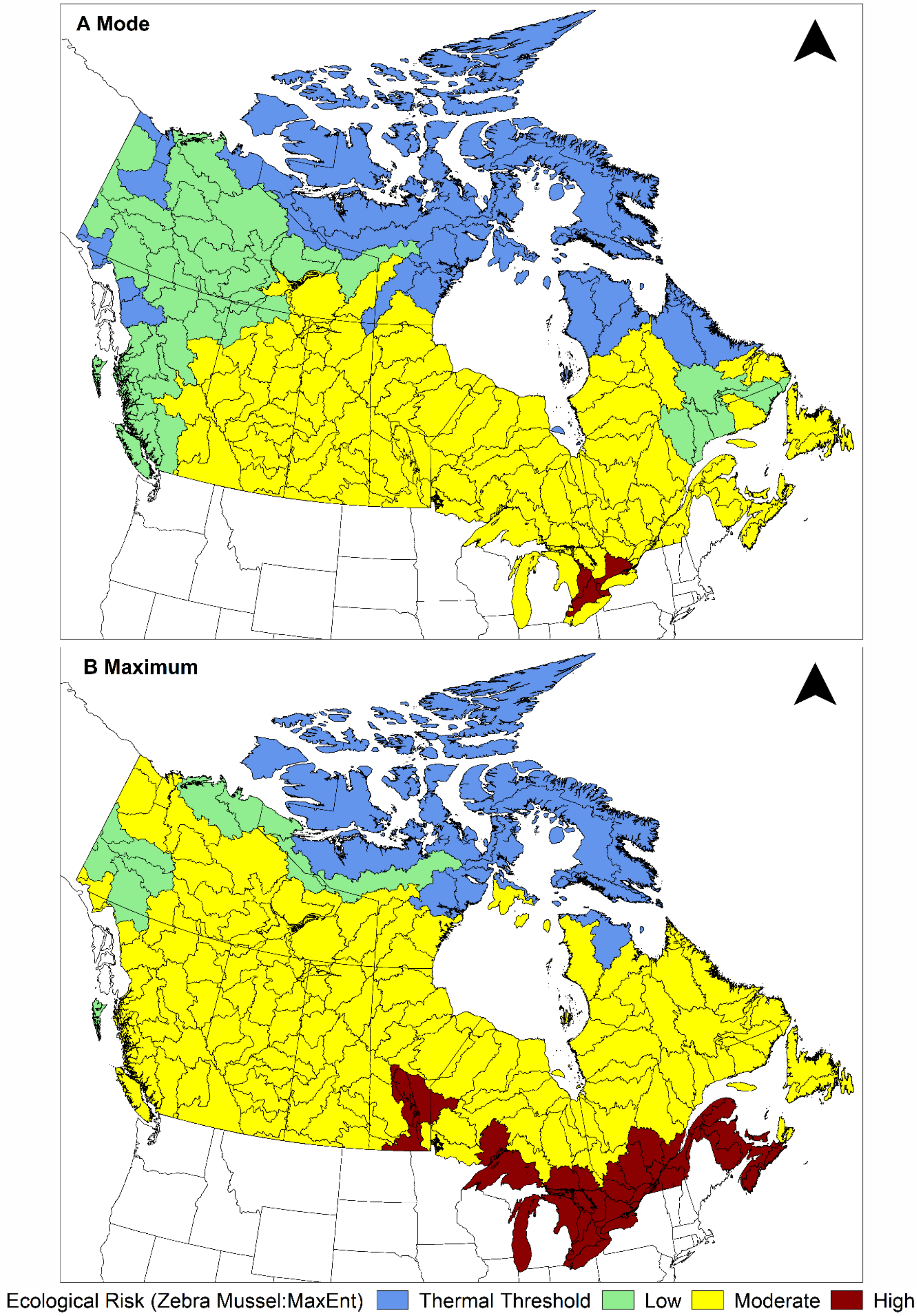

Figure A2. Mode (A) and maximum (B) Zebra Mussel Ecological Risk per Sub-drainage in Canada based on the MaxEnt-based habitat suitability model.

Table A1. Summary of Ecological Risk (mode and maximum) by sub-drainage for Zebra Mussel using the calcium-based and MaxEnt habitat suitability model.

Provinces and Territories	Code	Sub-drainage	Calcium-based model		MaxEnt-based model	
			Mode	Max	Mode	Max
NB and QC	01A	Saint John and Southern Bay of Fundy (N.B.)	Moderate	High	Moderate	High
NB and QC	01B	Gulf of St. Lawrence and Northern Bay of Fundy (N.B.)	Moderate	High	Moderate	High
PE	01C	Prince Edward Island	Moderate	High	Moderate	High
NS	01D	Bay of Fundy and Gulf of St. Lawrence (N.S.)	Moderate	High	Moderate	High
NS	01E	Southeastern Atlantic Ocean (N.S.)	Low	Moderate	Moderate	High
NS	01F	Cape Breton Island	Moderate	Moderate	Moderate	Moderate
QC and ON	020	Great Lakes and St. Lawrence	High	High	Moderate	High
ON	02A	Northwestern Lake Superior	Moderate	High	Moderate	High
ON	02B	Northeastern Lake Superior	Moderate	Moderate	Moderate	Moderate
ON	02C	Northern Lake Huron	Moderate	High	Moderate	High
ON	02D	Wanipitai and French (Ont.)	Moderate	Moderate	Moderate	High
ON	02E	Eastern Georgian Bay	Moderate	High	Moderate	High
ON	02F	Eastern Lake Huron	High	High	High	High
ON	02G	Northern Lake Erie	High	High	High	High
ON	02H	Lake Ontario and Niagara Peninsula	High	High	High	High
QC and ON	02J	Upper Ottawa	Moderate	High	Moderate	Moderate
QC and ON	02K	Central Ottawa	Moderate	High	Moderate	High
QC and ON	02L	Lower Ottawa	Moderate	High	Moderate	High
QC and ON	02M	Upper St. Lawrence	Moderate	High	Moderate	High
QC	02N	Saint-Maurice	Low	Moderate	Moderate	High
QC	02O	Central St. Lawrence	Moderate	High	Moderate	High
QC	02P	Lower St. Lawrence	Moderate	High	Moderate	High
NB and QC	02Q	Northern Gaspé Peninsula	Moderate	Moderate	Moderate	High
QC	02R	Saguenay	Low	Moderate	Moderate	Moderate

Provinces and Territories	Code	Sub-drainage	Calcium-based model		MaxEnt-based model	
			Mode	Max	Mode	Max
QC	02S	Betsiamites - Coast	Low	Moderate	Moderate	Moderate
QC	02T	Manicouagan and aux Outardes	Low	Moderate	Low	Moderate
QC	02U	Moisie and St. Lawrence Estuary	Low	Moderate	Low	Moderate
NL and QC	02V	Gulf of St. Lawrence - Romaine	Low	Low	Low	Moderate
NL and QC	02W	Gulf of St. Lawrence - Natashquan	Low	Moderate	Moderate	Moderate
NL and QC	02X	Petit Mécatina and Strait of Belle Isle	Low	Low	Low	Moderate
NL	02Y	Northern Newfoundland	Low	Moderate	Moderate	Moderate
NL	02Z	Southern Newfoundland	Low	Moderate	Moderate	Moderate
QC	03A	Nottaway - Coast	Moderate	Moderate	Moderate	Moderate
QC and NU	03B	Broadback and Rupert	Low	Moderate	Moderate	Moderate
QC	03C	Eastmain	Low	Low	Moderate	Moderate
QC and NU	03D	La Grande - Coast	Low	Moderate	Moderate	Moderate
QC and NU	03E	Grande rivière de la Baleine - Coast	Moderate	Moderate	Moderate	Moderate
QC and NU	03F	Eastern Hudson Bay	Moderate	Moderate	Moderate	Moderate
QC and NU	03G	Northeastern Hudson Bay	Thermal Threshold	Low	Thermal Threshold	Moderate
QC and NU	03H	Western Ungava Bay	Thermal Threshold	Thermal Threshold	Thermal Threshold	Thermal Threshold
QC and NU	03J	Aux Feuilles - Coast	Thermal Threshold	Moderate	Thermal Threshold	Moderate
QC	03K	Koksoak	Moderate	Moderate	Moderate	Moderate
QC	03L	Caniapiscau	Low	Moderate	Moderate	Moderate
NL, QC, and NU	03M	Eastern Ungava Bay	Thermal Threshold	Low	Thermal Threshold	Moderate
NL, QC, and NU	03N	Northern Labrador	Thermal Threshold	Low	Thermal Threshold	Moderate
NL	03O	Churchill (Nfld.)	Low	Moderate	Low	Moderate
NL	03P	Central Labrador	Low	Low	Moderate	Moderate
NL	03Q	Southern Labrador	Low	Low	Moderate	Moderate
ON and MB	04A	Hayes (Man.)	Moderate	Moderate	Moderate	Moderate
ON and MB	04B	Southwestern Hudson Bay	Moderate	Moderate	Moderate	Moderate
ON and MB	04C	Severn	Moderate	Moderate	Moderate	Moderate
ON	04D	Winisk - Coast	Moderate	Moderate	Moderate	Moderate

Provinces and Territories	Code	Sub-drainage	Calcium-based model		MaxEnt-based model	
			Mode	Max	Mode	Max
ON and NU	04E	Ekwan - Coast	Moderate	Moderate	Moderate	Moderate
ON and NU	04F	Attawapiskat - Coast	Moderate	Moderate	Moderate	Moderate
ON	04G	Upper Albany	Moderate	Moderate	Moderate	Moderate
ON and NU	04H	Lower Albany - Coast	Moderate	Moderate	Moderate	Moderate
ON	04J	Kenogami	Moderate	High	Moderate	Moderate
ON	04K	Moose (Ont.)	Moderate	Moderate	Moderate	Moderate
ON	04L	Missinaibi-Mattagami	Moderate	High	Moderate	Moderate
QC and ON	04M	Abitibi	Moderate	High	Moderate	Moderate
QC and ON	04N	Harricanaw - Coast	Moderate	Moderate	Moderate	Moderate
MB	050	Lake Winnepeg	Moderate	High	Moderate	High
SK and AB	05A	Upper South Saskatchewan	Moderate	Moderate	Moderate	Moderate
AB	05B	Bow	Moderate	High	Moderate	Moderate
SK and AB	05C	Red Deer	Moderate	High	Moderate	Moderate
AB	05D	Upper North Saskatchewan	Moderate	High	Moderate	Moderate
SK and AB	05E	Central North Saskatchewan	Moderate	High	Moderate	Moderate
SK and AB	05F	Battle	Moderate	High	Moderate	Moderate
SK and AB	05G	Lower North Saskatchewan	Moderate	High	Moderate	Moderate
SK and AB	05H	Lower South Saskatchewan	Moderate	High	Moderate	Moderate
MB and SK	05J	Qu'Appelle	Moderate	High	Moderate	Moderate
MB and SK	05K	Saskatchewan	Moderate	High	Moderate	Moderate
MB and SK	05L	Lake Winnipegosis and Lake Manitoba	Moderate	High	Moderate	Moderate
MB and SK	05M	Assiniboine	Moderate	High	Moderate	Moderate
MB and SK	05N	Souris	Moderate	High	Moderate	Moderate
MB	05O	Red	Moderate	High	Moderate	High
ON and MB	05P	Winnipeg	Moderate	High	Moderate	Moderate
ON	05Q	English	Moderate	Moderate	Moderate	Moderate
ON and MB	05R	Eastern Lake Winnipeg	Moderate	High	Moderate	High
MB	05S	Western Lake Winnipeg	Moderate	High	Moderate	High
MB	05T	Grass and Burntwood	Moderate	High	Moderate	Moderate
MB	05U	Nelson	Moderate	High	Moderate	Moderate
SK and AB	06A	Beaver (Alta.-Sask.)	Moderate	Moderate	Moderate	Moderate

Provinces and Territories	Code	Sub-drainage	Calcium-based model		MaxEnt-based model	
			Mode	Max	Mode	Max
SK and AB	06B	Upper Churchill (Man.)	Moderate	Moderate	Moderate	Moderate
SK	06C	Central Churchill (Man.) - Upper	Moderate	Moderate	Moderate	Moderate
MB and SK	06D	Reindeer	Low	Moderate	Moderate	Moderate
MB and SK	06E	Central Churchill (Man.) - Lower	Moderate	High	Moderate	Moderate
MB and NU	06F	Lower Churchill (Man.)	Moderate	Moderate	Moderate	Moderate
MB and NU	06G	Seal - Coast	Moderate	Moderate	Moderate	Moderate
MB, SK, NU	06H	Western Hudson Bay - Southern	Low	Moderate	Moderate	Moderate
NT and NU	06J	Thelon	Low	Low	Low	Moderate
NT and NU	06K	Dubawnt	Low	Moderate	Moderate	Moderate
MB, SK, NT, and NU	06L	Kazan	Thermal Threshold	Moderate	Thermal Threshold	Moderate
NU	06M	Chesterfield Inlet	Thermal Threshold	Thermal Threshold	Thermal Threshold	Thermal Threshold
NU	06N	Western Hudson Bay - Central	Thermal Threshold	Moderate	Thermal Threshold	Moderate
NU	06O	Western Hudson Bay - Northern	Thermal Threshold	Thermal Threshold	Thermal Threshold	Thermal Threshold
NU	06P	Hudson Bay - Southampton Island	Thermal Threshold	Moderate	Thermal Threshold	Moderate
NU	06Q	Foxe Basin - Southampton Island	Thermal Threshold	Thermal Threshold	Thermal Threshold	Thermal Threshold
NU	06R	Foxe Basin - Melville Peninsula	Thermal Threshold	Thermal Threshold	Thermal Threshold	Thermal Threshold
NU	06S	Foxe Basin - Baffin Island	Thermal Threshold	Thermal Threshold	Thermal Threshold	Thermal Threshold
NU	06T	Hudson Strait - Baffin and Southampton Islands	Thermal Threshold	Thermal Threshold	Thermal Threshold	Thermal Threshold
NT	070	Great Slave Lake	Moderate	Moderate	Moderate	Moderate
SK and AB	071	Lake Athabasca	Moderate	Moderate	Moderate	Moderate
AB	07A	Upper Athabasca	Moderate	Moderate	Moderate	Moderate
AB	07B	Central Athabasca - Upper	Moderate	Moderate	Moderate	Moderate
SK and AB	07C	Central Athabasca - Lower	Moderate	Moderate	Moderate	Moderate
SK and AB	07D	Lower Athabasca	Moderate	Moderate	Moderate	Moderate
BC	07E	Williston Lake	Low	Moderate	Low	Moderate
AB and BC	07F	Upper Peace	Low	Moderate	Moderate	Moderate

Provinces and Territories	Code	Sub-drainage	Calcium-based model		MaxEnt-based model	
			Mode	Max	Mode	Max
AB and BC	07G	Smoky	Moderate	Moderate	Moderate	Moderate
AB	07H	Central Peace - Upper	Moderate	Moderate	Moderate	Moderate
AB	07J	Central Peace - Lower	Moderate	Moderate	Moderate	Moderate
AB	07K	Lower Peace	Moderate	Moderate	Moderate	Moderate
SK and NT	07L	Fond-du-Lac	Low	Moderate	Moderate	Moderate
SK and AB	07M	Lake Athabasca - Shores	Low	Moderate	Moderate	Moderate
AB, NT	07N	Slave	Moderate	Moderate	Moderate	Moderate
AB, BC, and NT	07O	Hay	Moderate	Moderate	Low	Moderate
AB and NT	07P	Southern Great Slave Lake	Moderate	Moderate	Low	Moderate
SK, AB, and NT	07Q	Great Slave Lake - East Arm South Shore	Low	Moderate	Moderate	Moderate
NT	07R	Lockhart	Low	Low	Low	Moderate
NT	07S	Northeastern Great Slave Lake	Low	Moderate	Low	Moderate
NT	07T	Marian	Low	Moderate	Low	Moderate
AB, BC, and NT	07U	Western Great Slave Lake	Moderate	Moderate	Low	Moderate
BC and YT	08A	Alsek	Thermal Threshold	Moderate	Thermal Threshold	Moderate
BC	08B	Northern Coastal Waters of B.C.	Thermal Threshold	Moderate	Thermal Threshold	Moderate
BC	08C	Stikine - Coast	Thermal Threshold	Moderate	Thermal Threshold	Moderate
BC	08D	Nass - Coast	Low	Moderate	Low	Moderate
BC	08E	Skeena - Coast	Low	Moderate	Low	Moderate
BC	08F	Central Coastal Waters of B.C.	Low	Moderate	Low	Moderate
BC	08G	Southern Coastal Waters of B.C.	Low	Moderate	Low	Moderate
BC	08H	Vancouver Island	Low	Moderate	Low	Moderate
BC	08J	Nechako	Low	Moderate	Low	Moderate
BC	08K	Upper Fraser	Low	Moderate	Moderate	Moderate
BC	08L	Thompson	Low	Moderate	Moderate	Moderate
BC	08M	Lower Fraser	Low	Moderate	Low	Moderate
BC	08N	Columbia - U.S.A.	Moderate	Moderate	Moderate	Moderate
BC	08O	Queen Charlotte Islands	Low	Low	Low	Low
BC	08P	Skagit	Low	Moderate	Moderate	Moderate

Provinces and Territories	Code	Sub-drainage	Calcium-based model		MaxEnt-based model	
			Mode	Max	Mode	Max
BC and YT	09A	Headwaters Yukon	Low	Moderate	Low	Low
YT	09B	Pelly	Low	Moderate	Low	Low
YT	09C	Upper Yukon	Low	Moderate	Low	Low
YT	09D	Stewart	Low	Moderate	Low	Low
YT	09E	Central Yukon	Low	Moderate	Low	Low
YT	09F	Porcupine	Low	Moderate	Low	Moderate
YT	09H	Tanana	Thermal Threshold	Moderate	Thermal Threshold	Low
YT	09M	Copper	Thermal Threshold	Moderate	Thermal Threshold	Moderate
NT	100	Mackenzie River Delta (Main Channel)	Low	Moderate	Low	Moderate
BC, YT	10A	Upper Liard	Low	Moderate	Low	Moderate
BC and YT	10B	Central Liard	Low	Moderate	Low	Moderate
AB and BC	10C	Fort Nelson	Low	Moderate	Low	Moderate
AB, BC, YT, and NT	10D	Central Liard - Petitot	Low	Moderate	Low	Moderate
NT	10E	Lower Liard	Low	Moderate	Low	Moderate
NT	10F	Upper Mackenzie - Mills Lake	Low	Moderate	Low	Moderate
NT	10G	Upper Mackenzie - Camsell Bend	Low	Moderate	Low	Moderate
NT	10H	Central Mackenzie - Blackwater Lake	Low	Moderate	Low	Moderate
NT and NU	10J	Great Bear	Low	Moderate	Low	Moderate
NT	10K	Central Mackenzie - The Ramparts	Low	Moderate	Low	Moderate
NT	10L	Lower Mackenzie	Low	Moderate	Low	Moderate
YT and NT	10M	Peel and Southwestern Beaufort Sea	Thermal Threshold	Moderate	Thermal Threshold	Moderate
NT	10N	Southern Beaufort Sea	Low	Low	Low	Low
NT and NU	10O	Amundsen Gulf	Thermal Threshold	Low	Thermal Threshold	Low
NT and NU	10P	Coppermine	Thermal Threshold	Low	Thermal Threshold	Low
NU	10Q	Coronation Gulf - Queen Maud Gulf	Thermal Threshold	Thermal Threshold	Thermal Threshold	Thermal Threshold
NT and NU	10R	Back	Thermal Threshold	Low	Thermal Threshold	Low
NU	10S	Gulf of Boothia	Thermal Threshold	Thermal Threshold	Thermal Threshold	Thermal Threshold
NT and NU	10T	Southern Arctic Islands	Thermal Threshold	Thermal Threshold	Thermal Threshold	Thermal Threshold

Provinces and Territories	Code	Sub-drainage	Calcium-based model		MaxEnt-based model	
			Mode	Max	Mode	Max
NU	10U	Baffin Island - Arctic Drainage	Thermal Threshold	Thermal Threshold	Thermal Threshold	Thermal Threshold
NT and NU	10V	Northern Arctic Islands	Thermal Threshold	Thermal Threshold	Thermal Threshold	Thermal Threshold
SK and AB	11A	Missouri	Moderate	Moderate	Moderate	Moderate

Appendix B: Summary of Ecological Risk (mode and maximum) by sub-drainage for Quagga Mussel using the calcium-based and MaxEnt-based habitat suitability model.

For each of the two modeling approaches (calcium-based model and MaxEnt-based habitat suitability model) values for Ecological Risk for Quagga Mussel (Figure B1-2, Table B1) were assigned to each sub-drainage representing the mode (most common Ecological Risk value) and maximum risk values of grid cells within that sub-drainage. Sub-drainage designations (codes and names) from the Atlas of Canada (Natural Resources Canada 2016) can be found in Wilcox et al. 2024. Note that sub-drainage 020 (Great Lakes and St. Lawrence) includes both freshwater and marine habitats, however marine habitats are unsuitable for both species and thus the risk should be applied to only freshwater portions of this sub-drainage.

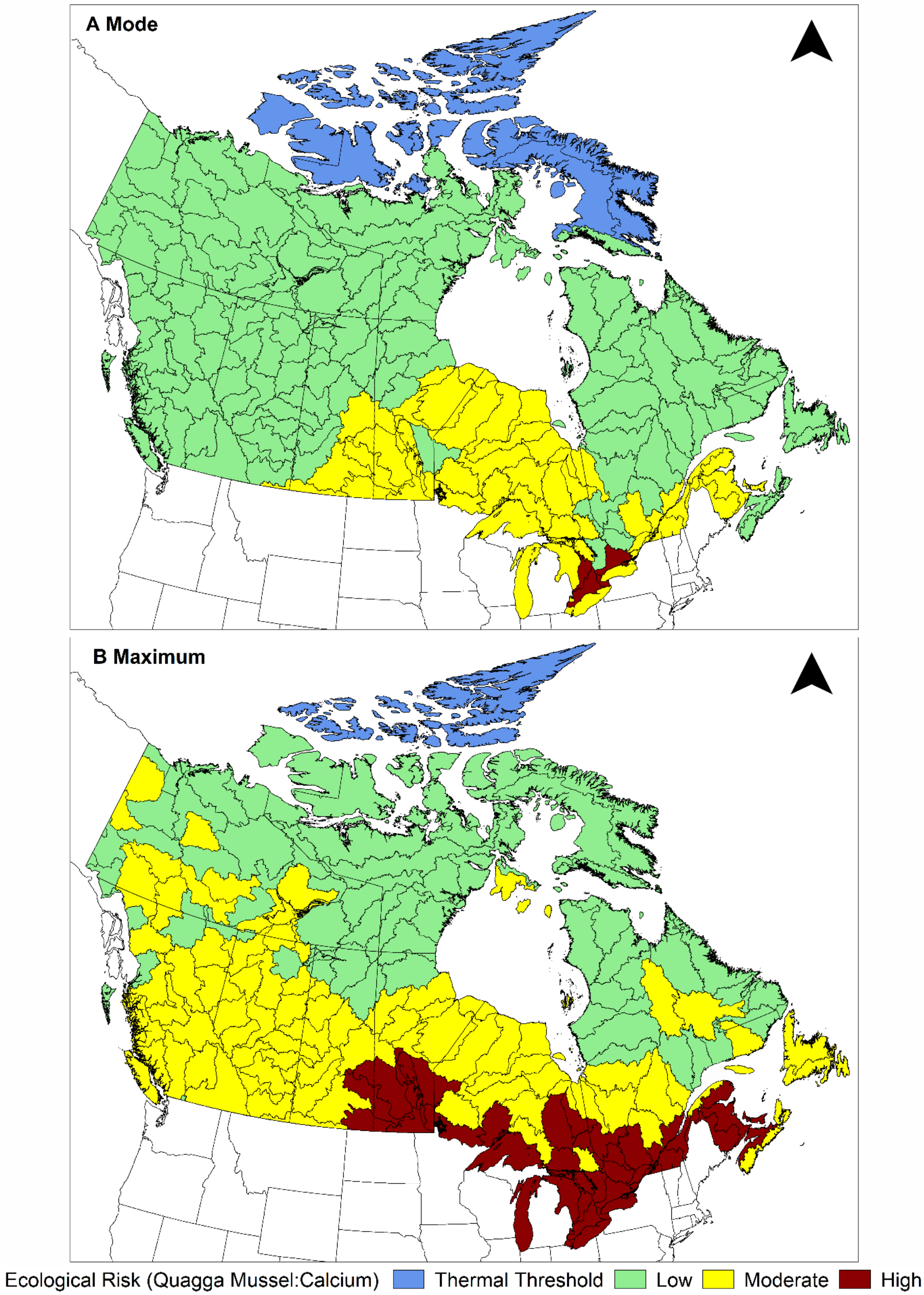

Figure B1. Mode (A) and maximum (B) Quagga Mussel Ecological Risk per Sub-drainage in Canada based on the Calcium-based model.

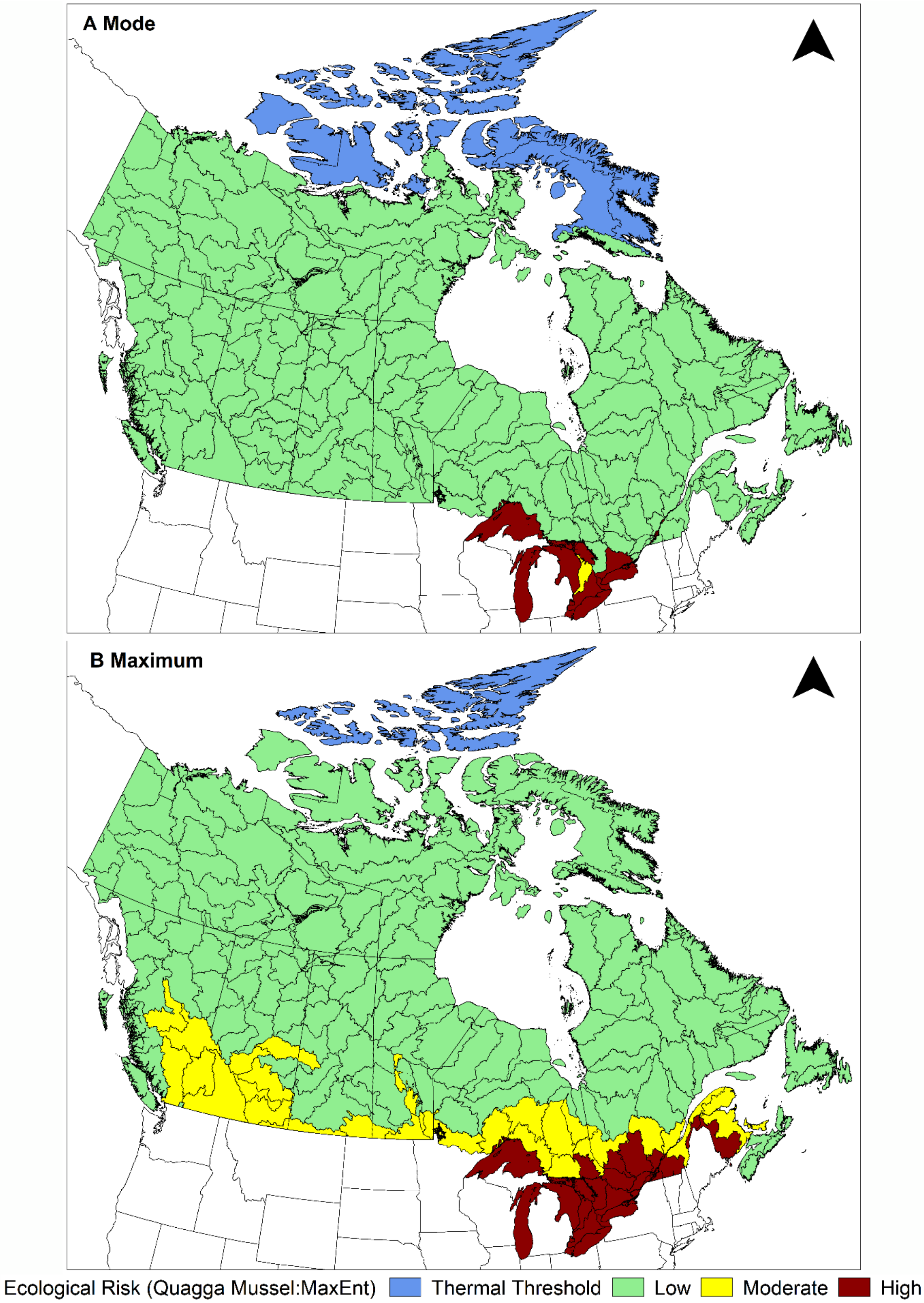

Figure B2. Mode (A) and maximum (B) Quagga Mussel Ecological Risk per Sub-drainage in Canada based on the MaxEnt-based habitat suitability model.

Table B1. Summary of Ecological Risk (mode and maximum) by sub-drainage for Quagga Mussel using the calcium-based and MaxEnt habitat suitability model.

Provinces and Territories	Code	Sub-drainage	Calcium-based model		MaxEnt-based model	
			Mode	Max	Mode	Max
NB and QC	01A	Saint John and Southern Bay of Fundy (N.B.)	Moderate	High	Low	High
NB and QC	01B	Gulf of St. Lawrence and Northern Bay of Fundy (N.B.)	Moderate	High	Low	Moderate
PE	01C	Prince Edward Island	Moderate	High	Low	Moderate
NS	01D	Bay of Fundy and Gulf of St. Lawrence (N.S.)	Low	High	Low	Low
NS	01E	Southeastern Atlantic Ocean (N.S.)	Low	Moderate	Low	Low
NS	01F	Cape Breton Island	Low	Moderate	Low	Low
QC and ON	020	Great Lakes and St. Lawrence	Moderate	High	High	High
ON	02A	Northwestern Lake Superior	Moderate	High	Low	Moderate
ON	02B	Northeastern Lake Superior	Moderate	Moderate	Low	Moderate
ON	02C	Northern Lake Huron	Moderate	High	Low	Moderate
ON	02D	Wanipitai and French (Ont.)	Moderate	Moderate	Low	High
ON	02E	Eastern Georgian Bay	Low	High	Low	High
ON	02F	Eastern Lake Huron	High	High	Moderate	High
ON	02G	Northern Lake Erie	High	High	High	High
ON	02H	Lake Ontario and Niagara Peninsula	High	High	High	High
QC and ON	02J	Upper Ottawa	Low	High	Low	Moderate
QC and ON	02K	Central Ottawa	Low	High	Low	High
QC and ON	02L	Lower Ottawa	Moderate	High	Low	High
QC and ON	02M	Upper St. Lawrence	Moderate	High	Low	High
QC	02N	Saint-Maurice	Low	Moderate	Low	Moderate
QC	02O	Central St. Lawrence	Moderate	High	Low	High
QC	02P	Lower St. Lawrence	Moderate	High	Low	Moderate
NB and QC	02Q	Northern Gaspé Peninsula	Moderate	Moderate	Low	Moderate
QC	02R	Saguenay	Low	Moderate	Low	Low
QC	02S	Betsiamites - Coast	Low	Moderate	Low	Low
QC	02T	Manicouagan and aux Outardes	Low	Low	Low	Low
QC	02U	Moisie and St. Lawrence Estuary	Low	Low	Low	Low

Provinces and Territories	Code	Sub-drainage	Calcium-based model		MaxEnt-based model	
			Mode	Max	Mode	Max
NL and QC	02V	Gulf of St. Lawrence - Romaine	Low	Low	Low	Low
NL and QC	02W	Gulf of St. Lawrence - Natashquan	Low	Moderate	Low	Low
NL and QC	02X	Petit Mécatina and Strait of Belle Isle	Low	Low	Low	Low
NL	02Y	Northern Newfoundland	Low	Moderate	Low	Low
NL	02Z	Southern Newfoundland	Low	Moderate	Low	Low
QC	03A	Nottaway - Coast	Low	Moderate	Low	Low
QC and NU	03B	Broadback and Rupert	Low	Moderate	Low	Low
QC	03C	Eastmain	Low	Low	Low	Low
QC and NU	03D	La Grande - Coast	Low	Low	Low	Low
QC and NU	03E	Grande rivière de la Baleine - Coast	Low	Low	Low	Low
QC and NU	03F	Eastern Hudson Bay	Low	Low	Low	Low
QC and NU	03G	Northeastern Hudson Bay	Low	Low	Low	Low
QC and NU	03H	Western Ungava Bay	Low	Low	Low	Low
QC and NU	03J	Aux Feuilles - Coast	Low	Low	Low	Low
QC	03K	Koksoak	Low	Low	Low	Low
QC	03L	Caniapiscau	Low	Moderate	Low	Low
NL, QC, and NU	03M	Eastern Ungava Bay	Low	Low	Low	Low
NL, QC, and NU	03N	Northern Labrador	Low	Low	Low	Low
NL	03O	Churchill (Nfld.)	Low	Moderate	Low	Low
NL	03P	Central Labrador	Low	Low	Low	Low
NL	03Q	Southern Labrador	Low	Low	Low	Low
ON and MB	04A	Hayes (Man.)	Moderate	Moderate	Low	Low
ON and MB	04B	Southwestern Hudson Bay	Moderate	Moderate	Low	Low
ON and MB	04C	Severn	Moderate	Moderate	Low	Low
ON	04D	Winisk - Coast	Moderate	Moderate	Low	Low
ON and NU	04E	Ekwan - Coast	Moderate	Moderate	Low	Low
ON and NU	04F	Attawapiskat - Coast	Moderate	Moderate	Low	Low
ON	04G	Upper Albany	Moderate	Moderate	Low	Low
ON and NU	04H	Lower Albany - Coast	Moderate	Moderate	Low	Low
ON	04J	Kenogami	Moderate	Moderate	Low	Moderate
ON	04K	Moose (Ont.)	Moderate	Moderate	Low	Low

Provinces and Territories	Code	Sub-drainage	Calcium-based model		MaxEnt-based model	
			Mode	Max	Mode	Max
ON	04L	Missinaibi-Mattagami	Moderate	High	Low	Moderate
QC and ON	04M	Abitibi	Moderate	High	Low	Moderate
QC and ON	04N	Harricanaw - Coast	Moderate	Moderate	Low	Low
MB	050	Lake Winnepeg	Moderate	High	Low	Low
SK and AB	05A	Upper South Saskatchewan	Low	Moderate	Low	Moderate
AB	05B	Bow	Low	Moderate	Low	Moderate
SK and AB	05C	Red Deer	Low	Moderate	Low	Moderate
AB	05D	Upper North Saskatchewan	Low	Moderate	Low	Moderate
SK and AB	05E	Central North Saskatchewan	Low	Moderate	Low	Moderate
SK and AB	05F	Battle	Low	Moderate	Low	Low
SK and AB	05G	Lower North Saskatchewan	Low	Moderate	Low	Low
SK and AB	05H	Lower South Saskatchewan	Low	Moderate	Low	Low
MB and SK	05J	Qu'Appelle	Moderate	Moderate	Low	Low
MB and SK	05K	Saskatchewan	Moderate	Moderate	Low	Low
MB and SK	05L	Lake Winnipegosis and Lake Manitoba	Moderate	High	Low	Low
MB and SK	05M	Assiniboine	Moderate	High	Low	Low
MB and SK	05N	Souris	Moderate	High	Low	Moderate
MB	05O	Red	Moderate	High	Low	Moderate
ON and MB	05P	Winnipeg	Moderate	High	Low	Moderate
ON	05Q	English	Moderate	Moderate	Low	Low
ON and MB	05R	Eastern Lake Winnipeg	Low	High	Low	Low
MB	05S	Western Lake Winnipeg	Moderate	High	Low	Moderate
MB	05T	Grass and Burntwood	Low	Moderate	Low	Low
MB	05U	Nelson	Moderate	Moderate	Low	Low
SK and AB	06A	Beaver (Alta.-Sask.)	Low	Moderate	Low	Low
SK and AB	06B	Upper Churchill (Man.)	Low	Moderate	Low	Low
SK	06C	Central Churchill (Man.) - Upper	Low	Moderate	Low	Low
MB and SK	06D	Reindeer	Low	Low	Low	Low
MB and SK	06E	Central Churchill (Man.) - Lower	Low	Moderate	Low	Low
MB and NU	06F	Lower Churchill (Man.)	Low	Moderate	Low	Low
MB and NU	06G	Seal - Coast	Low	Low	Low	Low

Provinces and Territories	Code	Sub-drainage	Calcium-based model		MaxEnt-based model	
			Mode	Max	Mode	Max
MB, SK, NU	06H	Western Hudson Bay - Southern	Low	Low	Low	Low
NT and NU	06J	Thelon	Low	Low	Low	Low
NT and NU	06K	Dubawnt	Low	Low	Low	Low
MB, SK, NT, and NU	06L	Kazan	Low	Low	Low	Low
NU	06M	Chesterfield Inlet	Low	Low	Low	Low
NU	06N	Western Hudson Bay - Central	Low	Low	Low	Low
NU	06O	Western Hudson Bay - Northern	Low	Low	Low	Low
NU	06P	Hudson Bay - Southampton Island	Low	Moderate	Low	Low
NU	06Q	Foxe Basin - Southampton Island	Low	Low	Low	Low
NU	06R	Foxe Basin - Melville Peninsula	Low	Low	Low	Low
NU	06S	Foxe Basin - Baffin Island	Thermal Threshold	Low	Thermal Threshold	Low
NU	06T	Hudson Strait - Baffin and Southampton Islands	Low	Low	Low	Low
NT	070	Great Slave Lake	Low	Moderate	Low	Low
SK and AB	071	Lake Athabasca	Low	Low	Low	Low
AB	07A	Upper Athabasca	Low	Moderate	Low	Low
AB	07B	Central Athabasca - Upper	Low	Moderate	Low	Low
SK and AB	07C	Central Athabasca - Lower	Low	Moderate	Low	Low
SK and AB	07D	Lower Athabasca	Low	Moderate	Low	Low
BC	07E	Williston Lake	Low	Moderate	Low	Low
AB and BC	07F	Upper Peace	Low	Moderate	Low	Low
AB and BC	07G	Smoky	Low	Moderate	Low	Low
AB	07H	Central Peace - Upper	Low	Moderate	Low	Low
AB	07J	Central Peace - Lower	Low	Moderate	Low	Low
AB	07K	Lower Peace	Low	Low	Low	Low
SK and NT	07L	Fond-du-Lac	Low	Low	Low	Low
SK and AB	07M	Lake Athabasca - Shores	Low	Low	Low	Low
AB, NT	07N	Slave	Low	Moderate	Low	Low
AB, BC, and NT	07O	Hay	Low	Moderate	Low	Low
AB and NT	07P	Southern Great Slave Lake	Low	Moderate	Low	Low

Provinces and Territories	Code	Sub-drainage	Calcium-based model		MaxEnt-based model	
			Mode	Max	Mode	Max
SK, AB, and NT	07Q	Great Slave Lake - East Arm South Shore	Low	Low	Low	Low
NT	07R	Lockhart	Low	Low	Low	Low
NT	07S	Northeastern Great Slave Lake	Low	Moderate	Low	Low
NT	07T	Marian	Low	Low	Low	Low
AB, BC, and NT	07U	Western Great Slave Lake	Low	Moderate	Low	Low
BC and YT	08A	Alsek	Low	Low	Low	Low
BC	08B	Northern Coastal Waters of B.C.	Low	Low	Low	Low
BC	08C	Stikine - Coast	Low	Moderate	Low	Low
BC	08D	Nass - Coast	Low	Low	Low	Low
BC	08E	Skeena - Coast	Low	Moderate	Low	Low
BC	08F	Central Coastal Waters of B.C.	Low	Moderate	Low	Low
BC	08G	Southern Coastal Waters of B.C.	Low	Moderate	Low	Low
BC	08H	Vancouver Island	Low	Moderate	Low	Low
BC	08J	Nechako	Low	Moderate	Low	Moderate
BC	08K	Upper Fraser	Low	Moderate	Low	Moderate
BC	08L	Thompson	Low	Moderate	Low	Moderate
BC	08M	Lower Fraser	Low	Moderate	Low	Moderate
BC	08N	Columbia - U.S.A.	Low	Moderate	Low	Moderate
BC	08O	Queen Charlotte Islands	Low	Low	Low	Low
BC	08P	Skagit	Low	Low	Low	Low
BC and YT	09A	Headwaters Yukon	Low	Moderate	Low	Low
YT	09B	Pelly	Low	Moderate	Low	Low
YT	09C	Upper Yukon	Low	Low	Low	Low
YT	09D	Stewart	Low	Low	Low	Low
YT	09E	Central Yukon	Low	Moderate	Low	Low
YT	09F	Porcupine	Low	Moderate	Low	Low
YT	09H	Tanana	Low	Low	Low	Low
YT	09M	Copper	Low	Low	Low	Low
NT	100	Mackenzie River Delta (Main Channel)	Low	Low	Low	Low
BC, YT	10A	Upper Liard	Low	Moderate	Low	Low
BC and YT	10B	Central Liard	Low	Low	Low	Low
AB and BC	10C	Fort Nelson	Low	Moderate	Low	Low

Provinces and Territories	Code	Sub-drainage	Calcium-based model		MaxEnt-based model	
			Mode	Max	Mode	Max
AB, BC, YT, and NT	10D	Central Liard - Petitot	Low	Low	Low	Low
NT	10E	Lower Liard	Low	Moderate	Low	Low
NT	10F	Upper Mackenzie - Mills Lake	Low	Low	Low	Low
NT	10G	Upper Mackenzie - Camsell Bend	Low	Moderate	Low	Low
NT	10H	Central Mackenzie - Blackwater Lake	Low	Low	Low	Low
NT and NU	10J	Great Bear	Low	Low	Low	Low
NT	10K	Central Mackenzie - The Ramparts	Low	Moderate	Low	Low
NT	10L	Lower Mackenzie	Low	Low	Low	Low
YT and NT	10M	Peel and Southwestern Beaufort Sea	Low	Low	Low	Low
NT	10N	Southern Beaufort Sea	Low	Low	Low	Low
NT and NU	10O	Amundsen Gulf	Low	Low	Low	Low
NT and NU	10P	Coppermine	Low	Low	Low	Low
NU	10Q	Coronation Gulf - Queen Maud Gulf	Low	Low	Low	Low
NT and NU	10R	Back	Low	Low	Low	Low
NU	10S	Gulf of Boothia	Low	Low	Low	Low
NT and NU	10T	Southern Arctic Islands	Thermal Threshold	Low	Thermal Threshold	Low
NU	10U	Baffin Island - Arctic Drainage	Thermal Threshold	Low	Thermal Threshold	Low
NT and NU	10V	Northern Arctic Islands	Thermal Threshold	Thermal Threshold	Thermal Threshold	Thermal Threshold
SK and AB	11A	Missouri	Moderate	Moderate	Low	Moderate

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