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ARTICLE

Horizon scan of conservation issues for inland waters in Canada

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Abstract: Horizon scanning is a systematic approach increasingly used to explore emerging trends, issues, opportunities, and threats in conservation. We present the results from one such exercise aimed at identifying emerging issues that could have important scientific, social, technological, and managerial implications for the conservation of inland waters in Canada in the proximate future. We recognized six opportunities and nine challenges, for which we provide research implications and policy options, such that scientists, policy makers, and the Canadian society as a whole can prepare for a potential growth in each of the topic areas we identified. The issues spanned a broad range of topics, from recognizing the opportunities and challenges of community-enabled science and the need to consider the legal rights of nature, to the likely increase of pharmaceuticals in wastewater due to an aging population. These issues represent a first baseline that could help decision makers identify and prioritize efforts while simultaneously stimulate new research avenues. We hope our horizon scan will pave the way for similar exercises related to the conservation of biodiversity in Canada.

Résumé : L'analyse prospective est une approche systématique de plus en plus utilisée pour explorer les nouvelles tendances, questions, occasions et menaces dans le domaine de la conservation. Nous présentons les résultats d'un de ces exercices visant à cerner les questions émergentes qui pourraient être importantes des points de vue scientifique, social, technologique et de la gestion relativement à la conservation des eaux intérieures au Canada, pour l'avenir rapproché. Nous relevons six occasions à saisir et neuf défis, dont nous abordons les répercussions sur la recherche et les possibilités d'action qu'ils présentent, afin que les scientifiques, les décideurs et l'ensemble de la société canadienne puissent se préparer en vue d'une croissance potentielle dans chacun des domaines cernés. Ces questions couvrent un vaste éventail de sujets allant de la reconnaissance des occasions et défis de la science facilitée par la collectivité et la nécessité de prendre en compte les droits de la nature en vertu de la loi, à l'augmentation probable des produits pharmaceutiques dans les eaux usées en raison du vieillissement de la population. Ces questions représentent un premier état de référence qui pourrait aider les décideurs à cerner et prioriser les efforts tout en stimulant de nouvelles avenues de recherche. Nous espérons que cette analyse prospective ouvrira la voie à des exercices semblables concernant la conservation de la biodiversité au Canada. [Traduit par la Rédaction]

Introduction

Rivers, lakes, springs, and other inland waters (i.e., all surface waters contained within lands; FAO 2008) are often classified among the most threatened ecosystems on the planet (Dudgeon et al. 2006; Reid et al. 2018). For example, less than 40% of large rivers remain fre-flowing (CBD 2014), and ~80% of the world's human population has experienced high levels of threat to water security for the last decade (Vörösmarty et al. 2010; Abell et al. 2019). Vertebrate populations in freshwater environments have shown to be particularly threatened, with declines in their abundances as dramatic as 83% since 1970 (WWF 2018) and ~⅓ being listed as threatened under the IUCN Red List (Collen et al. 2014). While inland water issues are of top concern for conservation biologists, economists, and national security experts alike, cur-

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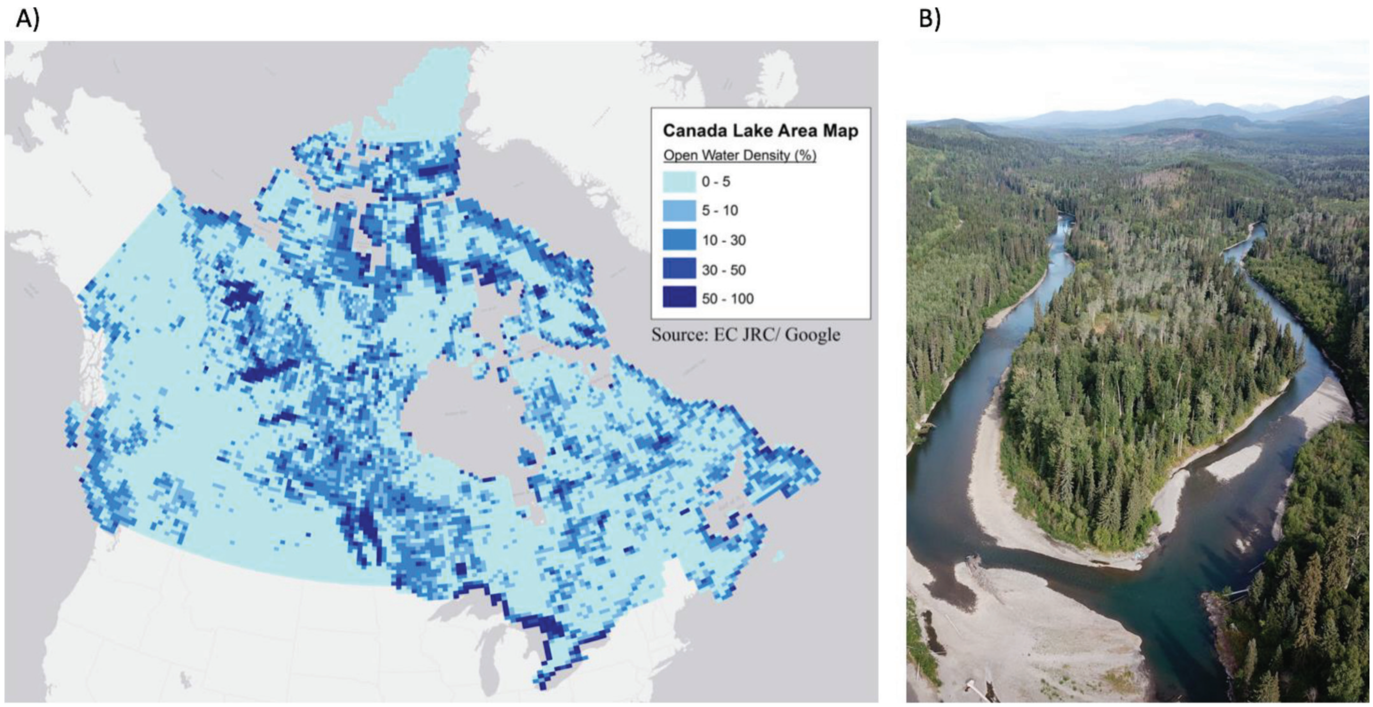
Fig. 1. Canada is home to 20% of the world's fresh water and over 2 400 000 lakes. Nonetheless, extreme events and reductions in water levels have been recently documented even in remote locations or in areas with few human settlements. (*a*) Proportion of permanent open fresh water across Canada within each 1:50 000 sheet of the National Topographic System. Water presence was estimated from multiple Landsat 30 m resolution images by the European Commission's Joint Research Centre and summarized in Google Earth Engine. (*b*) Extreme droughts (levels 3 and 4) were reported in 2018 for the Skeena–Nass river system in northern British Columbia, preventing salmon from reaching upstream fall spawning sites. [Colour online.]



rent approaches for managing inland waters have often failed to slow or reverse the declines in freshwater biodiversity (Strayer and Dudgeon 2010). Foreseeing future and emerging threats to inland waters as well as opportunities for improved monitoring or management can allow practitioners to prioritize research, plan strategically, and facilitate enhancements of management and conservation efforts in a pre-emptive way (Reid et al. 2018). For the last decade, horizon scans have facilitated such efforts by systematically exploring emerging trends, issues, opportunities, threats, and events relevant to various topics in conservation. In particular, Sutherland et al. (2019) have annually published horizon scans in global conservation, touching upon subjects that range from microplastic pollution (Sutherland et al. 2011) to the use of robots to target invasive species (Sutherland et al. 2017). Nonetheless, emerging issues specifically related to inland waters have been addressed only loosely and none specifically within the Canadian context.

Canada holds 20% of the world's fresh water and is home to more lakes than any other country, ~2 400 000 (Fig. 1*a*; Messager et al. 2016). Although Canada is a water-rich nation, there are a few key disconnects. For one, on a per capita basis, Canadians use more water than most other nations, only second to the USA (Hoekstra and Mekonnen, 2012; OECD 2016). Yet, the vast majority (92%) of Canadian water resources renew only over longer times scales (e.g., only a small fraction of our water is found in rivers and is replenished quickly, whereas the water residence time of lakes is much longer and renews over longer time scales; Sprague 2007). In addition, there is a disparity between the distribution of fresh water in Canada and the distribution of human populations, whereby the supply of water available to most Canadians is much smaller than the national total because a substantial fraction of the renewable water flows to the Arctic (Sprague 2007; Renzetti and Dupont 2017). Moreover, many changes in Canadian inland waters are occurring in remote regions and disproportionately affect Indigenous communities (Fig. 1*b*; Patrick 2011). Finally, a recent synthesis of Canadian watershed health (based on stream flow, quality, fish and invertebrate abundances) and stressors (e.g., pollution, water use, fragmentation, invasive species, and climate change) has highlighted the heterogeneity of data quality and availability for large regions of the country (WWF 2017). Therefore, Canada would benefit from proactive management and readiness to deal with future threats to its inland waters as well as opportunities to improve conservation efforts. Horizon scanning allows us to identify issues that are emerging and whose impact is currently unknown, in the hope of motivating the data collection required to inform policy and research decisions in the future. Here we report the results of a horizon-scan exercise that sought to identify issues and opportunities related to governance–management, technology, and society that might have an effect on the conservation of inland waters, and the biodiversity therein, in Canada within the next 5–10 years.

Materials and methods

Our horizon scan followed the methodological framework described in Sutherland et al. (2011). In the current exercise, representatives of the Groupe de recherche Interuniversitaire en Limnologie at McGill University invited 30 researchers with expertise in a wide range of topics related to fresh and (or) inland waters to participate in a 2-day workshop in Montréal in January 2019. The invitees were selected to maximize representation of expertise, gender, and backgrounds (in terms of where participants originated from): 17 agreed to participate. Prior to the workshop, participants submitted up to three issues (positive or negative in nature) that they considered will become important in the conservation of inland waters in Canada in the next 5–10 years, along with a description (200–300 words) and a relevant bibliography. These contributions were subsequently collated and consolidated

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to avoid repetition. The resulting 33 distinct issues were returned to the participants for evaluation and ranking. Each participant anonymously ranked all issues by taking into consideration their novelty (i.e., noting whether the issue was already widely recognized such as climate change), its potential impact, and its likelihood of occurrence. The median scores for these rankings were used as a starting point for discussions during the workshop. Workshop participants broke out into groups to discuss proposed issues and to consider any new issue that arose during the discussions. All participants then scored each issue individually and anonymously. Low scores identified issues that are already well known in Canada, unlikely to be important, and (or) unlikely to occur, whereas high scores denoted issues that could have a strong impact and are least mainstream issues in Canada. The submitted scores were converted to ranks, and the median rank for each issue was calculated. Through this procedure, the group identified 15 emerging issues and opportunities that are likely to have substantial implications for the conservation of inland waters in Canada. Importantly, we refer to inland waters as all continental waters that may be on the surface or underground. We specifically did not restrict our discussions to fresh waters, as many inland waters in Canada can be quite salty. Given that the expertise of the participants of the workshop was mainly related to research, NL and RP provided input on the manuscript and refined the policy implications of the 15 issues previously identified.

We acknowledge that the set of issues identified here could have been influenced by the composition of our group. However, it is worth noting that a recent review of a decade's worth of global horizon-scan efforts showed no association between the participants' expertise and the emerging issues selected (Sutherland et al. 2019). Our group was largely from the academic sphere spanning the fundamental–applied continuum and represented a population that was gender-balanced. Members originated from disparate regions of Canada or international locations and were from different career stages (i.e., one Ph.D. student, four postdoctoral fellows, two science professionals, and ten university professors). One participant was an Indigenous scientist, and another was a government employee. All issues were subjected to a democratic and confidential voting process, which minimizes biases arising from any one individual (Sutherland et al. 2019). We emphasize that our list of issues is not necessarily exhaustive but rather an important subset, as identified by our participants.

As a secondary evaluation of the novelty of each of the issues identified, we conducted a search in Web of Science of the past 5 years' worth of manuscripts published in the Canadian Journal of Fisheries and Aquatic Sciences. We searched for issue-specific keywords in the topic or title field tags. All entries were then manually verified to correspond to the target issue. We also quantified the relative frequency of the term climate change (in terms of the relative proportion of articles where this term appears), as a point of comparison for a timely issue that is already well studied.

Issues: from challenges to opportunities

Chromite mining in the Ring of Fire

The "Ring of Fire" is a 5000 km^2 crescent-shaped chromite deposit (North America's largest) in the Lowlands of Northern Ontario (Beukes et al. 2017). Chromite is needed for producing stainless steel but is mined in few countries. The Ring of Fire is thus the potential target of a massive development project, likely to proceed when the region's infrastructure is modernized. The project will involve several underground mines and possibly an open pit, both of which may cause water contamination through the release of chromium-6 (hexavalent chromium). Chromium-6 is a priority substance in the Canadian Environmental Protection Act because it is soluble, environmentally persistent, and induces a broad suite of toxicological effects on fish and birds (Velma et al. 2009). The Ring of Fire is in close proximity to the traditional territory of nine First Nations communities (The James Bay Treaty 1905). The mineral deposits in the Ring of Fire lie beneath a unique ecoregion that comprises the world's largest peatland and a global breeding hotspot for waterfowl (Beukes et al. 2017).

Research implications

1. Identify preventative and mitigative measures for chromium-6 and other contaminants from mining activities.
2. Forecast potential downstream or legacy effects (e.g., bioaccumulation).
3. Determine the natural occurrence and spatiotemporal variability of chromium-6 in soils, untreated chromite ore, and surface water–groundwater and identify areas of ecological sensitivity.

Policy options

1. Apply evidence-based decision-making processes regarding mining and ore processing in the region (e.g., advantages of wet milling over dry in terms of potential to generate chromium-6).
2. Include First Nations communities in the consultation process following commitments made in the United Nations Declaration on the Rights of Indigenous Peoples and the Calls to Action set forth by the Truth and Reconciliation Commission of Canada (2015).
3. Provide rigorously documented baseline studies to the public.

Consequences of dynamic winter conditions for aquatic life and its management

Winter in Canada is generally characterized by sub-zero temperatures, high snowfall, and ice-covered waterbodies. However, such winters are becoming increasingly rare in face of current rates of climate change in parts of southern Canada. Across such regions, the previously long "deep freeze" is becoming a more dynamic season with episodic freeze–thaw events and rapid fluctuations in temperature, along with shorter periods of ice cover (Sharma et al. 2019). Winter is regarded as a strong selective force on aquatic life, yet we know remarkably little about aquatic ecosystems during this season (Hampton et al. 2017). Some recent observations — such as extensive winter methane and CO_2 gas production and release in lakes (Denfeld et al. 2018), under-ice nitrification contributing to winter-kill events (Powers et al. 2017), and river ice dynamics altering the distribution of fish (Brown et al. 2011) — reveal that winter effects are still largely unknown. This gap in knowledge about how aquatic ecosystems function in winter, particularly when coupled with dynamic conditions related to climate change, generates important uncertainty for the management of inland waters in Canada.

Research priorities

1. Quantify the variation in freeze–thaw events (frequency, intensity) and associated impacts on aquatic life.
2. Harness the power of remote sensing and other tools like Earth Engine to interpret freeze–thaw timing by fusing data from optical satellites and radar satellites (e.g., Canada's Radarsat and IceSat series).
3. Study how animal habitat use and behaviour differ in winter compared with other seasons and identify conditions and events (such as the development of frazil ice) that may limit survival or reduce postwinter fitness of individuals.

Policy options

1. Recommend construction windows to protect sensitive aquatic habitats, based on knowledge of winter dynamics and changing climatic conditions.
2. Account for winter dynamics in aquatic management during other seasons (e.g., fish stocking, restoration, biomanipulation).

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3. Include important winter refuges when considering the protection of critical habitats for species at risk.

Considering effects of rapid global change requires integrating evolutionary adaptive capacity

Assessments of aquatic community responses to environmental stressors typically focus on biodiversity at the species level, thereby overlooking a key component of biodiversity: variation within species. Intraspecific variation can act as an evolutionary insurance policy against rapid environmental change, as well as having major effects on community dynamics and ecosystem services (Schindler et al. 2015; Mimura et al. 2017). For Canada to successfully manage and conserve its inland waters, standard environmental impact assessments could be complemented by "evolutionary impact assessments" (EvoIA). EvoIA entails the assessment of intraspecific variation and its potential for enabling adaptive responses that maintain the long-term health of aquatic communities and ecosystems (Laugen et al. 2014). EvolA allows for more targeted and efficient use of conservation resources, as it identifies not only current contributions of evolution to biodiversity and ecosystem function, but it can also predict how specific management actions will enhance future contributions to the same services — that is, "evosystem services".

Research priorities

1. Improve knowledge of within-species genetic differentiation to support the identification of designatable units used by the Committee on the Status of Endangered Wildlife in Canada.
2. Develop field-ready genomic monitoring kits for rapid and easy assessment of intraspecific diversity.

Policy options

1. Consider management procedures that account for adaptive capacity of populations (e.g., setting restrictions to avoid selective fishing–harvest, which cause genetic bottlenecks).
2. Train practitioners to enhance competency with evolutionary principles and methodology (e.g., through workshops or online training platforms).

Dynamics of state changes caused by multiple stressors

Most research and impact assessments have traditionally focused on how individuals, populations, communities, and ecosystems respond to a single stressor, such as temperature, turbidity, or acidity. Yet these and many other stressors likely act simultaneously in complex and often unpredictable ways (Folt et al. 1999). Despite multiple stressors being the norm on the Canadian landscape, it is still not well understood how multiple stressors interact to influence organisms, populations, communities, and ecosystems (Ormerod et al. 2010). Multiple stressors have the potential to combine additively, multiplicatively, or in other ways, making it difficult for environmental managers to predict responses (Jackson et al. 2016). It may also be possible for multiple stressors to trigger regime shifts between alternative system states or alter tipping points (e.g., Leichenko et al. 2004), such that shifts are accelerated, delayed, or made more or less abrupt (Piggott et al. 2015). Resource managers will face challenges in determining what to do in the face of regime shifts given the complexity arising from multiple stressors. Finally, multiple stressors have the potential to generate entirely new "non-analog" states to which systems might shift — states that would not be observed even at high levels of a single stressor.

Research priorities

1. Determine how multiple stressors influence the probability and nature of tipping points that influence shifts between system states.
2. Define which combinations of particular stressors generate the strongest nonadditive and nonlinear effects on organisms, populations, communities, and ecosystems.

Policy options

1. Integrate multiple stressors in environmental risk assessments and authorization–permitting decisions.
2. Integrate nonadditive and nonlinear effects of stressor combinations in conservation management.

Expansion of land and water use in northern Canada

Since 1900, surface temperature in the Arctic (60°N–90°N) has been increasing at a rate that is twice that of the global average (Overland et al. 2018). As such, northern areas hold considerable potential for both an expansion of agriculture (Arsenault 2017) and hydroelectric development (Canadian Hydropower Association 2009), among other climatic and development-related pressures. Although northern agricultural expansion could be a positive step towards northern food security and assist in feeding the growing global population, important considerations include heightened water use pressures and increased loading of agrochemicals to nearby water bodies. Also, the common perception of hydropower as "clean renewable energy", combined with increasing political pressure to reduce greenhouse gas emissions, could provide impetus for hydroelectric power development within vast areas of the Arctic (WWF 2017). Such development could produce an array of impacts on northern First Nations and Indigenous communities, as well as affect sensitive populations of invertebrates, fishes, and birds — as has been the case for many existing hydropower projects in Canada and the US (Willacker et al. 2016) and elsewhere in the world (Winemiller et al. 2016).

Research priorities

1. Conduct life cycle assessment research to fully characterize current and potential hydropower impacts in northern Canada.
2. Identify crops or strains that have the greatest local benefit, while mitigating their impacts on water resources.
3. Investigate the effects of agricultural expansion (northward) on land–water linkages (e.g., fragmentation).

Policy options

1. Develop northern-based farming and agricultural research institutes (e.g., Northern Farm Training Institute, Northwest Territories).
2. Develop a national-level plan for intensive land use projects in northern Canada.
3. Expand the National Hydrometric Program (Water Survey Canada) to provide more extensive flow and water level data for northern systems.

Expectation for increased rigour and transparency in environmental decision-making

The environmental assessment procedure in Canada has been under increased scrutiny recently and has launched this topic into the forefront of public policy discussions. Calls for transparency in the use and sharing of data and in the assessment of regional and cumulative impacts are mounting (Westwood et al. 2019). Additionally, the need to consider the impacts of such projects in the context of larger national goals (e.g., biodiversity targets, UN Sustainable Development Goals, and reduced carbon emissions) has been consistently highlighted. The changes made in 2012 to the Canadian Environmental Assessment Act, Fisheries Act, and Navigable Waters Protection Act (now Navigation Protection Act), as well as the subsequent review and introduction of Bills C-68 and C-69, have attempted to address such problems by putting an emphasis on creating registries to improve public access to environmental information. The aim of these changes is to encourage

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meaningful public participation in environmental decision-making (Jacob et al. 2018). Putting evidence-based decision-making into broader practice will require additional capacity within natural resource management agencies (Cooke et al. 2017), open data efforts, and regional assessments.

Research priorities

1. Determine how data collected from strategic impact assessments can be integrated into national databases, such that it is useful for conservation planning.
2. Conduct case studies to investigate the effects of legislative reforms on transparency, accountability, and meaningful public involvement.

Policy options

1. Provide open access to baseline and monitoring data, methodologies, and metadata.
2. Include rigorous scientific methodologies in environmental decision-making while facilitating the implementation of Indigenous knowledge.
3. Make publicly available all documents used to inform government regulatory impact analysis statements.

Geopolitical tensions over water access and trade

Under current climate change and human population growth, access to clean fresh water is a major global concern (World Economic Forum 2018). Stress on water resources will arise from direct consumption, and indirectly through the consumption of commodities that require substantial quantities of water for their production. Current analysis of national water footprints from around the world have placed Canada as the second largest user of fresh water, only second to the USA (OECD 2016). Serious water issues are already apparent within Canada, ranging from hundreds of boil-water advisories to the fragmentation of water management across multiple levels of government (Mitchell 2017). Growing global trade networks could further strain access to clean water in Canada, whether nations are geographical neighbours or not. Some recent examples that could spark geopolitical tensions over water include Wisconsin's approval for the diverting of 28 million litres of water per day from Lake Michigan to the Mississippi River watershed to support local industry (https://dnr.wi.gov/topic/WaterUse/Racine/). Although in 2013 the Parliament of Canada approved a law prohibiting bulk water exports, some water policy experts argue that considerable uncertainty remains over the strength of the protection afforded by Canadian laws, particularly as new trade deals are negotiated (Rivera 2015; Barlow et al. 2016). Moreover, it is expected that under climate change and with increased global environmental degradation, markets will become highly unstable, and over 200 million environmental refugees will seek asylum in Canada by 2050 (Murray 2010). In that context, preserving water security on a global scale can be a lynchpin to an equitable, prosperous, and sustainable future, and it is clearly in Canada' interest to contribute to that outcome.

Research priorities

1. Improve understanding of how climate change will influence water demand for agriculture and other intensive practices.
2. Identify Canadian waterbodies most likely to be affected by shifting water demands, and evaluate scenarios to determine which conservation strategies will be most effective.

Policy options

1. Determine the most effective policy levers to protect water quality and quantity while also encouraging a reduced national water footprint.
2. Engage in stakeholder activities to promote participatory process in water-related issues.
3. Explore options for Canada to contribute more fulsomely to the resolution of water issues in other countries.

Increased loading of pharmaceuticals in wastewater

Pharmaceuticals are emerging environmental contaminants that are increasingly used in human and veterinary medicine. Today, almost 70% of all Canadian citizens 65 years and older take five or more drugs (CIHI 2018), and by 2031 it is expected that one in four Canadians will be over 65 (Statistics Canada 2017). Many drugs are not efficiently eliminated by sewage treatment plants and are directly discharged into wastewater, finding their way into inland waters (Koné et al. 2013). Despite the relatively low concentrations reported in effluents of sewage treatment plants, several classes of drugs are expected to pose high environmental risks, including analgesics (e.g., salicylic acid, naproxen, and ibuprofen), antibiotics (e.g., sulphamethoxazole and ciprofloxacin), antidepressants (e.g., fluoxetine), and hormone disrupters (Koné et al. 2013). The effects of such compounds on aquatic organisms is often evaluated using acute toxicity assays. However, a major concern is that their chronic toxicity and their subtle effects are not understood (Fent et al. 2006). Although many pharmaceuticals are considered of low risk for lower-trophic-level taxa, the potential remains for food-web-mediated effects on primary consumers (Hamilton et al. 2016). Potential mitigation options include the development of advanced treatment technologies of municipal wastewaters, source reductions, and proper ecotoxicological testing of new generation drugs.

Research priorities

1. Determine the safety limits for drugs and drug combinations in the environment.
2. Determine the impacts of key drugs, with an emphasis on sublethal and chronic thresholds in individuals, populations, and communities.
3. Develop advanced wastewater treatment techniques–options across different scales, from communities to cities.

Policy options

1. Develop efficient treatment and mitigation approaches.
2. Reduce improper disposal or collection of unused pharmaceuticals.
3. Increase monitoring of pharmaceuticals in effluents.

Increased risk of petroleum spills arising from new pipelines

With growing oil production in Canada, there is increasing demand for transport of crude oil through pipelines to major refineries and terminals across North America. While most research on threats posed by oil spills has focused primarily on high-profile events in coastal marine environments, risks to inland aquatic ecosystems such as the Great Lakes have been largely overlooked (Murray et al. 2018). Nonetheless, existing and planned oil transport infrastructure poses important threats of ecologically important spills in sensitive fish habitats and species-rich environments such as estuaries, rivers, bays, and wetlands (Murray et al. 2018). Crude oil spills can impact all levels of an aquatic food web, and their effects on benthic invertebrates can persist beyond 25 years (Bertrand and Hare 2017). Moreover, laboratory experiments have revealed negative short-term and latent impacts on growth and development of several fish species, including the economically and culturally important salmonids (Alderman et al. 2018). However, the scope, magnitude, and persistence of the effects of crude oil on freshwater biota, the recovery capacities of aquatic habitats, and the behaviour and fate of oil products in freshwater systems remain poorly understood.

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Research priorities

1. Develop technologies and test models for rapid and accurate detection of spills (especially slow leaks that may go unnoticed for some time).
2. Understand the ecological effects of spills during different seasons (e.g., spring runoff versus frozen winters) to inform possible seasonal limits on oil transport.

Policy options

1. Consider sensitive aquatic habitats when planning pipeline routing and configurations (e.g., salmon-bearing streams and spawning–incubation–rearing seasons).
2. Ensure that the standards of response planning for inland spills meet those upheld for marine environments.
3. Incorporate modern safety standards and monitoring protocols into authorizations for the construction and operation of pipelines to minimize the risk of spills.

Increasing pressure for Canada to enshrine constitutional rights to a healthy environment and the rights of nature

Health Canada has estimated that, each year, over 14 000 premature deaths in Canada are the result of air pollution, toxic chemicals, and other environmental risk factors (Health Canada 2017). International comparisons have shown that Canadian environmental laws and policies are lagging behind other industrialized countries (Boyd 2015). For example, when a person or company obtains a legal right to land or water in Canada, these private rights often trump public rights regarding that water or land. As a result, the public often has little recourse for the negative impacts that the private use inflicts on the wider community. Many communities and environmental organizations are seeking innovative institutional arrangements that can address the environmental degradation of inland waters and improve our stewardship of ecosystem health (Curran 2015). As a result, more than 100 nations around the world now recognize constitutional environmental rights and responsibilities. Several provinces have forms of enforceable environmental rights, and 150 Canadian municipalities have passed declarations recognizing their residents' right to live in a healthy environment. Pressure is now increasing for the federal government to legislate similar rights and to include protection provisions in the Canadian constitution.

Research priorities

1. Establish quantitative, objective definitions for terms such as "healthy" and "harm" as they relate to inland waters so they can be applied in legal and policy frameworks.
2. Develop and track standardized nation-wide testing of key health indicators for inland waters

Policy options

1. Expand and unify municipal and provincial declarations of environment rights to all jurisdictions.
2. Determine what constitutes ecological harm from a legal perspective.
3. Apply the emerging approach "legal personality" to provide water systems with legal standing and enforceable rights.

Invasions by novel pathogens will challenge biosecurity and conservation

Invasive pathogens are being recorded with greater frequency in ecosystems worldwide (Fisher et al. 2012). Current rates of climate change, nutrient pollution, and global transport of organisms are creating conditions in Canada that are conducive to the spread and proliferation of pathogens that threaten endemic freshwater biodiversity and fisheries (Schmeller et al. 2018). Many pathogens can go undetected before producing die-offs or can remain an unrecognized cause of mortality (Adams et al. 2017). Immense numbers of undescribed taxa of bacteria, protozoa, oomycetes, and fungi are potentially transported between disparate regions and can undergo rapid evolutionary changes that affect their virulence or host repertoire in Canada (Hoberg and Brooks 2015; Robin et al. 2017). One such important emerging threat to Canadian freshwater biodiversity is *Batrachochytrium salamandrivorans*, the chytrid fungus responsible for recent catastrophic declines in wild salamanders in Europe after being introduced through the pet trade (Martel et al. 2014). Although we recognize that Canada has recently restricted the import of salamanders to limit the introduction of *B. salamandrivorans* into Canada (https://www.cbsa-asfc.gc.ca/publications/cn-ad/cn17-17-eng.html), continued vigilance is needed. The limited ability to detect emerging invasive pathogens will impede conservation efforts to prevent or promptly contain and manage outbreaks across the Canadian landscape.

Research priorities

1. Determine how global stressors promote the emergence and virulence of novel pathogens and whether synergistic interactions are at play.

Policy options

1. Reassess existing regulations concerning inspection of travellers and goods at ports of entry to maximize detection of new pathogens.
2. Exercise vigilance towards illegal importations of amphibians (e.g., Government of Canada 2017) and aquatic organisms in general using current mechanisms (e.g., the Aquatic Invasive Species Regulations SOR/2015-121 under the Fisheries Act).

New satellite and remote sensing technologies can transform our understanding of aquatic ecosystems and their dynamics

Recent advances in satellite and remote sensing technologies have set the stage for transforming aquatic ecosystem research and monitoring. In particular, several new satellites (launched since 2013) improve our ability to estimate lake properties. For example, Landsat-8 provides a greater depth of possible measurement values within images and thus improve the signal-to-noise ratio (Roy et al. 2014). More recently, Sentinel-2a and -2b have enhanced the frequency of imaging a given point on Earth's surface, when data are combined across satellites (Pahlevan et al. 2017). A second major area of advancement is the development of Google Earth Engine (Gorelick et al. 2016), which enables users to access and manipulate the full suite of satellite images remotely, greatly minimizing data storage and processing demands. Google Earth Engine has already allowed for planetary-scale assessments of global surface water distribution at fine resolution across multiple decades (Pekel et al. 2016), and it holds considerable promise for creating new time series of lake characteristics at regional, continental, and planetary scales.

Research priorities

1. Seek out effective ways to expand remote sensing training into high school and early undergraduate levels.
2. Develop remote sensing hardware and software to identify sensitive aquatic habitats, such as groundwater upwelling zones, salmon redds, and winter thermal refugia.
3. Improve multiscale (reach, watershed, ecoregion) assessments of aquatic habitat condition and stressors by incorporating new information available from emerging remote sensing technologies.

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Policy options

1. Incorporate systematic remote sensing into government monitoring programs at all levels (federal, provincial, territorial, municipal, Indigenous).
2. Develop planning methodologies that incorporate remotely sensed data and inform the prioritization of conservation and restoration actions.

Opportunities and challenges from technology-enabled community science

Over 85% of Canadians own a smartphone (CRTC 2019), which translates into approximately 31.7 million potential sampling platforms distributed across the country. Smartphones generate opportunities for community-based science and could help to fill important data gaps on aquatic ecosystems that exist for most Canadian watersheds (WWF 2017). Relying on engaged communities will be critical as monitoring resources are sparse, and resource management agencies are unable to provide complete coverage of the country — especially in the vast and difficult-to-access northern regions. Moreover, the increase in accuracy and the development of novel sensors in smartphones, in synergy with technological advances (e.g., computer vision), will enable important improvements in the data quality of community-based science (Kosmala et al. 2016) while facilitating the validation and geo-localization of entries. Beyond data acquisition, however, including schools and communities directly in the scientific process provides excellent opportunities to educate and engage the public. Existing successful programs, such as iFish (http://www.ifishalberta.com/; Papenfuss et al. 2015) and Water Rangers (https://waterrangers.ca/en/), rovide valuable models that could be further developed.

Research priorities

1. Develop robust processes for curation and validation of community-generated aquatic data.
2. Explore best practices for passive versus active engagement of community members.
3. Study how to incentivize the broader population and keep community scientists engaged.

Policy options

1. Further engage Northerners as technological stewards with formal funding opportunities.
2. Incorporate instantaneous public reporting into early detection and rapid response procedures for aquatic invasive species.
3. Explore options for linking with "Big Data" initiatives of commercial data providers, such as Google and Amazon, to increase the development and distribution of third-party applications and decision support tools.

Opportunities from national data integration

The landscape of nation-wide ecological data collection and curation is changing through the collaborative efforts among academic research networks, government scientists, and nongovernmental organization (NGO) partners. Large research networks focused on inland waters are paving the way to a new scale of ecological inference, mainly by integrating spatial, temporal, historical, and "dark" (collected but unused: Heidorn 2008) ecological data. This integration will naturally involve partnerships and multisector research co-design, stimulating in this way a long-term vision for data sharing and management while increasing data accessibility to researchers, stakeholders, and policy makers. With systematic and continuous nation-wide sampling, ecological variability across inland waters will be better understood (Soranno et al. 2015), and gaps between fundamental ecological research and its application by managers will be greatly narrowed (Cadotte et al. 2017). Current examples that provide a model for scaling up include the Natural Sciences and Engineering Research Council of Canada (NSERC) Canadian LakePulse Network in Canada (Huot et al. 2019) and the National Lakes Assessment Program in the USA. Programs such as these will be instrumental in ensuring that Canada meets its commitments under the 2030 Agenda and the implementation of the associated UN Sustainable Development Goals.

Research priorities

1. Develop best approaches for extrapolating from monitored to nonmonitored inland waters.
2. Improve forecasting of responses to environmental stressors such as invasive species, climate change, or pollution through large-scale surveys.

Policy options

1. Support the development and management of large, comparative datasets that will facilitate evidenced-based decision-making.
2. Promote data sharing, trust, and rights across sectors.
3. Establish open and long-term nation-wide monitoring databases.

Whole community monitoring opportunities arising from environmental DNA

The application of environmental DNA (eDNA) metabarcoding to biomonitoring of aquatic systems has remarkable potential. Although techniques are still developing (Goldberg et al. 2016; Pawlowski et al. 2018; Cristescu and Hebert 2018), there are tremendous opportunities for the use and development of eDNA surveys in Canada as a complement or supplement to conventional, time- and resource-intensive sampling. Scaled up, eDNA metabarcoding has the potential to transform the frequency and range at which aquatic communities are monitored, generating an unprecedented amount of biodiversity data. Additionally, because of the relatively simple field equipment required, it is feasible to sample eDNA across very large spatial scales and at high temporal frequencies. There remain several challenges, such as high rates of false positives and false negatives (Cristescu and Hebert 2018). However, with the establishment of coordinated efforts to standardize methods for metazoan community detection, the approach could soon be ready for widespread adoption and routine use in biodiversity assessments (Rees et al. 2014). The scale of data generation will foster collaborations with bioinformaticians, while taxonomists will be crucial for building and improving reference databases. These techniques have the potential to allow conservation practitioners to better inform policies related to invasive species spread, climate-related range shifts, and seasonal signals, among other critical conservation challenges.

Research priorities

1. Develop more comprehensive genetic libraries of aquatic species, with a focus on building localized and well-validated species libraries.
2. Address high incidences of false positives and false negatives, and deal with the complications arising from DNA decay, DNA advection, and primer bias.
3. Explore the use of environmental RNA (eRNA) as a means to examine the living biodiversity in an ecosystem (i.e., tracking species relative abundances through space and time).

Policy options

1. Consider the systematic use of eDNA in routine monitoring for the early detection of invasive species or climate-induced range shifts.
2. Manage fisheries and ecosystem heath based on detailed understanding of community composition and dynamics.

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Table 1. Summary of the 15 issues (presented in alphabetical order) identified with their corresponding research priorities and policy options.

Issue	Research priority	Policy option
Chromite mining in the Ring of Fire	1. Identify preventative and mitigative measures for chromium-6 and other contaminants from mining activities. 2. Forecast potential downstream or legacy effects (e.g., bioaccumulation). 3. Determine the natural occurrence and spatiotemporal variability of chromium-6 in soils, untreated chromite ore, and surface water–groundwater, and identify areas of ecological sensitivity.	1. Apply evidence-based decision-making processes regarding mining and ore processing in the region (e.g., advantages of wet milling over dry in terms of potential to generate chromium-6). 2. Include First Nations communities in the consultation process following commitments made in the United Nations Declaration on the Rights of Indigenous Peoples and the Calls to Action set forth by the Truth and Reconciliation Commission of Canada (2015). 3. Provide rigorously documented baseline studies to the public.
Consequences of dynamic winter conditions for aquatic life and its management	1. Quantify the variation in freeze–thaw events (frequency, intensity) and associated impacts on aquatic life. 2. Harness the power of remote sensing and other tools like Earth Engine to interpret freeze–thaw timing by fusing data from optical satellites and radar satellites (e.g., Canada's Radarsat and IceSat series). 3. Study how animal habitat use and behaviour differ in winter compared with other seasons and identify conditions and events (such as the development of frazil ice) that may limit survival or reduce postwinter fitness of individuals.	1. Recommend construction windows to protect sensitive aquatic habitats based on knowledge of winter dynamics and changing climatic conditions. 2. Account for winter dynamics in aquatic management during other seasons (e.g., fish stocking, restoration, biomanipulation). 3. Include important winter refuges when considering the protection of critical habitats for species at risk.
Considering effects of rapid global change requires integrating evolutionary adaptive capacity	1. Improve knowledge of within-species genetic differentiation to support the identification of designatable units used by the Committee on the Status of Endangered Wildlife in Canada. 2. Develop field-ready genomic monitoring kits for rapid and easy assessment of intraspecific diversity.	1. Consider management procedures that account for adaptive capacity of populations (e.g., setting restrictions to avoid selective fishing–harvest, which cause genetic bottlenecks). 2. Train practitioners to enhance competency with evolutionary principles and methodology (e.g., through workshops or online training platforms).
Dynamics of state changes caused by multiple stressors	1. Determine how multiple stressors influence the probability and nature of tipping points that influence shifts between system states. 2. Define which combinations of particular stressors generate the strongest nonadditive and nonlinear effects on organisms, populations, communities, and ecosystems.	1. Integrate multiple stressors in environmental risk assessments and authorization–permitting decisions. 2. Integrate nonadditive and nonlinear effects of stressor combinations in conservation management.
Expansion of land and water use in northern Canada	1. Conduct life cycle assessment research to fully characterize current and potential hydropower impacts in northern Canada. 2. Identify crops or strains that have the greatest local benefit while mitigating their impacts on water resources. 3. Investigate the effects of agricultural expansion (northward) on land–water linkages (e.g., fragmentation).	1. Develop northern-based farming and agricultural research institutes (e.g., Northern Farm Training Institute, Northwest Territories). 2. Develop a national-level plan for intensive land use projects in northern Canada. 3. Expand the National Hydrometric Program (Water Survey Canada) to provide more extensive flow and water level data for northern systems.
Expectation for increased rigour and transparency in environmental decision-making	1. Determine how data collected from strategic impact assessments can be integrated into national databases, such that it is useful for conservation planning. 2. Conduct case studies to investigate the effects of legislative reforms on transparency, accountability, and meaningful public involvement.	1. Provide open access to baseline and monitoring data, methodologies, and metadata. 2. Include rigorous scientific methodologies in environmental decision-making while facilitating the implementation of Indigenous knowledge. 3. Make publicly available all documents used to inform government regulatory impact analysis statements.

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Table 1 (*continued*).

Issue	Research priority	Policy option
Geopolitical tensions over water access and trade	1. Improve understanding of how climate change will influence water demand for agriculture and other intensive practices. 2. Identify Canadian waterbodies most likely to be affected by shifting water demands, and evaluate scenarios to determine which conservation strategies will be most effective.	1. Determine the most effective policy levers to protect water quality and quantity while also encouraging a reduced national water footprint. 2. Engage in stakeholder activities to promote participatory process in water-related issues. 3. Explore options for Canada to contribute more fulsomely to the resolution of water issues in other countries.
Increased loading of pharmaceuticals in wastewater	1. Determine the safety limits for drugs in the environment. 2. Determine the impacts of key drugs, with an emphasis on sublethal and chronic thresholds in individuals, populations, and communities. 3. Development advanced wastewater treatment techniques–options across different scales, from communities to cities.	1. Development of efficient treatment and mitigation approaches. 2. Reduce improper disposal or collection of unused pharmaceuticals. 3. Increase monitoring of pharmaceuticals in effluents.
Increased risk of petroleum spills arising from new pipelines	1. Develop technologies and test models for rapid and accurate detection of spills (especially slow leaks that may go unnoticed for some time). 2. Understand the ecological effects of spills during different seasons (e.g., spring runoff versus frozen winters) to inform possible seasonal limits on oil transport.	1. Consider sensitive aquatic habitats when planning pipeline routing and configurations (e.g., salmon-bearing streams and spawning–incubation–rearing seasons). 2. Ensure that the standards of response planning for inland spills meet those upheld for marine environments. 3. Incorporate modern safety standards and monitoring protocols into authorizations for the construction and operation of pipelines to minimize the risk of spills.
Increasing pressure for Canada to enshrine constitutional rights to a healthy environment and the rights of nature	1. Establish quantitative, objective definitions for terms such as “healthy” and “harm” as they relate to inland waters so they can be applied in legal and policy frameworks. 2. Develop and track standardized nation-wide testing of key health indicators for inland waters.	1. Expand and unify municipal and provincial declarations of environment rights to all jurisdictions. 2. Determine what constitutes ecological harm from a legal perspective. 3. Apply the emerging approach “legal personality” to provide water systems with legal standing and enforceable rights.
Invasions by novel pathogens will challenge biosecurity and conservation	1. Determine how global stressors promote the emergence and virulence of novel pathogens and whether synergistic interactions are at play.	1. Reassess existing regulations concerning inspection of travellers and goods at ports of entry to maximize detection of new pathogens. 2. Exercise vigilance towards illegal importations of amphibians (e.g., Government of Canada 2017) and aquatic organisms in general using current mechanisms (e.g., the Aquatic Invasive Species Regulations SOR/2015-121 under the Fisheries Act).
New satellite and remote sensing technologies can transform our understanding of aquatic ecosystems and their dynamics	1. Seek out effective ways to expand remote sensing training into high school and early undergraduate levels. 2. Develop remote sensing hardware and software to identify sensitive aquatic habitats, such as groundwater upwelling zones, salmon redds, and winter thermal refugia. 3. Improve multiscale (reach, watershed, ecoregion) assessments of aquatic habitat condition and stressors by incorporating new information available from emerging remote sensing technologies.	1. Incorporate systematic remote sensing into government monitoring programs at all levels (federal, provincial, territorial, municipal, Indigenous). 2. Develop planning methodologies that incorporate remotely sensed data and inform the prioritization of conservation and restoration actions.

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Table 1 (*concluded*).

Issue	Research priority	Policy option
Opportunities and challenges from technology-enabled community science	1. Develop robust processes for curation and validation of community-generated aquatic data. 2. Explore best practices for passive versus active engagement of community members. 3. Study how to incentivize the broader population and keep community scientists engaged.	1. Further engage Northerners as technological stewards with formal funding opportunities. 2. Incorporate instantaneous public reporting into early detection and rapid response procedures for aquatic invasive species. 3. Explore options for linking with "Big Data" initiatives of commercial data providers, such as Google and Amazon, to increase the development and distribution of third-party applications and decision support tools.
Opportunities from national data integration	1. Develop best approaches for extrapolating from monitored to nonmonitored inland waters. 2. Improve forecasting of responses to environmental stressors such as invasive species, climate change, or pollution through large-scale surveys.	1. Support the development and management of large, comparative datasets that will facilitate evidenced-based decision-making. 2. Promote data sharing, trust, and rights across sectors. 3. Establish open and long-term nation-wide monitoring databases.
Whole community monitoring opportunities arising from environmental DNA	1. Develop more comprehensive genetic libraries of aquatic species, with a focus on building localized and well-validated species libraries. 2. Address high incidences of false positives and false negatives and deal with the complications arising from DNA decay, DNA advection, and primer bias. 3. Explore the use of environmental RNA (eRNA) as a means to examine the living biodiversity in an ecosystem (i.e. tracking species relative abundances through space and time).	1. Consider the systematic use of eDNA in routine monitoring for the early detection of invasive species or climate-induced range shifts. 2. Manage fisheries and ecosystem heath based on detailed understanding of community composition and dynamics.

Discussion

Inland waters constitute an extremely valuable natural resource, in economic, cultural, aesthetic, scientific, and educational terms. Fresh water has been identified by Canadians as their most important natural resource for 10 years running (RBC Blue Water Project 2017). As stewards of one-fifth of the planet's inland waters, Canadians also bear a large international responsibility.

Despite the importance of inland waters, monitored populations of freshwater vertebrates have experienced marked declines since the 1970s, relative to terrestrial and marine ecosystems (WWF 2018). Forecasting future conservation issues concerning inland waters can identify important gaps in our knowledge, identify new tools, and help proactively manage these ecosystems through informed policy (Sutherland et al. 2017). Moreover, while efforts have been made to identify and highlight threats to global freshwater biodiversity (e.g., Reid et al. 2018) or broadly considered Canadian conservation issues (Boxall et al. 2012), these earlier studies have been not focused on Canadian aquatic systems, despite the vast freshwater resources within the region. The impetus for our horizon-scan exercise was to address this gap, and herein we have identified 15 issues (for a summary see Table 1). Our list of issues comprises a carefully derived subset of both challenges and opportunities that we assess as unrecognized or underappreciated and that require immediate attention to effectively prepare for the near future. Some of the issues we have listed are not unknown and have been addressed in other countries, yet they are relatively new in the Canadian context. Indeed, based on our search in Web of Science, we found that many issues have been addressed infrequently. For example, with the exception of changing winter dynamics, none of the issues have been addressed in more than 10 articles published in Canadian Journal of Fisheries and Aquatic Sciences (CJFAS) in the last 5 years, compared with climate change that has been the subject of 126 publications (Fig. 2).

We identified potential sociopolitical conflicts that could pose major threats to the management of Canada's water resources. Examples include debates among national and international stakeholders on access to and extraction of water, increased risk of oil spills arising from the development of new pipelines, and tensions over chromite mining in Northern Ontario. However, we also identified opportunities to improve the management of Canada's water resources in the face of rapid geopolitical and environmental changes. For example, community science (often referred to as citizen science) can play an important role in filling data gaps related to watersheds and aquatic ecosystems — including in the northern regions of the country. Similarly, the integration of ecological data at the national scale can stimulate a long-term collaborative vision in data sharing and water management and can allow for an increase in data accessibility to researchers, stakeholders, and policy makers. National-scale monitoring programs for inland waters are essential to achieve commitments under the 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals (Dickens et al. 2019; Huot et al. 2019).

A recurrent issue during our discussions was the influence of climate change on many of the emerging issues we have identified; its ramifying effects are still unclear and will almost certainly vary across the country (e.g., Sharma et al. 2019). In this context, it should not be surprising that we identified an expansion of land and water use in the north as an emerging issue. In light of climate change and warming temperatures in northern regions, integrating evolutionary adaptive capacity into environmental impact assessments, while making these more transparent, will allow for

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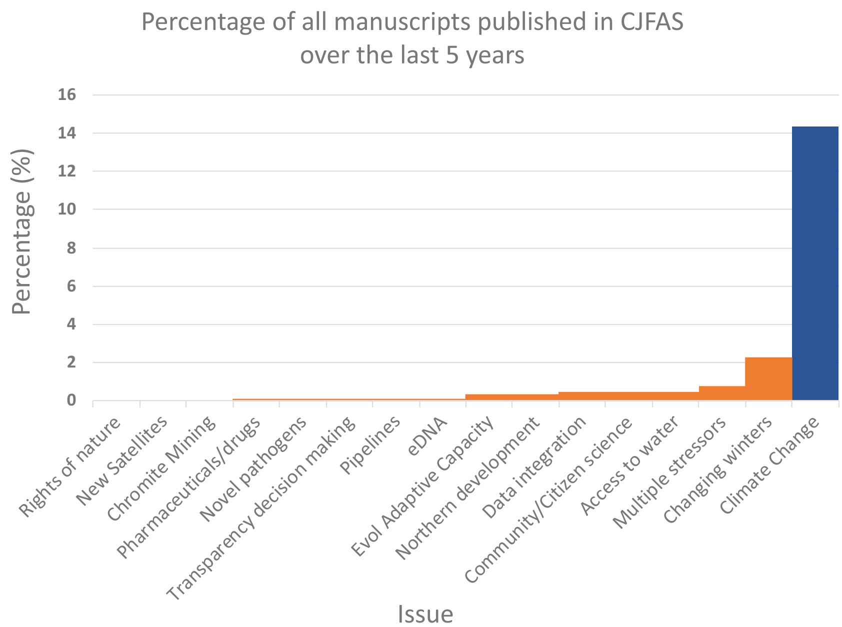
Fig. 2. Literature scan for all publications in the Canadian Journal of Fisheries and Aquatic Sciences (CJFAS) over the last 5 years that address the 15 issues identified in the horizon scan. Labels on the *x* axis represent the keywords used to search for each issue. Climate change was used as a control issue for novelty, as it is widely known and has received considerable attention. [Colour online.]



more targeted and efficient use of resources in conservation practices in an increasingly unpredictable future.

The emerging issues we have identified certainly reflect, in part, the interests and knowledge of the participants engaged in the exercise, which in our case was composed mainly of academics. In future efforts, we envisage engaging with a group with broader range of professions and backgrounds, with greater representation of Indigenous peoples, NGOs, and government employees, so that more perspectives are represented. Nevertheless, our group did identify a wide range of issues that are only loosely related to academic and pure research questions. We see this publication as a first step to engage the broader Canadian community to address the future of conservation of inland waters in Canada.

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