Canadian Journal of Fisheries and Aquatic Sciences

On the alarming state of freshwater biodiversity in Canada

Journal:	<i>Canadian Journal of Fisheries and Aquatic Sciences</i>
Manuscript ID	cjfas-2021-0073.R1
Manuscript Type:	Perspective
Date Submitted by the Author:	25-May-2021
Complete List of Authors:	<p>Desforges, Jessica; Carleton University Department of Biology, Biology Clarke, Julia; Carleton University Department of Biology Harmsen, Evaline; Carleton University Department of Biology Jardine, Alex; Carleton University, Department of Geography Robichaud, Jessica; Carleton University Department of Biology Serré, Serina; Carleton University Department of Biology Chakrabarty, Prosanta; Carleton University Department of Biology; Louisiana Museum of Natural Science; Beaty Centre for Species Discovery Bennett, Joseph; Carleton University Department of Biology Hanna, Dalal; Carleton University Department of Biology; Québec Centre for Biodiversity Sciences Smol, John; Queen's University Rytwinski, Trina; Carleton University, Canadian Centre for Evidence- Based Conservation, Department of Biology and Institute of Environmental and Interdisciplinary Science Taylor, Jessica; Carleton University, Canadian Centre for Evidence-Based Conservation, Department of Biology and Institute of Environmental and Interdisciplinary Science Martel, André ; Canadian Museum of Nature, Research and Collections Winegardner, Amanda K.; Fisheries and Oceans Canada Marty, Jérôme; Institute of the Environment, University of Ottawa Taylor, Mark; Parks Canada Agency, Banff National Park O'Connor, Constance; Wildlife Conservation Society Canada Robinson, Stacey; Ecotoxicology and Wildlife Health Division, Wildlife and Landscape Science Directorate, Science and Technology Branch, Environment and Climate Change Canada Reid, Andrea; Centre for Indigenous Fisheries, Institute for the Oceans and Fisheries, University of British Columbia Creed, Irena; University of Saskatchewan School of Environment and Sustainability Gregory-Eaves, Irene; McGill University Lapointe, Nicolas; Canadian Wildlife Federation Cooke, Steven; Carleton University, Department of Biology and Institute of Environmental Science</p>
Keyword:	FRESHWATER ENVIRONMENT < General, ENDANGERED SPECIES < General, MONITORING < General, DATA DEFICIENCY, CONSERVATION < General
Is the invited manuscript for	Not applicable (regular submission)

consideration in a Special Issue? :	

SCHOLARONE™
Manuscripts

On the alarming state of freshwater biodiversity in Canada

Jessica E. Desforges^{1*}, Julia Clarke¹, Evaline J. Harmsen¹, Alex M. Jardine², Jessica A. Robichaud¹, Serina Serré¹, Prosanta Chakrabarty^{1,3,4}, Joseph R Bennett¹, Dalal E. L. Hanna^{1,5}, John P. Smol⁶, Trina Rytwinski⁷, Jessica J. Taylor⁷, André L Martel⁴, Amanda K. Winegardner⁸, Jerome Marty⁹, Mark K. Taylor¹⁰, Constance M. O'Connor¹¹, Stacey A. Robinson¹², Andrea J. Reid¹³, Irena F. Creed¹⁴, Irene Gregory-Eaves¹⁵, Nicolas W.R. Lapointe¹⁶ and Steven J. Cooke¹

Journal Target = Canadian Journal of Fisheries and Aquatic Sciences as a Perspective Article (Synthesis)

¹ Department of Biology and Institute of Environmental and Interdisciplinary Science, Carleton University, 1125 Colonel By Dr., Ottawa, ON, K1S 5B6, Canada

² Department of Geography and Environmental Studies, Carleton University, 1125 Colonel By Dr., Ottawa, ON, K1S 5B6, Canada

³ Museum of Natural Science, Department of Biological Sciences, Louisiana State University, 119 Foster Hall, Baton Rouge, LA, 70803, USA

⁴ Beaty Centre for Species Discovery and Zoology, Research and Collections, Canadian Museum of Nature, 1740 Pink Road, Gatineau, QC, Canada. J9J 3E7, Canada

⁵ Quebec Centre for Biodiversity Sciences, Canada

⁶ Paleoecological Environmental Assessment and Research Lab (PEARL), Department of Biology, Queen's University, Kingston, Ontario, K7L 3N6 Canada

⁷ Canadian Centre for Evidence-Based Conservation, Department of Biology and Institute of Environmental and Interdisciplinary Science, Carleton University, 1125 Colonel By Dr., Ottawa, ON, K1S 14 5B6, Canada

⁸ Environment and Biodiversity Science Branch, Fisheries and Oceans Canada, 200 Kent St., Ottawa, Ontario, K1A 0E6 Canada

⁹ Institute of the Environment, University of Ottawa, 1 Stewart St., Ottawa, ON, K1N 7M9, Canada

¹⁰ Parks Canada Agency; Banff National Park, 100 Hawk Ave., Banff, Alberta, T1L 1K2, Canada

¹¹ Wildlife Conservation Society Canada, 344 Bloor St West, Suite 204, Toronto, ON M5S 3A7

¹² Ecotoxicology and Wildlife Health Division, Wildlife and Landscape Science Directorate, Science and Technology Branch, Environment and Climate Change Canada, Ottawa, Ontario, Canada

¹³ Centre for Indigenous Fisheries, Institute for the Oceans and Fisheries, The University of British Columbia, 2202 Main Mall, Vancouver, British Columbia V6T 1Z4

¹⁴ School of Environment & Sustainability, University of Saskatchewan, Saskatoon, SK, S7N 5C8

¹⁵ Department of Biology, McGill University, 1205 Dr Penfield Ave, Montreal QC, H3A 1B1

¹⁶ Canadian Wildlife Federation. 350 Michael Cowpland Dr. Ottawa, ON, K2M 2W1

***Author for Correspondence:** jdesforg@gmail.com

Abstract

Little is known about the current state of freshwater biodiversity in Canada, one of the countries with the greatest amount of surface waters in the world. To address this knowledge gap, we compiled a list of all available assessments of conservation status for freshwater species (over 3,000 taxa) and further evaluated the overall status of six distinct taxonomic groups, focusing on organisms reliant on freshwaters [i.e., aquatic plants, invertebrates (with a focus on freshwater mussels), fishes, herpetofauna (reptiles and amphibians), birds, and mammals]. Overall, 11.7% of all freshwater species of plants and animals assessed were found to be ‘at risk’ (i.e., listed as ‘Threatened’, ‘Endangered’, or ‘Extirpated’) and 17.9% identified as ‘Special Concern’. We found that 37.9% of species lacked sufficient data to enable their status to be assessed. Data gaps in Canada’s assessment of its freshwater species were most prevalent in invertebrates (excluding freshwater mussels). Given the alarming state of freshwater biodiversity in Canada, we conclude by providing recommendations that focus on evaluating temporal trends and informing conservation actions.

Keywords: Conservation, freshwater biome, threatened species, species at risk, monitoring, assessment, data deficient

1.0 Introduction

Despite occupying less than 1% of the Earth's surface, the freshwater biome is home to 12% of all described species, including as much as one third of all vertebrates (Dudgeon et al. 2006; Garcia-Moreno et al. 2014, Strayer and Dudgeon 2010). Freshwater plants and animals help maintain countless essential functions from production services (e.g., primary production and nutrient cycling; Lake et al. 2000) to providing many provisioning, regulating, and cultural ecosystem services (Postel and Carpenter 1997; Dudgeon 2010; Hanna et al. 2018). Increasing anthropogenic pressures and disturbance on the global water cycle (e.g., damming, increased use of freshwaters for agriculture, aquatic invasive species) have resulted in freshwaters becoming the most threatened biome on the planet, with inland water systems particularly at risk (Garcia-Moreno et al., 2014; Creed et al. 2017). According to the Living Planet Index (2020), monitored populations of freshwater vertebrates are currently experiencing the largest biodiversity decline (84% decline since 1970) relative to species that occupy terrestrial or marine environments, though we also acknowledge potential differences in defining freshwater (WWF 2020). In fact, the freshwater biodiversity crisis (see Abell 2002; Harrison et al. 2019; Reid et al. 2019; Albert et al. 2021) is so dire that it has inspired the development of an emergency action plan (see Tickner et al. 2020) intended to try to reverse these declines. Others have identified key areas to focus efforts on restoring freshwater biodiversity, such as developing plans to avoid extinctions regardless of incomplete knowledge or outlining management strategies to reduce the impact of climate change on freshwater ecosystems (Strayer and Dudgeon 2010). Nonetheless, it is

essential to understand the state of freshwater biodiversity across a broad range of scales, including at the national scale, which tends to be the level at which many freshwater biodiversity initiatives (ranging from policies, to monitoring to recovery planning and management) occur.

Canada contains 20% of the world's freshwater, including 7% of the Earth's free-flowing renewable freshwater resource, as well as nearly 25% of all wetlands (Rainer et al. 2017, Canada 2018). With approximately 891,163 km² of freshwater, including over 2 million lakes and 8,500 rivers (Monk and Baird 2014), Canada stewards a unique and important component of the world's biodiversity. This includes many well-known temperate species such as river otters (*Lontra canadensis*) and beavers (*Castor canadensis*), as well as Canadian endemics including the Copper Redhorse (*Moxostoma hubbsi*), Coldwater Pondsail (*Stagnicola woodruffi*), Banff Springs Snail (*Physella johnsoni*), Hungerford's Crawling Water Beetle (*Brychius hungerfordi*), and the Lake Erie Watersnake (*Nerodia sipedon insularum*) (Enns et al. 2020). Despite the abundance of freshwater biota in Canada, little is known about the state of freshwater biodiversity aside from taxon-specific and often regional (and project-specific) assessments. While reports on the conservation status of certain species in Canada exist and produce highly valuable information [e.g., Canadian Endangered Species Conservation Council (CESCC) Wild Species reports, Committee on the Status of Endangered Wildlife in Canada (COSEWIC) annual reports], a more complete picture of the status of Canada's freshwater biodiversity in its entirety is not yet available (Pérez-Jvostov et al. 2020). For example, the WWF Canada Watershed reports focus on indicator species (e.g., fish and macroinvertebrates) with the goal of assessing ecosystem health, but not total biodiversity (WWF-Canada 2020). Similarly, a review of biodiversity in the lakes and rivers (wetlands were excluded) of Canada by Monk and Baird (2014; wetlands were excluded) used proxies of biodiversity status (e.g., habitat quality and

quantity) rather than assessing the actual state of biodiversity. Further, Tognelli et al. (2017) reported on the state of freshwater biodiversity in Canada; however, not all freshwater-reliant species (e.g., birds, mammals, herpetofauna) were included and conservation status was not provided for all species. Additionally, other studies have focused on the status of individual freshwater taxonomic groups (e.g., Williams et al. 1993; Brown and Hecnar 2007; Collier et al. 2016).

Considering the rate of global biodiversity loss along with the urgent calls to implement action plans (WWF 2020, Tickner et al. 2020, Albert et al. 2021), we have a responsibility to gain a better understanding of the current state of Canada's freshwater biodiversity. This study seeks to address this knowledge gap by building towards a Canada-wide freshwater biodiversity assessment. This nation-wide assessment synthesizes the latest available information pertaining to the conservation status of Canada's freshwater species, providing researchers and practitioners with a description of freshwater biodiversity in Canada today, and highlighting data deficiencies where further research is needed.

2.0 Methods

The following sections summarize the methodology used to complete this assessment, broken down by the major steps, including: creation of a species list, collection of conservation status, and data analysis. We then described freshwater dependency and how conservation status terms were selected. A full comprehensive breakdown of how data were collected and selected in this study is provided in Section 2.1 and 2.2; data are available as supplemental material (S1)¹.

2.1 Species List Creation

¹ Supplementary data S1 contains species list and conservation status for 3130 taxa

A list of freshwater-dependent species in Canada was compiled from existing data sources to serve as a baseline to quantify the proportion of conservation status assessments completed among taxa. Species data were collected for the following macroscopic taxonomic groups: plants, invertebrates, fishes, herpetofauna (amphibians and reptiles), birds, and mammals. For each taxonomic group, freshwater species were identified and included if: (1) the species accomplished all or part of its lifecycle in, or on, inland waters (spanning from fresh to supersaline); or (2) the species showed dependency inland water habitats for food or habitat. For example, Culicidae (mosquitoes), which require inland waters for the deposition of egg rafts and early life stages were deemed a freshwater species and included in this study (Smith et al. 1994). Although we acknowledge that species residing in supersaline inland water bodies may experience different challenges compared to those living in fresh water, we opted to include them in this analysis for logistical reasons. Species that were historically present in Canada, but that have since become extinct or extirpated, were also included.

We excluded freshwater-dependent species that were considered non-native to Canada's freshwaters, since the main focus here is to address the state of freshwater biodiversity and to outline areas for improvement. While we acknowledge the importance of assessing the population trends and abundance of non-native species for management and monitoring purposes, management efforts tailored towards the conservation of native species are vastly different.

The species lists for plants, invertebrates, fishes, amphibians, reptiles, and mammals were created using data from COSEWIC, the International Union for Conservation of Nature (IUCN) Red List, and the CESSC 2015 Wildlife Species Report. Species lists were further augmented with data from FishBase (Froese and Pauly 2019) for fishes, the Canadian Herpetological

Society for herpetofauna, and the Canadian Wildlife Federation (CWF) for mammals and plants. We identified a total of 3,130 freshwater-dependent species in Canada, though we acknowledge that this process may have underestimated species richness.

A number of taxonomic groups were omitted from this study, due largely to a lack of available data. For example, there is a lack of assessment data in particular for microbial biota, zooplankton, copepods, and other micro-invertebrates. Of the few species for which data were available, a large portion are considered "unrankable" or "data-deficient" (Rozon et al., 2016). For example, when we examined a COSEWIC report on the status of freshwater ostracods in Canada, 81.5% of the freshwater species within the families Candonidae and Cyprididae were found to be "unrankable" (COSEWIC, 2012). Any taxonomic group that lacked enough data to make any accurate status assessments (including freshwater fungi, lichens, porifera, etc.) were also omitted from this study.

2.2 Conservation Data Collection

Following the creation of the species list, we obtained conservation status data for each species of the aforementioned six major taxonomic groups. COSEWIC was the primary source used for conservation status data rather than global assessments, because those assessments are specific to Canadian populations of species. We note that in some cases (e.g., species at the northern range edges), COSEWIC assesses species whose populations are globally secure as being at risk in Canada. Although the relative priority of conserving such species is debated (e.g. Raymond et al. 2018), there can be sound reasons for conserving them, including responsibility of a jurisdiction for its own biodiversity, as well as potential importance of northern populations for allowing range shifts as climate changes. In addition, when such species are protected under SARA, they have the same legal protection as species whose populations are globally imperilled.

189 When species were not assessed by COSEWIC, CESSC data were used to determine their status.
190 CESSC data were used to identify and assess species in an attempt to assist in guiding
191 COSEWIC assessment priorities (CESSC 2015) while monitoring population trends at five-year
192 intervals. It is important to note that although COSEWIC and CESSC provides conservation
193 status for Canadian species, they are not legal listings under the Species At Risk Act (SARA)
194 and are not given any specific rights or legal protection. CESSC rounded national ranks were
195 used to provide additional information about species status and to complement information
196 retrieved from COSEWIC.

197 COSEWIC conservation assessments statuses were categorized as follows: ‘Data
198 Deficient’, ‘Not at Risk’, ‘Special Concern’, ‘Threatened’, ‘Endangered’, ‘Extirpated’, and
199 ‘Extinct’. For species that had a COSEWIC assessment, that assessment was used as their
200 primary conservation status. For those species that did not have a COSEWIC assessment, but had
201 a conservation assessment from CESSC, the CESSC assessment term was matched to the
202 COSEWIC listing based on the definitions and justifications provided in Table 1. This
203 consolidation ensured that species were given an appropriate overall conservation status when
204 data came from CESSC and did not directly match the COSEWIC status terms. Species without
205 an assessment by either COSEWIC or CESSC were listed as “Not Available”. For the purpose of
206 this study, we considered species ‘at risk’ to include those assessed as ‘Threatened’,
207 ‘Endangered’, ‘Extirpated’, and ‘Extinct’. The category of ‘Special Concern’ was not included
208 since COSEWIC specifically states that although these species may be vulnerable in the near
209 future, they are not currently at risk. Species designated as ‘Special Concern’ also do not receive
210 legal habitat protection under SARA. COSEWIC assessments were given priority over CESSC
211 due to the thoroughness of the former assessment process.

2.3 Analysis

The data were summarized visually to depict the conservation statuses for each family of species in each taxonomic group (comparative bar graphs created in R version 3.6.1; R Core Team 2016, using ggplot2; Wickham 2016, and the viridis package; Garnier 2018). A proportional bar graph and a chord diagram (circlize; Gu 2014) were also generated to depict the overall differences in conservation status between broad taxonomic groups. Comprehensive lists with all Canadian freshwater species names and statuses were also created (Appendix A).

3.0 Taxonomic Results and Discussion

Each of the six major taxonomic groups (plants, invertebrates, fish, herpetofauna, birds, and mammals) were assessed individually and then in comparison to the other major taxonomic groups.

3.1 Freshwater Plants

According to our plant species list, Canada has 762 native freshwater plant species (Fig. 1; based on data from COSEWIC, CESSC, and IUCN). Of these plant species, six (0.8%) are listed as 'Extirpated', which included plants in the orders *Asterales*, *Poales*, *Malpighiales* and *Ranunculales*. Another 68 species (8.9%) were considered 'Endangered', 67 species (8.8%) as 'Threatened', and 175 species (23%) as 'Special Concern'. Interestingly, 58 species (7.6%) of all identified plant species were deemed 'Not Available', since they lack a conservation assessment in Canada. Therefore the number of at-risk freshwater plant species reported in this study could be either over or underestimated. Additionally, four species (0.5%) were listed as 'Data Deficient'. The most frequent status of plant species listed in this study (384 species, 50%) have been assessed as 'Not at Risk'.

Species-level information for freshwater plants was synthesized by order. Of the 45 plant orders assessed, three orders (Liliopsida, Magnoliopsida, and Charales) did not have any assessment information available in Canada. Further, 17 orders had more than 50% of their species considered to be at risk and of those, ten orders had 100% of their species listed as at risk. Comparatively, another 17 orders had more than 50% of their species considered to be not at risk and of those, nine orders had 100% of their species categorized as not at risk. The remaining eight orders were divided evenly among conservation categories. The orders Poales (grasses, bromeliads, etc.), Alismatales (pondweed), and Asterales contained the most freshwater plant species in Canada (247 species of Poales and 58 species of both Alismatales and Asterales). The orders containing more freshwater plant species tended to have an even division of conservation rankings with about 50% of those species considered to be at risk and 50% considered not to be at risk. While those orders with very few species (less than five) were either 100% not at risk or 100% at risk.

Notably, the Isoetales (quillworts) had one of the highest proportions of species that were at risk (in total 11 species, 91% at risk). Canada is home to multiple rare species of quillworts including *Isoetes prototypus*. This species is considered a regional endemic species and is only found in 12 lakes in Nova Scotia and New Brunswick, as well as one lake in Maine, USA (COSEWIC 2005). This species has been listed as ‘Threatened’ as it faces threats brought on by human recreational activities such as boating, fishing, and swimming (COSEWIC 2005). Additionally, another rare quillwort endemic to Canada is the recently described *Isoetes laurentiana*, located only in the fluvial freshwater portion of the St. Lawrence River (Brunton, et al., 2019). These endemic species point to the need to conserve some of the truly unique freshwater habitats in Canada, along with the conservation of the species that inhabit them.

Freshwater plants are key to maintaining aquatic biodiversity as they provide shelter, food, and act as a stabilizing force in maintaining water quality in aquatic ecosystems (Chambers et al. 2007). Considering the fundamental role of freshwater plants in aquatic ecosystems (Scheffer et al. 1993), decreases in populations will have detrimental impacts on other freshwater organisms. Freshwater plants in Canada face threats such as habitat degradation, pollution, flooding and drainage, as well as recreational activities such as the use of boats (Jain 1990; Perez-Jvostov et al. 2020). The direct application of aquatic herbicides to control invasive macrophytes also poses a risk to threatened native plant species (Sesin et al. 2018). Our results show that there is a significant portion (30%, 36 assessments) of plant species that remain at risk and these percentages are highly comparable to other groups considered.

3.2 Freshwater Invertebrates

A total of 1,952 freshwater invertebrate species were identified in Canada using IUCN, COSEWIC, and CESSC (Fig. 2). Of the 1,952 assessments for freshwater invertebrate species, 1032 species (53%) were considered 'Data Deficient', while 68 species (3.5%) were classified as 'Not Available' since they were not considered for conservation assessment by any source. Another 719 (37%) were not considered to be at risk (i.e. 398 'Not at Risk', 321 'Special Concern'). Based on the completed assessments to date, we know that at least 6.6% of all identified freshwater-dependent invertebrate species are considered to be have a classification of 'Threatened' or more severe.

The most evident trend pertaining to the state of freshwater invertebrate biodiversity was the lack of available data, particularly for insects. For example, Trichoptera (caddisflies) represent a large proportion of freshwater insect diversity in Canada (35.3%) with 688 species

279 listed, yet most of those listed have been classified as ‘Data Deficient’ due to lack of available
280 data (68%).

281 Some orders had a much greater proportion of assessed species such as Unionida
282 (freshwater mussels) and Odonata (dragonflies). Over half of freshwater Odonates (64.8%) were
283 not considered at risk, while 23.3% were considered to be at risk (of which approximately half of
284 the at risk group are ‘Endangered’). For example, Unionida (freshwater mussels) only had one
285 species listed as ‘Data Deficient’ while the majority of other species (55%) in this order were
286 considered to be at risk (and more than half of the at risk group are considered ‘Endangered’,
287 Fig. S1²). This coincides with global trends as freshwater mussels are among the most
288 endangered groups of organisms on Earth (Williams et al. 1993; Ricciardi and Rasmussen 1999).
289 One of the major threats and causes for declines in freshwater mussels is the inability to adapt to
290 altered water conditions associated with impoundment (Vaughn and Taylor 1999). There is also
291 evidence that suggests that the presence of invasive species (dresenid mussels in particular)
292 threaten native counterparts (Baker and Levinton 2003) This decline is particularly concerning
293 owing to the role of freshwater mussels in water filtration, sediment dynamics, and the overall
294 hydraulic environment, such that their decline can have catastrophic effects on freshwater
295 ecosystems (Strayer et al. 1994).

296 Based on our findings, severe knowledge gaps exist regarding the overall status of
297 freshwater invertebrates in Canada. Mayflies are among the groups of invertebrates that are
298 understudied (Ephemeroptera: 78% Data Deficient), five species of which are endemic to
299 Canada (Enns et al. 2020). Mayflies are highly important in freshwater ecosystems not only as
300 useful bioindicators, but also as climate regulators, water purifiers and pollinators (Leemans and

² Supplementary figure is available with the article through the journal website

De Groot 2003). Further, mayflies represent an important food source for freshwater fishes and aerial insectivore birds (Epanchin et al. 2010), serving as a link in the energy flow from primary production to secondary consumption, and across the aquatic-terrestrial interface (Jacobus et al. 2019).

A disproportionately large number of assessments were observed in some orders (e.g., Trichoptera, Diptera), which suggests a bias in conservation status assessments for socio-culturally important species. The bias towards species of human importance was most reflected in the orders Trichoptera (caddisflies, 688 total assessments) and Diptera (flies, 160). Caddisflies (Trichoptera) - which serve as important biological indicators of ecosystem health - were the most frequently assessed invertebrate group and are among the most common aquatic invertebrates in the world (Prommi 2018). Caddisflies are also known to be important to anglers who benefit from the predator-prey relationship between caddisflies and fish (Ames, 2008). Considering that the recreational fishing industry brings in about \$2.5B annually in Canada (DFO, 2015), it is perhaps not surprising that there has been a higher prioritization for conservation assessment of trichopteran compared to other invertebrate species. Based on the frequency of assessment for these particular orders, invertebrates that are commonly found to be interwoven with important ecosystem services value may be identified as candidates for assessment before less common species.

There also appears to be assessment bias towards species that are presumed to be imperiled prior to assessment. This is particularly noticeable in the assessment data from COSEWIC, which our report found listed 62% of freshwater invertebrates as 'Endangered', whereas CESSC only listed 3.2% as 'Endangered'. Notably, there are substantial differences in the number of species considered by COSEWIC and CESSC; however, it has been previously

acknowledged that a bias may exist for assessing species that are presumed to be imperiled or endangered, or that have already been assessed multiple times (Favaro et al., 2014). While these species require more frequent assessments to prevent further decline, it is equally important to acknowledge that data deficient species could be declining at similar rates.

3.3 Freshwater Fish

A total of 204 native freshwater-dependent fish species were evaluated for their conservation status in Canada (Fig. 3). Of these 204 assessments, nine (4.4%) were considered 'Data Deficient', while eight (4%) had no data available at all. Another 146 species (73%; 117 'Not at Risk', 32 'Special Concern') were not considered to be at risk, though particular attention should be focused on the 32 species progressing towards more critical stages. Additionally, 19 (9.3%) were considered 'Threatened', 13 (6.4%) as 'Endangered', 2 (1%) as 'Extirpated', and 4 (2%) as 'Extinct'. Overall, 38 (18.7%) of identified freshwater-dependent fish species were considered to be at risk. It is also important to recognize that this analysis was conducted at a species-level to identify national trends; these results could be masking more severe declines in population sizes on smaller geographic scales. For example, many commercially harvested fish are managed at a stock level and numerous stocks of Pacific salmon have been assessed to be at risk (see COSEWIC status reports). The management and conservation of mixed stock fisheries and genetically or spatially isolated populations is complex and assessment can vastly differ across regional scales.

Some orders have been assessed more than others, specifically Cypriniformes (carps and loaches), Perciformes (the diverse perch-like fishes), and Salmoniformes (salmon, trout, whitefish, etc.) (Fig. 3). While this could be a reflection of higher species richness in these orders (see Samarasin et al. 2015), it could also demonstrate unequal attention attributed across groups

and may represent a bias in the assessment process. For example, many species of Cypriniformes are common and highly abundant, facilitating the process of data collection in comparison to that of imperiled species. However, unlike Salmoniformes, Cypriniformes are not typically considered among the most economically or culturally important species, leading to many species being classified as ‘Not Available’ despite the relative ease of data collection. In contrast, Salmoniformes are considered important cultural and socio-economic native species, and have been well documented by COSEWIC in the past, making them ideal candidates for consistent assessments. The perception of value associated with particular species may skew the assessment processes.

Orders containing economically valuable migratory species, such as Salmoniformes and Acipenseriformes, also display higher numbers of assessments, many of which are considered at risk (22.2% and 66.6%, respectively). Globally, migratory fish have declined by an estimated 76% on average since 1970 (Deinet et al. 2020). We did not specifically conduct a temporal analysis, but our analysis suggested that migratory species may encounter more threats than orders containing non-migratory species. This seems to have been acknowledged by COSEWIC assessment committees, as these orders have been thoroughly assessed and prioritized for substantial monitoring and conservation efforts (Deinet et al. 2020). Likewise, Acipenseriformes is composed of several iconic species (e.g., Atlantic sturgeon *Acipenser oxyrinchus* and American paddlefish, *Polyodon spathula*) that are known to have suffered from human development and exploitation (e.g., Schloesser et al. 2016). Low catch rates were reported by fishers and have led to close monitoring and management of their populations (Scott and Crossman 1973; Pikitch et al. 2005). Similar to others, we observed a general trend that suggests that large, charismatic, and well-known species are more likely to be considered for assessment

than other less iconic species (supported by Olden et al. 2007; Walsh et al. 2012). The decline of recreationally, culturally, and socio-economically important or iconic native species seems to influence assessments of freshwater-dependent fishes in Canada. Evaluating the state of freshwater-dependent fish biodiversity in Canada relies on developing a transparent, non-biased system that ensures equal assessment of all endemic species.

In the past, freshwater fish have often been overlooked by policymakers and the general public (WWF 2021). Although there is evidence that points towards higher numbers of assessments in socio-economically or culturally valuable freshwater fishes (e.g., Donaldson et al. 2016), a recent report by WWF (2021) states that freshwater fish remain largely undervalued on a global scale. The proportion of fish species classified as ‘Extinct’ in Canada is over four times higher (1.96% of 204 identified species) than that observed worldwide by WWF (0.44% of 18075 identified species), though we also acknowledge that there could be differences in methodological processes involved in generating these results. Considering the magnitude of biodiversity loss observed not only across the globe but also within Canada, it is essential to implement management practices such as those outlined in the Emergency Recovery Plan for freshwater biodiversity (Tickner et al. 2020).

3.4 Freshwater Herpetofauna

A total of 61 species of freshwater-dependent Canadian amphibians and reptile species were evaluated for their conservation status in Canada (Fig. 4). This consisted of 16 reptiles (four snakes and 12 turtles) and 45 amphibians (25 frogs and 20 salamanders); 64% (27 ‘Not at Risk’, 12 ‘Special Concern’) were not considered to be at risk. Overall, 36% of freshwater herpetofauna were deemed to be at risk (nine ‘Threatened’, 11 ‘Endangered’ and two ‘Extirpated’), with a relatively high proportion of assessments ranking as ‘Endangered’ compared with other taxa.

Of the four freshwater snakes found in Canada, two were found to be not currently at risk – the Northern watersnake (*Nerodia sipedon sipedon*), and the Lake Erie watersnake (*Nerodia sipedon insularum*). The remaining species are considered at risk: the Eastern ribbonsnake (*Thamnophis saurita*) listed as ‘Threatened’; and the Queensnake (*Regina septemvittata*) listed as ‘Endangered’.

A total of 12 turtle species in Canada are freshwater dependant, all of which have been assessed for a conservation status. The Western painted turtle (*Chrysemys picta bellii*) is the only freshwater turtle species that was ‘Not at Risk’. Within the turtle group, 42% (five species) were listed as ‘Special Concern’: the Snapping turtle (*Chelydra serpentina*); the Midland painted turtle (*Chrysemys picta marginata*); the Eastern painted turtle (*Chrysemys picta picta*); the Northern map turtle (*Graptemys geographica*); and the Eastern musk turtle (*Sternotherus odoratus*). Several (17%) were listed as ‘Threatened’: the Blanding’s turtle (*Emydoidea blandingii*) and the Wood turtle (*Glyptemys insculpta*). Some ranked as ‘Endangered’ (17%, two species): the Spiny softshell turtle (*Apalone spinifera*) and the Spotted turtle (*Clemmys guttata*). Finally, the Pacific pond turtle (*Actinemys marmorata*) and the Eastern box turtle (*Terrapene carolina*) are listed as ‘Extirpated’ in Canada (17%).

Likely due to their sensitivity to anthropogenic threats and their relatively lower diversity, freshwater reptiles have been assessed more thoroughly relative to other freshwater-dependent species in this study. All native freshwater reptile species have a conservation assessment, with 50% considered to be at risk, making them a highly threatened taxonomic group (Fig. 4). Freshwater snakes and turtles face threats such as habitat degradation, destruction, and fragmentation, as well as pollution, disease, road mortality, human recreation, poaching, and climate change (Brown and Hecnar 2007; Lesbarrères et al. 2014). In Canada,

416 most freshwater reptiles and amphibians are at the northern edge of their range, wherein suitable
417 habitat is limited because of the cooler climate (Lesbarrères et al. 2014). This is particularly
418 concerning for freshwater amphibians whose required vegetation, wetland types, and thermal
419 regimes are limited (Lesbarrères et al. 2014). Notably, amphibians are globally one of the most
420 threatened vertebrate groups (Wake and Vredenburg 2008; Stanford et al. 2019).

421 We identified 25 species of freshwater-dependant frogs in Canada. Anurans are the least
422 threatened herpetological group in Canada, with 60% (15 species) assessed as 'Not at Risk'. The
423 remaining species assessments were ranked as follows: 16% (four species) as 'Special Concern';
424 12% (three species) as 'Threatened'; and 12% (three species) as 'Endangered'. Species listed as
425 'Special Concern' include the Great plains toad (*Anaxyrus cognatus*), the Coastal tailed frog
426 (*Ascaphus truei*), the Western chorus frog (*Pseudacris triseriata*), and the Red-legged frog (*Rana*
427 *aurora*). The Western toad (*Anaxyrus boreas*), the Rocky mountain tailed frog (*Ascaphus*
428 *montanus*), and the Great basin spadefoot (*Spea intermontane*) are all listed as 'Threatened'.
429 Finally, Blanchard's cricket frog (*Acris blanchardi*), Fowler's toad (*Anaxyrus fowleri*), the
430 Oregon spotted frog (*Rana pretiosa*), are listed as 'Endangered'.

431 Twenty salamander species in Canada are freshwater dependent which represents about
432 5% of the global species of salamanders; a highly endangered group (Milanovich et al. 2010). Of
433 these assessments, 50% (ten species) are listed as 'Not at Risk'; 10% (two species) as 'Special
434 Concern'; 15% (three species) as 'Threatened'; and 25% (five species) as 'Endangered'. Our
435 data suggest that salamanders have been relatively well-studied and there is sufficient assessment
436 data depicting changes in growth, decline, and threats to different populations. What is unclear is
437 the differentiation between species and subspecies observed in Canada, with some subspecies
438 being given their own COSEWIC rankings while simultaneously not being considered an

individual species in CESSC rankings or by species lists given by groups such as the Canadian Herpetological Society. Such is true for the unisexual mole salamander subspecies (*Ambystoma laterale* - (2) *jeffersonianum*); this specific subspecies of salamander has been assessed and listed as 'Not at Risk' by COSEWIC but is not listed as a species in CESSC data or under the Canadian Herpetological Society. Because of the lack of information surrounding subspecies of salamanders specifically, we chose to not include subspecies in this report, focusing on species and their overall conservation assessments. We did include subspecies for other groups that have more universally accepted taxonomic statuses and conservation assessments. However, it is important to note that this discrepancy is detrimental for species which have subspecies populations at higher risk levels and is something that should be considered and amended in national reports in the future to ensure vulnerable and unique populations are not overlooked.

A major reason for amphibian declines worldwide is chytrid fungus (*Batrachochytrium dendrobatidis*). This disease is thought to have been identified in North America in 1961 (Weldon et al. 2004), perhaps giving time for populations to develop some form of resistance. In tropical areas, amphibians have been exposed more recently, which could account for more severe declines observed in these areas (Ouellet 2005). This would likely explain why amphibian populations in Canada, although threatened, are less drastically threatened by extinction as tropical species overall. Nonetheless, the status of the freshwater herpetofauna of Canada is critically important to monitor, considering that 50% of freshwater reptiles and 31% of freshwater amphibians are currently at risk. The abundance of the herpetofauna data is likely due to the frequent study of both groups in response to habitat and land development interests, as well as their proximity to humans.

Canada's freshwater herpetofauna occupy habitats near shorelines, which are often valuable for land development and other economic activities (Lesbarrères et al. 2014). As such, the conservation status of these species are often assessed to consider potential threats related to land degradation. Stakeholder biases and political pressures to encourage development across the municipal, provincial, and federal levels may also be influential (Lesbarrères et al. 2014). Because northern range herpetofauna have limited suitable habitat in Canada, they often find themselves in densely populated areas such as southern Ontario and southern British Columbia where the climate is milder (Lesbarrères et al. 2014). Therefore, they are typically well-studied species because of their proximity to dense networks of anthropogenic activity.

3.5 Freshwater Birds

There are 678 species of birds reported in Canada, with 144 species (21%) requiring freshwater to complete their life cycle (Wild Species Report 2015). We evaluated the conservation status of all 144 freshwater-dependent bird species and found that 12 species (8.3%) were considered 'Endangered'; 17 species (11.8%) as 'Threatened'; 109 species (75.7%) were not considered to be at risk (21 species as 'Special Concern'; 88 species as 'Not at Risk'); and five species (3.5%) as 'Data Deficient'. Additionally, one species, *Plegais falcinellus*, was not assigned a status as it rarely occurs in Canada. Our analysis showed that 29 species (20.1%) of all freshwater birds in Canada are considered to be at risk. Out of the 24 families, nine had 100% of their species ranked as 'Not at Risk' (Accipitridae, Alcedinidae, Cinclidae, Icteridae, Pandionidae, Passerellidae, Pelecanidae, Troglodytidae, Tyrannidae), eight of the families had 50% or more of their species ranked as 'Not at Risk' (Anatidae, Gaviidae, Gruidae, Hirundinidae, Laridae, Phalacrocoracidae, Rallidae, Recurvirostridae), and seven families had less than 50% of their species ranked as 'Not at Risk' (Ardeidae, Charadriidae, Haematopodidae,

Parulidae, Podicipedidae, Scolopacidae, Threskionithidae). Three of the five assessments ranked as 'Data Deficient' were in the Laridae family. Scolopacidae (shorebirds) had the most species classified as at risk, with eight assessments ranked as 'Special Concern', eight considered 'Threatened', and three as 'Endangered'.

The conservation status of freshwater birds differs greatly among the 24 families of freshwater birds analyzed (Fig. 5). The most noticeable trend was observed in the Scolopacidae, which had the most significant declines in species populations. Scolopacidae is a family of waders or shorebirds. Canada's shorebirds are among the most vulnerable groups of birds in the nation with a 40% decline within populations reported since the 1970s (NABCI 2019). Shorebirds with longer-distance migrations have shown even steeper population declines in comparison to shorter-distance migrators due to the overall declining availability and degrading quality of stop-over habitats (Sutherland et al. 2012; NABCI 2019). Additional threats such as climate change, urban encroachment, industrial development, disturbance, increased predation, hunting, and pollution have been highlighted in contributing to the current population declines (Butler et al. 2004; Lafferty et al. 2006; Goss-Custard et al. 2006, Murray et al. 2014, Drever et al. 2018, Reed et al., 2018). Canada has a particularly unique and important position in that it provides over 75% of the breeding range of North American shorebird species and thus has a major responsibility in ensuring the conservation of these species (Donaldson et al., 2000). Other shorebird families included in our analysis (e.g., Recurvirostridae, Haematopodidae, Charadriidae) should also be carefully monitored for their conservation status as shorebird populations as a whole are vulnerable to declines.

The family Laridae is a group of seabirds including gulls, terns, and skimmers. This family is defined as a group of seabirds; however, these species are widespread throughout

Canada and thus inhabit areas far from the sea and can be fully reliant on freshwaters. Although half of the species in the Laridae family are listed in stable conservation categories, 42% of species are showing population declines and have been considered to be at risk or lack enough data to be fully assessed. Gulls are the most generalist species of all seabirds, occupying a variety of habitats from the arctic to seacoasts, to inland marshes (Burger and Gochfeld 2001). They are also generalist feeders, consuming anything from fish to invertebrates, small mammals, songbirds and famously, garbage (Ewins et al. 1994; Fox et al. 1990). Gull species have long been used as bioindicator species due to their generalist behaviours, as well as their rapid response to changing conditions (Hebert et al. 1999; Furness and Camphuysen 1997; Mallory et al. 2010). Our results should raise some concern considering that bioindicator species reflect the conditions of their environment. Declining populations of Laridae ultimately suggest the degradation of their aquatic habitats. We suggest future studies focus on gathering more information on 'Data Deficient' species as well as closely monitoring all members of the Laridae family; this is not only to gain a better understanding of species trends, but to also help monitor the status and quality of their freshwater habitats.

3.6 Freshwater Mammals

A total of seven mammal species that were deemed freshwater-dependent were evaluated for their conservation status: beaver (*Castor canadensis*), muskrat (*Ondatra zibethicus*), mink (*Mustela vison*), river otter (*Lutra canadensis*), star-nosed mole (*Condylura cristata*), and two species of water shrew (*Sorex palustris* and *Sorex bendirii*). All of the species have had conservation assessments performed. Among species identified, only one species (14%), the Pacific water shrew (*Sorex bendirii*), was assessed as 'Endangered'. The remaining six species (86%) were deemed 'Not at Risk'.

The Pacific water shrew is likely endangered due to habitat degradation in its already limited geographic range. The shrew's habitat consists of wetlands in the areas of southwest British Columbia that are being rapidly urbanized (SCCP 2020; COSEWIC 2006). Population trends are generally unknown for this shrew making it difficult to assess the species throughout its range. Multiple populations of the Pacific water shrew have been known to reside in abundance along the west coast of the United States, making this species only endangered in Canada (Cassola 2016). A recovery strategy for the Canadian populations was proposed in 2014; however, the last known assessment was completed in 2006 (Environment Canada 2014). An updated conservation assessment is needed for evaluating further declines or rebounding populations of this species.

The remaining six species that were assessed as 'Not at Risk' include keystone species such as beaver and river otter. Keystone species are those that have a disproportionately high impact on their surrounding environment and that influence the survival of other species (Bond 1994); thus, maintaining the 'Not at Risk' conservation status of river otter and beaver is important. Interestingly, the comeback of the beaver from intensive hunting in the 1700s and 1800s is a major success story in mammal conservation (Naiman et al. 1988). Currently, there are multiple conservation programs monitoring these keystone species at both a provincial and national level (e.g., National Conservancy Canada, Ontario Fur Managers Federation, Canadian Wildlife Federation). While these species appear to be stable at the national level, there may be regional differences that could warrant the conservation of specific populations at a more limited geographic scale. Similar to all the previous taxonomic groups included in our analysis, freshwater mammals still face local and global threats such as habitat degradation, water pollution, and climate change (He et al. 2017). Although potentially more resilient and common

than some of the other groups discussed, it remains important to monitor freshwater reliant mammal species for changes in population numbers.

4.0 All Taxonomic Groups

Out of 16,384 available assessments of Canada's native species (CESCC 2015), a total of 3,130 species were included in this study, suggesting ~19.1% of all macroscopic species in Canada rely on fresh water to complete part of their life cycle. One-third of all vertebrate species on Earth are confined to freshwater habitats, yet datasets on these organisms remain largely incomplete even within well-studied taxa such as fishes (Stiassny 2002; Dudgeon et al. 2006). Our findings highlight the large data deficiency among freshwater macroscopic species, with a total of 37.9% (1186, Fig. 6; Table S1³) of all freshwater species lacking enough information for proper conservation status assessment, with a majority of data deficiency observed within the invertebrate taxa. This information is considered crucial to understanding the status of freshwater biodiversity. It is also important to recognize that although species may be listed as ‘Not at Risk’ or as ‘Special Concern’, they could be exposed to rapid habitat destruction and could decrease in abundance at a similar rate. Conservation assessments do not necessarily represent the immediate status of particular species, though they are important in providing a robust description of the state of biodiversity in Canada.

Data deficiencies were especially evident for the invertebrate species evaluated in this report. Our results supported previous research where globally, invertebrates are the most data deficient in terms of status and diversity of species (Dudgeon et al. 2006). Invertebrates represented most of the species included in this study (62.4%), yet less than half were assessed for their conservation status, compared to 95% of vertebrates having assessments and 92% of

³ Supplementary table is available with the article through the journal website

plants. Invertebrates have high species richness and play critical functional roles, yet have received little attention in comparison to vertebrates. Invertebrates are generally not considered charismatic and do not garner as much public interest for motivating conservation initiatives relative to vertebrates (Bland et al. 2012; Barua et al. 2012; Collier et al. 2016). This bias hinders our ability to properly assess the extinction risk that invertebrates face (Bland et al. 2012). Considering the high species richness and the urgency to protect freshwater biodiversity, we suggest implementing management strategies that assess areas of high biodiversity rather than assessing each species individually. This review of the current state of species assessments in Canada's fresh waters clearly indicates a need to raise awareness among the general public, while bridging the gap between the scientific community and government policymakers (e.g. Rose et al. 2018).

Other major taxonomic groups such as plankton and bacteria also play fundamental roles in ecosystem health but are missing in our analyses due to a dearth of information. The lack of data is largely due to the difficulties associated with monitoring micro-eukaryotes, which can prove to be a challenging feat due to their microscopic size and vast species richness (Xiong et al. 2020). However, metabarcoding approaches are becoming increasingly popular (Hering et al. 2018) and will likely facilitate further efforts to study the distribution and dynamics of these poorly-studied taxonomic groups within Canada.

Anthropogenic threats such as habitat degradation, invasive species, and climate change continue to impair freshwater ecosystems, contributing to rapid biodiversity loss (Garcia-Morena et al. 2014). Efforts to understand freshwater biodiversity must be employed as soon as possible for all freshwater taxa in order to prevent further loss under increased anthropogenic pressures. Canada has the third largest national reservoir of fresh water in the world (FAO 2003), and the

598 global need for fresh waters may put added pressure on Canada and its freshwater biota in the
599 future.

600 The largest proportion of at-risk assessments were observed in reptiles and amphibians
601 (Fig. 7). The overall rankings were distinguished as follows, from most to least at risk: 50%
602 (eight species) of freshwater reptiles; 31.1% (14 species) of freshwater amphibians; 20.1% (29
603 species) of freshwater birds; 18.6% (38 species) of freshwater fishes; 18.5% (141 species) of
604 freshwater plants; and 14.3% (one species) of freshwater mammals. Our study reveals that a total
605 of 11.7% (367 species) of Canada's freshwater biodiversity is currently at risk, which could be
606 either an over- or under-estimate, depending on the remaining 37.9% (1186 species) that lack a
607 status ranking. An additional 17.9% of species are ranked as 'Special Concern' and could
608 progress to more severe assessments if threats are not addressed. Research shows that freshwater
609 invertebrates, fishes, and herpetofauna in North America are facing extinction rates as much as
610 five times higher than their terrestrial counterparts (Ricciardi & Rasmussen 1999). It is crucial to
611 acknowledge the current state of Canada's freshwater biology to bend the curve in biodiversity
612 loss.

613 While our Canada-wide study identifies substantial proportions of at risk and data
614 deficient species, similar trends have been observed on many scales across the globe.
615 Abundances of freshwater insects (Sánchez-Bayo and Wyckhuys 2019; Wagner 2019),
616 freshwater fish populations (Freyhof and Brooks 2017, WWF 2021), especially large fishes such
617 as sturgeon and paddlefish (Carrizo et al. 2017; He et al. 2019), as well as freshwater reptiles
618 (Gibbons et al. 2000) and amphibians (Gibbons et al. 2000; Vences and Köhler 2007), have been
619 declining at local and regional scales throughout a range of latitudes (Albert et al. 2021). The
620 Living Planet Index, which evaluates closely monitored vertebrates by considering species

richness, also shows that freshwater populations have been experiencing declines of 84% between 1970 and 2014. While it is important to note that the quantity of data prior to 1970 was limited and advances in conservation biology led to a shifting baseline syndrome (i.e., Pauly 1995; Papworth et al. 2009), the decline of freshwater biodiversity is still outpacing both the marine and terrestrial environments (WWF 2020).

Data deficiency has been identified as one of the major ongoing issues in assessing or monitoring the state of freshwater biodiversity (Balian et al. 2007). Studies that assess the state of freshwater biodiversity report high occurrences of ‘Data Deficient’ assessments (e.g., 60% of Canada’s sub-watersheds, 31.3% in the Eastern Himalayas, 21% in Central Africa, and 14.1% in North Africa, WWF-Canada 2020; Allen 2010; Brooks et al. 2011; García et al. 2010, respectively). The lack of data on the conservation status of freshwater-dependent species in Canada and throughout the rest of the world has been a limiting factor in establishing and achieving conservation goals (Darwall et al. 2011). Although some studies advocate for data deficiency to be perceived as ‘presumed threatened’, we opted to provide a more accurate description of the current state of biodiversity by suggesting that not all data deficient species are likely to be at risk. It is important to acknowledge that conservation initiatives tailored towards addressing data deficiency can be vastly different from those that target threatened species; both are important for safeguarding biodiversity.

Considering the general declining trends and paucity in data, we advocate that it is essential to bridge the gap between freshwater ecology and conservation regardless of incomplete knowledge to ensure sustainable freshwater resources (Strayer and Dudgeon 2010; Albert et al. 2021). Targeting key areas and unique ecosystems that are home to a diversity of taxa (e.g., key biodiversity areas, Eken et al. 2004) can prevent further decline while avoiding

taxonomic bias. As we improve protocols and grow reference libraries, it is possible that major leaps forward in biodiversity assessments across landscapes and through time (by studying natural archives such as lake sediment cores) will be possible by adopting environmental DNA analyses in routine monitoring programs (Balint et al. 2018, Perez-Jvostov et al. 2020). Although the current state of freshwater biodiversity in Canada is alarming, the future will be largely shaped by the timely implementation of the Emergency Recovery Plan to bend the curve of freshwater biodiversity loss (Tickner et al. 2020). This plan recommends a number of actions that targets key threats, such as improving water quality, implementation of environmental flows, protecting and restoring critical habitats, managing the exploitation of freshwater ecosystem resources, preventing and controlling non-native species invasions, and restoring river connectivity (Tickner et al. 2020). Implementing the plan will require the collective action of many including practitioners (Twardek et al. In Press) and communities (Arthington 2021).

Conclusion

Canada has the third largest reservoir of freshwaters of any country. Yet, there is a paucity of knowledge surrounding the status of much of Canada's freshwater biodiversity. To address this knowledge gap, the most recent data on the conservation status of freshwater species in Canada were compiled and analysed. Our analysis revealed that 11.7% (367) of freshwater species were considered to be at risk, 50.5% (1,575) of species were not considered to be at risk ('Special Concern' or 'Not at Risk'). The remaining 37.9% (1,186) of species could not be classified due to the lack of available data. Given the importance of freshwater biodiversity to ecosystems and societies alike, the 11.7% that were at risk, extirpated or extinct, and the 37.9% without data to assess their status, suggests emergency action is needed. We advocate for a coordinated call-to-action by public and private sectors as well as citizens to improve our state-

of-knowledge on freshwater biodiversity, to overcome knowledge gaps, and to work to reduce if not reverse the freshwater biodiversity declines.

We acknowledge that knowing the state of freshwater biodiversity is not a prerequisite for embracing the emergency action plan (Tickner et al. 2020) but doing so will be important to assess progress. Although we certainly call for more monitoring and assessment (such as the recent GEO BON initiatives that are being downscaled and in Canada will presumably lead to a CAN BON initiative; see <https://www.theglobeandmail.com/canada/article-harmonizing-co-ordinating-scientific-initiatives-key-to-filling-gaps/>), we also recognize the importance of action. Indeed, a recent analysis in Canada suggested that although lack of knowledge about the status of biodiversity was important, the most significant barrier to conservation action were mechanisms to translate knowledge to action (Buxton et al. 2021). Some actions can be undertaken without explicit knowledge about the state of all aspects of biodiversity. For example, we suggest that resources be allocated towards protecting functional ecosystems that include high levels of species richness from all taxonomic groups (e.g., key biodiversity areas, Eken et al. 2004) to prevent taxonomic bias in conservation initiatives. There are also opportunities to embrace additional conservation approaches such as citizen (or community) science (Chandler et al. 2017), Indigenous knowledge systems (Reid et al. 2020; Buxton et al. 2021), and emerging technologies (such as environmental DNA; Deiner et al. 2015) to help address these deficiencies. The vast amount of fresh water in Canada does not make the country immune to freshwater threats and biodiversity loss. This paper should serve as a call to action for academia, governments, and community members alike. Freshwater biodiversity and healthy freshwater ecosystems are foundational to the well-being of all beings and peoples in Canada, and it is clear

that we have major knowledge gaps that need to be overcome if we are to better ensure the continuation and effective protection of fresh waters and their biota well into the future.

Author statements

Acknowledgments

Funding for this project was made possible through the Fulbright Canada Fellowship awarded to P.C., the Social Sciences and Humanities Research Council of Canada Knowledge Synthesis Grant awarded to S.J.C., J.B., I.C., J.P.S., and I.G.E., and support from the Canada Research Chairs program and the Natural Sciences and Engineering Research Council of Canada. We would also like to thank the two anonymous reviewers for their input that greatly improved the quality of this manuscript.

Competing interests

The authors declare there are no competing interests.

Contributors' statement

This project was conceptualized by SJC, DH, PC, JED, JC, EJH, AMJ, JAR, and SS as part of a graduate course offered by SJC at Carleton University. JED, JC, EJH, AMJ, JAR, and SS contributed to the data collection and writing. JED generated figures and performed major edits. JRB, JPS, TR, JJT, ALM, AKW, JM, MKT, CMO, SAR, AJR, IFC, IG-E, NWRL, SJC, PC, and DH provided comments and guidance that greatly improved the quality of this manuscript.

Funding statement

Funding for this project was made possible through the Fulbright Canada Fellowship awarded to P.C., the Social Sciences and Humanities Research Council of Canada Knowledge

712 Synthesis Grant awarded to S.J.C., J.B., I.C., J.P.S., and I.G.E., and support from the Canada
713 Research Chairs program and the Natural Sciences and Engineering Research Council of
714 Canada.

715 **Data availability statement**

716 Data is available with the published manuscript online through the journal website.

Draft

718 **References**

- 719 Abell, R. 2002. Conservation biology for the biodiversity crisis: a freshwater follow-up.
720 *Conserv. Biol.* **16**:1435-1437.
- 721 Albert, J.S., Destouni, G., Duke-Sylvester, S.M., Magurran, A.E., Oberdorff, T., Reis, R.E.,
722 Winemiller, K.O. and Ripple, W.J., 2020. Scientists' warning to humanity on the
723 freshwater biodiversity crisis. *Ambio* pp.1-10.
- 724 Allen, D.J. 2010. The status and distribution of freshwater biodiversity in the Eastern Himalaya.
725 IUCN.
- 726 Ames, Jr. T. 2008. Caddisflies: A Guide to Eastern Species for Anglers and Other Naturalists.
727 Stackpole Books. Mechanicsburg, PA.
- 728 Arthington, A.H. 2021. Grand challenges to support the Freshwater Biodiversity Emergency
729 Recovery Plan. *Front. Environ. Sci.* <https://doi.org/10.3389/fenvs.2021.664313>
- 730 Baker, S. M., and Levinton, J. S. 2003. Selective feeding by three native North American
731 freshwater mussels implies food competition with zebra mussels. *Hydrobiologia* **505**: 97-
732 105.
- 733 Balian, E.V., Segers, H., Martens, K., Lévêque, C. 2007. The freshwater animal diversity
734 assessment: an overview of the results. In: Balian, E.V., Segers, H., Martens, K.,
735 Lévêque, C. (eds) *Freshwater animal diversity assessment*. Springer, Dordrecht, pp 627-
736 637.
- 737 Barua, M., Gurdak, D.J., Ahmed, R.A., Tamuly, J. 2012. Selection of flagships for invertebrate
738 conservation. *Biodivers. Conserv.* **21**:1457-1476.
- 739 Bland, L.M., Collen, B., Orme, C.D.L., Bielby, J. 2012. Data uncertainty and the selectivity of
740 extinction risk in freshwater invertebrates. *Divers Distrib* **18**:1211-1220.

- 741 Bond, W. 1994. Keystone species. In: Schulze E, Mooney HA (eds) Biodiversity and ecosystem
742 function. Springer, Berlin, pp. 237-253.
- 743 Brooks, E.G.E., Allen, D.J., Darwall, W.R. 2011. The status and distribution of freshwater
744 biodiversity in central Africa. IUCN.
- 745 Brown, C.L., Hecnar, S.J. 2007. Species loss and shifting population structure of freshwater
746 turtles despite habitat protection. *Biol Conserv* 138:421-429
- 747 Burger, J., Gochfeld, M. 2001. Laridae, sternidae, and rynchopidae. In: Steele JH (ed)
748 Encyclopedia of Ocean Sciences Elsevier, 2nd edn, pp.18-30.
749 <https://doi.org/10.1016/B978-0-12-409548-9.11521-0>
- 750 Butler, R.W., Ydenberg, R.C., Donaldson, G.D., Brown, S. 2004. Hypotheses to explain census
751 declines in North American shorebirds. Shorebird Research Group of the Americas
752 Report 1.
- 753 Buxton, R.T., Bennett, J.R., Reid, A.J., Shulman, C., Cooke, S.J., Francis, C.M., Nyboer, E.A.,
754 Pritchard, G., Binley, A.D., Avery-Gomm, S. and Ban, N.C., 2021. Key information
755 needs to move from knowledge to action for biodiversity conservation in Canada. *Biol*
756 *Conserv* 256:108983.
- 757 Canadian Endangered Species Conservation Council (2016) Wild Species 2015: The General
758 Status of Species in Canada. National General Status Working Group. Available:
759 [https://www.canada.ca/en/environment-climate-change/services/species-risk-public-](https://www.canada.ca/en/environment-climate-change/services/species-risk-public-registry/publications/wild-species-2015.html)
760 [registry/publications/wild-species-2015.html](https://www.canada.ca/en/environment-climate-change/services/species-risk-public-registry/publications/wild-species-2015.html)
- 761 Canadian Wildlife Federation (CWF). 2020. Turtle Resources: Red Eared Slider. Available:
762 www.cwf-fcf.org. Accessed 20 November 2020

- 763 Carrizo, S.F., Jähnig, S.C., Bremerich, V., Freyhof, J., Harrison, I., He, F., Langhans, S.D.,
764 Tockner, K., Zarfl, C. and Darwall, W., 2017. Freshwater megafauna: Flagships for
765 freshwater biodiversity under threat. *Bioscience* **67**:919-927.
- 766 Cassola, F. 2016. *Sorex bendirii* (errata version published in 2017). *The IUCN Red List of*
767 *Threatened Species* 2016:
768 e.T41389A115183051.[https://dx.doi.org/10.2305/IUCN.UK.2016-](https://dx.doi.org/10.2305/IUCN.UK.2016-3.RLTS.T41389A22313946.en)
769 [3.RLTS.T41389A22313946.en](https://dx.doi.org/10.2305/IUCN.UK.2016-3.RLTS.T41389A22313946.en). Accessed 20 Nov 2020
- 770 Chandler, M., See, L., Copas, K., Bonde, A.M., López, B.C., Danielsen, F., Legind, J.K.,
771 Masinde, S., Miller-Rushing, A.J., Newman, G. and Rosemartin, A., 2017. Contribution
772 of citizen science towards international biodiversity monitoring. *Biol. Conserv.* **213**:280-
773 294.
- 774 Chambers, P.A., Lacoul, P., Murphy, K.J., Thomaz, S.M. 2007. Global diversity of aquatic
775 macrophytes in freshwater. In: Balian, E.V., Lévêque, C., Segers, H., Martens, K. (eds)
776 *Freshwater Animal Diversity Assessment. Developments in Hydrobiology*, vol 198.
777 Springer, Dordrecht. pp 9-26 https://doi.org/10.1007/978-1-4020-8259-7_2
- 778 Collier, K.J., Robert, P.K., Jeffries, M. 2016. Conservation of aquatic invertebrates: concerns,
779 challenges and conundrums. *Aquat. Conserv.* **26**:817-837
- 780 COSEWIC. 2005. COSEWIC Assessment and Status Report on the Prototype Quillwort *Isoetes*
781 *prototypus* in Canada, Ottawa: Committee on the Status of Endangered Wildlife in
782 Canada.
- 783 COSEWIC. 2006. COSEWIC assessment and update status report on the Pacific watershrew
784 *Sorex bendirii* in Canada, Ottawa: Committee on the Status of Endangered Wildlife in
785 Canada.

- 786 COSEWIC, COSEPAC. 2012. List of Prioritized Crustaceans and Related Groups at Risk in
787 Canada. Available:
788 [https://cosewic.ca/images/cosewic/pdf/Crustaceans_Special_report_related_groups_at_ris](https://cosewic.ca/images/cosewic/pdf/Crustaceans_Special_report_related_groups_at_risk_2012_e.pdf?fbclid=IwAR1fmKooke4c9EZquTbmlpRVyc019Yac3ULuEUjoNVLA-b9RQHQqe_calw4)
789 [k_2012_e.pdf?fbclid=IwAR1fmKooke4c9EZquTbmlpRVyc019Yac3ULuEUjoNVLA-](https://cosewic.ca/images/cosewic/pdf/Crustaceans_Special_report_related_groups_at_risk_2012_e.pdf?fbclid=IwAR1fmKooke4c9EZquTbmlpRVyc019Yac3ULuEUjoNVLA-b9RQHQqe_calw4)
790 [b9RQHQqe_calw4](https://cosewic.ca/images/cosewic/pdf/Crustaceans_Special_report_related_groups_at_risk_2012_e.pdf?fbclid=IwAR1fmKooke4c9EZquTbmlpRVyc019Yac3ULuEUjoNVLA-b9RQHQqe_calw4). Accessed 12 Dec 2020.
- 791 Creed, I.F., Lane, C.R., Serran, J.N., Alexander, L.C., Basu, N.B., Calhoun, A.J., Christensen,
792 J.R., Cohen, M.J., Craft, C., D'Amico, E. and DeKeyser, E., 2017. Enhancing protection
793 for vulnerable waters. *Nat. Geosci.* **10**:809-815.
- 794 Darwall, W.R., Holland, R.A., Smith, K.G., Allen, D., Brooks, E.G., Katarya, V., Pollock, C.M.,
795 Shi, Y., Clausnitzer, V., Cumberlidge, N. and Cuttelod, A. 2011. Implications of bias in
796 conservation research and investment for freshwater species. *Conserv. Lett.* **4**:474-482.
- 797 Deinet, S., Scott-Gatty, K., Rotton, H., Twardek, W.M., Marconi, V., McRae, L., Baumgartner,
798 L.J., Brink, K., Claussen, J.E., Cooke, S.J., Darwall, W., Eriksson, B.K., Garcia de
799 Leaniz, C., Hogan, Z., Royte, J., Silva, L.G.M., Thieme, M.L., Tickner, D., Waldman, J.,
800 Wanningen, H., Weyl, O.L.F., Berkhuysen, A. 2020. The Living Planet Index (LPI) for
801 migratory freshwater fish - Technical Report. World Fish Migration Foundation, The
802 Netherlands.
- 803 Deiner, K., Walser, J.C., Mächler, E., Altermatt, F. 2015. Choice of capture and extraction
804 methods affect detection of freshwater biodiversity from environmental DNA. *Biol.*
805 *Conserv.* **183**:53-63.
- 806 Donaldson, G.M., Hyslop, C., Morrison, R.I.G., Dickinson, H.L., Davidson, I. 2000. Canadian
807 shorebird conservation plan. Canadian Wildlife Service, Environment Canada, Ottawa,
808 Ontario.

- 809 Donaldson, M.R., Burnett, N.J., Braun, D.C., Suski, C.D., Hinch, S.G., Cooke, S.J., Kerr, J.T.
810 2016. Taxonomic bias and international biodiversity conservation research. *FACETS*
811 **1**:105-113.
- 812 Drever, M.C., Provencher, J.F., O'Hara, P.D., Wilson, L., Bowes, V., Bergman, C.M. 2018. Are
813 ocean conditions and plastic debris resulting in a 'double whammy' for marine birds?
814 *Mar. Pollut. Bull.* **133**:684–692.
- 815 Dudgeon, D. 2010. Prospects for sustaining freshwater biodiversity in the 21st century: linking
816 ecosystem structure and function. *Curr. Opin. Environ. Sustain.* **2**:422-430.
- 817 Dudgeon, D., Arthington, A.H., Gessner, M.O., Kawabata, Z.I., Knowler, D.J., Lévêque, C.,
818 Naiman, R.J., Ne Prieur-Richard, A.-H., Soto, D., Stiassny, M.L.J., Sullivan, C.A. 2006.
819 Freshwater biodiversity: importance, threats, status and conservation challenges.
820 Cambridge Philosophical Society **81**:163–182.
- 821 Eken, G., Bennun, L., Brooks, T.M., Darwall, W., Fishpool, L.D.C., Foster, M., Knox, D.,
822 Langhammer, P., Matiku, P., Radford, E., Salaman, P., Sechrest, W., Smith, M.L.,
823 Spector, S., Tordoff, A. 2004. Key Biodiversity Areas as Site Conservation Targets.
824 *Bioscience* **54**:1110-1118.
- 825 Enns, A., Kraus, D., Hebb, A. 2020. Ours to save: the distribution, status and conservation needs
826 of Canada's endemic species. NatureServe Canada and Nature Conservancy of Canada.
- 827 Environment Canada. 2014. Recovery Strategy for the Pacific Water Shrew (*Sorex bendirii*) in
828 Canada [Proposed]. Species at Risk Act Recovery Strategy Series. Environment Canada,
829 Ottawa. 35 pp. + Appendix.
- 830 Epanchin, P.N., Knapp, R.A., Lawler, S.P. 2010. Nonnative trout impact an alpine-nesting bird
831 by altering aquatic-insect subsidies. *Ecology* **91**:2406-2415.

- 832 Ewins, P.J., Weseloh, D.V., Groom, J.H., Dobos, R.Z., Mineau, P. 1994. The diet of Herring
833 Gulls (*Larus argentatus*) during winter and early spring on the lower Great Lakes.
834 Hydrobiologia **279**:39–55.
- 835 Favaro, B., Claar, D.C., Fox, C.H., Freshwater, C., Holden, J.J., Roberts, A. 2014. Trends in
836 extinction risk for imperiled species in Canada. PLoS One
837 doi:<https://doi.org/10.1371/journal.pone.0113118>
- 838 Froese, R., Pauly, D. Editors. 2019. FishBase. World Wide Web electronic publication.
839 <http://www.fishbase.org>. Accessed 10 Oct 2020.
- 840 Fisheries and Oceans Canada. 2015. Survey of Recreational Fishing in Canada, 2015. Ottawa,
841 Ontario. Catalogue no. 978-0-660-29278-6.
- 842 Food and Agriculture Organization of the United Nations. 2003. Review of World Water
843 Resources by Country. Rome.
844 www.fao.org/landandwater/aglw/aquastat/water_res/index.stm. Accessed 12 January
845 2021.
- 846 Fox, G.A., Allan, L.J., Weseloh, D.V., Mineau, P. 1990. The diet of herring gulls during the
847 nesting period in Canadian waters of the Great Lakes. Can. J. Zool. **68**:1075-1085.
- 848 Freyhof, J., Brooks, E. 2017. European red list of freshwater fishes. Luxembourg: Publications
849 Office of the European Union.
- 850 Furness, R.W., Camphuysen, C.J. 1997. Seabirds as monitors of the marine environment. ICES
851 J. Mar. Sci. **54**:726-737.
- 852 Garcia-Moreno, J., Harrison, I.J., Dudgeon, D., Clausnitzer, V., Darwall, W., Farrell, T., Savy,
853 C., Tockner, K., Tubbs, N. 2014. In: Bhaduri, A., Bogardi, J., Leentvaar, J., Marx, S.

- 854 (eds.) Sustaining Freshwater Biodiversity in the Anthropocene. The Global Water System
855 in the Anthropocene. Springer Water. pp 247-270.
- 856 García, N., Cuttelod, A., Malak, D.A. 2010. The status and distribution of freshwater
857 biodiversity in Northern Africa. IUCN.
- 858 Garnier, S. 2018. Viridis: Default Color Maps from ‘matplotlib’. R package version 0.5.1.
- 859 Gibbons, J.W., Scott, D.E., Ryan, T.J., Buhlmann, K.A., Tuberville, T.D., Metts, B.S., Greene,
860 J.L., Mills, T., Leiden, Y., Poppy, S. and Winne, C.T., 2000. The Global Decline of
861 Reptiles, Déjà Vu Amphibians: Reptile species are declining on a global scale. Six
862 significant threats to reptile populations are habitat loss and degradation, introduced
863 invasive species, environmental pollution, disease, unsustainable use, and global climate
864 change. *BioScience* **50**:653-666.
- 865 Goss-Custard, J.D.D., Triplet, P., Sueur, F., West, A.D.D. 2006. Critical thresholds of
866 disturbance by people and raptors in foraging wading birds. *Biol. Conserv.* **127**:88–97.
- 867 Gu, Z. 2014. circlize implements and enhances circular visualization in R. *Bioinformatics*.
- 868 Hanna, D.E., Tomscha, S.A., Ouellet Dallaire, C. and Bennett, E.M., 2018. A review of riverine
869 ecosystem service quantification: research gaps and recommendations. *J. Appl.*
870 *Ecol.* **55**:1299-1311.
- 871 Harrison, I., Abell R., Darwall W., Thieme M.L., Tickner, D., Timboe, I. 2018. The freshwater
872 biodiversity crisis. *Science* **362**:1369-1369.
- 873 He, F., Zarfl, C., Bremerich, V., David, J.N., Hogan, Z., Kalinkat, G., Tockner, K., Jähnig, S.C.
874 2019. The global decline of freshwater megafauna. *Glob. Change. Biol.* **25**:3883–3892.

- 875 He, F., Zarfl, C., Bremerich, V., Henshaw, A., Darwall, W., Tockner, K., Jaehnig, S.C. 2017.
876 Disappearing giants: a review of threats to freshwater megafauna. Wiley Interdisciplinary
877 Reviews: Water 4:e1208.
- 878 Hebert, C.E., Shutt, J.L., Hobson, K.A., Weseloh, D.V. 1999. Spatial and temporal differences in
879 the diet of Great Lakes herring gulls (*Larus argentatus*): evidence from stable isotope
880 analysis. Can. J. Fish. Aquat. Sci. **56**:323-338.
- 881 Hering, D., Borja, A., Jones, J.I., Pont, D., Boets, P., Bouchez, A., Bruce, K., Drakare, S.,
882 Hänfling, B., Kahlert, M. and Leese, F. 2018. Implementation options for DNA-based
883 identification into ecological status assessment under the European Water Framework
884 Directive. Water Res. **138**:192-205.
- 885 Jacobus, L.M., Macadam, C.R., Sartori, M. 2019. Mayflies (Ephemeroptera) and Their
886 Contributions to Ecosystem Services. Insects **10**:1–26.
- 887 Jain, S. 1990. Conservation of aquatic plants. Ecology and management of aquatic vegetation in
888 the Indian Subcontinent pp. 237-241.
- 889 Lafferty, K.D., Goodman, D., Sandoval, C.P. 2006. Restoration of breeding by snowy plovers
890 following protection from disturbance. Biodivers. Conserv. **15**:2217.
- 891 Lake, P., Palmer, M.A., Biro, P., Cole, J., Covich, A.P., Dahm, C., Gibert, J., Goedkoop, W.,
892 Martens, K., Verhoeven, J. 2000. Global change and the biodiversity of freshwater
893 ecosystems: Impacts on linkages between above-sediment and sediment biota. Bioscience
894 **50**:1099–1107.

- 895 Leemans, R., de Groot, R.S. 2003. Millennium Ecosystem Assessment: Ecosystems and human
896 well-being: a framework for assessment. (Millenium assessment contribution). Island
897 Press. <https://edepot.wur.nl/22188>
- 898 Lesbarrères, D., Ashpole, S.L., Bishop, C.A., Blouin-Demers, G., Brooks, R.J., Echaubard, P.,
899 Govindarajulu, P., Green, D.M., Hecnar, S.J., Herman, T., Houlihan, J., Litzgus, J.D.,
900 Mazerolle, M.J., Paszkowski, C.A., Rutherford, P., Schock, D.M., Storey, K.B.,
901 Loughheed, S.C. 2014. Conservation of herpetofauna in northern landscapes: Threats and
902 challenges from a Canadian perspective. *Biol. Conserv.* **170**:48-55.
- 903 Mallory, M.L., Robinson, S.A., Hebert, C.E., Forbes, M.R. 2010. Seabirds as Indicators of
904 Aquatic Ecosystem Conditions: A Case for Gathering Multiple Proxies of Seabird Health.
905 *Mar. Pollut. Bull.* **60**:7–12.
- 906 Milanovich, J.R., Peterman, W.E., Nibbelink, N.P., Maerz, J.C. 2010. Projected loss of a
907 salamander diversity hotspot as a consequence of projected global climate change. *PloS*
908 *one* **5**:e12189.
- 909 MNRF. 2019. Eurasian water milfoil. [https://www.ontario.ca/page/eurasian-water-](https://www.ontario.ca/page/eurasian-water-milfoil#section-1)
910 [milfoil#section-1](https://www.ontario.ca/page/eurasian-water-milfoil#section-1). Accessed 24 January 2021.
- 911 Monk, W.A. and Baird, D.J. 2014. Biodiversity in Canadian lakes and rivers. Canadian
912 Biodiversity: Ecosystem Status and Trends 2010, Technical Thematic Report No. 19.
913 Canadian Councils of Resource Ministers. Ottawa, ON. vi +92 p.
914 <http://www.biodivcanada.ca/default.asp?lang=En&n=137E1147-1>
- 915 Murray, N.J., Clemens, R.S., Phinn, S.R., Possingham, H.P., Fuller, R.A. 2014. Tracking the
916 rapid loss of tidal wetlands in the Yellow Sea. *Front. Ecol. Environ.* **12**:267–272.

- 917 Naiman, R. J., Johnston, C. A., Kelley, J. C. 1988. Alteration of North American streams by
918 beaver. *BioSci.* **38**:753–762.
- 919 North American Bird Conservation Initiative (NABCI). 2019. The State of Canada's Birds.
920 Available: www.stateofcanadasbirds.org
- 921 Olden, J.D., Hogan, Z.S., Zanden, M.J.V. 2007. Small fish, big fish, red fish, blue fish:
922 size-biased extinction risk of the world's freshwater and marine fishes. *Glob. Ecol.*
923 *Biogeogr.* **16**:694-701.
- 924 Ouellet, M., Mikaelian, I., Pauli, B.D., Rodrigue, J., Green, D.M. 2005. Historical evidence of
925 widespread chytrid infection in North American amphibian populations. *Conserv. Biol.*
926 **19**:1431-1440.
- 927 Papworth, S.K., Rist, J., Coad, L., Milner-Gulland, E.J. 2009. Evidence for shifting baseline
928 syndrome in conservation. *Conserv. Lett.*, **2**:93-100.
- 929 Pauly, D., 1995. Anecdotes and the shifting baseline syndrome of fisheries. *Trends Ecol. Evol.*
930 **10**:430.
- 931 Pérez-Jvostov, F., Sutherland, W.J., Barrett, R.D., Brown, C.A., Cardille, J.A., Cooke, S.J.,
932 Cristescu, M.E., St-Gelais, N.F., Fussmann, G.F., Griffiths, K., Hendry, A.P. 2020.
933 Horizon scan of conservation issues for inland waters in Canada. *Can J Fish Aquat*
934 *Sci* **77**:869-881.
- 935 Pikitch, E.K., Doukakis, P., Lauck, L., Chakrabarty, P., Erickson, D.L. 2005. Status, trends and
936 management of sturgeon and paddlefish fisheries. *Fish. Fish.* **6**:233-265.
- 937 Postel, S., Carpenter, S. 1997. Freshwater ecosystem services. In: *Daily GC Nature's Services:*
938 *Societal Dependence on Ecosystem Services.* Island Press, Washington D.C., U.S.A. pp.
939 195-214

- 940 Prommi, T.O. 2018. Ecological and Economic Importance of Trichoptera (Aquatic Insect).
941 Kasetsart University, Kamphaeng Saeng, Thailand.
942 <http://www.thaiscience.info/Journals/Article/SDUJ/10989801.pdf>. Accessed on: 20
943 November 2020.
- 944 R Core Team. 2016. R: A language and environment for statistical computing. R Foundation for
945 Statistical Computing, Vienna, Austria.
- 946 Rainer, R., Bennett, B., Blaney, S., Enns, A., Henry, P., Lofroth, E., Mackenzie, J. 2017. On
947 Guard for Them: Species of Global Conservation Concern in Canada. NatureServe
948 Canada: Ottawa, ON.
- 949 Raymond, C.V., Wen, L., Cooke, S.J. Bennett, J.R., 2018. National attention to endangered
950 wildlife is not affected by global endangerment: A case study of Canada's species at risk
951 program. Environmental Science & Policy **84**:74-79.
- 952 Reed, E.T., Kardynal, K.J., Horrocks, J.A., Hobson, K.A. 2018. Shorebird hunting in Barbados:
953 Using stable isotopes to link the harvest at a migratory stopover site with sources of
954 production. Condor **120**:357-370.
- 955 Reid, A.J., Carlson, A.K., Creed, I.F., Eliason, E.J., Gell, P.A., Johnson, P.T.J., Kidd, K.A.,
956 MacCormack, T.J., Olden, J.D., Ormerod, S.J., Smol, J.P., Taylor, W.W., Tockner, K.,
957 Vermaire, J.C., Dudgeon, D., Cooke, S.J. 2019. Emerging threats and persistent
958 conservation challenges for freshwater biodiversity. Biol. Rev. Camb. Philos. Soc.
959 **94**:849-873.
- 960 Reid, A.J., Eckert, L.E., Lane, J.F., Young, N., Hinch, S.G., Darimont, C.T., Cooke, S.J., Ban,
961 N.C., Marshall, A. 2021. "Two-Eyed Seeing": An Indigenous framework to transform
962 fisheries research and management. Fish Fish. **22**:243-261.

- 963 Ricciardi, A., Rasmussen, J.B. 1999. Extinction rates of North American freshwater fauna.
964 *Conserv. Biol.* **13**:220–222.
- 965 Rose, D.C., Sutherland, W.J., Amano, T., González-Varo, J.P., Robertson, R.J., Simmons, B.I.,
966 Wauchope, H.S., Kovacs, E., Durán, A.P., Vadrot, A.B., Wu, W. 2018. The major
967 barriers to evidence-informed conservation policy and possible solutions. *Conserv.*
968 *Lett.* **11**:p.e12564.
- 969 Rozon, R.M., Bowen, K.L., Niblock, H.A., Fitzpatrick, M.A.J., Currie, W.J.S. 2016. Assessment
970 of the phytoplankton and zooplankton populations in the Niagara River (Canada) Area of
971 Concern in 2014. Canadian Technical Report of Fisheries and Aquatic Sciences 3184.
972 <https://waves-vagues.dfo-mpo.gc.ca/Library/4059760x.pdf>
- 973 Samarasin, P., Minns, C.K., Shuter, B.J., Tonn, W.M., Rennie, M.D. 2015. Fish diversity and
974 biomass in northern Canadian lakes: northern lakes are more diverse and have greater
975 biomass than expected based on species–energy theory. *Can. J. Fish. Aquat. Sci.* **72**:226-
976 237.
- 977 Sánchez-Bayo, F., Wyckhuys, K.A. 2019. Worldwide decline of the entomofauna: A review of
978 its drivers. *Biol. Conserv.* **232**:8–27.
- 979 SCCP. 2020. Pacific Water Shrew. <http://www.sccp.ca/species-habitat/pacific-water-shrew>.
980 Accessed 13 November 2020.
- 981 Scheffer, M., Hosper, S.H., Meijer, M.L., Moss, B., Jeppesen, E. 1993. Alternative equilibria in
982 shallow lakes. *Trends Ecol. Evol.* **8**:275-9. Doi: 10.1016/0169-5347(93)90254-M. PMID:
983 21236168.
- 984 Schloesser, J., Quinlan, H., Pratt, T. 2016. Report: Lake Superior’s Lake Sturgeon Index Survey.

- 985 Scott, W.B., Crossman, E.J. 1973. Freshwater Fishes of Canada. Galt House Publications Ltd:
986 82-89.
- 987 Sesin, V., Dalton, R.L., Boutin, C., Robinson, S.A., Bartlett, A.J., Pick, F.R. 2018. Macrophytes
988 are highly sensitive to the herbicide diquat dibromide in test systems of varying
989 complexity. *Ecotoxicology and Environmental Safety*. *Ecotox. Environ. Saf.* **165**:325-
990 333.
- 991 Smith, T., Desser, S.S., Martin, D.S. 1994. The development of *Hepatozoon sipedon* sp. nov.
992 (*Apicomplexa*: *Adeleina*: *Hepatozoidae*) in its natural host, the Northern water snake
993 (*Nerodia sipedon sipedon*), in the culicine vectors *Culex pipiens* and *C. territans*, and in
994 an intermediate host, the Northern leopard frog (*Rana pipiens*). *Parasitol. Res.* **80**:559-
995 568.
- 996 Stanford, C. B., Rhodin, A. G., van Dijk, P. P., Horne, B. D. 2019. Turtles in trouble: The
997 world's 25+ most endangered tortoises and freshwater turtles—2018.
- 998 Stiassny, M.L.J. 2002. Conservation of freshwater fish biodiversity: the knowledge impediment.
999 *Verhandlungen der Gesellschaft für Ichthyologie* **3**:7-18.
- 1000 Strayer, D.L., Dudgeon, D. 2010. Freshwater biodiversity conservation: recent progress and
1001 future challenges. *J. N. Amer. Benthol. Soc.* **29**:344-358.
- 1002 Strayer, D.L., Hunter, D.C., Smith, L.C. and Borg, C.K., 1994. Distribution, abundance, and
1003 roles of freshwater clams (*Bivalvia*, *Unionidae*) in the freshwater tidal Hudson
1004 River. *Freshw. Biol.* **31**:239-248.
- 1005 Sutherland, W.J., Alves, J.A., Amano, T., Chang, C.H., Davidson, N.C., Finlayson, C.M.A.X.,
1006 Gill, J.A., Gill, R.E., González, P.M. Jr., Gunnarsson, T.G., Kleijn, D., Spray, C.J.,

- 1007 Székely, T., Thompson, D.B.A. 2012. A horizon scanning assessment of current and
1008 potential future threats to migratory shorebirds. *Ibis* **154**:663–679.
- 1009 Tickner, D., Opperman, J.J., Abell, R., Acreman, M., Arthington, A.H., Bunn, S.E., Cooke, S.J.,
1010 Dalton, J., Darwall, W., Edwards, G. and Harrison, I., 2020. Bending the curve of global
1011 freshwater biodiversity loss: an emergency recovery plan. *BioScience* **70**:330-342.
- 1012 Tognelli, M.F., Máiz-Tomé, L., Kraus, D., Lepitzki, D., Mackie, G., Morris, T., Carney, J.,
1013 Alfonso, N., Tonn, B., Cox, N.A. and Smith, K.G. 2017. Freshwater Key Biodiversity
1014 Areas in Canada. Informing species conservation and development planning in
1015 freshwater ecosystems. Gland, Switzerland, Cambridge, UK and Arlington, USA: IUCN.
- 1016 Twardek, W.M., E.A. Nyboer, D. Tickner, C.M. O'Connor, N.W.R. Lapointe, M.K. Taylor, I.
1017 Gregory-Eaves, J.P. Smol, A.J. Reid, I.F. Creed, V.M. Nguyen, A.K. Winegardner, J.N.
1018 Bergman, J.J. Taylor, T. Rytwinski, A.L. Martel, A.R. Drake, S.A. Robinson, J. Marty,
1019 J.R. Bennett and S.J. Cooke. In Press. Mobilizing practitioners to support the
1020 Emergency Recovery Plan for freshwater biodiversity. *Conservation Science and*
1021 *Practice*. **00**:000-000.
- 1022 Vaughn, C.C. and Taylor, C.M., 1999. Impoundments and the decline of freshwater mussels: a
1023 case study of an extinction gradient. *Conserv. Biol.* **13**:912-920.
- 1024 Vences, M., Köhler, J. 2007. Global diversity of amphibians (Amphibia) in freshwater. In:
1025 Balian, E.V., Segers, H., Martens, K., Lévêque, C. (eds) *Freshwater animal diversity*
1026 *assessment*. Springer, Dordrecht, pp 627-637.
- 1027 Wagner, D. L. 2019. Insect declines in the Anthropocene. *Annual Review of Entomology*.
- 1028 Wake, D.B., Vredenburg, V.T. 2008. Are we in the midst of the sixth mass extinction? A view
1029 from the world of amphibians. *PNAS* **105**:11466-11473.

- 1030 Walsh, J.C., Watson, J.E., Bottrill, M.C., Joseph, L.N., Possingham, H.P. 2013. Trends and
1031 biases in the listing and recovery planning for threatened species: an Australian case
1032 study. *Oryx* **47**:134-143.
- 1033 Weldon, C., Du Preez, L. H., Hyatt, A. D., Muller, R., Speare, R. 2004. Origin of the amphibian
1034 chytrid fungus. *Emerg. Infect. Dis.* **10**:2100.
- 1035 Wickham, H. 2016. *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag New York.
1036 ISBN 978-3-319-24277-4.
- 1037 Williams, J.D., Warren, M.L. Jr., Cummings, K.S., Harris J.L., Neves, R.J. 1993. Conservation
1038 status of freshwater mussels of the United States and Canada. *Fisheries* **18**:6-22.
- 1039 WWF-Canada. 2020. Watershed Reports: A national reassessment of Canada's freshwater.
1040 Paquette C. Hemphill L. Merante A. Hendriks E. World Wildlife Fund Canada. Toronto,
1041 Canada.
- 1042 WWF. 2020. Living Planet Report 2020 – Bending the curve of biodiversity loss. Almond,
1043 R.E.A, Grooten, M. and Petersen, T. (Eds.). WWF, Gland, Switzerland.
- 1044 WWF. 2021. The World's Forgotten Fishes. Hughes, K. WWF International pp. 5-47.
- 1045 Xiong, W., Zhan, A. 2020. Zooplankton biodiversity monitoring in polluted freshwater
1046 ecosystems: A technical review. ESE doi: <https://doi.org/10.1016/j.esr.2019.100008>
1047

1048 **Tables and Figures**1049 **Table 1.** Basis for the translation of CESSC status categories into COSEWIC status categories.

COSEWIC Ranking Term	Corresponding CESSC Ranking	Justification
Extinct	Extinct	All definitions declare that there is no reasonable doubt the species still exists
Extirpated	Presumed Extirpated	All definitions state that the species has not been located in Canada but may exist elsewhere
Endangered	Critically Imperiled/ Imperilled	All are defined as having a very high or imminent risk of extirpation
Threatened	Vulnerable	All are defined in terms of being likely, or at a high risk, of becoming endangered/extirpated.
Special Concern	Apparently Secure	All are defined as species that may become threatened or endangered but are presently not currently at an immediate risk
Data Deficient	Unrankable	All definitions highlight a lack of available information to make an assessment
Not at Risk	Secure	All definitions mention being assessed to have no risk of extirpation or not qualifying for any at-risk categories ('Extirpated', 'Endangered', 'Threatened')

1050

1051

1052 **Figure 1.** Number of assessments by order of freshwater-dependent plant species in Canada.

1053 Data are further subdivided by assessment status, from “Not Available” to “Extirpated”

1054 according to the most recent COSEWIC/CESCC assessment (Table 1), with the percentage of

1055 each assessment included next to the status category.

Figure 2. Number of assessments by order of freshwater-dependent invertebrate species in Canada, split according to a low vs. high number of assessments. Data are further subdivided by assessment status, from “Not Available” to “Extirpated” according to the most recent COSEWIC/CESCC assessment (Table 1), with the percentage of each assessment included next to the status category.

Figure 3. Number of assessments by order of freshwater-dependent fish species, split according to a low vs. high number of assessments. Data are further subdivided by assessment status, from “Not Available” to “Extinct” according to the most recent COSEWIC/CESCC assessment (Table 1), with the percentage of each assessment included next to the status category.

1069

1070

1071

1072

1073

Figure 4. Number of assessments by order of freshwater-dependent amphibian and reptile species in Canada. Data are further subdivided by assessment status, from “Not Available” to “Extirpated” according to the most recent COSEWIC/CESCC assessment (Table 1), with the percentage of each assessment included next to the status category.

1074

1075

Figure 5. Number of assessments by order of freshwater-dependent bird species in Canada. Data are further subdivided by assessment status, from “Not Available” to “Endangered” according to the most recent COSEWIC/CESCC assessment (Table 1), with the percentage of each assessment included next to the status category.

1076

1077

1078

1079

1080 **Figure 6.** A visual representation of the distribution of conservation statuses (on the right) for
 1081 each of the six taxonomic groups (on the left). Invertebrates represent the most species rich taxa,
 1082 followed by plants, fishes, birds, herpetofauna, and mammals. Invertebrates also have the largest
 1083 proportion of data deficient assessments, whereas fishes are the only group that have been
 1084 assessed as 'Extinct'. The plot was generated using circlize (v.0.4.12; Gu 2014; <https://cran.r->

- 1085 [project.org/package=circlize](https://www.r-project.org/package=circlize)) with R (v.4.0.2; <https://www.r-project.org/>) in RStudio
- 1086 (v.1.3.1093; <https://rstudio.com/>).

Draft

1087

1088 **Figure 7.** The overall status of freshwater biodiversity in Canada represented by the proportion

1089 of conservation status listings in each major taxonomic group.