



Hydrological Responses to Disturbance in Peatland River Systems

Conceptual Modelling Study for the Ring of Fire
Regional Assessment Area

FINAL REPORT

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Hydrological Responses to Disturbance in Peatland River Systems

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REPORT PREPARED BY

Nicole Balliston, PhD

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PLAIN LANGUAGE EXECUTIVE SUMMARY

Purpose of the Report

This report explains how different types of development and disturbance could change water movement in peatland river systems within the Ring of Fire Regional Assessment Area (RAA). The report does not use a numerical model to predict exact numbers. Instead, it uses conceptual models, diagrams, and process-based explanations to show how water movement may change, where impacts may happen, and what should be monitored in the future.

The main focus is on streamflow and water quality. Streamflow means the amount of water moving through a river or stream. In peatland landscapes, rivers and streams do not function in isolation. They receive water from wetlands, forests, lakes, groundwater, snowmelt, rainfall, and other smaller rivers. This means that changes in any part of the surrounding connected landscape can eventually affect rivers and streams downstream.

Proper assessment and understanding of these changes are important environmental and scientific issues. Changes in water levels, water quality, flow timing, wetlands, plants, fish habitat, and access routes can affect travel safety, harvesting, drinking water concerns, medicinal plants, wildlife, and confidence in using lands and waters for the communities that live there and wish to uphold environmental integrity for future generations.

Chapter 2: Background Concepts and Definitions

This chapter introduces the main water concepts used in the report. It explains how water enters the landscape through rain and snow, how it is stored in wetlands and peat, how it moves above and below the ground, and how it eventually reaches rivers and streams.

A key idea is that **streamflow is the result of many connected parts of the landscape working together**. Rivers receive water from wetlands, groundwater, lakes, ponds, and tributaries. Because of this, a disturbance far away from a river can still affect the river if it changes how water moves through the landscape.

The chapter also explains why peatlands are especially important. Peat can store large amounts of water, but water does not always move through peat in the same way. When the water table is high, shallow peat layers can move water more easily. When the water table drops, parts of the peatland can become disconnected. This means even small changes in water level can affect whether wetlands, streams, and groundwater remain connected.

Chapter 3: Regional Setting Within the RAA

This chapter describes the broader landscape and climate setting of the RAA. The RAA includes different kinds of land, including the Precambrian Shield, Hudson Plains, Clay Belt, wetlands, rivers, lakes, forests, and peatlands.

The report explains two major regional patterns. The first is the **Shield-to-coast gradient**. In the Shield, the land is generally higher, rockier, more forested, and more channelized by lakes and streams. Toward the Hudson Plains, the land becomes flatter, wetter, and more dominated by peatlands. Water moves more slowly in these low-gradient peatland areas and is often controlled by wetland storage and shallow flowpaths.

The second is the **north-south climate gradient**. Temperature, snow, ice, growing season length, and permafrost conditions change across the region. These differences affect snowmelt, frozen ground, evapotranspiration, wetland storage, and seasonal streamflow.

This chapter also explains that water movement changes throughout the year. Spring snowmelt often produces the largest flows. Summer is strongly affected by evaporation and plant water use. Fall conditions depend on how wet or dry the summer was. Winter usually has low flow because much of the water is frozen as snow and ice. These seasonal patterns matter for travel, flooding, fish habitat, access, and water quality.

Chapter 4: Major Watersheds of the RAA

This chapter groups the landscape into hydrological units. These are landscape types that store and move water in different ways. The main hydrological units include bogs, fens, swamps, marshes, open water, forests, exposed bedrock, mineral soils, and disturbed areas.

The chapter also summarizes the major watersheds in the RAA, including the Winisk, Ekwan, Attawapiskat, Albany, Moose, and Lake Superior watersheds. These watersheds contain different mixes of wetlands, forests, lakes, rivers, and peatlands. Because of this, the same disturbance may have different effects depending on where it happens.

A key message is that wetlands are not just background features. They often act as the starting points of water movement in headwater areas and help control how much water reaches rivers and streams.

Chapter 5: Key Hydrological Units of the RAA

This chapter explains how each major hydrological unit stores water, moves water, and loses water to the atmosphere.

Fens are usually wetter and more connected. They can receive water from groundwater and surface water and pass it along to other wetlands or streams. Bogs are often more isolated and mainly receive water from precipitation. They can store large amounts of water but may only release water during wet periods. Swamps are often transitional areas that connect forests, wetlands, and streams. Marshes and open water areas store water at the surface and provide important habitat.

Forests, bedrock, and mineral areas also matter. Forests affect interception, snow storage, evapotranspiration, and runoff. Bedrock and mineral areas may have less storage and can produce faster runoff, especially where soils are thin.

The chapter shows that water moves through the landscape as a connected system. Water leaving one hydrological unit can become water entering another hydrological unit. This matters because a disturbance in one place may affect other places downstream or downgradient.

Chapter 6: Characterizing and Assessing Disturbances

This chapter explains how different disturbances may affect water storage, connectivity, evapotranspiration, water quality, and streamflow.

Disturbances considered in the report include roads and other linear features, dams and diversions, dewatering, climate change, wildfire, contaminant releases, forestry, work camps, exploration, infrastructure footprints, and renewable energy development.

Many disturbances affect water in similar ways. They may remove vegetation, compact soil, lower water tables, block shallow flowpaths, increase runoff, create ponding, dry out downgradient wetlands, increase erosion, warm streams, or move sediment and contaminants into waterways.

Some examples include:

- Linear disturbances, such as roads, can block shallow peatland flow. This may cause ponding on one side and drying on the other.
- Dams and diversions can change the natural timing of flow, water levels, ice conditions, and downstream habitat.
- Dewatering can lower groundwater and wetland water levels, reducing streamflow or drying nearby wetlands.
- Climate change can cause earlier snowmelt, more variable rainfall, lower summer water levels, warmer water, and more extreme flow conditions.
- Wildfire is a natural part of boreal landscapes and is not always negative. However, severe or frequent fires can increase runoff, sediment, nutrients, metals, water temperature, and flow variability, especially soon after burning.
- Contaminant releases can move through connected wetlands, groundwater, streams, and rivers, especially where flowpaths are active.
- Forestry can reduce interception, change snowmelt timing, compact soils, increase runoff, affect stream temperature, and increase sediment, DOC, nutrients, or herbicide-related concerns.
- Work camps, exploration, and infrastructure may have small individual footprints, but many small features together can create cumulative effects. Camps, drill pads, roads, crossings, wastewater, fuel handling, and boreholes can all affect water movement and quality.
- Renewable energy development, including wind, solar, and geothermal, is poorly studied in boreal peatland settings. The largest concerns are likely linked to construction, access roads, grading, drainage, vegetation removal, water use, chemicals, and subsurface drilling, rather than the energy structures alone.

A key message is that the size of a disturbance is not the only thing that matters. Its location, timing, connection to water pathways, and relationship to important wetlands or streams may be more important.

Chapter 7: Cumulative Impacts and Feedbacks

This chapter explains why impacts should not be considered one at a time only. In the RAA, many disturbances could happen in the same watershed or along the same flowpath.

Cumulative impacts happen when multiple changes build on each other. For example, a road may block flow, a mine may lower groundwater, climate change may create drier summers, wildfire may increase runoff and sediment, and wastewater or spills may add water-quality concerns. These effects may combine in ways that are larger or different than each impact alone.

An important message is that water quantity changes do not always cancel each other out. For example, adding pumped water back into a stream does not necessarily replace natural wetland flow. The water may arrive at a different time, come from a different source, have different chemistry or temperature, or fail to support the same wetland and stream functions.

From a community perspective, cumulative effects matter because people experience them in real places: travel routes, fishing areas, wetlands, crossings, rivers, harvesting areas, and culturally important sites. Future assessment should therefore ask not only “how much water changes?” but also “where does the change happen, when does it happen, what is it connected to, and who or what does it affect?”

Chapter 8: State of Knowledge and Framework for Quantitative Assessment

This chapter explains what information is available and what is still needed to better assess future disturbance effects.

A major finding is that there are important data gaps in the RAA. Many areas do not have enough long-term streamflow, groundwater, water-table, water-quality, or wetland monitoring data. Some disturbance types, such as renewable energy, work camps, exploration activities, and cumulative combinations of disturbance, are especially poorly studied in northern boreal peatlands.

The report recommends using three types of information together:

- Field monitoring is needed to measure water tables, streamflow, groundwater levels, water quality, soil and peat properties, and flowpaths.
- Remote sensing is useful for mapping wetlands, surface water, vegetation change, disturbance footprints, and landscape patterns over large areas.
- Modelling can help test possible disturbance scenarios, but models need field data and community input to be useful.

Future work should also develop indicators and thresholds. Some thresholds can be scientific, such as a certain amount of water-table decline, higher turbidity, warmer stream temperature, or reduced summer flow. Other thresholds should be defined with communities, such as when water becomes too low for travel, when wetlands become unsafe to cross, when fish habitat is affected, or when changes to plants and medicinal plants become a concern.

Overall Conclusions

This report shows that protecting rivers and streams in the RAA requires more than looking only at the river channel. It also requires understanding the connected wetlands, peatlands, groundwater pathways, lakes, tributaries, and seasonal flow processes that support those rivers.

The most important hydrological changes are not always the largest or most obvious ones. Small changes in water table, flowpaths, timing, or water quality can matter if they happen in sensitive places or during important seasons.

The report provides a conceptual framework for understanding how disturbance may change water movement and water quality. The next step is to connect this framework more directly to community priorities. This should include identifying important waterways, wetlands, crossings, harvesting areas, fish habitat areas, plant gathering areas, and seasonal travel routes.

Future monitoring and assessment should be designed with communities to answer practical questions: where is water changing, when is it changing, what is causing the change, what places are affected, and what indicators should trigger action?

In summary, hydrological change in the RAA matters because water supports wetlands, rivers, fish, wildlife, plants, travel, harvesting, and community well-being. The goal of future assessment should be to protect not just the amount of water, but the right water, moving through the right pathways, at the right time, with the right quality, to support both ecosystems and communities.

HOW TO USE THIS REPORT

This report is written for multiple audiences. Readers looking for the main messages can use the executive summary, figures, and **purple highlight boxes**, which focus specifically on community relevance. Readers looking for more detail can refer to the main text, where technical explanations and supporting references are provided. The main technical concepts are introduced in Chapter 1, while the definitions appendix provides short explanations of technical terms used throughout the report.

STATEMENT ON THE USE OF AI

AI-assisted tools were used during report preparation to support language editing, figure formatting, and visual refinement of selected conceptual diagrams. These tools were not used as a source of scientific evidence. All content, interpretations, references, and final figures were generated, reviewed, and verified by the author.

1.0 INTRODUCTION

The Regional Assessment in the Ring of Fire Area is a co-led assessment process involving the Government of Canada, Matawa First Nations, Mushkegowuk First Nations, and Weenusk First Nation. The Regional Assessment Working Group has been established to conduct the assessment and includes community members from each First Nation partner and representatives of the Impact Assessment Agency of Canada.

The Regional Assessment was initiated in recognition that multiple, interrelated development proposals are being considered within a large, ecologically sensitive, and culturally significant region of northern Ontario home to ~30,000 Indigenous people.¹ The assessment is intended to address issues that cannot be adequately considered through project-by-project impact assessments alone.¹

The Government of Canada's commitments under section 35 of the *Constitution Act, 1982*, the Duty to Consult, and the implementation of the United Nations Declaration on the Rights of Indigenous Peoples, including free, prior, and informed consent, also guide the Regional Assessment and the assessment of potential future developments in the assessment area (herein referred to as the Regional Assessment Area (RAA)).

1.1 Purpose and Objectives of the Regional Assessment

The purpose of the Regional Assessment is to provide regional-scale information on priorities of importance to the First Nation partners and the Government of Canada, and to assess potential positive and negative effects, including cumulative and interactive effects, associated with possible development activities in the RAA.²

The Regional Assessment is intended to support future impact assessments and other decision-making processes by identifying key conditions, risks, uncertainties, management approaches, governance needs, and follow-up steps. Its objectives include improving understanding of environmental, health, cultural, social, and economic conditions; assessing potential impacts on Indigenous Peoples; identifying ways to reduce negative effects and enhance positive outcomes; and providing regional context for future development decisions.²

One of the key identified priorities, and the subject of this project, is the potential for alterations in streamflow and water quality, both directly and through hydrological alteration in upgradient ecosystems, particularly peatlands.

1.2 Purpose of This Project

The RAA contains an extensive network of watercourses (i.e., rivers, streams, and creeks) that drain peatland-rich landscapes through a network of watersheds and into Hudson and James Bays (Figure 1-1). Through the Regional Assessment process, watercourses have been described as central to community life and well-being.² From a hydrological perspective, they also act as integrators of landscape change, because they receive water, sediment, solutes, and contaminants from connected wetlands (particularly peatlands), forests, lakes, groundwater

pathways, and upstream tributaries. As a result, watercourses are both indicators and pathways of hydrological change, making them key features for understanding how disturbance might move through the RAA.

For First Nations communities, hydrological changes extend far beyond physical changes in water movement. Changes in the amount, timing, quality, and location of water can affect travel safety, access to harvesting areas, fish and wildlife habitat, drinking water safety, flooding and drying of culturally important areas, and confidence in the continued use of lands and waters. For this reason, the concepts, impacts, and recommendations discussed in this report are considered not only for their environmental and scientific importance, but also for their relevance to short- and long-term community health and well-being. However, this report does not replace direct community engagement or consultation. Community concerns and potential pathways of effect are discussed based on available reports, Regional Assessment materials, and published literature, and are interpreted through a Western scientific lens. The author is not Indigenous, and the discussion should therefore be understood as a synthesis of available information rather than a substitute for community-led knowledge, priorities, interpretation, or review.

The objective of this project is to develop conceptual models explaining the potential hydrological responses of watercourses in the RAA to a set of anticipated disturbances, both individually and cumulatively. The conceptual models are intended to support qualitative assessment of flow changes under different disturbance scenarios for a selected system, or to provide a general framework that can be applied across multiple systems.

The work focuses on how disturbances may affect streamflow by altering water storage, water table position, groundwater supply, source-water contributions, flow routing, and water quality. Because peatlands are a dominant land cover in the RAA and play an important role in regulating water storage, runoff generation, groundwater exchange, and streamflow, many of the hydrological processes discussed in this report emphasize peatland-dominated systems. Other land cover types, including forests, lakes, rivers, mineral uplands, and exposed bedrock areas, are also included to the extent possible because they are important components of connected watershed systems and may influence how disturbances affect watercourses.

This report also addresses the current availability of baseline and monitoring data within the RAA, the information required to build quantitative models of flow change, and the risks, limitations, and uncertainties associated with the absence of quantitative models to support decision-making. The information presented reflects the best available understanding that could be developed from the reports, datasets, and literature reviewed for this project. However, available data for the RAA are limited, uneven across land cover types and disturbance pathways, and not exhaustive. As a result, the conclusions should be interpreted as a best-effort synthesis based on the information available at the time of writing, rather than a complete or final characterization of all hydrological processes, community concerns, or potential disturbance effects in the region.

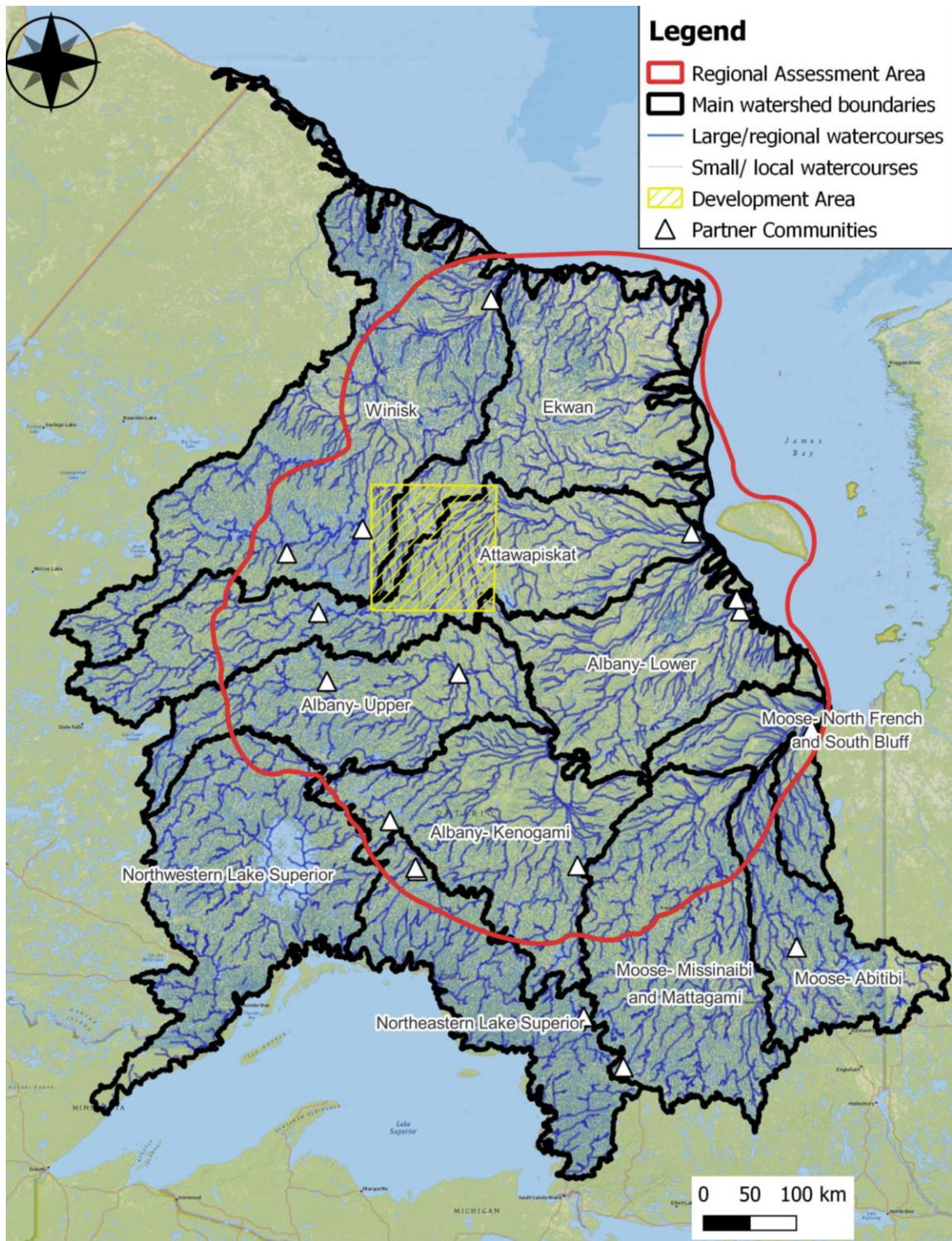


Figure 1-1: Main watershed boundaries intersecting the Regional Assessment Area (RAA; red outline) and associated mapped watercourse network. Watershed boundaries are shown in black, while watercourses are shown in blue, with thicker lines representing larger channels. Within the RAA boundary, the mapped hydrographic network includes more than 206,500 km of watercourse.



CONCEPT HIGHLIGHT: WHY THIS REPORT MATTERS TO COMMUNITIES

1 CONNECTED WATERS



Rivers and streams receive water from wetlands (especially peatlands), lakes, groundwater, and upstream areas.

2 COMMUNITY IMPORTANCE



Changes in water can affect travel, harvesting, fish and wildlife, plants, drinking water concerns, and wetland access.

3 REPORT SCOPE



This report looks at how disturbance could change streamflow, water quality, water tables, storage, and flowpaths.



KEY TAKEAWAY:

Disturbance does not need to happen right beside a river to affect water downstream. Connected landscapes mean effects can travel far from their source.

1.3 Structure of This Report

This report is not a numerical modelling exercise. Instead, it provides a process-based framework for organizing current hydrological understanding and assessing how disturbances may alter streamflow through changes in landscape storage, connectivity, groundwater exchange, and flow paths.

The report begins in Chapter 2 by introducing core hydrological concepts needed to assess streamflow change, including water balance, hydrological connectivity, peatland storage, groundwater and surface-water exchange, and threshold-based flowpaths.

Chapters 3–5 then describe the regional setting of the RAA, including major landscape gradients, watershed organization, and seasonal hydrological patterns, and define hydrological units and their key hydrological processes.

Chapter 6 assesses how key stressors may alter streamflow and associated water conditions. These stressors include linear disturbance, river damming and diversions, dewatering, climate change, wildfire, contaminant releases, forestry, and renewable energy. The report considers how these disturbances may affect hydrological units individually and cumulatively, with attention to both local changes and downstream propagation through stream and river networks.

The final Chapters 7–9 identify cumulative impact pathways, knowledge gaps, available baseline and monitoring data, and the field observations, remote sensing products, and modelling approaches required to support future quantitative assessment of flow change.

2.0 BACKGROUND CONCEPTS AND DEFINITIONS

This chapter introduces the hydrological principles used throughout the report to assess potential disturbance effects on peatland river systems. It begins with general hydrological concepts, then focuses on wetlands (with an emphasis on peatlands), streamflow, water balance, hydrological connectivity, and the spatial scales used to organize the conceptual framework.

These concepts provide the foundation for interpreting the regional setting, dominant landscape cover, disturbance pathways, and cumulative effects discussed in later chapters. Terms defined in this chapter are bolded throughout. Terms not defined in this chapter but that may need further definition are *italicized and underlined*; definitions for these additional terms are provided in written and visual form in the definition table in Appendix A.

2.1 Hydrological Systems and Conceptual Models

Hydrology is the study of water in the environment. It examines where water comes from, where it is stored, how it moves across and beneath the land surface, and how it is exchanged among the atmosphere, vegetation, soils, streams, lakes, and groundwater. In a regional assessment context, hydrology provides the foundation for understanding how landscapes function, how water supports ecosystems and communities, and how changes to land, climate, or infrastructure may alter water movement and availability.

Hydrological processes are physical processes that move, store, and exchange water within a landscape. As shown by the arrows and labels in Figure 2-1, water enters the system mainly through precipitation such as rain and snow. Once water reaches the land surface, it may be intercepted by vegetation, infiltrated into the soil, stored or moved across the surface as snow or runoff, stored in wetlands or lakes, or transported through streams and rivers as streamflow. Some water returns to the atmosphere through evaporation from open water, wet soils, and vegetation surfaces, or through transpiration from plants. Water that moves downward through soil and sediment may recharge groundwater, where it can be stored and slowly transported through subsurface materials before discharging back to wetlands, streams, rivers, or lakes.

The environment shown in Figure 2-1, together with all its hydrological processes, can be referred to as a **hydrological system**. The parts of this system are not isolated from one another but are linked by the movement of water. For example, precipitation falling on the land may become surface runoff, enter a wetland, infiltrate into soil, recharge groundwater, or eventually contribute to streamflow. Similarly, groundwater may support surface water by discharging into streams, lakes, and wetlands, especially during dry periods. Understanding these connections is important because a change in one part of the system can affect water movement, storage, and availability elsewhere.

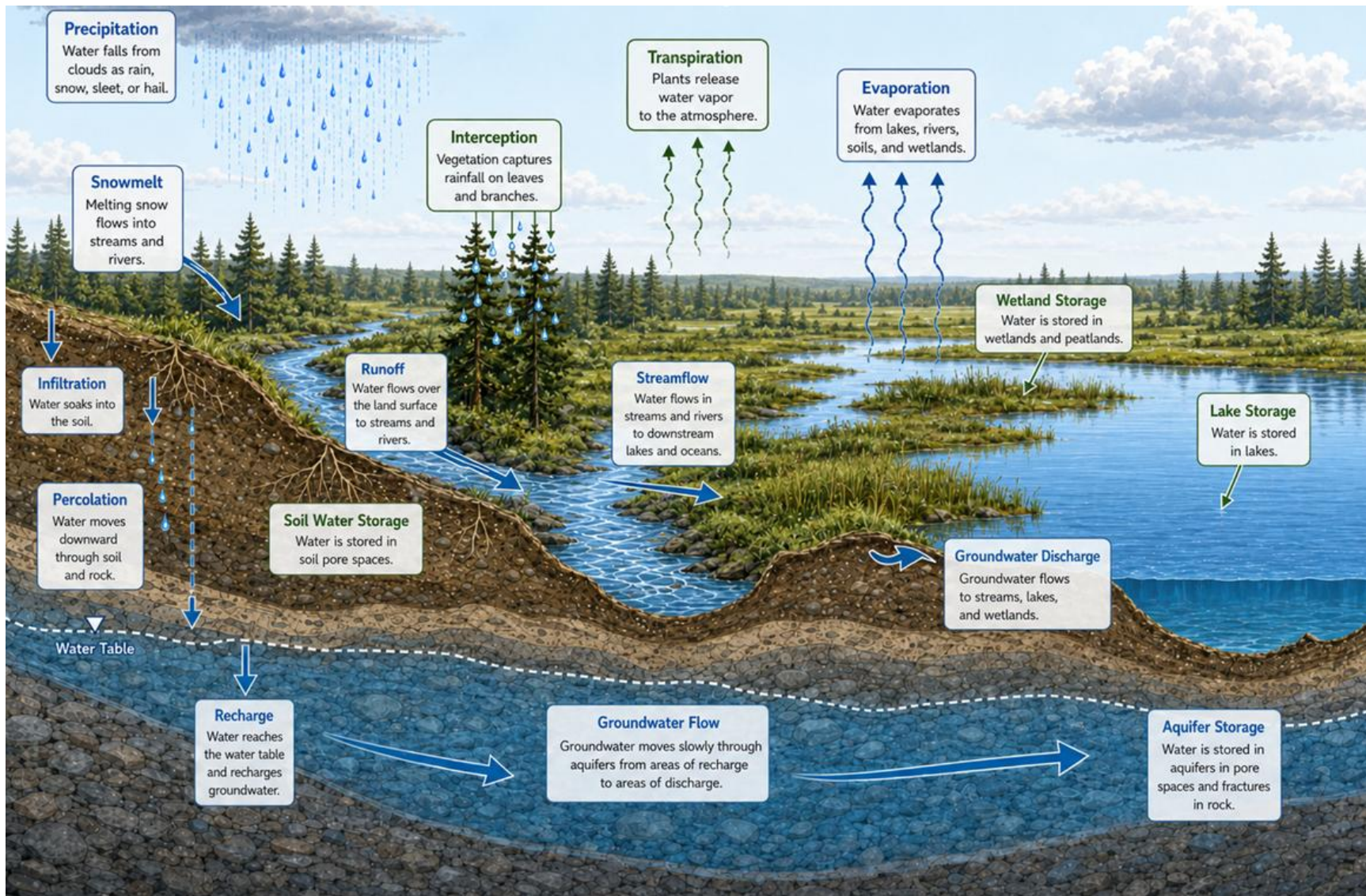
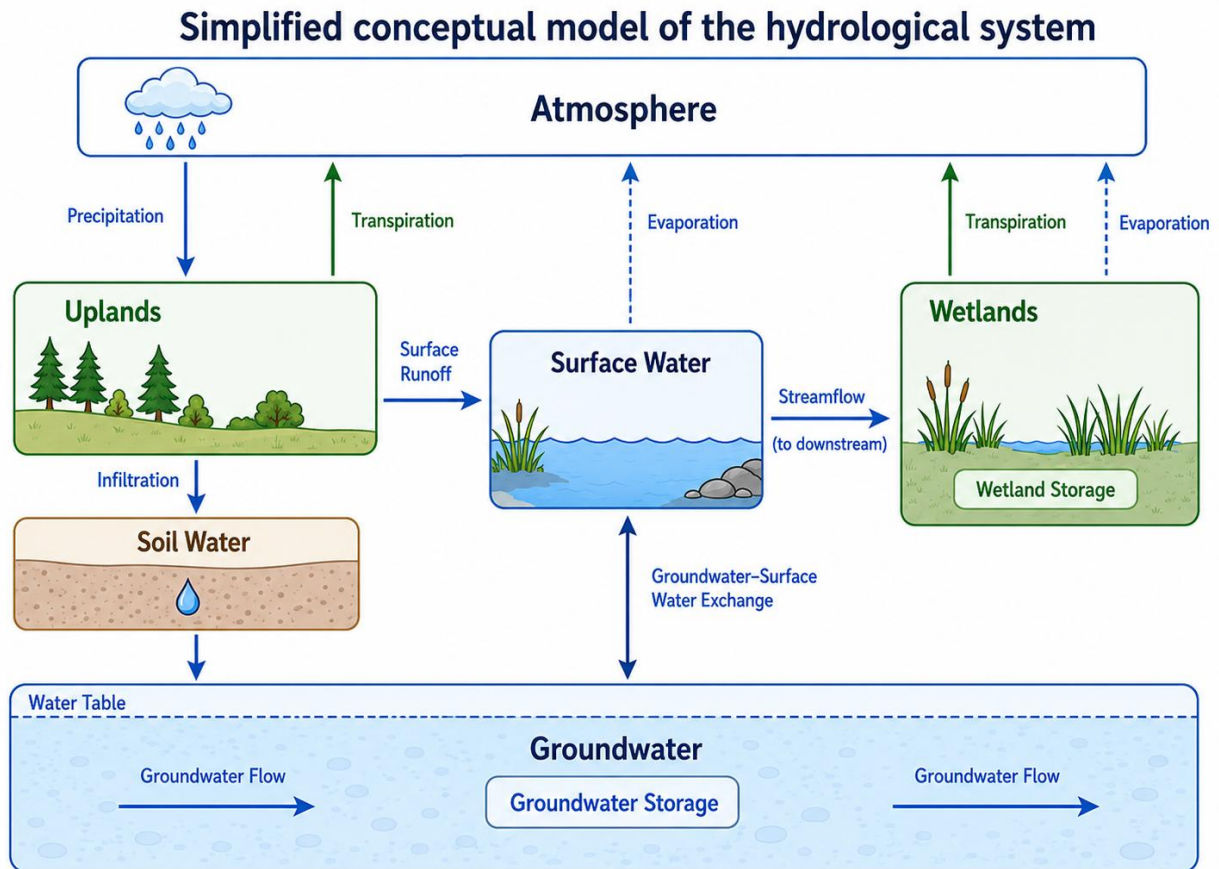


Figure 2-1: Conceptual representation of a hydrological system, showing major water inputs, outputs, storage zones, and exchange pathways among the atmosphere, vegetation, soils, wetlands, groundwater, lakes, streams, and rivers.

Conceptual models are simplified representations of real hydrological systems. They are used to organize components, communicate key processes, identify important connections, and support the assessment of how a system may respond to change. Conceptual models do not include every detail of a landscape. Instead, they focus on the components and pathways that matter most for the question being asked. For example, Figure 2-2 is a conceptual model of the system shown in Figure 2-1. In this report, conceptual models are used to describe how water moves through river systems in the RAA, how different parts of the landscape are connected, and how disturbances may alter water storage, flowpaths, and downstream water conditions.



Arrows indicate major water pathways and exchanges among atmospheric, surface, and subsurface components.

Figure 2-2: Simplified conceptual model of the hydrological system shown in Figure 2-1, highlighting the major components and pathways used to assess water storage, movement, and exchange.



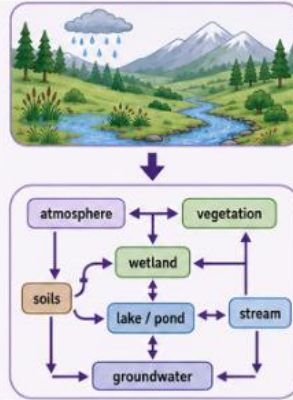
CONCEPT HIGHLIGHT: HYDROLOGICAL SYSTEMS AND CONCEPTUAL MODELS

1 WHAT IS A HYDROLOGICAL SYSTEM?



Water moves between the atmosphere, vegetation, soils, wetlands, lakes, streams, and groundwater.

2 WHAT IS A CONCEPTUAL MODEL?



A conceptual model simplifies a real landscape by showing the main water stores, pathways, and connections.

3 RELEVANCE TO THIS REPORT



This report uses conceptual models to show how disturbance may change water storage, flow pathways, and downstream water conditions.

Conceptual models focus attention on the parts of the system that matter most.



KEY TAKEAWAY:

A hydrological system is made of connected parts. Conceptual models help identify which parts and pathways matter most for understanding how change moves through the system.

2.2 Wetlands, Peatlands, and Muskeg

A **wetland** (Figure 2-3) is an area where water is present at or near the land surface long enough to influence soil development, vegetation, and ecosystem function.³ Wetlands include a range of ecosystem types, such as bogs, fens, swamps, marshes, and shallow open water, which are further described in Chapters 4 and 5. In the RAA, wetlands are a major part of the landscape and play an important role in storing water, slowing runoff, supporting groundwater and surface water exchange, and regulating flow to watercourses (e.g., rivers, streams, and creeks) and waterbodies (e.g., ponds and lakes). They are also important habitat for diverse fauna such as woodland caribou, moose, beaver, and waterfowl.

A **peatland** (Figure 2-3) is a specific type of wetland that develops where wet or saturated conditions slow decomposition and allow organic plant material to accumulate over time. This accumulated organic soil is called **peat**. In Canada, peatlands are commonly defined as **wetlands** with 40 cm or more of peat depth.³ This distinguishes peatlands from wetlands with thinner organic layers or mostly mineral soils (i.e., soils formed mainly from weathered rock and sediment, such as sand, silt, clay, or till). Peatlands are known for containing many medicinal plants such as labrador tea (*Rhododendron groenlandicum*), also known as muskeg tea, as well as *Sphagnum spp.* Mosses, traditionally used for their antiseptic and moisture-absorbing properties as diapers and bandages.^{4,5}

The term **muskeg** (L^{ᑎᑦᑭ}) (Figure 2-3) is often used to describe wet, peat-forming northern landscapes with mosses, sedges, shrubs, trees, standing water, and near-surface groundwater.⁶ In this sense, muskeg refers broadly to the landscape of peatlands, while peat refers to the organic soil material within the landscape. Because peat stores and transmits water differently than mineral soils, its presence and thickness are major controls on wetland connectivity, flowpaths, water storage, and water delivery to rivers and streams.

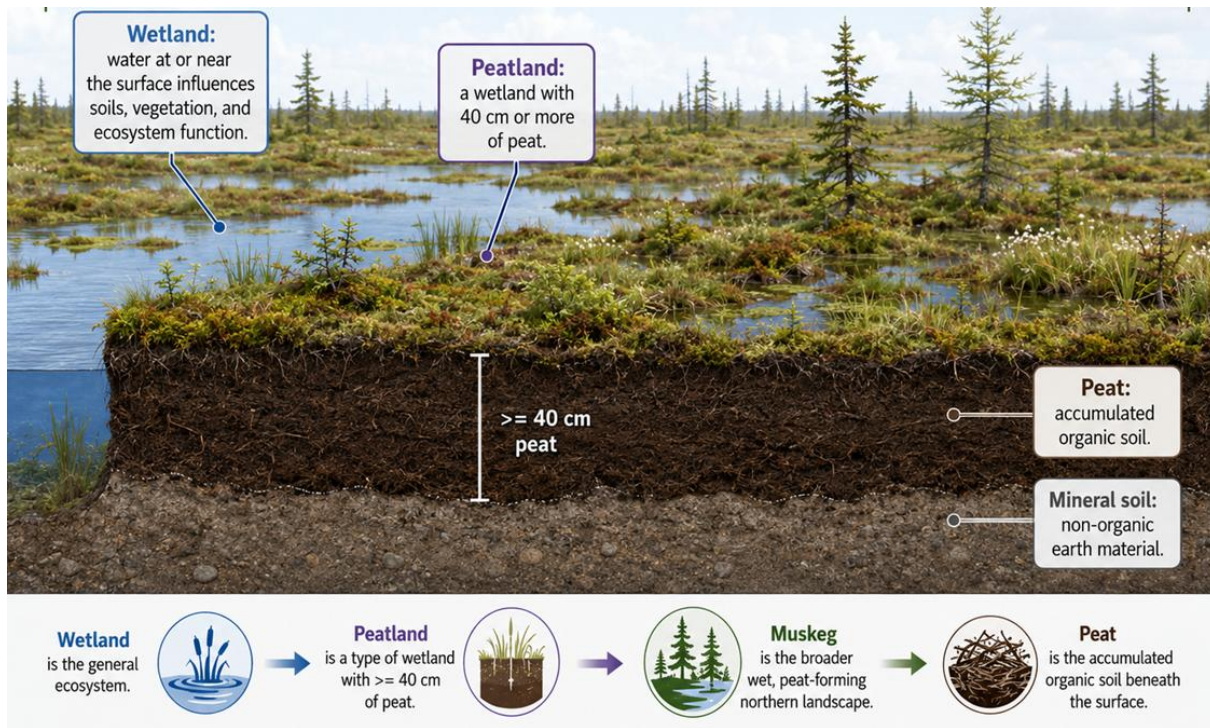


Figure 2-3: Conceptual comparison of wetlands, peatlands, muskeg, and peat.

2.3 Peat Structure, Storage, and Transmissivity

Peat behaves differently from most mineral soils because it is highly porous (loose and fluffy), compressible (easily squished), and layered. As shown in Figure 2-4, it can store large amounts of water, but its ability to release that water changes with depth and degree of decomposition.⁷ The upper peat layer, called the **acrotelm**, is closer to the surface and usually contains living roots and less decomposed plant material.⁸ It tends to let water flow through it faster, especially when water tables are high. Beneath this layer is the **catotelm**, which is generally more decomposed, almost always saturated, and slow to transmit water.⁸

This soil layering creates unique patterns in water movement across peatlands (see arrows in Figure 2-4). When the water table rises into the upper peat (i.e., acrotelm), water can move through the soil more easily and therefore travels across the peatland faster. When the water table falls into deeper peat (i.e., catotelm), this flow slows, and parts of the landscape may become less connected.⁹ This relationship is often described as a **transmissivity feedback**, meaning that the ability of peat to transmit water depends strongly on water table position.¹⁰

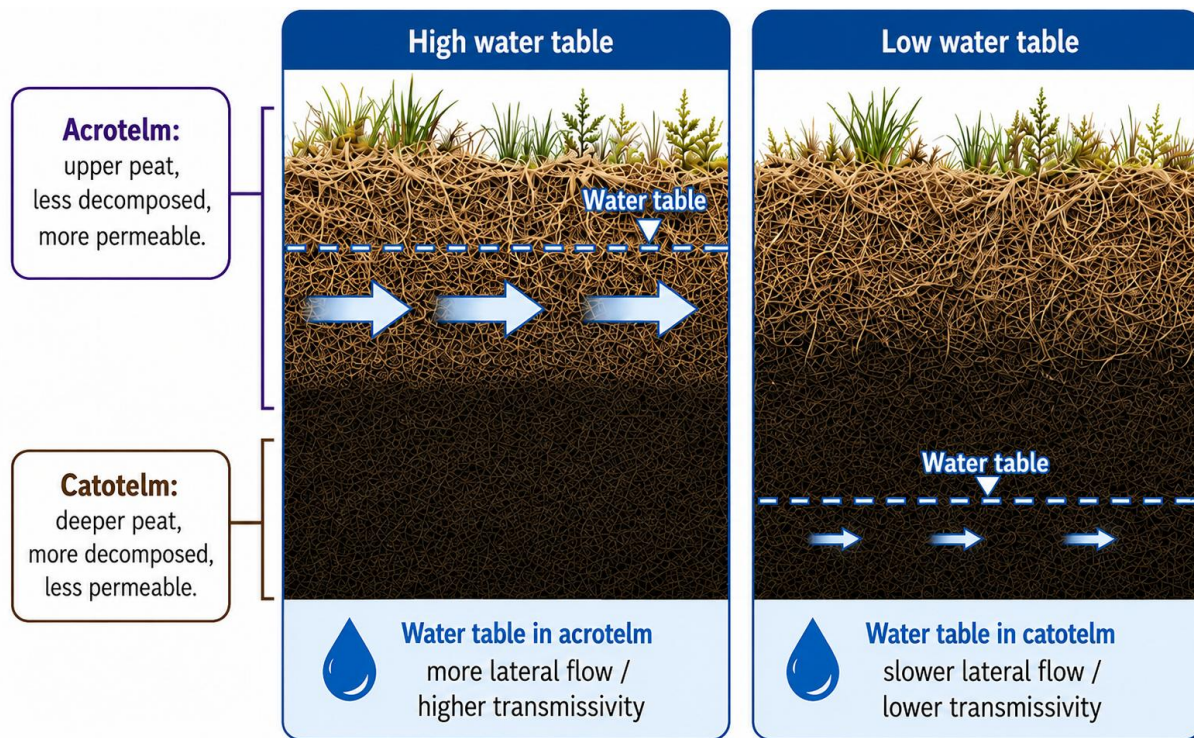


Figure 2-4: Conceptual representation of peat structure, showing the near-surface, less decomposed acrotelm and the deeper, more decomposed and saturated catotelm. Conceptual illustration of the relationship between water table position and flow across a peatland.

2.3.1 Hydrological Connectivity and Thresholds

Hydrological connectivity refers to the degree to which water and water-mediated components can move between different parts of a landscape both above and below ground.¹¹ In many wetland systems, particularly in peatlands, these connections are **threshold-based**, meaning they are not always active. Instead, they may seem to “turn on or off” when water levels rise above or fall below certain points in the landscape.

Figure 2-5 summarizes what this would look like in a peatland draining into a river. When a lot of water enters the system, such as during snowmelt or large rainfall events, rising water tables may activate shallow flowpaths, connect wetlands and ponds, and increase delivery of water to streams. During dry periods, water levels may fall below these thresholds, reducing flow and limiting the connection between parts of the landscape. In peatlands, even small changes in water level can cause large changes in connectivity because water movement is strongly controlled by whether the water table intersects the more *permeable* upper peat.

Threshold-based connectivity, sometimes called “**fill-and-spill**,” therefore helps explain why peatland river systems may respond rapidly during wet periods, but become more disconnected during dry or frozen conditions.¹² In peatland-dominated landscapes like the one shown in Figure 2-5, water table thresholds for high connectivity are often within 30 cm of the surface; however, exact thresholds are quite variable and have not yet been studied across the diversity of systems found within the RAA.^{13,14}

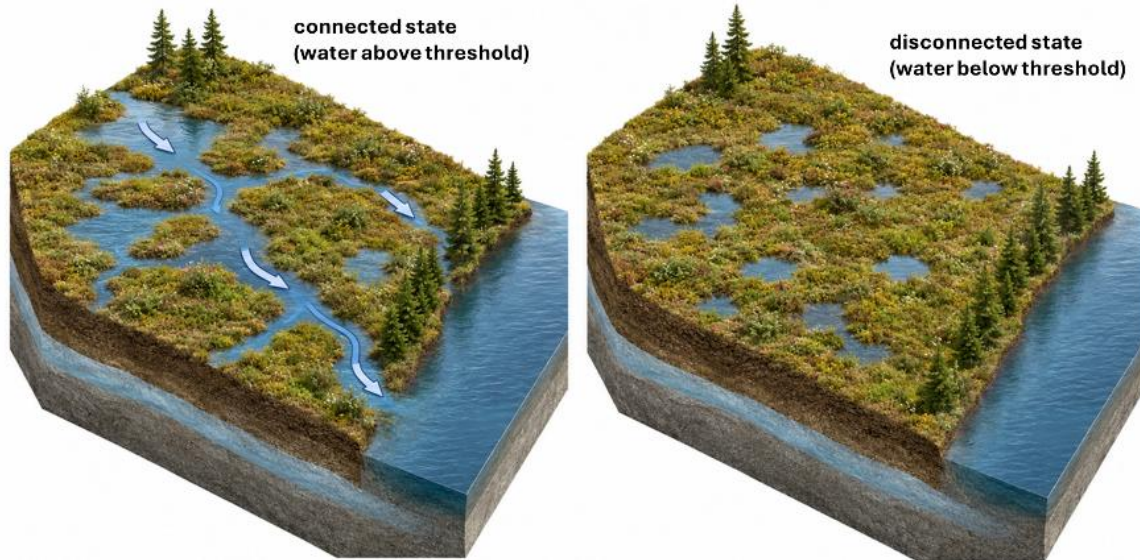


Figure 2-5: Conceptual representation of threshold-based connectivity in a peatland draining toward a river, showing how rising water tables activate shallow flowpaths and increase connection between wetlands and surface water.

CONCEPT HIGHLIGHT: PEATLAND / MUSKEG RESPONSE TO WATER LEVEL CHANGE

1 PEAT STRUCTURE AND WATER STORAGE

Peat forms in layers. The upper layer stores and moves water more easily than the deeper layer below.

2 FLOWPATHS CAN SWITCH ON AND OFF

higher water table

more connected
faster flow

lower water table

less connected
slower flow

When the water table rises into the shallow peat, water moves faster and the landscape becomes more connected.

When the water table lowers into the deep peat, flow slows and the landscape becomes less connected.

☆ KEY TAKEAWAY: Muskeg is a common term for wet, peat-forming northern landscapes, often called peatlands. Small changes in water level can strongly affect peatland wetness, water storage, and how much water reaches streams downstream.

2.4 Streamflow

Watercourses act as integrators of hydrological processes across the landscape. They receive water from a range of sources and transfer it through watersheds toward downstream receiving environments.¹⁵ In the wetland-dominated, particularly peatland-rich, watersheds characteristic of the RAA, streamflow is strongly influenced by the storage, release, and transmission of water within wetlands. Peatlands, in particular, act as both reservoirs and regulators of water, moderating the timing and magnitude of flow contributions to river systems.⁷

Streamflow plays a critical role in supporting aquatic and terrestrial ecosystems, influencing habitat availability, water quality, and nutrient transport, as well as sustaining community activities, including travel routes and traditional land use practices. Because rivers integrate processes occurring across the landscape, disturbances in upgradient areas, such as land cover change, drainage, or water extraction, can propagate through hydrological pathways and alter downgradient flow regimes.

2.4.1 Conceptualizing Streamflow Components

At a conceptual level, streamflow reflects the balance between water inputs, outputs, and internal processes operating across both the surrounding landscape and within the watercourse itself (Figure 2-6). These components can be broadly categorized as:

- Upgradient inflows, representing water contributions from surrounding land and upstream areas, including surface runoff, shallow subsurface flow, groundwater inputs, and streamflow from tributaries and upstream within the watercourse;
- Downgradient losses, representing water transferred from the watercourse to adjacent landscapes or downstream systems, including bank storage, floodplain exchange, and groundwater recharge; and
- In-channel and atmospheric exchanges, including processes such as evaporation, precipitation, and channel–floodplain interactions, which are influenced by river morphology and surface area.

Together, these components reflect the degree of hydrological connectivity across the landscape and determine how water is stored, transferred, and released through watersheds. In wetland environments, this connectivity is often governed by shallow water tables and low-relief topography, which can produce **threshold-dependent flowpaths** that can be very different across wetland types, landforms, and positions in the watershed.

Upgradient inflows and downgradient outflows vary across the landscape and over time. Hydraulic gradients help move water from areas with a water surplus (where water is more available) toward areas with a water deficit (where less water is available). These gradients are influenced not only by water availability, but also by land cover, peat and soil properties, and topographic controls that regulate storage capacity and flowpaths.

Climatic conditions further influence these dynamics by controlling the inputs and losses of water to the system. Precipitation, evapotranspiration, and seasonal processes such as snow accumulation and melt govern the timing and magnitude of water availability, thereby shaping the relative importance of different flowpaths throughout the year.

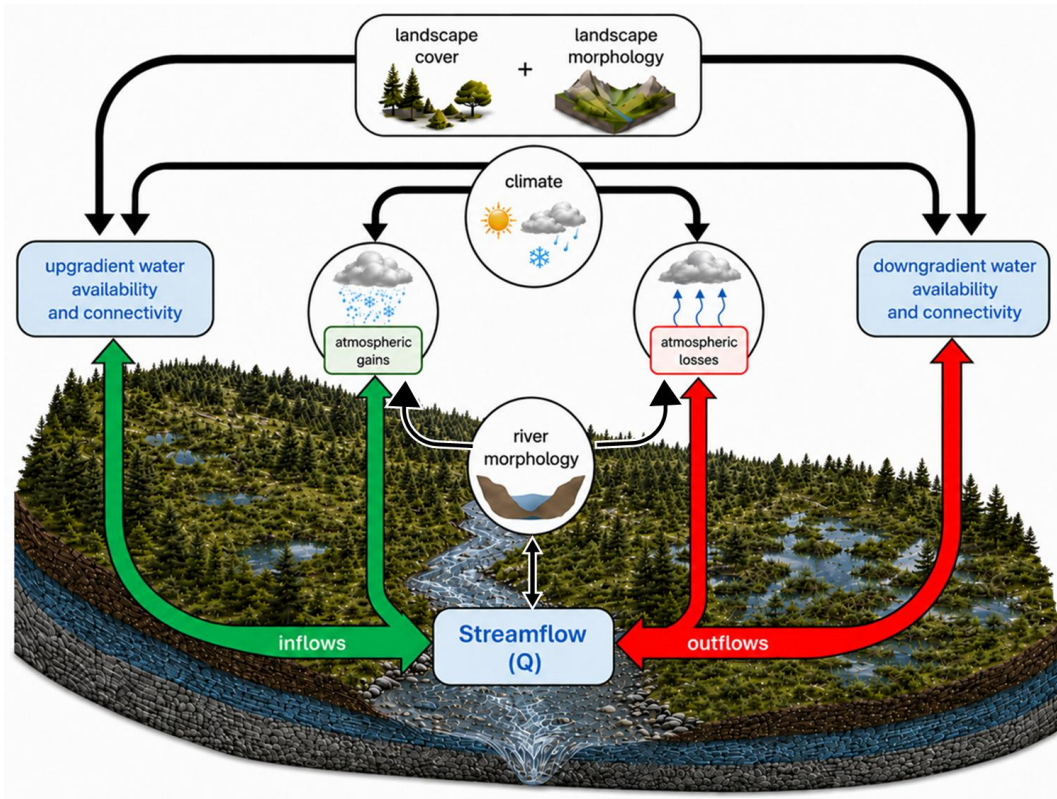


Figure 2-6: Conceptual representation of streamflow components, including upgradient inflows, downgradient losses, and in-channel and atmospheric exchanges.

2.4.2 Quantifying Streamflow

Quantitatively, streamflow is defined as the volume of water moving through a river channel over a given period and is typically expressed in cubic metres per second (m^3/s). This is distinct from flow velocity, which describes the speed of water movement (m/s). These quantities are related through the expression:

$$Q=VA$$

where Q = streamflow/discharge in m^3/s , V = velocity in m/s , and A is the cross-sectional area of the channel at a given point in m^2 . In field applications, streamflow is commonly estimated using cross-sectional methods, where velocity and depth are measured at multiple points across a channel and integrated to calculate total discharge.

Quantifying how these interacting controls regulate streamflow provides a foundation for assessing how disturbances may alter hydrological processes and propagate through river systems in the RAA.¹⁵ Changes in streamflow can affect the amount, timing, and duration of water available in rivers, wetlands, lakes, and connected floodplain areas, with implications for habitat availability and ecosystem function. For example, shifts in high-flow, low-flow, or seasonal flow conditions may alter access to spawning, rearing, feeding, or refuge habitats for fish and wildlife.^{16,17}

Altered streamflow can also influence water quality by changing water temperature, dilution capacity, sediment transport, and the movement of nutrients, contaminants, and other compounds like dissolved organic matter through the river network. These changes can affect downstream aquatic conditions and the delivery of water, sediment, nutrients, and carbon from upstream landscape units to downstream rivers, lakes, and wetlands. Because river systems also support human activities, changes to flow conditions may affect travel routes, access to harvesting areas, and the continued use of waterways and surrounding lands for traditional land use practices. In this way, understanding streamflow controls is important not only for assessing hydrological change, but also for evaluating the broader ecological, water quality, and human-use implications of disturbance across the RAA.

2.4.3 Assessing Streamflow Contributions Using a Water Balance Approach

To evaluate the contributions of different landscape components to streamflow, water balance approaches are used to quantify the storage and movement of water within defined areas. In this report, the term “water availability” refers to the amount of liquid water held in storage (S), both above the ground as surface water (S_{sw}), and below the ground in soil (S_{gw}). In the river channel, surface water storage (S_{sw}) corresponds to the volume of water contributing to flow. Below the ground, water table depth is a common measure of storage, where the deeper the water table, the less water is held in storage in the soil column.

Within any defined portion of the landscape, changes in water storage (ΔS) can be evaluated using a simplified water balance framework that incorporates all the **hydrological processes** (Figure 2-7).

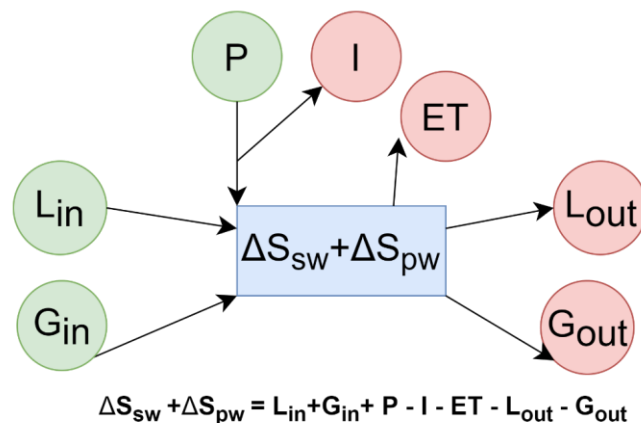


Figure 2-7: Conceptual water balance framework showing climate-driven and connectivity-mediated fluxes that control water storage (ΔS) and availability. Variable definitions: P is incoming precipitation, I is precipitation intercepted by vegetation, ET is evaporation and/or transpiration (i.e., evapotranspiration), L_{in} and L_{out} are lateral surface or near-surface inflows and outflows, respectively, and G_{in} and G_{out} are groundwater inflows and outflows.

Furthermore, storage (S) and the change in storage (ΔS) can be measured directly by measuring the depth of the water table over time.

2.5 Spatial Scales and Hydrological Units

The conceptual model of streamflow (Figure 2-6) and the water balance framework (Figure 2-7) provide the foundation for assessing hydrological and streamflow change.

This analysis can be examined across a range of spatial scales. Larger-scale climatic, geological, and physiographic controls strongly influence watershed organization, while smaller-scale processes can be important for capturing detailed water balance components.¹⁸ For this reason, all scales are considered within this report, from regional to local, reflecting the hierarchical controls on water availability, connectivity, and flowpaths across the landscape:

- **Regional Scale: > 5000 km²**

This scale is used to characterize broad climatic patterns, physiographic gradients, and large-scale landscape organization. In the RAA, this includes ecozones and ecoregions, regional climate regimes, and major hydrological gradients. These factors establish the overall hydrological context and strongly influence the distribution and function of hydrological units across the landscape. Chapter 3 discusses regional characteristics.

- **Watershed Scale: 100–5000 km²**

This scale is used to characterize hydrological processes within river basins and drainage networks. It includes the assessment of major watersheds (e.g., Albany, Attawapiskat, and Moose), patterns in land cover and connectivity, and integrated streamflow responses. At this scale, analysis is conducted across networks of interacting units, and water balances are linked across the watershed to describe system-level behavior. Watershed-scale analyses often require the integration of data from multiple representative local-scale studies. Chapter 4 introduces the major watersheds of the RAA.

- **Local (sub-watershed): 10–100 km²**

This scale is used when a detailed, process-based understanding of hydrological behaviour is required. It is at this scale that water balance components, storage dynamics, and connectivity between hydrological units are most directly observed and measured.

To apply the water balance framework across *heterogeneous* peatland landscapes, this report introduces the concept of **hydrological units** (Figure 2-8). A **hydrological unit** represents a subdivision of the landscape with internally consistent physical characteristics, including land cover (e.g., bog, fen, forest, and open water), average soil properties, and landscape position.

Changes in water storage occur within *upgradient* and *downgradient* hydrological units, as well as within the river channel itself. At any given location, streamflow reflects the integrated response of these storage dynamics across connected units. As such, understanding streamflow requires consideration of water balances across multiple hydrologically linked portions of the landscape.

Water balances can be defined for individual hydrological units and connected through lateral surface and subsurface fluxes. Outflows (L_{out} , G_{out}) from *upgradient* units become inflows (L_{in} , G_{in}) to *downgradient* units, enabling water movement to be traced across the landscape. The magnitude and direction of these flows are governed by spatial gradients in water availability and the degree of hydrological connectivity.

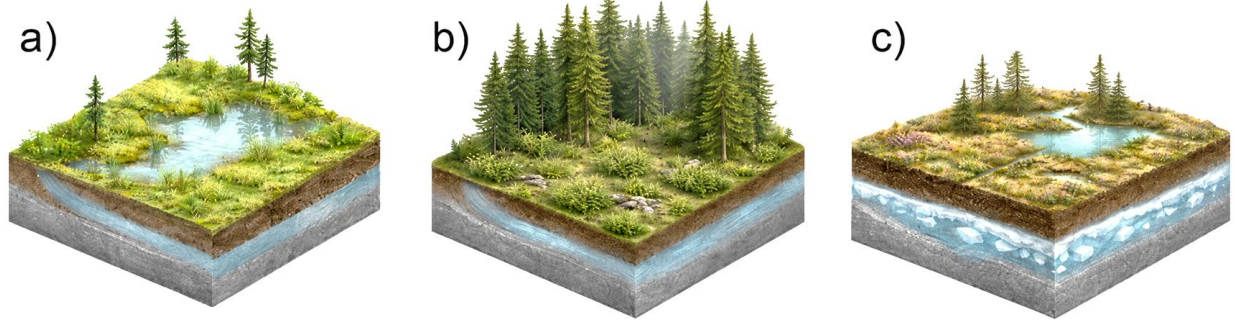


Figure 2-8: Conceptual representations of three hydrological unit types within the RAA including (a) open water, (b) forested, and (c) permafrost-based systems.

Observations at the local (hydrological unit) scale provide the foundation for assessing disturbance impacts. Chapter 4 characterizes the dominant hydrological unit types within the RAA, while Chapter 5 examines how disturbances alter water storage, connectivity, and flowpaths within these units. Placed within their broader watershed and regional context, these local-scale responses can be used to infer system-wide hydrological change. Chapters 6 and 7 then synthesize feedbacks to disturbance and cumulative landscape effects, and identify key data limitations and priorities for future work.



CONCEPT HIGHLIGHT: WATER BALANCE FRAMEWORK AND TERMINOLOGY

1 WATER BALANCE OF A SINGLE HYDROLOGICAL UNIT



A hydrological unit is any portion of the landscape (such as a wetland, peatland, forest, lake, or stream) that stores and moves water in a characteristic way. A water balance describes how all water inputs, storage, and outputs combine within and between these units.

2 WATER BALANCE TERMINOLOGY USED IN THIS REPORT

Term	Definition	Role in the System
P	Precipitation Incoming rain and snow	The primary source of water entering the system; drives seasonal and storm-driven changes in storage
Q	Streamflow Water moving through a river or stream (in from upstream and out to downstream)	Measures the total water delivered downstream; integrates all upstream inputs and storage changes
S _{sw}	Surface Water Storage Water held on the land surface in streams, lakes, wetlands, and ponds	Controls ponding, flooding, and water levels in lakes and wetlands
S _{gw}	Groundwater Storage Water stored below ground in organic (peat) or mineral soil	Indicates wetland wetness, soil moisture, and depth to the water table
L _{in} / L _{out}	Lateral Inflow / Lateral Outflow Water moving across or near the land surface	Determines the degree of surface connectivity between wetlands, peatlands, and streams
G _{in} / G _{out}	Groundwater Inflow / Groundwater Outflow Water moving through subsurface pathways between landscape units	Determines whether subsurface flow supports wetlands, maintains baseflow, or recharges streams
ET	Evapotranspiration Water lost to the air by evaporation and transpiration	The primary pathway by which water returns to the atmosphere; drives seasonal drying across the landscape

★ KEY TAKEAWAY:

A water balance describes how water enters, moves through, and leaves a landscape unit. This framework is used throughout the report to assess how disturbance may affect water availability and streamflow.

3.0 REGIONAL SETTING

As described in Chapter 2, the regional scale is used in hydrological studies to characterize broad climatic patterns, physiographic gradients, drainage organization, and large-scale landscape controls on water movement. These regional characteristics are summarized below to provide context for the hydrological and streamflow analyses that follow. The geography and physiography of the RAA, and consequently its large-scale hydrological dynamics, are strongly controlled by its glacial history. This history has been described in previous regional reports and academic studies and is only summarized here to provide the context needed for the conceptual models developed in this report.^{18–21}

For the purposes of this project, the most important outcome of this glacial history is that the RAA contains a highly variable landscape of bedrock, glacial deposits, glaciolacustrine sediments, marine sediments, wetlands, rivers, and lakes. These features influence how water is stored, transmitted, and routed across the region. In particular, the glacial history of the RAA has resulted in:

- **Northward and northeastward drainage patterns**, with most watersheds draining toward Hudson Bay and James Bay, and smaller southern portions draining toward Lake Superior¹⁸
- **Major river systems that organize regional flow**, including the Severn and Winisk Rivers flowing toward Hudson Bay, and the Attawapiskat, Albany, and Moose rivers flowing toward James Bay¹⁸
- **Extensive glaciolacustrine and marine sediments**, which were deposited following deglaciation when parts of the region were inundated by proglacial lakes and marine waters. These low-relief, fine-grained sediments continue to influence present-day drainage, water storage, groundwater movement, wetland development, and surface water connectivity^{18–20,22}
- **Strong spatial variability in subsurface materials**, because glacial and glaciolacustrine deposits vary in thickness, texture, and distribution across the region²³
- **Ongoing isostatic rebound and differential uplift**, which have shaped regional topography, drainage gradients, and the relative position of headwater and lowland areas^{21,24–27}

These post-glacial processes established strong regional gradients in several key controls on hydrological processes across the RAA. In general, elevation, slope, and substrate conditions change from southwest to northeast along what is commonly referred to as the Shield-coast gradient. Climatic controls on water storage, infiltration, and hydrological connectivity also change from south to north along the latitudinal gradient. Together, these two gradients provide a simplified way to describe how regional landscape position influences hydrological processes across the RAA.

3.1 Shield-Coast Gradient: How Elevation, Slope, and Substrate Shape Regional Drainage

The Shield-coast gradient represents a primary control on hydrology within the RAA, influencing water availability, connectivity, and flowpaths across the landscape. Transitions in elevation, substrate, and drainage structure along this gradient result in distinct ecological and hydrological regimes,^{26,28,29} as reflected in differences in streamflow generation and routing from headwaters to coastal systems. Under the Ontario Ecological Land Classification system, the Shield-coast gradient is reflected in the transition between two primary ecozones within the RAA (Figure 3-1): the Precambrian Shield to the south and west, which is generally higher in elevation (150–450 m asl), and the Hudson Plains to the northeast, which is lower-lying and closer to Hudson Bay and James Bay (60–120 m asl).^{18,30} These ecozones are separated by a distinct physiographic boundary that corresponds to the contact between Precambrian Shield bedrock and overlying sedimentary limestone deposits.

The nature of this transition varies spatially. In some areas, it is abrupt, marked by rapids and waterfalls, while in other areas it is more gradual, with an intermediate region known as the Clay Belt or Intermediate Plains occurring between the two ecozones.³¹ While the two smaller watersheds in the RAA that drain toward Lake Superior are confined to the Shield, all major river systems flowing to Hudson Bay and James Bay originate on the Shield and terminate in the Plains.¹⁸



Figure 3-1: Ecozones and Ecoregions in the RAA. Data Source: Ontario Ministry of Natural Resources (MNR), Ecological Land Classification (ELC) – Ecozones, Ecoregions, and Ecodistricts. Note: The Intermediate Plains are not shown as a distinct mapped zone, as their spatial boundaries are not formally defined.

3.1.1 Precambrian Shield

The Precambrian Shield forms the upland headwaters of all major river systems within the RAA. The landscape is generally characterized by variable topography, with exposed bedrock, thin overburden, and relatively well-drained tills.^{19,32} Compared to downstream regions, land cover is more strongly dominated by boreal forest,³³ with wetland cover typically densely treed,³⁴ or otherwise confined to depressions such as rock basins and infilled post-glacial lakes.¹⁸

This terrain supports a dense network of small streams, lakes, and channelized watercourses, with frequent rapids and waterfalls associated with abrupt changes in relief,^{18,35} resulting in smaller catchment areas compared to the flat expanse of the Hudson Plains.²⁸

3.1.2 Hudson Plains

In contrast, the Hudson Plains are characterized by extremely low relief and poorly drained terrain, underlain by flat sedimentary bedrock and thick deposits of fine-grained glaciolacustrine and marine sediments,^{19,30,36} which are highly spatially *heterogeneous* both in thickness and in composition.³⁷

The detailed hydrophysical characterization of these sediments remains a significant research gap in the RAA. Generally, these sediments have low permeability, and, combined with the minimal topographic gradients available to drive flow, water movement is constrained across the landscape. As a result, drainage density is low, and water is frequently stored and transmitted through extensive peatland complexes rather than well-defined channel networks.^{31,38} River systems are less dendritic and more parallel,^{38,39} and lakes are less common than in the Shield.³⁵ Where channels are present, larger rivers are often incised into underlying mineral sediments, while smaller systems may remain confined within organic peat layers (Figure 3-2).^{19,36,39}

The five major rivers in this region as well as their tributaries are often cut tens of metres deep through this mineral clay/till, which influences their geochemistry.¹⁸ Smaller rivers that originate within the Plains are generally confined within the organic peat soils, though some cut deeper into the marine sediment layer, and others even reach the bedrock or glacial drift below.¹⁹ Near the coast, flowpaths and flow patterns are also highly influenced by ice jamming, which causes preferential erosion that shapes channel development over time.^{21,38}

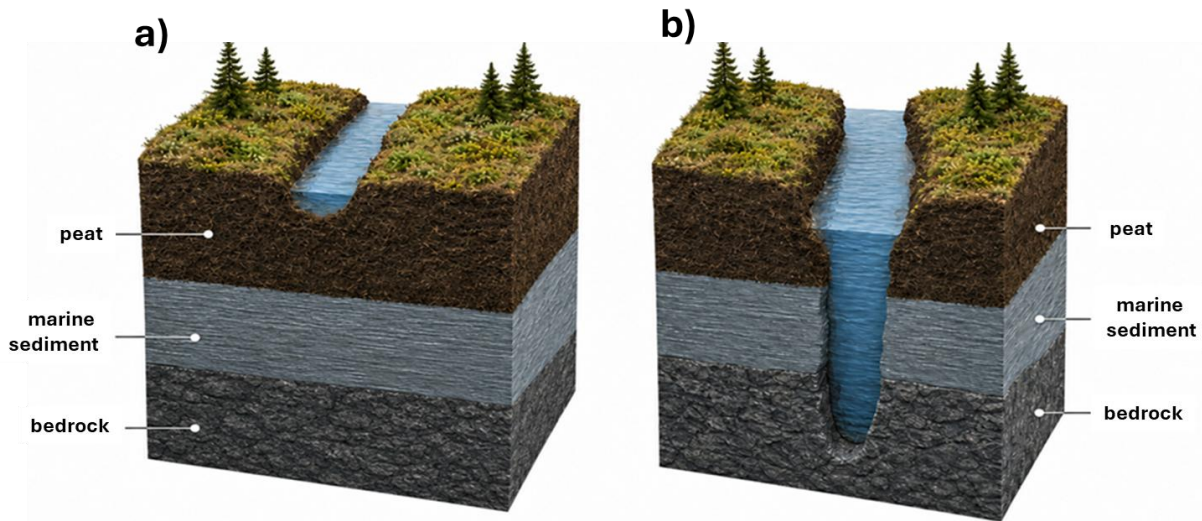


Figure 3-2: Smaller tributaries in the Hudson Plains are often (a) shallow with an organic peat bottom, while larger rivers (b) cut deep through the marine/lacustrine clay and into the bedrock below.

3.1.3 Intermediate Plains/Clay Belt

The Intermediate Plains, or Clay Belt, is a transitional zone without clearly defined spatial boundaries between the Shield and Hudson Plains, combining elements of both landscapes. This region includes both bedrock-controlled terrain and low-relief areas underlain by fine-grained lacustrine sediments associated with former glacial lakes.^{30,31} Hydrologically, this transitional character results in mixed behaviour, with both channelized flowpaths and areas of increased water storage. Features such as in-line lake systems, interspersed with zones of higher relief and localized rapids, reflect this transitional structure. As a result, connectivity patterns are more complex and variable than in either the Precambrian Shield or the Hudson Plains alone. Recent work has identified more extensive peatland development within portions of the Intermediate Plains than previously recognized, indicating that localized storage and connectivity processes may be more important than historically assumed.⁴⁰

3.2 Latitudinal Gradient: How Solar Input and the Hudson Bay Influence Shape Climate and Hydrology

The latitudinal gradient within the RAA exerts a strong control on climate and hydrology, primarily through decreasing solar input and increasing influence of Hudson Bay toward the north. Lower solar angles reduce surface energy inputs,^{26,29} while onshore winds from Hudson Bay further suppress air temperatures, particularly where sea ice persists.^{34,41}

As a result, mean annual air and ground temperatures decrease from south to north, corresponding with increasing permafrost extent. Permafrost, defined as ground remaining below 0°C for two or more consecutive years, varies from absent in southern regions to continuous in

northern coastal areas, with substantial local variability driven by vegetation, soil properties, and microclimate.⁴²

Permafrost exerts a strong influence on hydrology by storing water as ground ice and altering the amount of subsurface storage available for liquid water. Because frozen ground acts as a barrier to infiltration, water is often unable to move vertically into deeper soil or groundwater systems. Instead, water tends to move laterally through the shallow unfrozen soil above the permafrost, creating more surface-dominated flowpaths and stronger connections between saturated soils, wetlands, ponds, and streams.^{43,44}

This also makes permafrost-influenced systems highly sensitive to seasonal thaw dynamics. As the active layer (the seasonally non-frozen layer) thickens during the warm season, the amount of unfrozen soil available for water storage and lateral movement increases. In contrast, when the active layer is shallow or frozen, storage capacity is reduced and water is more likely to remain near the surface or move rapidly downslope. Changes in the timing, depth, or extent of seasonal thaw can therefore alter runoff generation, wetland connectivity, groundwater recharge, and the timing and magnitude of flows to downstream rivers and lakes.⁴⁵⁻⁴⁸ Variation in air temperature and permafrost extent broadly correspond to ecoregions, which are a sub-division of ecozones (Figure 3-1; Table 3-1).

Table 3-1: Historical permafrost presence, air temperature and growing season length across the ecozones and ecoregions of the RAA.^{30,42,49}

Ecozone	Ecoregion	Historical Permafrost Presence	Historical Mean Annual Air Temperature (°C)	Historical Mean Annual Ground Temperature (°C)	Growing Season length (days)
Hudson Plains	Coastal Hudson Bay Lowland	Continuous (90-100%)	<-8	<-5	<65
	Hudson Bay Lowland	Discontinuous (50-90%)	-6 to -8	-5 to -2	138-157
	James Bay Lowlands	Sporadic (10-50%) to absent (0%)	<-2	-3 to 1	154-173
Precambrian Shield	Big Trout Lake	Sporadic (10-50%) to absent (0%)	<1	-4 to 0	147-170
	Abitibi Plains	absent (0%)	>1	-1 to 3	167-185
	Lake Nipigon	absent (0%)	>1	-2 to 2	161-182
	Lake St. Joseph	absent (0%)	>1		

3.3 Regional Variation in Annual Precipitation

Precipitation represents the primary climatic input to water availability within the RAA and exhibits both spatial and temporal variability. While local variability is high, broader regional patterns reflect the combined influence of large-scale atmospheric circulation and the latitudinal and Shield–Coast gradients.

Spatially, total annual precipitation generally increases from north to south and from inland Shield regions toward the coast, reflecting moisture inputs from Hudson Bay, the Great Lakes, and more southerly air masses (Table 3-2).^{18,34} The proportion of precipitation that falls as snow increases from south to north due to lower temperatures associated with the latitudinal gradient.

Temporally, interannual variability in precipitation is influenced by large-scale climate oscillations, such as the Arctic Oscillation (AO), Pacific Decadal Oscillation (PDO), and El Niño–Southern Oscillation (ENSO).³³ These drivers affect both the magnitude and timing of precipitation inputs, with implications for seasonal water availability and streamflow generation.

Table 3-2: Historical Annual Precipitation and the percentage of precipitation that falls as snow within the Ecozones and Ecoregions of the RAA.¹⁸

Ecozone	Ecoregion	Historical Annual Precipitation (mm)	Historical % Snow
Hudson Plains	Coastal Hudson Bay Lowland	490-614	33-54
	Hudson Bay Lowland	490-614	33-54
	James Bay Lowlands	528-833	27-54
Precambrian Shield	Big Trout Lake	550-786	28-54
	Abitibi Plains	652-1029	21-45
	Lake Nipigon	654-879	26-46
	Lake St. Joseph	613-787	31-49

3.4 Temporal Variation

While spatial patterns in precipitation and climate provide baseline controls on water availability within the RAA, hydrological processes are also strongly influenced by temporal variability. Seasonal and interannual fluctuations in temperature and precipitation govern the timing, magnitude, and pathways of water movement across the landscape and within river systems.

Hydrological processes within the RAA are strongly seasonal, driven by shifts in both precipitation inputs and temperature regimes. These seasonal changes influence the state of water across its liquid, solid, and gaseous phases, including surface and subsurface water, snow and ice storage,

and evapotranspiration. As a result, seasonal transitions significantly influence water availability, hydrological connectivity, and streamflow dynamics.

The timing and magnitude of streamflow are closely linked to these seasonal processes. In particular, spring snowmelt represents a major hydrological event, often generating the highest annual flows, while late summer and winter periods are typically characterized by reduced flow and increased water residence times. These seasonal dynamics also influence water quality. Studies indicate that the annual flow cycle is a primary control on river chemistry, with low-flow periods associated with higher concentrations of compounds such as dissolved organic carbon (DOC), and ions such as calcium derived from marine sediment and bedrock, while spring runoff typically causes dilution of these compounds.⁴⁷

Cree and Ojibway calendars are sometimes divided into five (Ziigwan, Minookimi, Niibin, Dagwaagin, and Biboon) or six (Pipon, Sikwan, Mithoskāmin, Nīpin, and Tākwākin) seasons, reflecting the importance of shoulder-season snow and ice formation and melt. This recognition of transitional seasons is also reflected in the six-season ecological framework, which more closely reflects regional environmental processes, and is commonly used alongside the standard astronomical four-season calendar (winter, spring, summer, and fall) to describe temporal patterns in this region. The six-season framework divides the year into spring (prevernal), blooming earth (vernal), summer (aestival), fall (serotinal), freezing-up (autumnal), and winter (hibernal), each representing approximately two-month intervals.

3.4.1 Spring (Prevernal to Vernal, March–June)

Spring represents a critical transition from frozen to thawed conditions and is the dominant period of hydrological reactivation within the RAA. This period is characterized by rising air temperatures, snowmelt, and the thawing of ground frost, river ice, and surface water bodies. Key hydrological processes during this period are summarized in Figure 3-3.

Both snowpack amount and the timing of melt are extremely important. Rapid (“premature”) melt occurring before ground frost has thawed limits infiltration, promoting increased overland flow, resulting in sharp streamflow peaks and increased flood risk. In contrast, gradual (“over-mature”) melt allows for greater infiltration and groundwater recharge, producing lower peak flows.⁵⁰ This reduced infiltration can limit groundwater recharge, driving water deficits later in the year.¹⁴ Spatial variability in melt timing is also important, with later melt in bogs compared to fens^{14,51} and longer snow persistence in forested areas.^{52,53}

3.4.2 Summer (Aestival, June–August)

Summer represents the period of peak growing season, during which landscape hydrology and streamflow are strongly controlled by the balance of precipitation inputs and atmospheric losses (i.e., evapotranspiration: water loss through evaporation from soil, water bodies, and wet surfaces, and water released from plants).^{14,54} Key hydrological processes during this period are summarized in Figure 3-3.

3.4.3 Fall (Serotinal, August–October)

Fall represents a transition from peak growing season conditions to freeze-up and senescence, marked by the decline of air temperatures below 0°C. Key hydrological processes during this period are summarized in Figure 3-3. Notably, fall response is highly dependent on antecedent summer conditions.^{14,37}

3.4.4 Winter (Autumnal to Hibernial, October–February)

Winter is the least hydrologically active period, with water largely stored as snow and ice, and minimal connectivity across the landscape. Key hydrological processes during this period are summarized in Figure 3-3.

3.4.5 Interannual Variability

Hydrological processes within the RAA exhibit substantial variability over years to decades, driven by fluctuations in climate and precipitation patterns.

Only two long-term study sites could be located, with data collection over a period longer than 10 years: a permafrost-dominated coastal segment of the Hudson Plains near Churchill, Manitoba (~40 years of intermittent studies at various local field sites in the area), and a *patterned* peatland complex in the Hudson Plains ~90 km west of Attawapiskat, Ontario (12 years of continuous record). Long-term observations in both regions demonstrate:

- **Air temperature variability**, with differences of several degrees in annual average temperatures, and up to 15–20°C differences between years, particularly during transitional seasons^{14,48}
- **Precipitation variability**, with total annual rainfall varying by more than twofold and strong dependence on a small number of storm events^{14,48,55}
- **Snow and frost variability**, influencing melt timing, duration, and hydrological response^{14,37,56}
- **Water storage variability**, with multi-year deficits and surpluses influencing subsequent conditions^{14,48,51}
- **Streamflow variability**, with substantial differences in runoff magnitude and timing across years^{57,58}

 **Spring (Prevernal to Vernal, March–June)**



- Snowmelt and thaw increase water availability and connectivity^{36,38}
- River ice break-up, ice jams and flooding occur^{36–37}
- ET increases and may exceed rainfall in late spring³¹
- Peak annual streamflow commonly reached^{32–33,38}
- Lakes, ponds and active layers begin to thaw³⁹
- Recharge of wetland, surface water and groundwater storage^{20,29,31–33,40}
- Sea ice break-up reduces coastal cooling later in spring⁴¹

 **Summer (Aestival, June–August)**



- Peak temperatures cause ET to dominate water losses³¹
- Active layer reaches maximum thaw depth in permafrost areas^{29,31,39,41}
- Water levels in HUs often decline to annual minima and some shallow ponds may dry completely^{38–39,43}
- Lateral connectivity between HUs decreases, reducing delivery of water to streams^{23,32–33}
- Water movement direction may reverse (e.g., from stream to wetland) to fill deficits in landscape storage^{31,33}
- Rainfall events can temporarily reconnect the landscape and raise streamflow^{29,32–34,44}

 **Fall (Serotinal, August–October)**



- cooling temperatures reduce evapotranspiration
- rainfall becomes more effective at replenishing storage
- wetland and groundwater levels recover
- connectivity between hydrological units increases
- a secondary peak in streamflow may occur
- freeze-up begins as snow, ground frost, and sea ice start to form

 **Winter (Autumnal to Hibernial, October–February)**



- Water is stored mainly as snow and ice
- Rivers, lakes, wetlands, and coastal waters progressively freeze³⁶
- Hydrological connectivity is minimal across the landscape^{1,32}
- Subsurface flow is strongly reduced, with limited winter baseflow^{1,32}
- Minimum annual streamflow is commonly reached in late winter^{32–33,40}
- Snow and ice accumulation varies with vegetation and topography^{31,46}

Figure 3-3: Four-season summary of the seasonal hydrological processes in the RAA.



CONCEPT HIGHLIGHT: TIMING MATTERS

1 SEASONAL CHANGE



Spring: snowmelt reconnects wetlands and streams and often brings high flows.

Summer: evapotranspiration is high and water levels may lower.

Fall: conditions depend on how wet or dry the summer was.

Winter: water is stored as snow and ice and flow is usually low.

2 INTERANNUAL CHANGE



Hydrological conditions can differ considerably from one year to the next.

Variations in snowmelt timing, total precipitation, temperature, and storm patterns mean that no two years are alike.

3 WHY IT MATTERS



The same disturbance can produce different hydrological effects depending on the season and year in which it occurs.

Assessments and monitoring programs should not rely on data from a single season or year, since conditions can vary greatly over time.



KEY TAKEAWAY:

Water conditions change through the seasons and from year to year. The timing of a disturbance can be just as important as its location in determining what impacts follow.

4.0 MAJOR WATERSHEDS

Remotely sensed (i.e., satellite-derived) land cover classification data can be used to approximate hydrological unit types within the RAA. The Far North Land Cover dataset provides a regionally appropriate representation of surface conditions across the RAA. Its regional coverage makes it well suited for defining hydrological units and scaling process-based understanding across the landscape.

This dataset classifies the landscape into 24 land cover categories, which can be grouped into eight hydrologically distinct units: four wetland types (bog, fen, swamp, and marsh), open water, forest, exposed bedrock, and disturbed/unclassified. While variability exists within each category, hydrological behaviour is generally more similar within these groupings than between them. Note that while disturbance is included as a land cover class, it reflects landscape alteration rather than a true hydrological unit and is addressed in more detail in Chapter 6.

The eight major hydrological units and their defining characteristics are as follows:

- **Bogs:** open or treed precipitation-fed systems with high water storage and threshold-based lateral connectivity
- **Fens:** open or treed groundwater-influenced systems with threshold-based lateral connectivity and more sustained lateral flow than bogs
- **Swamps:** forested wetlands with variable storage and connectivity, often acting as transitional units
- **Marshes:** surface water-dominated systems with fluctuating water levels and strong seasonal connectivity
- **Open water:** lakes and rivers that integrate upstream inputs and regulate downstream flow
- **Forests:** upland or better-drained systems that influence infiltration, evapotranspiration, and runoff generation
- **Exposed bedrock/mineral soils:** low-storage areas with rapid runoff and limited subsurface flow
- **Disturbed/unclassified:** areas of altered hydrology due to natural or anthropogenic disturbance, or areas that cannot otherwise be identified

The distribution of these hydrological units varies across the RAA (Figure 4-1). In general, the Precambrian Shield contains a greater proportion of treed units (forest, swamp), while the Hudson Plains are dominated by peatlands (bogs and fens). Open water and exposed bedrock occur in similar proportions across both ecozones, while disturbed/unclassified land cover is more prevalent in the Shield, in part due to development in the southern portion of the region. Of this disturbance, approximately 12% in the Shield and 2% in the Plains are due to wildfire footprints.⁴² Marsh land cover occupies similar proportions of area in the Shield and Plains, occurring primarily as ecosystems bordering rivers and lakes in the Shield and saltwater-to-freshwater transition marshes at the coast in the Plains.

Permafrost is not included in this land cover analysis; however, regional estimates suggest that, over the entire Hudson Plains, ~1% of the land cover is composed of tundra, palsa, and peat plateau.⁴² General permafrost zones provided by the Permafrost Atlas of Canada are shown in Figure 4-2.

Wetlands (bog, fen, swamp, and marsh) comprise a considerable portion of both ecozones (40% and 83% in the Shield and Plains, respectively). Wetland hydrological units are of particular importance, as they are often regarded as a form of “0th” order stream,³⁷ providing water to larger watercourses.

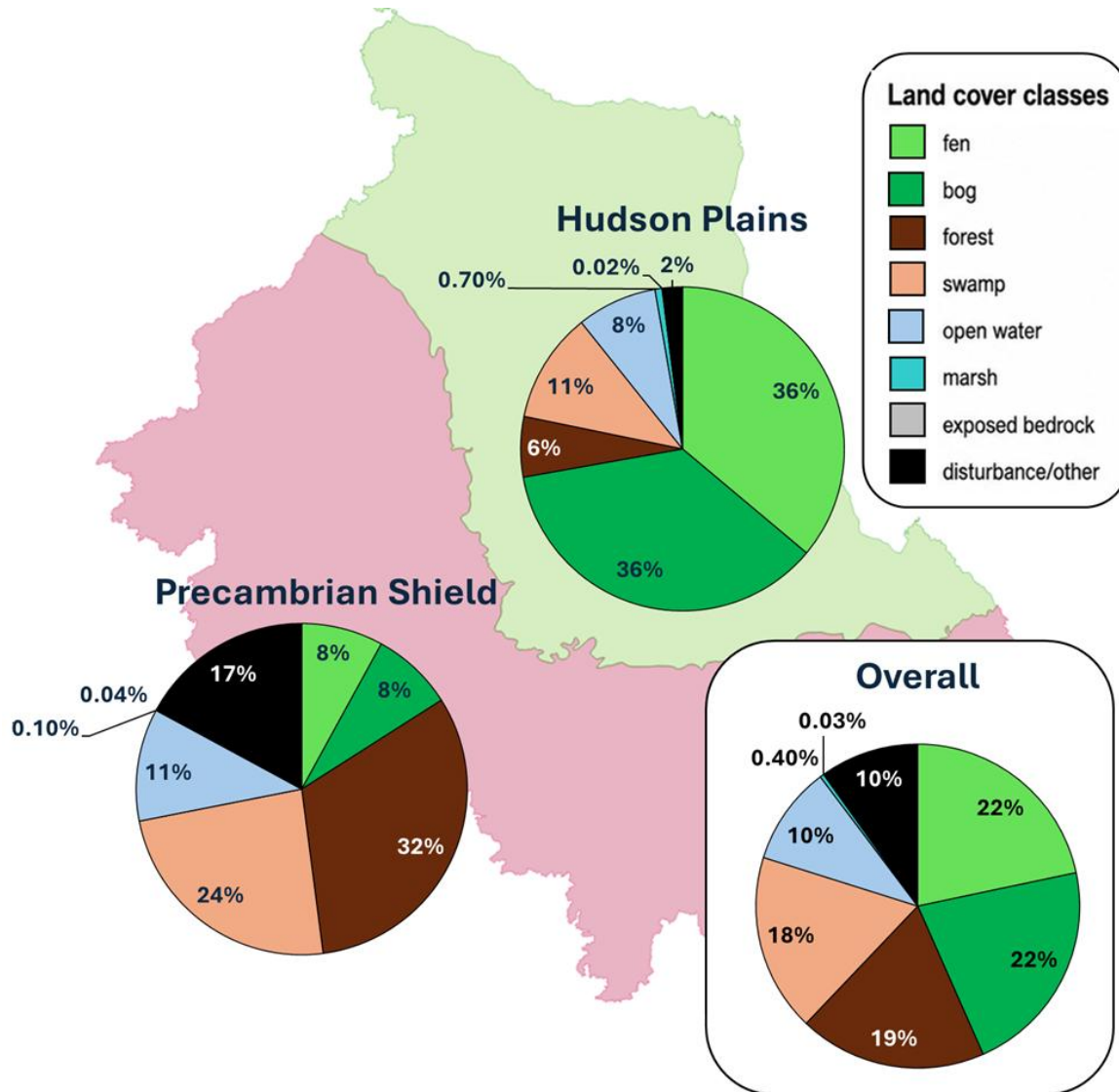


Figure 4-1: Proportions of the eight major hydrological unit within the RAA, shown for each of the Precambrian Shield and Hudson Plains ecozones.

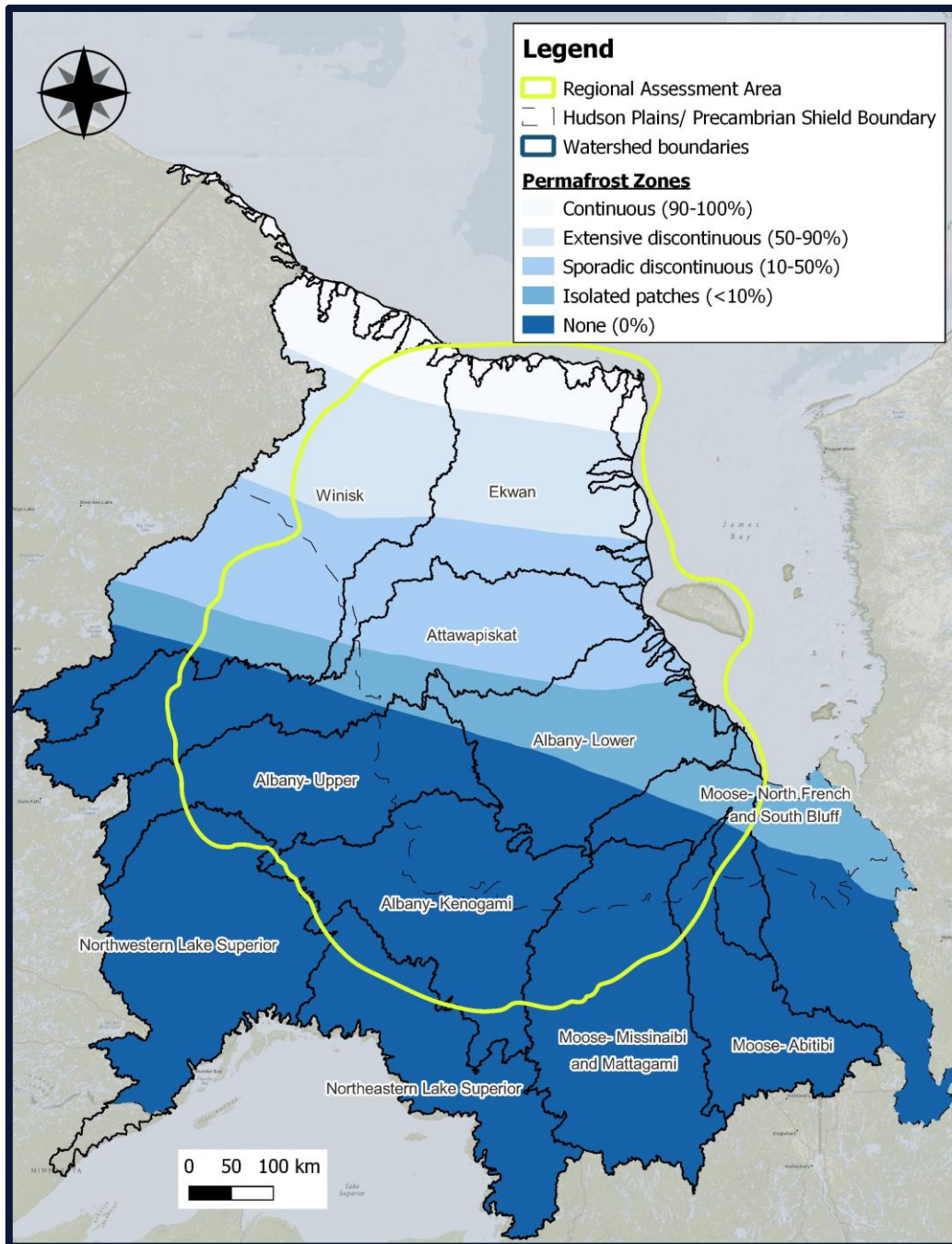


Figure 4-2: Permafrost zones across the RAA, ranging from continuous in the north to isolated patches and absent in the south, as defined by the Permafrost Atlas of Canada.

The following subsections summarize the distribution of these hydrological units within the six major watersheds of the RAA. Chapter 5 then describes the hydrological processes defining water balance components of each hydrological unit.

CONCEPT HIGHLIGHT: LAND COVER HELPS IDENTIFY HYDROLOGICAL UNITS

1 MAPPED LAND COVER

2 COMMUNITY IMPORTANCE

Wetland (especially muskeg) condition
Shows where water may be ponded, stored, or lost to drying.

Downstream connections
Shows how changes in wetlands can travel to downstream waters.

Fish, wildlife, and plant habitat
Shows which areas are important for fish and wildlife habitat and plant communities, including medicinal plants.

Travel access and water quality
Shows where runoff, sediment, or changing water levels may affect travel, crossings, or downstream waters.

Satellite-derived land cover maps broad surface conditions across the RAA.

Knowing where different land covers occur helps communities track changes in wetland (especially muskeg) condition, fish and wildlife habitat, plant communities, and travel access to downstream waters.

★ KEY TAKEAWAY:
Land cover helps identify where wetlands (especially muskeg), forests, lakes, and rivers may store and move water differently. These differences can affect downstream water, travel access, fish and wildlife habitat, plant communities, and areas communities rely on.

4.1 The Winisk River Watershed

The Winisk River is the 18th largest river draining into Hudson and James Bay, contributing approximately 2% of total discharge.⁵⁷ Approximately 55% of the ~55,000 km² watershed lies within the RAA. The river originates on the Precambrian Shield and flows northeast into the Hudson Plains, with major tributaries including the Pipestone, Asheweig, Shamattawa, and Mishamattawa rivers.¹⁸

Limited information is available describing hydrological processes within the watershed; however, the Far North Land Cover provides insight into the distribution of hydrological units (Figure 4-3 and 4-4). The Shield portion of the watershed is dominated by conifer forested and swamp hydrological units, with substantial open water coverage associated with lake-rich terrain. In contrast, the Hudson Plains portion is dominated by bog and fen muskeg. Bog cover within the Plains is primarily associated with both treed and open peat plateau systems,²⁹ indicating strong permafrost influence on storage and connectivity. Small, localized sand and gravel aquifers are also present, estimated to comprise approximately 5% of the watershed area,¹⁸ suggesting potential zones of enhanced groundwater flow. Permafrost cover, according to the Canadian Permafrost Atlas, is continuous to the north, decreasing to absent in the far south of the watershed, with watershed-wide estimates ranging from 30–70%,⁵⁹ though this is likely lower present day due to climate change.

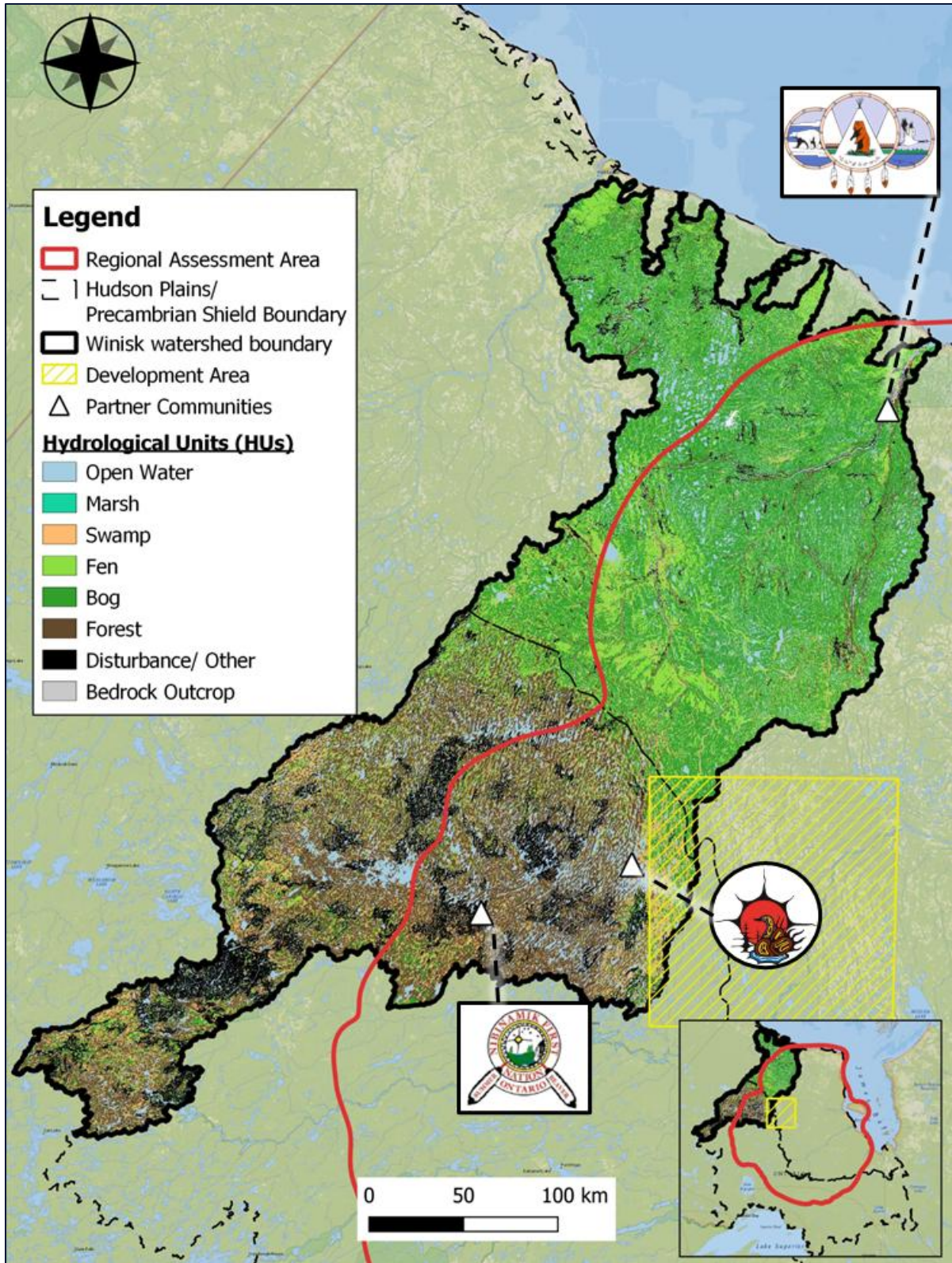


Figure 4-3: Hydrological units in the Winisk River watershed. Data Source: Ontario Ministry of Natural Resources (MNR). Far North Land Cover Data Specifications Version 1.4.

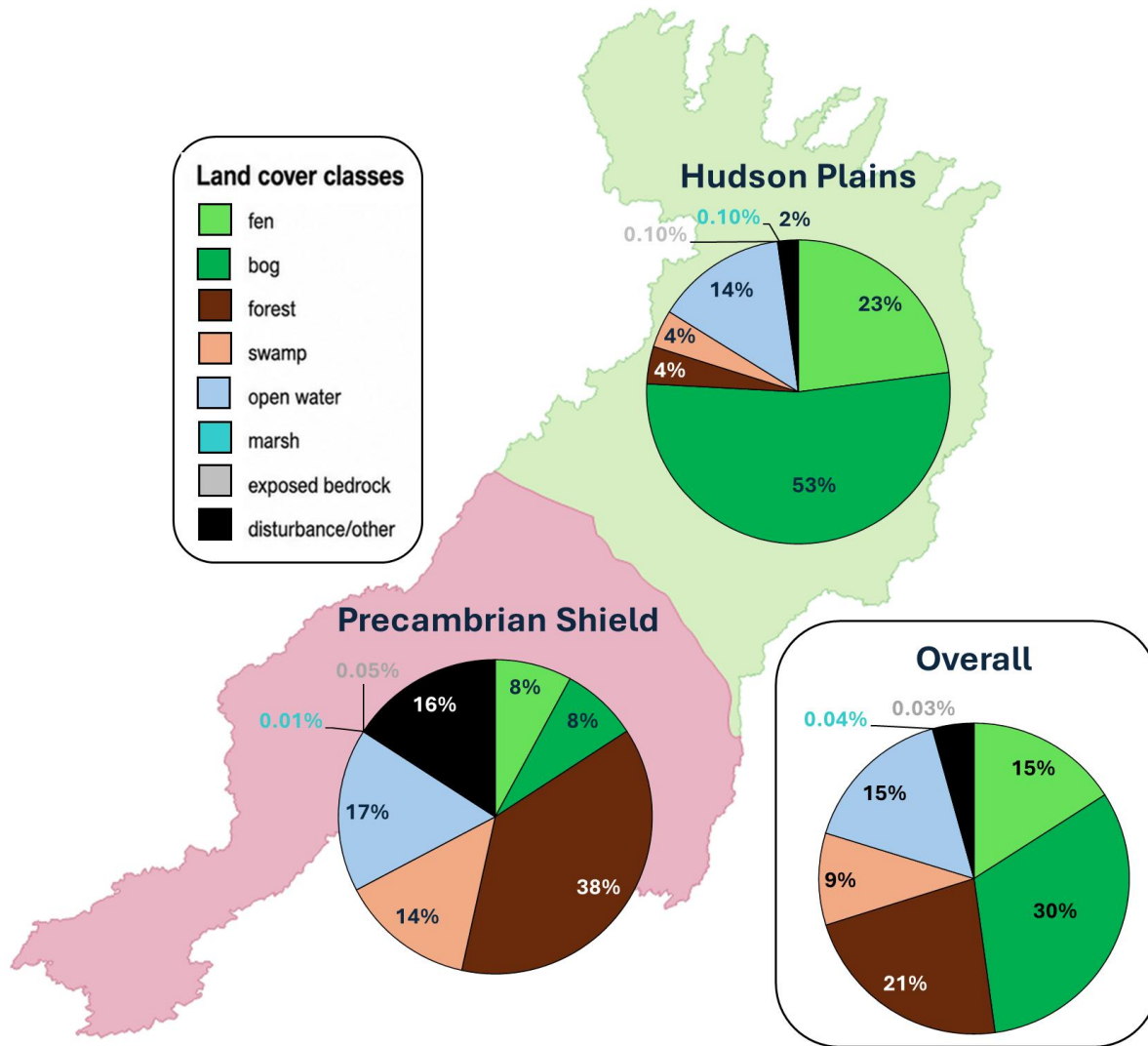


Figure 4-4: Hydrological unit distribution in the Precambrian Shield and Hudson Plains ecozones of the Winisk River watershed.

4.2 The Ekwan River Watershed

The Ekwan River is the 33rd largest river draining into Hudson and James Bay, contributing approximately 0.5% of total discharge.⁵⁷ The entire watershed lies within the RAA, and over 95% of it is located within the Hudson Plains.

Very limited information summarizing the major water features and representative hydrological processes of the Ekwan River watershed exists. The distribution of hydrological units according to the Far North Land Cover reflects the large proportion of the watershed that is within the Plains, where the flat landscape promotes peatland development (Figure 4-5 and 4-6). The landscape is primarily dominated by bog and fen muskeg, with smaller contributions from swamp and open water. Forest hydrological units are limited and largely confined to the small Shield-influenced

portion of the watershed. Bog cover is extensive and occurs in both treed and open peat plateau forms,²⁹ indicating that permafrost influences water storage and connectivity there. Permafrost cover, according to the Canadian Permafrost Atlas, is continuous to the north and decreases to isolated patches in the far south of the watershed, with watershed-wide estimates ranging from 40–80%,⁵⁹ though this is likely lower present day due to climate change. Open water features have been reported as typically shallow and associated with glacially derived ponds and lakes⁶⁰. Saltwater-to-freshwater marshes are locally significant near (< 5 km from) the coast.

This hydrological unit distribution reflects a hydrological system characterized by low relief, limited channel development, and strong dependence on peatland connectivity for water movement. As a result, streamflow is likely more attenuated and controlled by threshold-driven connectivity compared to more channelized Shield systems.

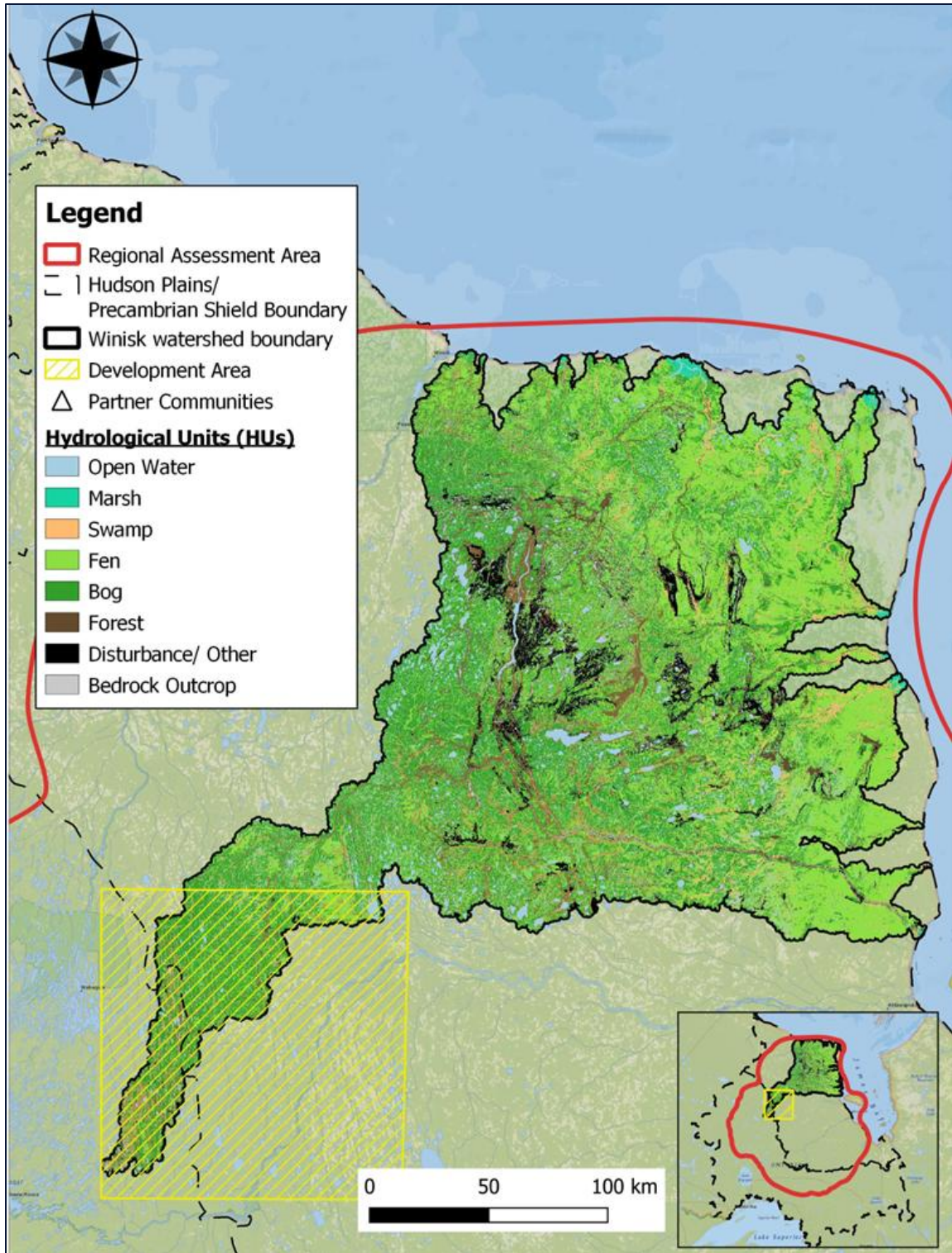


Figure 4-5: Hydrological units in the Ekwan River watershed. Data Source: Ontario Ministry of Natural Resources (MNR). Far North Land Cover Data Specifications Version 1.

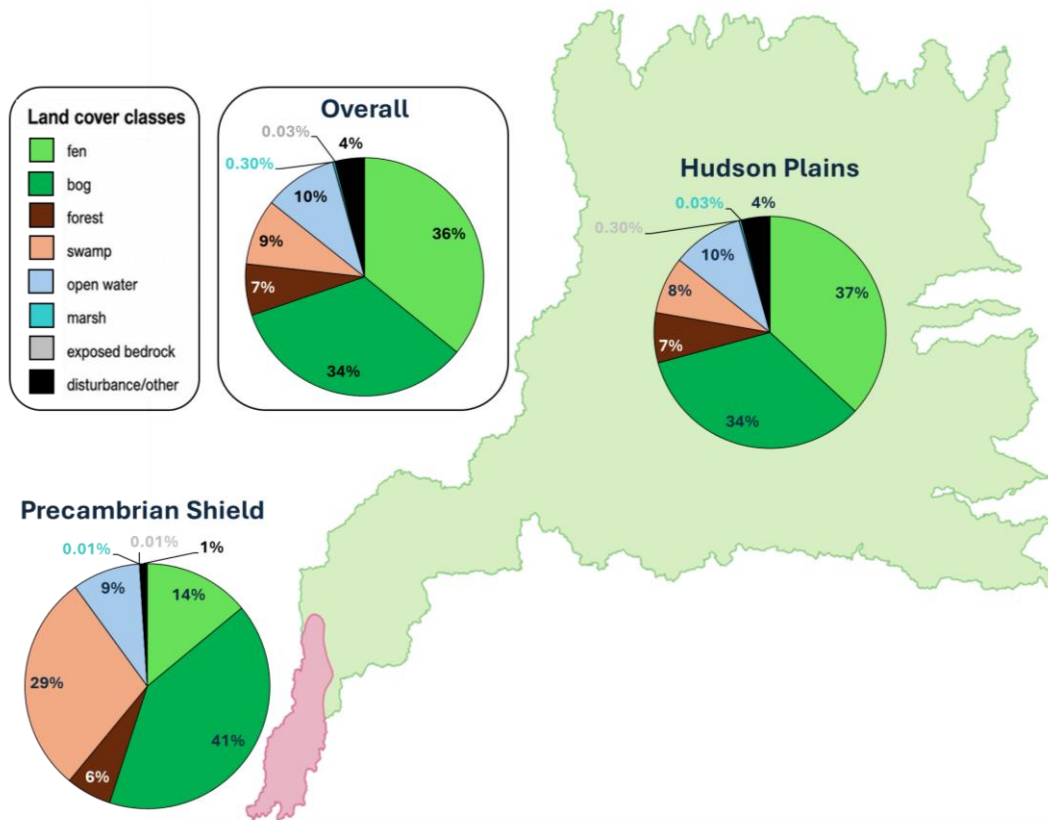


Figure 4-6: Summary of hydrological unit distribution in the Precambrian Shield and Hudson Plains ecozones of the Ekwan River watershed.

4.3 The Attawapiskat River Watershed

The Attawapiskat River is the 21st largest river draining into Hudson and James Bay, contributing approximately 1.6% of total discharge.⁵⁷ Approximately 80% of the watershed lies within the RAA. The river originates on the Shield and flows northeast across the Plains to the coast, with major tributaries including the Otokwin, Pineumuta, Muketei, Nayshkootayaow, and Missisa rivers.^{18,63}

According to the Far North Land Cover (Figure 4-7 and 4-8), the Shield portion of the watershed is dominated by forest, swamp, and bog hydrological units, while the Plains portion is dominated by bog and fen muskeg and open water. Peatland systems in the Plains are often *patterned*, with increasing presence of treed bogs and fens toward the south.²⁹ Localized permafrost features, including palsas and peat plateaus, are present in the northern portion of the watershed, though they occupy a relatively small proportion of the total area (~3–5% near the Victor Mine, 90 km west of Attawapiskat).⁶⁴ Permafrost cover, according to the Canadian Permafrost Atlas, is sporadic discontinuous to the north decreasing to absent in the southwestern half, with watershed-wide estimates ranging from 5–35%,⁵⁹ though this is likely lower present day due to

climate change. Saltwater and freshwater marshes are locally significant near (< 5 km from) the coast.^{61,62}

Limited process-based studies provide insight into hydrological processes within the watershed. Observations from a single study indicate that lateral inflow represents a consistent contribution to streamflow (~50–60%), while groundwater contributions increase with stream order and are proportionally greater during dry periods.⁶³ In contrast, rainfall contributions are disproportionately important during wet periods, and preferential flowpaths likely play a role in rapidly transmitting water through the landscape. Bedrock outcrops (bioherms) and karstic features have been identified within the watershed as preferential conveyors of water, though studies are limited.^{22,23,65}

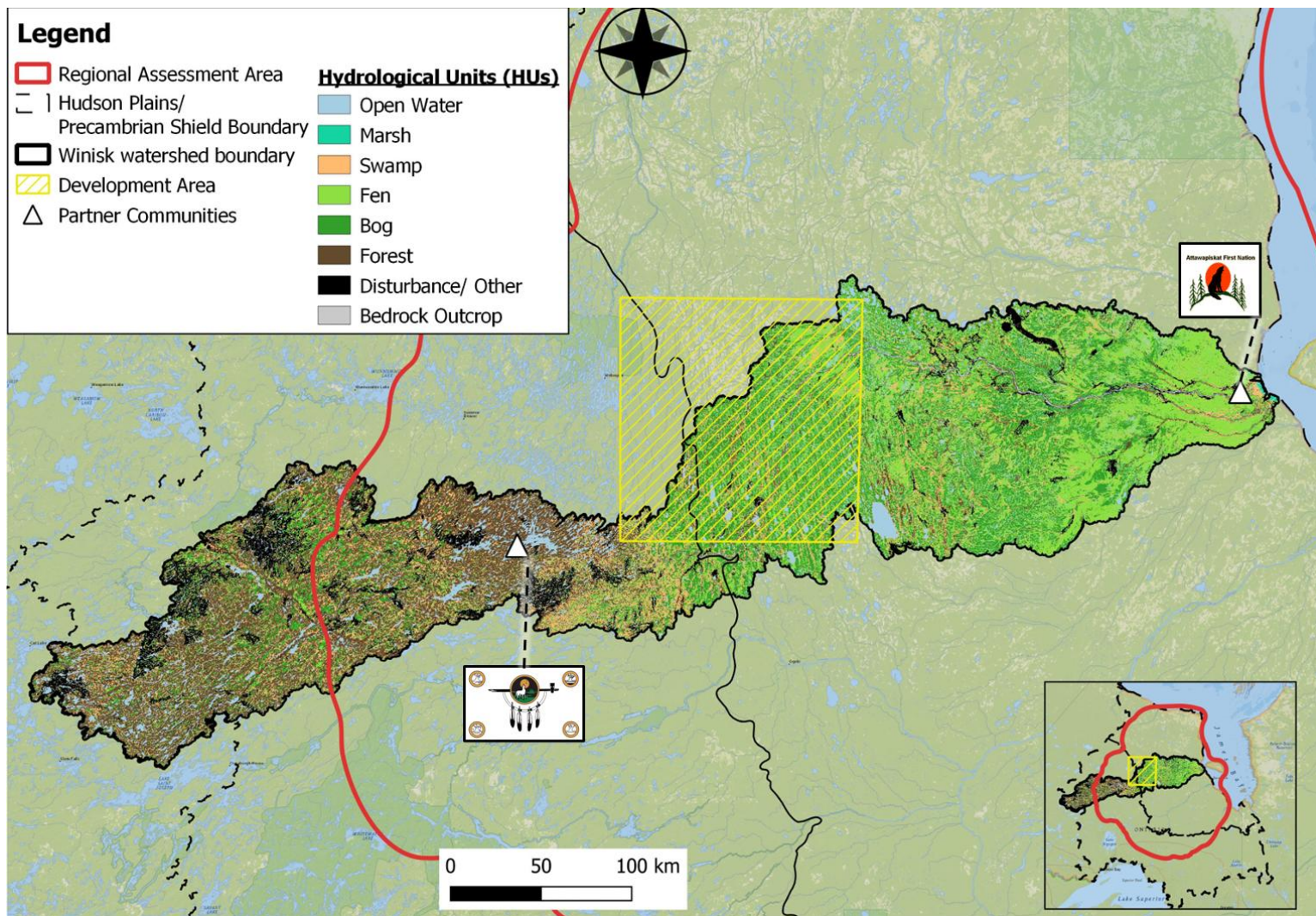


Figure 4-7: Hydrological units in the Attawapiskat River watershed. Data Source: Ministry of Natural Resources (MNR). Far North Land Cover Data Specifications Version 1.4

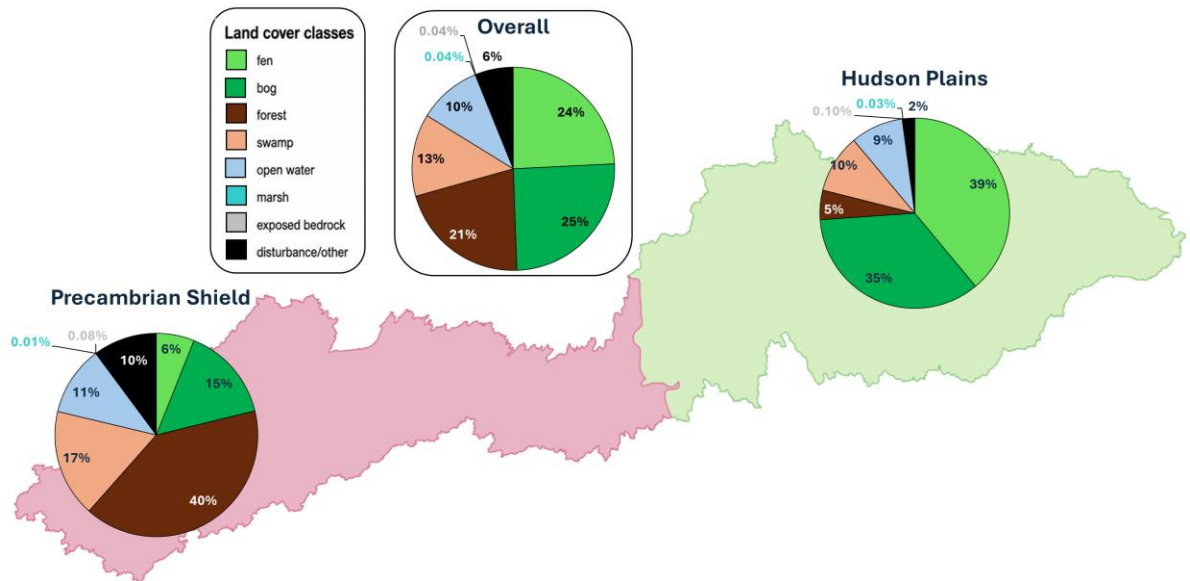


Figure 4-8: Summary of hydrological unit distribution in the Precambrian Shield and Hudson Plains ecozones of the Attawapiskat River watershed.

4.4 The Albany River Watershed

The Albany River is the 8th largest river draining into Hudson and James Bay, contributing approximately 5.4% of total discharge, with a disproportionately high contribution during early spring due to its more southerly location and therefore earlier freshet.⁵⁷ It is the largest watershed in Ontario,⁶⁶ ~90% of which lies within the RAA, across both the Precambrian Shield and Hudson Plains. Major tributaries include the Kenogami, Kabinakagami, Chipie, and Stopping rivers.¹⁸

The Shield portion is dominated by forest, swamp, and open water hydrological units, while the Plains portion is dominated by bog, fen, and swamp muskeg (Figure 4-9 and 4-10). The Plains region is transitional between northern *patterned* peatlands and more southerly treed peatlands and swamps, reflecting gradients in vegetation, drainage, and permafrost influence.^{29,31,39} A large bog–fen complex separates the Albany from the Moose watershed to the south, further emphasizing the importance of peatland storage in this region.²⁹ Saltwater-to-freshwater marshes are locally significant near (< 5 km from) the coast.^{61,62} Permafrost cover, according to the Canadian Permafrost Atlas, is sporadic discontinuous to the north, decreasing to absent to the southwest, with watershed wide estimates ranging from 1–20%,⁵⁹ though this is likely lower present day due to climate change.

Hydrologically, the watershed is strongly influenced by peatland. In some areas, smaller streams have been observed to disappear into the peatlands and either re-emerge downstream or lose clearly defined flowpaths.³⁹

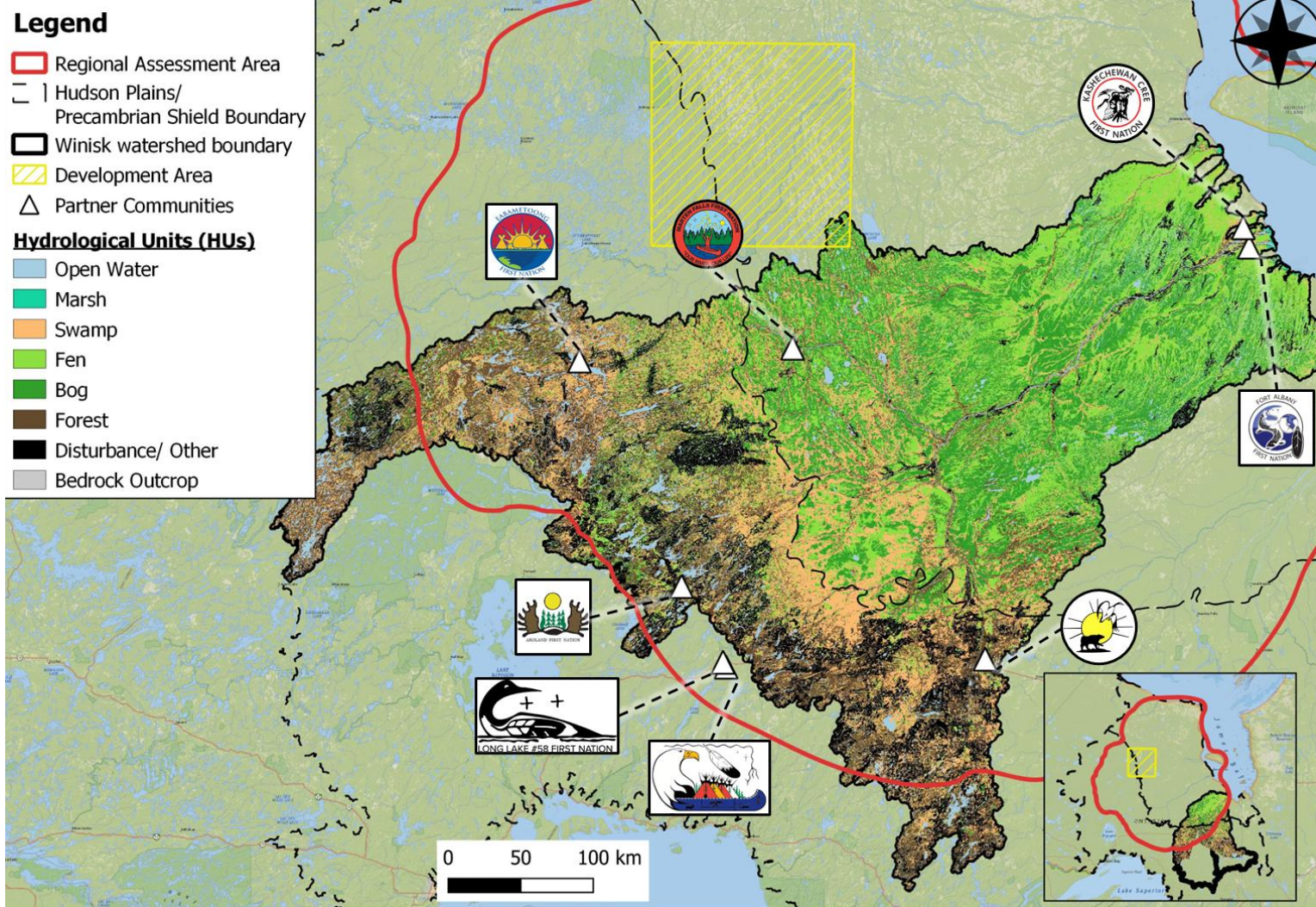


Figure 4-9: Hydrological units in the Albany River watershed. Data Source: Ontario Ministry of Natural Resources (MNR). Far North Land Cover Data Specifications Version 1.4.

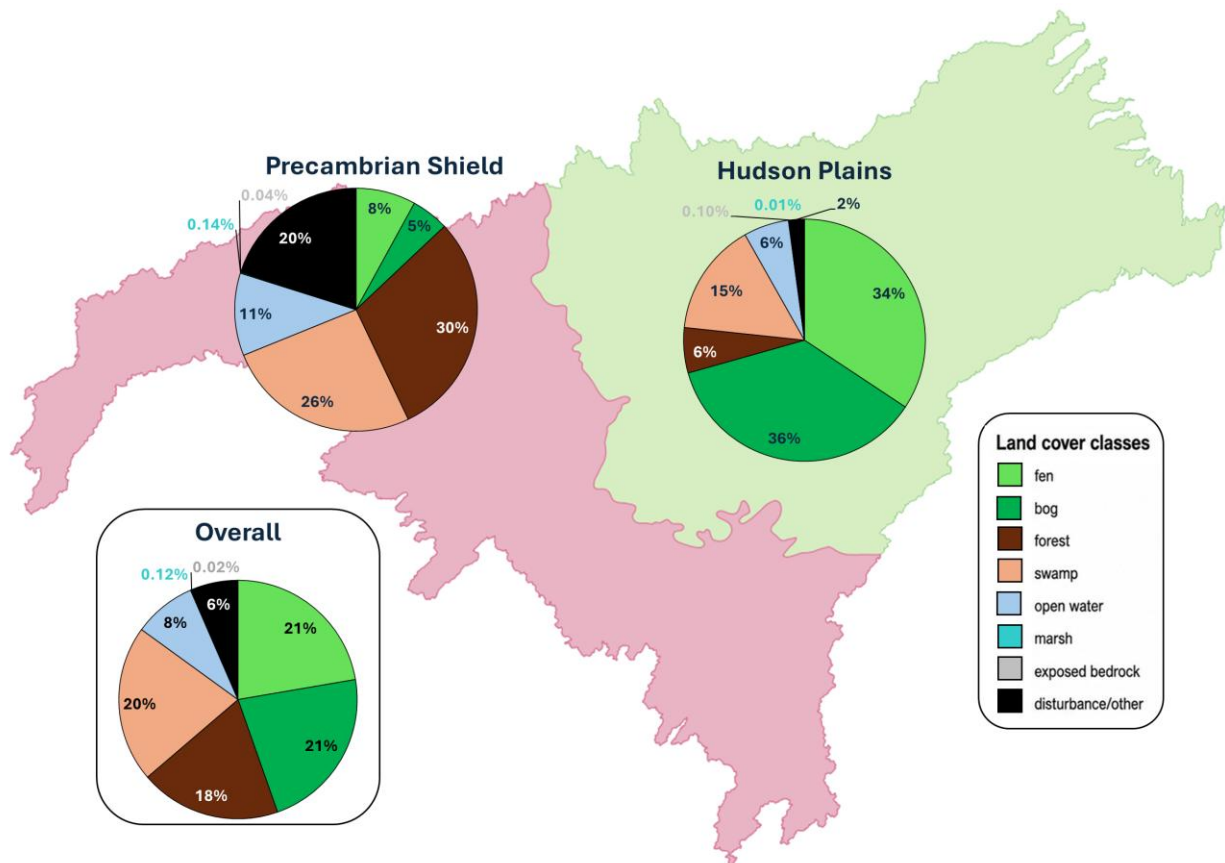


Figure 4-10: Summary of hydrological unit distribution in the Precambrian Shield and Hudson Plains ecozones of the Albany River watershed.

4.5 The Moose River Watershed

The Moose River is the 5th largest river draining into Hudson and James Bay, contributing approximately 5.6% of total discharge, with a relatively high contribution during early spring due to its southerly position and therefore earlier freshet.⁵⁷ Approximately 35% of the watershed lies within the RAA, with the majority of this portion located within the Precambrian Shield.

The watershed is composed of three major sub-basins—the Abitibi, Mattagami, and Missinaibi—which each originate on the Shield and flow northeast toward the Hudson Plains.^{18,31} Within the Shield, river systems are typically confined within bedrock and till- controlled channels, often aligned northeast to southwest with glacial flow direction.^{25,67} The transition to the Plains is notably gradual here and therefore often denoted separately as the Intermediate Clay Plains, where glaciolacustrine sediment interfaces with Precambrian bedrock³¹. Major tributaries include Black, Frederick House, Little Abitibi, and North French Rivers in the Abitibi sub-basin, the Groundhog and Kapuskasing rivers in the Mattagami sub-basin, and the Opatatika, Mattawishkwia, and Pivabiska in the Missinaibi sub-basin.^{18,31}

The Far North Land Cover only includes ~60% of the watershed and is therefore biased towards the upper portion of the Shield (Figures 4-11 and 4-12), which is dominated by swamp, forest,

and bog hydrological units, while the Plains portion is characterized by fen, bog, and swamp muskeg, many of which are patterned.^{36,68} Forest hydrological units remain locally important, particularly on better-drained features such as beach ridges near the coast, and in the non-classified land cover in the southern portion of the Shield.^{25,67} Permafrost cover, according to the Canadian Permafrost Atlas, is limited to isolated patches near the coast, and absent for the remainder of the watershed, with watershed-wide estimates from 0–5%,⁵⁹ though this is likely lower present day due to climate change. Localized sand and gravel aquifers are present, comprising approximately 13% of the watershed area,¹⁸ suggesting areas of enhanced groundwater contribution within a predominantly storage-controlled system.

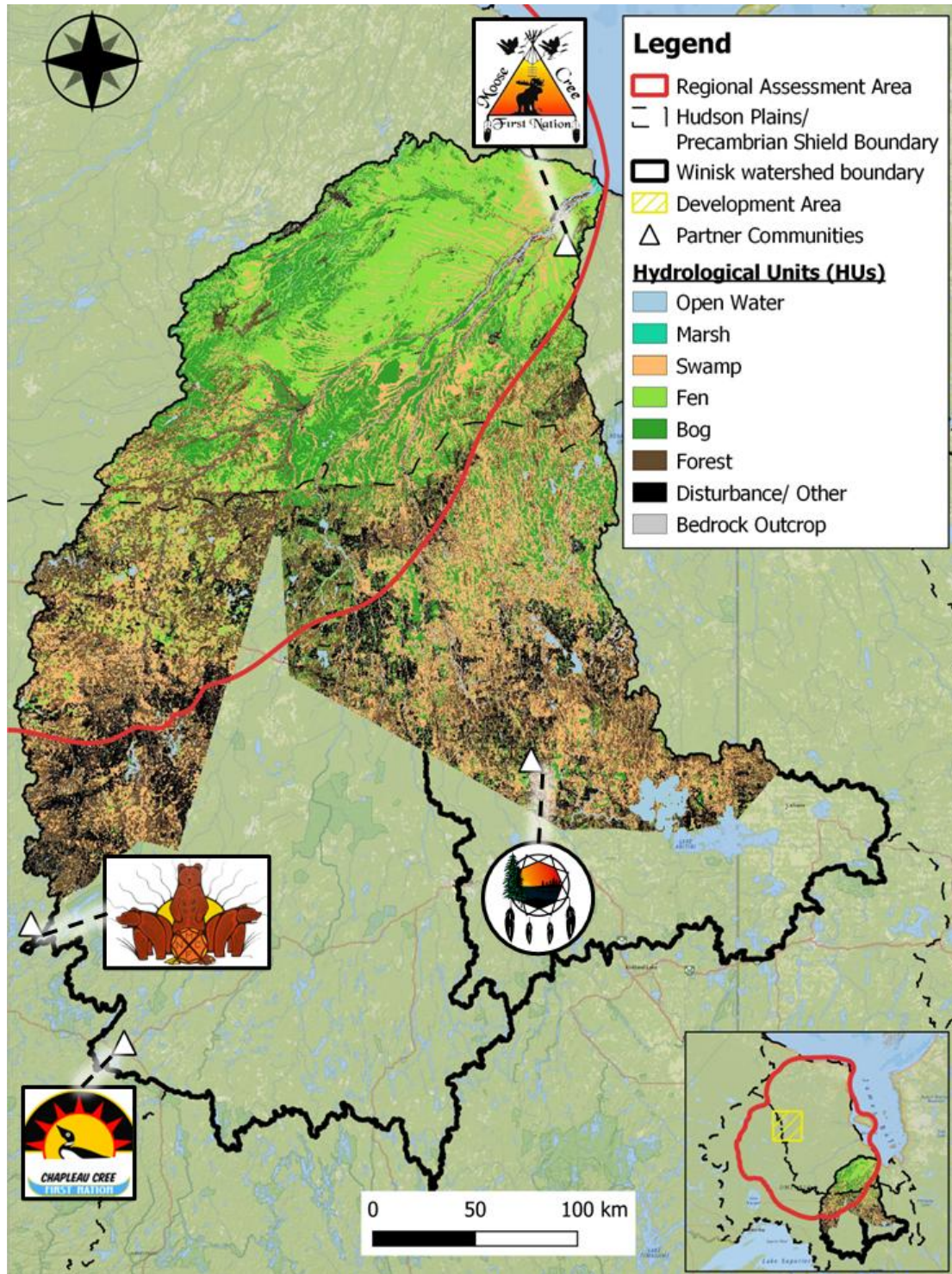


Figure 4-11: Hydrological units in the Moose River watershed. Data Source: Ontario Ministry of Natural Resources (MNR). Far North Land Cover Data Specifications. Version 1.4.

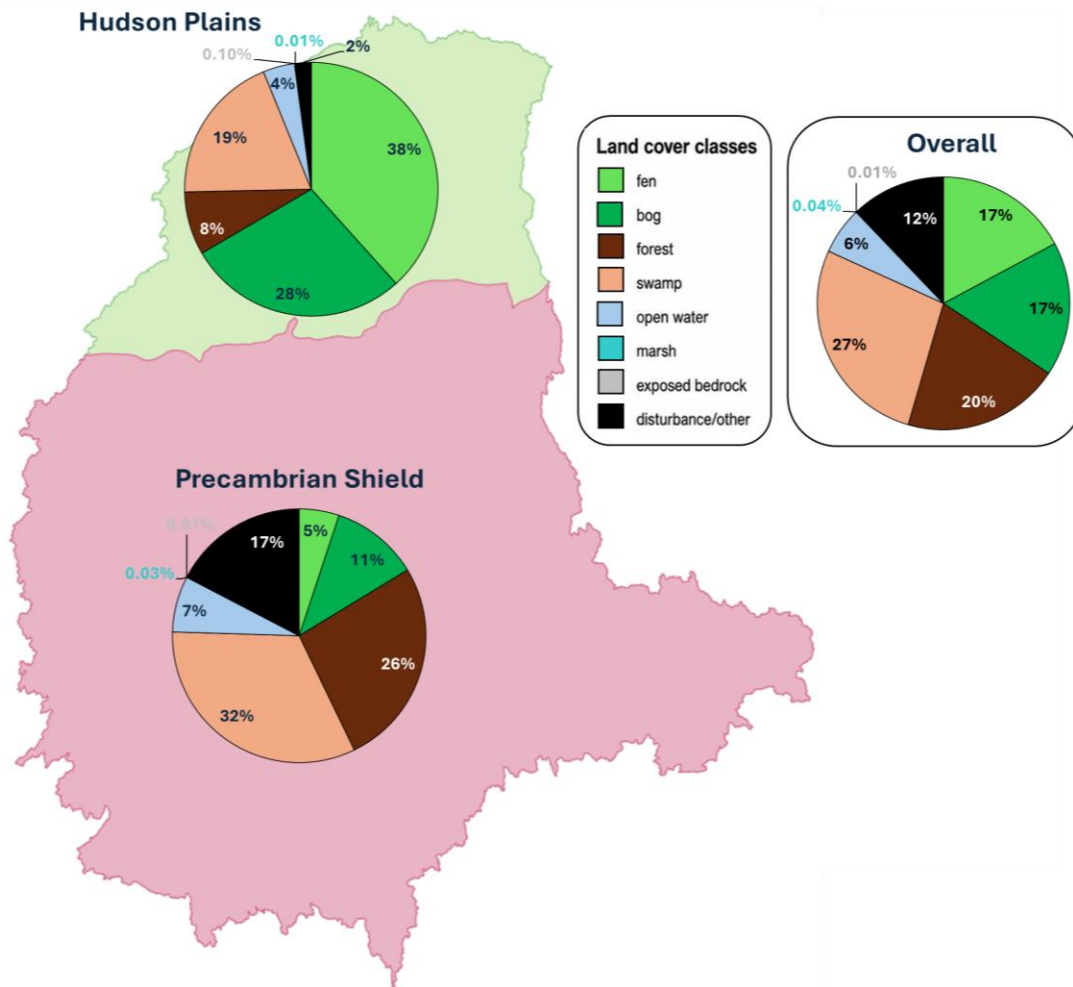


Figure 4-12: Hydrological unit distribution in the northmost 40% of the Moose River watershed, covering the entire Hudson Plains section of the watershed and a portion of the Precambrian Shield transition.

4.6 The Lake Superior Watershed

A small portion of the southwestern RAA drains into Lake Superior through the Northeastern and Northwestern Lake Superior watersheds. In contrast to the Hudson and James Bay watersheds, this region lies entirely within the Precambrian Shield and represents a minor component of the overall drainage area. This area is not covered in the Far North Land Cover and no studies were found regarding the hydrological processes occurring in this area.

5.0 KEY HYDROLOGICAL UNITS OF THE RAA

The previous chapter described the distribution of eight distinct hydrological units across the RAA (bog, fen, swamp, marsh, open water, forest, bedrock, and disturbed/unclassified) and their organization within major watersheds. Building on this spatial framework, this chapter focuses on the hydrological processes that govern water storage, movement, and release within and between these units.

Each hydrological unit exhibits characteristic water balance behaviour, defined by the relative importance of precipitation inputs, evapotranspiration losses, and lateral surface and groundwater exchanges. These processes determine both the availability of water within individual units and the degree of hydrological connectivity across the landscape.

By examining these processes at the hydrological unit scale, this chapter provides a process-based foundation for understanding how water is stored, transferred, and released, ultimately contributing to streamflow within the river systems of the RAA. This framework supports subsequent assessment of how disturbances may alter hydrological function at both local and watershed scales.

It is important to note that this information is based off generally limited numbers of studies often conducted over one or two years on only a handful of sites, sometimes with decades between studies. Therefore, this information should be considered only a starting point rather than a definitive guide to hydrological processes in these systems.

5.1 Wetland Hydrological Units: Bogs

Bog wetlands represent ~22% of the land cover over the RAA. The relative proportion of bog generally decreases from ~30% in the northern half of the RAA to ~20% in the south, with greater proportions in the Plains than in the Shield ecozones (~35% and 8% of land cover, respectively). The functional definition of a bog is an organic (peat-accumulating) wetland with a minimum of 40 cm of organic soils that is only precipitation-fed, with no surface or groundwater inflow.³ Bogs are hydrologically upgradient systems, often forming drainage divides in watersheds, and are characterized by high water storage and threshold-dominated downgradient lateral water movement.^{14,39,51} Key hydrological components are described below and summarized Figure 5-1.

Storage (S_{sw} , S_{gw}): Water storage in bogs is primarily held within peat deposits, which can exceed several metres in thickness.^{39,67} Water tables are typically shallow and perched above the surrounding landscape, resulting in high storage capacity.²⁹ During high water table conditions, bogs generally replenish both shallow and deep groundwater storage³⁷ as well as laterally downgradient hydrological units such as fens and rivers.^{36,51} During lower water table conditions, storage is often retained within the peat profile, limiting the release of water to adjacent systems.

Connectivity (L_{in} , L_{out} , G_{in} , G_{out}): Bogs are generally less connected systems than fens, receiving only water from direct precipitation with no lateral inflows. Lateral outflows are generally limited and occur only under high water table conditions, when storage thresholds are exceeded. As a

result, connectivity between bogs and adjacent hydrological units is episodic and strongly controlled by water table position.

Evapotranspiration (ET): Evapotranspiration represents a major water loss from bog systems during the growing season, often accounting for a large proportion of incoming precipitation.⁵¹ Vegetation composition (e.g., *Sphagnum* mosses and low shrubs) and surface exposure contribute to high evaporation rates relative to more forested systems.

5.1.1 Bog Subtypes

Open Bogs: Open bogs are characterized by sparse or absent tree cover. These systems are typically wetter at the surface than treed bogs and may contain small pools that increase surface water storage.⁴² Open bogs can be patterned or non-patterned, and many well-developed bogs inland have both patterned and non-patterned sections with ladder fens on their sloped edges.³⁹ Compared to non-patterned bogs, patterned bogs can shuttle greater proportions of surface and near-surface lateral outflow due to their open pools, particularly during high water table conditions.

Treed Bogs: Treed bogs occur more frequently toward the Precambrian Shield and in transitional regions, and are characterized by the presence of black spruce (*Picea mariana*) and other conifer species.⁶⁷ Increased canopy cover leads to greater interception and transpiration, and reduced surface evaporation compared to open bogs. These systems are often slightly drier than open bogs, with lower water tables and more limited connectivity.⁴²

Permafrost Bogs (Peat Plateaus/Palsas): Permafrost bogs mainly occur in northern portions of the RAA; however, they have been documented as far south as the Attawapiskat watershed.⁶⁴ They are characterized by slightly elevated, frozen peat surfaces underlain by permafrost.^{72,76} The presence of permafrost limits vertical water movement, restricting active layer storage and lateral connectivity within the top 10–100 cm on average.^{45,75} These systems are typically drier relative to surrounding wetlands and often act as upgradient sources to adjacent fens and thermokarst features.^{29,72}

Palsas are smaller, more localized features than peat plateaus and are generally found in areas towards the southern limit of permafrost accumulation³⁸ or as fragmented peat plateaus.⁴² Like peat plateaus, liquid water storage and both surface/near-surface and groundwater flows only occur within the active layer, often flowing to downgradient non-permafrost fens through shallow lateral flow.^{72,73}

BOG MUSKEG HYDROLOGICAL UNIT

Organic (peat-accumulating) wetlands fed only by precipitation, with no surface or groundwater inflow.

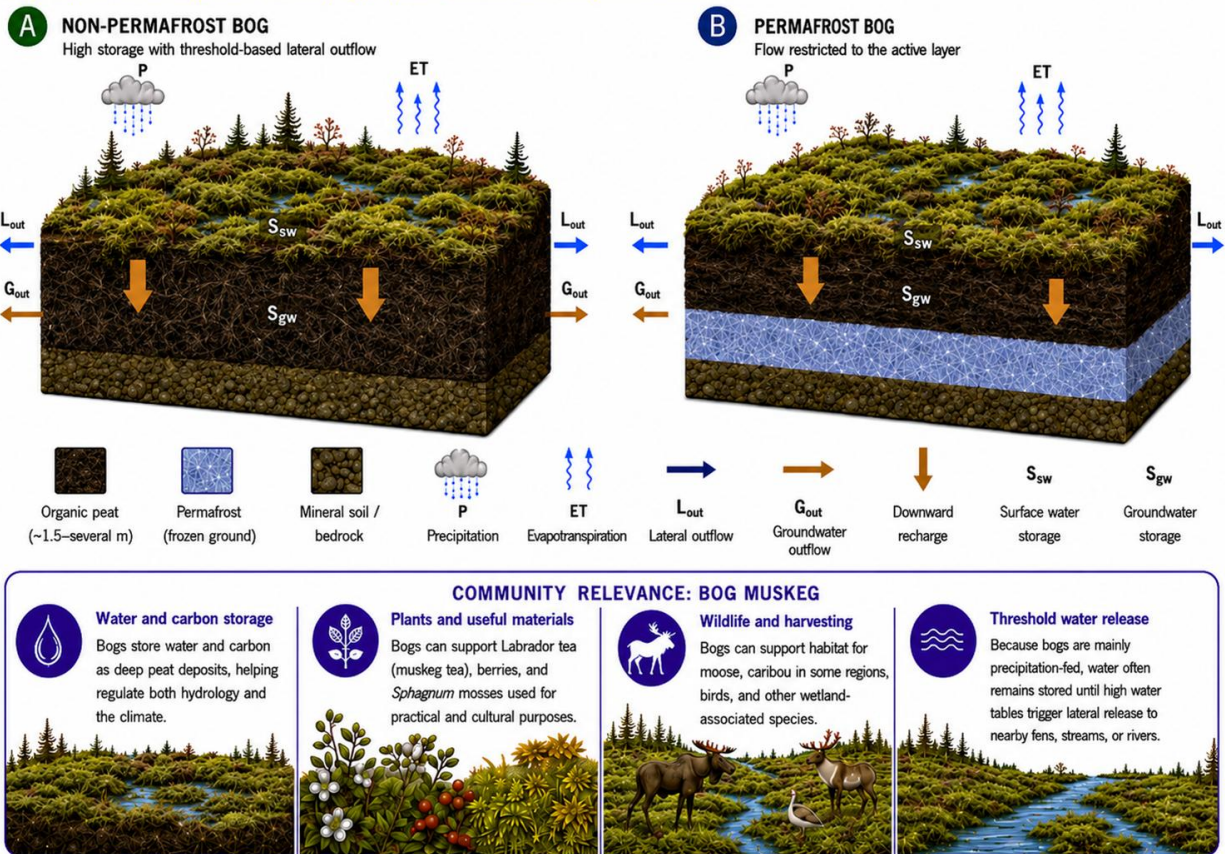


Figure 5-1: Conceptual water balance for (a) non-permafrost bog hydrological units showing vertically and laterally connected flowpaths, and (b) permafrost bog hydrological units (peat plateaus and palsas) where flow is restricted to the active layer, limiting vertical connectivity.

5.2 Wetland Hydrological Units: Fens

Fen muskeg wetlands represent ~22% of the land cover over the RAA. The relative proportion of fen is constant along the north-south gradient, with greater proportions in the Plains than in the Shield ecozones (~35% and 8% of land cover, respectively). The functional definition of a fen is an organic (*peat*-accumulating) wetland with a minimum of 40 cm of organic soils and both surface and groundwater inflows and outflows.³ They are highly *hydrologically connected* systems and are among the most important contributors to lateral water movement within peatland-dominated landscapes. Key hydrological components are described below, and summarized in Figure 5-2.

Storage (S_{sw} , S_{gw}): Water storage in fens is primarily held within their organic peat soils, which are typically 1.5 – 2.0 m thick.¹⁹ Water tables are generally shallow (<20 cm below ground surface) and relatively stable, resulting in consistently high water availability.^{29,45}

Connectivity (L_{in} , L_{out} , G_{in} , G_{out}): Fens are highly connected systems, receiving water from both surface and groundwater sources and transmitting it laterally across the landscape. Flow occurs

through surface channels, near-surface peat layers, and groundwater pathways,²⁹ linking upgradient and downgradient hydrological units. Connectivity is highly sensitive to water table position (i.e., threshold-based).

Evapotranspiration (ET): Evapotranspiration is high during the growing season due to open water and plant growth, often representing a large proportion of incoming precipitation.^{45,51,69}

5.2.1 Fen Subtypes

Fen wetlands in the RAA are grouped as open, treed, or permafrost-associated fens. Open and treed fens primarily differ in vegetation structure, with open fens having limited tree cover and treed fens supporting a more developed canopy. Permafrost-associated fens are distinguished separately because frozen ground can alter fen hydrology, drainage, surface stability, and vegetation patterns, particularly in the northern portion of the RAA.

Open Fens: Existing information suggests that open fens are often more prevalent within 100 km of the coast,²⁵ and are far more prevalent in the Plains than the Shield.³² Open fens can be both non-patterned or patterned; patterned fens (e.g., ribbed and ladder fens) are more common in the Plains in low-gradient (flatter) environments and contain ridges and pools that enhance surface water storage and flow.^{38,51,70} These fens can efficiently transmit water across the landscape and act as important sources of water to rivers,⁷¹ particularly under high water table conditions. Ladder fens are usually found on the sloped edges of bogs and have very localized groundwater connections.^{12,22} Larger ribbed fens, usually found between bogs, could also maintain connections to deeper groundwater systems, though this is not well defined in literature.^{29,36}

Within permafrost areas, open fens are beginning to increase in prevalence at the edge of permafrost plateaus or palsas, as the permafrost thaws.⁷² These are called thermokarst fens and have extremely shallow water tables.⁷³

Treed Fens: Treed fens occur more frequently inland toward the Shield and are generally drier than open fens.²⁵ Increased canopy cover results in higher interception and transpiration rates and reduced evaporation compared to open fens. Connectivity remains high but is more strongly influenced by subsurface pathways.

Permafrost Fens: Permafrost fens occur in northern portions of the RAA and are characterized by flow restricted to the seasonally thawed active layer (typically 1–2 m thick).^{74,75} Surface water storage may be extensive following snowmelt, but connectivity is constrained vertically by frozen ground.⁶⁹ Permafrost fens generally receive water from upgradient hydrological units such as palsas or peat plateaus, and transmit water to downgradient fens, ponds, and rivers.⁷⁴

FEN MUSKEG HYDROLOGICAL UNIT

Organic (peat-accumulating) wetlands with both surface and groundwater inflows and outflows.

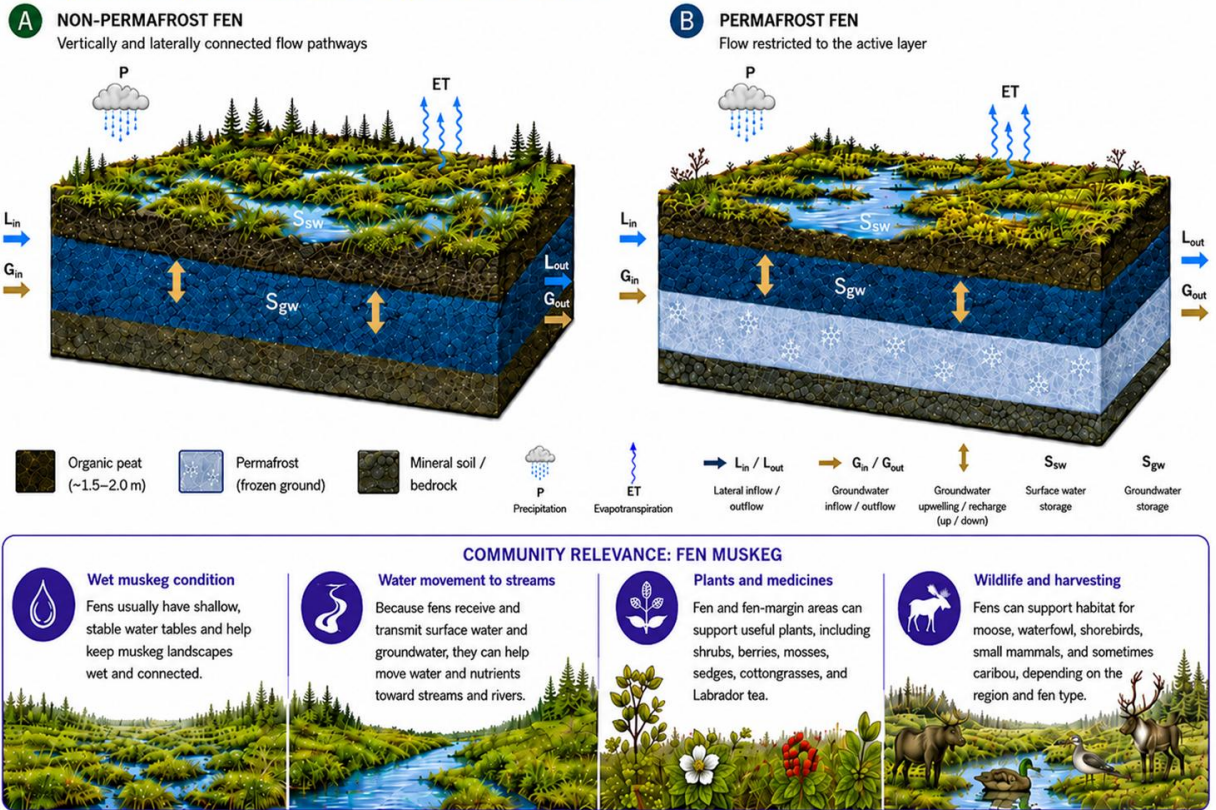


Figure 5-2: Conceptual water balance for (a) non-permafrost fens hydrological units showing vertically and laterally connected flowpaths, and (b) permafrost fens where flow is restricted to the active layer, limiting vertical connectivity.

5.3 Wetland Hydrological Units: Swamps

Swamp wetlands represent ~18% of the land cover over the RAA. The relative proportion of swamp increases along the north-south gradient, with greater proportions in the Shield than in the Plains ecozones (~25% and 11% of land cover, respectively). The functional definition of a swamp is a mineral or organic (i.e., *peat*-accumulating) wetland characterized by standing or slow-moving water and dominated by woody vegetation, with a minimum of 30% cover of shrubs and/or coniferous/deciduous trees.³ Swamps occupy transitional positions within the landscape and have a high degree of water table variability relative to bogs and fens.³ Key hydrological components are described below, and summarized in Figure 5-3.

Storage (S_{sw} , S_{gw}): Water storage in swamps occurs within both surface water and underlying soils, which can be mineral or organic peat. Water tables fluctuate seasonally, often rising to or above the ground surface during spring and drying out during summer.^{77,78}

Connectivity (L_{in} , L_{out} , G_{in} , G_{out}): Swamps have moderate connectivity, receiving water from both upgradient surface and groundwater sources and transmitting it laterally to adjacent hydrological

units such as downgradient rivers, though only during wet portions of the year like freshet after large rainfall events.⁷⁷ Flowpaths include shallow surface flow, near-surface soil flow, and groundwater exchange, and are strongly influenced by local topography and water table position.⁷⁸

Evapotranspiration (ET): Evapotranspiration is a major component of the water balance in swamps, driven largely by transpiration from trees. Canopy interception and transpiration rates are typically higher than in open wetlands, while shading reduces direct evaporation from the surface.⁷⁸ As a result, total evapotranspiration is often high, particularly during the growing season.

5.3.1 Swamp Subtypes

Coniferous Swamps:

Coniferous swamps are generally more common than deciduous swamps in the RAA, and are typically dominated by species such as black spruce, cedar, and tamarack.³⁶ They often form within transitional areas between fens, lakes, and mineral uplands, or in areas of locally steeper slopes.^{36,67} Coniferous swamps in the RAA often have organic-rich soils (reportedly up to 5 m deep^{40,78}) and can exhibit hydrological characteristics similar to treed fens and bogs, with moderate to high connectivity and sustained water availability.⁴⁰

Deciduous/Mixed Swamps:

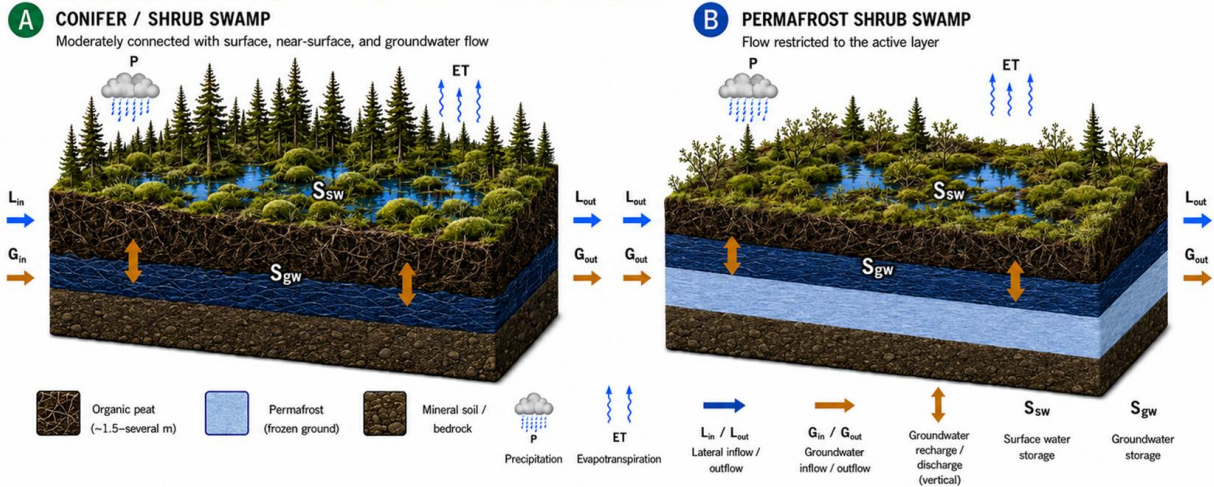
Deciduous and mixed swamps are more common in southern portions of the RAA zones. In other areas of the boreal zone, deciduous swamps have elevated water losses when compared to conifers, particularly in the spring,⁷⁹ which can influence the timing and magnitude of water release to downstream systems.

Shrub/Thicket Swamps:

Shrub and thicket swamps occur both near the coast on beach ridges and more broadly across the RAA at the margins of lakes, rivers, and uplands, as well as in areas of recent disturbance such as wildfire.⁴⁵ They are dominated by low woody vegetation (e.g., willow (*Cornus* spp.), birch (*Betula* spp.), alder (*Alnus* spp.), and aspen (*Populus* spp.)) with short canopy heights (generally <1 m), resulting in lower transpiration rates relative to coniferous swamp systems.^{45,52} Shrub swamps can be underlain by permafrost in the far north of the RAA.⁴⁵ The active layer in shrub swamps is often over 1 m deep in the summer, more closely resembling permafrost fens than palsas or peat plateaus.⁴⁵

SWAMP HYDROLOGICAL UNIT

Mineral or organic wetlands with standing or slow-moving water and dominated by woody vegetation.



COMMUNITY RELEVANCE: SWAMPS

- Tree and wood resources**
Swamps can support black spruce, tamarack, cedar, birch, and other woody plants used for practical and cultural purposes.
- Wildlife and harvesting**
Swamps can provide habitat for beaver, muskrat, waterfowl, and other wetland-associated wildlife.
- Water movement and downstream protection**
Connected swamps can store, filter, and slowly release water, supporting downstream water quality and fish habitat.
- Riparian and travel corridors**
River and floodplain swamps can link wetlands, rivers, and uplands, supporting shoreline stability, wildlife movement, and travel or harvesting corridors.

Figure 5-3: Conceptual water balance for (a) conifer/shrub swamps showing vertically and laterally connected flowpaths, and (b) permafrost shrub swamps where flow is restricted to the active layer, limiting vertical connectivity.

5.4 Wetland Hydrological Units: Marshes

Marsh hydrological units occur within the RAA but represent a relatively small portion of the landscape. They are found mainly near the coast, where they occur along a saltwater-to-freshwater marsh continuum. As this report does not address coastal processes, marsh hydrological units are not considered further.

5.5 Open Water Hydrological Units: Waterbodies and Watercourses

Open water hydrological units (Figure 5-4) include waterbodies (lakes and ponds) and watercourses (rivers, streams, and creeks). These hydrological units receive and integrate water from upgradient hydrological units and, in some cases, other open water units. By cover, open water represents ~10% of the RAA, with similar proportions along the north-south and Shield-to-Plains gradients. The sizes and shapes of waterbodies and watercourses depend on substrate, permafrost presence, surrounding catchment land cover, topography, and landscape position.

Storage (S_{sw}): In open water systems, most water is stored above the surface, and the total storage capacity is controlled by the size and shape of the river channel or lake. Storage is often substantial in Shield lakes, but shallower and spatially distributed in peatland ponds and permafrost waterbodies.^{82,83}

Connectivity (L_{in} , L_{out} , G_{in} , G_{out}): Surface water systems are major receivers and transmitters of lateral flow within the landscape. Connectivity is generally continuous in river systems, but more variable in lakes and ponds, particularly in low-gradient peatland or permafrost environments where connections may expand or contract seasonally.¹⁸

Evaporation (E): Evaporation from surface water units can represent a major water loss during the open-water season.^{84,85} The amount of water lost is influenced by surface area, depth, temperature, and wind exposure, and may be especially important in shallow peatland and thermokarst ponds, which can dry completely over the summer.

5.5.1 Surface Water Subtypes

Non-Permafrost Waterbodies:

Non-permafrost lakes and ponds occur throughout the RAA and include both mineral-soil or bedrock-underlain lakes and organic-soil-peatland pools. These systems are generally larger and deeper within the Shield, and smaller and shallower in the Plains.⁸² They are commonly connected to adjacent wetlands and river systems and can act as localized storage features that buffer short-term variability in inflows.

Permafrost and Thermokarst Waterbodies:

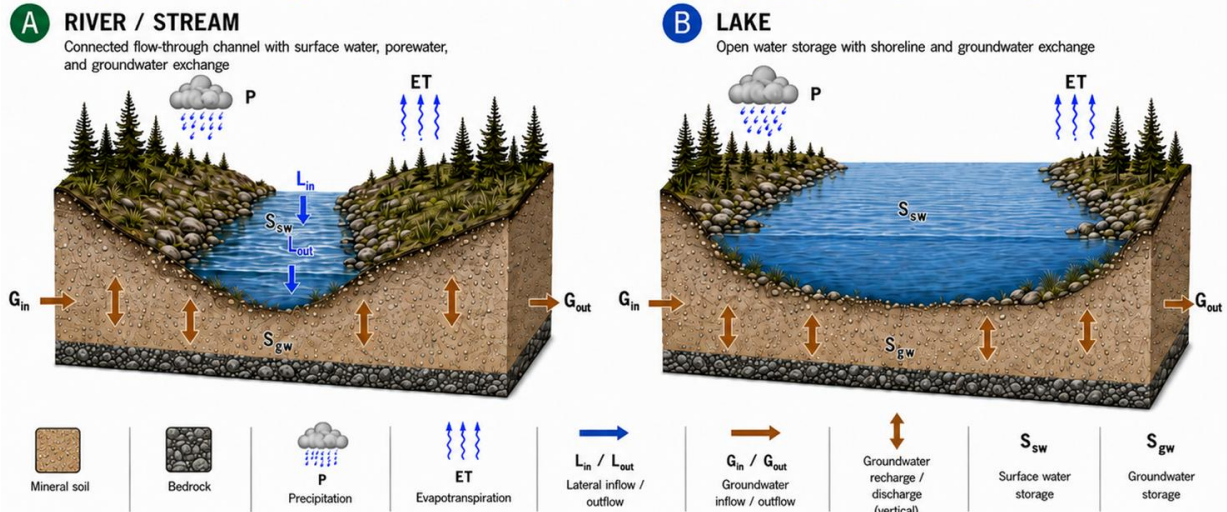
Permafrost waterbodies occur in northern portions of the RAA and are typically small and shallow, with basin morphology controlled by underlying permafrost or thaw processes.^{20,72} Connectivity is often restricted to near-surface lateral flow from adjacent peat plateaus, palsas, and fens, and these systems may exhibit strong seasonal variability in extent due to thaw and evaporation.⁵⁴

Watercourses:

Watercourses are the most connected surface water subtype and function as the ultimate receivers of lateral and groundwater flow from upgradient hydrological units. In the Shield, even smaller tributaries are typically channelized and incised into till or bedrock, while toward the Plains rivers become wider, shallower, and less dendritic as regional slopes decrease, and many small rivers are underlain by low-conductivity marine sediment.^{31,78,86} In peatland-dominated areas, smaller channels may be weakly defined (difficult to see and trace) and may disappear and re-emerge from the surrounding peatlands.

RIVER AND LAKE HYDROLOGICAL UNIT

Surface-water systems connected to surrounding groundwater and shorelines, with water storage, inflow, outflow, and exchange supporting aquatic ecosystems and community use.



COMMUNITY RELEVANCE: RIVERS AND LAKES

Fishing and aquatic harvesting
Rivers, lakes, shorelines, bays, and tributary mouths provide habitat for fish and other aquatic species harvested for food, trade, cultural practice, and community well-being.

Travel corridors
Rivers function as natural highways connecting communities, camps, harvesting areas, portage routes, lakes, wetlands, and seasonal gathering places. Travel includes canoe, boat, snowmobile, and river-ice travel.

Camp and gathering areas
Lakeshores and riverbanks provide places for camps, cabins, teaching areas, fish processing, cooking, drying, smoking, and family gatherings, especially where there are safe landing sites, access to fish, drinking water, firewood, and travel routes.

Drinking and household water
Rivers and lakes provide surface water used directly or indirectly for drinking, cooking, washing, travel, and camp use, so water quality is closely tied to health, safety, and the ability to spend time on the land.

Figure 5-4: Conceptual water balance for surface water hydrological units showing (a) a watercourse with flow from left to right, and (b) a waterbody with lateral inflows and outflows within predominantly aquitard-forming mineral substrates or bedrock.

5.6 Upland Hydrological Units: Forests

Forest represents ~19% of the land cover over the RAA. The relative proportion of forest is consistent along the north-south gradient, with greater proportions in the Shield than in the Plains ecozones (~29% and 6% of land cover, respectively).^{31,45} The functional definition of forest is an upland (non-wetland) system with little to no organic soil. Forests generally receive water from precipitation, lateral inflow, and groundwater, and release water through both surface and subsurface flow. Within the RAA, forests are associated with well-drained areas, including bedrock, coarser glacial deposits, river margins, and coastal beach ridges. Compared to treed wetlands, forests have denser tree cover and deeper and more variable water tables, resulting in lower water availability. Key hydrological components are described below and summarized in Figure 5-5.

Storage (S_{sw} , S_{gw}): Water in forests is primarily held within mineral soils and shallow organic layers, and therefore these systems generally have lower water storage than wetlands.

Connectivity (L_{in} , L_{out} , G_{in} , G_{out}): Forests are generally well-connected to adjacent hydrological units during precipitation and snowmelt events, and during this time water can flow through small temporary (ephemeral) streams and as overland runoff.⁵² Outside of these events, water movement is primarily through subsurface or near-surface preferential pathways.^{32,45,80}

Evapotranspiration (ET): Evapotranspiration is a dominant component of the forest water balance, driven by canopy interception and transpiration. Forests often exhibit high growing-season water losses, which can substantially reduce the amount of water available for runoff and shallow flow.

5.6.1 Forest Subtypes

Coniferous Forest:

Coniferous forest in the RAA is generally dominated by black spruce, with additional species including pine (*Pinus* spp.), balsam fir (*Abies balsamea*), and white spruce (*Picea glauca*).^{31,52,81} In the southern Shield, coniferous forest forms extensive, continuous cover between river systems, with wetlands occupying localized depressions.^{31,32} In northern portions of the RAA, coniferous forest occurs more sparsely near the coast, often interspersed with and draining laterally toward adjacent fens.⁴⁵

Mixed and Deciduous Forest:

Mixed forest typically occurs in the southern portion of the RAA, as localized patches within coniferous-dominated forests, often associated with rivers, lakes, or areas recently burned by wildfire. More common deciduous species include birch, trembling aspen (*Populus tremuloides*), and willow, with purely deciduous stands largely restricted to southern portions of the Shield, and are uncommon to absent in the Plains.³²

FOREST HYDROLOGICAL UNIT

Upland (non-wetland) systems with little to no organic soil, dominated by trees.

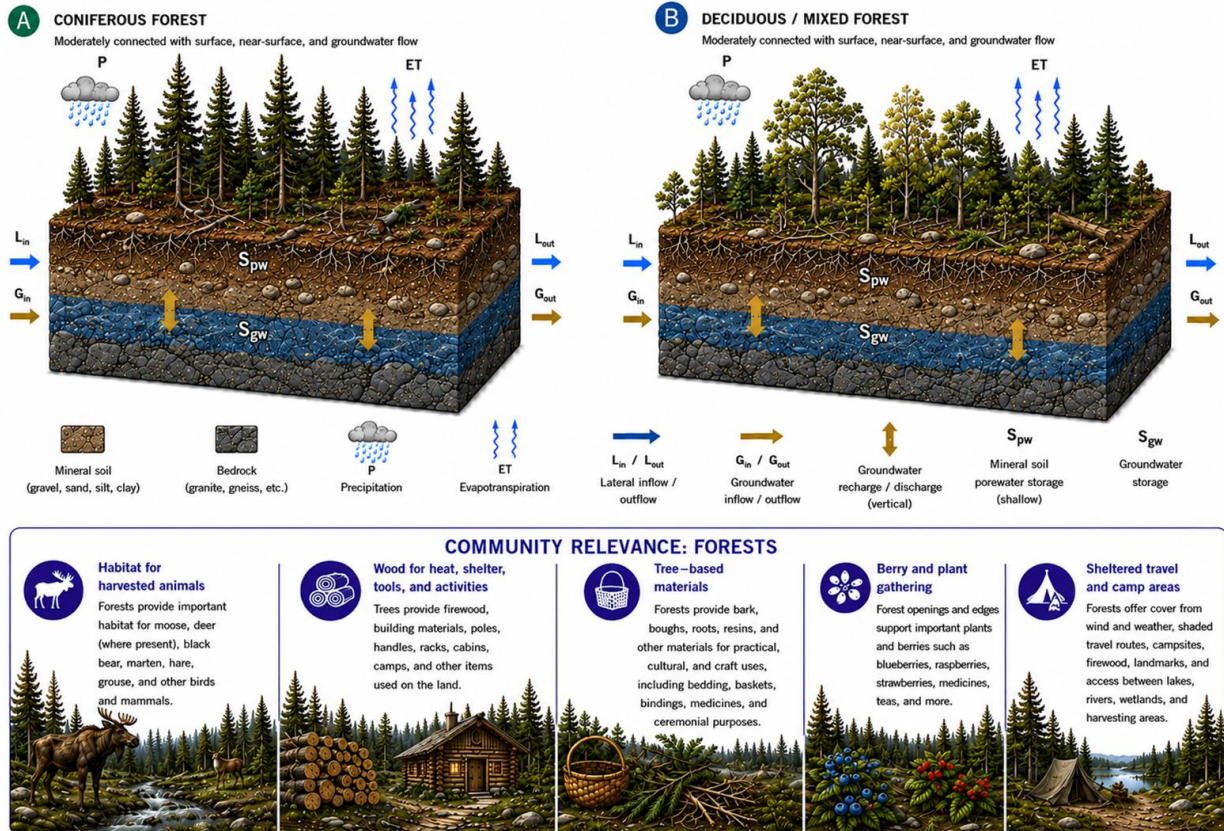


Figure 5-5: Conceptual water balance for forest hydrological units showing vertically and laterally connected flowpaths in predominately mineral soils.

5.7 Upland Hydrological Units: Exposed Bedrock/Mineral Soils

Bedrock and mineral substrate hydrological units (Figure 5-6) include areas of exposed or shallow bedrock as well as exposed glacial deposits and coarse-textured sediment. By land cover, this hydrological unit represents ~0.03% of the land over the RAA. Cover by proportion is consistent along the north-south gradient and is slightly higher in the Shield compared to the Plains (0.04% compared to 0.03%, respectively). Although hydrological units have a small total area, their presence can exert strong control on flow through localized *aquifers*, particularly where soils are coarse-grained or bedrock contains fractures (Precambrian Shield) or *karst* features (Hudson Plains). Key hydrological components are described below.

Storage (S_{sw} , S_{pw}): Water storage is typically limited due to shallow soil depth and the low permeability of the rock relative to peatland systems. The amount of groundwater storage can be limited unless the soil is coarse-grained (sands and gravels) or there if the bedrock is fractured.

Connectivity (L_{in} , L_{out} , G_{in} , G_{out}): Connectivity in these systems is strongly controlled by soil or bedrock characteristics. In areas of exposed or fractured bedrock, water is rapidly transmitted through surface runoff and shallow subsurface flow, with preferential flowpaths developing along fractures, joints, and soil–bedrock interfaces. In mineral soils, macropores and coarse textures can facilitate rapid vertical and lateral flow. Where present, sand and gravel aquifers may enhance groundwater connectivity and sustain baseflow to adjacent wetlands and rivers.

Evapotranspiration (ET): Evapotranspiration is generally low in these hydrological units due to limited near-surface soil moisture availability and reduced vegetation cover, especially on bedrock outcrops. Well-drained areas of coarse-grained mineral deposits may be forested, increasing transpiration and interception.

5.7.1 Exposed Bedrock and Mineral Soils Subtypes

Bedrock (non-fractured):

Shallow bedrock systems are characterized by minimal soil cover overlying exposed or near-surface bedrock. Generally, these areas exhibit very low storage capacity and rapid hydrological response to precipitation, with flow dominated by surface runoff and shallow preferential pathways along bedrock interfaces.

Bedrock (fractured/karstic):

Where fractures or karst features exist, flow can be rapid and unpredictable, transmitting water over great distances in the subsurface and acting as significant groundwater recharge points.^{37,87,88} Belowground preferential flow has been documented primarily within the limestones of the Attawapiskat area, where bedrock outcrops exist along the main riverbanks.^{22,23} These are poorly studied, however, and may be of significant potential influence on regional hydrology.

Mineral Soils and Glacial Deposits:

Mineral substrate systems include tills, sands, and glaciofluvial deposits of varying texture and permeability. These systems exhibit greater storage capacity than shallow bedrock and can support both vertical infiltration and lateral subsurface flow to river systems.¹⁸ Coarse-textured deposits may facilitate rapid drainage, while finer materials may restrict flow and promote localized storage.¹⁸

BEDROCK HYDROLOGICAL UNIT

Exposed bedrock and shallow mineral soils where water movement is strongly controlled by fractures, joints, and surface runoff.

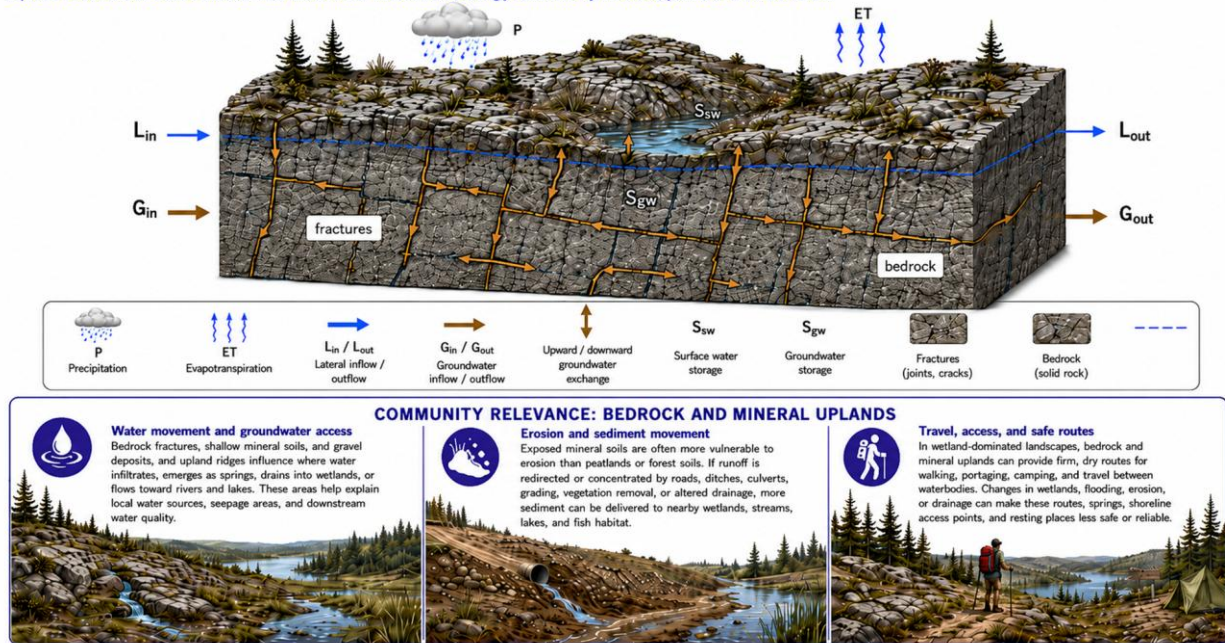


Figure 5-6: Conceptual water balance for a bedrock/shallow till hydrological unit showing fracturing features act as preferential conduits of flow.

6.0 CHARACTERIZING AND ASSESSING DISTURBANCE

6.1 Linear Disturbances

Linear disturbances represent one of the most immediate and widespread hydrological stressors within the RAA due to the requirement for transportation and access infrastructure prior to resource development. Linear disturbances can include roads (permanent and seasonal), rail lines, hydro corridors, seismic lines, and pipelines, as well as any associated infrastructure such as drainage ditches, culverts, and cleared rights-of-way. Several large-scale projects are already planned or underway within the RAA, including the Webequie Supply Road, Northern Road Link, and Ring of Fire access corridor.^{89,90}

Four main aspects of linear features alter landscape hydrology:

- 1) vegetation clearance on the linear feature and in the buffer (i.e., the area surrounding the feature),
- 2) landscape re-grading such that the linear feature becomes a local high or low,
- 3) soil compaction and/or introduction of road materials (e.g., non-native fill or asphalt), and
- 4) the placement of drainage features such as culverts and ditches.

Hydrological impacts are strongly controlled by the density of linear features on the land (e.g., road network or seismic line grid) as well as by their orientation relative to dominant flow direction (in the RAA, this is generally to the east/northeast, though this can vary locally). The greatest impacts occur with linear features placed perpendicular to flow direction.

The design and construction methods also influence the magnitude and type of hydrological impact. Where low-impact or seasonal access is required, floating or corduroy roads, which are designed to spread the road load across soft organic terrain, are generally more suitable for deep, saturated peat or muskeg crossings and can reduce peat excavation and maintain some flow if they remain permeable.^{91,92} In contrast, mineral-fill roads are typically more suitable for long-term, all-season, or heavy-load access; however, where they cross peatlands, the fill embankment can act as a barrier to surface and subsurface flow unless adequate cross-drainage is installed.⁹¹

Hydrological impacts from linear features (Figure 6-1) can be divided into modifications to water storage, landscape connectivity, and evapotranspiration across the upgradient and downgradient portions of the landscape, as well as on the linear feature itself.

Storage (S_{sw} , S_{gw}): Linear disturbances alter the spatial distribution of water storage by interrupting lateral flowpaths. Where flow is interrupted, water accumulates on the upgradient side of the disturbance, resulting in increased surface and subsurface storage and frequent ponding (accumulation of standing water on the land surface). At the same time, downgradient areas experience reduced water inputs, leading to drying, lowering of water tables, and, in some cases,

the disappearance of open water.^{72,93} The degree of impact depends on the orientation of the disturbance relative to natural flow direction, the presence and spacing of culverts or drainage openings, the permeability and compressibility of the peat or soil, the local slope, and the extent to which downgradient wetlands, ponds, or streams depend on the blocked flow source.^{94,95} Impacts are therefore expected to be greatest in low-gradient peatlands and wetlands where water moves laterally through shallow peat or surface pathways, and where the affected hydrological units have limited ability to receive compensating water from groundwater, rainfall, other hydrological units, or other flowpaths.⁹⁴ Hydrological units already experiencing drying from other disturbances or climate-related water deficits will also be more sensitive to storage losses.

On the footprint of the linear disturbance, storage is typically reduced due to soil compaction and the use of low-permeability materials (e.g., gravel or asphalt), which limit infiltration and decrease subsurface water retention.^{89,96} In permafrost environments, however, thaw induced by disturbance may also increase subsurface storage through the melting of previously frozen water.^{72,89,92,97}

Connectivity (L_{in} , L_{out} , G_{in} , G_{out}): Connectivity is the primary hydrological component affected by linear disturbances. Compacted soils and impervious materials can act as partial barriers to both surface and subsurface flow, reducing lateral connectivity between upgradient and downgradient hydrological units.^{91,92,98} This results in decreased transmission of water across the landscape and contributes to the asymmetric storage patterns described above (i.e., wetting on one side and drying on the other).^{89,99} In some cases, flow may be redirected along the disturbance itself or through adjacent drainage ditches, creating new preferential flowpaths that differ from natural flow patterns.⁹⁹

Although culverts are often installed to restore connectivity, their effectiveness is variable and frequently limited by inadequate spacing, size, and maintenance issues such as blockage, frost heave, settlement, or beaver activity.^{91,100,101} As a result, connectivity is typically only partially restored, with large portions of the landscape remaining hydrologically disconnected.^{99,102} Connectivity can also be enhanced through the addition of coarser fill materials below the road to help facilitate under-road flow. FP Innovations and Ducks Unlimited Canada (2016) developed a useful guidance document for the proper sizing, spacing, and installation of culverts in a Canadian wetland context, titled *Resource Roads and Wetlands: A Guide for Planning, Construction and Maintenance*.

Evapotranspiration (ET): Changes in evapotranspiration occur due to removal of vegetation, especially trees, as well as the creation of impervious surfaces (e.g., asphalt or consolidated soil). Vegetation clearing along the access corridor^{98,103} and reduced tree growth and die-off upgradient due to waterlogging^{89,100,104} both reduce canopy cover, and thus result in decreased interception and transpiration.^{98,105} In contrast, drying in downgradient areas may promote increased tree growth and transpiration, in extreme cases shifting treed wetland hydrological units towards forest.^{93,104}

Changes in surface water extent also influence evaporation, with increased ponding upgradient potentially increasing open water evaporation.^{98,105} Disturbance-related changes to snow accumulation and melt dynamics may further modify seasonal evapotranspiration patterns.⁹⁸

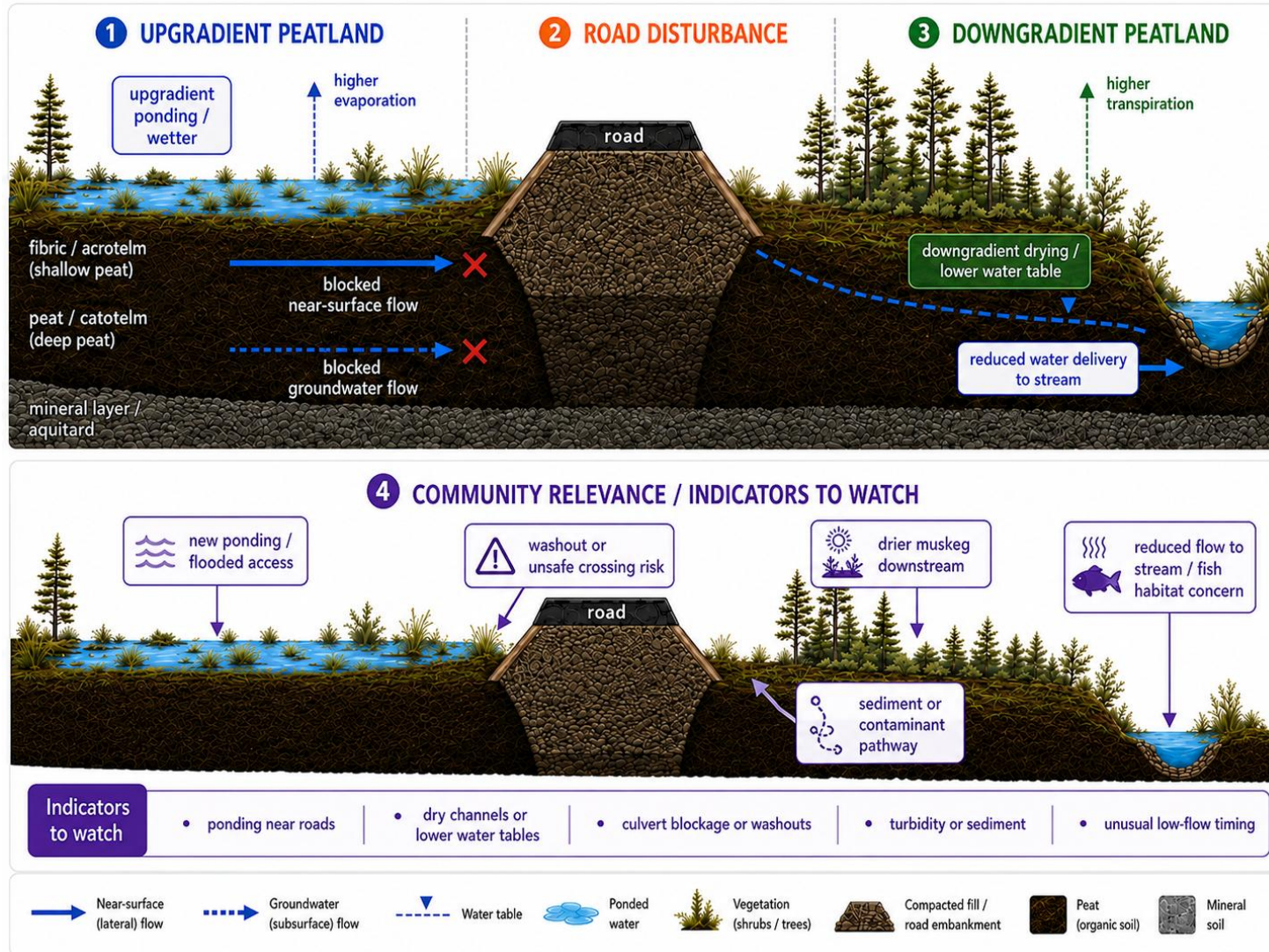


Figure 6-1: Conceptual impacts of a road or other linear disturbance on peatland hydrology and community-relevant indicators.

6.1.1 Linear Disturbance Sub-Types

Permanent Roads and Rail Lines

Permanent roads and rail lines often represent the most significant linear disturbances due to their long-term presence and structural modification of the landscape.⁸⁹ The combination of vegetation clearing, fill placement, and soil compaction creates a persistent barrier to lateral flow, resulting in increased storage and ponding upgradient and reduced water availability downgradient.

Culverts may partially restore connectivity but are often insufficient to maintain natural flow patterns.^{95,100,102} The magnitude of impact varies depending on road orientation, spacing of drainage structures, and local topography. The spatial influence of this flow interruption is highly varied, in some studies extending hundreds of metres on one or both sides of the disturbance,^{72,95} while extending < 100 m in others in similar landscape types.^{93,94} The spatial extent of flow interruption likely varies for the same reasons that the magnitude of hydrological change varies: road orientation relative to dominant flow direction, the amount of surface and shallow subsurface flow that occurred before disturbance, local slope and topography, peat or soil permeability, and the placement, spacing, sizing, and maintenance condition of culverts. Antecedent moisture conditions also influence the response, as snowmelt, wet years, or large rainfall events can increase the volume of water requiring passage through drainage structures, while dry periods may amplify downgradient water deficits. As a result, culverts may reduce local ponding or drying where they are well-aligned with natural flowpaths; however, they may be insufficient where diffuse wetland flow is forced through too few or poorly positioned crossing points.

In permafrost environments, these disturbances can accelerate thaw through increased soil temperatures, enhanced snow insulation, and altered moisture conditions, further modifying storage and connectivity.^{89,106}

Winter Roads

Winter roads are seasonal features constructed from snow and ice and generally have lower impacts than permanent roads, though studies are limited. In some cases, repeated use of these roads may lead to soil compaction, which can reduce infiltration and disrupt lateral flowpaths. However, the single study on a winter road in the RAA determined that no ground subsidence or changes in landscape topography could be detected, though the five study roads were used for four years or less at the time of characterization.¹⁰⁷

Some evidence suggests that thickened ice at river crossings may delay spring breakup and potentially influence flooding dynamics.¹⁰⁸ Vegetation clearing associated with these roads may also reduce interception and transpiration locally, though this has not been quantified.

One study in the western boreal forest reported an increase in active layer thickness and permafrost degradation on winter roads.¹⁰⁶

Exploration and Hydro Corridors

Exploration corridors (e.g., seismic lines, cut lines, and drill access pathways) and hydro corridors involve vegetation clearing and localized soil disturbance. No studies were available within the RAA detailing the impacts of this disturbance type. In the western boreal forest, compaction along these features has been shown to alter soil properties and storage, resulting in more variable water tables and reduced connectivity near the surface.^{105,109}

In some cases, these features may become localized depressions, promoting ponding and increased surface storage.^{105,110} Alternatively, they may act as *preferential flowpaths*, redirecting water along the disturbance depending on landscape position.¹¹⁰ Numerous studies within the western boreal forest have shown an increased *active layer* thickness and accelerated permafrost degradation along exploration corridors due to enhanced ponding and vegetation removal.^{97,106}

Pipelines

Hydrological impacts of pipelines are not well studied. Studies that do exist show generally similar impacts to those of other linear disturbances. Installation may result in soil disturbance, compaction, and the introduction of non-native materials,^{95,111} all of which can alter storage and connectivity. Additionally, the pipeline itself may act as a barrier to subsurface flow, further contributing to reduced connectivity between upgradient and downgradient hydrological units.⁹⁸

Disturbances Parallel to Flow

Studies in the western boreal forest have shown that generally, where linear disturbances are oriented parallel to the dominant direction of flow, impacts on lateral connectivity may be reduced due to the absence of clear upgradient and downgradient divisions.⁹⁹ However, water may be redirected along the disturbance (often resulting in flooding on the feature) or within adjacent drainage features, altering local flow patterns.^{94,97}

6.1.2 Potential Changes to Water Quality

Linear disturbances can significantly alter water quality through the introduction of non-native materials and the mobilization of *solutes*, sediments, and contaminants across the landscape. Construction and maintenance activities introduce materials such as gravel, limestone, road salt, and petroleum products, which can contribute ions (e.g., calcium and chloride), nutrients (e.g., nitrogen and phosphorus), heavy metals, and other contaminants to adjacent hydrological units.^{18,89,112} These materials may be transported through multiple pathways, including infiltration through fill materials, surface runoff, and erosion during high-flow periods such as snowmelt. Where linear disturbances are elevated above the surrounding land, the amount of washout to adjacent hydrological units generally increases.^{91,101,104}

Water quality impacts of linear disturbances are closely linked to changes in hydrological connectivity. Where connectivity is maintained or enhanced (e.g., via culverts or *preferential flow paths*), contaminants may be transported efficiently to downstream systems, including watercourses. Where connectivity is reduced, contaminants may accumulate in upgradient ponded areas.

Cumulative effects may arise due to the spatial extent of linear disturbance networks as well as increased vehicular traffic, which raises the likelihood of contaminant spills and ongoing inputs of pollutants. In addition, vegetation changes and the introduction of non-native species may further influence biogeochemical cycling and water quality over time.

Though direct peatland-related studies are not available, the impacts of water quality changes arising from linear features have been documented in broader contexts. In some cases, changes in water quality arising from the construction and operation of linear features may affect aquatic habitat and downstream water quality by increasing salinity¹¹³, turbidity¹¹⁴, metal exposure¹¹⁵, or nutrient availability. Such changes may contribute to ecological stress, though this has not yet been studied in the RAA.

6.1.3 Impacts to Streamflow

The main factors related to linear disturbances that increase and decrease streamflow are conceptualized in Figure 6-2. The net impacts of linear disturbances on river flow depend on how storage and connectivity are altered across the landscape. Where disturbances redirect water toward rivers, discharge may increase. Conversely, where connectivity is reduced upstream of a river, discharge may decrease.

Reductions in landscape storage capacity on the linear feature may also result in flashier flow regimes, with higher peak flows during wet periods and reduced baseflow during dry periods. Changes in snow accumulation and melt timing may further alter the timing and magnitude of seasonal flow peaks.

In permafrost environments, thaw-induced increases in water availability may enhance flow, provided that connectivity to the river is maintained.

Because linear features are seldom localized impacts (road, rail, and hydro corridors often span hundreds of kilometres, and exploration corridors such as seismic lines are often created in large grids), cumulative effects are likely to occur as the proportion of disturbance increases. It is therefore important to assess the proportion of a watershed impacted by these disturbances not just by area of disturbance, but also by the area associated with hydrological impact and the specific vulnerability of hydrological units within the impacted area.

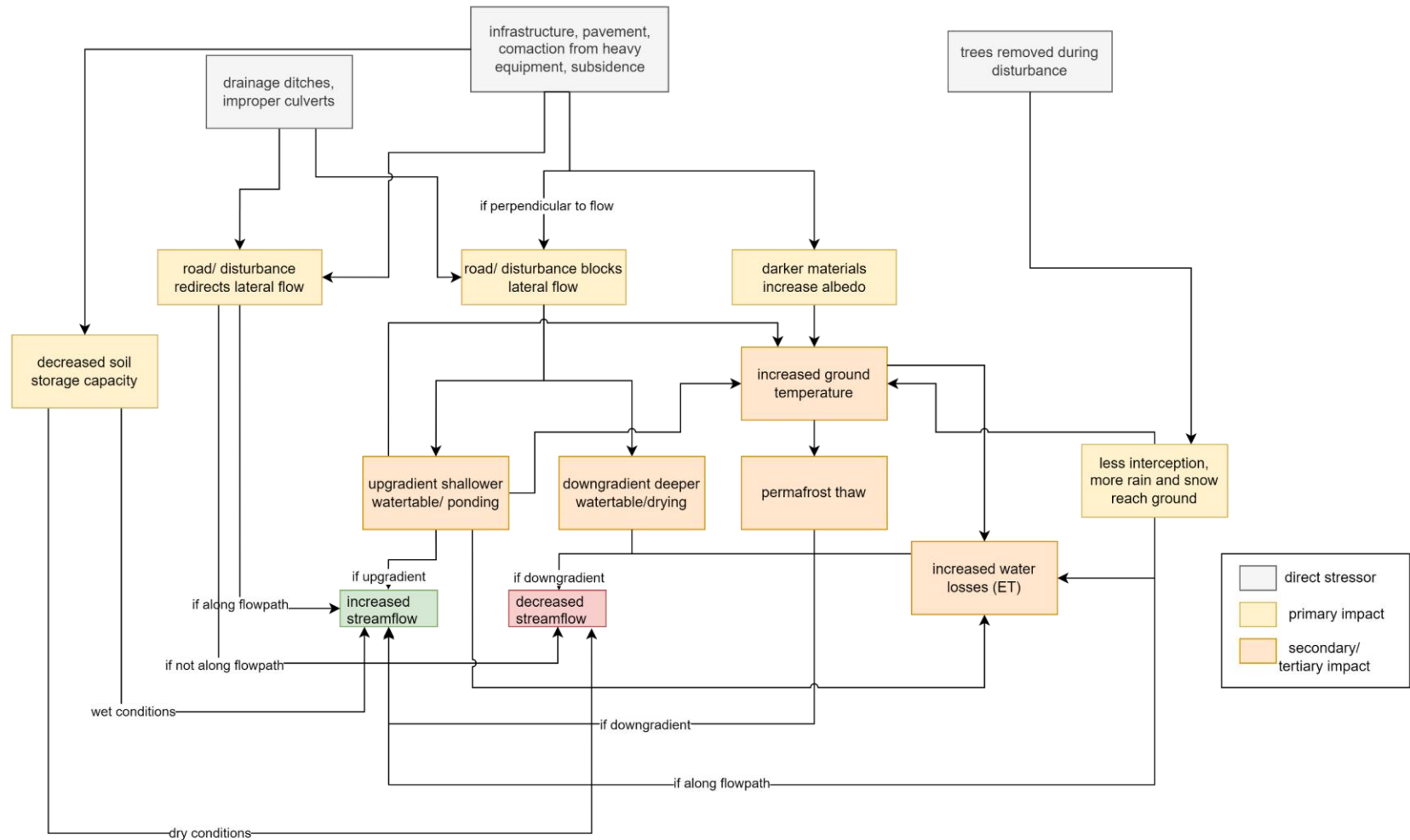


Figure 6-2: Potential alterations to streamflow derived from hydrological impacts associated with linear features in permafrost and non-permafrost environments.

6.2 Direct Streamflow Manipulation (Dams and Diversions)

Unlike linear disturbances, which primarily disrupt the connectivity in the landscapes that feed the watercourses, dams and diversions directly modify flow within river systems, with secondary impacts on both upgradient and downgradient hydrological units. Direct streamflow manipulation includes large-scale hydroelectric dams, beaver dams, and engineered flow diversions. No studies could be found that were conducted within the RAA. Studies from comparable systems in the Hudson Bay Lowland (HBL; Quebec) and Peace River (Alberta) were used to provide insight into expected hydrological responses. No information could be found regarding impacts of damming and diversion in permafrost environments.

Hydrological impacts of river damming and diversion (Figure 6-3) can be categorized into changes to storage, connectivity, and evapotranspiration across upstream, downstream, and adjacent hydrological units.

Storage (S_{sw} , S_{gw}): The damming of river systems substantially increases surface water storage upstream, causing the formation of a reservoir (i.e., large pond or lake). This expansion of open water at a reservoir often floods adjacent hydrological units, particularly wetlands,¹¹⁶ increasing both surface and groundwater storage. For example, in the La Grande River watershed (Quebec), reservoir creation increased open water coverage from 15% to 24%.¹¹⁷

In contrast, downstream hydrological units experience reduced water availability, resulting in declining surface water extent and lower water tables, and therefore lower storage. The magnitude of these changes varies depending on reservoir size, operation regime, and landscape characteristics.¹¹⁷

Connectivity (L_{in} , L_{out} , G_{in} , G_{out}): Dams fundamentally alter landscape connectivity by interrupting flow within river systems. Upstream, connectivity between hydrological units may increase due to flooding and expansion of surface water. Downstream, however, connectivity is reduced or becomes artificially controlled through regulated discharge.

In many cases, the presence of dams can completely alter the seasonality of water levels within the dammed system, as flow is no longer governed by natural gradients in water availability, but instead by operational decisions, resulting in altered timing and magnitude of water movement across the landscape.¹¹⁶⁻¹¹⁸

Evapotranspiration (ET): Evapotranspiration is altered primarily through changes in surface water extent and vegetation cover. Expansion of reservoirs increases open water evaporation, while flooding of vegetated areas reduces transpiration and interception.

In downstream areas, drying may promote increased vegetation growth and transpiration, depending on the extent of water table decline. Changes in snow accumulation and ice dynamics may further influence seasonal evapotranspiration patterns.¹¹⁹

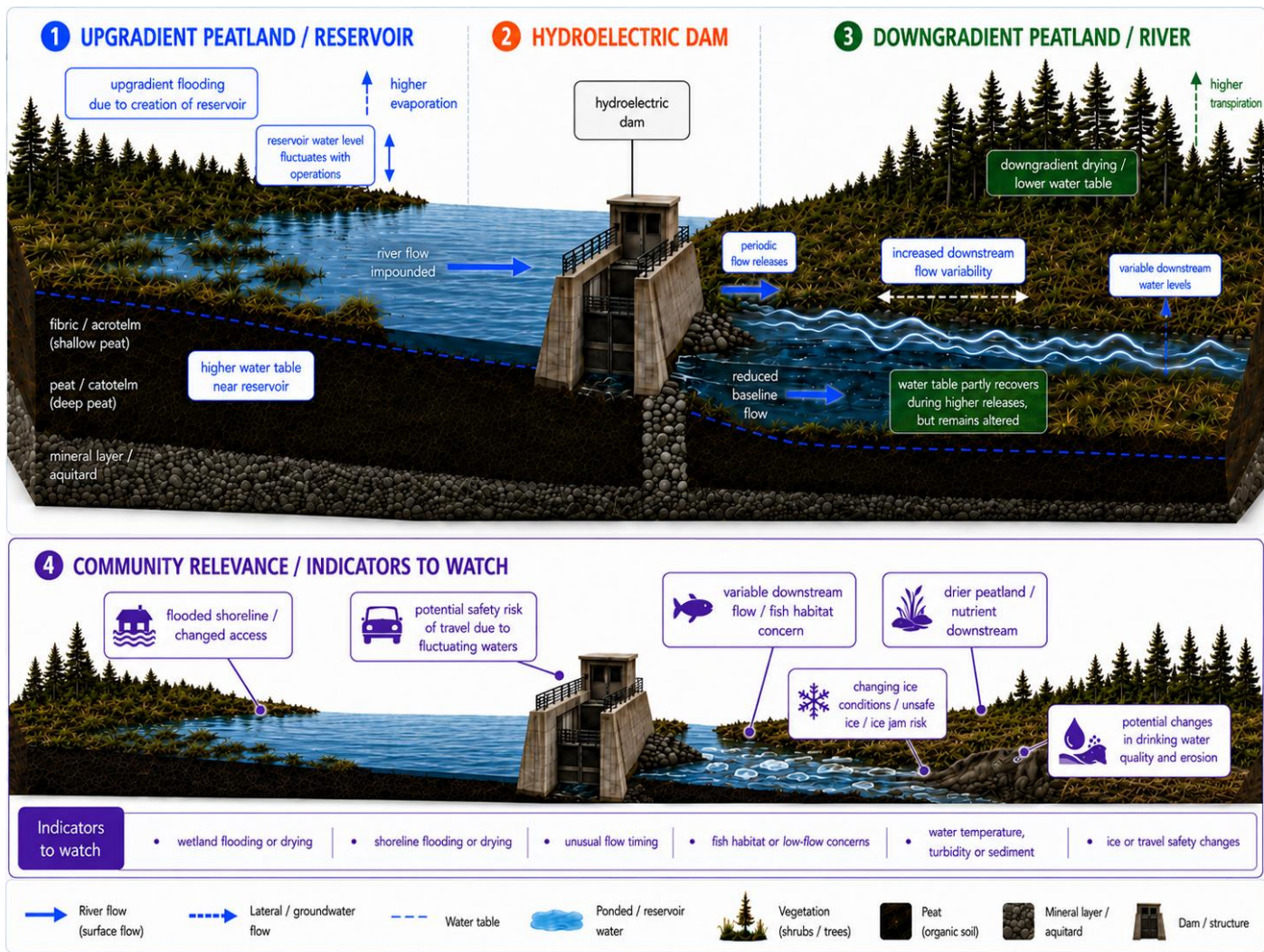


Figure 6-3: Water balance components impacted by a hydroelectric dam that is (a) closed and (b) open allowing some water to flow through. A beaver dam more closely resembles scenario (b), where some water can flow through or overtop of the structure.

6.2.1 River Damming/Diversion Subtypes

Hydroelectric Dams

Hydroelectric dams represent the most significant direct anthropogenic modification to river systems in the RAA. By impounding water and regulating discharge, these systems alter both the magnitude and timing of flow. Currently, most hydroelectric dams in the RAA are within the Moose River watershed, which contains more than 40 dams and associated infrastructure.¹²⁰

A key feature of hydroelectric dams is that they can change river flow from a natural seasonal pattern to one controlled by dam operations and electricity demand (Figure 6-4). On short timescales (daily to weekly), flow is controlled by energy demand, resulting in rapid fluctuations between high and low discharge. On seasonal timescales, this often produces a reversal of the natural *hydrograph*, with increased flows in fall and winter and reduced flows during spring and early summer.¹¹⁶⁻¹¹⁸ For example, in the La Grande River system, winter flow increased from 2–18% of annual discharge under natural conditions to approximately 31% following dam construction.¹¹⁷ These altered flow regimes can have secondary impacts. For example, downstream elevated winter flows disrupt ice formation and spring breakup dynamics,^{116,118} whereas upstream flooded areas may freeze more deeply, altering thaw timing and ice-free periods.¹¹⁹

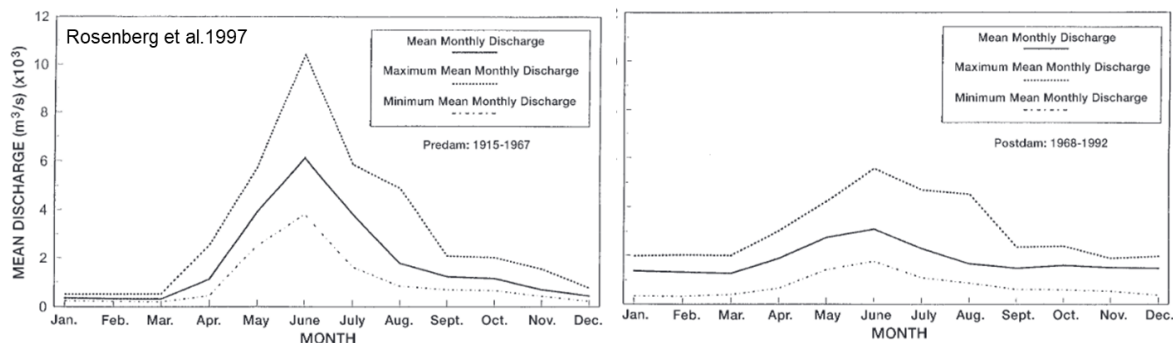


Figure 6-4: Changes to a streamflow hydrograph in Peace River, Alberta due to the installation of a hydroelectric dam.¹¹⁸

Beaver Dams

Beaver dams represent a natural analogue to hydroelectric dams, though they are generally much smaller in scale. Because they are smaller, individual beaver dams typically have smaller impacts on storage, connectivity, and evapotranspiration. Generally, beaver dams increase surface water storage upstream, resulting in ponding and elevated water tables in adjacent hydrological units.¹¹⁸ Flooding may lead to tree death, which reduces rates of transpiration, while increasing open water evaporation.

Unlike engineered dams, beaver dams are semi-*permeable* (i.e., release some water rather than retaining it all) and dynamic (may change in size and functionality over time). They typically “leak” some amount of river flow, and water level differences between the upstream and downstream

areas are small (< 1–5 m).^{121,122} However, sudden beaver dam failure can result in rapid drainage of impounded water.⁶⁷

The cumulative influence of beaver activity can be substantial. In coastal HBL systems, densities of up to 60 dams per km² have been reported, with nearly 20% of stream networks affected in some watersheds.^{122,123} Studies on the large-scale effects of beaver activity on RAA watersheds are extremely limited, with existing studies focused on small areas close to the HBL coast.

Diversions

Stream diversions change the hydrology of the watershed by redirecting rather than reducing flow. Within the RAA, diversions have primarily been applied in the Albany River watershed, where approximately 17% of historical flow has been diverted towards Lake Superior for hydroelectric production.^{124,125}

The primary hydrological impact of diversion is a reduction in water availability within the original channel and previously connected hydrological units. In the now disconnected hydrological units, this can lead to:

- declining water tables
- reduced lateral connectivity
- decreased groundwater contributions to streams

The magnitude of these effects depends on the proportion of flow diverted and the connectivity of the affected system.

6.2.2 Potential Changes to Water Quality

Damming can significantly alter water quality through both physical and biogeochemical processes.

Flooding of organic-rich soils can increase the movement of DOC and nutrients that were once “trapped” in the soil, while also creating conditions favourable for mercury methylation and bioaccumulation.¹²⁶ In northern Quebec, elevated mercury concentrations have been observed in hydroelectric-impacted watersheds for decades following reservoir creation, with levels up to six times background detected up to 100 km from dams.¹¹⁸

Reservoirs may also retain or transform nutrients and solutes, resulting in altered patterns of release downstream. For example, decreases in total phosphorus and total nitrogen movement downstream were observed, alongside increases in total nitrogen release during dam operation, in La Grande River, Quebec.¹¹⁷ Operational variability may also influence water quality, with sediment accumulation behind dams when the dam is closed, resulting in episodic increases in turbidity when flow is released.¹¹⁶

Together, these changes can affect downstream aquatic habitat and ecosystem health by altering nutrient availability, organic matter supply, turbidity, light penetration, oxygen conditions, and contaminant exposure. In some cases, this may contribute to food-web disruption, reduced habitat

quality for fish and benthic organisms, and increased mercury exposure for fish, wildlife, and people who rely on aquatic foods.^{127–129}

6.2.3 Impacts to Streamflow

Damming and diversion fundamentally alter river flow regimes across multiple timescales, depending on dam operation (Figure 6-5). On shorter timescales, hydroelectric dams artificially control discharge, with flow regulated by energy demand rather than by natural variability in hydrological conditions. Over the long term, streamflow may decrease due to the diversion of water away from the system or as a result of increased evaporative losses from reservoirs. This is less pronounced in beaver dams, which tend to delay and attenuate flow rather than actively regulate it, except in cases of dam failure, where rapid drainage may occur.

Additional impacts arise from changes in storage and connectivity across the landscape. Increased upstream storage may lead to flooding and, in some cases, spill-over into adjacent systems, while reduced contributions from disconnected hydrological units can further decrease downstream flow. Changes to ice formation and melt dynamics may also alter the timing and magnitude of seasonal discharge.

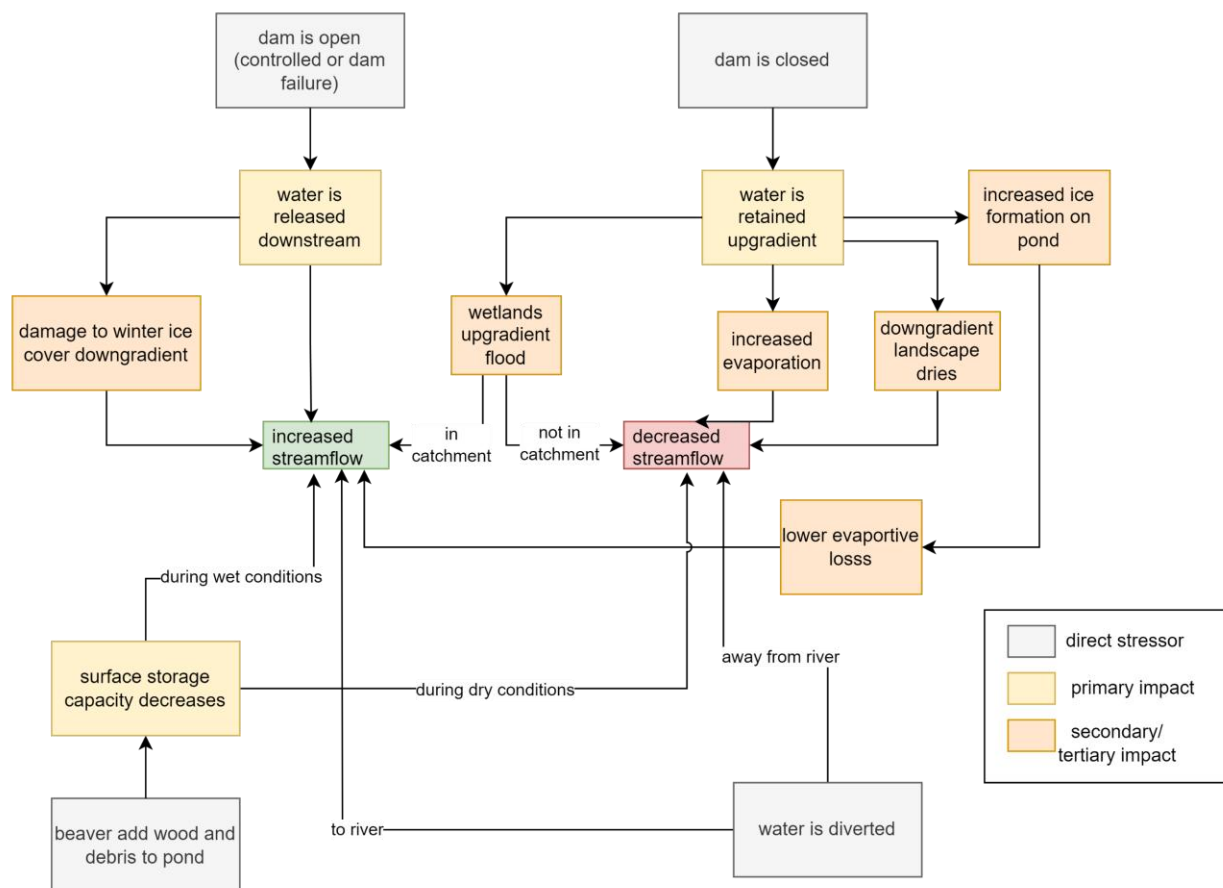


Figure 6-5: Potential alterations to streamflow derived from hydrological impacts associated with damming and diversions.

6.3 Mine Dewatering

Mine dewatering involves removing water from an active mine or quarry to depress the water table below the mineable resource, enabling safe access for resource extraction. Pumped water is typically diverted outside the mine footprint to nearby rivers or water bodies. Unlike other disturbance types, dewatering induces a persistent downward *hydraulic gradient*, drawing water vertically and laterally from surrounding hydrological units into deeper subsurface systems (Figure 6-6). As a result, impacts are dominated by reductions in storage and connectivity across affected areas.

Given the limited availability of studies on dewatering within the RAA or comparable peatland-dominated systems, the De Beers Victor Diamond Mine (Victor Mine) in the Hudson Plains, located approximately 90 km west of Attawapiskat, provides the basis for evaluating hydrological impacts in the following sections.

Storage (S_{sw} , S_{gw}): Dewatering results in substantial reductions in subsurface and surface water storage within affected hydrological units. The imposed downward *hydraulic gradient* draws water from peat, soil, and shallow groundwater systems into deeper bedrock, as water is removed by mining activities, leading to declines in water table position and reduced surface water extent.

At the Victor Mine, over the mine's lifespan, downward groundwater flow increased by one to three orders of magnitude relative to baseline conditions, resulting in water table declines of between 1–4 m in peatland systems, particularly where the protective *aquitard* (the marine sediment and other bedrock with low water flow) is thin or absent.^{37,65,130} Modelled results suggest an average ~75 cm decline in wetland water tables within the impacted areas.¹³¹ Hydrological units that rely primarily on internal storage (e.g., bogs) are therefore particularly sensitive to both immediate and long-term storage losses, while systems receiving external inflows (e.g., fens) may exhibit more moderate responses.^{37,88}

Over the long term, continued dewatering and storage depletion can result in ground subsidence, particularly in organic hydrological units, where soil structure is dependent on saturated conditions. As a result, the hydrological response of these systems changes over time, with reduced capacity to retain water leading to increased ponding during wet conditions and more rapid declines in water levels during dry periods.^{98,130}

Connectivity (L_{in} , L_{out} , G_{in} , G_{out}): Dewatering strongly alters landscape connectivity by redirecting water movement vertically (downwards) rather than laterally.

At the Victor Mine, dewatering resulted in a significant decrease in the amount of water moving across the landscape. While reference systems (non-impacted peatlands) transmitted water to downgradient units approximately 95% of the time during the non-frozen season, dewatered systems transmitted flow only 55–75% of the time where protective layers of marine sediment were thicker, and less than 25% of the time where marine sediments were thin or absent.¹³² Detailed research at the Victor Mine characterized dewatering impacts extending approximately 5 km from the mine pit where dewatering occurred.¹³²

Additional regional modelling efforts completed as part of De Beers' compliance monitoring estimated that dewatering effects in the underlying bedrock could extend up to 18 km from the point of dewatering¹³³; however, this broader modelling likely did not fully capture the subsurface complexity identified in detailed field studies. As a result, the full radius of hydrological influence remains uncertain and may extend beyond the area characterized by site-specific investigations.

Evapotranspiration (ET): The decrease in water availability associated with dewatering likely reduces rates of evapotranspiration due to a decrease in open water and in near-surface moisture, particularly in peatland systems, where vegetation depends on shallow water tables. Reduced surface moisture limits plant water uptake and may also promote longer-term changes in vegetation composition and peat structure. At the Victor Mine, evapotranspiration in impacted peatland hydrological units decreased by approximately 13–14% relative to reference conditions.^{37,134} Theoretically, if shrub or tree growth were enhanced due to drying, transpiration could increase; however, there was no evidence of increased tree growth within the Victor Mine dewatered area in the single study available.¹⁴¹

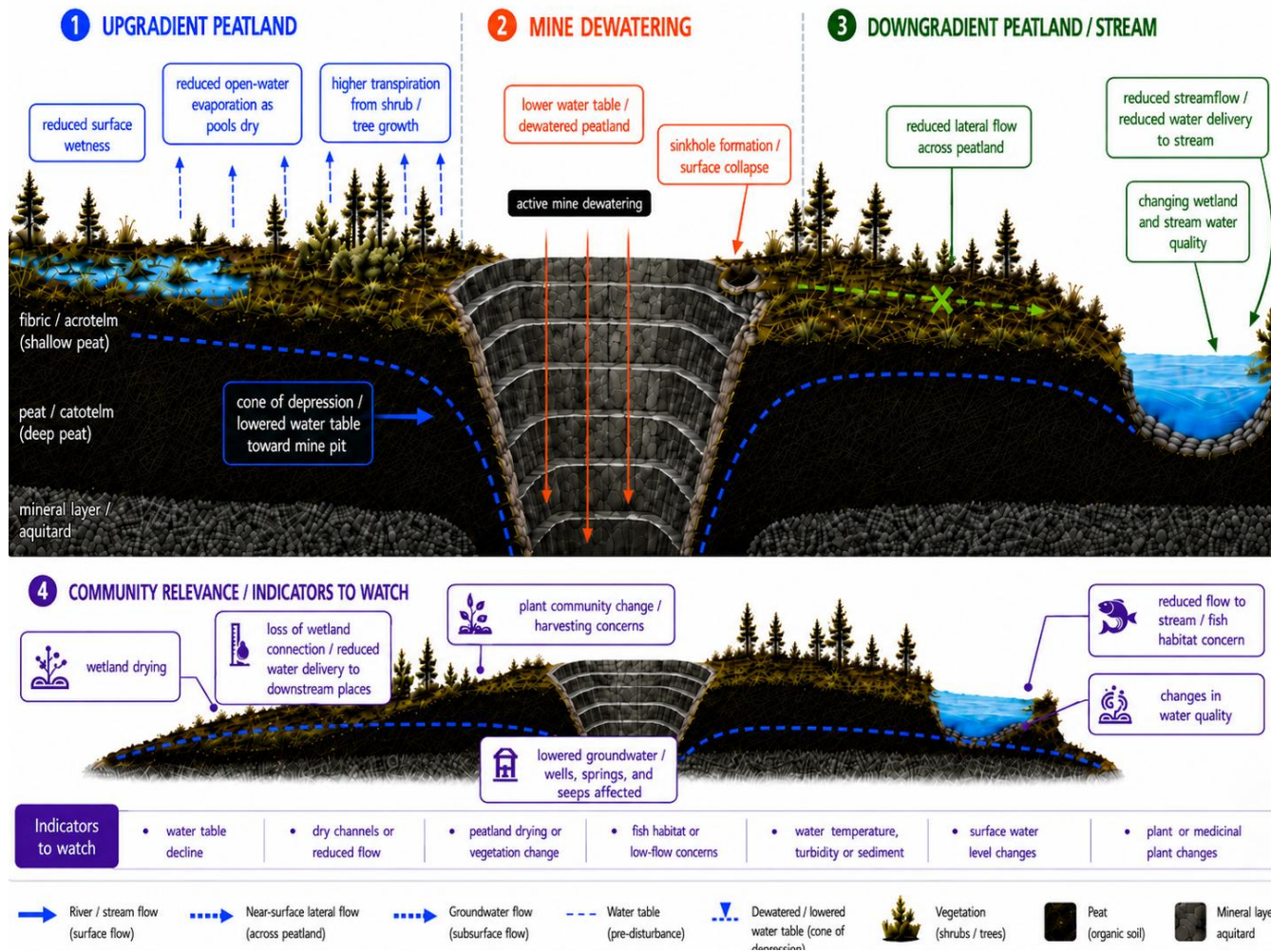


Figure 6-6: Water balance components impacted by mine dewatering in dewatered peatland and open water hydrological units, as well as adjacent non-dewatered hydrological units.

Dewatering Volumes

The volume of water required to maintain mineable conditions depends on several factors, including initial water table depths, climatic conditions, hydraulic conductivity of soils and bedrock, presence of fractures or karst features, and mine geometry and depth.^{135,136}

Prior to mine development, dewatering requirements are typically estimated using numerical groundwater models, such as MODFLOW or FEFLOW, which incorporate site-specific data on topography, geology, aquifer properties, and projected mine design.^{135,136} Mixing models may also be used to estimate the relative contributions of different water sources.¹³⁷ However, the majority of these models were originally developed for landscapes not characterized by organic soils; the availability of models appropriate for predicting dewatering effects across the broader RAA remains limited. Existing groundwater models are generally developed for individual projects and rely on detailed site-specific hydrogeological data, which are sparse across much of the region.

The required volume of water removed to maintain mineable conditions is also highly site specific, and data were only readily available for the De Beers Victor Mine operation. At the Victor Mine, water volume requirements increased from 8,000–18,000 m³/day in the first year of operation, to 80,000–85,000 m³/day, which was reached by year five at a mine depth of ~90 metres, after which rates fluctuated more in relation to water availability than to increasing depths.^{88,132}

6.3.1 Mining Approaches

Dewatering requirements and associated hydrological impacts occur in both open pit and underground (closed shaft) mining operations. While the physical layout of these mine types is different, the fundamental mechanism of impact is the same: the removal of water to maintain a dry state in the mine pit or shaft.

The source of water that is removed generally differs between open pit and underground mines. Open pit mines receive both surface and groundwater inflows and typically require dewatering across a larger surface area. In contrast, underground mines primarily intercept groundwater through shafts and tunnels at depth. However, dewatering rates are not consistently lower in underground systems, as they are strongly controlled by hydrogeological conditions, including aquifer connectivity, fracture networks, and the presence of karst features.¹³⁷

In both cases, dewatering creates a persistent downward hydraulic gradient that draws water from surrounding hydrological units into the subsurface. As a result, the impacts described for open pit mining are broadly applicable across mining approaches, with variability driven primarily by local geological and hydrological conditions rather than mine type alone.

At the Victor Mine, the large role of site-specific hydrogeology was evidenced most notably by the development of collapse features (sinkholes and subsidence pits) and dry ponds (exposed areas of bare soil) near the mine (Figure 6-7). Some of these features, activated due to dewatering, formed depressions between 4–7 m deep in organic hydrological units.²³ The presence of these collapses indicates strong vertical connectivity between near-surface systems and deeper subsurface pathways.

The known presence of fractured bedrock in the Precambrian Shield as well as *karstic* limestone formations throughout the Hudson Plains suggests that collapse features are possible throughout the RAA in a dewatering scenario. This is important because fracture and *karst* flow systems can be spatially *heterogeneous* and difficult to identify from surface conditions alone; their hydraulic significance is commonly assessed using subsurface investigations such as boreholes, geophysics, pumping tests, and tracer studies.¹³⁸

Preferential flow is increasingly recognized as an important driver of watershed hydrology in peatland and lake systems,⁴⁰ and fractured bedrock and *karst* systems have been shown to function as significant *aquifers* in comparable regions, including the Northwest Territories, the Abitibi region of Quebec, and the Muskoka–Haliburton region of Ontario.^{12,139–141} As a result, whether or not these subsurface features are present is likely to exert a stronger control on hydrological response than mine type alone. In mining contexts, this creates uncertainty for dewatering assessments, because reliable estimates of groundwater inflow and hydraulic connectivity depend on site-specific hydrogeological investigations, including pumping tests, monitoring wells, and characterization of fracture or conduit-controlled flowpaths.¹⁴²

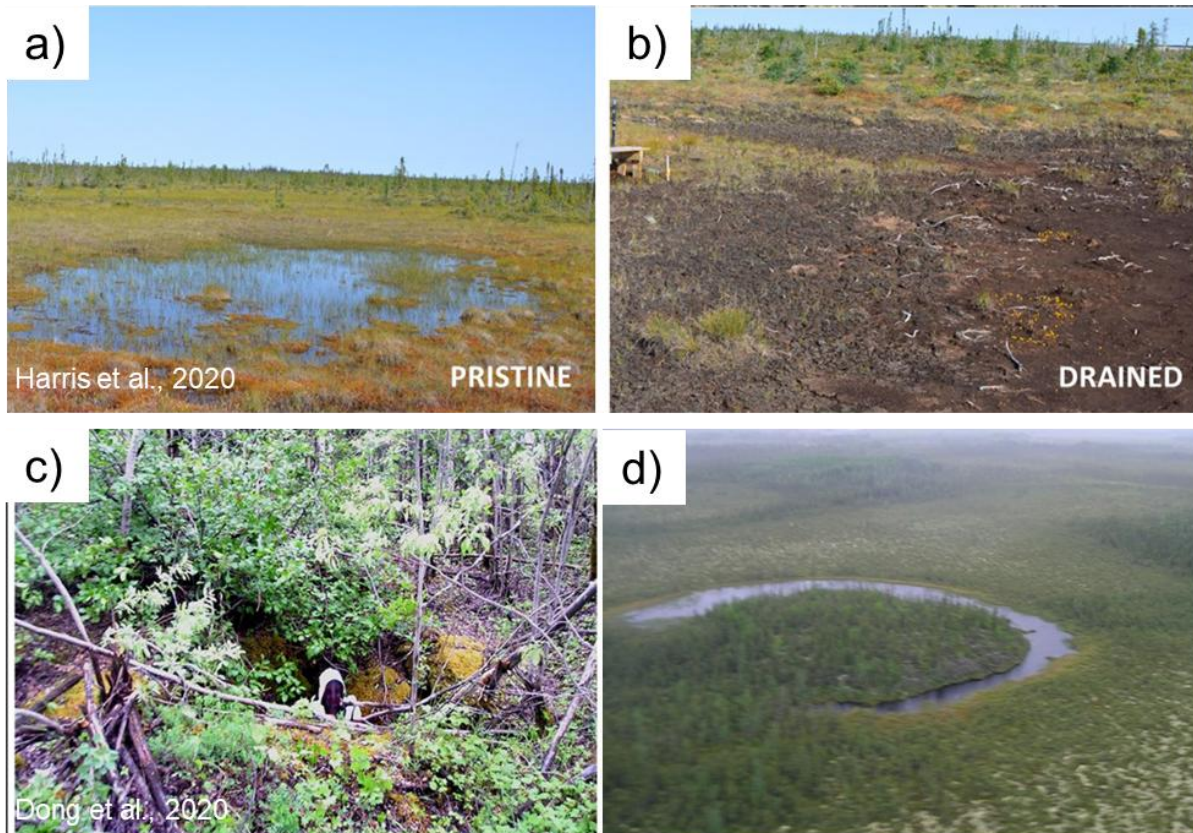


Figure 6-7: Key karstic and karst-indicative features around the De Beers Victor Diamond Mine including (a) and (b) a dry pond formed 5 km from the point of dewatering, (c) a large collapse feature near Attawapiskat River, and (d) a nearby sinkhole at a bioherm in the unimpacted landscape.

6.3.2 Potential Changes to Water Quality

Dewatering alters water quality through changes in groundwater–surface water interactions and soil drying. Reduced connectivity between hydrological units limits the transport of groundwater-derived *solute*s, while drying of organic soils can increase decomposition and release DOC and nutrients during rain or snowmelt events.

At the Victor Mine, decreasing concentrations of groundwater-derived solutes (e.g., calcium and chloride) and increasing DOC were observed, likely as a consequence of reduced upward groundwater flow and increased peat decomposition.¹³² Although impacts on stream water quality remain uncertain, peatland drying in general has been associated with increased nutrient release, sedimentation, and DOC export in streams.¹⁴³

6.3.3 Impacts to Streamflow

Dewatering results in overall reductions in streamflow within affected watersheds (Figure 6-8). In addition to direct water losses from streams, lower lateral connectivity and the loss of water from ground and surface water storage also result in less water flowing from hydrological units to streams.

At the Victor Mine, reduced landscape connectivity resulted in delayed and decreased spring flow peaks, as snowmelt instead infiltrated to replace depleted groundwater storage. Modelling results suggest reductions of 15–30% in catchment runoff (lateral flow) and up to 66% reductions in river flow under full watershed dewatering scenarios, with spring flows particularly affected.¹³¹

Water extracted from the dewatering radius must be discharged to external systems, potentially increasing flow in receiving water bodies; however, limited information is available on the hydrological implications of this redistribution.

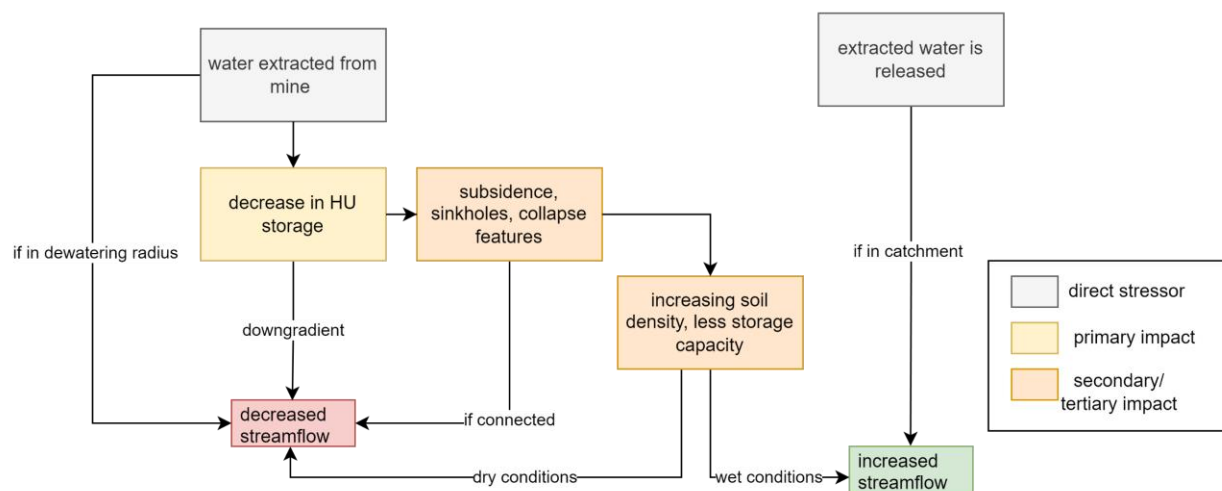


Figure 6-8: Potential changes in streamflow derived from hydrological impacts associated with dewatering in non-permafrost environments.

6.4 Climate Change

Hydrological impacts associated with climate change in the RAA (Figure 6-9) are primarily attributed to changes in air temperature and precipitation patterns. Northern latitudes are experiencing accelerated warming, with increases of up to 5°C reported in parts of the Hudson Plains.^{108,125} There is a high degree of uncertainty around changes in precipitation frequency, intensity, and timing in climate change scenarios. Many more recent modelling efforts predict increases in precipitation, particularly summer and fall rainfall; however, volume estimates range too significantly to draw quantitative conclusions.^{119,144–146}

Unlike discrete disturbances, climate change acts continuously across all hydrological units, modifying the balance between storage, landscape connectivity, and evapotranspiration at very large scales. These changes are altering seasonal hydrological processes, including snow accumulation and melt, evapotranspiration, and the distribution of water storage across the landscape.

Storage (S_{sw} , S_{gw}): Climate-driven changes in temperature and precipitation alter both the timing and magnitude of water storage changes across the landscape. Earlier and more rapid snowmelt has been observed across the region. In recent decades, snowmelt occurs on average 4–8 days earlier and completes more quickly than under historical conditions.^{57,120} This results in earlier seasonal increases in lateral flow across the landscape and may also lead to more rapid depletion of surface and groundwater storage early in the growing season. Earlier melt can also decouple snowmelt from the timing of frost thaw, thereby limiting infiltration and groundwater storage replenishment that would otherwise buffer dry summer conditions, and potentially worsening summer water deficits.¹⁴

Rising temperatures and longer growing seasons may increase evapotranspiration, which, in the absence of sufficient increases in precipitation, will reduce water storage across hydrological units.^{42,147} It has been estimated that precipitation would need to increase by approximately 25% to offset these additional predicted losses.¹⁴⁸

In permafrost-affected hydrological units, warming promotes *active layer* deepening^{144,146} and permafrost thaw,¹⁴⁹ increasing the proportion of liquid water stored in the subsurface. Thawing peat plateaus and palsas may transition into thermokarst features such as ponds, lakes, and fens, increasing surface and subsurface storage locally while altering the spatial distribution of water across the landscape.^{54,150}

Where drying persists over the long-term, particularly in organic soils, reductions in storage may occur due to peat decomposition and subsidence. Irreversible soil collapse can reduce the storage capacity of soil and alter hydrological responses.¹⁵¹

Connectivity (L_{in} , L_{out} , G_{in} , G_{out}): Changes in storage directly influence hydrological connectivity across the landscape. Earlier snowmelt may increase lateral flow earlier in the season, but reduced water availability later in the growing season can decrease connectivity between hydrological units.

Projected increases in precipitation variability, including more intense rainfall events, may result in more episodic connectivity, with short periods of high flow separated by longer periods of disconnection.⁸² Where drying occurs, reduced storage will decrease the flow of water to downgradient systems, decreasing both surface and groundwater contributions to streams.^{84,145} In some cases, a lack of water near the surface may cause deeper groundwater to begin to replace it.⁸⁴

In permafrost environments, thaw increases *active layer* thickness and can enhance subsurface connectivity, promoting increased lateral and groundwater flow. However, these effects are highly variable and depend on landscape position, with some areas experiencing increased connectivity and others becoming more disconnected due to drying or drainage reorganization.^{144,146}

Evapotranspiration (ET): Evapotranspiration from both vegetation^{48,152} and open water^{144,145} is expected to increase under warming conditions due to longer growing seasons, higher temperatures, and increased vegetation growth. These increased rates of evapotranspiration can lead to further reductions in water storage.^{42,147,153}

Shifts in vegetation communities in response to climate change may further amplify these effects. Drying may temporarily reduce transpiration due to drought stress, but over the long term it could promote shrubification and afforestation, increasing transpiration and interception both directly and through the reduction of non-vascular vegetation cover, which normally regulate evaporation in peatland systems.^{34,154} In permafrost regions, thaw-induced expansion of open water and saturated areas may increase evaporation locally, while increased vegetation growth in drier areas may further enhance transpiration.

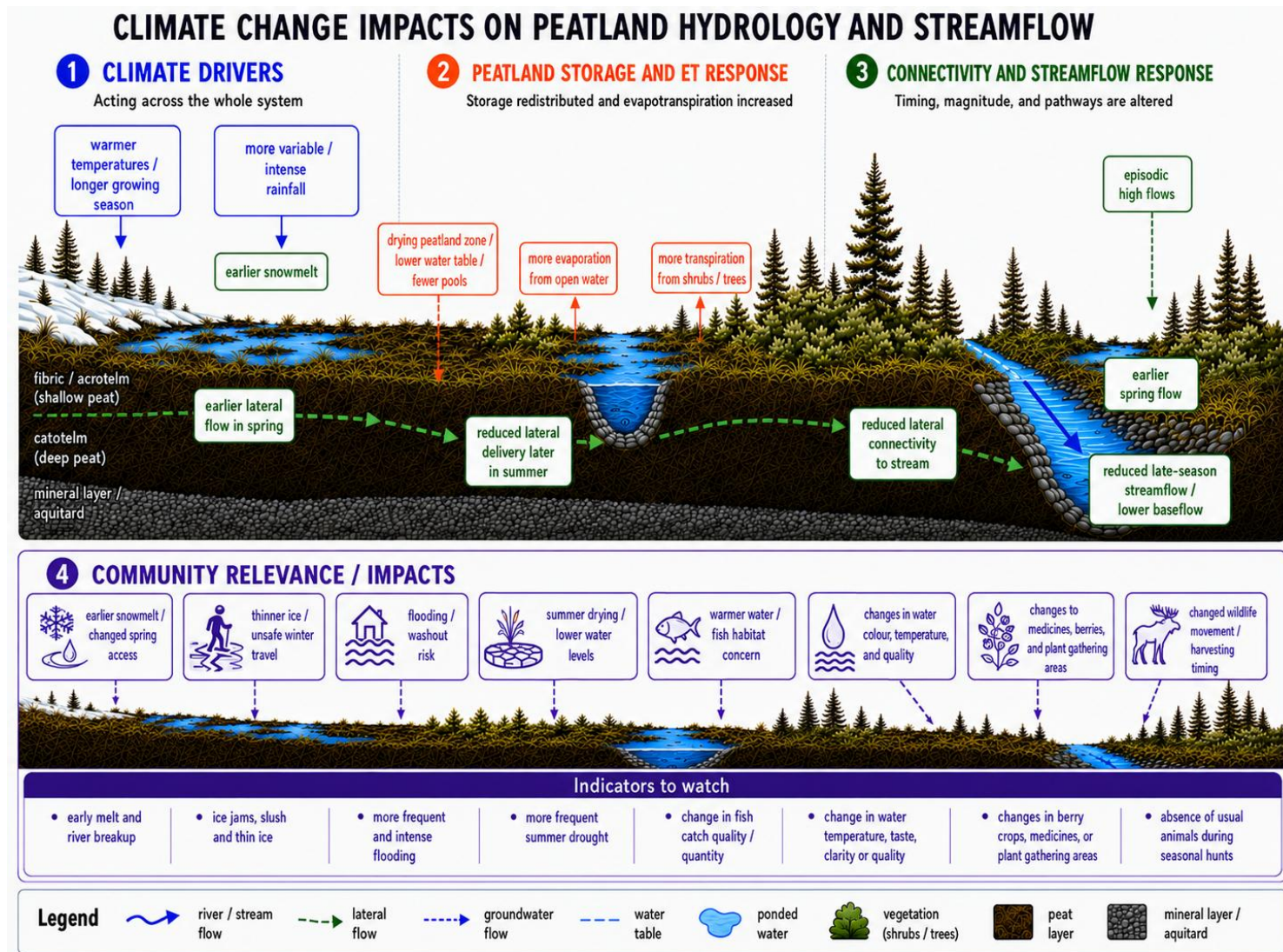


Figure 6-9: Water balance components impacted by climate change across different landscape elements.

6.4.1 Potential Changes to Water Quality

Climate change is expected to influence water quality through changing water temperatures and altering land and stream biogeochemical processes. Increased air temperatures will lead to warming of surface waters, potentially reducing habitat suitability for cold-adapted species.^{125,155,156} Higher temperatures and increased drying may alter nutrient cycling and DOC production in decomposing soils. Subsequent precipitation events may result in increased flushing of these materials to downstream systems, contributing to greater variability in water quality.^{82,144}

Where increased temperatures and elevated nutrient availability occur together, the risk of algal blooms and related impacts to aquatic ecosystems can increase. Elevated phosphorus is a primary cause of lake eutrophication and algal bloom development, while warming can further favour bloom formation by increasing water temperatures, strengthening stratification, and altering oxygen and nutrient cycling.^{157,158}

6.4.2 Impacts to Streamflow

Climate change is expected to increase variability in river flow across the RAA, changing the pattern of streamflow across different seasons (represented by a *hydrograph* of river flow over time; Figure 6-10).¹⁴⁶ As introduced in Section 3.3, streamflow in the RAA is typically highest after snowmelt following low winter flows. Flows generally decline from spring through summer, as water storage is depleted and evapotranspiration increases, with smaller rainfall-driven pulses and sometimes a secondary fall increase before freeze-up.

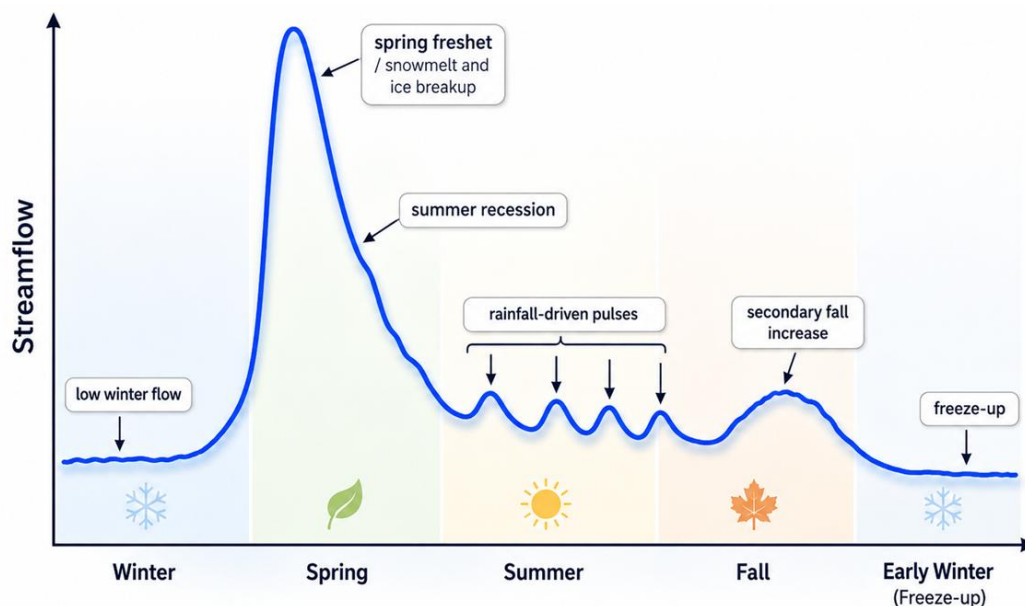


Figure 6-10: A hydrograph showing the typical pattern of streamflow in the RAA, which is lowest in the winter, peaks in spring due to snowmelt, and increases after rainfall events in the summer and during fall cooling.

With projected climate change scenarios (Figure 6-11), earlier snowmelt will likely cause streamflow to peak earlier, with shifts of up to one month observed or predicted in some rivers.^{108,131} Earlier melt over still-frozen ground may also contribute to more rapid and higher peak flows, particularly where ice jamming occurs, increasing flood risk in coastal communities.^{14,50,159,160}

During summer months, increased evapotranspiration and longer growing seasons may reduce streamflow, as precipitation will increasingly infiltrate to replenish groundwater storage rather than flowing laterally downgradient as runoff.^{48,131} In the fall, an increase in the proportion of precipitation that falls as rain rather than snow is anticipated to lead to a secondary peak in river flow,¹³¹ while warmer winter conditions may increase overwinter discharge.

Model projections suggest overwinter flow may increase by 7–14% in some rivers.^{66,120} Overall, climate change is expected to produce more variable and less predictable river flow regimes across the region (Figure 6-12).

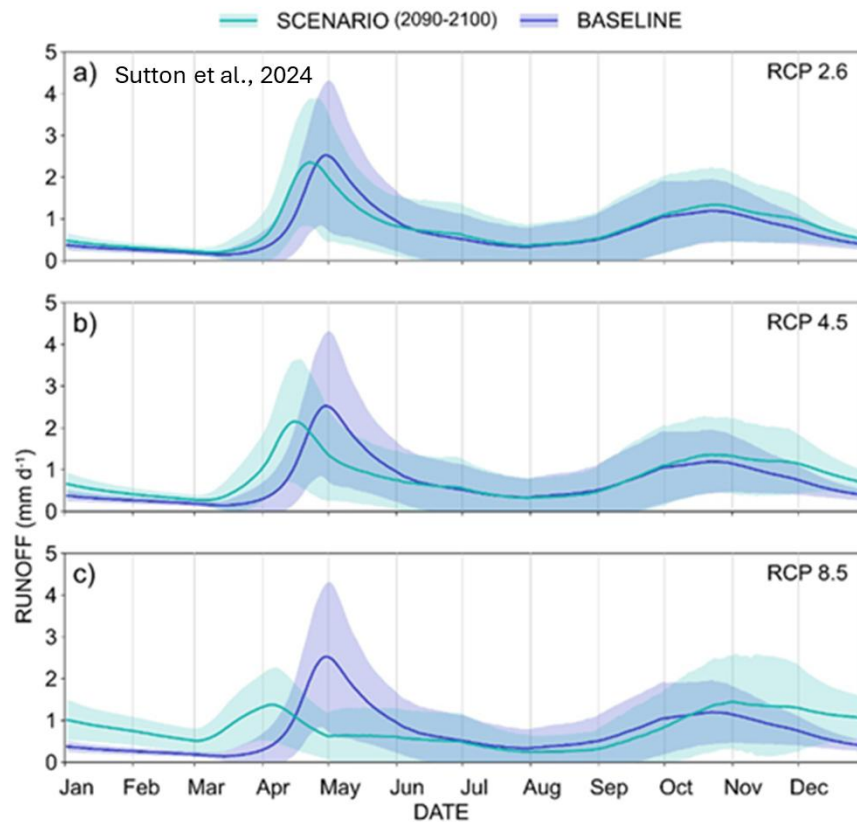


Figure 6-11: Modelled changes to streamflow in the Attawapiskat River for each month under a) RCP 2.6, b) RCP 4.5 and c) RCP 8.5 climate scenarios.

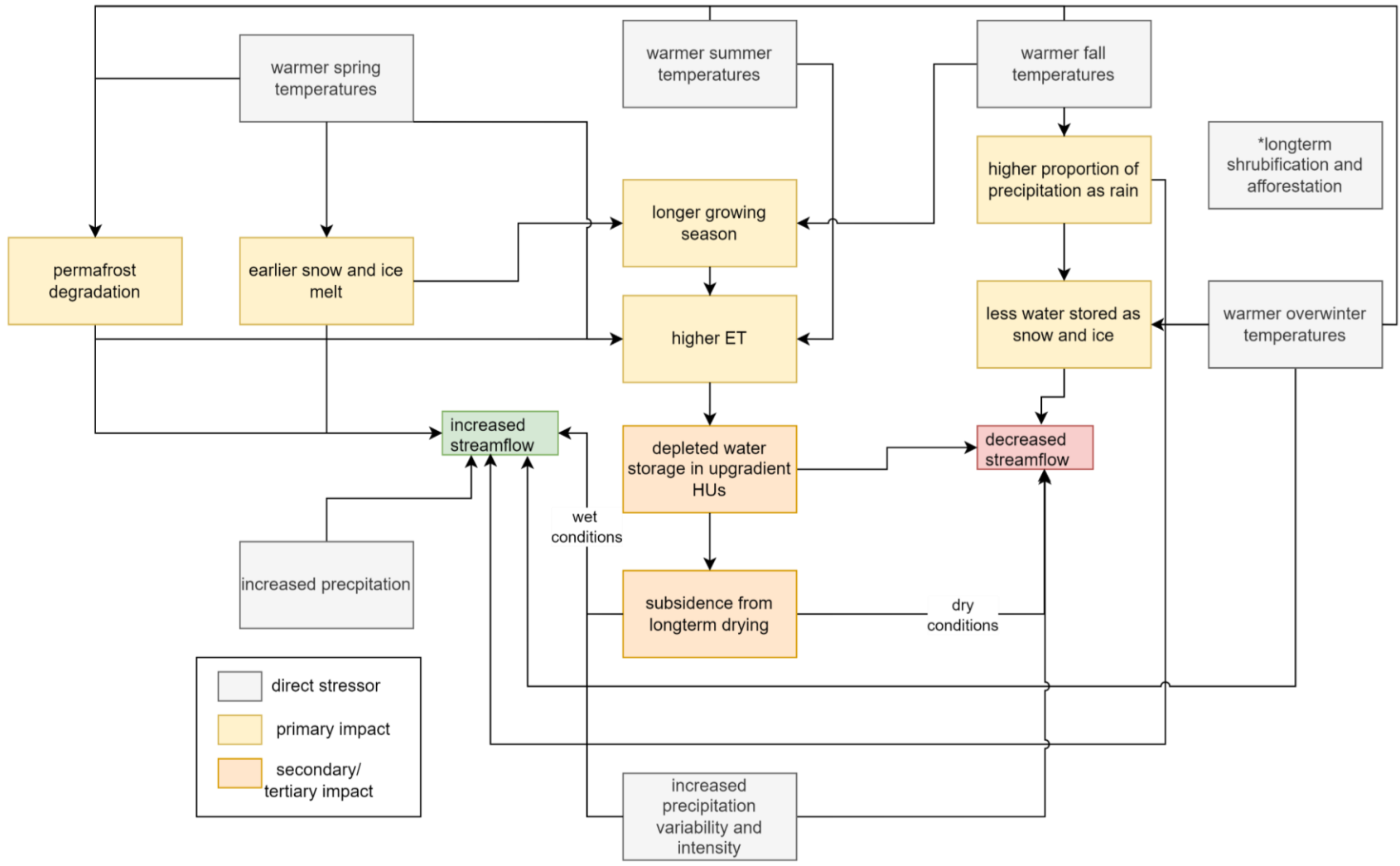


Figure 6-12: Potential alterations to streamflow derived from hydrological impacts associated with climate change in permafrost and non-permafrost environments.

6.5 Wildfire

Wildfire is a natural part of boreal ecosystem succession. However, human activities are increasing both the frequency and intensity of fires, necessitating the inclusion of wildfire as a disturbance within the RAA.

Fire occurrence is controlled by a combination of local weather during ignition, water availability on the land, fuel load (e.g., trees and woody debris), and land cover.¹⁶¹ No wildfire studies directly conducted in the RAA could be found. Studies from elsewhere in the Canadian boreal forest show an overall increased risk of wildfire in drier conditions and in treed hydrological units, including forests, swamps, and treed bogs and fens, with species such as black spruce, tamarack, and white cedar particularly susceptible due to their shallow rooting and thin bark.^{162,163} As a result, wildfire risk is generally higher in the Precambrian Shield portion of the RAA, where historical fire return intervals are shorter (50–200 years) compared to the Hudson Plains, where historical fire return intervals are longer (150–6,000+ years).³⁰ The potential shortening of return interval as well as potential increase of wildfire severity is a research gap in the RAA.

Hydrological impacts from wildfire (Figure 6-13) are largely associated with the burning of vegetation and near-surface organic soils, which changes both the structure and the vegetational succession of the landscape.

Storage (S_{sw} , S_{gw}): Wildfire changes water storage primarily through the burning of surface organic layers, which changes the soil structure. The removal of organic material reduces the depth of living and poorly decomposed soils at the surface and exposes denser underlying soils, often resulting in shallower water tables and increased soil moisture in the short term.^{23,154,164}

In permafrost hydrological units, the loss of insulating vegetation and organic soils post-burn can promote thaw, increasing active layer thickness and releasing previously frozen water into the subsurface.^{64,75,165} This may increase local storage in the short term through the formation of thermokarst features such as ponds and saturated depressions. Over longer timescales, however, the combined effects of soil combustion, compaction, and thaw can reduce storage capacity, resulting in greater variability in water storage.

Connectivity (L_{in} , L_{out} , G_{in} , G_{out}): Changes in soil structure and surface conditions following wildfire can alter hydrological connectivity. The exposure of denser soils, combined with the development of hydrophobic (i.e., water-repelling) layers, can increase surface runoff while also reducing subsurface lateral flow.¹⁶⁶ This may increase landscape connectivity in the short term by promoting rapid runoff and lateral water movement. However, longer-term changes depend on vegetation recovery and soil development, with connectivity potentially decreasing as systems dry.

Evapotranspiration (ET): Evapotranspiration is initially reduced following wildfire due to the loss of vegetation, particularly canopy cover, which decreases interception and transpiration. However, increased soil temperatures resulting from reduced shading may enhance evaporation from exposed soils.¹⁶⁷ Over time, evapotranspiration recovers as vegetation re-establishes. Early successional species such as mosses, grasses, and shrubs may establish within 1–10 years,

reducing soil temperatures and stabilizing evaporation rates.^{34,163} In some cases, fire may alter long-term vegetation composition, promoting fire-adapted species such as jack pine (*Pinus banksiana*) and potentially limiting the re-establishment of wetland hydrological units.⁶⁷

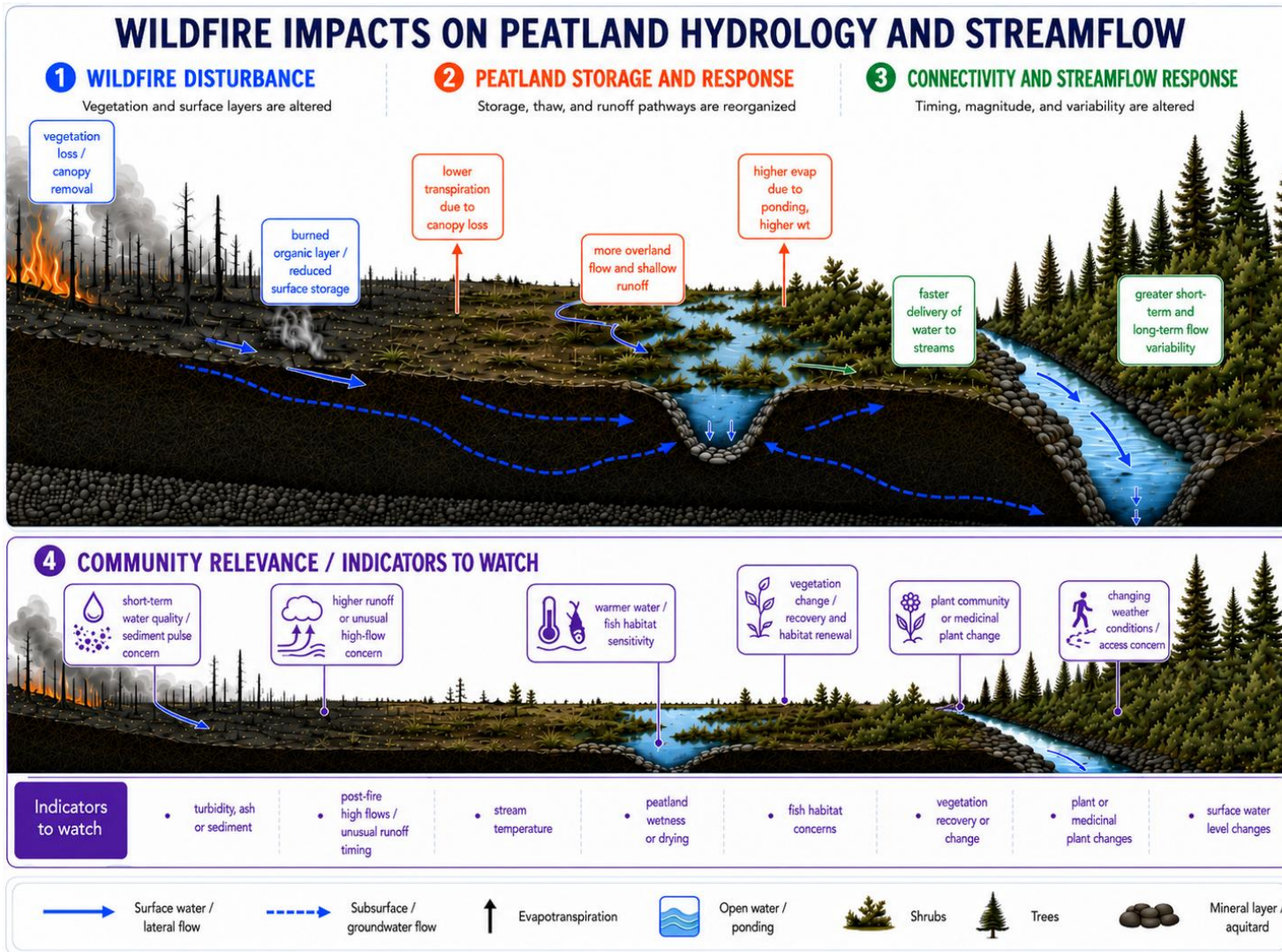


Figure 6-13: Water balance components impacted by wildfire across different landscape elements.

6.5.1 Impacts of Wildfire on Water Quality

Wildfire can significantly impact water quality through the release of compounds from burned soils. Elevated concentrations of sediments, DOC, nutrients, mercury, strontium, and arsenic have been observed in downgradient rivers following fire,^{34,164,166,168} with potential for increased bioaccumulation of mercury and other toxic metals in downgradient aquatic ecosystems.¹⁶⁹

Limited research available within northern watersheds shows high variability in changes to water quality after wildfire. In some studies, impacts were typically most pronounced in the years immediately following fire and were short-lived, while in others peaks were delayed but persisted for up to a decade or more.^{170,171} The timing, magnitude, and downstream ecological impacts of these changes are likely highly site-specific. Consequently, the lack of studies within the RAA itself represents a significant knowledge gap.

6.5.2 Impacts to Streamflow

Wildfire is generally associated with increased streamflow in the short term (Figure 6-14), prior to vegetation re-establishment.¹⁷² This is primarily due to a net reduction in evapotranspiration and increased soil moisture following the removal of vegetation and top organic layers.¹⁶⁴ Higher-severity and larger fires have been shown to produce greater increases in annual streamflow compared to smaller, low-intensity burns.¹⁷² In addition, reduced storage capacity in the soils and increased runoff may result in higher peak flows and greater variability in streamflow, particularly during periods of low water availability.¹⁶⁴

The cumulative impacts of increasing wildfire frequency and severity, particularly within the RAA, remain uncertain and have not been well quantified.

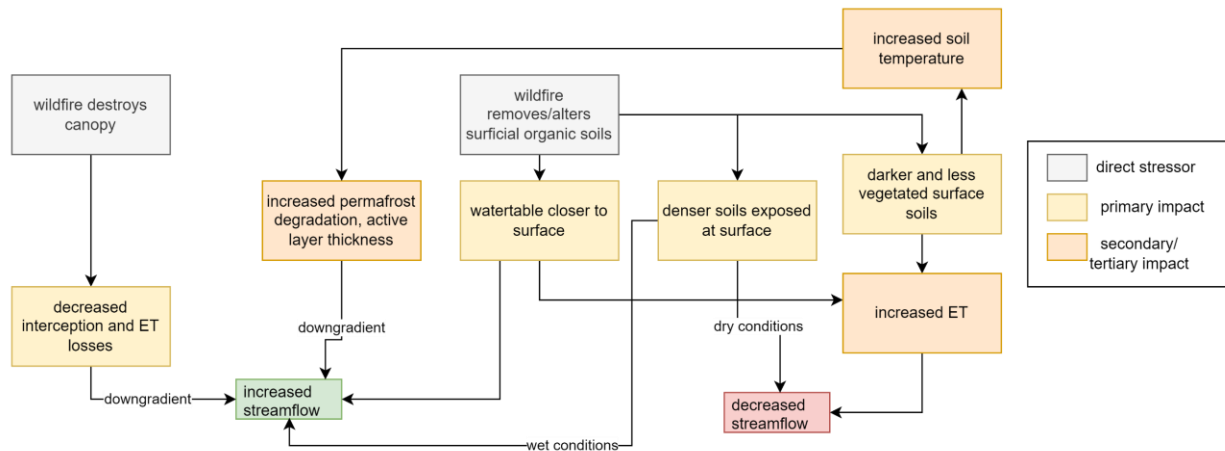


Figure 6-14: Potential alterations to streamflow derived from hydrological impacts associated with wildfire in permafrost and non-permafrost environments.

6.6 Contaminant Releases

Contaminant releases (Figure 6-15) represent a primarily water quality-driven disturbance within the RAA and are not expected to significantly alter runoff volumes. They are included due to the high potential of contaminant release associated with resource extraction activities and the strong hydrological connectivity of this landscape.

6.6.1 Accidental Leaks and Spills

Accidental contaminant releases may occur through a range of activities projected in the RAA, including but not limited to surface tailings leaching, process chemical spills, industrial waste storage leaks, transportation accidents, and wastewater discharge.¹⁸ Historical contaminants of concern to the communities of the region include hexavalent chromium, PCBs, petroleum hydrocarbons, pesticides, methyl mercury, and other heavy metals.¹⁷³⁻¹⁷⁶

Although limited studies exist within the RAA, legacy contamination associated with Mid-Canada Radar Line sites demonstrates the potential for long-term persistence of contaminants in this environment.¹⁷⁴⁻¹⁷⁶ At Anderson Island near Fort Albany, elevated concentrations of petroleum hydrocarbons were detected up to one metre below the surface more than a decade after remediation efforts.¹⁷⁴ Similarly, elevated concentrations of PCBs (up to 21,000 ppm in soils and 550 ppm in plants), DDT, and lead have been documented.^{175,176} These contaminants have also been detected in wildlife and local food systems, indicating long-term storage and remobilization through soils and hydrological pathways.

Contaminant movement in the RAA is governed by the surface and subsurface pathways that link hydrological units. A better understanding of where water moves through the landscape can therefore help reduce impact risk by identifying high-risk flowpaths, informing infrastructure siting, guiding monitoring network design, and improving spill-response planning.

However, contaminant transport in peatland-dominated systems is unlikely to be fully predictable or easily contained once a release occurs. Contaminants may move through connected surface-water pathways, shallow organic soils, deeper peat layers, mineral interfaces, fractures, and *preferential* subsurface flowpaths that link wetlands, lakes, and rivers. tracer (saltwater) test spill conducted on peatlands in the proximity to the Victor Mine showed rapid tracer movement through the organic soils at multiple depths, producing complex plume patterns controlled by local *hydraulic gradients*.¹⁷⁷ This indicates that contaminants may be difficult to contain and may be transported to river systems.

Better characterization of hydrological pathways can reduce uncertainty and support prevention, monitoring, and mitigation, but it cannot eliminate the risks associated with spills in landscapes where flowpaths are spatially variable, seasonally dynamic, and difficult to observe without detailed subsurface investigation.

6.6.2 Tertiary Wastewater Treatment

Wetland hydrological units have historically been considered for use in tertiary wastewater treatment, or wastewater polishing, because they can store water, attenuate flow, and support

physical, chemical, and biological processes that retain or transform certain contaminants after primary and secondary treatment. However, evidence from the RAA suggests that these systems may not reliably retain all contaminants.

An experimental study conducted in a patterned fen near the Victor Mine found that while some contaminants, such as nitrate and phosphorus, were retained within surface pools, others, including ammonium and sulphate, moved quickly through the wetland with minimal retention.^{178,179} The addition of water also increased lateral connectivity and accelerated water and contaminant movement through near-surface pathways, further reducing treatment effectiveness.¹³ Importantly, sulphate additions were associated with increased methylmercury production and transport, representing a significant ecological and human health risk.

6.6.3 Atmospheric Deposition

Atmospheric deposition represents both a local and potentially regional source of contamination within the RAA. Emissions from fuel combustion and smelting processes can result in the deposition of metals and other contaminants onto surrounding hydrological units over large areas. Additionally, historical emissions of sulfur- and nitrogen-containing compounds from smelters, coal-fired power plants, vehicles, and industry resulted in the formation of acid compounds in the atmosphere, acidifying rain, snow, and fog.

Studies near metal smelters in northern Quebec have documented elevated concentrations of copper, zinc, and lead in organic soils, forming spatial patterns extending 50–100 km from the source.^{180,181} More broadly, long-range atmospheric transport has been linked to elevated concentrations of persistent organic pollutants and mercury in the HBL since the 1980s, including compounds such as PCBs, DDT derivatives, chlordane, and hexachlorobenzene.^{47,182,183}

The acidification of precipitation (referred to as “acid rain”) remains relevant to the RAA as both a historical stressor and a potential future modifier of water chemistry, although direct studies within the RAA appear limited. Peer-reviewed studies from northeastern and central Ontario, generally near smelter operations in the Sudbury area, show that acid deposition has historically lowered lake and wetland pH, increased sulphate and metal concentrations, and contributed to biological changes in sensitive aquatic systems.¹⁸⁴ In peatlands, higher-deposition areas had more acidic waters and higher sulphate, mineral, and metal concentrations than lower-deposition areas, showing that acid rain can affect organic wetland systems as well as lakes.¹⁸⁵

Since reductions in sulphur emissions in these areas, many Ontario lakes have shown chemical recovery, including rising pH and alkalinity and declining sulphate and metal concentrations. However, recovery has often been incomplete because of legacy soil acidification, calcium depletion, changes in DOC, and climate-related hydrological variability.^{184,186}

For the RAA, these findings suggest that acidification sensitivity is likely greatest in low-buffering Shield headwaters, while areas influenced by marine or carbonate-rich sediments in the HBL may have a greater buffering capacity but may still experience deposition-related effects on sulphur cycling, metal mobility, organic acidity, and downstream water quality.

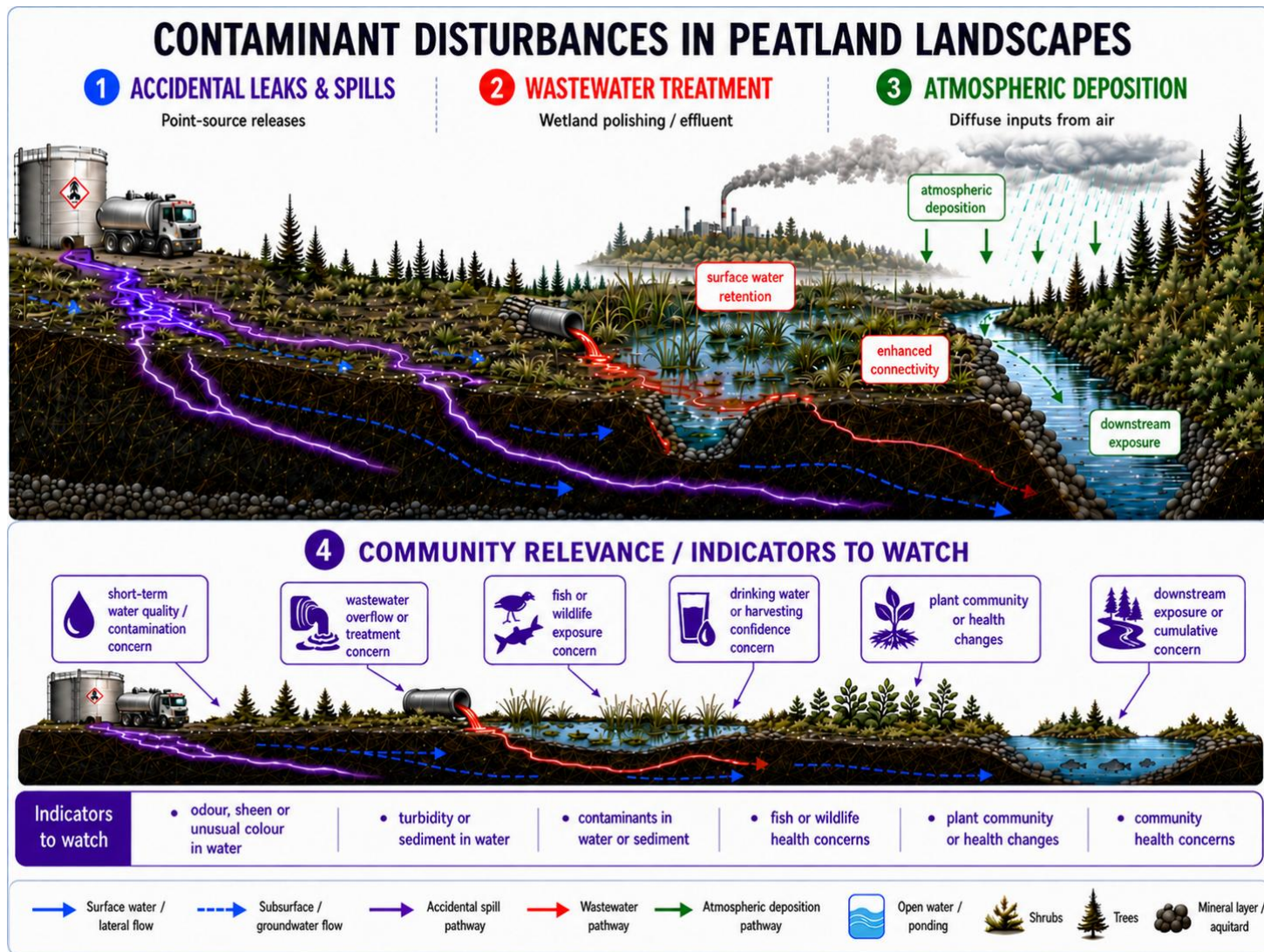


Figure 6-15: Water balance components impacted by contaminant release across different landscape elements.

6.7 Logging/Forestry

Forestry activities can affect hydrological processes through vegetation removal, soil disturbance, road construction, and, in some cases, drainage or dewatering prior to harvest (Figure 6-16). Like other disturbances, the magnitude and direction of hydrological change depend on the specific forestry practices used, the size and spatial arrangement of the impacted area, and the properties of the forest canopy prior to harvest.⁹⁶ The scale of impact is also influenced by the use of heavy machinery, the proportion of the area cleared, the presence or absence of riparian buffers, topography, soil type, and local environmental conditions, particularly meteorological conditions.¹⁸⁷

Storage (S_{sw} , S_{gw}): Forestry can alter water storage by changing the balance between precipitation inputs, evapotranspiration losses, soil infiltration, and runoff. Removal of forest canopy reduces the interception of rain and snow, allowing more precipitation to reach the ground surface. In winter, this can increase snow accumulation beneath harvested areas or redistribute snow across the land due to wind.^{188–190} Soil disturbance and compaction from heavy machinery can reduce infiltration capacity and hydraulic conductivity, reducing soil storage capacity (see Section 6.1 for impacts on soil capacity due to surface compaction).^{191,192} In wetland (especially peatland) areas, drainage or dewatering prior to harvest can also lower local water tables and reduce groundwater storage (see Section 6.3 for dewatering-related impacts).¹⁸⁷

Connectivity (L_{in} , L_{out} , G_{in} , G_{out}): Increased water storage from tree removal and soil compaction during harvest can increase surface runoff during wet conditions. However, soil compaction will likely decrease lateral flow during dry conditions. Additionally, forestry roads and access corridors may intercept, concentrate, or redirect surface and near-surface water, creating artificial flowpaths that alter the timing and location of water delivery to streams (see Section 6.1 for impacts of linear disturbances).^{188,193–195} Drainage networks and ditches can further alter groundwater–surface water interactions and may shift both the amount and seasonality of water delivered to streams (Section 6.3).^{188,193–195}

Evapotranspiration (ET): Forestry generally reduces evapotranspiration immediately following harvest due to the removal of trees and associated vegetation. Reduced canopy cover lowers transpiration rates, increasing the amount of water available for soil storage, groundwater recharge, or runoff.^{196,197} Clear-cut areas typically experience larger reductions in ET than selectively harvested areas because more canopy cover is removed. Over time, evapotranspiration may recover as vegetation regrows, although recovery rates depend on species composition, site wetness, and post-harvest management.

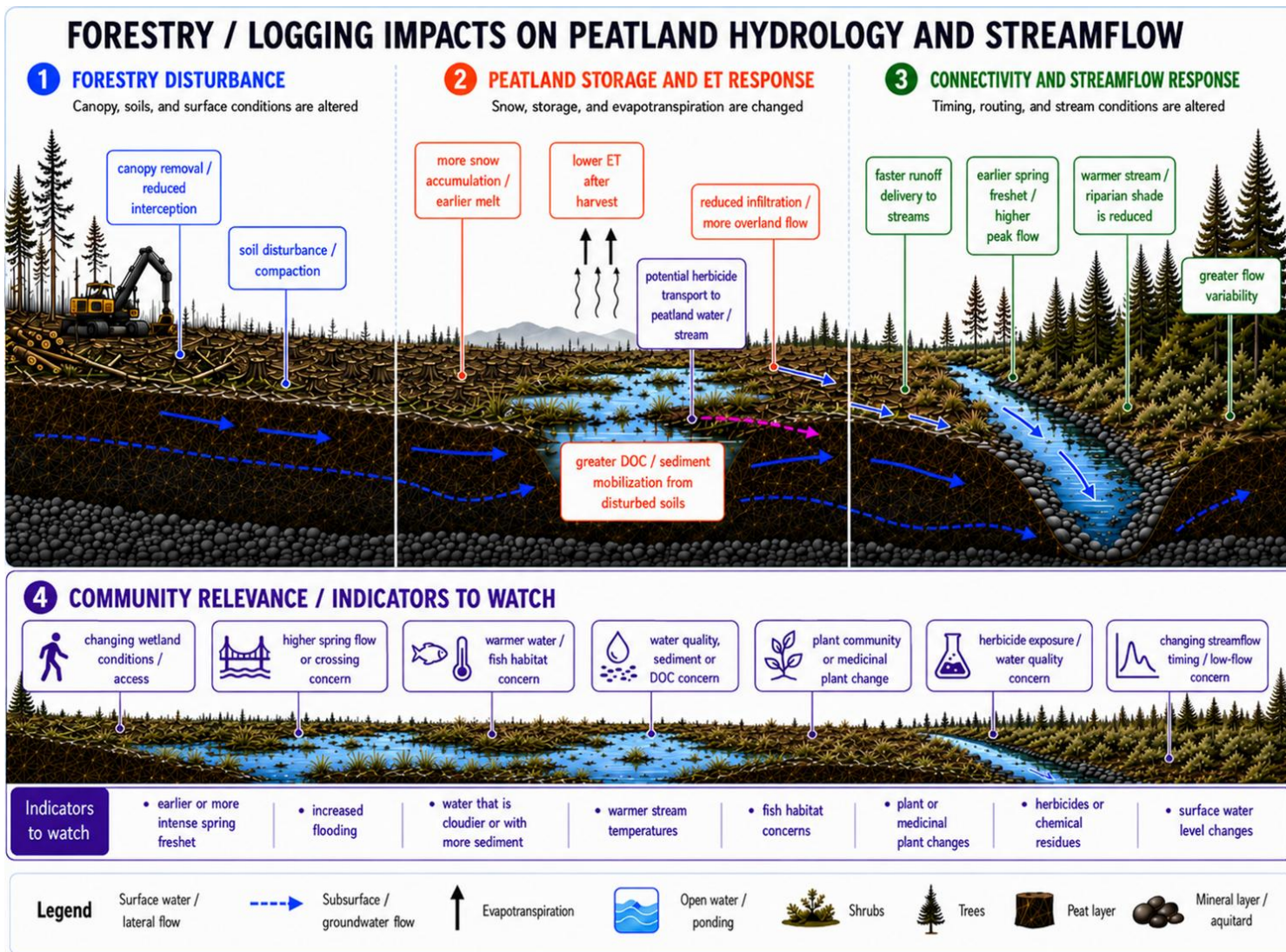


Figure 6-16: Water balance components impacted by contaminant release across different landscape elements.

6.7.1 Potential Changes to Water Quality

Forestry activities have been associated with increased DOC and nutrient release to downgradient rivers and aquatic systems, especially where organic soils are disturbed, drained, and then rewetted during the process of tree removal.^{187,198,199} Dewatering activities required to maintain harvest conditions can further increase sediment and DOC transport following rewetting (Section 6.3.2).¹⁸⁷ Removal or narrowing of riparian buffers can further reduce shading and increase stream temperature, particularly where harvesting occurs close to stream channels.²⁰⁰ In some forestry systems, prescribed fire may also be used to prepare sites for replanting, creating additional water quality concerns associated with vegetation removal, soil heating, and post-fire runoff processes (Section 6.5).²⁰¹

A historical community concern is the application of herbicides during the replanting process. Limited information is available on the effects of forestry herbicides on stream water quality specifically within peatland-dominated landscapes. Most forestry herbicide studies have been conducted in upland or mixed forest catchments, while peatland-specific evidence is more often related to drainage, harvesting, ditch maintenance, and nutrient or sediment export rather than herbicide residues directly. This creates uncertainty for the RAA, where high water tables, organic soils, wet channels, and connected drainage pathways may increase the potential for downstream transport during or after herbicide application.

Available evidence from forest systems shows that herbicides can enter surface waters during or shortly after application, especially where buffer strips are absent, aerial application occurs over water, or rainfall occurs soon after treatment.²³² Canadian guidance also notes that glyphosate has been detected in surface waters following forestry spraying in Manitoba, although reported half-lives in surface water were short (< 24 hours), suggesting rapid removal from the water column through degradation, photolysis, and adsorption to sediment or organic matter.²³³ Reviews of forestry herbicide studies report that residue concentrations in surface waters are generally low and do not persist for long periods when label directions and best management practices are followed, but higher short-term concentrations can occur where applications overlap with wet channels or where riparian buffers are insufficient.

6.7.2 Impacts to Streamflow

Forestry activities often result in an increase in annual streamflow and associated increases in upgradient water storage (Figure 6-17).^{184,191,193} Canopy removal can also increase exposure to solar radiation, leading to greater snowmelt rates and potentially earlier melt timing.^{202,204} These effects may produce larger or earlier spring runoff pulses, particularly in clear-cut areas where snow accumulation and melt responses are strongest. However, streamflow responses are not uniform across landscapes. In drier areas or landscapes with existing storage deficits, increased water availability following harvest may be retained in soil or groundwater storage rather than exported as streamflow, resulting in limited or no increase in downstream flows.^{205,206}

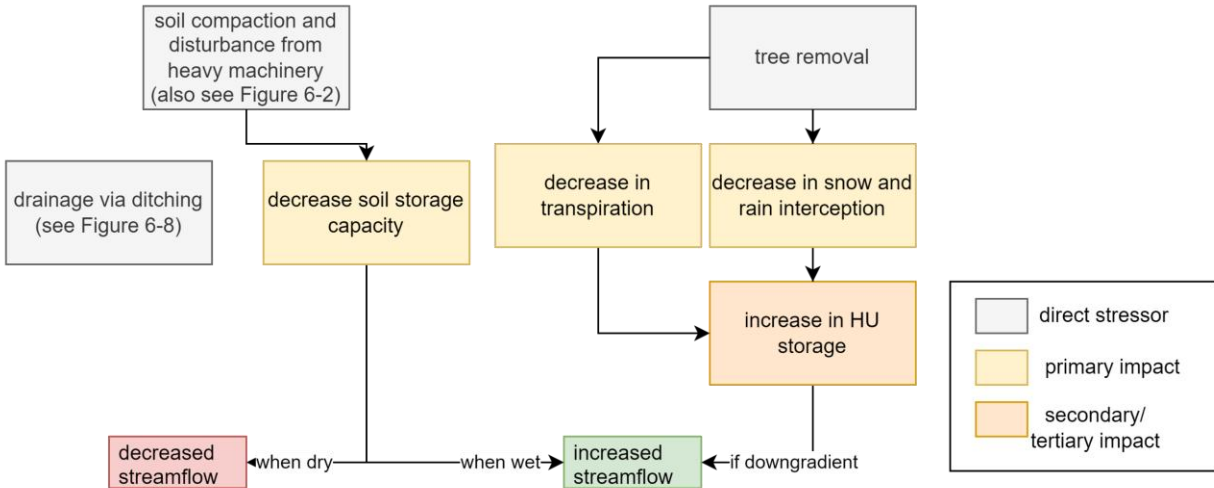


Figure 6-17: Potential alterations to streamflow derived from hydrological impacts associated with wildfire in permafrost and non-permafrost environments.

6.8 Work Camps, Exploration, and Infrastructure Footprints

Work camps, exploration activities, and infrastructure footprints are poorly studied in a boreal context and are virtually absent within the RAA, therefore representing an important research gap in this region. Generally, these disturbances can affect hydrology through several overlapping pathways (Figure 6-18), including vegetation clearing, soil compaction, installation of impervious surfaces, grading, excavation, drilling, trenching, drinking and process water withdrawals, wastewater and sewage disposal, stream and wetland crossings, and fuel or waste handling. These disturbances may be temporary, such as exploration camps, drill pads, temporary access roads, or permanent, such as all-season roads, airstrips, buildings, laydown areas, processing areas, parking areas, bridges, and other compacted or hardened surfaces. Although individual features can have small footprints, their effects are often cumulative with previously described activities, or, in the case of exploration activities, are precursors to increasing disturbance.

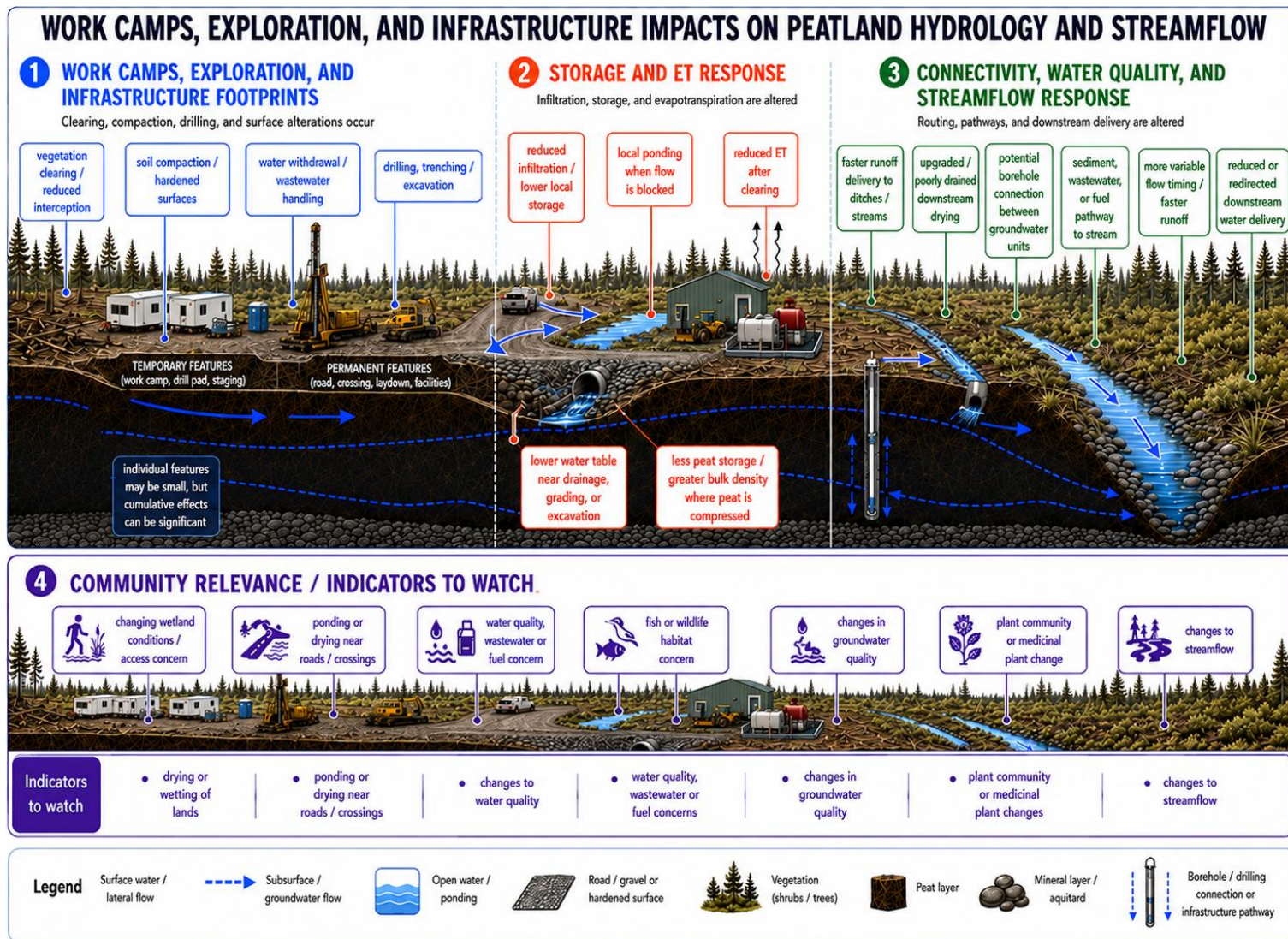


Figure 6-18: Water balance components impacted by contaminant release across different landscape elements.

Storage (S_{sw} , S_{gw}): Infrastructure footprints can alter storage by removing vegetation and organic soils, compacting the soils, replacing *permeable* surfaces with gravel or hardened materials, and changing local infiltration and retention (see also Section 6.1). In peatlands, analogous to linear features, infrastructure construction would likely compress the peat column, increase bulk density, and alter the hydrophysical properties that regulate water table position and storage capacity.^{95,207,208} Drainage, ditching, grading, or excavation may lower water tables locally, while blocked or redirected flow can increase ponding in adjacent areas (see also Section 6.3).

Connectivity (L_{in} , L_{out} , G_{in} , G_{out}): Depending on the size, density, and landscape positioning of infrastructure footprints, ditches, stream crossings, and exploration features, connectivity may be increased through concentration of runoff and rapid routing of water, sediment, or contaminants toward ditches and streams. Alternatively, connectivity may be decreased by blocking sheet flow or shallow subsurface flow, resulting in upgradient ponding and downgradient drying.^{95,207,208}

Exploration drilling can create additional subsurface connectivity risks. Improperly constructed, sealed, or abandoned boreholes may connect previously separated groundwater units, alter vertical *hydraulic gradients*, or create *preferential* pathways for groundwater movement.^{209,210}

Evapotranspiration (ET): Impacts to evapotranspiration occur mainly through vegetation removal and surface alteration. Clearing for camps, drill pads, roads, airstrips, laydown areas, and other infrastructure reduces canopy interception and transpiration, increasing the amount of water available for runoff, infiltration, or storage. However, compacted or hardened surfaces may reduce infiltration and instead increase rapid overland flow. Temporary footprints may partially recover as vegetation re-establishes, while permanent infrastructure maintains reduced vegetation cover, altered surface roughness, and modified ET patterns for much longer periods.⁹⁸

6.8.1 Potential Changes to Water Quality

Due to the diversity of potential activities associated with mining, impacts to water quality may occur through a number of pathways including but not limited to erosion, sediment transport, wastewater and sewage disposal, fuel storage, accidental spills, drilling fluids, exposed soils, and altered runoff pathways. Compacted pads, roads, and cleared areas can increase surface runoff and sediment delivery, particularly during rainfall or snowmelt. Camps and permanent facilities may also introduce risks associated with wastewater treatment, greywater discharge, solid waste storage, hydrocarbons, and other contaminants. Drilling wastes can also pose water-quality risks if fluids, cuttings, or sumps are not properly contained, especially in northern environments where ground ice, permafrost conditions, salinity, and thaw can affect waste stability over time.²⁰⁹

6.8.2 Impacts to Streamflow

Impacts to streamflow are likely to occur through changes in runoff generation, flow routing, and the timing of water delivery. Compacted or hardened surfaces can increase rapid runoff during storms and snowmelt, while drainage ditches, roads, and culverts can concentrate flows and deliver water more quickly to streams (see Figures 6-2 and 6-8). Conversely, infrastructure that blocks or impounds shallow flow may reduce downstream water delivery during some periods while increasing local ponding.

6.9 Renewable Energy: Wind, Solar, and Geothermal

Renewable energy developments, including wind, solar, and geothermal projects, may become increasingly relevant within the RAA as interest grows in low-carbon energy and remote energy security. However, limited information is currently available on the hydrological impacts of these developments in the boreal forest or in wetland-dominated regions, particularly in northern Canada. As a result, much of the available evidence comes from studies in other regions or from general assessments of renewable energy infrastructure rather than from directly comparable landscapes.

6.9.1 Wind Energy

Most available peatland-specific information comes from the United Kingdom, where wind farms have been constructed in peatland catchments. Some studies there have reported increased DOC, nutrients, and suspended sediment during construction, indicating that peat disturbance, drainage, road construction, and exposed soils can affect downstream water quality.^{211–213} However, other studies found no detectable changes in water quality, aquatic macroinvertebrates, or fish health during wind farm construction, suggesting that impacts may vary depending on site conditions, construction practices, mitigation measures, and the sensitivity of monitoring programs.²¹⁴ Available evidence also suggests that some of the largest hydrological and water quality effects may be linked to land clearance, forestry, and associated infrastructure rather than the presence of turbines themselves.²¹⁵ Because comparable studies are limited for Canadian boreal peatlands, the transferability of these findings to the RAA remains uncertain.

6.9.2 Solar Energy

Information on the impacts of solar energy on hydrological processes and streamflow is extremely limited, particularly for boreal forest and wetland-dominated landscapes. Generally, large solar facilities can require substantial land areas, in some cases covering tens to hundreds of hectares depending on energy demand, design, and spacing requirements (see Section 6.9), and may also require access roads, transmission corridors, grading, and vegetation management (see Section 6.1). Solar panels can also act as impervious surfaces that intercept precipitation and concentrate runoff into the spaces between panels, potentially altering small-scale runoff routing, infiltration, soil moisture, and water storage.^{218,219} However, recent modelling efforts found that solar panels may not significantly alter runoff volume, peak discharge, or time to peak when vegetation was maintained beneath the panels.²¹⁹

Solar facilities may also influence evapotranspiration by changing shading, soil moisture, wind exposure, and vegetation composition beneath and between panels. Reduced solar radiation beneath panels can lower potential evapotranspiration, but actual evapotranspiration will depend on the type, density, and health of vegetation maintained at the site.^{218,220,221} During construction and routine operation, there is also potential for sediment, nutrients, dust suppressants, synthetic oils, rust inhibitors, antifreeze, herbicides, or other materials to enter nearby soils or waters if not properly managed.²¹⁸ Water may also be required for panel cleaning, dust suppression, or cooling systems, depending on facility design and operational needs.²²² However, because little

information is available for boreal wetland or peatland settings, the likely magnitude and direction of these impacts in the RAA remain uncertain.

6.9.3 Geothermal Energy

Information on the impacts of geothermal energy on hydrological processes and streamflow is extremely limited, particularly for boreal forest and wetland-dominated landscapes. Most geothermal energy impact literature focuses on broader sustainability, groundwater, and operational risks rather than the impacts on watershed function and streamflow. Generally, geothermal energy may influence streamflow through process water use, changes to groundwater quality, land disturbance during construction, and chemical handling.²²³ Because geothermal development is closely connected to subsurface conditions, potential impacts would depend strongly on the type and scale of development, the depth of drilling, the nature of fluid circulation used for the geothermal energy, and the degree of connection between groundwater, wetlands, streams, and lakes.²²³

In the RAA, geothermal development would require careful assessment of *aquifer* properties, groundwater flowpaths, peat thickness, permafrost conditions, mineral substrate, and hydraulic connections between groundwater and surface water. Reviews of geothermal energy impacts generally describe many environmental risks as manageable with appropriate design and monitoring, but identify water use, groundwater contamination, induced subsurface changes, and improper reinjection or well integrity as key issues requiring assessment.^{223–226} Given the current lack of region-specific evidence, geothermal energy should be considered a poorly constrained disturbance pathway within the RAA.

6.10 Offshore (Marine) Activities

Potential offshore impacts associated with tidal or marine renewable energy development, as well as seaport development in James Bay, are recognized as important considerations for the development of the RAA. However, because these activities are primarily governed by marine and coastal processes, including tides, coastal circulation, sediment transport, ice dynamics, and estuarine mixing, discussion of the potential impacts of these activities is outside the scope of this report.

7.0 CUMULATIVE IMPACTS IN THE REGIONAL ASSESSMENT AREA

Cumulative impacts are the combined effects of multiple past, present, or reasonably foreseeable disturbances that overlap across space or time. In other words, cumulative impacts occur when the effects of multiple disturbances interact so that their combined result is greater, different, longer lasting, or more difficult to reverse than the effect of any single disturbance alone. In the peatland-dominated river systems of the RAA, cumulative impacts are especially important because water storage, landscape connectivity, streamflow, water quality, carbon cycling, vegetation succession, permafrost condition, and aquatic habitat are closely linked. A disturbance that affects one part of a watershed may therefore create secondary effects elsewhere, including in downstream watercourses, wetlands, wildlife habitat, and communities. For communities, cumulative impacts may be experienced not only as changes to individual sites, but also as changes to the reliability, safety, and timing of access, harvesting, drinking water, and culturally important places across connected landscapes.

7.1 Conceptualizing Cumulative Impacts

The “ball-and-cup” model (Figure 7-1) can be used to represent how an ecosystem or watershed responds to disturbance. In this analogy, the ball represents the peatland–river system, while the cup represents the range of conditions where the system can absorb disturbance and remain relatively stable.

In the RAA, individual disturbances such as roads, mine dewatering, hydroelectric regulation, wildfire, vegetation clearing, or climate-driven drying may each “push” the ecosystem by changing water levels, flowpaths, water quality, or the timing of water delivery. On their own, these disturbances may not immediately shift the system into a new state. Cumulative impacts become a greater concern when multiple disturbances weaken the resilience of the ecosystem or push the ecosystem closer to a critical threshold. As resilience declines and/or conditions become increasingly difficult, even a smaller additional disturbance may be enough to push the system past a threshold and into a new state. In peatland–river systems, this could result in persistent drying, loss of wetland–stream connectivity, altered streamflow, degraded water quality, vegetation change, permafrost thaw, increased wildfire susceptibility, or reduced reliability of water conditions for fish, wildlife, travel, harvesting, and downstream community use.

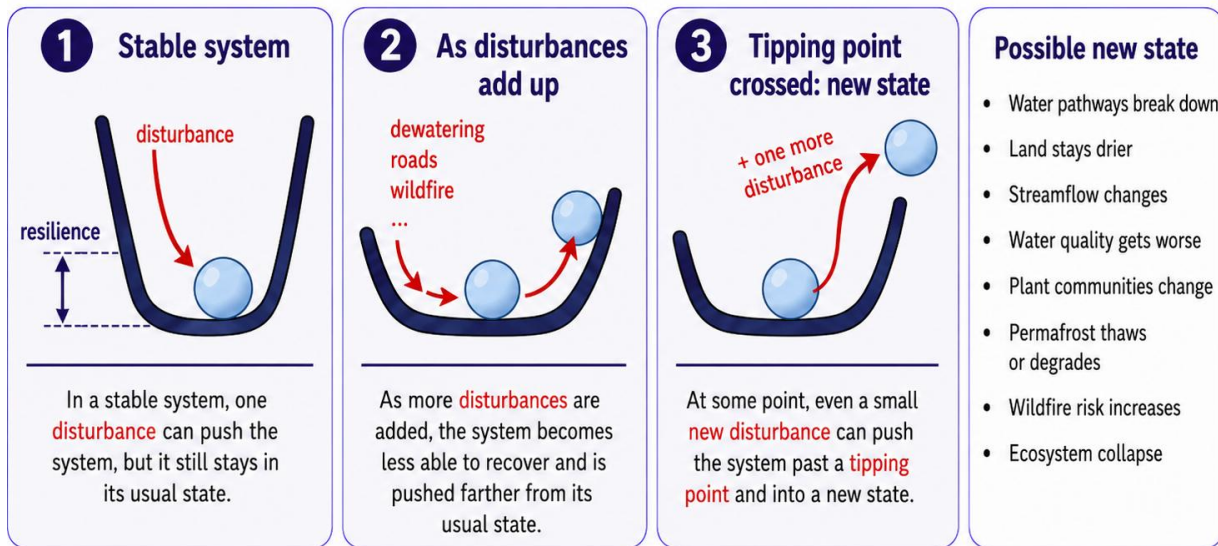


Figure 7-1: The ball-and-cup model representing ecosystem states, cumulative impacts, and the crossing of a tipping point into a new ecosystem state.

7.2 Key Considerations for Assessing Cumulative Impacts in the Regional Assessment Area

The following considerations highlight why cumulative impacts in peatland–river systems cannot be assessed as simple additions or losses of water. They must instead be understood through changes in location, timing, connectivity, source water, feedbacks, ecological function, and community use.

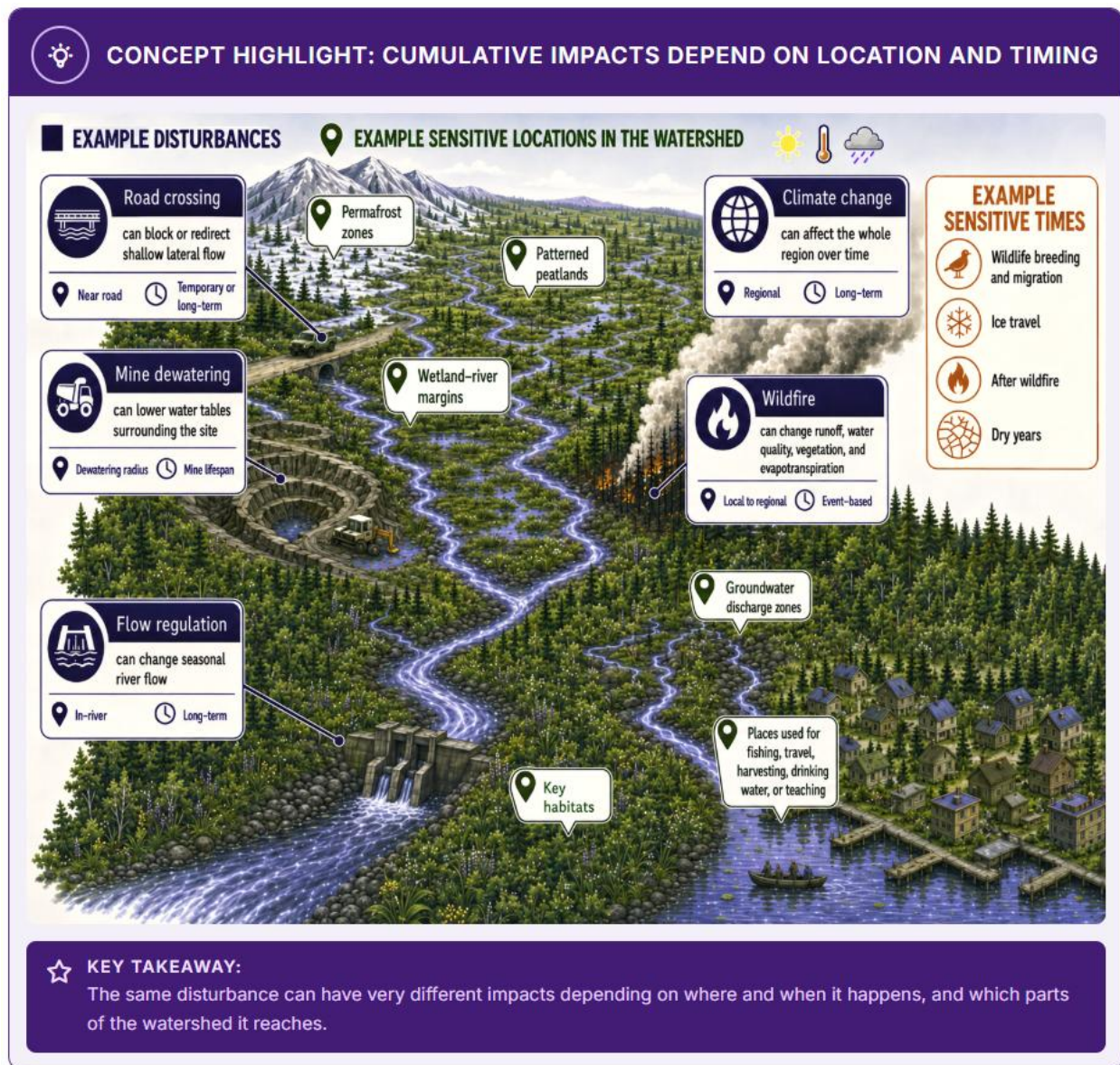
7.2.1 Disturbances Act Across Different Places and Times

Cumulative impacts must be assessed contextually because different disturbances do not necessarily act in the same place, at the same time, or through the same hydrological pathway. For example, a road may block shallow lateral flow across an upgradient peatland within a single stretch of river, mine dewatering may lower groundwater levels near an excavation, a dam may alter seasonal river flow upstream, and wildfire or climate change may affect runoff, evapotranspiration, water quality, and vegetation over broader areas. Although these disturbances may be in close proximity, their effects may emerge at different spatial scales and over different timeframes. Some effects may be immediate and local, such as ponding behind a road or sediment release after a washout. Others may be delayed, cumulative, or regional, such as vegetation change, peat drying, permafrost degradation, or altered low-flow conditions.

7.2.2 Some Places and Times are Inherently More Sensitive than Others

Cumulative impacts may be most critical where disturbances overlap with hydrologically sensitive locations or time periods. For example, headwater systems, wetland–river margins, patterned peatlands, groundwater discharge zones, and already disturbed ecosystems (e.g., degrading permafrost or recently burned areas) may be particularly sensitive and/or may disproportionately influence downstream water delivery, storage, connectivity, and water quality. Culturally significant areas and locations used for travel, harvesting, fishing, drinking water, or teaching are also of particular importance.

Seasonal context is also critical. Disturbances that alter snowmelt, spring freshet, summer low flows, fall recharge, or winter baseflow may have different consequences for streamflow, aquatic habitat, travel, and land use. A disturbance that appears minor during high-flow periods may become more important during dry years, late-summer low flows, winter low-flow conditions, or after wildfire.



7.2.3 Added and Removed Water Does not Necessarily Cancel Out

As mentioned above, one disturbance may add water to part of the system while another removes water elsewhere. Although these changes may appear to offset each other in a basic water balance, they may still represent two separate stressors if they alter the source, timing, pathway, temperature, chemistry, or ecological function of water movement. For example, pumped discharge from a dewatered mine may be used to increase river flow volume, but it does not necessarily replace natural wetland-derived flow if the water arrives at a different time of year, from a different source, or with different chemical and thermal characteristics.

7.2.4 Feedbacks Can Amplify or Buffer Change

Cumulative impacts are not always linear because disturbances can trigger feedbacks that either amplify or dampen change over time. Positive feedbacks occur when an initial disturbance makes the system more vulnerable to further change. For example, local dewatering may reduce peatland connectivity, increase shrub growth, and elevate wildfire risk. Fire and shrub presence can then further reduce peat storage, alter runoff pathways, and degrade water quality, reinforcing the original drying effect. In contrast, negative feedbacks may partly dampen change. In the dewatering scenario, soils may start to decompose and the surface of the wetland may sink, bringing the surface close to the groundwater and reducing the amount of drying at the surface.

Because feedbacks can be delayed, spatially uneven, or difficult to reverse, cumulative effects assessment should consider not only the initial disturbance, but also the chain of secondary changes it may trigger.

7.2.5 Full Development Pathways Should be Assessed Together

Major development activities often require supporting infrastructure and secondary activities that create additional hydrological disturbances. Mining, forestry, road construction, hydroelectric development, renewable energy development, and aggregate extraction may involve access roads, camps, laydown areas, borrow pits, pipelines, drainage works, water crossings, wastewater handling, fuel transport, vegetation clearing, and increased traffic.

These associated activities can create cumulative effects before, during, and after the primary development activity. For example, a mining project may require exploration lines, access roads, hydro corridors, aggregate extraction, mine dewatering, water re-routing, wastewater discharge, fuel delivery, work camps, and closure activities. As a result, cumulative effects assessment should evaluate the full development pathway rather than assessing each activity as an isolated footprint.



CONCEPT HIGHLIGHT: WATER OFFSETS, FEEDBACKS, AND DEVELOPMENT PATHWAYS

1 ADDED AND REMOVED WATER DOES NOT SIMPLY CANCEL OUT



Why it does not cancel out:

Timing Water may arrive at a different time of year.	Source Water comes from a different place.	Pathway Water may follow a different route.	Temperature Water may be warmer or colder.	Chemistry Water may have different quality or minerals.	Ecological function These differences affect what habitats and species are supported.

Even if water increases in one place while it decreases elsewhere, this does not represent a true offset. The water may arrive at a different time, from a different source, or with different characteristics, meaning the system can still be under stress.

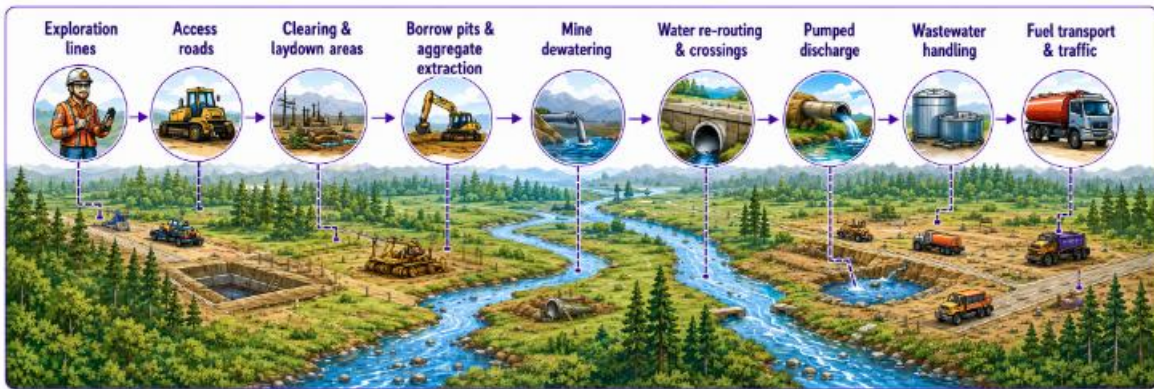
2 FEEDBACKS CAN AMPLIFY OR BUFFER CHANGE



Feedbacks can amplify change: dewatering dries peatlands, increasing shrub growth and wildfire risk, which further alters runoff pathways, water quality, and peat water storage.

Feedbacks can buffer change: dewatering dries peatlands, peat may begin to decompose and the ground surface may sink closer to groundwater, reducing surface drying.

3 FULL DEVELOPMENT PATHWAYS SHOULD BE ASSESSED TOGETHER



Major developments involve many associated activities, such as access roads, clearing, borrow pits, water crossings, and wastewater handling. Each of these activities creates their own hydrological disturbances. Cumulative effects assessment should evaluate the full development pathway together, rather than each activity as an isolated footprint.

☆ KEY TAKEAWAY:

Water gains and losses in different parts of a system do not simply cancel out. Feedbacks can amplify or dampen change over time. All parts of a development need to be assessed together to understand cumulative impacts, not just the main activity.

7.3 Major Cumulative Disturbance Pathways Relevant to the Regional Assessment Area

Building from the considerations above, cumulative impacts in the RAA can be organized into several major disturbance pathways (Table 7-1). Importantly, this list is not exhaustive, and these pathways do not represent isolated categories. Rather, they often interact within the same watershed, development scenario, or community-use area. Together, these pathways show that cumulative impacts are not simply the sum of individual disturbances. They emerge from the way disturbances interact across connected hydrological systems. In the RAA, this means assessment should focus on whether multiple activities change the timing, source, pathway, quality, and function of water movement in ways that affect wetlands, rivers, lakes, groundwater, permafrost, aquatic habitat, wildlife, and community use over time.

Table 7-1: A non-exhaustive summary of cumulative disturbance pathways, example individual disturbances, and potential cumulative effects. Watercourse streamflow or water quality effects are **bolded**.

Cumulative disturbance pathway	Example individual disturbances	Potential cumulative effects
Hydrological fragmentation	Roads, rail lines, well pads, pipelines, trails, seismic lines, water crossings, blocked culverts, construction corridors, infrastructure and work camp footprints	Unequal water distribution resulting in wetting in some areas and drying in others, altered flow paths, reduced wetland-stream connectivity, increased or decreased streamflow , increased erosion or sediment delivery, permafrost thaw
Water removal	Mine dewatering, ditching, peat extraction, forestry drainage, construction dewatering, climate-change-induced drought, hydrological fragmentation (dry areas)	Lowered water tables and peatland water storage, reduced wetland–river connectivity, altered baseflow, vegetation change, increased peat decomposition, increased wildfire susceptibility, reduced streamflow
Altered water distribution	Pumped mine-water discharge, wastewater discharge, wetland water re-routing, stormwater re-routing, climate-change-induced alterations in precipitation, wildfire, impervious surface construction	Increased or decreased streamflow , changing source waters to streams, increased sediment load, increased nutrients, changing DOC dynamics, altered connectivity and storage, permafrost thaw
Soil disturbance	Dewatering, construction and exploration activities, wildfire, infrastructure, and work camp footprints, forestry, climate-change-induced drought	Reduced groundwater storage capacity of soil, increased water table variability, changes in landscape topography, permafrost thaw, increased streamflow during wet conditions, decreased streamflow during dry conditions

In-stream flow regulation and channel modification	Hydroelectric dams, stream diversions, channelization, culvert installation, water-control structures	Altered seasonal hydrographs, reduced or increased peak and low streamflow, altered sediment transport, disrupted wetland connectivity
Altered land and stream water quality	Spills, road washouts, mine discharge, wastewater discharge, exposed mineral soils, wildfire runoff, construction runoff, building material or stockpile erosion, climate-change-induced soil decomposition	Increased turbidity, sediment, nutrients, metals, contaminants, DOC, water temperature, changing water quality patterns

7.4 Case Study: Assessing Cumulative Effects in the Proposed Ring of Fire Development Area

Under the federal *Impact Assessment Act, 2019*, cumulative effects are generally assessed through five main steps: scoping, analysis, mitigation, description of effects, and follow-up.²²⁷ In peatland–river systems, these steps should be applied in a way that reflects hydrological connectivity, source-water change, water quality, seasonal variability, ecological function, and community use.

The proposed Ring of Fire development area provides a useful case study for applying a cumulative effects lens because it is of representative land cover (i.e., wetland-dominated, particularly peatlands) where multiple disturbances are likely to occur in close proximity over a relatively short development period. The area also occupies an important hydrological position within the RAA because it is generally upgradient of many of the watersheds and watercourses it intersects. Disturbances within the development area may therefore influence downstream wetlands, watercourses, and connected aquatic habitats.

This case study is not intended to predict one specific future outcome. Rather, it illustrates the types of cumulative disturbance pathways that should be considered when multiple activities overlap in a hydrologically connected peatland–river system.

7.4.1 Step One: Scoping

Scoping identifies the valued components, spatial boundaries, temporal boundaries, and physical activities that should be included in the assessment.²²⁷ For peatland–river systems, scoping should extend beyond individual project footprints to include connected wetlands, sub-watersheds, tributaries, groundwater–surface water exchange zones, and downstream river reaches.

Valued components should include, at minimum, wetland water level spatial and temporal patterns (e.g., hydroperiods, *hydrographs* and distributions), streamflow timing and magnitude, peatland–river connectivity, groundwater–surface water exchange, water quality, DOC export, carbon storage, permafrost condition, and habitat for keystone species. Key water quality indicators could include mercury/methylmercury, heavy metals, temperature, nutrients, turbidity, sediment, and DOC. Scoping should also include community-identified culturally important areas in the land and water, including areas used for land access, harvesting, fishing, drinking water, teaching, and habitation.

Scoping should also position the targeted area within the RAA ecozones and watersheds, as well as define and characterize the dominant land cover (Figure 7-2). For example, in the proposed Ring of Fire development area, 75% of the land is located within the Plains and 25% is located within the Shield. This area overlaps several watersheds, including the Attawapiskat, Ekwan, Winisk, and Albany, and includes the entire Shield portion of the Ekwan watershed. By land cover, the development area is ~95% wetland, dominated by bog and fen peatlands, many

of which are *patterned*. Because these systems are hydrologically connected to downstream watercourses, assessment boundaries should extend beyond individual mining footprints to include connected sections of wetland complexes, headwater tributaries, groundwater discharge zones, and downstream watercourse reaches.

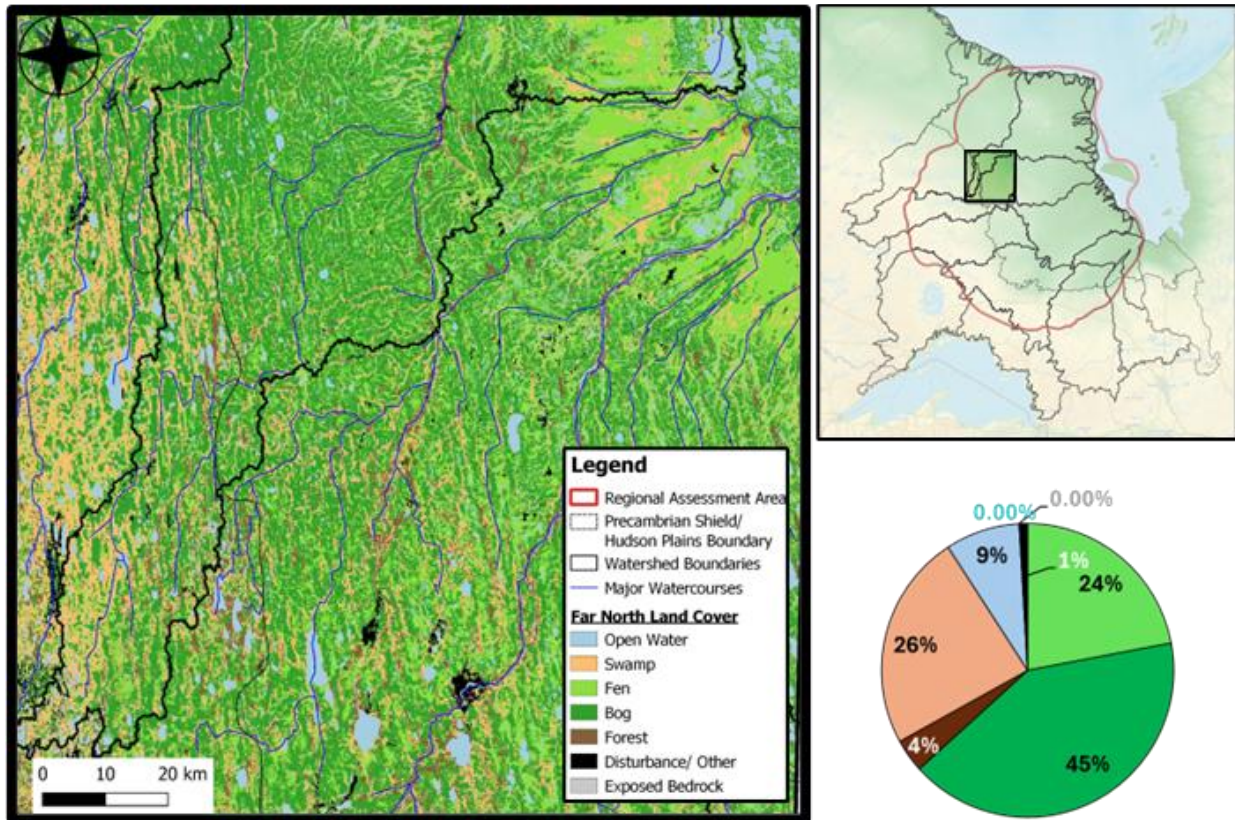


Figure 7-2: Positioning of the proposed Ring of Fire development area using ecozone boundaries, major watersheds, and Far North Land Cover spatial information.

7.4.2 Step Two: Impact Assessment

Cumulative impact assessment evaluates how multiple disturbances may interact across space and time.²²⁷ Figure 7-3 illustrates one possible cumulative impact scenario for a peatland river system within the Ring of Fire development area. The scenario is not intended to represent a prediction of future conditions, but to show how different disturbance pathways could overlap within a connected watershed.

In this example, there are disturbances that act upon all six disturbance pathways discussed in Section 7.3:

- **Hydrological fragmentation:** access roads to the dam, mine, and river block or redirect shallow peatland flow unevenly, producing wetting on one side and drying on the other

- **Water removal:** mine dewatering lowers local water tables and dries nearby peatlands within the dewatering radius, which, in this scenario, has increased wildfire risk resulting in a wildfire to the north of the mine
- **Altered water distribution:** water pumped from the mine is piped directly to the nearby river
- **Soil disturbance:** drying from dewatering, construction activities, linear features, and the wildfire have all changed the local soil properties
- **In-stream flow regulation:** a hydroelectric dam has been installed in one of the rivers, causing increased ponding and drying in the rivers downstream
- **Altered water quality:** mine dewatering discharge, accidental spills from the fuel tanker, road washout, increased soil decomposition due to drying, and wildfire ash runoff are just a few of the contaminants that are impacting local water quality, resulting in increased methylmercury production and metal transport downstream, as well as altered water chemistry, impacting downstream watercourses and wetland health

Importantly, these disturbances are also all occurring within a region experiencing an accelerated rate of climate change, which also acts on all six disturbance pathways.



Figure 7-3: Conceptual cumulative disturbance scenario for a peatland river system in the Ring of Fire development area. The figure illustrates interacting biogeochemical disturbance pathways

associated with a mine and hydroelectric dam, as well as associated infrastructure and cumulative effects.

7.4.3 Step Three: Mitigation

Mitigation identifies measures to eliminate, reduce, control, restore, replace, or compensate for adverse cumulative effects.²²⁷ In peatland–river systems, mitigation should be evaluated based on whether it maintains hydrological and ecological function, not only whether it offsets a single metric such as streamflow volume.

For the Ring of Fire development area, mitigation should focus on maintaining connectivity between upgradient hydrological units, headwater tributaries, groundwater discharge zones, and downstream receiving waters. Sample measures could include avoiding *patterned* peatlands, protecting headwater tributaries and wetland–river margins, maintaining shallow and deep flowpaths through appropriately designed crossings, minimizing the spatial extent and duration of dewatering, treating and monitoring pumped discharge, and preventing road washouts, sediment pulses, spills, and uncontrolled runoff.

Mitigation should also apply to supporting infrastructure, not only the primary development footprint. Access roads, borrow pits, aggregate sources, camps, pipelines, hydro corridors, water crossings, wastewater systems, fuel storage areas, stockpiles, landfills, laydown areas, and all other related disturbances may each contribute additional hydrological or water quality impacts. These associated activities should therefore be included in mitigation planning from the project outset.

Where replacement flow or pumped discharge is proposed, it should be managed to approximate natural seasonal variability, temperature, chemistry, sediment, and biological suitability as much as possible. However, replacement flow should not be treated as a full substitute for maintaining natural wetland–river connectivity. More water being introduced into a watercourse does not necessarily replace water lost from wetland storage, groundwater exchange, or natural flowpaths.

7.4.4 Step Four: Cumulative Impacts Description

Cumulative impacts should be described using criteria such as magnitude, geographic extent, timing, frequency, duration, reversibility, uncertainty, and ecological context. For RAA river systems, additional descriptors are also needed, including hydrological directionality, source-water change, connectivity, feedbacks, and seasonal vulnerability.

For this case study, impacts should be grouped according to cumulative disturbance pathway rather than described only as individual project-specific impacts. Each pathway should identify whether the effect is expected to make conditions wetter, drier, more variable, more disconnected, more regulated, or more vulnerable to water-quality change. Effects should also be described in terms of where they occur, when they occur, and what they may affect downstream.

For example, mine dewatering may be described not only by the volume of water removed, but also by the area of lowered water tables, the duration of dewatering, the peatland types affected, the loss of groundwater or surface-water connectivity, the potential for vegetation change, and the consequences for downstream tributaries. Pumped discharge should be described not only

by volume, but also by timing, source water, temperature, chemistry, sediment, DOC, nutrient, and contaminant conditions. Road and crossing effects should be described in terms of altered lateral flow, ponding, drying, culvert concentration, washout risk, and downstream sediment delivery.

Cumulative effects should also be described in relation to community-relevant outcomes. These may include changes to travel routes, water levels, drinking or camp water quality, fish habitat, wildlife habitat, harvesting areas, culturally important wetlands and waterways, and the reliability of seasonal water conditions. Scenario-based modelling can be used to test how cumulative disturbance pathways may alter these outcomes under different development, climate, and mitigation scenarios. Chapter 8 provides further guidance on developing quantitative models for these types of scenarios.

7.4.5 Step Five: Follow-up

Follow-up verifies whether predictions were accurate and whether mitigation measures are effective. In peatland–river systems, a key aspect of meaningful follow-up is the active monitoring of both local project effects and broader cumulative changes across connected wetlands, tributaries, groundwater discharge zones, and downstream river reaches. Because cumulative effects may be delayed, spatially uneven, and difficult to separate from natural variability, monitoring should be sustained over multiple years and should include both seasonal and interannual variability.

For the proposed Ring of Fire development area, proper baseline monitoring is a key requirement for effective cumulative effects assessment. Baseline monitoring should, at minimum, establish natural ecohydrological functioning within all hydrological unit subtypes that fall within any area of potential impact. Sample useful indicators include water-table depth, surface and subsurface connectivity, streamflow timing and magnitude, water temperature, turbidity, sediment, DOC, nutrients, contaminants of interest such as methylmercury, vegetation distribution and health, and *active layer* depth in permafrost hydrological units. Disturbance monitoring should compare potentially affected areas against baseline or reference conditions and should assess whether changes are approaching ecological or hydrological thresholds. In many cases, specific ecological thresholds for disturbance impacts are not yet well established for peatland and wetland systems in the RAA. Under these conditions, a risk-based adaptive management approach is recommended.

Monitoring should use multiple hydrological, biogeochemical, and ecological early-warning indicators; compare potentially affected areas against baseline or reference conditions; and establish precautionary trigger levels that prompt management action before change becomes severe or difficult to reverse. These trigger levels should be organized to reflect increasing levels of concern and should be linked to predefined management responses.

Depending on the disturbance pathway, responses could include reducing or modifying dewatering rates, pausing operations, changing discharge locations, improving or relocating road crossings, increasing water retention, expanding water-quality treatment, stabilizing erosion-prone areas, improving spill prevention, or increasing monitoring intensity where early-warning

indicators suggest ecosystem stress. Until locally relevant thresholds are better defined, management should rely on precautionary triggers, reference-condition comparisons, and adaptive responses that can be adjusted as field evidence improves.

7.4.6 Key Take-aways and Next Steps

This case study demonstrates that cumulative impacts description in the proposed Ring of Fire development area cannot rely on simple estimates of added or removed water. In connected peatland–river systems, the timing, source, pathway, chemistry, and ecological role of water determine whether disturbance effects remain local or propagate downstream. However, many of these processes remain difficult to quantify across the RAA because field datasets are spatially uneven, remote sensing cannot directly resolve subsurface connectivity, and existing models are not yet fully calibrated for the region’s wetland-dominated watersheds.

Chapter 8 therefore evaluates the current state of knowledge and outlines a framework for developing the field observations, remote sensing products, and quantitative models needed to assess disturbance effects more defensibly.



CASE STUDY: HOW TO LOOK AT CUMULATIVE EFFECTS TOGETHER

1. Reduce harm where possible

Mitigation should focus on keeping wetlands, streams, and rivers connected and healthy.



Avoid the most sensitive peatlands and headwater streams



Keep shallow and deep water moving through road crossings



Limit the size and duration of dewatering



Treat and monitor pumped discharge



Prevent spills, washouts, sediment, and uncontrolled runoff



Look at supporting infrastructure too: roads, borrow pits, camps, pipelines, crossings, and storage areas.

3. Monitor and respond over time

Follow-up should track both local project effects and broader downstream changes.



Measure baseline conditions before disturbance



Monitor water levels, streamflow, and connectivity



Track water quality, sediment, nutrients, DOC, and contaminants



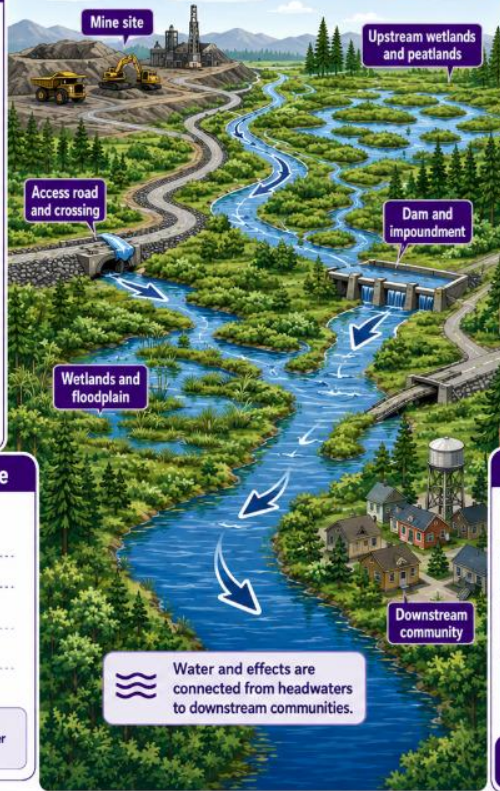
Watch vegetation, peatland condition, and permafrost where relevant



Use early-warning triggers so action happens before damage becomes severe



Responses may include changing dewatering rates, moving discharge, improving crossings, adding water treatment, or increasing monitoring.



Water and effects are connected from headwaters to downstream communities.

2. Describe what is changing

Do not just count water. Describe how the system is changing.



Is the land getting wetter or drier?



Is water flow becoming more blocked, redirected, or regulated?



Is water quality changing?



Where are the changes happening, and when?



What could be affected downstream?



How could this affect travel, fishing, wildlife, harvesting, or drinking water?

4. Key take-aways and next steps



Cumulative effects are about more than added or removed water.



Timing, source, pathway, chemistry, and ecological function all matter.



Small upstream changes can spread through connected peatlands, streams, and rivers.



Better field data, remote sensing, and models are needed to support future decisions.



Use a precautionary, adaptive approach and act early when warning signs appear.



KEY TAKEAWAY:

When communities, regulators, industry, and scientists work together, they can help protect water, land, wildlife, and plants, as well as the ways of life that depend on these, both today and for future generations.

8.0 STATE OF KNOWLEDGE AND FRAMEWORK FOR QUANTITATIVE MODELLING

Chapter 7 identified how cumulative disturbances may alter water storage, routing, timing, connectivity, source waters, and water quality within peatland–river systems. Quantitative assessment is needed to estimate the likely magnitude, spatial extent, timing, duration, reversibility, and uncertainty of these changes, particularly where multiple disturbances may overlap or where effects may propagate downstream through connected wetlands, tributaries, rivers, and aquatic habitats.

This chapter evaluates the current state of knowledge available to support quantitative cumulative effects assessment within the RAA. The objective is not only to summarize available tools and datasets, but also to identify the major limitations currently restricting defensible prediction of cumulative hydrological change across wetland-dominated watersheds.

The chapter also focuses on three complementary sources of information: field-based observations, remote sensing products, and modelling approaches. Field observations provide direct evidence of hydrological processes, connectivity, and disturbance response within specific hydrological units. Remote sensing supports regional characterization of landscape structure, vegetation, surface water, and disturbance features across large and difficult-to-access areas. Modelling provides a framework for integrating field and spatial information, testing disturbance scenarios, and estimating how local changes may scale to subwatershed, watershed, or regional effects.

These approaches are most effective when applied as part of an integrated and iterative assessment framework. Field programs must be designed to capture the dominant processes and hydrological units most relevant to regional assessment; remote sensing products must be validated against field observations; and models must be constrained using both process-based measurements and spatial datasets. Together, these approaches provide the foundation for moving from conceptual understanding and qualitative scenario analysis toward more quantitative cumulative effects assessment.

A foundational element of this approach is the incorporation of community Traditional Ecological Knowledge from the outset of project design. Knowledge holders play a critical role in identifying dominant processes, areas of hydrological significance, culturally important waterways, observed environmental changes, and disturbance pathways that may not be evident from spatial datasets or short-term monitoring efforts alone. This integration supports assessments that are in the spirit of reconciliation, in addition to being more scientifically robust, regionally relevant, and aligned with ecosystem-level processes and community priorities.

8.1 Field-Based Observations

Field-based observations are required to quantify how disturbances alter hydrological processes within and between hydrological units, and to identify the thresholds, connectivity changes, and feedbacks most relevant to cumulative effects assessment. These observations provide the process-level understanding necessary to interpret spatial patterns, validate remote sensing

products, parameterize models, and distinguish short-term variability from persistent disturbance-related change.

8.1.1 Data Availability

Although data constraints remain a key limitation for quantitative assessment in the RAA, several existing monitoring programs provide important context for regional hydrological variability and environmental change. Data accessibility remains a key concern, and the following descriptions are likely non-exhaustive due to difficulties in data procurement. In particular, a substantial amount of industry-collected hydrological, hydrophysical, geochemical, and ecological data likely exists within the RAA. These datasets may represent an important but currently under-accessed resource for regional assessment. Readily accessible long-term regional datasets (Figure 8-1 and Table 8-1) include 5 currently operating greenhouse gas flux towers co-managed by the Ontario Ministry of the Environment, Conservation and Parks and researchers at Carleton University; 41 currently operating streamflow gauges operated by the Water Survey of Canada; and 12 currently operating meteorological stations operated by the Canadian Centre for Climate Services.

Provincial monitoring efforts have also collected surface water, peat porewater, vegetation, and soil data within portions of the RAA.²²⁸ These datasets provide valuable baseline information, particularly for understanding peatland hydrochemistry and ecological variability. However, their usefulness for cumulative effects assessment depends on integration with targeted field programs designed to represent dominant hydrological units, connectivity gradients, and disturbance pathways.

Table 8-1: Currently operating streamflow gauges and climate stations within RAA watersheds.

Watershed	Streamflow Gauges		Climate Stations	
	Precambrian Shield	Hudson plains	Precambrian Shield	Hudson plains
Winisk	3	1	0	2
Ekwan	0	1	0	0
Attawapiskat	3	3	2	1
Albany	5	4	2	0
Moose	16	5	3	2

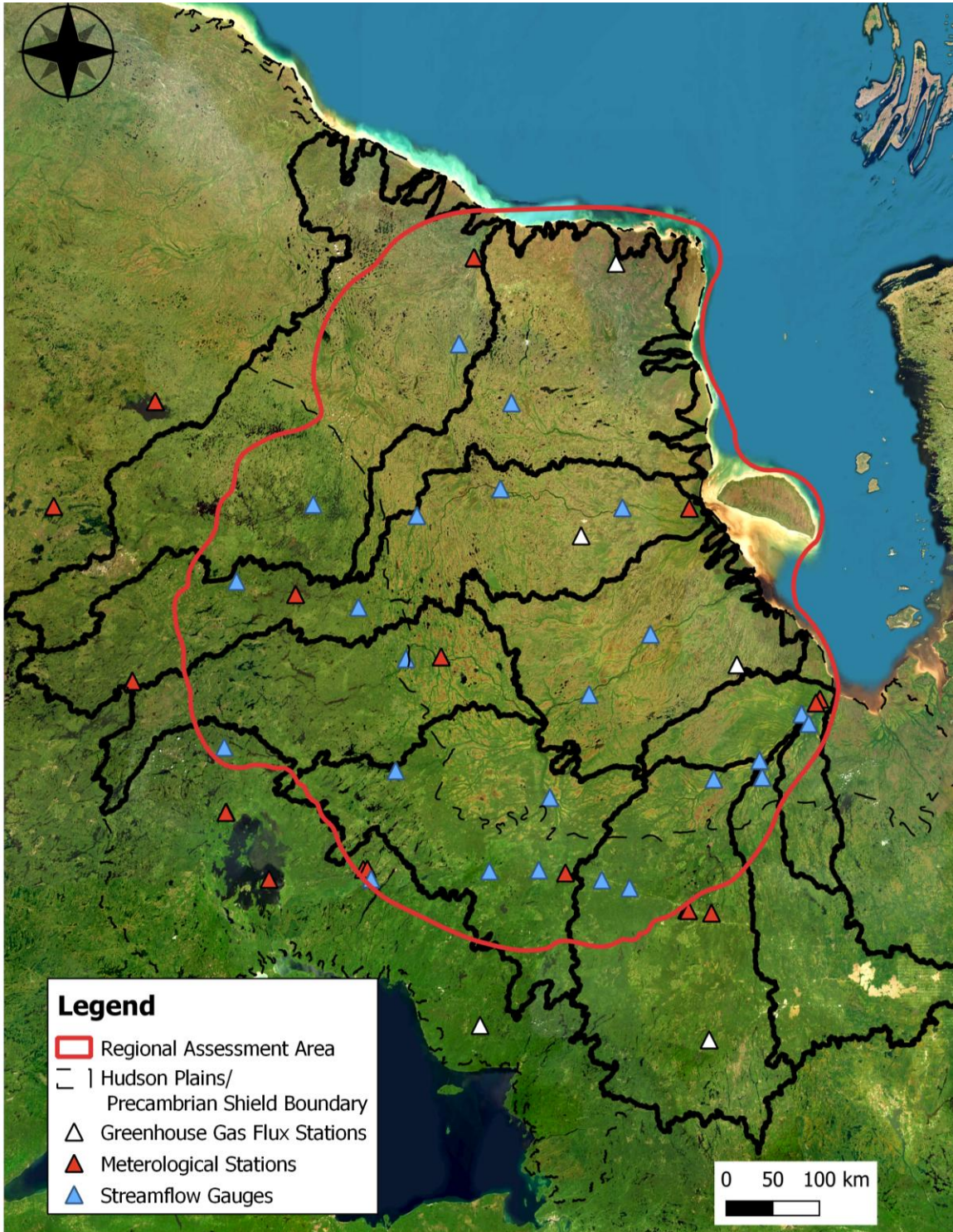


Figure 8-1: Research greenhouse gas flux towers, Canadian Centre for Climate Services Meteorological Stations, and Water Survey of Canada Streamflow gauges available within and adjacent to the RAA.

8.1.2 Data Gaps and Limitations

Current field datasets within the RAA are insufficient to resolve hydrological processes across the spatial and temporal scales required for proper quantitative assessment. In particular, there is a lack of long-term, process-oriented studies that quantify storage dynamics, dominant flowpaths, connectivity thresholds, and disturbance responses across multiple hydrological units. Spatial coverage of field observations is also uneven and does not adequately represent key hydrological gradients within the RAA. For example, a critical gap exists across the transition between the Precambrian Shield and the HBL, where sharp contrasts in the topographical and depositional environment are expected to strongly influence storage dynamics, subsurface connectivity, and downstream transmission of water and solutes.

Field observations of disturbance impacts are similarly limited. Although disturbance density is relatively low across much of the RAA, existing disturbances, including hydroelectric development, forestry, and mining, are present, particularly within the Moose and Albany River watersheds. However, available datasets are heavily concentrated around a small number of sites, most notably the Victor Mine in the Attawapiskat watershed. This creates bias in both hydrological setting and disturbance type, limits the transferability of observed responses, and restricts the ability to evaluate cumulative or interacting effects.

A related research gap is the development of locally relevant thresholds that link the magnitude, duration, timing, and spatial extent of disturbance to changes in hydrological function, ecological condition, water quality, and habitat suitability. Without locally grounded thresholds, it is difficult to define acceptable limits of change or to determine when adaptive management actions should be triggered.

8.1.3 Field Program Recommendations

Field programs should be designed to support both baseline characterization and long-term cumulative effects monitoring. At minimum, monitoring sites should represent dominant hydrological units, disturbance pathways, and connectivity gradients across the RAA. Site selection should occur in close collaboration with Indigenous communities to ensure monitoring includes hydrologically, ecologically, and culturally significant areas. Traditional knowledge holders can provide critical insight into landscape function, seasonal variability, observed environmental change, culturally important waterways, and disturbance pathways that may not be evident from spatial datasets alone.

Field measurements should prioritize variables that directly support process understanding, disturbance detection, threshold identification, and model development. Example indicators and measurements are summarized in Table 8-2.

Table 8-2: Example indicators of change in RAA systems and the measurements that can quantify them.

Indicator category	Example measurements
Hydrological	Water-table depth and distribution, hydraulic gradients, hydroperiods, streamflow hydrograph, groundwater-surface water flows, duration of dry periods, flow direction, pool morphological change, permafrost active layer depth
Water Quality	Water temperature, pH, specific conductance, dissolved oxygen, DOC, nutrients, metals, contaminants (e.g., methylmercury, PCBs, and hydrocarbons), total suspended sediments (TSS), turbidity
Soil hydrophysical	peat subsidence, hydraulic conductivity, soil hydrophysical properties (e.g. hydraulic conductivity and porosity), decomposition, carbon content,
Western ecological	Vegetation composition, vegetation cover, wetland habitat condition, benthic invertebrate condition, fish habitat, fish reproductive health, fauna contaminant loads
Traditional Ecological	Timing and reliability of travel routes; observed water-level changes at culturally important sites; changes in fish movement and harvesting areas; observations of drying, flooding, erosion, sediment, or altered water quality; ice condition and breakup timing; medicinal plant abundance and condition; wildlife movement patterns; and intergenerational observations of environmental change.

Baseline or reference conditions should be established before disturbance wherever possible. These observations are needed to define the natural range of variability to distinguish natural fluctuations from disturbance-related change. Long-term infrastructure, such as permanent vegetation plots, observation wells, climate stations, streamflow gauges, and repeating water-quality sampling campaigns, should then be used to detect departures from expected conditions

over time. Where possible, targeted field studies should be co-located with existing monitoring infrastructure.

8.2 Remote Sensing Approaches

Remote sensing provides an essential tool for characterizing hydrological units, disturbance features, vegetation condition, surface water extent, and temporal environmental change across large and difficult-to-access regions. Within the RAA, remote sensing is particularly valuable because the region is large and diverse in land cover, and field access is financially and logistically challenging due to remoteness.

8.2.1 Data Availability

A range of remote sensing datasets are currently available to support characterization of landscape structure and hydrological conditions within the RAA. A non-exhaustive list of products with coverage in the RAA include the following:

- Land cover and wetland classification products, such as the Canadian National Wetland Inventory and Far North Land Cover mapping
- Forest structure and composition datasets, such as Canada's National Forest Inventory
- Hydrographic datasets, such as the Ontario Hydro Network
- Digital elevation products, including the Canadian Digital Surface Model, Canadian Digital Elevation Model, and other LiDAR-derived data often localized around industry
- Synthetic Aperture Radar (SAR) products, including RADARSAT-2 and Sentinel-1 for detecting surface wetness, inundation, and freeze–thaw dynamics; and
- Optical sensors, such as Landsat 8, enable the derivation of vegetation and moisture indices

8.2.2 Data Gaps and Limitations

Despite recent advances, remote sensing approaches remain limited in their ability to directly resolve many of the hydrological processes controlling storage, connectivity, and flow within peatland-dominated systems. One major limitation is the difficulty of characterizing hydrological connectivity, particularly subsurface flowpaths, shallow groundwater exchange, and threshold-driven activation of flowpaths in low-gradient peatlands. These limitations restrict the ability to determine how disturbances alter transmission of water and solutes across connected landscapes.

Additional limitations include incomplete coverage of high-resolution elevation datasets such as LiDAR; uncertainty in land cover and wetland classification products; and the inability of remote sensing to directly measure streamflow. While remotely sensed products can provide important proxies for hydrological conditions, they should be viewed as complementary tools rather than standalone representations of hydrological function.

8.2.3 Remote Sensing Recommendations

Remote sensing products should be applied within an integrated framework that links spatial observations to field-based process understanding and quantitative modelling. Remote sensing

is particularly valuable for delineating hydrological units, mapping disturbance features, characterizing vegetation condition, and assessing temporal variability in surface water and inundation patterns across large and difficult-to-access watersheds.

Multi-sensor approaches combining SAR, optical imagery, land-cover datasets, and elevation products are recommended because they capture complementary hydrological and ecological information. Where available, high-resolution elevation and LiDAR datasets should be incorporated to improve representation of microtopography and potential flow routing pathways within low-gradient peatland systems.

Because remote sensing cannot directly resolve many subsurface processes or connectivity pathways, all analyses should be validated against field observations wherever possible. Remote sensing products should also be integrated directly into modelling workflows to support hydrological unit delineation, parameterization, calibration, disturbance mapping, and cumulative effects scenario assessment.

8.3 Modelling Approaches

Modelling provides a framework for integrating field observations, remote sensing products, and process understanding to quantify hydrological responses across scales and evaluate cumulative disturbance scenarios. Within the river systems of the RAA, modelling is particularly important because hydrological response is strongly influenced by nonlinear interactions among storage, connectivity, vegetation, climate, groundwater exchange, and disturbance. Quantitative models therefore provide one of the primary tools available for evaluating how local disturbances may propagate through connected watersheds over time.

8.3.1 Model Availability

Though large-scale modelling efforts in this region are extremely limited, several modelling approaches have been applied within or near the RAA to support assessment of streamflow, source-water contributions, hydrological sensitivity, and disturbance response.

Conceptual and simple numerical models are useful in predicting relatively narrow hydrological processes or responses. For example, relatively simple numerical models such as the rainfall–runoff model HBV (Hydrologiska Byråns Vattenbalansavdelning) have been used to predict streamflow within ungauged basins by transferring information from monitored watersheds,²²⁹ and groundwater flow model Topodrive has been used to predict changes to flowpaths and surface–groundwater connectivity in disturbed systems.¹³⁰ Conceptual water balance and water table/runoff models have also been used to evaluate changes in storage, evapotranspiration, and runoff under varying climatic and disturbance conditions.^{37,58,71}

To assess water quality changes, geochemical and end-member mixing models have been applied to identify the relative contribution of rainfall, snowmelt, peat porewater, shallow groundwater, and deeper groundwater to streamflow generation. These approaches provide important insight into source-water contributions and hydrological connectivity in both natural and disturbed conditions.^{63,132}

At larger spatial scales, watershed mass-balance models and semi-distributed models such as Raven¹³¹ have been used to integrate field observations, land cover data, remote sensing products, and disturbance scenarios. These approaches provide a useful foundation for evaluating cumulative impacts associated with mine dewatering, climate change, flow regulation, and land-cover disturbance across connected watersheds.

8.3.2 Data Gaps and Limitations

Despite advances in hydrological and ecohydrological modelling, significant limitations remain in representing peatland systems and cumulative disturbance pathways within the RAA. A major limitation is that no existing modelling framework currently provides a fully transferable or regionally calibrated representation of low-gradient, wetland-dominated peatland river systems. Important processes remain difficult to simulate, including shallow subsurface flowpaths, connectivity thresholds, groundwater–surface water exchange, peatland storage dynamics, vegetation–hydrology feedbacks, and disturbance interactions.

Disturbance representation also remains highly uncertain because hydrological response depends strongly on local controls such as peat depth, vegetation condition, substrate, microtopography, connectivity, and disturbance history. These factors limit transferability among watersheds and increase uncertainty in regional cumulative effects prediction.

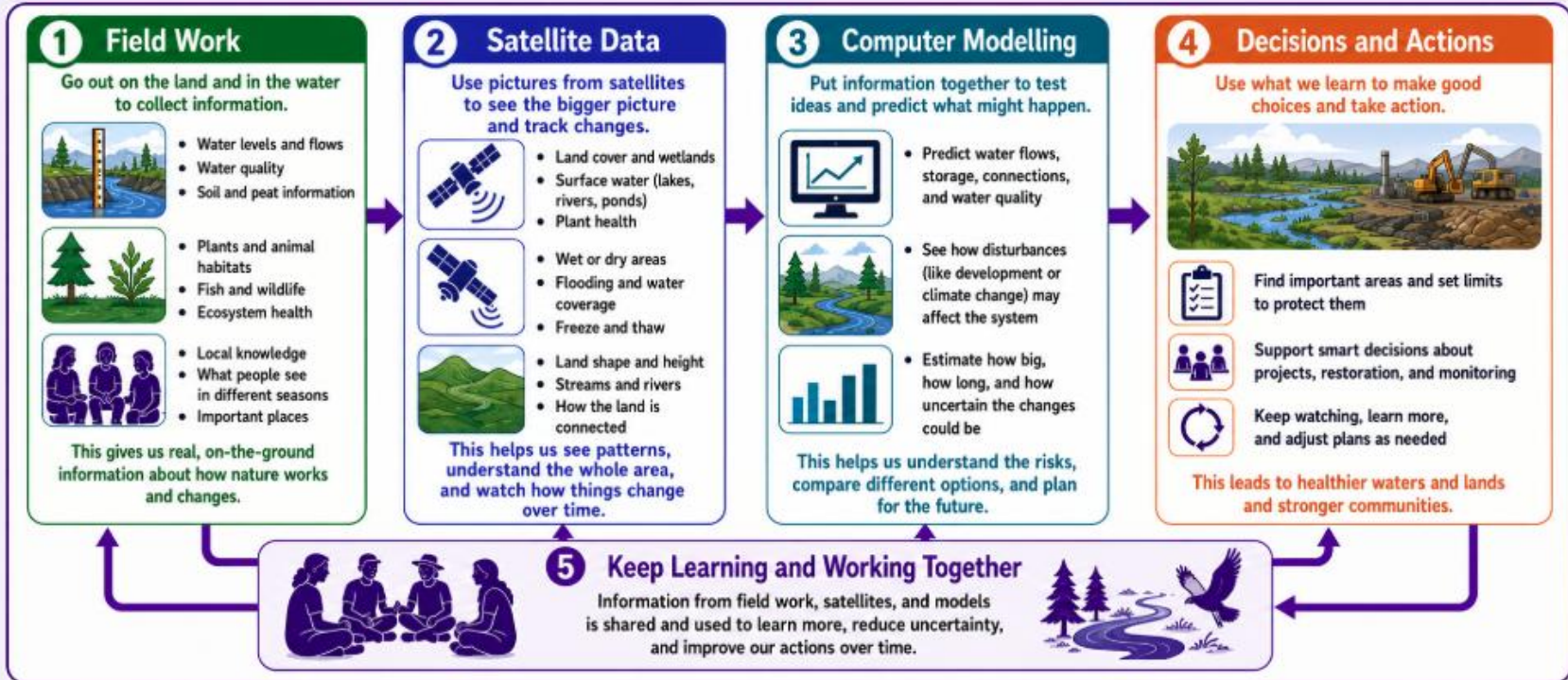
Model application is further constrained by limited availability of streamflow, climate, groundwater, soil hydrophysical properties, vegetation, geochemical, and water-quality datasets needed for calibration and validation. Without stronger integration among field observations, remote sensing, and Traditional Ecological Knowledge, model outputs may not adequately represent dominant flowpaths, seasonal variability, source-water contributions, or disturbance responses within the RAA.

8.3.3 Modelling Recommendations

No single modelling framework can simultaneously represent all hydrological, ecological, and biogeochemical processes relevant to cumulative impacts assessment. For example, high-resolution physically based models can better resolve local heterogeneity, microtopography, subsurface flowpaths, and infrastructure effects, but are difficult to apply regionally. Larger-scale or semi-distributed approaches are better suited for watershed and regional assessment, but often simplify connectivity dynamics and threshold behaviour. As a result, quantitative assessment within the RAA should adopt a multi-scale modelling framework that integrates field observations, remote sensing products, process understanding, and scenario testing. Section 8.4 details a proposed framework for the selection, development, calibration, validation, and application of quantitative hydrological models for cumulative effects assessment within the wetland-dominated watersheds of the RAA.



CONCEPT HIGHLIGHT: WORKING TOGETHER TO UNDERSTAND AND PROTECT OUR WATERS AND LAND



KEY TAKEAWAY:

When communities, knowledge holders, scientists, and government share what they know and learn from each other, we can better understand how our waters and land are changing and make better informed choices to protect them for future generations.

8.4 Quantitative Streamflow Model Development Plan

Until a quantitative modelling framework is developed and validated for the RAA, disturbance assessment will remain reliant on conceptual models, qualitative scenario analysis, and precautionary assumptions. These approaches are useful for identifying potential disturbance pathways and managing risk where data are limited, but they cannot fully quantify the magnitude, spatial extent, timing, duration, or cumulative nature of predicted impacts. This creates uncertainty in assessing how disturbances may interact across hydrological units, watersheds, and river networks, particularly where impacts involve subsurface connectivity, threshold responses, downstream propagation, water-quality change, or delayed ecological effects. Localized or delayed changes may be underestimated if they are not immediately visible at the surface or if multiple disturbance pathways overlap.

For this reason, quantitative hydrological and ecohydrological model development should proceed through a staged workplan that progressively reduces uncertainty, improves predictive capacity, and supports defensible cumulative effects assessment. This process should integrate field observations, remote sensing, community knowledge, and technical modelling expertise from the outset.

Together, these following six steps provide an iterative framework for quantitative model development in the RAA (Figure 8-2), linking community priorities, field observations, remote sensing, modelling, and adaptive management.

8.4.1 Step 1: Define Priority Questions, Thresholds, Parameters, and Modelling Approach

This step defines the model purpose, priority management questions, and indicators needed to support decision-making. It should be directly informed by community priorities and concerns. Key tasks include

- **Identify the ecosystem components and hydrological functions to represent**, such as streamflow, wetland water tables, water quality, connectivity thresholds, and community-defined priorities (such as navigation availability, ceremonial land use, burial ground preservation, harvesting access, medicinal plant availability, and wildlife health and populations)
- **Define the priority questions the model should address**, for example, if the focus is a specific disturbance area or impact
- **Identify hydrological, ecological, and community-relevant thresholds** that can be measured against baseline conditions and used to trigger adaptive management responses
- **Select a general modelling approach appropriate to the question and scale**, such as a local water-balance model, regional hydrological model, groundwater model, or ecohydrological model.

Outcome: A clear modelling scope that identifies the basic model purpose, relevant disturbance scenarios, priority components, thresholds, indicators, and decision needs.

8.4.2 Step 2: Delineate Spatial and Temporal Scales, Hydrological Units, and Priority Areas

This step defines model boundaries, relevant landscape units, priority monitoring areas, and existing data availability. Key tasks include:

- **Define the spatial and temporal boundaries of the model** based on Step 1
- **Compile remote sensing products and existing datasets** such as wetland maps, topography, surficial geology, land cover, disturbance features, and previous field studies
- **Delineate dominant hydrological units** within the model boundaries and identify representative locations for field monitoring
- **Work with communities to identify priority places** within the model boundaries where hydrological change could have particularly important cultural, ecological, or land-use consequences

Outcome: A spatial framework that identifies representative hydrological units, priority monitoring and modelling areas, culturally and ecologically important locations, and key data gaps.

8.4.3 Step 3: Establish Baseline Field Monitoring and Develop a Preliminary Model

This step collects the data needed to characterize baseline conditions and support preliminary model development. Monitoring should address both technical modelling needs and community-identified priorities. Key tasks include:

- **Compile existing baseline data** within the pre-defined model boundaries
- **Co-design monitoring programs with communities** so station locations, sampling frequency, and measured variables reflect both model requirements and locally meaningful indicators of change
- **Measure key hydrological and water-quality variables**, such as water-table depth, *hydraulic gradients*, streamflow, hydroperiod, water temperature, DOC, nutrients, sediment, turbidity, and contaminants
- **Identify and characterize hydrological units** including soil, peat, vegetation, substrate, permafrost, and topographic conditions that influence water movement and storage
- **Develop a preliminary quantitative model** to identify dominant inflows, outflows, storage components, seasonal patterns, and connectivity pathways under baseline conditions
- **Use early model outputs, field observations, and community knowledge** to identify data gaps and refine the monitoring design

Outcome: A baseline dataset and preliminary model that describe current hydrological function and identify key processes requiring further measurement or refinement.

Step 4: Scale field observations using remote sensing datasets

This step is context- and model-dependent and supports the scaling of representative field observations across the larger model area. It is especially important for larger-scale models where not all modelled areas can be accessed or instrumented directly. Key tasks include:

-
- **Validate remote sensing spatial products** using field observations as well as community knowledge
 - **Develop relationships between remotely sensed indicators and field-measured variables**
 - **Use validated spatial products to extend field-based relationships across unmonitored portions of the modelled area**
 - **Identify areas where remote sensing uncertainty remains high** and additional field validation or community review is needed

Outcome: Validated spatial datasets that support upscaling, improved model parameterization, and identification of additional monitoring requirements.

8.4.4 Step 5: Refine Model and Run Disturbance Scenarios

This step is continuous and iterative, as it uses the integrated field, spatial, and community-informed datasets to test disturbance scenarios and refine model predictions. It should build directly from the conceptual disturbance pathways, cumulative impacts, and feedbacks identified in this report. Key tasks include:

- **Incorporate disturbance scenarios into the model** from field-collected data where possible or known processes and disturbance scenarios
- **Conduct uncertainty and sensitivity analyses** to identify which parameters, processes, or assumptions most strongly influence model predictions
- **Refine model structure**, parameters, scenarios, thresholds, and monitoring priorities based on model performance, uncertainty, and review by communities and technical experts

Outcome: A calibrated and scenario-tested model that can estimate potential disturbance effects, identify key uncertainties, and support comparison among alternative development, mitigation, and climate scenarios.

8.4.5 Step 6: Link Model Outputs to Adaptive Management and Community Needs

This step connects model outputs to decision-making, monitoring, communication, and management responses. It should remain iterative so models can be updated as new monitoring data and community observations become available. Key tasks include:

- **Present results using plain-language summaries**, maps, *hydrographs*, conceptual diagrams, and other visual media for review by communities, technical reviewers, and decision-makers
- **Compare model predictions with monitoring results and community observations** to assess whether predicted changes match observed changes on the land and water
- **Link thresholds and indicators to management responses**, such as increased monitoring, modified dewatering or discharge, improved road crossings, water treatment changes, seasonal restrictions, water retention measures, or activity pauses

- **Use model results to support follow-up programs**, such as additional cumulative effects assessments, future scenario planning, and mitigation evaluation

Outcome: An adaptive modelling and monitoring framework that links predictions, observations, thresholds, and management responses over time.

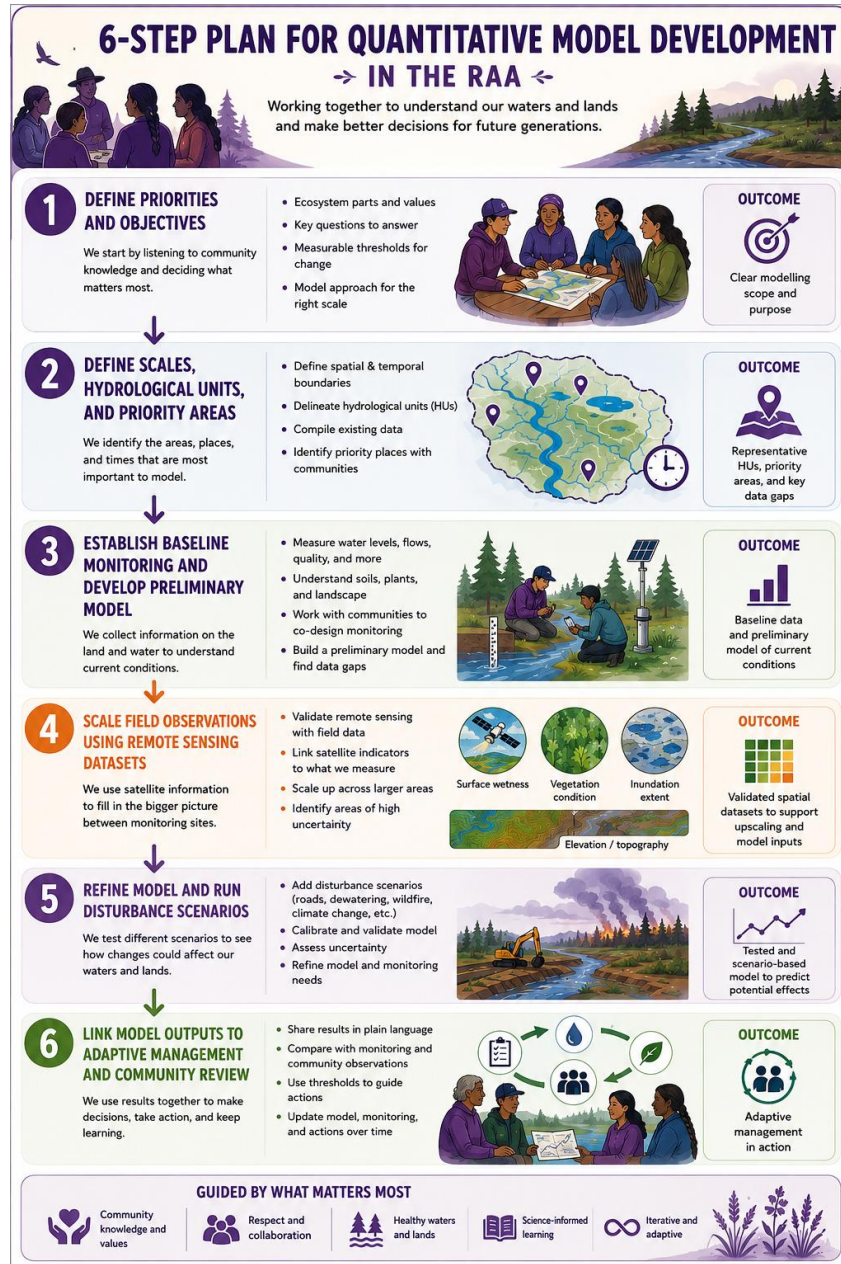


Figure 8-2. Recommended six-step framework for quantitative hydrological model development in the Regional Assessment Area (RAA). The framework integrates community priorities, field monitoring, remote sensing, model development, scenario testing, and adaptive management to support cumulative effects assessment.

9.0 CONCLUSIONS

The RAA encompasses an ecologically sensitive and culturally significant landscape where multiple interrelated development proposals must be understood in the context of hydrological connectivity. The conceptual framework developed in this report for assessing the hydrological responses of RAA watercourses to anticipated disturbances is built on the understanding that watercourses integrate change across connected landscapes, receiving water, sediment, solutes, and contaminants from upgradient wetlands, peatlands, lakes, groundwater pathways, tributaries, and upstream catchments.

Streamflow and water quality are therefore not isolated channel conditions, but expressions of broader landscape function: changes in peatland storage, water-table position, hydrological connectivity, source-water contributions, evapotranspiration, flow routing, and many other variables can propagate through the river network and affect downstream aquatic ecosystems and community-valued waterways.

A central conclusion of this report is that the hydrological significance of disturbance depends not only on the size of the footprint, but also on where it occurs, when it occurs, what flowpaths it intersects, and how it affects connected hydrological units. For example, in peatland-dominated landscapes, small changes in water-table position can significantly alter the movement of water, DOC, sediment, nutrients, and contaminants. Disturbances that appear localized, such as roads, exploration pads, drill sites, crossings, camps, or small infrastructure footprints, may therefore have broader effects if they block, redirect, accelerate, or contaminate flowpaths that connect wetlands to streams and rivers.

Foundational to the assessment of disturbance is the incorporation of community priorities and concerns, and the treatment of streamflow as more than a hydrological parameter. Landscape and stream processes are also connected to the lived conditions on the land and water. Changes in water level, timing, quality, and connectivity may affect travel safety, access to harvesting areas, fish and wildlife habitat, wetland condition, drinking water concerns, plant communities including medicinal plants, human health impacts, and confidence in the continued use of lands and waters. For this reason, the variables used throughout this report should be interpreted in relation to both environmental function and short- and long-term community health and well-being.

The disturbance pathways assessed in this report all have the potential to alter one or more parts of the watershed and the amount, pattern, and quality of that water that flows through it. These impacts may include changes to storage, connectivity, evapotranspiration, water quality, and streamflow timing. However, the direction and magnitude of change are highly site-specific. For example, some disturbances may increase runoff or local ponding, while others may reduce water delivery to streams. Some may increase downstream flow during one season while reducing flow during another. Others may alter the chemistry, temperature, or source of water without producing an obvious change in total flow volume. As a result, disturbance assessment should avoid relying only on simple water balances or total discharge metrics.

Cumulative impacts are especially important in the RAA because disturbances are unlikely to occur in isolation. A mine, road, camp, dam, transmission corridor, dewatering system,

wastewater discharge, wildfire, or climate-driven low-flow period may affect different parts of the same watershed at different times. These effects cannot be fully understood by simply adding or subtracting water volumes. Water added to a river through pumped discharge, for example, does not necessarily replace natural wetland-derived flow if it arrives at a different time, follows a different pathway, has different chemistry or temperature, or no longer supports the same ecological or community functions. The report's cumulative effects section emphasizes that cumulative impacts must be interpreted through changes in location, timing, connectivity, source water, feedbacks, and ecological function, not only through total water quantity.

The report also concludes that some places and seasons are likely to be more vulnerable than others. Headwater wetlands, wetland–river margins, groundwater discharge zones, tributary junctions, low-gradient peatland complexes, permafrost transition zones, road and stream crossings, and areas near culturally or ecologically important waterways may require particular attention. Seasonal vulnerability is also critical. Spring freshet, summer low-flow periods, fall recovery, and winter frozen conditions each create different risks for flow, access, water quality, fish habitat, and contaminant movement. Monitoring and assessment should therefore be designed to capture seasonal timing, not only annual averages.


A major knowledge gap remains the limited availability of region-specific, long-term hydrological and water-quality data across the RAA. This is especially important because many disturbance types are poorly studied in boreal peatland and northern wetland systems. Renewable energy development, exploration activities, work camps, infrastructure footprints, and some cumulative disturbance combinations are particularly uncertain. Research on many listed disturbances in boreal forest, wetland, and peatland-dominated regions remains limited, and much of the existing information comes from other regions such as the western boreal Plains rather than directly comparable RAA-specific landscapes.

Because of these uncertainties, the conceptual models developed in this report should be understood as a foundation for future assessment rather than a final predictive tool. They provide a structure for identifying likely pathways of hydrological change, but additional work is required to quantify thresholds, evaluate disturbance scenarios, and identify which changes matter most to communities. Future phases should work with partner communities to identify community-priority waterways, wetlands, crossings, harvesting areas, fish habitat areas, culturally important places, and seasonal periods of concern. These priorities should then be linked directly to hydrological indicators and monitoring thresholds.

At the conceptual level, the report does address the core concern that disturbances may alter streamflow and water quality both directly and indirectly through changes in upgradient wetlands, peatlands, groundwater pathways, and connected hydrological units. However, the next step is to translate this framework into locally meaningful indicators and thresholds of concern. Some thresholds can be defined biophysically, such as water-table decline, reduced baseflow, increased turbidity, elevated stream temperature, altered freshet timing, or detectable contaminant movement. Other thresholds should be community-defined, based on when changes begin to affect travel, harvesting, fish habitat, wetland access, plant use, drinking water confidence, or the ability to safely use and rely on lands and waters.

Overall, this report shows that maintaining hydrological function in peatland river systems requires more than protecting river channels alone. It requires protecting, monitoring, and mitigating disturbances in the connected wetlands, forests, groundwater pathways, tributaries, and water bodies that sustain those rivers. For future assessment and decision-making, the most useful approach will be one that combines process-based hydrological understanding with community-defined priorities, field monitoring, remote sensing, and scenario-based modelling. This combined approach can help identify where disturbance is most likely to matter, what indicators should be watched, what thresholds should trigger action, and how mitigation should be designed to maintain the ecological, hydrological, and community functions of water across the RAA.

Report Prepared by:

A handwritten signature in black ink, appearing to read 'N. Balliston', with a long horizontal flourish extending to the right.

Nicole Balliston, PhD

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APPENDIX A: HYDROLOGICAL DEFINITIONS