National Freshwater Science Agenda:

A report on national freshwater science priorities

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Environment and Climate Change Canada
Environnement et Changement climatique Canada

Canada

Environment and Climate Change Canada
Public Information Centre
Place Vincent Massey building
351 St-Joseph boulevard
Gatineau Quebec K1A 0H3
Toll free: 1-800-668-6767
Email: enviroinfo@ec.gc.ca

Aussi disponible en français

Foreword from the Minister

Fresh water is a fundamental element of our Canadian national identity and an essential resource for Canadians' health, quality of life, and recreational activities. From swimming in lakes, to skating and ice fishing on frozen rivers, to the glaciers that shape our landscape, fresh water defines how we live and experience the environment.

Fresh water also plays a critical role in a healthy environment and environmental resilience. Freshwater ecosystems—including wetlands, rivers, and groundwater—supply, purify, and protect freshwater resources. It's also a pillar of the Canadian economy, supporting sectors such as agriculture, energy, tourism, manufacturing, fisheries, and recreation.

Canada is home to 20% of the world's fresh water and about 7% of the global renewable supply. However, increasing pressures due to climate change, land use, and pollution are resulting in changes to both the quality and quantity of fresh water. The consequences of these changes include the high economic costs associated with a changing climate and risks to human health, ecosystems, and ways of life, particularly for Indigenous peoples.

The National Freshwater Science Agenda reflects a broad understanding of the most vital science needs to respond to these increasingly complex threats and equip us to make decisions informed by the collective efforts of the diverse freshwater Knowledge Holders across Canada.

It is now more important than ever that we take a coordinated and collaborative approach to improving our understanding of these science priorities to protect the fresh water that helps define our nation. By preserving this aspect of our national identity, we can ensure that Canada's freshwater resources remain resilient, dynamic, and capable of supporting our communities, economies, and ecosystems for generations to come.

– The Honourable Julie Dabrusin, Minister of the Environment, Climate Change and Nature

Executive Summary

Freshwater in Canada is an irreplaceable natural resource, forming an integral part of Canada's national identity. Freshwater is crucial to Canada, vital for our economy, our health, food, energy, and culture. Freshwater underpins our daily lives, essential for recreation, agriculture, industry, and ecosystem health, making its protection a national priority. For Indigenous peoples, water is not simply a resource but a distinct, living being with its own spirit and life-giving power. Indigenous people maintain unique relationships with water that reflect their specific cultural landscapes, histories, and ways of knowing. These relationships shape Indigenous beliefs and sustain biological, spiritual, and cultural well-being, as well as sacred traditions. However, despite its importance, freshwater and freshwater resources in Canada face growing threats to both quality and quantity, including those linked to climate change.

Freshwater, including surface water, the cryosphere, and groundwater, is essential to the environment, communities, human health and well-being, and the economy (**Figure ES-1**). Across the country, freshwater science is carried out by a diverse and extensive community of scientists and knowledge holders, encompassing government, Indigenous, academic, non-governmental, and community-based expertise and knowledge.

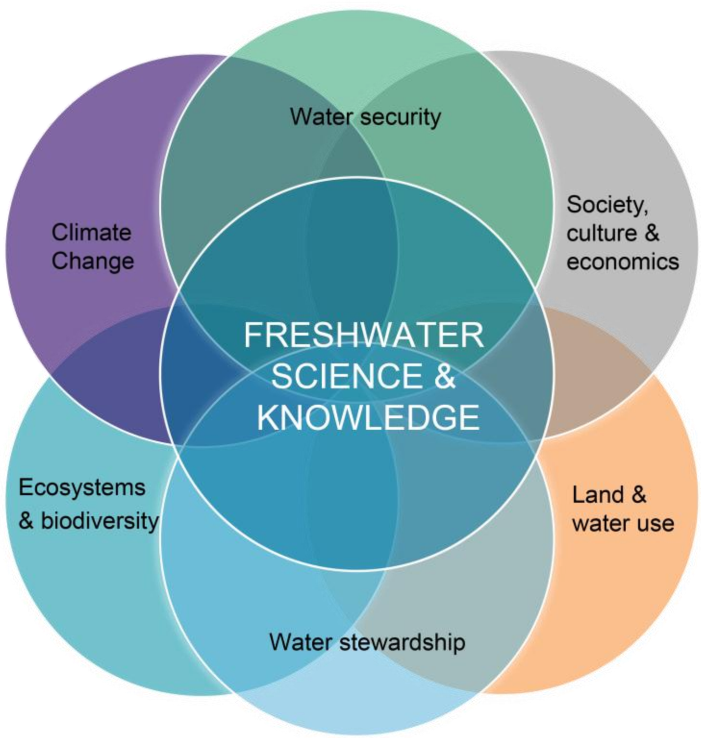

Figure ES-1: Integrated and multi-dimensional nature of freshwater science.

The **National Freshwater Science Agenda** (NFSA) identifies national priorities for freshwater science that reflect diverse voices, knowledge systems, and regional contexts. This report is not an implementation road map for freshwater science. Rather, it serves as a tool to support and guide planning, collaboration, and coordination in freshwater science and research across Canada.

The NFSA was developed with input from freshwater science experts, knowledge holders, and science users across Canada. The priorities identified are intended to focus the attention of the freshwater science community and create a foundation for more coordinated and collaborative action. By aligning common interests, strengthening relationships, and building partnerships, the NFSA aims to ensure that freshwater science responds effectively to the most pressing freshwater challenges facing the country.

The freshwater science priorities are organized under a set of common themes:

- Indigenous science and knowledge systems
- Water availability
- Land use stressors and water pollution
- Freshwater ecosystem resilience and biodiversity
- Regional perspectives
- Social-ecological and economic freshwater research
- Freshwater science and decision-support systems

Each theme outlines key priorities needed to advance freshwater science in Canada. **Figure ES-2** provides an overview of these themes and their associated priorities. Although the priorities are presented by theme, they are deeply interconnected. Priorities identified under one theme often have complex relationships with those in other themes, reflecting the integrated nature of freshwater systems and the science that supports them.

These national freshwater science priorities represent common topics and shared interests identified across the freshwater science community, while also recognizing the diversity of geographic, socio-economic, and jurisdictional contexts that shape freshwater management and decision-making across Canada. At the same time, many priorities are regional or place-based in nature. To reflect these regional realities, the report also highlights a number of key regional freshwater science priorities.

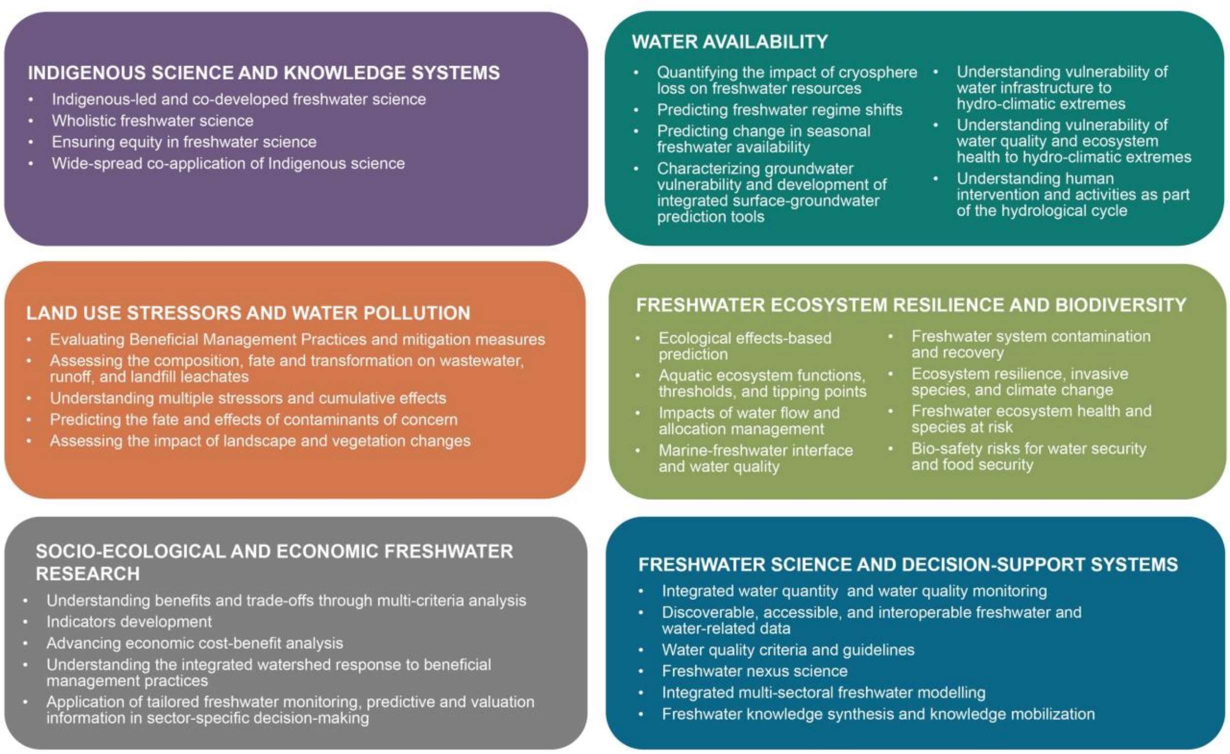

Figure ES-2: National freshwater science priorities.

Both freshwater science and freshwater data play essential roles in supporting evidence-based decisions to protect and manage freshwater in Canada. While the NFSA focuses on freshwater science, it also recognizes the importance of accessible and reliable freshwater data. The National Freshwater Data Strategy, currently being developed by the Canada Water Agency, will provide guidance on how freshwater data and information should be organized, stored, and shared across Canada. The goal of this strategy is to promote greater collaboration and coordination in freshwater data and to make data more easily accessible to Canadians.

Throughout the development of the NFSA, five overarching and cross-cutting foundational elements for advancing national freshwater science emerged (**Figure ES-3**):

1. **Comprehensive understanding and reporting on freshwater:** Develop a more complete understanding of, and reporting on, the state and trends of freshwater and the vulnerabilities across surface and groundwater systems by watershed. This includes consideration of intra- and international jurisdictional boundaries and the influence of hydrological factors such as water retention infrastructure (e.g., dams), water use efficiency technologies (e.g., conservation), and ecosystem-based approaches that enhance the sustainable management and storage of freshwater.
2. **Source attribution and cumulative effects of contaminants**: Continue advancing knowledge on the source attribution, transformation, and fate of contaminant mixtures, as well as the cumulative effects of legacy and emerging contaminants. This includes addressing the combined impacts of urban, industrial, mining, and agricultural sources on freshwater ecosystems, water and food safety, human health, biodiversity, and aquatic ecosystem integrity.

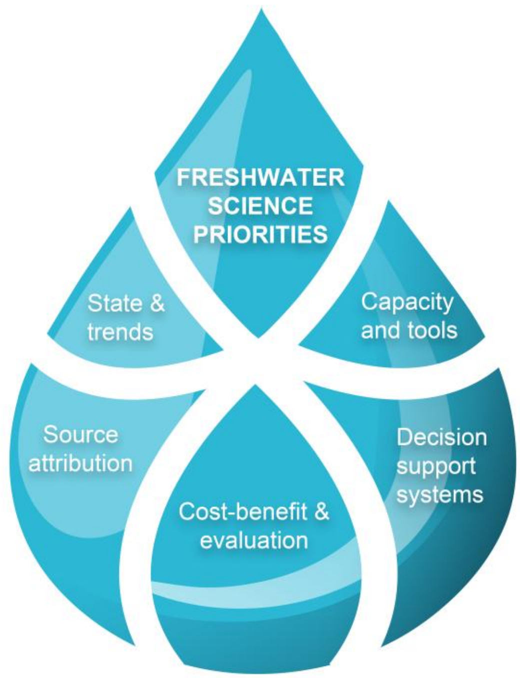

Figure ES-3: Overarching elements for advancing freshwater science.

3. **Understanding freshwater management trade-offs and social dynamics**: Strengthen understanding of the trade-offs, cost-benefit implications, cultural values, and social behaviours that shape freshwater stewardship. Effective water allocation requires understanding competitive demands between extractive and non-extractive uses, the upstream–downstream distribution of costs and benefits, and the environmental justice and cultural values connected to water as part of the broader landscape. Trade-off research should also explore how perceptions of risk and institutional or social behaviour influence decision-making and management outcomes.
4. **Solution-oriented freshwater science and decision-support systems**: Advance science that enables integrated decision-support systems with watershed-based monitoring and predictive capabilities. This includes developing multi-scale approaches and synthesizing knowledge from diverse sources, anchored in indicators that reflect valued water outcomes and management responses to multiple stressors.

5. **Enhancing freshwater science capacity and tools**: Strengthen the scientific foundation and technical infrastructure needed to advance the NFSA priorities. This includes improving access to environmental, social, and economic freshwater data across data providers and holders; expanding watershed-based adaptive monitoring and prediction frameworks; and developing freshwater science assessment initiatives grounded in regional stewardship contexts.

Responsibility for implementing the freshwater science priorities outlined in the NFSA is shared among federal, provincial, and territorial governments, Indigenous governments and organizations, academia, industry, and non-government and community-based organizations—and will depend on collaboration across the freshwater science community. Implementation will need to reflect the needs and realities of the jurisdictions and organizations involved in freshwater science.

Successful implementation is expected to require strengthened coordination mechanisms for freshwater science across Canada. In addition, the knowledge mobilization necessary to connect science with decision-making may open new opportunities for participatory research and capacity building at regional and watershed scales.

In defining and implementing the science priorities, the NFSA highlights several key needs:

- Developing freshwater science coordination structures, supported by the Canada Water Agency and its mandate to enhance collaboration for freshwater management, along with strengthened federal, provincial, and territorial reporting on the state and trends of freshwater.
- Establishing strong and well-supported monitoring and surveillance networks that incorporate new technologies, applications, and nationally standardized protocols, while also leveraging Indigenous- and community-led monitoring to strengthen the foundation of freshwater science and services.
- Improving access to and mobilization of freshwater science and research through the National Freshwater Data Strategy currently being developed by the Canada Water Agency, to ensure that freshwater data in Canada are discoverable, accessible, shareable, and usable.
- Coordinating watershed-based hydroclimate and freshwater modelling that integrates surface and groundwater, water availability, and water quality, through collaboration among government, academia, and water users' organizations and corporations.
- Supporting Indigenous-led cumulative effects science and joint Indigenous and Western freshwater research to inform effects-based monitoring and prediction activities at the watershed scale.
- Fostering multi-disciplinary science teams and research objectives that align with watershed-based decision-support systems and integrate land use and economic data to help value freshwater ecosystem services.
- Aligning monitoring networks and model development with ecosystem and health effects-based knowledge outcomes, tailoring scientific outputs for multiple stressor and One Health contexts (e.g., antimicrobial resistance, new waterborne pathogens, and chemical substances).
- Enhancing user-targeted, watershed-based knowledge synthesis and freshwater literacy initiatives to mobilize existing data and knowledge for sustainable freshwater management. Working closely with decision-makers to advance freshwater science priorities also presents an opportunity to strengthen freshwater literacy across all levels of decision-making.

By clearly identifying national freshwater science priorities while recognizing regional realities and respecting jurisdictional responsibilities, the freshwater science community can foster a more coordinated, collaborative, and responsive approach to addressing the most pressing freshwater challenges over the next decade.

The priorities outlined in the NFSA reaffirm the essential role of clean, safe, and secure freshwater in sustaining the environment, human health and well-being, communities, and the economy in Canada. To realize the full potential of the NFSA, the freshwater science community is encouraged to work together to identify opportunities for collaboration and to take collective action on the priorities presented in the NFSA.

1. Introduction

Canada has one of the largest supplies of freshwater in the world, encompassing vast networks of lakes, rivers, wetlands, aquifers, glaciers, and seasonal snowpacks. These freshwater systems extend across diverse ecozones, climatic regions, and hydrological regimes. Freshwater sustains the environment, communities, human health and well-being, and the economy. It is also an essential part of Canada's national identity and of the biological, spiritual, and cultural well-being and sacred traditions of Indigenous people. As such, freshwater is an irreplaceable natural resource that is vital to Canada and to all Canadians.

However, groundwater, surface water, cryosphere, and freshwater ecosystems in Canada face growing and complex pressures. Pollution, changes in land and water use, invasive species, and the loss of aquatic biodiversity and ecosystem services continue to threaten freshwater systems. Climate change further intensifies these challenges. Addressing them requires stronger coordination and collaboration in freshwater science to support evidence-based decision-making and to respond effectively to the most pressing freshwater challenges facing the country.

Freshwater science forms the foundation for strong, evidence-based decisions to protect and manage freshwater in Canada. Across the country, a diverse and extensive community of scientists and knowledge holders contributes to this work, drawing from government, Indigenous, academic, non-governmental, industry, and community-based expertise. Taking a more strategic and coordinated approach to freshwater science—encompassing research, monitoring, modelling, and knowledge mobilization—would enable this community to build on existing strengths, identify clear priorities, and guide collaborative planning and coordination efforts across Canada.

The 2024 Synthesis of freshwater science in Canada highlighted a range of threats to freshwater systems, from hydroclimatic extremes to agricultural and industrial pollution, and identified the science needed to maintain biodiversity and ecosystem services. It recognized that many freshwater challenges are multidisciplinary and interconnected, shaped by cumulative effects and driven by climate change, land and water use intensification, and contamination from both established and emerging substances.

The Synthesis also emphasized the need for stronger coordination among federal departments with interrelated water mandates, and between all levels of government—federal, provincial, territorial, and Indigenous—as well as academia, Indigenous and non-governmental organizations, communities, industry, and other partners. This coordination is critical for advancing relevant, solution-oriented science that responds effectively to Canada's diverse freshwater policies, frameworks, regulations, management actions, and local initiatives.

Box 1.1 Freshwater governance in Canada

Freshwater governance in Canada is complex, involving federal, provincial, territorial, Indigenous, and municipal governments, as well as Indigenous Nations and communities. The legislative instruments that guide the protection and use of freshwater span national, federal, and international contexts.

The Constitution Act of 1867 does not explicitly define responsibility for water within the division of powers. However, provinces and territories are generally understood to hold authority over the regulation and use of water within their boundaries, while the federal government retains certain rights and responsibilities related to fisheries, navigation and associated infrastructure, and partnerships on water issues of national or international concern.

Indigenous people also hold inherent rights to water, rooted in Indigenous laws, worldviews, and longstanding relationships with waterbodies. The role of Indigenous Nations and governments in collaborative water governance is increasingly recognized within domestic and international policies and water management practices. In broad terms:

- The **federal government** oversees water-related matters connected to federal lands, fisheries, shipping and navigation, and international and transboundary waters.
- **Provinces and territories** manage public lands, create and regulate municipal governments, oversee intra-provincial water flow, and authorize water use.
- **Municipal governments** are responsible for providing drinking water, wastewater treatment services, and land-use planning.
- **Indigenous people** exercise rights and responsibilities for water within their traditional lands and territories.

In addition to governments, Indigenous organizations and communities, academia, non-governmental organizations, and the private sector all contribute to freshwater governance. Their work in research, community-based monitoring, and freshwater stewardship plays a vital role in protecting water quality and supporting the health of freshwater ecosystems in Canada.

Similar freshwater challenges are outlined in Canada's National Adaptation Strategy and Canada's 2030 Nature Strategy, both of which reinforce the need for national and watershed-based integration of scientific data, information, and knowledge to inform targeted policy, regulatory, and management actions. The 2021 Government of Canada report Toward the Creation of a Canada Water Agency: Stakeholder and Public Engagement – What We Heard, which in part helped to inform creation of the Canada Water Agency, further reflected broad interest in science coordination, improved decision-support tools, better access to scientific data and information, and continued development of cutting-edge science to address freshwater challenges. Stakeholders also emphasized growing concern about climate change impacts and the integrity of freshwater ecosystems.

The **National Freshwater Science Agenda** (NFSA) builds on these insights by identifying national freshwater science priorities and providing a foundation for collective action over the next decade. It calls on the freshwater science community—including federal, provincial, territorial, and municipal governments; Indigenous governments and organizations; academia; non-governmental and funding organizations; industry; and community partners—to work together in a coordinated and collaborative way. By aligning common interests, strengthening relationships, building new partnerships, reducing duplication, and focusing on shared priorities, the NFSA aims to ensure that freshwater science directly supports the most pressing freshwater challenges facing Canada.

The priorities presented in the NFSA were informed by a national online survey that engaged approximately 800 freshwater science experts, knowledge holders, and science users from across Canada. Participants represented federal, provincial, and territorial government departments; Indigenous governments and organizations; academia; industry; national water associations; regional water boards; and non-governmental organizations. The survey results informed subsequent engagement activities, including academic roundtables and meetings with organizations holding national or regional freshwater management mandates. These discussions helped to identify knowledge gaps and refine the science priorities. A review of Canadian and international freshwater science strategies and management plans also informed the development of the NFSA.

Canada's vast geography, diverse hydrology and ecology, and complex freshwater governance landscape call for different geographic approaches to advancing freshwater science and implementing the priorities outlined in the NFSA. At the national scale, coordinated science activities and tools—such as remote sensing, Earth observation, water quality and quantity monitoring networks, and environmental DNA (eDNA) surveillance—can strengthen the consistency and comparability of freshwater science across the country. These tools and activities can also improve data sharing, reduce duplication, and align resources across regions to generate consistent baseline information, support national assessments, and enable early detection of emerging freshwater issues. Such national-scale approaches are particularly valuable for addressing issues that are urgent, cross-jurisdictional, or have broad impacts, including flood and drought forecasting, algal bloom detection, tracking endangered or invasive aquatic species, and monitoring large-scale ecosystem changes.

In other cases, a watershed-based approach may offer a more wholistic[1] framework for advancing freshwater science. Working at the watershed scale supports integrated and multidisciplinary monitoring, research, and modelling that reflect natural hydrological and ecological boundaries, local land and water use, and the specific freshwater needs and values of communities. This approach also provides a practical foundation for collaboration and reporting across organizational and jurisdictional boundaries.

Both freshwater science and freshwater data play essential roles in supporting evidence-based decisions to protect and manage freshwater in Canada. While the NFSA focuses on freshwater science, it also highlights the critical importance of data. The National Freshwater Data Strategy, currently being developed by the Canada Water Agency, will establish guidelines and principles for organizing, storing, and sharing freshwater data and information across the country. This strategy aims to promote greater collaboration and coordination in freshwater science and to make freshwater data more accessible to all Canadians.

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[1] The term "wholistic" is used in preference to "holistic," reflecting the evolution of the term toward an emphasis on "wholeness."

Box 1.2 What we heard from freshwater science contributors and users

Freshwater science contributors and users emphasized that the identification and implementation of science priorities must reflect several key messages. They stressed the need for science that:

- Shifts toward multi-scale, whole-system, and interdisciplinary approaches to environmental and watershed-based monitoring, research, analysis, and prediction.
- Supports Indigenous science leadership in the co-definition and co-development of science plans and collaborative activities.
- Improves coordination and integration between water quality and water quantity monitoring and modelling.
- Strengthens prediction tools that connect modelling and monitoring across groundwater and surface water systems, including at the watershed scale.
- Expands cumulative effects analysis through effect-driven approaches that use advanced monitoring and analytical methods and tools.
- Develops predictive models that incorporate climate scenarios and cumulative effects.
- Builds understanding of aquatic ecological resilience in sensitive and valued landscapes, including along the continuum between freshwater and marine environments.
- Encourages the development and adoption of new observation technologies and analytical tools to improve spatial and temporal coverage and diagnostic capacity.
- Promotes the mobilization and integration of freshwater and related data from multiple data owners.

The NFSA represents a concrete step toward enhancing national science coordination through user-driven and user-centred approaches that bring together Indigenous science and knowledge with western science. By identifying clear national freshwater science priorities, while recognizing regional realities and respecting jurisdictional responsibilities, Canada's freshwater science community can foster a more coordinated, collaborative, and responsive approach to advancing science that informs decision-making on the most pressing freshwater challenges of the next decade.

This coordinated approach will also help the freshwater science community meet the information needs of those involved in national and regional freshwater management. It complements other national strategic science initiatives such as Climate Science 2050, Science and knowledge needs to support Canada's implementation of the Kunming-Montreal Global Biodiversity Framework, and Canada's Plastics Science Agenda, and can offer a solid evidence-based foundation to inform new freshwater policies or strategies. A national approach to freshwater science can further support Canada's global commitments under international initiatives such as the United Nations Sustainable Development Goals. It can position Canada as a leader in freshwater science and innovation, while strengthening international collaboration on transboundary water issues, information sharing, and technology transfer.

The NFSA identifies *what* science is needed, rather than *how* it should be implemented. Advancing these science priorities depends on collaboration across the freshwater science community. Implementation will be a shared responsibility among federal, provincial, and territorial governments; Indigenous governments and organizations; academia; industry; non-governmental organizations; and funding organizations. Leadership and support should develop in ways that align with the mandates and contexts of each jurisdiction and organization within the freshwater science community.

Structure of this report

Building on the foundational elements identified in the Synthesis as key outcomes for action, this report uses those elements as guiding principles for advancing freshwater science and knowledge priorities in Canada:

- **National science coordination** to promote multidisciplinary and interdisciplinary collaboration on shared national priorities and needs.
- **User-driven freshwater science** to support watershed, regional, and local priorities within a coordinated national framework.
- **User-centred knowledge mobilization** as an integrating mechanism that connects tools and experts to better translate and address the needs of freshwater science users across Canada.
- **Digital tools, innovative infrastructure**, and common standards to strengthen freshwater science and enable the effective connection, sharing, and use of freshwater knowledge.
- **Indigenous-led freshwater science and knowledge**, emphasizing co-development of science programs and strategies, and the respectful **bridging, braiding, and weaving** of diverse knowledge systems to represent distinct Indigenous perspectives and ways of knowing

Guided by these principles, the NFSA presents national freshwater science priorities that address the most pressing scientific issues while reflecting diverse knowledge systems and regional priorities identified through the NFSA engagement process. The science priorities are organized by chapter under common themes that apply broadly across the country and are complemented by perspectives from Canada's five major drainage areas: the Atlantic, Great Lakes, Hudson Bay, Pacific, and Arctic.

The remainder of this report is organized around major themes in freshwater science:

- **Chapter 2**: Bridging, braiding, and weaving Indigenous science and knowledge.
- **Chapter 3**: Climate change and freshwater science for water availability.
- **Chapter 4**: Freshwater science on land use and pollution impacts on freshwater resources and aquatic ecosystems.
- **Chapter 5**: Freshwater science for aquatic biodiversity and ecosystem resilience.
- **Chapter 6**: Regional science.
- **Chapter 7**: Socio-ecological and economic freshwater research.
- **Chapter 8**: Solution-oriented freshwater science for knowledge mobilization and decision-support systems.
- **Chapter 9**: Overarching freshwater science needs.

Each chapter outlines key scientific priorities and the main knowledge outcomes expected from implementing them. It also includes a short list of science tools that should evolve or be strengthened to advance freshwater science. Annex 1 presents specific science questions related to these priorities, as identified by the science community during the engagement process. Text boxes throughout the report provide additional context or highlight examples of how freshwater science initiatives may develop to align with these priorities (**Figure 1-1**).

Although the freshwater science priorities are organized by theme, these themes are deeply interconnected. Priorities identified within one theme often have complex relationships with those in other themes, reflecting the integrated and multi-dimensional nature of freshwater science.

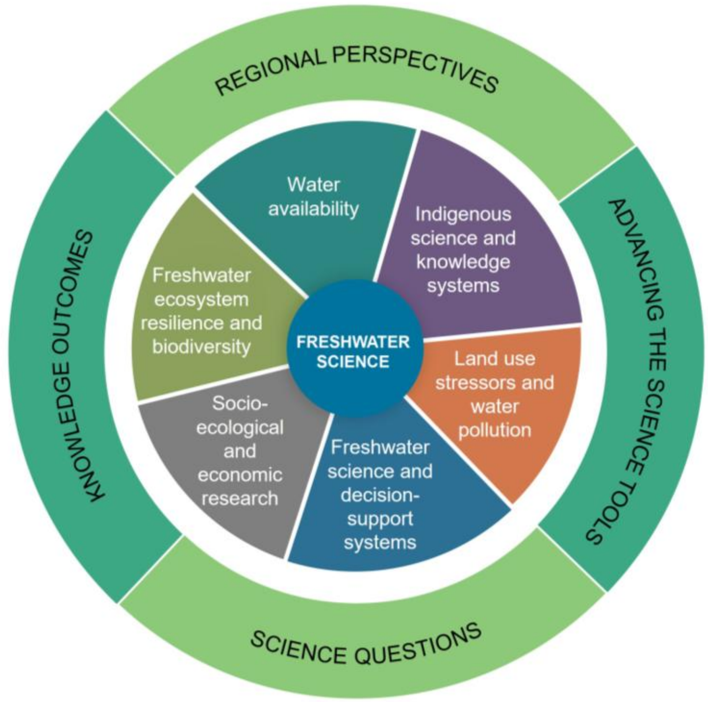

Figure 1-1: Themes covered in the NFSA.

Box 1.3 Key freshwater terminology used in this report

Freshwater includes surface water (streams, rivers, wetlands, and lakes), groundwater, and water stored in the cryosphere (snow, ice, and glaciers). Freshwater science refers to the study of the full hydrological and annual water cycle, including precipitation, runoff and ice melt, soil moisture, water retention in natural and built reservoirs, snow, and vegetation cover as it relates to evapotranspiration.

Watershed or basin describe an area of land where rivers, lakes, and streams flow to a common outlet. Groundwater recharge and discharge, as well as groundwater stored within the basin, are part of the watershed, which may also include multiple sub-watersheds and tributaries. These terms are analogous to major drainage areas. “Watershed” is used throughout the NFSA in a general sense rather than to denote specific stream orders, and the “watershed scale” may vary depending on context.

Aquatic ecosystems are freshwater environments where organisms interact with each other and with the physical and chemical components of their surroundings. These ecosystems include habitats such as wetlands, rivers, lakes, and estuaries. Aquatic ecosystems also encompass groundwater-dependent systems such as aquifers, karst formations, and hyporheic zones. While they are connected to coastal and marine environments, the latter fall outside the focus of the NFSA.

Water security is used in this document to refer broadly to the availability of acceptable quantity and quality of freshwater to sustain ecosystems, human health, and social, economic and cultural needs. The definition of water security may vary according to the context, values, and priorities of organizations and individuals. The United Nations, for example, has defined water security as “the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability.”

Indigenous science and knowledge systems refer to culturally specific methods of generating, refining, and applying knowledge, grounded in the deep wholistic understanding of the natural world held by First Nations, Inuit, and Métis people. This knowledge has been built and refined over generations through lived experience, observation, and practice.

Bridging means fostering awareness, understanding, and recognition of Indigenous science as a distinct and equal science alongside western scientific approaches. Bridging occurs through mutual respect, relationship building, repatriation, engagement, and the creation of shared learning opportunities.

Braiding involves bringing together different ways of knowing and being. The braiding of Indigenous and western science seeks a more wholistic understanding of the environment while maintaining the integrity of each knowledge system. Braiding builds on the principles of bridging and emphasizes reciprocity, renewal, mutual learning, and collective benefits from science outcomes.

Weaving encompasses all the elements of bridging and braiding, along with the inclusion of self-determined Indigenous methodologies, research paradigms, and worldviews. Weaving involves applying Indigenous science tools and approaches to environmental issues and species management in ways that align with the guidance of Indigenous Nations, governments, and communities, as well as international instruments such as the United Nations Declaration on the Rights of Indigenous Peoples.

Western science refers to a system of knowledge based on the scientific method, which relies on observation, testing, experimentation, and evidence to explain and understand natural phenomena.

2. Bridging, braiding, and weaving Indigenous science and knowledge systems

This chapter reflects the contributions of Indigenous science and knowledge holders who shared their experiences and perspectives during the development of the National Freshwater Science Agenda. It does not represent the views and priorities of all First Nations, Inuit, and Métis communities but is intended to encourage continued dialogue and collaboration.

First Nations, Inuit and Métis people[2] maintain an unbreakable and sacred connection with the land, water, and all living beings that inhabit these spaces. These relationships, built on respect and reciprocity, have existed since time immemorial. Indigenous science and knowledge are rooted in the understanding of interconnectedness and the recognition that humans are part of ecosystems, with roles and responsibilities that contribute to maintaining balance and protection.

Indigenous water and land stewardship reflects a wholistic worldview that emphasizes shared responsibility and reciprocal relationships between humans and the environment. These teachings are passed from generation to generation. For example, during engagement on the NFSA, members of the Maa-nulth Treaty Society described how water sustains the biological, spiritual, and cultural well-being of their people, as well as the millions of plants, animals, and other life forms within their territories (hahuułi), for which they hold a responsibility of care and protection.

Many Indigenous languages also serve as repositories of water knowledge, containing specialized terms to describe seasonal changes, water quality, and other indicators of freshwater ecosystem health. Because each First Nation, Inuit, and Métis community has its own culture, language, history, rights, laws, and systems of governance, it is essential to respect and acknowledge distinction-based differences in their interests, priorities, and concerns when managing freshwater.

First Nations, Inuit, and Métis people, many of whom historically lived near rivers and waterways, are the original stewards of freshwater ecosystems in Canada. They are uniquely positioned to continue this guardianship within their territories and to lead efforts to restore lands and waters affected by historic and ongoing colonial development. Meaningful and effective freshwater protection and management depend on recognizing and advancing Indigenous people's inherent rights to apply their intergenerational and place-based knowledge to landscape and waterscape management. This includes recognizing water rights and ensuring participation in governance, licensing, and decision-making related to both surface and groundwater.

Article 25 of the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP) affirms the special relationship Indigenous people have with water. Similar principles appear in the preamble of the revised *Canadian Environmental Protection Act*, 1999, which recognizes the right of every individual in Canada to a healthy environment. Applying Article 25 of UNDRIP within Canada through Indigenous laws offers a path forward for recognizing Indigenous water sovereignty and supporting the wholistic relationships and responsibilities that Indigenous people hold in caring for water.

Many Indigenous cultures honour the life-giving nature of water and recognize its connection to all living things. The understanding that life cannot exist without clean water reflects a sacred relationship between women and water. In many Indigenous cultures, women have traditionally held primary responsibility for the stewardship and care of water. This role is deeply rooted in cultural practices and protocols that form part of specific systems of Indigenous knowledge, accessible only through local, community-defined processes.

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[2] Throughout this report, the terms "Indigenous people" and "First Nations, Inuit and Métis" are understood to include off-reserve and non-status Indigenous people.

For example, from a Métis woman's perspective, water "holds a special place in our collective memory and wisdom."[3] Similarly, the Nishnawbe Aski Nation's 2025 Water Summit identified four guiding principles, including the recognition that "Ceremony must be at the centre of water protection: Water ceremonies are passed down and performed by women, and these ceremonies remind us of the importance of water and life. Ceremony must be integrated at every step of the water journey."

Historical and ongoing colonization has undermined the credibility and inclusion of Indigenous science and knowledge in policy by imposing western legal and scientific frameworks that devalue Indigenous knowledge systems. This exclusion stems from colonial structures that sought to erase Indigenous cultures and sever connections to land and water. As a result, many policies have failed to recognize Indigenous rights, self-determination, and the value of Indigenous perspectives in decision-making, despite clear evidence of their effectiveness and depth of understanding.

Colonization has also deeply affected the roles of Indigenous women in their societies. It disrupted traditional understandings of gender and identity and diminished women's influence in domestic, familial, political, spiritual, and cultural spheres. These disruptions have weakened the wholistic interconnections between Indigenous women and water, affecting the transmission of knowledge, practices, and skills to younger generations.[4] Restoring these connections requires making space for Indigenous women and youth, as well as other equity-seeking groups, to actively participate in freshwater science, management, and policy. Including Indigenous women in freshwater conservation efforts must go hand in hand with addressing and dismantling the colonial systems that historically excluded both Indigenous women and Indigenous people as a whole from environmental decision-making.

Indigenous knowledge systems bring undeniable benefits to freshwater research (**Box 9.1**). The terms ***bridging*, *braiding*, and *weaving*** describe respectful ways of bringing together different knowledge systems—Indigenous and western science—without diminishing the integrity or unique qualities of either.[5] **Bridging** acknowledges each knowledge system as equal, **braiding** fosters a more wholistic understanding, and **weaving** combines these strengths to inform freshwater policy, management, and scientific practice. This approach not only deepens our collective understanding of freshwater challenges but also broadens the evidence base, strengthens trust, and enhances legitimacy in decision-making (**Figure 2-1**).

Indigenous knowledge systems are grounded in deep, interconnected relationships between Indigenous people, the land, water, ice, animal life, and surrounding habitats. Distinction-based perspectives, gender roles, and intergenerational knowledge transfer are all essential and interdependent elements of meaningful relationship-building with First Nations, Inuit, and Métis communities. These must be considered from the outset of any effort to bridge, braid, or weave knowledge systems (**Figure 2-1**, inner ring).

When woven together, these distinct and complementary approaches can support stronger, shared responses to challenges such as climate change and water quality (**Figure 2-1**, middle ring). Achieving this integration, however, requires conscious and sustained collaboration that advances shared science priorities while respecting self-determination, governance, sovereignty, and capacity building (**Figure 2-1**, outer ring).

Crucially, the concepts of bridging, braiding, and weaving do not imply that Indigenous knowledge holds value only when integrated with other knowledge systems. Indigenous knowledge stands on its own as a complete and valid way of understanding the world.

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[3] https://metiswomen.org/wp-content/uploads/2025/04/water_booklet_LFMO.pdf

[4] McGregor D. 2015. Indigenous Women, Water Justice and Zaagidowin (Love). Canadian Woman Studies Les Cahiers De La Femme 30 (2-3): 71–78. https://cws.journals.yorku.ca/index.php/cws/article/view/37455

[5] Bartlett C, Marshall M, and Marshall A. 2012. Two-Eyed Seeing and other lessons learned within a co-learning journey of bringing together indigenous and mainstream knowledges and ways of knowing. Journal of Environmental Studies and Sciences 2: 331–340. https://doi.org/10.1007/s13412-012-0086-8

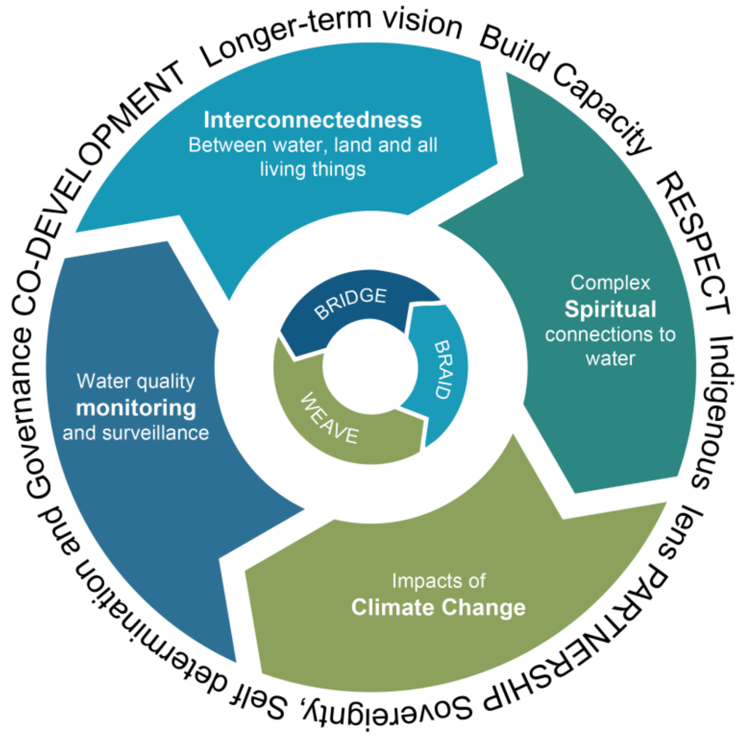

Figure 2-1: Indigenous science and freshwater challenges in Canada.[6]

Indigenous-led and co-developed approaches that reflect community-specific contexts—such as those used to address cumulative effects (**Box 2.1**)—offer effective pathways for advancing freshwater conservation. These approaches produce more meaningful and relevant science outcomes by incorporating distinctions-based and place-based perspectives.

Achieving successful freshwater conservation that upholds Treaty rights and aligns with the principles of the United Nations Declaration on the Rights of Indigenous Peoples requires respectful, ongoing dialogue and long-term, flexible funding mechanisms. Such support enables better strategic planning for future generations.[7]

Ultimately, this work depends on building genuine partnerships founded on free, prior, and informed consent, supported through open communication, mutual respect, and enduring relationship-building.

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[6] Chaulk, K., Ballard, M., Hill, S., Wolfrey, D., Campbell, M., Sutherland, M., Wawatie, S., and Auger, L. 2025. Bridging, Braiding, and Weaving Indigenous and Western science to understand and make predictions about weather and climate change. Ecology and Evolution, In Press, DOI:10.1002/ece3.72085

[7] McGregor D, Latulippe N, Whitlow R, Gansworth K L, McGregor L, and Allen S. 2023. Towards Meaningful Research and Engagement: Indigenous Knowledge Systems and Great Lakes Governance. Journal of Great Lakes Research 49: 22–31 https://doi.org/10.1016/j.jglr.2023.02.009

Box 2.1 Indigenous-led cumulative effects initiatives

Cumulative effects studies are becoming increasingly common across Canada, reflecting the values of Indigenous knowledge systems and the leadership of Indigenous science. Guided by a vision in which Indigenous people have the capacity and authority to assess, monitor, and manage the cumulative effects occurring within their waters, lands, and communities, organizations such as the Indigenous Centre for Cumulative Effects (ICCE - CAEC) are leading this work. ICCE's mission is to create, develop, and share knowledge that empowers community-based approaches.

These approaches enable culturally relevant cumulative effects assessment, monitoring, and management that support Indigenous well-being and inform decision-making. The ICCE's guiding principles include Etuaptmumk (Two-Eyed Seeing),* which teaches the importance of viewing the world through both the strengths of Indigenous knowledge and ways of knowing, and the strengths of western science and knowledge systems.

* Bartlett, Marshall, and Marshall, 2012

Meaningful inclusion helps build capacity through professional development and training opportunities, though needs vary widely across communities (McGregor et al., 2023). Research opportunities developed in equal partnership between Indigenous people and researchers[8] must reflect the interconnectedness of freshwater systems with other habitats, as well as the complex spiritual relationships that shape the cumulative impacts of climate change, biodiversity loss, and pollution.

Co-developed approaches to braiding knowledge systems, including knowledge co-development described in the United Nations Decade of Ocean Science for Sustainable Development and discussed in the Synthesis of Freshwater Science in Canada, demonstrate the value of Indigenous scientists, knowledge holders, and western-trained researchers working together from the beginning of a project. Collaborating on the design, implementation, and evaluation of research strengthens both the science and its relevance to communities.

Moving forward, respecting and building meaningful, long-term working relationships between Indigenous and non-Indigenous partners will be an essential first step in advancing inclusive and effective freshwater science.

2.1 Indigenous science priorities

- **Indigenous-led and co-developed freshwater science**

Indigenous science is grounded in knowledge systems that emphasize **wholistic**, relational, reciprocal, respectful, and community-based understandings of the environment, passed down through generations. In contrast, western science often relies on experimentation and reductionist methods to explain natural phenomena. Because water crosses boundaries and jurisdictions, it demands innovative approaches that integrate diverse knowledge systems and recognize the competing interests of different water users.

Effective management of freshwater in Canada requires a **wholistic** approach to water governance. This, in turn, depends on Indigenous-led and co-developed scientific research that informs freshwater policies and regulations while recognizing, respecting, and upholding Indigenous laws, rights, and jurisdiction.

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[8] Note, some estimates suggest that Indigenous representation in STEM (Science Technology Engineering and Math) fields is less than 1% and Indigenous women make up less than 0.1% of all students enrolled in STEM fields.

💧 It's all connected – wholistic freshwater science

Indigenous science and knowledge systems are based on the understanding that humans are part of ecosystems and must live in balance with the land, water, ice, and air (**Box 9.1**, "Respecting Indigenous People as Scientists"). For instance, research on Indigenous food systems consistently shows that when the land and water are not healthy, the communities that depend on them cannot be healthy either.

Bridging, braiding, and weaving Indigenous and western science requires the participation of **wholistic** thinkers who focus on broad freshwater stewardship outcomes, such as food system revitalization, and who recognize the many ways water is used and valued.

💧 Water is life – ensuring equity in freshwater science

Indigenous women hold a unique and sacred role in protecting water. Colonization has disrupted this role, limiting the ability of Indigenous women to pass traditional knowledge to their children and to sustain their daily livelihoods, especially in communities with matrilineal leadership structures.

It is essential to integrate gender equity into freshwater science by addressing the distinct needs and perspectives of Indigenous women in policies, programs, and funding decisions. Creating inclusive spaces that also welcome Two-Spirit (2S) and gender-diverse people will strengthen the diversity and inclusivity of freshwater science and governance.

💧 Widespread co-application of Indigenous science in all watersheds

Currently, the bridging, braiding, and weaving of Indigenous and western science in Canada occur mainly in Pacific and northern regions and are often focused on fisheries, such as whitefish and salmon. Expanding this work across all regions is one of the most significant challenges moving forward. Many water bodies and waterways, particularly in remote areas, are ecologically significant yet remain understudied and underfunded, with limited resources to support relationship-building with local Indigenous communities.

To address this, greater support is needed to ensure continuity, coordination, and capacity-building for Indigenous-led, place-based research initiatives. Any research involving Indigenous knowledge or co-generated data must be managed respectfully, in alignment with community expectations for data sovereignty. This includes adhering to locally developed data sovereignty frameworks, such as the MÂMAWI-ATOSKÎWIN "integrating cultural protocols" toolboxes created by Ărramăt | Indigenous-led conservation and relationships with Biodiversity, and other existing Indigenous data sovereignty frameworks, such as the First Nations OCAP® principles, Inuit Nunangat Policy, and the Principles of Ethical Métis Research.

3. Water availability

Climate change is altering freshwater systems in Canada in profound ways. Rising temperatures are changing snowfall patterns, snowpack accumulation, and the timing of snowmelt and freeze–thaw cycles in cold regions, leading to reduced water availability in spring. At the same time, more frequent and severe hydroclimatic extremes—such as intense precipitation, floods, and droughts—are degrading water quality and reducing water security across many regions. Warming temperatures are also shrinking the cryosphere in Canada,[9] resulting in less snow cover, shorter lake and river ice seasons, glacier retreat, and permafrost degradation. These changes are reshaping the hydrological cycle and the spatial and temporal distribution of surface water (streams, lakes, and wetlands) and groundwater across Canada.[10]

Climate Science 2050 highlights the urgent need to better understand how climate change affects freshwater systems. Shifts in temperature and precipitation will continue to influence both water quantity and quality, with significant implications for freshwater supply in Canada. These changes not only threaten human water availability and security but also pose major risks to the health, integrity, and resilience of freshwater ecosystems and aquatic biodiversity.

Future freshwater science must therefore consider the condition and functioning of aquatic ecosystems under a range of plausible climate scenarios. This understanding will be essential for developing near-term and long-term approaches to freshwater stewardship and adaptation. Because of the deep interconnections between freshwater and climate, the science priorities identified here should advance in parallel with the water–climate nexus priorities described in Chapter 5: Convergence research topics in Climate Science 2050: National Priorities for Climate Change Science and Knowledge Report.

Engagement with the freshwater science community identified several key priorities for this theme. While presented under water availability, these priorities are closely linked to themes explored in subsequent chapters of this report. Specific science questions related to these priorities are provided in Annex 1.

3.1 Science priorities

Quantifying the impact of cryosphere loss (rate and extent) on freshwater

Expanding knowledge about the rapidly shrinking cryosphere in Canada—including permafrost degradation, glacier melt and disappearance, changing snowpacks, and the reduction of lake and river ice—is essential to understanding the resulting impacts on freshwater quantity, quality, and aquatic biodiversity. Research should focus on quantifying and predicting the effects of:

- Melting permafrost on surface and groundwater quantity and quality.
- Leaching from landfills and contaminated sites located on vulnerable permafrost.
- Continued warming and reduced snow and glacier runoff on freshwater storage, water temperatures, and related impacts on agricultural production, municipal water supplies, hydroelectric generation, and groundwater recharge.

It is also important to assess future changes in the duration and thickness of lake and river ice, along with their implications for shoreline erosion, water temperature, and open-water evaporation rates. These factors directly influence water quantity, water quality, and the health of aquatic ecosystems.

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[9] The cryosphere refers to locations where water exists in its frozen state. This includes all forms of ice, such as snow, ice sheets, glaciers, permafrost, sea ice, lake ice, and river ice.

[10] Much of the research and development related to hydroclimate science, as well as freshwater–climate data and prediction tools, is already addressed through existing climate change and meteorological science planning initiatives. As a result, these areas are not included within the scope of this report. See Climate Science 2050 and the Canadian Centre for Climate Services.

💧 Predicting changes in seasonal freshwater availability

Future freshwater supplies, water budgets, and water chemistry must be quantified at seasonal and watershed scales. Significant changes are expected due to altered snowpacks, earlier snowmelt, loss of glacier ice, more rainfall than snowfall, and higher evapotranspiration. Heavy precipitation events, now more common in spring, summer, and autumn, and even during droughts, can still lead to local water shortages, even in places that receive more total rainfall.

These seasonal changes influence aquatic ecosystem function and integrity, particularly through effects on environmental flows that sustain aquatic species and habitats. Understanding how the “loss of winter” will affect the hydrological cycle, including multi-year and seasonal variability in surface water and groundwater, is essential for improving integrated predictions of water quality and quantity. These insights will support the development of beneficial management practices for urban, industrial, forestry, and agricultural sectors.

Predicting changes in seasonal freshwater availability is also essential for maintaining environmental flows that support aquatic ecosystems and fish species, especially the freshwater and cold-water refugia they rely on during summer drought and heat.

It is also important to include Indigenous science, recognizing that Indigenous knowledge holders may have unique insights into water sources and seasonal variability.

💧 Predicting freshwater regime shifts

Scientists need to identify the global and regional air temperature thresholds that drive regime shifts in freshwater systems. These shifts may include:

- Irreversible changes in freshwater chemistry in northern streams.
- Permanent shifts in streamflow regimes affecting seasonal water availability.
- Alterations in aquatic ecosystems, such as changes to lake trophic states.

Temperature-driven changes to freshwater systems remain poorly characterized, despite temperature being a key factor influencing aquatic chemical and biological processes, as well as lake stratification and mixing. Some regime shifts may already be underway, such as the loss of mountain glaciers and associated changes to streamflow regimes.

It is essential to identify the dominant catchment processes (e.g., runoff generation, groundwater recharge) and functions (e.g., nutrient or chemical source–sink dynamics) that control freshwater availability and quality. These processes must be incorporated into hydroclimatic and water quality models to protect public health and guide water allocation planning. For long-term planning, these processes and functions should be modelled and projected on decadal timescales to inform effective freshwater management and adaptation strategies.

Box 3.1 Groundwater resources

Like surface water, groundwater is vulnerable to contamination, overuse, and the impacts of climate change. It serves as the primary water source for many communities and industries and supports agricultural production across much of Canada. Groundwater also plays a critical role in maintaining surface water flow during low-flow periods.

Despite its importance, information about groundwater in Canada remains limited. Data gaps exist regarding the spatial extent of aquifers, recharge and discharge rates, and groundwater quality. The lack of comprehensive mapping of aquifer locations and properties makes it difficult to effectively monitor, assess, and report on groundwater conditions and trends.

In many regions, surface and groundwater monitoring and modelling are not well integrated, reducing the ability to manage water use and demand sustainably within a watershed. Expanding scientific coordination and establishing standardized data collection and reporting practices for both surface and groundwater would greatly enhance understanding and support more integrated and sustainable freshwater management.

- **Characterizing groundwater vulnerability and developing integrated surface-groundwater prediction tools**

Expanding the monitoring and assessment of groundwater reserves and water quality across Canada is essential for sustainable management of freshwater resources. This work must balance municipal, agricultural, and industrial water demands, as well as dewatering needs for construction and resource extraction. Currently, there is limited understanding of the combined impacts of climate change and human water use on groundwater resources, or of how surface water and groundwater systems interact and offset each other during droughts.

These knowledge gaps are particularly critical in regions that rely primarily on groundwater for freshwater supply. Researchers need to evaluate how climate change affects aquifer recharge and discharge rates, as these influence both surface and near-surface water availability. For aquifers that are disconnected from surface water or that recharge slowly, quantifying sustainable withdrawal rates is key to preventing overuse.

Monitoring groundwater quality is also vital, particularly in areas that depend on groundwater for drinking water and food production, or that face risks of saltwater intrusion in coastal regions. Studies should consider various climate and water demand scenarios to inform sustainable groundwater management at the watershed scale and across transboundary aquifers. This work must be supported by hydrological baseline studies (e.g., hydrogeological conditions, aquifer dynamics) that can feed into the development of integrated surface–groundwater models.

- **Understanding vulnerability of water quality and ecosystem health to hydroclimatic extremes**

Research is needed to assess how increased frequency and intensity of floods and droughts under different future climate scenarios will affect freshwater quality. This includes evaluating the vulnerability of aquatic ecosystems to these extremes and understanding how they influence ecosystem function, biodiversity, and the provision of ecosystem services.

Scientists must determine how droughts and freshwater scarcity affect water quality, biodiversity, and the ecosystem services that depend on them. Warmer water temperatures also influence water quality and aquatic ecosystem health, regardless of whether a watershed experiences more or less water. In addition, more research is needed to understand how severe forest fires—particularly in steep terrain—affect flash flood severity through hydrophobic soil formation and the resulting impacts on water quality.

- **Understanding vulnerability of water infrastructure to hydroclimatic extremes**

A warmer climate will intensify heatwaves and droughts, raise water temperatures, and alter precipitation patterns (e.g., rain-on-snow events), leading to more frequent and severe floods. Improved understanding of flood impacts is essential for predicting and mitigating risks to water infrastructure, including drinking water systems.

Flooding can overwhelm municipal water management infrastructure through combined sewer overflows or dyke and dam failures, resulting in overland flooding and agricultural runoff that pose public health risks. Groundwater-dependent systems, such as private wells and groundwater-fed municipal supplies, as well as northern water infrastructure, face unique vulnerabilities to these changing conditions. Risk assessment and resilience planning are needed to address these challenges.

Research on this topic will also help estimate the economic costs and benefits—including avoided costs—of maintaining and upgrading water infrastructure to improve resilience in a changing climate.

- **Understanding human intervention and activities as part of the hydrological cycle**

Human activities and interventions—such as dams, diversions, wetland drainage, agriculture, forestry, and industrial and municipal water use—are deeply intertwined with the hydrological cycle. These actions influence the availability, flow, and quality of freshwater, as well as the health and resilience of aquatic ecosystems and their functions and services.

Wetlands play a crucial role in water storage and drought mitigation, making them central to water conservation for both human and ecological needs. Expanding freshwater science on wetlands will improve understanding of their role in the hydrological cycle and support more effective management practices.

Climate change further compounds the effects of human interventions, influencing both the quantity and quality of available freshwater. Prioritizing the collection and interpretation of water use data across multiple sectors is therefore critical. Even where data exists, gaps remain in understanding how water allocation policies, land use decisions, reservoir operations, and bulk water transfers will respond to climate change and how these changes will affect the hydrological cycle.

Land use decisions (see Chapter 4) and interventions that alter natural flow regimes and environmental flows (see Chapter 5) intersect with climate adaptation actions, collectively shaping future water availability and chemistry. A better understanding of these interconnected dynamics—spanning land use, climate, and human water management—will inform sustainable water infrastructure design, operation, and investment.

Emerging technologies for water saving, storage, conservation, and treatment are creating new opportunities for improved water management, particularly for irrigation. Innovations that address fluctuating water availability, drought, and variable demand can enhance conservation and storage capacity. New water storage and recycling technologies are being developed across industrial sectors, communities, and households. Understanding the location, scale, and timing of these activities will improve watershed-level hydrological models and inform how water management technologies can be most effectively coordinated and applied.

3.2 Knowledge outcomes

The following are several possible outcomes that are expected if the above priorities are implemented:

- Improved understanding of regime shifts in freshwater quantity, quality, and aquatic ecosystems resulting from future temperature increases and cryosphere changes. This knowledge will help guide risk assessment and support the development of integrated hydroclimatic monitoring and modelling initiatives
- Enhanced knowledge of the range and likelihood of future water budgets and water chemistry conditions to inform effective water allocation, planning, assessment, and infrastructure design that supports sustainable water management practices.
- Improved ability to forecast outcomes of future climate adaptation strategies for water management to better understand the benefits and trade-offs in freshwater stewardship and climate adaptation, particularly in the context of changing freshwater supply and demand.

3.3 Advancing the science tools

To strengthen Canada's ability to understand, predict, and manage water availability, the following science tools and approaches should be advanced:

- **Data:** More detailed water-use data—across both surface water and groundwater—is essential for understanding and managing water availability and water security. Expanding long-term baseline monitoring of water quality and quantity in both human-impacted and sensitive environments is equally important for detecting changes over time and assessing the effects of mitigation measures. Monitoring should prioritize areas with significant human intervention, supported by modernized technologies, while also increasing coverage in sensitive environments such as wetlands, headwater streams, and pristine watersheds to capture baseline conditions and identify early ecological changes

  Information on reservoir operating rules, including flow and timing, is also needed to accurately account for human influences in water budgets and availability estimates. Standardized data protocols are critical for integrating national and regional hydroclimate, water quality, and groundwater monitoring and modelling systems with ecosystem models. Additional aquifer mapping and characterization are required to support modelling and reporting on groundwater availability. Because snow plays a major role in water budgets in Canada, greater emphasis is needed on using snow-related data products (e.g., snow water equivalent, density, and cover extent) to understand snow loss under different climate scenarios.

- **Integrated monitoring, modelling, and analysis:** Evolve toward more integrated, multi-scale climate, hydrology, and water-quality monitoring, modelling, and research programs that encompass both groundwater and surface water systems. This integration should support the development of freshwater indices that describe water availability, supply, and demand. There is also a need to link surface- and groundwater-monitoring and prediction systems, and to create tools that assess how changes in the cryosphere affect water quality and freshwater availability. Extending these hydroclimate-ecosystem projections across the Canada–United States border is essential for building a comprehensive transboundary picture.

- **Assessments of infrastructure vulnerability:** Make evaluating the vulnerability of water infrastructure (hydroelectric generation, municipal water supply systems, wells, etc.) under future scenarios of drought and/or extreme weather scenarios a priority.

- **Multi-scale prediction systems:** Implement modelling platforms that take advantage of high-performance computing systems to simulate daily, monthly, seasonal, annual, and multi-decadal periods as part of watershed-focused, integrated surface and groundwater prediction systems spanning continental to local watershed scales. These modelling platforms form the basis for improvements in early warning systems to identify abrupt changes in water quantity and quality in response to extreme weather events.

- **Integrating monitoring technologies**: Combine innovations in sensor systems, satellite and unmanned aerial vehicle-based remote sensing systems, and real-time and in-situ monitoring, including community-based monitoring programs, to enhance the spatial and temporal resolution of water quantity and quality data across Canada's vast geography, improving timely responses and supporting long-term planning. Leveraging data-driven AI and machine learning can help to synthesize diverse monitoring datasets, capturing complex interactions and enhancing anomaly detection, predictive modelling, and longer-term forecasting of water quantity and quality.

4. Land use stressors and water pollution

Human activities such as municipal development, agriculture, industry, and resource extraction—combined with land use and land degradation—have major impacts on the quantity and quality of freshwater, as well as on aquatic ecosystems and biodiversity. Although many management practices, conservation measures, and remediation actions have been implemented, key science and knowledge gaps remain regarding their effectiveness and the cumulative effects of land development and contaminant releases.

Land use and land-cover changes that affect freshwater systems are also being amplified by climate change. However, the processes and extent to which temperature and precipitation shifts alter freshwater quality and availability are still not well understood. As discussed in Chapter 3, human interventions in the hydrological system—such as diversions, reservoirs, and groundwater withdrawals—add further complexity to the biochemical stresses that land use imposes on water quality, which are not yet fully represented in monitoring and modelling frameworks.

The freshwater science community identified the following science priorities to advance understanding of how land use affects freshwater systems. While presented under the theme of land use stressors and water pollution, these priorities also intersect with several themes discussed in other chapters of this report. Specific science questions related to these priorities are provided in Annex 1.

4.1 Science priorities

- **Evaluating beneficial management practices and mitigation strategies**

The intensification of agricultural activities and associated water use, combined with forestry, wetland drainage, floodplain development, and watercourse alteration for irrigation and drainage, continues to affect freshwater quality and contribute to eutrophication and sedimentation. The ongoing integration, management, and evaluation of beneficial management practices (BMPs) are essential to mitigate the impacts of agricultural, forestry, urban, and industrial land use on freshwater quality and fish habitat.

Research is needed to better understand the seasonal geochemical dynamics of nutrients (e.g., carbon, nitrogen, and phosphorus) and contaminants (e.g., chloride, metals) and how they move between groundwater and surface water systems. This understanding will help refine management practices. Beyond the geochemical impacts, there is an equally important need to understand the physical impacts of forestry and the efficacy of BMPs at avoiding or mitigating them. Operations, such as harvesting on steep, unstable slopes, construction of forestry roads, and logging in riparian areas—also contribute to sedimentation that affects stream geomorphology, water quality, and aquatic habitat.

Because climate and landscape conditions vary across Canada, watershed-specific land use models under different climate and BMP scenarios are needed, particularly in regions with intensive land use. These models will help refine BMPs to ensure their continued effectiveness and adaptability under future climate conditions.

- **Assessing the composition, fate and transformation of wastewater, runoff, and landfill leachates**

Stormwater runoff and effluents from municipal, industrial, mining, agricultural, and landfill sources contain complex mixtures of chemical and biological contaminants, including viruses, bacteria, micropollutants, pharmaceuticals, pesticides, plastics, nutrients, and other unknown compounds. While most wastewater undergoes treatment before discharge, extreme weather events such as heavy rainfall or flooding can overwhelm treatment systems, allowing untreated effluent and runoff to enter surface and groundwater. These events increase risks to freshwater quality, human health, and aquatic ecosystems.

Persistent and mobile contaminants that resist treatment under normal conditions present additional challenges. Understanding the properties, fate, and transformation of these chemical and biological mixtures in surface and groundwater systems remains a significant science gap.

Monitoring programs must better capture baseline water quality and long-term trends, especially in relation to extreme precipitation events, wastewater management practices, and the implementation of BMPs. As northern communities grow, it is also essential to characterize runoff and leachates in vulnerable northern aquatic systems, particularly those underlain by permafrost or dependent on surface water supplies.

Advances in non-target analysis provide valuable tools to address these knowledge gaps. Developing non-target methods to measure complex chemical compositions and degradation products, combined with organism-level effects assessments (e.g., in vitro, in vivo, and multi-generational studies), will strengthen risk assessment. Understanding how groundwater interacts with geological materials and how residence time affects contaminant fate is also critical for assessing long-term risks to water quality and ecosystem health.

- **Understanding multiple stressors and cumulative effects**

Freshwater ecosystems are exposed to multiple stressors that vary across space and time. These include point and non-point source pollution from municipal wastewater, private septic systems, landfills, agriculture, forestry, pulp and paper production, oil and gas, mining, and renewable and non-renewable energy development. Addressing cumulative effects requires an interdisciplinary, effects-based monitoring approach that accounts for past, present, and future activities, as well as broader influences such as climate change and atmospheric deposition.

Research should focus on high-priority chemical mixtures, continuing to investigate endocrine-disrupting chemicals (EDCs) and expanding attention to “forever chemicals,” including per- and polyfluoroalkyl substances (PFAS), which pose well-documented risks to aquatic life and human health. Adaptive, watershed-based monitoring networks that integrate water, air, and wildlife observations and align with land use changes are needed to improve understanding of cumulative effects and inform risk assessments for both human and ecosystem health.

- **Predicting the fate and effects of contaminants of concern**

Improved stochastic and probabilistic water quality models are required to predict chemical dispersion, long-term cumulative effects, and the impacts of pollution events or spills under varying climate scenarios (e.g., temperature increases, altered precipitation patterns, floods, and droughts). These models should incorporate spatial and seasonal variability in water quality, hydrology, and groundwater conditions to reflect the combined effects of multiple land use stressors on freshwater ecosystems.

Long-term, year-round monitoring data are essential to support model development and enhance representation of chemical properties, water–sediment interactions, and the behaviour of chemical mixtures. Contaminants of particular concern include endocrine disruptors, persistent organic pollutants, and microplastics, all of which pose known risks to human and ecosystem health.

Research on emerging contaminants must use robust analytical methods capable of detecting low concentrations. Predictive modelling should also integrate detailed sectoral activity data to capture the effects of mitigation measures and the cumulative impact of BMPs across watersheds. Understanding contaminant fate and transport is particularly important for assessing food safety risks in communities that depend on fishing for sustenance. Complementary social science research can help explain how concerns about contamination affect local food security and cultural practices.

- **Assessing the impacts of landscape and vegetation changes**

Changes in land cover and vegetation from activities such as agriculture, forestry, hydroelectric development, renewable energy expansion, and urbanization can significantly affect freshwater and groundwater systems. Riparian zones and vegetation play vital roles in regulating water quality, preventing erosion and sedimentation, maintaining nutrient flow, supporting biodiversity, and influencing hydrological processes such as runoff and evaporation.

Long-term monitoring of riparian–freshwater interactions is needed to establish baselines and guide management practices that reduce ecosystem vulnerabilities. At the watershed scale, more research is needed to understand how forestry practices, including reforestation and afforestation, influence water cycles, retention, and release. Conservation and restoration of riparian and buffer zones adjacent to water bodies can help protect water quality and freshwater habitats.

Increasing wildfire occurrence and intensity under climate change also pose growing risks. Watershed-scale studies are needed to assess how fire events alter freshwater quality through contaminant release and deposition. Land use changes that reduce surface permeability or alter drainage—such as paving, earthworks, and the conversion of agricultural or forested lands—can disrupt water balance, groundwater recharge, and overall water availability. Evaluating these changes is essential for sustainable watershed and land management.

Box 4.1 Soil health and freshwater

Maintaining healthy, high-quality soils is essential for sustaining and managing both the quality and quantity of freshwater. Soil quality—measured through parameters such as moisture content, pH, nutrient levels, biodiversity, and structure—is closely linked to the availability and condition of freshwater and plays a vital role in supporting agriculture.

Effective soil quality management also helps prevent desertification and improves resilience to drought, buffering the agricultural sector against the growing impacts of climate change. Soil nutrient content (e.g., phosphorus, nitrogen, and carbon) directly influences the quality of water that runs off into nearby freshwater ecosystems. Managing nutrient inputs and improving soil quality are therefore critical components of protecting freshwater systems.

In this way, soil health and freshwater management are deeply interconnected: improving soil quality enhances water retention, reduces runoff pollution, and strengthens the overall resilience of both agricultural and aquatic ecosystems.

4.2 Knowledge outcomes

The following are several knowledge outcomes that are expected if the above priorities are implemented:

- **Broadened and accessible data** on land use and management practices, along with point and non-point contaminant sources, to improve understanding of their effects on water quality over time and strengthen predictions of future impacts.
- **Enhanced knowledge of cumulative effects** of contaminants to better inform risk assessments and evaluate the effectiveness of regulatory measures.
- **Improved understanding of management practice interactions**, including how agricultural, forestry, urban, and industrial beneficial management practices intersect and perform, to guide the evolution of more effective interventions that reduce cumulative impacts on freshwater.
- **Advanced predictive capabilities** to model the dispersion, fate, and combined effects of multiple stressors and cumulative impacts on aquatic ecosystem health under changing climate conditions.

- **Improved landscape change prediction and forecasting** using land use and land cover data, remote sensing technologies, and deep learning methods to anticipate future landscape transformations and their consequences for freshwater systems. These models should also account for climate-driven changes to water cycles, forest fire regimes, and shifting ecozone boundaries.

4.3 Advancing the science tools

The following science tools will help strengthen the ability to assess, predict, and manage the impacts of land use and pollution on freshwater systems in Canada:

- **Data**: Make groundwater and surface water flow and reserve data, as well as land use and water use information, more accessible for water quality model development and evaluation. These datasets should draw from multiple sources and reflect high-resolution land use, water use, and sectoral activities (e.g., remote sensing data, land and resource allocation data, and data from agricultural, industrial, and commercial landowners).
- **Data systems**: Develop discoverable and interoperable, multidisciplinary data systems that integrate water quality and sector-based information. These systems should serve as inputs for developing, evaluating, and applying multi-scale models to assess the outcomes and effectiveness of beneficial management practices and other land use–related freshwater stewardship measures.
- **Watershed-based knowledge synthesis of land use stressors**: Conduct science and knowledge assessments that examine the cumulative impacts of human activities (e.g., municipal, agricultural, industrial, and resource extraction) to better understand the chemical mixtures and multiple point and non-point source stressors affecting tributaries, rivers, lakes, wetlands, and groundwater. These assessments will support sector-by-sector and integrated analyses of cumulative impacts within the same watershed, helping to inform land-use planning and the implementation of beneficial management practices.
- **Targeted water quality monitoring**: Strengthen monitoring and surveillance networks to align with cumulative effects mitigation strategies in priority areas and regions of concern, including northern ecosystems. Monitoring should focus on establishing baselines, tracking long-term trends, and evaluating progress toward recovery targets and environmental standards.
- **Water quality analysis methods**: Advance the use of bioinformatics, molecular tools (e.g., DNA-based techniques), and data analytics to improve water quality assessments. In areas where data are limited, apply advanced statistical methods to evaluate water quality status, trends, and cumulative impacts from multiple stressors and land uses across landscape and watershed scales.
- **Numerical water quality models**: Enhance water quality prediction systems by incorporating updated aquatic ecosystem processes and ensuring compatibility with climate scenario data, hydrological and biogeochemical models, and ecosystem models. These scalable models—from local to watershed levels—can support the establishment of biophysical boundaries, standards, guidelines, and risk assessment frameworks.
- **New technologies**: Leverage advances in nanotechnology, microprocessors, and drone technologies to develop next-generation sensors that improve the spatial and temporal resolution of monitoring. Real-time measurements from these systems can enhance early detection of water quality issues and support more timely decision-making to reduce risks to both ecosystem and human health.

5. Freshwater ecosystem resilience and biodiversity

Freshwater systems shape the structure, function, and resilience of aquatic ecosystems, and the quality and quantity of freshwater directly affect aquatic biodiversity. Healthy communities and overall quality of life also depend, both directly and indirectly, on the functions and services provided by these ecosystems. However, climate change, land use, and water use continue to drive major changes in freshwater systems, with significant consequences for aquatic biodiversity, ecosystem functions, and long-term ecosystem resilience.

Canada's 2030 Nature Strategy: Halting and Reversing Biodiversity Loss recognizes that biodiversity loss is accelerating and that freshwater ecosystems are among the most threatened. Advancing freshwater science is therefore essential for providing the evidence needed to inform conservation, restoration, and sustainable management of aquatic ecosystems, particularly in the context of a changing climate.

Building on existing research, enhancing and evolving understanding of aquatic ecosystem health requires integrated approaches that connect knowledge on land use stressors and the effectiveness of beneficial management practices. This interdisciplinary effort should combine traditional in-situ ecosystem studies with modern scientific tools such as genomics, microbiomics, metabolomics, machine learning, and remote sensing. These advances will help predict changes, identify ecological tipping points, and develop early warning systems to detect unsustainable ecosystem changes.

Box 5.1 One Health

One Health is an integrated and unifying approach that seeks to sustainably balance and optimize the health of people, animals, and ecosystems. It recognizes that human health is closely linked to the health of the environment and other species, and that coordinated, cross-sectoral action is essential for managing complex health risks.

The importance of strengthening multi-sectoral risk assessment has been internationally recognized through initiatives such as the Quadripartite One Health Joint Plan of Action and the World Health Organization Pandemic Instrument, with Canada among the countries leading implementation. Federal sectors, including the tri-agencies, can play a key role in supporting national and regional multi-sectoral research and collaboration across departments and external partners.

One Health addresses a wide range of threats—biological, chemical, environmental, and meteorological—through integrated assessment and management. The goal is to develop high-quality, evidence-based risk assessments that improve understanding of health risks and enable timely, effective action to protect people, animals, plants, and ecosystems.

One Health Approach in Risk Assessment

Stronger coordination between aquatic ecosystem science and end-users will enable informed risk assessments and effective management interventions. These include mitigating the spread of invasive species, protecting and restoring habitats for aquatic and semi-aquatic species, reducing the threat of waterborne pathogens that impact both food and water safety, and safeguarding the ecosystem services that support human and ecological well-being.

The following freshwater science priorities were identified through engagement with the freshwater science community. Specific science questions related to these priorities are included in Annex 1.

5.1 Science priorities

Aquatic ecosystem functions, thresholds, and tipping points

Aquatic ecosystems are vulnerable to abrupt regime shifts when critical thresholds—such as temperature, species abundance, or ecosystem processes—are crossed. These shifts may be triggered by climate change, hydrological alterations, land-use changes, pollution, nutrient loading, and invasive species. While ecosystems may withstand individual stressors, the combined influence of multiple pressures can push them beyond recovery thresholds, resulting in long-term or irreversible change.

Understanding how stressors interact and where key thresholds lie is critical because changes in aquatic ecosystem function can alter water quality, disrupt food webs, reduce carbon sequestration, and weaken resilience to extreme events. Research should focus on identifying temperature, species, and biodiversity thresholds that regulate ecosystem functions and on assessing how factors such as invasive species, climate extremes, altered hydrology, and pollution disrupt these relationships.

Particular attention should be given to aquatic ecosystems already under stress, as well as to better understanding tipping points (e.g., eutrophic or acidic systems). Data on water temperature, species responses, and biogeochemical processes such as respiration, nitrification, and carbon or phosphorus cycling remain limited. Collaborative research is needed to understand how contamination and eutrophication influence carbon sequestration in both surface and subsurface aquatic systems—information that is essential for modelling their role in global carbon cycles.

Targeted data collection, particularly in remote or vulnerable regions, is key to defining ecological thresholds and tracking ecosystem trends. This work underpins the development of indicators for ecosystem function and services that inform adaptive management strategies.

Ecological effects-based prediction

Improving ecological effects-based prediction through a combination of visual methods and modern analytical tools will allow for a deeper understanding of biodiversity and ecological resilience under multiple stressors. The suite of “omics” tools—such as genomics, metabolomics, and microbiomics—remains underutilized for characterizing aquatic species assemblages. Applying these tools can support the development of biomarkers and strengthen both in-vitro and in-situ analyses of biodiversity, ecotoxicity, and ecosystem health.

Interdisciplinary approaches that braid Indigenous and western sciences, particularly through co-developed assessments rooted in community-based monitoring, can broaden the scope and relevance of ecological predictions. These include the integration of Indigenous indicators, such as organoleptic (sensory) observations, that complement western scientific data.

Managing wetland preservation and environmental flows

Water allocation decisions, shaped by land use, water demand, and climate change, can pose significant risks to aquatic ecosystems. Wetlands, which act as natural buffers against nutrient loading, contaminants, and extreme weather, are particularly vulnerable. However, knowledge gaps remain regarding how fluctuating water levels in wetland transition zones—driven by both management practices and climate change—affect ecosystem services.

Existing wetland models need to more fully incorporate groundwater–surface water interactions and water column dynamics to assess ecosystem vulnerability. Existing wetland models need to more fully incorporate water-column characteristics and groundwater–surface water interactions to assess their combined response and vulnerability to water-level management, water allocation practices, and climate change. Advancing knowledge on aquatic ecosystem integrity, and filling data gaps needed to assess environmental flow management, is also essential, including understanding how changes in flow, temperature, and water levels affect navigability, ecosystem function, and biodiversity. This knowledge would inform e-flow criteria and support the protection and restoration of the socially valued benefits of healthy, resilient, and biodiverse aquatic ecosystems. In many areas, data are still lacking to understand the full water balance across diverse user demands and the available integrated groundwater and surface water resources.

Environmental flow criteria should be co-developed with Indigenous people, local communities, and resource sectors to reflect multiple cultural, ecological, and economic outcomes. Improved understanding of the water balance across user demands and connected groundwater and surface water systems is essential for sustainable management.

- **Marine–freshwater interface and water quality**

Estuaries and deltas serve as vital transition zones between freshwater and marine ecosystems, supporting diverse habitats and species. Water quality and salinity in these areas determine their ability to sustain ecological and economic functions. However, land-use activities in coastal watersheds can introduce excess sediment and nutrients, degrading water quality and altering habitat conditions.

Coastal aquifers face increasing risks from saltwater intrusion, which threatens drinking water and irrigation supplies. There are substantial knowledge gaps regarding groundwater–surface water interactions in these transition zones, as well as the extent and rate of saltwater intrusion into groundwater sources.

The marine–freshwater interface also supports critical habitats for anadromous fish and coastal birds. Changes in streamflow, temperature, and sea level rise may alter salinity gradients, reshape coastal ecosystems, and impact species distributions. Understanding these dynamics is essential for effective protection, conservation, and recovery planning.

- **Freshwater system contamination and recovery**

Aquatic ecosystems recover at varying rates depending on land use, fragmentation, and climate conditions. In northern regions, recovery may be particularly slow due to limited regrowth and natural attenuation. Understanding how aquatic ecosystems recover from disturbances—their recovery processes and long-term ecological responses—is essential. These recovery contexts include impacts from mercury and permafrost thaw, as well as a wide range of human-driven disturbances such as oil and chemical spills, pharmaceutical contamination, agricultural nutrients and pesticides, acid mine drainage, releases from retention basins or tailings dams, untreated wastewater, runoff, landfill seepage, contaminated sediment remobilization, and mercury methylation in dams and reservoirs. In a changing climate, these events are likely to recur more frequently and with greater impact. Research should focus on recovery processes across spatial and temporal scales, from small streams to large lakes, and over timescales within groundwater flow systems, reflecting the time lag in transport and ecological responses, ranging from years to centuries.

Climate change accelerates the bioavailability and bioaccumulation of contaminants such as mercury, nutrients, and persistent organic pollutants, emphasizing the need for predictive models that integrate chemical, biological, and hydrological data.

- **Ecosystem resilience, invasive species, and climate change**

Invasive species remain one of the leading causes of biodiversity loss worldwide and pose serious risks to food security, economies, and human health. Climate change is amplifying these impacts by allowing invasive aquatic and semi-aquatic species to expand into new regions, reproduce more rapidly, and persist year-round.

Changes in hydrology, water quantity, and water quality can create conditions that favour invasive species and stress native populations, particularly species at risk. These pressures can compound, leading to reduced water quality, eutrophication, and habitat loss, affecting ecosystem resilience.

Advancing the use of remote sensing, environmental DNA (eDNA), and in-situ monitoring can improve early detection and tracking of invasive species. Socio-economic and biological assessments can help prioritize high-risk species and pathways. Collecting the data needed to fill key gaps, along with developing predictive risk models and assessing prevention actions (including stewardship and communication approaches informed by social science), will also help guide more effective prevention activities.

Freshwater ecosystem health and species at risk

Freshwater habitats provide essential support for many species at risk. Advancing monitoring and research to detect population changes, identify cumulative threats and impacts, and model species and habitat vulnerability to climate change will improve conservation and recovery efforts.

Mapping and prioritizing critical habitats and applying multi-species approaches—where suitable—can enhance recovery strategies while providing broader ecosystem benefits. Species at risk often serve as indicators of ecosystem health; their decline signals broader ecological stress. Monitoring their condition and habitats is therefore vital for sustainable freshwater management and biodiversity protection.

Bio-safety risks for water security and food security

Waterborne antimicrobial resistance (AMR) and pathogens from municipal and agricultural runoff pose growing bio-safety risks to both human and ecosystem health. Pharmaceuticals and other pollutants entering freshwater systems contribute to the spread of AMR, while extreme weather events can overwhelm treatment systems, leading to contamination of drinking water and aquatic food sources.

Research is needed to better understand how pharmaceuticals and non-pharmaceutical pollutants influence AMR development and transmission, leveraging both standard and new methods to address this gap. Expanding surveillance of municipal wastewater and agricultural runoff will strengthen the ability to assess, model, and mitigate outbreaks. AMR and pathogens also weaken ecological resilience, with consequences for fisheries that support community economies and food security.

Integrating these studies with One Health approaches (**Box 5.1**) and effects-based prediction systems can directly inform decision-making in response to spills, wastewater overflows, and future contamination events. Strengthened monitoring networks that integrate surface and groundwater systems will be key to managing risks to public health, food security, and freshwater ecosystem resilience.

Freshwater science for environmental emergencies

Environmental emergency science plays a critical role in supporting preparedness and response to incidents involving the release of pollutants into freshwater systems. This science is particularly important in regions such as the Great Lakes, the St. Lawrence Seaway, and the Fraser River, where shipping, industrial activity, and resource extraction are concentrated. In the Arctic, climate change, warming temperatures, and thinning ice are introducing new risks as traditional ice roads become unstable and commercial shipping expands into previously inaccessible waters.

Current knowledge gaps limit the ability to effectively plan for and respond to freshwater contamination events. There is insufficient hydrodynamic characterization of rivers and near-shore environments that may be vulnerable to spills, particularly with respect to their bathymetry and morphology. Improved flow estimates and near-real-time flow observations using technologies such as high-frequency radar are needed to better predict the fate and transport of spilled materials in rivers, lakes, and connecting channels.

Enhanced shoreline baseline characterization is also essential to improve emergency preparedness and inform spill mitigation strategies.[11] Further research should focus on refining and targeting the use of aerial, surface, and subsurface remote sensing for detecting and tracking spills through freshwater systems.

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[11] Improved shoreline baseline characterization of physical features, sediment type, vegetation cover and wave exposure, aligned with spill response practice as per A field guide to oil spill response on freshwater shorelines: chapter 5 - Canada.ca

Additionally, hydrodynamic models that connect rivers, tributaries, and lakes—especially within the Great Lakes basin—need improvement to better represent water flows under various conditions. Currently, these models are often developed for specific regional applications and vary in their data requirements for coastal versus inland systems. Coordinating the development and evaluation of a suite of compatible hydrodynamic models, along with establishing standardized data repositories for model outputs, would greatly enhance the ability to plan for, respond to, and mitigate the impacts of environmental emergencies across freshwater systems in Canada.

5.2 Knowledge outcomes

The following are several knowledge outcomes that are expected if the above priorities are implemented:

- **Enhanced predictive capability** to assess ecosystem resilience and biodiversity under the combined pressures of climate change and human activities. This includes identifying critical species and biodiversity thresholds to guide habitat conservation, protection, and freshwater management decisions that also consider human health risks.
- **Improved contamination response and recovery insights** through advanced environmental monitoring, surveillance, and interdisciplinary research on freshwater contamination processes (e.g., spills, antimicrobial resistance). These efforts will support more effective emergency planning and public health protection.
- **Improved understanding of water management interventions** by assessing how actions such as water allocation, conservation, protection, and transfers influence ecosystem services and biodiversity, enabling more sustainable and adaptive management approaches.
- **Interdisciplinary and co-developed monitoring and research approaches** that integrate multiple knowledge systems to generate wholistic understanding needed to sustain biodiversity and ensure the safety and security of food and water resources.

5.3 Advancing the science tools

The following science tools will enhance Canada's ability to predict, monitor, and respond to environmental change, contamination, and ecosystem disruption in freshwater systems:

- **Data:** Improve access to real-time groundwater and surface water flow data, particularly in nearshore environments (0–200 m) and connecting river–lake and river–ocean systems. These data are essential for informing spill trajectory models and improving prediction of contaminant transport.
- **Data systems:** Integrate and improve accessibility to water quality and One Health surveillance data to better inform biosafety risks and emergency responses. Strengthen surveillance systems, including those tracking antimicrobial resistance (AMR), by leveraging existing public health sentinel sites, effluent discharge points, and water quality monitoring networks. Incorporating environmental DNA (eDNA) and "omics" approaches will enhance detection, monitoring, and risk assessment capabilities.
- **Remote sensing, mapping, and monitoring tools:** Expand the use of satellite observations, airborne LiDAR, unmanned aerial vehicles (e.g., drones), underwater vehicles, and ground-based sensors (e.g., ground-penetrating radar) for assessing shallow subsurface and surface water conditions. Combine these technologies with AI-based analytics to detect and monitor real-time and long-term ecosystem changes such as eutrophication, trophic state shifts, algal blooms, effluent releases, and industrial or urban disturbances in wetlands, rivers, and lakes.
- **High-resolution elevation and topographical data:** Use detailed topographic and elevation datasets to support habitat delineation, hydrological modelling, and change detection, such as

assessing volumetric changes in natural lake and pond storage capacity. These tools will increase spatial and temporal monitoring resolution—particularly in remote regions—and strengthen early warning systems and long-term environmental assessments.

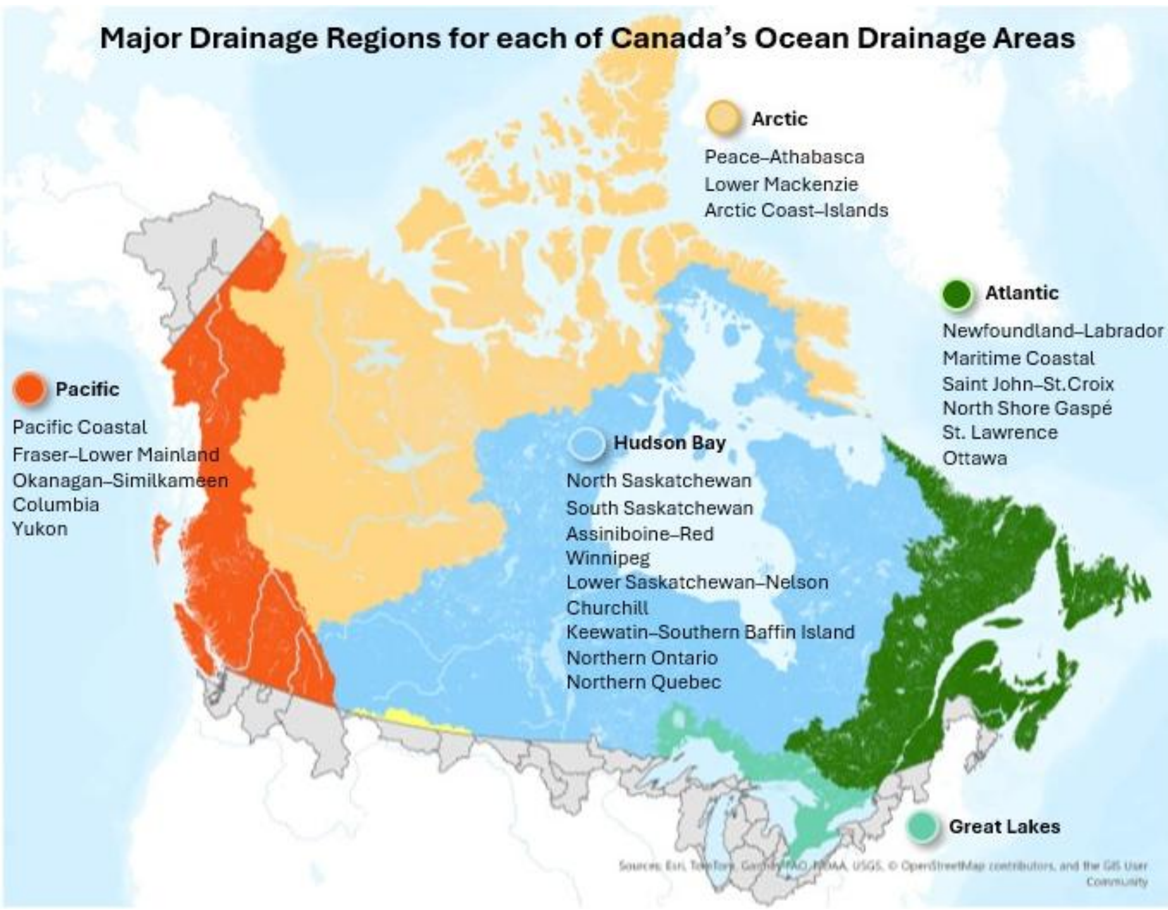
- **Standardized "omics" (DNA-based) protocols and indicators:** Apply standardized "omics" techniques to freshwater diagnostics to assess interspecies and intraspecies relationships, genetic diversity, microbial loading, and aquatic zoonotic or spillover infections. These methods can provide powerful indicators of ecosystem health and biological change at multiple levels—from genes to entire communities.
- **New Approach Methodologies (NAMs):** Advance the use of NAMs to reduce reliance on vertebrate aquatic animal testing. These less invasive methods—including toxicogenomics, metabolomics, and cell-based assays—support the assessment of acute and chronic toxicity while aligning with ethical and sustainable research practices.
- **Targeted and long-term in-situ studies:** Conduct systematic, ecosystem-based studies that improve mechanistic and real-time understanding of aquatic processes driving ecosystem resilience. These studies help fill critical knowledge gaps on the ecological effects of chemical mixtures, invasive species, landscape disturbances, and habitat changes. They also provide opportunities to test restoration and recovery approaches and incorporate socially and culturally significant species into monitoring frameworks.
- **Predictive models:** Integrate remote sensing data, deep learning, and machine learning to develop predictive models for detecting, monitoring, and forecasting the spread of aquatic invasive species. Advance ecological response modelling for major lakes, rivers, and groundwater systems to better understand food web dynamics and inform restoration and management decisions. Coordinate the development and standardization of regional hydrodynamic models to strengthen emergency response capabilities and support long-term freshwater stewardship.

6. Regional perspectives

Hydrologic regions provide a strong foundation for wholistic freshwater science planning, monitoring, targeted research, and management. Across Canada, many science partnerships already exist among Indigenous nations, governments, communities, non-governmental organizations, and other stakeholders within these regions.

Each hydrologic region has distinct social, economic, and ecological characteristics, as well as unique hydrological regimes. Consequently, while similar stressors—such as pollution, climate change, or land use—may occur across multiple regions, their impacts and the most effective management responses can differ significantly. This variation underscores the need for region-specific freshwater science priorities.

Using a hydrologic regional approach allows for focused action to address the priorities outlined in previous chapters. Five Canadian hydroclimatic regions, defined by natural topographic boundaries that encompass regional hydrology, ecosystems, ocean drainage areas, and major freshwater sources, form the basis for identifying these regional priorities (**Figure 6-1**). These regions include the major drainage areas listed in each of the boxes in **Figure 6-1**, which together capture Canada's watersheds, sub-watersheds, and coastal water systems.



Notes: (1) the Great Lakes, which drain into the Atlantic Ocean Drainage Area, were separated for the purposes of this chapter, since stakeholders and water managers have a long-standing and well-established set of international agreements, collaborative scientific activities, and governance. (2) The Missouri drains a very small portion of Canada and has been excluded from the analyses in this chapter.

Figure 6-1: Watershed regions for freshwater science priorities, aligned with the major drainage areas identified in the Statistics Canada, 2009, special tabulation data from Pearse, P.H., F. Bertrand and J.W. MacLaren, 1985, Currents of Change: Final Report of the Inquiry on Federal Water Policy.

First Nations, Inuit, and Métis leadership in Indigenous knowledge and science, as discussed in Chapter 2 and throughout this report, is most effectively expressed through place-based and co-designed watershed science approaches. A distinctions-based, inclusive, and wholistic perspective on freshwater science is therefore embedded across all priorities outlined in this regional chapter and is not repeated in the following tables. Similarly, community-based monitoring and cumulative effects research are understood to be integral to addressing regional science and knowledge gaps and are not listed separately.

Each regional context requires tailored, user-friendly science interfaces that integrate state-of-the-art freshwater science tools to support effective decision-making. These decision-support systems should provide real-time monitoring, prediction, and data visualization capabilities to inform timely management responses—for example, early detection of invasive species, drought and water demand management, or public health interventions. When freshwater prediction frameworks also incorporate factors such as land use change, population growth, economic development, and energy demand, they become even more relevant to local and regional decision-making.

Much like climate services, regional or watershed-based freshwater data and information products should be tailored to meet sector-specific needs in areas such as water allocation, remediation, and conservation. Strengthening knowledge synthesis and mobilization efforts will make existing science more accessible and actionable for decision-makers. Reporting by watershed, supported by clear indicators and the integration of community-based monitoring within decision-support systems, can enhance freshwater stewardship, guide management of competing water uses, support conservation and protection objectives, and identify adaptation or mitigation options.

While science and reporting are critical at regional and watershed scales, integrating knowledge across watershed boundaries is increasingly important. This integration supports decision-making related to bulk water transfers, water exports, and cross-boundary freshwater management. In addition, the socio-ecological and economic knowledge gaps identified in the next chapter provide opportunities to align science with watershed-specific contexts, enabling more robust benefit-cost analyses and improved freshwater stewardship.

Table 6-1 through **Table 6-5** provide an overview of key freshwater science priorities identified for each of Canada's major hydrologic regions under three themes: Water – Climate Change Science, Water – Land Use Science, and Water – Biodiversity Science.

Table 6-1: Freshwater science priorities: Atlantic (including the St. Lawrence River).

Water – Climate Change Science	Water – Land Use Science	Water – Biodiversity Science
Atlantic (including the St. Lawrence River)		
Predict concurrent climate change impacts—including changes in snowmelt patterns, adaptation measures, and flow management—in systems such as the St. Lawrence River and its tributaries.	**Develop a data integration tool** to model and predict changes in land use and water use, incorporating sector-based data and information on impaired areas such as contaminated sites.	**Identify, assess, and predict changes** in bacterial, planktonic, nektonic, and benthic (fauna, flora, and bacteria) populations, and examine their linkages to algal blooms and fish mortality in high-

Water – Climate Change Science	Water – Land Use Science	Water – Biodiversity Science
Atlantic (including the St. Lawrence River)		
Enhance freshwater monitoring to address knowledge gaps in baseline water quality and quantity, and develop appropriate benchmarks to support hydroclimate modelling and assessment of cumulative effects and risks from land-based development. This is particularly important for Atlantic coast rivers draining into areas such as the Bay of Fundy and the Northumberland Strait. **Develop scalable hydroclimate models** at the sub-watershed level (e.g., St. Lawrence tributaries and Atlantic rivers) to assess freshwater availability and associated risks, including connectivity between freshwater and marine systems such as the St. Lawrence estuary. **Link hydroclimate model outputs with water quality models** to evaluate how climate change affects sediment, nutrient, and contaminant loadings, as well as the effectiveness of pollution control measures. **Assess water quality and ecosystem risks**—including those affecting tidal waters—related to intensive agriculture, and evaluate the impacts of surface water and marine saltwater intrusion resulting from groundwater use, particularly in Prince Edward Island. **Assess local and regional variability** in key watersheds to better understand how climate change affects hydrology, water quality, and ecosystem function	**Assess cumulative effects** by establishing multi-media, integrated monitoring sites (covering surface water, groundwater, sediment, and biota) in key systems such as the St. Lawrence River, the Wolastoq/St. John River, and Lake St. Pierre. **Monitor baseline conditions** and cumulative effects risks proactively in remote regions where new or expanded land-based developments are expected, particularly in areas with strategic mineral development in northern Quebec and Newfoundland and Labrador. **Evaluate cumulative effects** of intensive agriculture and climate change on surface and groundwater systems, and assess the effectiveness of existing and emerging mitigation measures. **Assess risks and the effectiveness of beneficial management practices** (BMPs) related to fish kills and anoxic events in the southern Gulf of St. Lawrence, focusing on the transport of excess nutrients from intensive agricultural practices through both surface water and groundwater pathways.	biodiversity and sensitive areas such as Lake St. Pierre. **Develop an early alert system** to detect and prevent the spread of new invasive species, including microorganisms, aligned with existing Great Lakes alert systems to strengthen regional response capacity. **Assess ecological impacts and recovery** in sensitive freshwater systems such as Lake St. Pierre, acidic lakes in Nova Scotia, and impaired rivers discharging to coastal areas, taking into account downstream effects on adjacent marine environments. **Identify and monitor freshwater ecosystem responses** to climate change and human land use that influence cold-water refugia and river connectivity, which are essential for maintaining habitats that support vulnerable and at-risk species. **Integrate aquatic biomonitoring** into wetland ecosystem surveys to develop models linking biodiversity and ecosystem functioning at the watershed scale, enabling more effective prioritization of protection, restoration, and conservation efforts.

Water – Climate Change Science	Water – Land Use Science	Water – Biodiversity Science
Atlantic (including the St. Lawrence River)		
across diverse environmental conditions.		

Table 6-2: Freshwater science priorities: Great Lakes.

Water – Climate Change Science	Water – Land Use Science	Water – Biodiversity Science
Great Lakes		
Apply downscaled climate scenario data to predict nutrient loading, mobilization, and remobilization during extreme weather and flooding events, improving understanding of how climate variability influences water quality. **Assess the impacts of declining lake and snow cover** across watersheds, including the effects of increasing temperatures, enhanced stratification, and associated changes in biota, water quality, and net basin water supply. These assessments should also consider concurrent nearshore land use impacts, both positive and negative. **Conduct tributary-specific (sub-watershed) assessments** of water availability to evaluate how extreme weather events collectively affect both water quality and quantity downstream within the Great Lakes system. **Address winter season data gaps** by improving monitoring and research during ice-covered periods, and assess how seasonal changes in temperature, precipitation, and ice cover influence contaminant dynamics,	**Conduct cumulative effects studies** on transboundary industrial activities, municipal wastewater effluents, and combined point-source discharges over time, in alignment with pollution reduction strategies under the Great Lakes Water Quality Agreement. **Predict the combined impacts** of pollutant loadings and biological responses from diffuse pollution sources in tributaries, connecting channels, and lake systems to improve understanding of land-to-lake connections and how climate change may alter these interactions. **Develop standardized modelling approaches** and integrated assessments of groundwater and surface water contamination, incorporating both legacy and current landfill and wastewater disposal sources (municipal and industrial). Focus these studies in key areas such as the Grand River, including assessments of downstream effects on drinking water quality. **Evaluate cumulative impacts** of intensive agriculture under a changing climate, including how evolving nutrient management practices and ongoing monitoring of	**Continue assessing ecosystem recovery** within the Great Lakes Areas of Concern (AOCs), accounting for multiple management actions that address beneficial use impairments and evaluating progress toward restoration goals. **Implement adaptive monitoring programs** to support a transboundary alert system for detecting microbiological changes and pathogen presence in the Great Lakes, enhancing early warning capabilities and public health protection. **Apply comprehensive analytical tools** to evaluate changes in Great Lakes and tributary food webs, including indirect impacts on human health and food security (e.g., through fisheries and aquatic resource use). **Develop lake-wide, low-cost, and integrated observation platforms** equipped with multiple sensors to monitor both air and water parameters, improving large lake observation capacity and data integration. **Expand lake-wide remote sensing surveillance** to track the

Water – Climate Change Science	Water – Land Use Science	Water – Biodiversity Science
Great Lakes		
hydrology, and related policy and management decisions.	watershed loadings influence freshwater quality. This includes assessing the effectiveness of beneficial management practices (BMPs) across the Great Lakes basin. **Continue monitoring and research** on emerging contaminants, such as microplastics, to better understand their sources, environmental behaviour, ecological impacts, and potential mitigation strategies.	development, spread, and intensity of algal blooms, supporting early intervention and management strategies. **Enhance biological surveillance** using emerging technologies such as environmental DNA (eDNA) metabarcoding to detect and monitor the arrival or spread of invasive species, and to assess their cascading impacts on food webs, nutrient cycling, and ecosystem functions.

Table 6-3: Freshwater science priorities: Hudson Bay (including the Prairies).

Water – Climate Change Science	Water – Land Use Science	Water – Biodiversity Science
Hudson Bay (including the Prairies)		
Monitor and model cryosphere change by tracking declining glaciers and snowpack, snowmelt timing, and snowmelt–groundwater dynamics to assess implications for regional water and energy supply. **Assess "loss of winter" navigation risks** by conducting comprehensive risk assessments of how shorter, warmer winters may worsen navigation challenges linked to low river levels (e.g., the Lower Athabasca River). **Analyze streamflow dynamics** by evaluating responses to shifting flow regimes, irrigation expansion, wetland management, and the influence of non-contributing areas on basin runoff. **Quantify lake and wetland volume change** by determining	**Apply downscaled climate scenarios** to assess sector-specific land use change and water resource risks for agriculture, energy, and mining, with attention to large lake systems (e.g., Lake Winnipeg). **Establish baseline monitoring** for critical minerals development by undertaking water quality and quantity monitoring and applying predictive tools to evaluate potential risks from expanding mining (e.g., the Ring of Fire region). **Evaluate cumulative effects** of intensive agriculture and climate change on surface and groundwater, and assess the effectiveness of mitigation measures.	**Undertake adaptive monitoring** of aquatic and terrestrial invasive species locations and transboundary movement, particularly in the Lake Winnipeg watershed, across the Prairies, and across the Canada–United States border, to enable timely reporting and response. **Assess the role of invasive species** in nutrient dynamics and fisheries, as observed in Lake Winnipeg, and evaluate ecosystem vulnerability to prioritize management actions. **Improve watershed-scale wetland biodiversity assessments**, especially in areas affected by excess nutrients and chemical contaminants.

Water – Climate Change Science	Water – Land Use Science	Water – Biodiversity Science
Hudson Bay (including the Prairies)		
how lake and wetland storage is changing across the Prairies and the resulting implications for groundwater systems. **Evaluate groundwater resources** by assessing groundwater availability and usability, climate change impacts on surface water–groundwater interactions, aquifer recharge, and runoff generation. **Track wetland hydroperiod shifts** by examining the spatially variable responses of wetland hydroperiods (e.g., prairie potholes) to a changing climate. **Expand monitoring in permafrost regions** by monitoring water quality and quantity in areas experiencing rapid permafrost thaw (e.g., northern Hudson Bay). **Study multi-year drought effects** by investigating the hydrologic consequences of consecutive drought years for prairie systems, including snowpack reductions and changing groundwater–surface water use and interactions. **Focus on Lake Winnipeg tributaries** by assessing climate-driven changes in tributaries (e.g., flood and drought frequency) and implications for municipal and community water availability.	**Expand nature-based solutions** to build climate resilience (e.g., protecting wetlands, planting trees to restore natural flows, riparian and river restoration to reduce flooding and increase biodiversity, improving river connectivity, and enhancing grazing land management). **Continue nutrient monitoring** and assessment of sources, loadings, and BMP effectiveness in the Lake Winnipeg watershed to evaluate cascading effects in lakes and reservoirs (e.g., Lake of the Woods, Lake Winnipeg, Lake Winnipegosis, Cedar Lake), including transboundary contributions (e.g., the Red River). **Assess hydroelectric production** scenarios considering future demand and downstream community impacts—especially land use change and mercury methylation—with emphasis on large reservoirs (e.g., the Saskatchewan River, the Churchill River, and La Grande River). **Broaden Lake Winnipeg basin science** to include cumulative effects assessments of multiple stressors at local and watershed scales, including transboundary transport of contaminants.	**Expand Lake Winnipeg basin science** to examine multi-species interactions that support sustainable fisheries. **Assess how climate, water quality, and water availability influence** the recovery of threatened and endangered fishes. **Apply remote sensing** to conduct surveillance of algal bloom development and expansion.

Table 6-4: Freshwater science priorities: Pacific.

Water – Climate Change Science	Water – Land Use Science	Water – Biodiversity Science
Pacific		
Study the implications of declining glaciers and snowpack for regional water and energy supply, including shifts in seasonal water availability as flow regimes transition from snowmelt-dominant to hybrid or rainfall-dominant systems. **Undertake an integrated assessment** of freshwater resources, encompassing precipitation, evapotranspiration, groundwater recharge, and the identification of sensitive watershed hot spots. **Assess the impacts** of extreme hydroclimatic events (e.g., atmospheric river–driven floods, meteorological, agricultural, and hydrological drought, summer heatwaves) on water quantity and quality. **Evaluate the effects** of permafrost thaw on regional water quality and availability in the northern part of the region. **Determine cumulative water management** response capacity and limits, including the performance of dams, dikes, and irrigation systems under future hydroclimatic extremes (e.g., in the Fraser River Valley).	**Conduct cumulative effects studies** on land use practices (e.g., urbanization, agriculture, forestry, industrial and resource development), land cover change (e.g., wildfire, forest harvesting, insect infestation), and climate change to determine impacts on hydrologic cycles, surface and groundwater, and the performance of water retention infrastructure for future water use and demand. **Evaluate cumulative effects** of mining (e.g., liquefied natural gas, minerals) on water quantity and quality—including groundwater—to assess downstream water availability and risks of source-water contamination. **Establish baseline/reference conditions** and targeted surveillance to guide remediation of legacy mining (e.g., minerals, gold, natural gas extraction), with meaningful community engagement to co-define remedial actions and priorities. **Assess water–energy trade-offs** for sustainable hydropower and clean energy production by considering future changes in water supply and demand, downstream effects of reservoir regulation, and transboundary issues (e.g., the Columbia River Treaty). **Monitor groundwater and mainstem waters** (e.g., Okanagan Lake) to quantify nutrient and contaminant transport from agriculture, mining, and	**Study warming river temperatures** and biogeochemical processes to understand effects on carbon and nutrient cycling and on river ecosystem health, with emphasis on cold-water fish species (e.g., salmon, trout) that rely on Pacific coastal rivers for spawning. **Assess the effectiveness** of current environmental flow management in protecting aquatic habitat and maintaining ecosystem services, and identify adjustments needed to meet future conditions. **Improve knowledge** of the freshwater–marine coastal interface by monitoring keystone species and sensitive or sentinel biota (e.g., salmon) that underpin ecosystem function, services, food security (country foods), and community well-being. **Evaluate the condition and resilience** of ecological functions and services in vulnerable, pristine rivers (e.g., the Skeena River) to guide protection and conservation actions.

Water – Climate Change Science	Water – Land Use Science	Water – Biodiversity Science
Pacific		
	urbanization, and to apportion sources to downstream pollution (i.e., source apportionment)	

Table 6-5: Freshwater science priorities: Arctic Region.

Water – Climate Change Science	Water – Land Use Science	Water – Biodiversity Science
Arctic Region		
Assess combined climate impacts on the hydrological cycle by evaluating how permafrost thaw, declining snowpack, and climate variability (e.g., snow-rain shifts) alter groundwater regimes and affect Arctic aquatic ecosystem health, water quality, and community and industrial water supply. **Advance process-based ecosystem research and monitoring** by building comprehensive, long-term programs to track climate-driven changes from snowpack through to freshwater ecosystem services that support sustainable agriculture and food security in northern and remote communities (e.g., impacts on species used as "country foods"). **Apply data mining and machine learning** by using advanced analytics to identify and characterize patterns in Arctic water availability and water pollution, improving early detection and diagnosis of emerging risks. **Integrate climate and hydrological modelling and monitoring** by developing forecasting capacity aligned with	**Apply downscaled climate scenarios** to assess sector-specific land use change and water resource risks for energy and mining, with a focus on large lakes (e.g., Great Slave Lake and Lake Athabasca). **Monitor and assess cumulative effects** of resource extraction, land reclamation, and other land use changes in key systems (e.g., the Peace–Athabasca and Mackenzie River watersheds), accounting for climate variability and change. **Conduct large-scale assessments** of north–south gradients in atmospheric deposition trends in rivers and lakes to evaluate the effectiveness of past, current, and future pollution reduction strategies under changing climate conditions. **Monitor atmospheric contaminant deposition** to aquatic ecosystems from southern source regions, including future risks from increased thaw and re-release via the "grasshopper effect." **Undertake place-based cumulative effects studies** on bioaccumulation and	**Define water quantity and quality triggers** to protect nature and ecosystem services, and use these to inform co-managed environmental flow approaches in the Peace–Athabasca Delta, Wood Buffalo National Park, and the Saskatchewan River Delta. **Strengthen Arctic freshwater biodiversity research and monitoring** by aligning with international circumpolar initiatives, refining standardized assessment methods, and incorporating emerging genomic tools. **Advance understanding of ecological risks** to Arctic aquatic ecosystems associated with large-scale environmental shifts, including permafrost thaw and landscape greening. **Monitor and predict climate-driven northward range expansions** of terrestrial, aquatic, and semi-aquatic species, and assess resulting impacts on ecosystem function and integrity.

Water – Climate Change Science	Water – Land Use Science	Water – Biodiversity Science
Arctic Region		
Arctic ecoregions, including atmospheric deposition in cold regions, and by integrating surface observations with satellite data for pan-Arctic coverage to enhance predictions of freshwater quality and to pinpoint vulnerable areas for targeted, process-based water quality and biodiversity studies.	biomagnification of pollutants and on chemicals of emerging Arctic concern (CEACs) associated with expanding economic activity. Include prediction of future risks from the re-release of legacy persistent organic pollutants (POPs) from secondary sources, particularly due to permafrost thaw and related wildlife impacts. **Assess changing land cover** (e.g., shrubification and the northward shift of the treeline) and implications for evapotranspiration, snow distribution, and groundwater recharge.	

7. Socio-ecological and economic freshwater research

Decision-making for sustainable water stewardship must capture the diversity of values and perspectives that shape how freshwater is used and protected. While existing indicators for water quality and quantity reflect aspects of water use and supply, they do not adequately represent the full range and complexity of freshwater uses or the many valued outcomes associated with stewardship. Strengthening monitoring and predictive data systems is essential to develop more comprehensive indicators that reflect ecological, cultural, and socio-economic priorities.

Understanding both market and non-market values of clean freshwater is critical to inform decisions and assess trade-offs. For example, choices related to the use of groundwater versus surface water, the protection of recreational waters, the maintenance of navigable waterways, or hydropower production all involve balancing diverse interests. Economic valuation can be a useful tool not only for evaluating trade-offs in specific contexts but also for revealing how different communities perceive, prioritize, and value freshwater in decision-making.

Box 7.1 Environmental justice

The 2024 NFSA survey emphasized the importance of interconnectedness in understanding freshwater challenges. Interconnected factors and intersectional identities can amplify or modify risks for certain populations, including Indigenous communities, who are often disproportionately affected by changes in freshwater quality and quantity caused by natural disasters, pollution, and other stressors. Recognizing these interconnections highlights the need for comprehensive water-related data on sectoral and development activities that describe where and how water is used, and by whom. Such data can support analyses of cumulative effects and deepen understanding of community-level experiences with water quality issues.

The *National Strategy Respecting Environmental Racism and Environmental Justice Act* establishes new responsibilities to address inequities in environmental outcomes. Similarly, environmental justice principles are embedded in the Northwest Territories' *Environmental Rights Act* and the Yukon *Environmental and Socio-economic Assessment Act*, reinforcing the need for inclusive, just, and transparent freshwater decision-making.

Freshwater stewardship takes place within a complex landscape of competing demands, diverse rights, and varied stakeholder interests. To navigate this complexity, multiple-criteria approaches can help inform decision-making by integrating different types of information—qualitative, semi-quantitative, and quantitative (including economic data). In many cases, decision-making will also require consideration of cultural, ethical, and justice perspectives to ensure that freshwater management reflects the full range of societal values and responsibilities.

In Indigenous worldviews, water is not merely a resource but a distinct, living being with its own spirit and agency. Water holds life-giving power, sustains all beings, and maintains balance within ecosystems. This profound relationship with water shapes Indigenous beliefs that it cannot be "governed" in the traditional Western sense.[12] However, in the context of water management, many Indigenous peoples advocate for practices that honour water's sacred role, including the importance of Indigenous women who have a particular role and connection to water as protectors and givers of life.[13,14] Different Indigenous groups

[12] Meanings of indigenous land-based healing and the implications for water governance
[13] Water Song: Indigenous Women and Water - resilience
[14] Sacred Science – Indigenous women and our relationship with water

have unique relationships with water, reflecting their specific cultural landscapes and histories, and different ways of knowing and being such as Inuit Qaujimajatuqangit.[15] For example, for Inuit communities water is part of an interconnected flow that sustains Arctic life and connects them to their ancestral hunting and fishing grounds.[16] The Métis hold traditions around rivers and watersheds as critical to their transportation, trade, and sustenance on the prairies.[17] For many First Nations, water is revered through teachings of reciprocity and respect, where individuals have responsibilities to care for water as a relative.[18] These responsibilities are rooted in the understanding that harming water ultimately harms all forms of life, highlighting the importance of risk awareness in stewardship practices. For many Indigenous Peoples, "the protection of water is bound by traditional lore and customs, which provide a system of sustainable management". As shared by the First Nations of the Maa-nulth Treaty Society through engagement on the NFSA, socio-ecological considerations must also reflect socio-hydrology and the restoration and maintenance of the connection between water and Indigenous people as water stewards, and accounting for cultural flows.

7.1 Science priorities

Understanding benefits and trade-offs through multi-criteria analysis

There is limited information at the sub-watershed level on how implemented beneficial management practices influence cumulative responses to land use impacts on water quality and quantity, or how land-based solutions can improve water use efficiency and reduce downstream pollution. Similarly, there are significant knowledge gaps regarding the implications of water allocation and treatment choices across municipal, industrial, and other sectors. These gaps make it difficult to fully assess trade-offs in freshwater conservation and protection decisions. Multi-criteria participatory analysis offers a valuable complement to sector-specific economic assessments by incorporating ecological, social, and cultural dimensions. Such analyses can express impacts in non-monetary terms and provide insights into the broader ecological and societal value of freshwater, including its contributions to public health and biodiversity.

Indicators development

Indicators play a critical role in shaping and informing monitoring systems and predictive frameworks that evaluate the effectiveness of interventions and assess risks related to water allocation, equitable access, conservation, protection, and remediation. Developing national, scalable, multi-criteria indicators that align with human and ecosystem health, energy resilience, and sustainable economic growth will strengthen Canada's ability to address food and water security challenges. Standardizing these indicators across jurisdictions would also improve reporting consistency and knowledge mobilization. Examples of potential indicator categories include:

- Biophysical-chemical indicators of water quality and quantity, contaminant loading, and water use. These indicators exist but often fail to capture the integrated nature of surface and groundwater systems as ecosystem services that support human health and food and water security. In many cases, indicators must be refined or developed to better align with beneficial management outcomes, pollution prevention, or mitigation objectives.
- Indigenous-led indicators that connect the state of water to ecosystem services, biodiversity, and cultural and spiritual values, reflecting Indigenous science and knowledge systems.
- Socio-ecological indicators that capture diverse valued outcomes of water stewardship, including rights-based, cultural, and intergenerational perspectives. These indicators can also reflect social

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[15] Step 4: Approach and Methods - Indigenous Climate Monitoring Toolkit

[16] The Arctic Ocean and the Sea Ice Is Our Nuna. United Nations

[17] Métis Knowledge, Land Use And Occupancy Study For The Lake St. Martin And Lake Manitoba Permanent Outlet Channels Project

[18] Land as teacher: understanding Indigenous land-based education. Canadian Commission for UNESCO

preferences and non-monetary aspects of well-being related to freshwater. Economic indicators that link freshwater monitoring and predictive data to economic outcomes. These indicators can help identify the incremental change in one or more water indicators in response to human or economic activity, supporting more transparent assessments of trade-offs—such as gains or losses—among competing water uses, quality objectives, and landscape management priorities.

Box 7.2 Cost – benefit and multi-criteria analysis

Cost–benefit analysis (CBA) is a structured decision-making tool used to evaluate the economic, social, and environmental costs and benefits of a proposed policy, project, or regulation. CBA assesses the incremental changes between the current situation and trajectory and a potential alternative using both quantitative and qualitative methods. While CBA often involves assigning monetary values to impacts, it can also incorporate non-monetary factors when monetization is not feasible.

In the context of freshwater stewardship, CBA supports the inclusion of environmental goods and services in decision-making. This can involve a range of valuation techniques, such as estimating the cost of replacing a natural service (e.g., the role of wetlands in filtering contaminants), analyzing how people's behaviour reflects the value they assign to an environmental benefit (e.g., property values near clean water sources), or conducting surveys to understand public preferences. Rather than placing a definitive price on nature, these methods emphasize the economic importance of ecological benefits, ensuring they are properly considered in policy and management decisions.

Multi-criteria analysis (MCA) and CBA often complement one another and can lead to similar conclusions. The rigour of CBA stems from its methodological rules and quantitative structure, while MCA emphasizes inclusivity and transparency. MCA is participatory in nature, making explicit how qualitative and quantitative factors are weighted, whereas CBA tends to be more technical and analytical, with the weighting of qualitative factors left to the decision-maker. To achieve balanced and equitable outcomes, it is essential that MCA adequately reflects economic aspects and that CBA does not overlook non-monetary and social dimensions of value.

Advancing economic cost-benefit analysis

Assessing the economic costs of regulatory and technical (infrastructure) investments is increasingly common; however, the absence of standardized methodologies and the limited availability of benefits-related data often result in inconsistent findings. To address this, assessments must integrate information, perspectives, and methods that reflect equity and environmental justice. Broader frameworks are also needed to account for climate change, biodiversity responses, and the implications of climate action. Conducting case studies at the watershed level will help evaluate the adequacy of available data and the suitability of methods in specific contexts.

Despite data limitations, several types of economic studies can meaningfully inform the development of regulations, standards, guidelines, and broader decision-making processes:

- Estimating the costs and benefits of avoided freshwater pollution, including monetization of impacts on human and ecosystem health from short- and long-term contaminant exposure, and considering cumulative effects. These analyses can inform risk assessments and guide policies, programs, and services.
- Evaluating trade-offs between the economic benefits of major resource projects and their impacts on water quantity and quality as part of environmental and policy assessments.

- Quantifying the value, costs, and benefits of freshwater availability for water-dependent sectors (e.g., hydropower, oil and gas, agriculture, recreation, and tourism).
- Measuring the costs of environmental damage and public health impacts associated with extreme weather events that affect freshwater availability, quality, and flow, as well as those related to infrastructure failures, untreated wastewater releases, atmospheric deposition, and the spread of invasive species and pathogens. Estimating the value and benefits of nature-based solutions, as alternatives or complements to grey infrastructure, that harness ecological services (e.g., flood mitigation, contaminant filtration, nutrient cycling, and support for biodiversity).

Understanding the integrated watershed response to beneficial management practices

Improving understanding of watershed-scale responses requires data collection strategies and standardized methodologies that allow for consistent evaluation of diverse management interventions using both quantitative and qualitative measures. This broader perspective can guide when and where to apply existing tools or adopt new ones. To enhance policy relevance, economic assessments should apply approaches such as avoided cost analysis, dynamic optimization, and valuation under uncertainty, using clearly defined baseline counterfactuals ("what would happen without the intervention") to assess effectiveness.

Examples include:

- Farm, greenhouse, and forestry unit-level assessments, extrapolated to watershed and sub-watershed scales to evaluate beneficial management scenarios that account for climate and land use change, soil–water dynamics, and timing of interventions.
- Evaluations of the effectiveness of economic tools designed to encourage beneficial management practices or sustainable land and water use. These tools—ranging from incentives to regulatory measures—should be assessed for their ability to drive behavioural change, stimulate innovation, and deliver intended outcomes. Smaller-scale studies could test interventions (e.g., environmental flow standards, subsidies, payments for ecosystem services) to understand their uptake, economic implications, and regional relevance. Investigations into barriers and success factors across different management tools, programs, and regulations. Cumulative economic effects assessments that integrate multiple variables could help identify interactions between interventions—whether synergistic, additive, or antagonistic.

Application of tailored freshwater monitoring, predictive and valuation information in sector-specific decision-making

Multi-scale studies that examine how decision-makers use freshwater data can help improve management approaches for public health protection and economic sustainability. Such studies can also inform the creation of tailored data and information products and link empirical findings to economic forecasting models (e.g., dynamic stochastic general equilibrium or real options analysis).

For example:

- Managing the growing water and energy demands of computing and data infrastructure alongside municipal, agricultural, and industrial needs.
- Using public health risk forecasting (e.g., for disease outbreaks, infrastructure failures, or floods) to inform proactive water management and mitigation strategies.
- Applying advanced irrigation technologies in water-scarce regions or during drought conditions to optimize use and minimize waste.

Cost–benefit and multi-criteria analyses together provide a robust framework for freshwater management decisions that involve trade-offs. Ideally, freshwater stewardship should draw from a suite of approaches that integrate co-development, participatory engagement, and explicit consideration of equity. Inclusive decision-making processes—such as multi-criteria assessments, deliberative dialogues, and community-based evaluations—ensure that the perspectives of rights holders, the public, and stakeholders are meaningfully reflected.

Open-source analytical tools can further support transparent and participatory decision-making. These platforms enable users to model the costs and benefits of various freshwater management options (e.g., dam removal, wetland restoration, pricing mechanisms), explore trade-offs among multiple objectives (e.g., ecological integrity, agricultural productivity, cultural values), and compare scenarios to guide sustainable and equitable freshwater outcomes.

7.2 Knowledge outcomes

Advancing socio-ecological and economic freshwater research will strengthen understanding of how water management decisions, policies, and practices shape environmental, social, and economic outcomes across scales. The following knowledge outcomes reflect key areas where improved insight and integration are needed:

- **Improved understanding of the costs and benefits** of water management and freshwater ecosystem services, recognizing multiple user demands and the range of established and proposed interventions occurring simultaneously across a watershed.
- **Broader understanding of trade-offs and co-benefits** in freshwater stewardship, incorporating diverse worldviews, values, rights, and interests to better balance ecological integrity, cultural priorities, and economic development in decision-making.

7.3 Advancing the science tools

Strengthening socio-ecological and economic freshwater research depends on robust data, monitoring, and modelling systems that connect environmental science with social and economic analysis. The following science tools will help build the evidence base needed to support integrated decision-making for sustainable freshwater management:

- **Data**: Develop accessible and consistent data records and analytical tools to enable multidisciplinary economic and multi-criteria research on the benefits and costs of freshwater stewardship.
- **Monitoring and surveillance**: Address information gaps related to water use, as well as the costs and benefits of water management, to support the development and reporting of freshwater socio-ecological and economic indicators. Monitoring systems should be scalable to meet the needs of multiple users.
- **Predictive modelling frameworks**: Create modelling frameworks that link coupled hydro-geo-climate–aquatic ecosystem models with economic and multi-criteria valuation models, allowing for more comprehensive and integrated analyses of freshwater management options and outcomes.

8. Freshwater science and decision-support systems

Society's use of freshwater—both surface and groundwater—is a fundamental part of the water cycle. The secure and reliable availability of clean, fit-for-purpose water supports healthy communities, a strong economy, and a resilient environment. Ensuring water security and sustainable water supplies requires not only understanding the integrated surface and groundwater resources within a watershed but also the patterns of water demand, use, and their associated impacts. A comprehensive understanding of the water balance at the watershed or sub-watershed scale is essential to guide complex water allocation decisions. These decisions must balance trade-offs where water scarcity, declining water quality, or competing economic and social priorities place pressure on freshwater systems.

The concept of sustainable use reflects that freshwater is vital for quality of life, economic security and development, human well-being and environmental health. Sustainable management must engage participatory approaches that recognize water's economic, ecological, and cultural significance, as well as its role as a public good. These principles highlight the need for collaboration across multiple scientific disciplines—including the social and economic sciences—while incorporating diverse knowledge systems and perspectives. This integrated approach provides the foundation for evidence-based decisions on water allocation, conservation, remediation, treatment, and infrastructure planning.

Box 8.1 CEPA and the right to a healthy environment

The 2023 modernization of the *Canadian Environmental Protection Act, 1999* (CEPA) through the *Strengthening Environmental Protection for a Healthier Canada Act* affirms, in the preamble, that every individual in Canada has a right to a healthy environment, as provided under the Act. An implementation framework is being developed to elaborate on three new guiding principles: environmental justice, non-regression to maintain levels of protection, and intergenerational equity. These principles are directly relevant to how freshwater science is conducted and how knowledge is shared.

The draft framework outlines five key factors—scientific, environmental, health, social, and economic—and emphasizes the importance of incorporating Indigenous knowledge across these areas. This approach aligns with Indigenous science leadership in freshwater research and supports collaboration with communities to ensure that the distinct knowledge systems, worldviews, and values of First Nations, Inuit, and Métis people are bridged, braided, and woven into CEPA-related activities in meaningful and appropriate ways.

Freshwater science contributes essential data and information that can inform the assessment and management of toxic substances in aquatic environments under CEPA, as well as the development of guidelines to protect aquatic life and sustain healthy freshwater ecosystems.

Actionable freshwater science focuses on developing fully integrated national watershed monitoring systems and linking hydroclimate and hydro-economic models to decision-support tools. These systems must be capable of evaluating competing demands for clean water across communities, industry, energy, agriculture, forestry, mining, and ecosystem services—supporting decisions at time scales ranging from days to decades.

8.1 Science priorities

Integrated water quantity and water quality monitoring

Strengthening the connection between surface and groundwater monitoring networks, supported by improved data management, is essential for advancing multi-scale predictions, early warning systems, and watershed-based assessments of freshwater and vulnerabilities:

- Community and citizen science can complement in-situ and remote sensing–based monitoring, adding an effects-based perspective. Insights at the population level help identify risks, exposures, and source attribution, distinguishing between point, non-point, and accidental releases.
- Seamless monitoring networks and shared data systems are needed where transboundary waters cross international, provincial, territorial, and Indigenous lands.
- State-of-the-art monitoring tools, including Earth observation technologies, advanced sensors, and "omics" techniques, should be paired with artificial intelligence–based analytics that integrate observations across multiple platforms to fill spatial and temporal information gaps

Discoverable, accessible, and interoperable freshwater and water-related data

Current groundwater, surface water, and water quality datasets are underused due to limited curation and inconsistent data standards. To unlock their full potential, national standardization of data collection and observation protocols is needed to ensure interoperability among diverse datasets. This is particularly important given the vast landmass and complex water systems in Canada.

Development of shared economic and land use data and common analytical frameworks will improve the valuation of costs and benefits related to freshwater ecosystem services, as well as support decisions on water allocation and sharing mechanisms. Data must be discoverable and accessible across sectors, jurisdictions, and institutions, and compatible with machine-readable analytics and visualization tools. This will allow the use of statistics, artificial intelligence, and deep learning methods to analyze spatial and temporal patterns critical for source attribution and risk assessment. The FAIR data principles—Findable, Accessible, Interoperable, and Reusable—remain foundational.

Water quality criteria and guidelines

Developing new water quality criteria and guidelines for freshwater assessment and reporting (e.g., for drinking water and aquatic life) is essential. Existing derivation methods need continuous updating to address site-specific conditions, emerging substances, and cumulative effects.

Advancements in "omics" sciences—including genomics, proteomics, and metabolomics—show strong potential for establishing biologically relevant water quality thresholds. Decision-making approaches must also reflect multiple valued outcomes of water stewardship and aquatic ecosystem services, integrating Indigenous perspectives and values into guideline development.

Freshwater nexus science

Progress in freshwater science requires multidisciplinary data collection and modelling to better understand trade-offs and co-benefits across interconnected policy areas. Freshwater management directly influences and supports climate change adaptation and biodiversity conservation goals.

For instance, soil health and soil quantity management, particularly in agricultural regions, are closely linked to freshwater quality and quantity. Similarly, the energy transition and increasing electrification have major implications for water use, storage, and transfer. Framing research within the water–energy–food–climate nexus can help design tailored analyses that promote wholistic, integrated decision-making for freshwater management and sustainability.

Looking forward: freshwater data

Canada's freshwater data landscape is highly complex, and accessing or using these data remains a significant challenge. Freshwater data are collected, shared, and managed through many different systems and by a wide range of organizations. However, inconsistent data standards and limited interoperability continue to present barriers to integration and use. Data are held by numerous entities, including the Government of Canada, provincial and territorial governments, municipalities, Indigenous people, academic institutions, industry, and non-governmental organizations.

The ability to use these diverse datasets to report on freshwater conditions and trends by watershed—or to address the multidisciplinary freshwater science priorities identified in this report—is constrained by the absence of standardized approaches and interoperable data systems for collecting, organizing, and sharing information.

The European Union's Freshwater Information Platform provides a valuable model of a systems-based approach that Canada's National Freshwater Data Strategy could emulate to develop:

- Integrated freshwater data systems that enable seamless connectivity across jurisdictions and data holders (public sector, private sector, and academic), while adhering to the FAIR principles of being Findable, Accessible, Interoperable, and Reusable. Advanced freshwater data tools for analytics, mapping, and visualization, capable of integrating information across monitoring networks, observational platforms, and predictive modelling frameworks.

To maximize their usefulness, freshwater data systems must be aligned and interoperable with related domains, including climate, atmospheric, soils, biodiversity, land use, and socio-economic data systems. Without this alignment, the ability to conduct robust multidisciplinary environmental science will remain limited. Addressing these challenges will be essential for advancing a national, coordinated, and accessible freshwater science and data ecosystem in Canada.

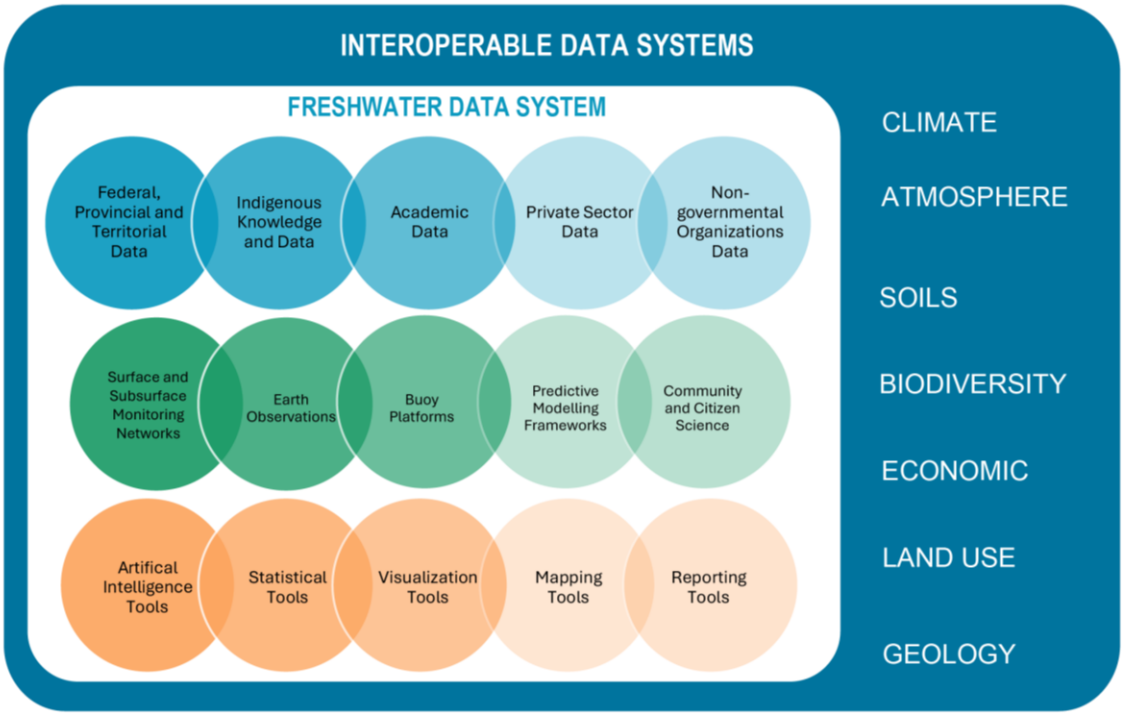

Figure 8-1: Key elements of freshwater data systems and interoperability linkages with climate, atmospheric, soils, biodiversity, economic and land use data systems.

Box 8.2 The Water-Energy-Food Nexus

Water–energy–food nexus (WEFN) science seeks to understand the interconnected dependencies among water, energy, and food systems—specifically how energy supply depends on water availability, how food production depends on both water and energy, and how water supply, treatment, and distribution depend on energy. These relationships are becoming increasingly complex under the combined pressures of climate change and growing global demand for all three resources.

Research in this area must consider both equitable access to water, food, and energy and economic prosperity at multiple scales, including national, watershed, sectoral, community, and individual levels. Advancing WEFN knowledge requires interdisciplinary and cross-sectoral analyses that integrate hydrological prediction tools (covering cryosphere, land surface, and precipitation processes), economic models and datasets, and detailed water use and demand information.

There are unique knowledge needs for the Arctic, where food insecurity, rapid climate change, and increasing economic development intersect to create complex sustainability challenges.

WEFN science can guide the creation of coherent, well-aligned policy and regulatory frameworks that strengthen water management resilience while supporting sustainable energy production and food systems.

Integrated multi-sectoral freshwater modelling

Developing integrated, multi-sectoral watershed hydrology and water quality models can provide outputs tailored to specific water use contexts across geopolitical and jurisdictional boundaries. By incorporating diverse land use activities and socio-economic factors, these models can generate scalable analyses that serve a wide range of users and applications. Integrated modelling frameworks play a critical role in supporting evidence-based decision-making—informing policies, regulations, and management strategies—and in evaluating the effectiveness of interventions such as beneficial management practices, conservation programs, and environmental flow allocations designed to sustain water quality and availability at the watershed level.

Specific activities may include:

- Assessing transboundary economic impacts (both intra- and international) related to water levels, infrastructure, flow regulation decisions, and inter-basin transfers, accounting for upstream and downstream costs and benefits.
- Coupling hydroclimate and water quality models with economic analysis at multiple scales to evaluate the costs, benefits, and relative effectiveness of different management interventions.
- Assessing cumulative and legacy contaminant sources across transboundary waters, integrating economic and social dimensions to provide more comprehensive evaluations of long-term impacts.
- Advancing research to connect environmental, economic, and multi-criteria evaluation models, improving data compatibility and uncertainty estimation to enable the integration of diverse datasets and ensure that valuations remain robust under a range of climate and freshwater management scenarios.
- Evaluating physical and biological watershed conditions and dynamics, together with land and water use activities and climate scenarios, to guide, track, and assess restoration priorities, methods, investments, and outcomes.

Looking forward: a freshwater quality modelling strategy

Access to safe, clean freshwater is not consistent across Canada. Many small and remote communities, including some Indigenous communities, continue to face persistent drinking water challenges. Urban areas may also experience water quality issues following extreme weather events—particularly flooding, which can lead to wastewater overflows or infrastructure failures. In rural regions, where households rely on private wells, groundwater quality often remains unknown or unmonitored.

Effective decision support systems depend on predictive tools that operate across multiple timescales—from hours to days, to provide early warnings of human and environmental health risks; through days to months, to guide management of short-term water quality issues; and over years to decades, to inform infrastructure investments, long-term planning, and responses to emerging demands (e.g., water needs for artificial intelligence data centres). Predictive capacity across these timescales supports informed decisions on water allocation, conservation, and protection, ensuring that freshwater ecosystem services continue to sustain economic sectors, food production, and biodiversity.

A national freshwater quality modelling strategy should therefore:

- **Collaboratively leverage existing models** in climate, hydrology, and groundwater sciences to build on Canada's strong foundation of environmental prediction systems.

- **Develop new models** that capture contaminant sources, infiltration, and runoff dynamics, along with biogeochemical processes that describe degradation, bioaccumulation, and chemical transformations of contaminants within aquatic systems.
- **Integrate and standardize data** and modelling protocols across disciplines—such as atmospheric science, hydrology, hydrogeology, terrestrial systems, and Earth observations—supported by distributed computing infrastructure for efficiency and scalability.
- **Provide flexible, scalable modelling tools** that can be applied from the watershed to national scale, aligning with the needs of different jurisdictions, sectors, and resource management contexts.
- **Interface water quality data and model outputs** with other predictive systems (e.g., weather and environmental predictions) at multiple temporal and spatial scales.

A national freshwater quality modelling strategy could help coordinate the development of comprehensive water quality modelling systems that enable consistent state-of-water reporting, including source apportionment directly linked to water quality outcomes. Such a coordinated approach would strengthen Canada's ability to report on future ecosystem and human health risks using reliable freshwater indicators and improve understanding of how water quality is changing across regions and watersheds.

Most importantly, the strategy would address critical knowledge gaps related to vulnerabilities and opportunities for protecting and managing source waters, which are foundational to safe drinking water and ecosystem health. Building robust water quality modelling capacity depends on closing existing freshwater data gaps—ensuring access to high-quality, standardized, and interoperable data.

Equally essential is enhancing knowledge mobilization capacity to ensure that the integration of water quality and water quantity information reaches end users—such as communities, decision-makers, and industry—in ways that support informed, timely, and effective freshwater management.

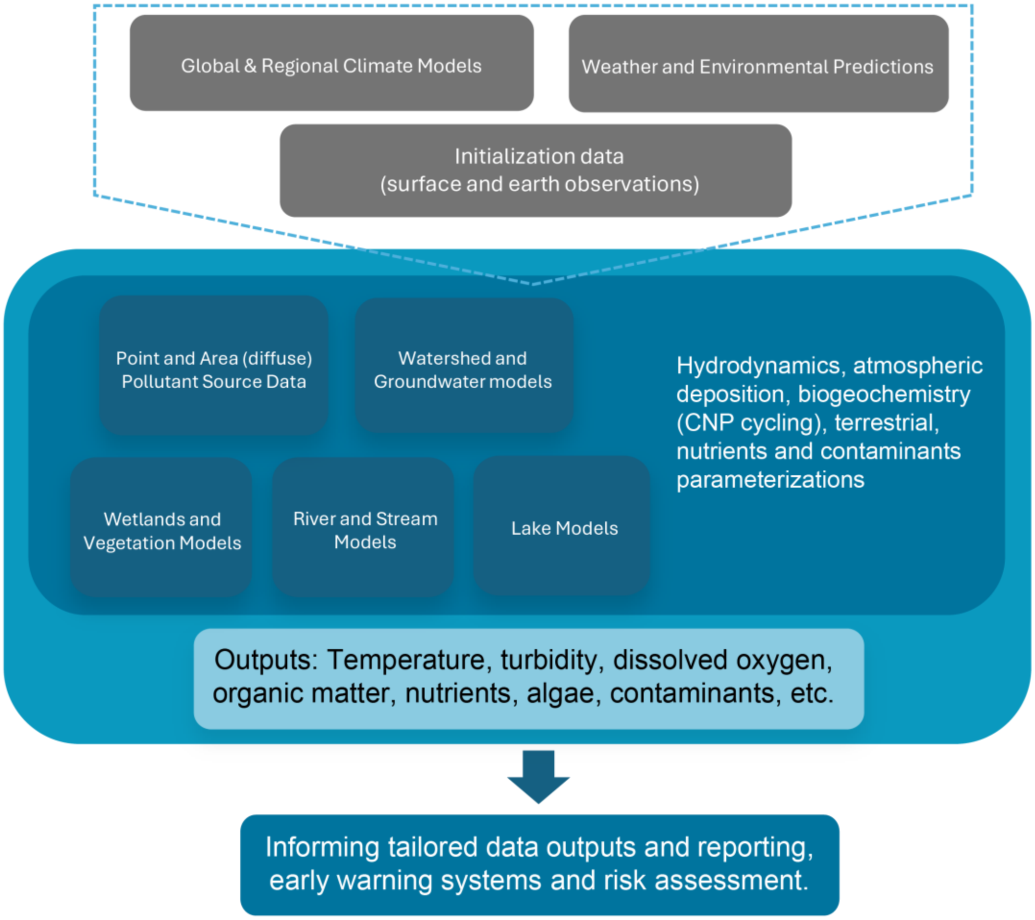

Figure 8-2: The building blocks of a freshwater quality modelling strategy.

Freshwater knowledge synthesis and knowledge mobilization

Advance multidisciplinary and interdisciplinary science assessment, synthesis, and mobilization to support evidence-based decision-making and freshwater literacy, while including diverse knowledge systems and voices. Specifically:

- Produce knowledge synthesis reports on multiple stressors and cumulative effects; groundwater resources (including withdrawals, integrated surface–groundwater characterization, and climate impacts); current and future water demand in the context of societal drivers (e.g., population change, energy transition, evolving land use choices, water equity); water balance and availability reflecting combined climate and societal pressures; and wholistic assessments of the water–food–biodiversity nexus.
- Clarify water injustices by documenting how limited knowledge of water quality and availability affects vulnerable populations in urban and non-urban regions; identify inequities in access to monitoring and research resources; and address related gaps that limit risk understanding for vulnerable communities.

- Report on watershed and national state of water through regular science assessments and co-developed synthesis initiatives that track trends in freshwater quality and availability and align findings with ecosystem and human health risks.
- Strengthen environmental learning initiatives that build freshwater literacy, embrace diversity and multi-generational perspectives, and highlight the essential role of water in sustaining public health, food and water security, ecosystem integrity, and economic productivity.

Box 8.3 Science and decision-support for nature-based freshwater solutions

Freshwater systems, including wetlands, are essential natural infrastructure that can be integrated into decision-support frameworks for sustainable water management. Applying science and modelling enhances the ability to plan, predict, and evaluate how these systems contribute to pollution control, water storage, and ecosystem resilience. Advancing this science enables nature-based solutions to function as part of evidence-based decision-making for climate adaptation, community infrastructure, and biodiversity protection. Examples include:

- **Wetlands** (natural or constructed) used to filter contaminants and nutrients from non-point sources, including agricultural and municipal runoff, and as part of wastewater treatment systems to remove organic and heavy metal contaminants. Wetlands also provide important water storage capacity that helps mitigate drought.
- **Green infrastructure**, such as bioswales, rain gardens, and green roofs, that manages stormwater quantity and quality in urban environments by replacing impervious surfaces and allowing water to percolate into the ground.
- **Protection of wetland transition zones**, including riparian areas around rivers and lakes, to buffer extreme precipitation and flood risk.
- **Habitat creation, restoration, or conservation** of riverine or lake systems to support the recovery of aquatic and semi-aquatic species, including spawning habitats.
- **Protection and preservation of key groundwater sources** to maintain base flows in rivers and wetlands during dry periods when surface waters are low.
- **Sustainable use of water for electricity generation** (e.g., hydroelectricity and nuclear energy production) that maintains aquatic ecosystem integrity.
- **Sustaining aquatic ecosystem integrity** to enhance carbon sequestration and storage in aquatic and terrestrial systems (e.g., forests and soils).

8.2 Knowledge outcomes

Advancing freshwater science and decision-support tools will generate several key knowledge outcomes that strengthen Canada's ability to manage water sustainably and equitably. These include:

- **An integrated understanding of surface and groundwater resources** by watershed or region—including availability, supply, use, balance, state, and quality—under future climate scenarios.
- **Strengthened understanding of human and environmental health risks** and exposure to contaminants (individually and cumulatively), supported by improved source attribution knowledge.

- **Improved understanding of biological stressors and disease transmission** across species to enable One Health approaches that protect human and environmental health and food safety.
- **Enhanced baseline data**, predictive capacity, and cumulative effects knowledge to inform impact assessments and regulatory permitting where development may affect freshwater availability or quality.
- **Expanded understanding of the value of natural ecosystem functions** and the cost-benefit of nature-based solutions for mitigating or managing impacts on freshwater quality and quantity, particularly in a changing climate.
- **Strengthened freshwater literacy** and greater public understanding of sustainable freshwater stewardship and its links to health, biodiversity, and economic resilience.
- **Improved understanding of the economic, social, and cultural trade-offs** associated with management interventions and changes in water quality and availability at the watershed scale.

8.3 Advancing the science tools

Advancing the tools that support freshwater science will improve the ability to monitor, analyze, and apply knowledge for decision-making across scales and sectors. The following areas of focus will strengthen how freshwater data and insights are generated, integrated, and used:

- **Data**: Improve access to standardized baseline data on water supply, use, and quality to assess trends and changes in the state of freshwater in response to water management practices and interventions in the hydrological cycle.
- **Digital decision-support structures**: Develop interfaces and tools specific to freshwater management contexts (e.g., complex demand and allocation, equitable access, ecosystem services, conservation, biodiversity) that include tailored data and visualization capabilities to deliver user-focused analyses for transparent, watershed-based, and evidence-informed decision-making.
- **Knowledge synthesis**: Advance methods and collaborative structures for participatory and multidisciplinary reporting on the state and trends of freshwater systems, supporting integration of diverse knowledge systems and improved accessibility of synthesized information for decision-makers.

9. Overarching needs

Freshwater management challenges vary across regions, users, and spatial scales, yet common overarching science priorities can guide future work and strengthen decision-making. As knowledge continues to evolve, these priorities will help address complex and interconnected freshwater management contexts across Canada.

A central need for advancing each science priority and implementing effective decision-support systems is inclusivity. Every group within the national freshwater science community—including governments, Indigenous nations, academic and research institutions, industry, and non-governmental organizations—has an important role to play in developing, sharing, and applying these priorities. Success will depend on meaningful collaboration, shared responsibility, and open exchange of knowledge across this broad community.

In all cases, the freshwater science priorities respond to fundamental questions that remain at the core of water management: Who is using freshwater, how much, when, and for what purpose? How are freshwater quality and availability changing from baseline conditions within each watershed? What are the simultaneous drivers of change, and what do these mean for short- and long-term management? Finally, are current interventions (e.g., beneficial management practices, regulations) achieving their intended outcomes for water quality and availability?

All freshwater science must be grounded in plausible future climate scenarios that influence water on time scales from days to decades. This underscores the need to optimize and expand freshwater monitoring, modelling, and data systems that can effectively interface with climate change data and modelling frameworks.

While the NFSA emphasizes future directions for freshwater science, it also recognizes that the breadth of data, information, and knowledge already available could be far better mobilized. Strengthening knowledge sharing and application across disciplines, sectors, and jurisdictions is essential to inform evidence-based freshwater management and policy in Canada.

Across the thematic and regional science priorities identified in the NFSA, five overarching and cross-cutting elements can guide national freshwater science coordination and strengthen multi-disciplinary collaboration across Canada. These elements provide a foundation for advancing integrated, inclusive, and solution-oriented freshwater science:

1. **Comprehensive understanding and reporting on freshwater**: Develop a more complete understanding of, and reporting on, the state and trends of water and their vulnerabilities across surface and groundwater systems by watershed. This includes consideration of intra- and international jurisdictional boundaries and the influence of hydrological factors such as water retention infrastructure (e.g., dams), water use efficiency technologies (e.g., conservation), and

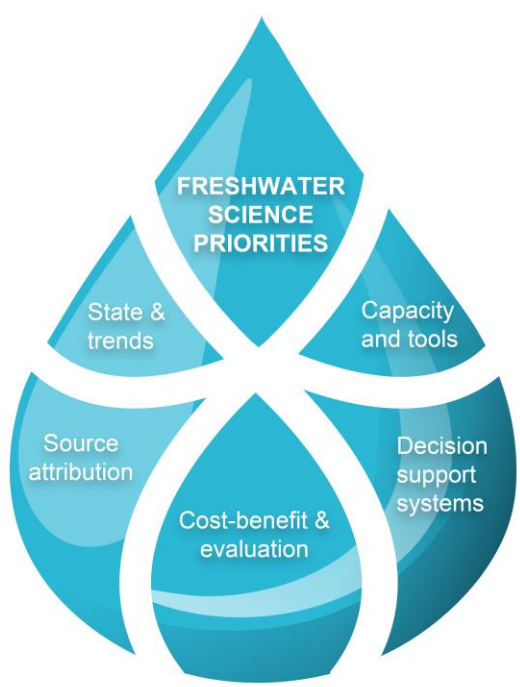

Figure 9-1: Overarching needs for advancing freshwater science.

ecosystem-based approaches that enhance the sustainable management and storage of freshwater.

2. **Source attribution and cumulative effects of contaminants**: Continue advancing knowledge on the source attribution, transformation, and fate of contaminant mixtures, as well as the cumulative effects of legacy and emerging contaminants. This includes addressing the combined impacts of urban, industrial, mining, and agricultural sources on freshwater ecosystems, water and food safety, human health, biodiversity, and aquatic ecosystem integrity.
3. **Understanding freshwater management trade-offs and social dynamics**: Strengthen understanding of the trade-offs, cost-benefit implications, cultural values, and social behaviours that shape freshwater stewardship. Effective water allocation requires understanding competitive demands between extractive and non-extractive uses, the upstream–downstream distribution of costs and benefits, and the environmental justice and cultural values connected to water as part of the broader landscape. Trade-off research should also explore how perceptions of risk and institutional or social behaviour influence decision-making and management outcomes.
4. **Solution-oriented freshwater science and decision-support systems**: Advance science that enables integrated decision-support systems with watershed-based monitoring and predictive capabilities. This includes developing multi-scale approaches and synthesizing knowledge from diverse sources, anchored in indicators that reflect valued water outcomes and management responses to multiple stressors.
5. **Enhancing freshwater science capacity and tools**: Strengthen the scientific foundation and technical infrastructure needed to advance NFSA priorities. This includes improving access to environmental, social, and economic freshwater data across agencies; expanding watershed-based adaptive monitoring and prediction frameworks; and developing freshwater science assessment initiatives grounded in regional stewardship contexts.

Advancing each of these five cross-cutting elements depends on improving the acquisition, curation, accessibility, and machine readability of data that describe the chemical, biological, and physical state of water, as well as the sectoral and economic data that reflect how water is used. These data are distributed across multiple agencies, governments, organizations, private sector actors, and academic institutions involved in water monitoring, surveillance, and prediction. Assessing the effectiveness of freshwater stewardship—and balancing the complex demands of economic and non-economic water uses and values in a changing climate—requires substantial progress in how this information is collected, standardized, and curated.

Participatory research methods play a vital role in delivering user-centred, actionable science. Collaborative inquiry with those directly affected by water-related issues can strengthen the relevance and uptake of knowledge in decision-making, while also addressing issues of power, access, and equity. The freshwater science community should continue to create space and build capacity for Indigenous science leadership, recognizing its essential role in understanding and managing freshwater systems.

Community-based monitoring remains fundamental for capturing cultural and traditional land use information that informs baseline conditions and valued outcomes in cumulative effects studies. As freshwater science continues to evolve, both methods and practices must adapt to reflect new scientific advances, emerging technologies, and evolving knowledge systems—ensuring that freshwater science in Canada remains inclusive, responsive, and forward-looking.

Box 9.1 Indigenous Peoples as environmental scientists

The relationships between Indigenous people, the land, water, ice, animal life, and surrounding habitats form the foundation of Indigenous science and knowledge. This science offers context, interpretation, and deep insight into the interconnectedness of all elements within ecosystems.

Article 25 of the United Nations Declaration on the Rights of Indigenous Peoples affirms the rights of Indigenous people to maintain and strengthen their distinctive spiritual relationships with the land and water. Indigenous science and knowledge are inherently integrative and relational, grounded in the understanding that humans are part of ecosystems and must live in balance with them.

Looking forward: freshwater decision-support systems

Canada's established weather and climate services illustrate the value of formal partnerships, tailored data and information products, and clear communication to support regional decision-making. Freshwater stewardship would benefit from a similar coordinated approach. While some freshwater services currently exist within hydroclimate and hydro-meteorological organizations, many freshwater planners and decision-makers are not fully aware of these resources or how to access them.

More importantly, there remains a significant gap in developing tailored freshwater data and information products related to surface and groundwater supply (water availability), water quality, aquatic ecosystem health, and invasive species. Establishing watershed-based or regional freshwater decision support systems that incorporate user-centred knowledge mobilization would help close this gap. Such systems could also strengthen and empower community-based monitoring and Indigenous knowledge systems, ensuring that regional decisions reflect both scientific and local perspectives.

Climate and freshwater services continue to evolve to meet the growing information needs of freshwater management. Examples, such as the Canadian Centre for Climate Services - Canada.ca, AquaWatch Australia - CSIRO, and the European Union's WISE Freshwater initiative demonstrate the potential of integrated, user-oriented systems. Developing similar tailored freshwater data, information, and knowledge mobilization capacities in Canada is essential to fully applying existing freshwater science and knowledge in decision-making.

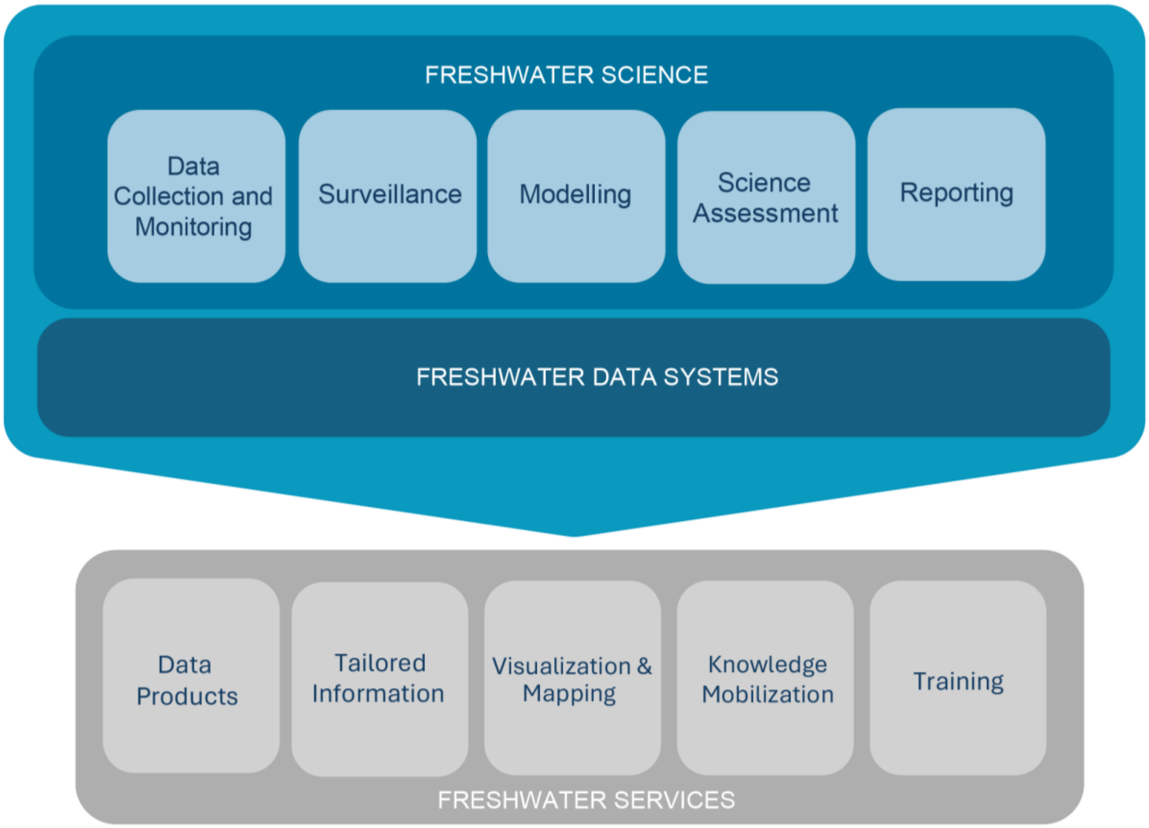

Figure 9-2: The building blocks for freshwater decision support systems.

Successful implementation of freshwater science

Successful implementation of freshwater science depends on addressing the fragmented nature of current monitoring and research activities across Canada. Encouragingly, watershed-based projects that integrate social and physical science research objectives are beginning to emerge, signalling progress toward a more coordinated approach.

Advancements in freshwater science would be enabled by the following actions:

- Developing freshwater science coordination structures, supported by the Canada Water Agency and its mandate to enhance collaboration for freshwater management, along with strengthened federal, provincial, and territorial reporting on the state and trends of freshwater.
- Establishing strong and well-supported monitoring and surveillance networks that incorporate new technologies, applications, and nationally standardized protocols, while also leveraging Indigenous- and community-led monitoring to strengthen the foundation of freshwater science and services.
- Improving access to and mobilization of freshwater science and research through the National Freshwater Data Strategy currently being developed by the Canada Water Agency, to ensure that freshwater data in Canada are discoverable, accessible, shareable, and usable.

- Coordinating watershed-based hydroclimate and freshwater modelling that integrates surface and groundwater, water availability, and water quality, through collaboration among government, academia, and water users' organizations and corporations.
- Supporting Indigenous-led cumulative effects science and joint Indigenous and Western freshwater research to inform effects-based monitoring and prediction activities at the watershed scale.
- Fostering multi-disciplinary science teams and research objectives that align with watershed-based decision-support systems and integrate land use and economic data to help value freshwater ecosystem services.
- Aligning monitoring networks and model development with ecosystem and health effects-based knowledge outcomes, tailoring scientific outputs for multiple stressor and One Health contexts (e.g., antimicrobial resistance, new waterborne pathogens, and chemical substances).
- Enhancing user-targeted, watershed-based knowledge synthesis and freshwater literacy initiatives to mobilize existing data and knowledge for sustainable freshwater management. Working closely with decision-makers to advance freshwater science priorities also presents an opportunity to strengthen freshwater literacy across all levels of decision-making.

Freshwater science and knowledge form the foundation for evidence-based decision-making. They are essential to understanding and strengthening the relationship between Canadians and their freshwater resources, ensuring long-term sustainability and security. Scalable and relevant freshwater data, supported by robust monitoring and prediction frameworks, allow for more effective assessment of status and trends, identification of risks, and evaluation of management responses. These tools are vital for planning and decision-making related to intra- and inter-basin water management that balance ecosystem integrity, human needs, and economic priorities.

Engagement during the development of the NFSA emphasized the need for stronger collaboration between the social and natural science communities. Such collaboration provides critical insights into human behaviour, governance, and equitable access—enabling a more wholistic and inclusive approach to freshwater management. While Canada already possesses a substantial knowledge base to guide stewardship, continued development of this knowledge will help better characterize risks, trade-offs, benefits, and the effectiveness of ongoing freshwater management actions

While the NFSA is not intended to serve as an implementation road map for freshwater science, it provides a framework to guide planning and coordination over the next decade, strengthening coordination, collaborative and partnered freshwater science efforts across Canada on a shared set of priorities.

In developing the NFSA, it became clear that freshwater science must unfold in ways that resonate with the unique contexts of jurisdictions and organizations. It must also remain responsive to the freshwater relationships, priorities, and valued outcomes of those jurisdictions, communities, rights holders, and stakeholders.

Realizing the full potential of the NFSA will depend on collaboration among federal, provincial, and territorial governments; Indigenous governments, communities, and organizations; academia; industry; and non-governmental and community-based organizations, and the freshwater science community is encouraged to work together to identify opportunities for collaboration and to take collective action on the priorities presented in this report.

Annex 1. Science Questions

The following tables present an overview of the science questions identified by freshwater science experts, knowledge holders, and decision-makers during the development of the national freshwater science priorities. These questions are organized according to the overarching freshwater science themes (i.e., chapters) and their associated science priorities. Together, they reflect the collective insight and curiosity driving the advancement of freshwater science in Canada.

A1.1 Freshwater availability and climate change

Overarching questions	How will freshwater quality and availability—including both surface water and groundwater—as well as freshwater ecosystems and biodiversity, be affected by climate change across watersheds under a range of plausible future climate scenarios?
	What role can emerging technologies (e.g., artificial intelligence and systems-generated water science) play in monitoring, modelling, and assessing the impacts of climate change to inform future water allocation and water security decision-making over timescales ranging from days to decades?
	What are the socioeconomic costs and benefits of climate action for freshwater quality and availability?
	How can co-development of knowledge mobilization at local and watershed scales—such as on drought frequency and intensity, or shifts in seasonal variability and surface water quality—inform beneficial management practices across municipal, industrial, forestry, mining, and agricultural sectors?
Cryosphere loss	How will loss of the cryosphere (snow, ice, and permafrost) in Canada affect freshwater resources— including hydrology, streamflow regimes and seasonality, groundwater storage, release of sequestered metals, carbon and other contaminants, nutrient transport and loadings, freshwater biodiversity, and habitats—by watershed?
	Which methods and methodological standards are most effective for investigating environmental flows, aquifer recharge needs, and related processes?
	Which parameters should be used to identify cryosphere tipping points (e.g., duration and thickness of lake and river ice, snow cover extent, snow amount and duration [snow water equivalent], evaporation rates, water quality, quantity, and temperature), and what are the implications for freshwater storage, water security, ecological habitat, and hydroelectric generation?
	How will cryosphere change interact with other drivers of freshwater ecosystem change and with ecological and biodiversity impacts across watersheds?
Regime shifts	How is climate change (i.e., cryosphere, temperature, and precipitation changes) altering hydrologic and physiographic regimes? What are the thresholds (e.g., global, regional air temperature) that result in regime shifts in seasonal freshwater availability and quality, and aquatic ecosystem states and health?
	What are critical climate thresholds and tipping points for hydrology, aquatic ecosystems and freshwater biodiversity? Have they been reached? How can they be avoided? Are they inevitable?
	What are the tipping points in climatic and hydrological systems? Where are these thresholds, and how might they lead to fundamental changes in catchments and alter water balance and availability?
	How will climate change and related hydrology changes affect water balance and availability by watershed?

Seasonal availability	What are the predicted freshwater supplies, budgets, and water chemistry changes over time on a watershed scale, for a range of plausible future climate scenarios?
	How will the future climate, or “loss of winter” impact the hydrological cycle, including seasonal variability in surface water and groundwater quality and availability?
	How do different water conservation and efficiency measures impact the seasonal water balance and sustainability of freshwater ecosystems?
Groundwater	What are the current state and trends of groundwater quality and quantity across Canada, by aquifer and watershed?
	How can contaminated aquifers be effectively remediated, and under what hydrogeological conditions do specific approaches perform best?
	How do interactions among groundwater, surface water, and climate influence water quality and quantity, and what are the characteristic time lags for these processes?
	Which methods and methodological standards are most effective for investigating environmental flows, aquifer recharge needs, and related groundwater–surface water exchanges?
	Which new or innovative technologies (e.g., remote sensing, fibre-optic Distributed Temperature Sensing, autonomous sensors) can improve groundwater monitoring coverage, resolution, and continuity?
	What additional science and tools are needed to incorporate groundwater inputs into water balance and prediction models, including coupled hydroclimate, water quality, and ecosystem models?
Hydroclimatic extremes	How will increased climate variability and climate change affect agriculture, forestry, mining and industrial water use and water supplies? What are the associated cost and benefit implications between proactive and reactive measures related to environmental risks from hydroclimatic extremes?
	What are the predicted impacts from increased frequency and intensity of floods and droughts on freshwater quality? What are the implications for public health such as with water management infrastructure?
	How often will drought and flood events impact freshwater quality and to what extent?
Human intervention	What impacts do human interventions in response to climate change-triggered water scarcity (e.g., allocations, dams, storage, conservation) have on surface and groundwater resources, and what are the implications for future water availability? What are the unintended consequences of climate action for freshwater?
	How are major development activities (e.g., for mining, for energy) and land use change influencing surface water and groundwater exchange, and groundwater quantity and quality?
	What is the integrated freshwater response (surface and groundwater) to the simultaneous changes in land use and hydrology, due to climate change in terms of water balance and availability by watershed?

A1.2 Freshwater use, land use, and pollution

Overarching questions	At a national scale, where are the greatest impacts to groundwater and surface water quality? What are the major sources and what is the extent and severity of these impacts?
	What is the magnitude and extent of geogenic groundwater contamination (e.g., As, Mn, U, etc.)? How are human activities exacerbating this contamination?
	What are the emerging watershed monitoring needs associated with anticipated growth and development of new critical mineral and rare earth mines in remote areas? What monitoring strategies are most appropriate to establish baseline conditions and track potential ecosystem and health risks?
	What is the dominant contaminant source by sector (e.g., agriculture, forestry, mining, waste, industry, urban) in each watershed? How can this improved source apportionment understanding inform remediation and improved beneficial management practices which reflect the simultaneous impact of multiple source types?
	What new or innovative tools and technologies (e.g., metabolomics, other "omics") can help to assess the current and future impact of land use practices such as nutrient-contaminant interactions on biological communities?
	How can we improve adaptive watershed monitoring strategies, such as the inclusion of community-based monitoring, to provide a broader range of data to inform environmental, human, and ecosystem risks and development of societally relevant indicators?
Beneficial management practices	What are the ecological regional differences in trade-offs between nitrogen, phosphorus, sediment, pesticides, and land use practices (e.g., agriculture) which will most affect water quality (and quantity) by watershed? What mix or evolution in BMPs would confer the maximum benefits to local watersheds?
	What are the ecological effects of nutrient-contaminant interactions from land use activities (e.g., agriculture) on biological communities and ecosystem health? How do these compare across different land use types and across the country?
	How will climate change impact agricultural water use and availability and agricultural practices (e.g., crop timing, varieties)?
	How will climate change, including seasonal and annual changes, affect surface and groundwater and nutrient availability, delivery, loading, and dynamics in freshwater systems?
	To what extent does climate change influence nutrient flux from watersheds to surface and ground waters? How do climate change and hydrological variability impact nutrient loadings, nutrient cycling, and the extent or severity of eutrophication and changes in biological communities?
	What are the status and trends in nutrient concentrations in groundwater bodies across Canada? How much does groundwater contribute to nutrient loading in surface waters?
	How are freshwater biological communities changing at various trophic levels in response to changing nutrient inputs/sources and what indicators would best inform tipping points at which point these changes are unsustainable?
	From a regional perspective, what are the primary sources and pathways of nutrient loading (nitrogen and phosphorus) and how do they vary seasonally in a changing climate?
	How do the seasonal geochemical dynamics of nutrients and contaminants impact BMPs?

	What are the transport mechanisms of nutrients and contaminants between groundwater and surface water systems and the impact on BMPs?
	How can we better enhance watershed-specific land use modelling to predict impacts of BMPs under different climate scenarios?
Wastewater, runoff, and landfill leachates	How can municipal sewage treatment systems broadly and efficiently upgrade to accommodate urbanization and climate change?
	What are the fate, distribution, and effects of key substances released in effluents, and how might they react with both point and non-point source inputs, existing/legacy contaminants already in the environment, and other pressures such as climate change?
	Is the freshwater carrying capacity of an urban ecosystem primarily limited by chemical (pollutant) or physical (barriers and lack of physical habitat needs) considerations?
	How can we better understand the chemical properties, and biological mixtures and their transformation, in surface and ground water and the effect on biota?
	How can we better monitor and characterize effluents to capture baseline water quality in response to extreme precipitation events?
	How can we better characterize landfill leachates in the north, considering potential contaminant releases?
	Is non-target analysis an effective approach to measure chemical compositions and degradation of contaminants in the environment?
	What are the most effective analytical tools for monitoring effluent discharge in freshwater ecosystems and for detecting emerging contaminants such as plastics?
	What efficient and innovative water treatment technologies could broadly address and treat industrial and municipal effluents?
	How does municipal drainage infrastructure impact local and regional flooding?
	How protective are current minimum water quality standards (e.g., TSS, sulphates) for avoidance of unacceptable cumulative effects? What are the implications for revising water quality standards?
	What are the ecological effects of municipal water management and wastewater releases on biodiversity and aquatic ecosystem health?
	Is the freshwater carrying capacity of an urban ecosystem primarily limited by chemical (pollutant) or physical (barriers and lack of physical habitat needs) considerations?
Multiple stressors and cumulative	What are the most appropriate models to test hypotheses about multiple stressor/complex mixture effects?
	What diagnostic indicators (using “omics”) would best identify stressors in complex freshwater environments?
	What are the cumulative effects of effluent and contaminant inputs on eutrophication?

	For cumulative effects, how can stochastic and probabilistic water quality models be improved to include spatial variability and seasonal trends in water quality, chemical concentrations, water flow, and hydrological conditions? How can socio-economic data such as best management practices be integrated into these models?
	How can we effectively account for the different timescales across which stressors act on freshwater ecosystems?
	Which effluent constituents are most likely to cause additive, and/or synergistic effects that need to be addressed from a cumulative effects perspective?
	What are the effects of multiple stressors within and alongside effluents of concern (e.g., temperature changes, nutrients.)?
Contaminants	How can we improve predictive modelling to better understand the dispersion, fate, and effects of multiple stressors and cumulative impacts on aquatic ecosystem health in response to concurrent land use change and changing climate?
	How can place-based and site-specific cumulative effects studies support the assessment of chemicals of emerging Arctic concern (CEACs), and the prediction of future releases of legacy persistent organic pollutants (POPs) and the presence of methyl-mercury, particularly from permafrost thaw and changing natural disturbance regimes?
	How can detailed economic sector data be captured effectively, such as from BMPs, to enhance predictive capacity?
Landscape and vegetation changes	What are the interactions between terrestrial and freshwater ecosystems and how do forestry management practices impact water quality, hydrological cycles, and biodiversity?
	How can the preservation and restoration of riparian zones protect freshwater and groundwater systems?
	What are the physical and chemical impacts of increased wildfires associated with climate change on freshwater and groundwater systems?
	In what ways can we broaden our knowledge of baseline data of the riparian freshwater interaction zone? How can this better inform management practices?
	What are the consequences of hydropower development on aquatic habitats, water quality and biodiversity?
	How have changes in land use affected the number, distribution, and condition of wetlands and groundwater=dependent ecosystems?
	In the North, how will vegetation and landscape changes resulting from permafrost thaw and wildfires impact hydrological systems and aquatic ecosystems?

A1.3 Freshwater ecosystem function, resiliency and biodiversity

Overarching questions	How are freshwater ecosystem functions and services altered by individual and multiple stressors (e.g., water and land use, ecosystem change, hydrologic change, extreme events, climate change)?
	What are the best techniques for assessing aquatic ecosystem health and what tools can be developed to monitor water quality more effectively?
	What are the primary spatial and temporal drivers for freshwater ecosystem change and how do they interact?
	How do we evaluate the economic and social value of ecosystem functions and services and how these can be integrated into decision-making processes?
Ecological effects-based predictions	Are there early warning ecological indicators (e.g. "omics") that could allow for successful interventions before changes to ecosystem health occur or ecological tipping points are reached?
	What are the most effective tools and best practices for detecting and monitoring the presence of aquatic invasive species in freshwater ecosystems, including early detection methods? How can these same tools provide complementary assessment of freshwater biodiversity dynamics? How can we apply "omics" tools to different aquatic species and environments to develop biomarkers?
	How can long-term and *in-situ* study sites, when leveraged with remote sensing and "omics" techniques, improve mechanistic understanding of ecosystem response to real-world conditions and improve predictive capacity?
	How can new tools be implemented to support integrated, One Health surveillance for environmental antimicrobial resistance (AMR) and pathogens of risk to humans and aquatic animal species?
Ecosystem functions, thresholds, and tipping points	What are the critical species and biodiversity profile thresholds (considering species sensitivity to water quality and quantity stressors), the role of invasive species, and the cascading risks of irreversible shifts in aquatic biodiversity? How can lakes that are already close to biophysical tipping points be prioritized?
	What is the relationship between ecological regime shifts in lakes, rivers, wetlands, groundwater, and changes in biogeochemical cycles that impact key ecosystem functions and services?
	What monitoring data is needed to capture reference or baseline conditions and biodiversity thresholds, and how pressures such as climate change will impact them? Is method development required for monitoring these parameters such as on food-web interactions, invasive species, energy flow, and process variables?
	What baseline measurements are reflective of current ecosystem status across gradients of anthropogenic impact? What is the threshold or tipping point(s) for change in different freshwater ecosystems?
	Which components of an ecosystem are under greatest threat and should be prioritized to maintain, protect or restore? What suite of ecosystem structure and function indicators best capture key freshwater ecosystem services?
	Where are freshwater biodiversity hotspots and where are species experiencing the greatest population reductions? Which are most critical to ecosystem function and services?
	What are the key aquatic and semi-aquatic species and diversity thresholds that regulate ecosystem functions and are they watershed-specific?

	How can relationships – and modelling - between ecological regime shifts and changes in biogeochemical cycles be better characterized, and considered in the global carbon budget?
	How can we better define how contamination and eutrophication affect carbon sequestration in aquatic ecosystems? Can this be integrated into global carbon budget modelling?
	How is climate change affecting carbon flux, particularly for wetlands ecosystems?
	What baseline monitoring is needed with respect to species thresholds, ecosystem processes, and impacts of climate change in remote and vulnerable areas? How can we track ecological trends to inform management strategies?
Impacts of e-flow and allocation management	How can we integrate water column characteristics into wetland models?
	How can modelling help assess wetland integrated response and vulnerability to managing water levels, allocation practices and climate change?
	How do changes in water flows, temperature, and water levels impact navigability, ecosystem function, and biodiversity and inform e-flow criteria?
Marine interface	How important are freshwater nutrient exports in contamination of nearshore coastal ecosystems and biological productivity?
Contamination and recovery	What are the knowledge, data and modelling gaps that exist on lake recovery processes from oil and chemical spills? How can long term recurrent or cumulative releases be better assessed?
	Can aquatic ecosystems be restored to full function and how long would the recovery process take?
Ecosystem resilience and invasive species	What monitoring data is needed to capture reference or baseline conditions and changes in critical species, and how does climate change impact them?
	What are the most effective monitoring and early detection methods for identifying the presence of invasive species in freshwater ecosystems?
	How do invasive species spread and establish in freshwater ecosystems, and what are the key pathways and vectors of introduction? What are the morphological, physical, chemical, and geological conditions that affect species interactions and biodiversity patterns that are impacted by invasive species?
	How do cumulative effects of habitat loss and climate change impact the ecological integrity of aquatic ecosystems once invasive species have established?
	What are the long-term ecological and economic impacts of invasive species on freshwater ecosystems and local communities?
Species at risk	How can we collect the necessary data to inform population models in freshwater habitats, particularly for species at risk
	How can indicator species be used to more effectively assess the health of interconnected aquatic and terrestrial ecosystems?

	How can we better integrate studies of species at risk and invasive species?
Bio-safety and water and food security	How can monitoring better capture municipal wastewater and agricultural runoff for antimicrobial resistance (AMR)? What parameters should be considered and at what frequency?
	Which environmental conditions and contamination sources promote the development and transmission of pathogens and AMR and how can these processes be assessed, managed, and communicated?
	How can AMR awareness be strengthened to support modelling and mitigation of future outbreak risks?
Environmental Emergencies	How can the application of new technologies be used to detect and track environmental incidents or spills?
	How can predictive modelling be used to better inform the development of emergency response strategies?