Hydro-Climatic Monitoring Roadmap:
A guide to enabling hydro-climatic monitoring for Indigenous Communities

March 31, 2020

This project was undertaken with the financial support of:

Ce projet a été réalisé avec l'appui financier de:

Environment and
Climate Change Canada

Environnement et
Changement climatique Canada

Prepared by:

ESSA

Hydro-Climatic Monitoring Roadmap:

A guide to enabling hydro-climatic monitoring for Indigenous Communities

March 31, 2020

This project was undertaken with the financial support of the Government of Canada through the federal Department of Environment and Climate Change. Ce project a été realisé avec l'appui financier du gouvernement du Canada agnissant par l'entremise du ministère fédéral de l'Environment et du Changement climatique.

Project Contact:

Shianne McKay, Senior Project Manager

Centre for Indigenous Environmental Resources (CIER)

204-956-0660 ext. 9

smckay@yourcier.org

Lead Authors:
Darcy Pickard, Cumulative Effects Assessment Lead and Senior Statistician
Andrew Thompson, Research Assistant
Marc Nelitz, Adaptive Management Lead and Senior Systems Ecologist

Author Contact:
Marc Nelitz
mnelitz@essa.com
604-677-9554

Suggested Citation:
Pickard, D., A. Thompson, and M. Nelitz. 2020. Hydro-Climatic Monitoring Roadmap: A guide to enabling hydro-climatic monitoring for Indigenous Communities. Report prepared by ESSA Technologies Ltd. and Centre for Indigenous Environmental Resources for Environment and Climate Change Canada. 23 pp. + Appendices

Cover Photo: Bog Sampling © 2011 Andrew Thompson

ESSA Technologies Ltd.
Vancouver, BC Canada V6H 3H4
www.essa.com

Table of Contents

List of Figures

List of Tables

Glossary

Anthropogenic:	Relating to, or a result of human activity.
Bias:	A systematic error resulting in a difference between the observed statistical parameter and the true value of the parameter. Biases may result from errors in site selection, errors in response design, or other errors.
Collaborative Monitoring:	An initiative of Environment and Climate Change Canada that aims to strengthen the national capacity to monitor weather, water and climate change through increased collaboration with provinces and territories, federal departments as well as other network operators and data owners (communities, academia, regional/municipal governments, private sector).
Hydro-climactic:	Pertaining to water and climate (e.g., temperature, precipitation, flow).
Indicator:	A physical, chemical, or biological attribute that directly characterizes environmental conditions.
Metric:	A quantifiable measurement unit that informs the condition or magnitude of an indicator.
Probabilistic:	In a probabilistic sampling design, all sampling units have a known probability of selection. Probabilistic sampling designs enable statistical inferences to be made about the target population.
Remote sensing:	Imagery or other data acquired from sensors aboard satellites.
Response design:	A set of protocols outlining how field data will be collected, including which instruments to use and how to use them.
Sample effort:	The total cost of sampling, which is a function of upfront and ongoing expenses involved in the sampling plan, as well as the number of sites.
Sample frame:	The complete list of sampling units (objects, individuals, etc.) from which samples are taken. Often, the sample frame is not precisely matched to the target population due to logistical constraints (e.g., if the target population is all lakes in a watershed, the sample frame may exclude lakes that are too costly to access or where access is unsafe).
Sample unit:	The actual unit of measurement in a sample. This could be a discrete feature (e.g., a person, a tree, or a fish), or an arbitrarily defined unit of a continuous feature (e.g., a vegetation plot within a larger forest).
Sampling design:	Protocols detailing when, and where measurements are to be made, including the process by which those locations and times are selected.
Simple random sampling:	A sampling approach in which sampling units are selected at random and each unit has an equal probability of selection.
Stratified sampling:	A sampling approach in which the target population is divided into non-overlapping strata (and sample units then selected within each strata).
Systematic sampling:	A sampling approach in which sampling units are chosen according to a fixed interval (e.g., every 2nd, or every 5th sampling unit is sampled), and in which the first sampling unit is randomly selected.
Target population:	The entire set of units (e.g., trees, fish, lakes) which researchers are interested in sampling and drawing conclusions about.

1 Introduction and Context

Environment and Climate Change Canada (ECCC) has established the Collaborative Monitoring Initiative to strengthen the national capacity to monitor weather, water and climate change through increased collaboration with provinces and territories, federal departments as well as other network operators and data owners (e.g. academia, regional/municipal governments, communities, private sector). ECCC's Meteorological Service of Canada (MSC) envisions an observing system that encourages and facilitates access to observations from a variety of network operators, within a structured national framework. This observing system leverages the long-term investments of all Canadian institutions, and improves the overall quantity, quality and accessibility of hydro-meteorological monitoring data in Canada.

The Network of Networks component of Collaborative Monitoring is a multi-participant, collaborative approach to monitoring, supported by a modern data management system. It includes data policies and standards to encourage and facilitate timely and open exchange of data among many contributors. Under a network of networks model, multiple sources of hydro-climactic (i.e., water and climate) data are gathered and integrated, to support data sharing and dissemination, improve nation-wide data quality, and increase local, regional, and national-scale understanding of spatial and temporal hydro-climactic trends (Roy et al. 2017).

While there is no single best recipe for developing a monitoring framework, there are a number of common components which form the basis of most monitoring programs. This report describes these components and provides a step by step guide for how to build an overarching monitoring framework that is scientifically rigorous, technically feasible, decision-oriented, and scalable. The guidance described herein will help to clarify monitoring priorities, set spatial and temporal boundaries, manage expectations as to what monitoring can and cannot achieve, and provide additional relevant considerations and contextual guidance. This guidance is applied to two different Indigenous communities (Matawa First Nations Management and Dehcho First Nations) to illustrate how it can be applied more broadly.

- **Section 1** (this section) introduces the Collaborative Monitoring Initiative, its purpose, why it matters, and describes the structure and content of the report;
- **Section 2** describes common challenges of long-term monitoring, and proposes solutions to those challenges, and provides context about monitoring within a network of networks;
- **Section 3** describes the essential components involved in the development of a monitoring framework; and,
- **Section 4** describes how the components described in Section 3 can be brought together for the development of a monitoring framework.
- **Appendix A** provides a framework for enabling hydro-climactic monitoring for Matawa First Nations Management.
- **Appendix B** provides a framework for enabling hydro-climactic monitoring for Dehcho First Nations.

2 Background

2.1 Challenges with long-term monitoring

Capacity, Funding, and Consistency

For many Indigenous communities, long-term access to funding to support environmental monitoring is a perpetual challenge (Cave et al. 2016). Agency sourced funding typically supports monitoring efforts for a few months to a few years at the most (Johnson et al. 2015; Carlson and Cohen 2018). Furthermore, access to monitoring funds sometimes comes with strings attached. For example, funds from a government program may require that a certain proportion be spent on training, or that the funds be directed at species at risk (Gordon Parker 2018, personal communication).

These challenges require communities to patch together funds from multiple sources to sustain long-term monitoring programs, which places an additional burden on communities and may result in discontinuities in the monitoring record (e.g., Figure 1 A.) (Johnson et al. 2015). Patchy funding not only threatens the consistency of data-collection itself, but can also lead to data gaps (e.g., time-periods during which no data are collected, large areas where no data are collected, inconsistency in methodologies, or the loss of existing data after a program is discontinued) (Danielsen et al 2005; Pollock and Whitelaw 2005; Mike Low 2018, personal communication; Gordon Parker 2018, personal communication). Data gaps can lead to differing interpretations among stakeholders, which can in turn lead to conflicts over resource use and management within and among communities (Plisnier et al. 2018).

The lack of continuity in a data record is a serious barrier to addressing and systematically understanding environmental change. This is particularly true when trying to understand long-term climate related changes. Long-term monitoring is crucial to understand climate processes at multiple scales, and to disentangle the effect of climate change from other anthropogenic impacts as well as natural environmental variability (Hobday and Evans 2013).

With limited technical staffing, and technology resources, communities must prioritize among monitoring objectives and activities, while continuing to address social, health, cultural and economic priorities of community members. Long-term monitoring should be designed such that key (core) indicators are consistently monitored over a long-term basis, while secondary indicators (i.e., less pressing monitoring targets, or research questions that can be resolved on a shorter time span) should be monitored only when the funding and capacity are available (Plisnier et al. 2018). A multi-tiered structure makes monitoring flexible, able to take advantage of additional funding, as it emerges, and resolve issues as they crop up. Tiered monitoring programs can effectively utilize the resources available, ensuring that community interest is maintained over a long period, and that human resources are not over-taxed. Figure 1 B. illustrates such a scheme, demonstrating how two monitoring tiers can be integrated into a single monitoring framework.

> ***"It is preferable to build a continuous and low-cost time series of a few main parameters rather than a wide, frequent but expensive and unsustainable monitoring including too many parameters." (Plisnier et al. 2018)***

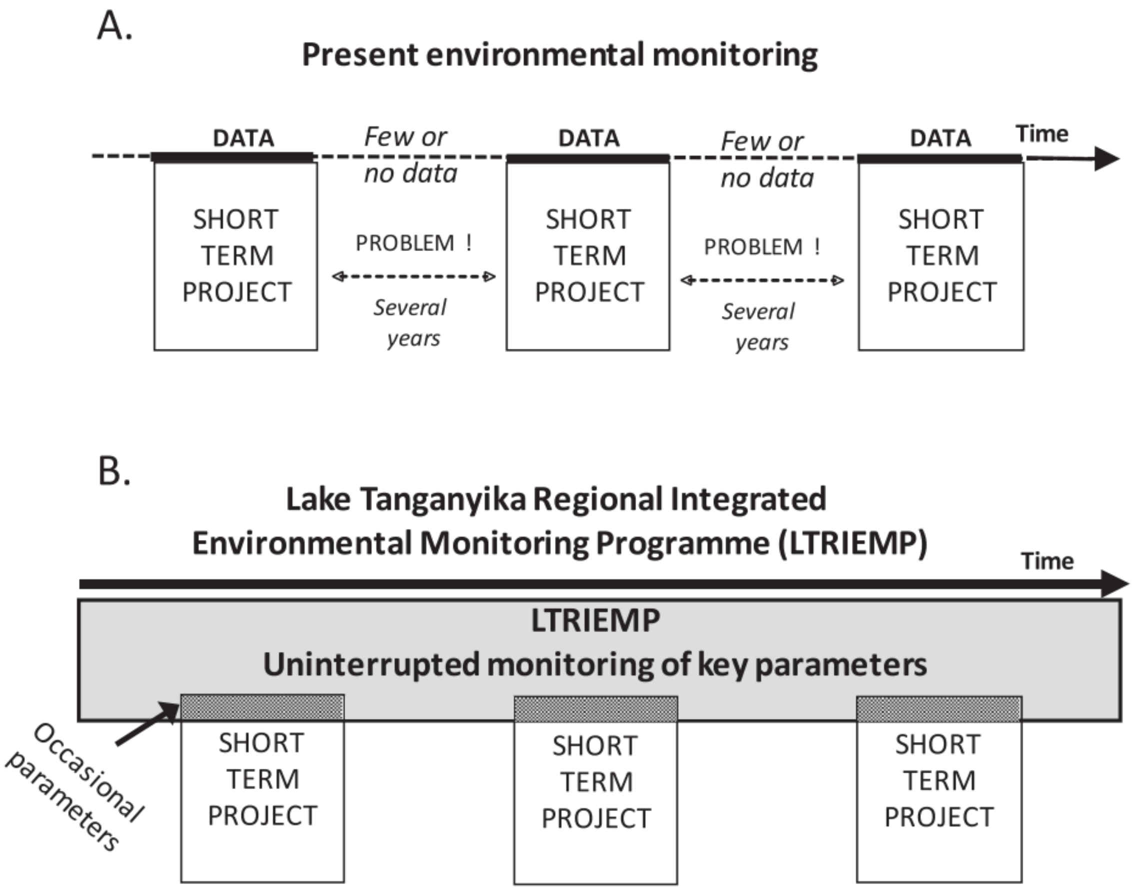


Figure 1. ***Panel A:*** *Many local monitoring programs operate in short bursts, operating opportunistically when funding and community interest is present. This leaves gaps in the data record which compromise its integrity.* ***Panel B:*** *A proposed solution is a tiered approach: in the first tier, core parameters are monitored consistently over a long-time-span. In the second tier, additional parameters are monitored on an ad-hoc basis. From Plisnier et al. (2018).*

Geographic Scope

Many Indigenous communities' traditional territories are very large, and include vast regions where access is challenging (i.e., costly and or time-consuming). Though restricted access may reduce anthropogenic impacts, it also means that monitoring the environmental conditions across a large territory is challenging and expensive for Indigenous communities, which often operate with limited monitoring budgets.

Remotely sensed **data (i.e., satellite or aerial imagery) can help circumvent the challenges of limited budgets and large territories. Remotely sensed data can provide real- or near-real-time monitoring of environmental parameters over very large regions, at a low cost (Turner et al. 2015). Some remotely sensed data extends back to the 1970s,** making it a useful data source for the detection of long-term trends. Remote sensing as a tool is discussed in greater detail in Section 3.3.

Links Between Data and Decision Making

Lack of clear objectives is one of the most common failures of monitoring programs (Reynolds et al., 2016). It is tempting for program managers to skip to data collection before devising a well thought out question, especially when issues require urgent resolution. Often, it is not until after the data collection period is over that a program manager will recognize that the data which have been collected are not appropriately able to answer the underlying question or uncertainty (Reynolds 2012). Furthermore, the data collected in monitoring activities are frequently mis-aligned with the needs of local decision-makers (Lemos et al. 2012).

This reduces the usefulness of monitoring data and speaks to a lack of communication and collaboration between decision-makers and monitoring program managers. The disconnect between the two has historically resulted in the loss of interest among monitoring practitioners, loss of funding, and a poor perception among decision-makers of the value of local monitoring (Whitelaw et al. 2003, Sharpe and Conrad 2006; Johnson et al. 2015). As a result, a holistic assessment of data needs and decision-making processes can aid in ensuring that monitoring data can be collected in such a way that it is of use to decision makers (Lemos et al. 2012). The monitoring framework components described in Section 3 and the steps described in Section 4 are consistent with the US EPA's (2006) decision driven approach to data collection, 'data quality objectives.'

2.2 Monitoring in a Network of Networks

Relevance of Hydro-Climatic Monitoring

For Indigenous communities, long-term monitoring can be employed in service of environmental stewardship, particularly for the protection and maintenance of water resources. Well-designed long-term monitoring of hydro-climactic indicators can help assess risks to, and make decisions about (*inter alia*):

- Water allocation (surface and groundwater);
- Well-water protection;
- Watershed governance and community partnerships;
- Water infrastructure;
- Transportation infrastructure (e.g., monitoring winter roads, ice thickness, permafrost); and
- Flood and drought risk mitigation and management (Cave et al. 2016).

Monitoring hydro-climactic indicators can also support the development of an evidence base to address broader issues, including:

- Climate change adaptation;
- Protection of human health;
- Preservation of ecological integrity; and
- Access to country foods (Cave et al. 2016).

Benefits of Sharing in Collection of Hydro-Climatic Data

Sharing information within a network of networks (e.g., Indigenous communities and Government) can foster a more nuanced and thorough understanding of local and regional phenomena, can help generate and sustain interest in monitoring among communities, facilitate sharing of monitoring techniques, and help generate novel questions to investigate (Conrad and Daoust 2008; Johnson et al. 2015; Johnson et al. 2016).

A network of local monitoring programs will enable the collection of hydro-climactic data at finer time-scales and in broader geographic regions (including novel locations) than what is feasible for governments or academic research programs alone, due to the high cost associated with field data collection (Cohn 2008, Soroye et al. 2018). The large datasets that a network of monitoring activities will generate will fill in data gaps (in both space and time), helping scientists to answer fundamental questions about the environment, and generate a more complete picture about the state of the environment at local, regional, and national scales (e.g., Soroye et al. 2018).

Long term data collection through local monitoring helps to track changes in the environment, and to disentangle natural variation from anthropogenic impacts and management activities (Plisnier et al. 2018).

Long-term monitoring may also result in cost-effective use of monitoring resources, achieved by the adaptive management of monitoring actions, and the continuous revision of monitoring priorities and management responses (Hedge et al. 2017).

Monitoring data generated by government or academic programs are typically not locally relevant, and recent government cutbacks have further reduced the government's monitoring capabilities (Whitelaw et al 2003). The growth of a local monitoring programs (including community-based monitoring and citizen science initiatives) has filled this vacuum, addressing the need to monitor locally relevant indicators and foster stewardship of water (among other) resources (Savan et al. 2003; Whitelaw et al. 2003; Danielsen et al 2005).

Approaches to Shared Data Collection

Local environmental monitoring involves citizens, governments, and collaborators (i.e., academia, industry, other community groups, etc.) developing approaches to, and carrying out monitoring, tracking, and managing of environmental issues (Whitelaw et al. 2003). Taking ownership over local monitoring allows communities to leverage their knowledge, experience, institutions, and governance systems for the monitoring and stewardship of water resources, which is typically associated with responsive action by decision makers (in contrast with academic or government monitoring programs) (Folk et al 2005; Danielsen et al. 2010).

Locally based monitoring is extensively used in environmental and ecological contexts, where monitoring by citizens and community monitors is technically and financially feasible (Silvertown 2009). It is well suited to address local environmental issues and track parameters that government and academia does not (Conrad and Daoust 2008). As local environmental (and in particular, hydro-climactic) conditions are altered by anthropogenic impacts like climate change and land use change, local monitoring can contribute to baseline data collection, tracking changes in areas of interest, as well targeting monitoring efforts to address specific questions or concerns.

Validity of Hydro-Climatic Monitoring

Community driven monitoring approaches are not always validated by credentialed scientists, which has prompted criticisms that they generate unreliable, inaccurate, and or biased data (Conrad and Hilchey 2011). However, scientific monitoring is just as susceptible to biases and errors as citizen science projects, suggesting that some criticisms are based in perception and not evidence based (Kosmala et al. 2016). Scientists have also argued that some field-protocols can be too complicated for citizen scientists or community monitors to follow; this can be remedied for by designing simplified protocols that reduce bias and error, or by avoiding unnecessarily complicated field or laboratory methods which may require expert techniques (Cohn 2008; Conrad and Hilchey 2011;Carlson and Cohen 2018).

3 Key Components of a Monitoring Framework

Key components of any monitoring framework include: *why* (decisions or questions), *what* (indicators), *when* and *where* (sampling design), how (how the data will be collected, analyzed, and reported), and *who* (important local context) (Figure 2). It is natural to sequentially consider each component, beginning with defining a problem or asking a question, and progressing towards considering *how* a monitoring program may be implemented. However, all components are interrelated, and the choices made for each component will influence other components. For example, the chosen indicators will restrict the possible response designs, while consideration of a data analysis plan can help refine the selection of indicators. For this reason, it may be useful to iterate through the components multiple times as needed (i.e., it is not necessary to finalize details for one component before moving on to the next).

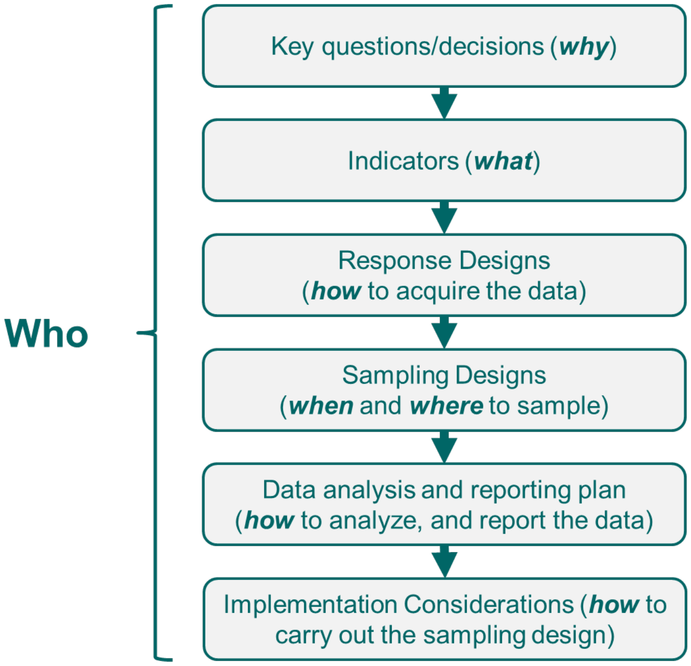


Figure 2. Components of a monitoring framework include why, what, when, where, and how data are collected and analyzed.

The following sections (3.1 through 3.6) of this document describe the components involved in developing a framework for monitoring.

3.1 Clarify the Monitoring Questions (why)

A monitoring framework should be organized around a well-defined question (or problem) which articulates why the problem is important to the community (Reynolds et al. 2016). A monitoring question should clarify the following contextual elements (Reynolds et al. 2016):

- The relevancy or importance of the issue itself (i.e., how does the issue intersect with community concerns, priorities, and values?);
- The social, cultural, political, legal, financial and other elements that shape decision-making and governance;
- The information about the resource that is needed to improve decision making (including tie-ins with existing monitoring or stewardship activities, and existing knowledge on the subject); and

- The stakeholders and rights-holders that will be impacted by a decision.

3.2 Select Indicators and Metrics (what)

This section details the indicators and metrics the monitoring activity seeks to inform.

An **indicator** is a physical, chemical, or biological attribute that directly characterizes environmental conditions and can be either qualitative or quantitative (e.g., flooding risk; Porter et al. 2013). A **metric** is a quantifiable measurement unit (e.g. snowmelt rate) that informs the condition or magnitude of an indicator (Porter et al. 2013, Stalberg et al. 2009). The metric is not always a perfect reflection of the underlying indicator of interest.

With limited resources, a monitoring program must prioritize among many possible indicators. Chosen indicators should match the following criteria (Karr 2008; Douvere and Ehler 2011; Ehler 2014; Belfiore et al. 2006; Jackson et al. 2000):

- **Directly related** to the question being posed, and supported by baseline data;
- **Responsive** – i.e., providing reliable feedback to system attributes, but with a small signal to noise ratio;
- **Specific** – i.e. tied to the condition of one system attribute, (and isolated from others; or, where the influence of others is understood). It is especially important that an indicator be able to disentangle the effects of management actions from natural variation within a system;
- **Relevant** socially and culturally, and related to management objectives (i.e., they must represent something the community cares about);
- **Measurable** within the capacity of a monitoring program;
- **Cost-effective**, building on existing information;
- **Interpretable** – easily understood; and
- **Grounded** in theory and evidence (i.e., western science or Indigenous Knowledge).

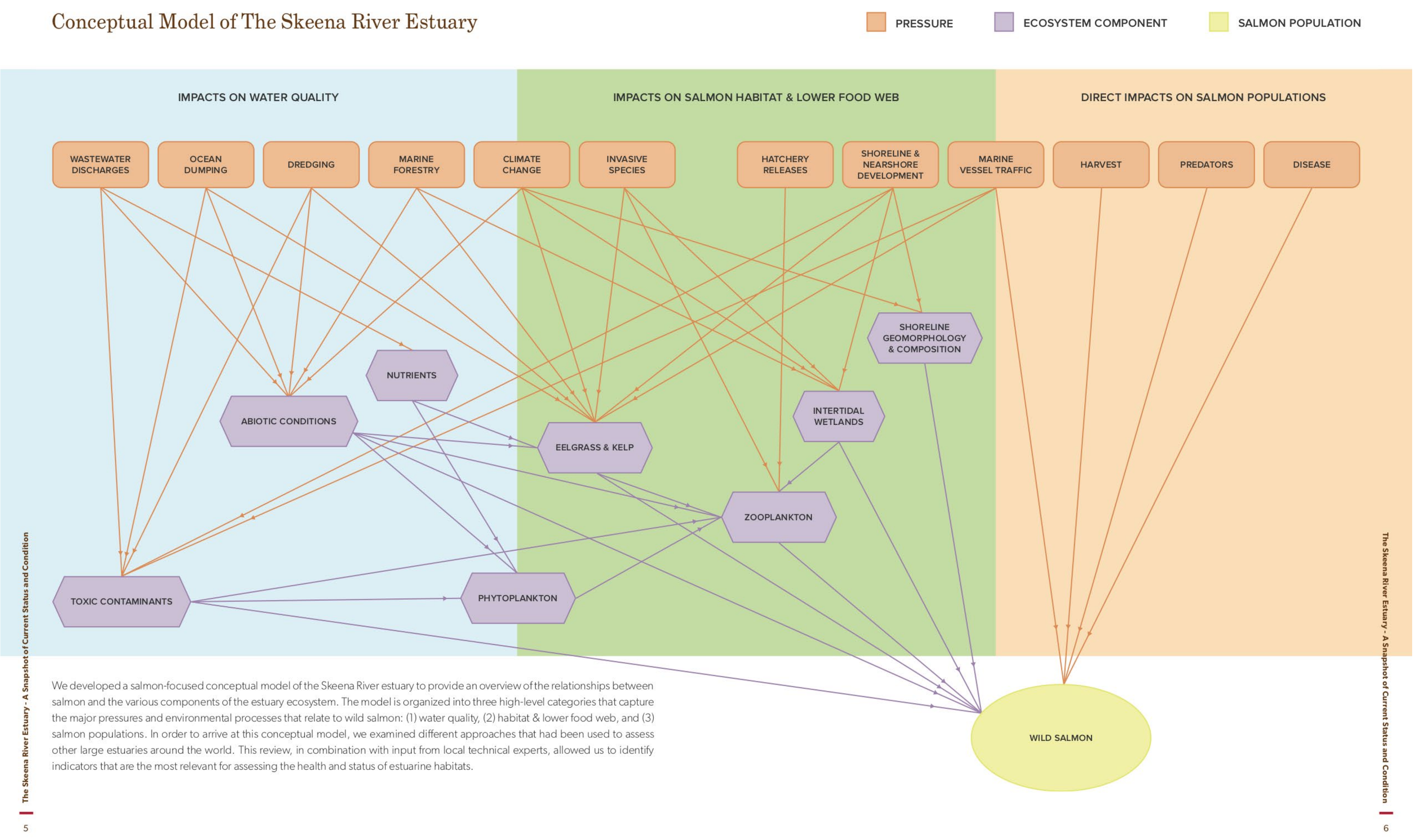
Well selected indicators will prove useful in informing future management decisions and direction (Rapport and Hildén 2013). The selection of indicators is a crucial step in developing a monitoring plan. Indicators should be tailored to the specific question, and the environmental system being considered (Ehler 2014).

In the case of multiple indicators for a given question, monitoring programs should prioritize indicators (i.e., core vs. secondary; see Table 1).

Table 1. There may be multiple indicators for each question and multiple metrics for each indicator.

Question	Indicators	Metrics
Question 1	Flooding Risk (**Core**)	Lake level (metres above sea level) Snowmelt (cm^3)
	Lake Health (**Secondary**)	Lake pH Dissolved Oxygen

A simple **conceptual model** that summarizes knowledge about interrelationships between environmental components can be useful in clarifying a question and selecting appropriate indicators and metrics (US EPA 2006; MRAG 2010) (e.g., Figure 3). A conceptual model visually communicates and distills the complex network of drivers, pressures, and important objectives and helps isolate the influence of factors like climate change and the effects of management initiatives (Reynolds et al. 2016).



Conceptual Model of The Skeena River Estuary

🟧 PRESSURE 🟪 ECOSYSTEM COMPONENT 🟨 SALMON POPULATION

We developed a salmon-focused conceptual model of the Skeena River estuary to provide an overview of the relationships between salmon and the various components of the estuary ecosystem. The model is organized into three high-level categories that capture the major pressures and environmental processes that relate to wild salmon: (1) water quality, (2) habitat & lower food web, and (3) salmon populations. In order to arrive at this conceptual model, we examined different approaches that had been used to assess other large estuaries around the world. This review, in combination with input from local technical experts, allowed us to identify indicators that are the most relevant for assessing the health and status of estuarine habitats.

Figure 3. Example conceptual model for wild salmon in the Skeena River Estuary. From Pacific Salmon Foundation (2015).

3.3 Identify Response Design (how)

The response design describes how data will be collected, including which instruments to use, and specific field protocols. Different response designs for monitoring hydro-climactic parameters may include (*inter alia*):

- Visual surveys (by boat, quad, snow-machine, truck, or foot);
- Spatial extent surveys;
- Transect and quadrat surveys and/or sampling;
- Field-based physical measurements;
- Deployment and retrieval of data loggers; and
- Remote sensed methods (imagery from satellites, drones or airplanes).

Often, one can choose between multiple ways to monitor one indicator, and each will have its own advantages, disadvantages, and unique considerations. Monitoring programs face multiple constraints, so evaluating trade-offs among alternative response designs which can monitor the same indicator can be useful (e.g., Table 2).

Table 2. Mock response design options for water surface temperature monitoring.

Response design	Cost per sampling unit	Temporal resolution	Spatial coverage	Relevance	Number of sampling units feasible given a fixed budget
Temperature Probe + Data Logger	High (high upfront cost; low ongoing cost)	Every minute	Low	High	10
Hand-held temperature Probe	Medium (medium upfront cost, high ongoing cost)	Weekly	Medium	Med	50
Remotely sensed surface temperature	Low (no upfront cost, low ongoing cost)	Monthly	High	Low	1000

Trade-offs that should be considered include:

- **Upfront vs. Ongoing Sampling Costs**. Some response designs will come with a large upfront cost and require little resources afterwards, while others will have ongoing costs that must be accounted for in annual budgets;
- **Spatial vs. Temporal Coverage**. Certain response designs are designed for monitoring large regions, while others are optimized for providing high temporal frequency coverage select areas. For example, remotely sensed data may give you the soil moisture for a large area, but the return frequency and spatial coverage may be low. On the other hand, piezometers with a data-logger can give measurements of water pressure at high temporal frequency, but only for the few areas where they are deployed.
- **Capacity**. A response design must be realistic, given the hardware and software resources of a community, as well as budgetary and human resource restrictions. Scientific instruments and field protocols vary in complexity. Selecting a response design that is feasible given the qualifications and level of interest of community monitors is important.
- **Relevance**. It is important to determine just how suitable the selected response design is to measure the metric of interest. For example, if it is necessary to monitor a metric year-round, selecting an instrument that is suitable in all weather conditions will be a key consideration. It may be tempting to

reduce costs by using equipment on hand, but it is important to evaluate how appropriately the measurements that will be generated inform the true state of an indicator. A response design should offer the appropriate level of accuracy (measurements closely approximate the true value of the indicator) and precision (variability among measurements) for the question of interest.

Remotely sensed data can be employed for a variety of environmental monitoring purposes, including land cover classification, ecosystem indicator measurement (e.g., surface temperature, vegetation productivity, chlorophyll) as well as tracking changes in key parameters over time (e.g., habitat loss, fragmentation, climate change) (Kerr and Ostrovsky 2003). Furthermore, sensors like Landsat, AVHRR, MODIS, Sentinel, and others provide nearly global coverage of the earth at no or low cost. Remote sensing platforms provide a diversity of sensors, each of which have benefits and disadvantages, and should be selected so that they are compatible with the indicator in mind. Optical (multi-spectral or panchromatic) imagery has the benefit of being easily interpreted, and has many use cases (e.g., differentiating between vegetation classes, assessing land use change (e.g., deforestation, fire, snowmelt mapping). Radar-based satellites capture imagery in the micro- and radio-wave spectrum, which can detect different properties of the earth's surface than optical imagery. Radar satellites can tell us about forest, soil, and wetland attributes, create 3-dimensional imagery, and have the benefit of being able to image the earth's surface during cloudy conditions (which interfere with optical imagery) (Crisp 2004; Aplin 2005).

3.4 Identify Sampling Design (where, when)

The sampling design describes where and when measurements are to be made, and the process by which those locations and times are selected (Stevens and Urquhart 2000). Developing a sampling design involves making critical choices about how to allocate sampling effort within and among years, and across sites. It also entails continually re-evaluating the allocation of sampling effort as information is gathered about variations in the target population (Larsen et al. 2001). A sampling design is constrained by the response design (i.e. what is feasible given budget, available technology, and other constraints). However, the optimal sampling design should also inform the response design. When developing the sampling design, the following elements should be considered:

Target Population

The **target population** is the population we would like to know about. In many cases, there are mismatches between the population we sample (the sampling population) and the population we are interested in (target population). The closer the match the better. We cannot make inference to any individuals or sites within the target population that do not have some probability of being selected (i.e., those which are not in the sample frame).

Sample Frame

The **sample frame** is the complete list of sampling units from which a sample unit is selected. Ideally the sample frame includes all individuals or sites in the target population although in practice there are usually some mismatches. The sample frame may be a list of discrete units (e.g., proposed riparian restoration sites) or a spatial layer describing continuous features (e.g., an entire stream network within a watershed). When an area frame is used, sites are usually selected by choosing a random starting point within the area. In some cases, defining the sample frame may require GIS analyses or expert opinion.

Sample Unit

The **sample unit** is the actual unit of measurement. Sample units may be discrete features or may be an arbitrarily defined unit from a continuous feature (e.g., a point sampling site in a lake, or a 20m * 20m vegetation plot). In many cases, a multi-stage sampling design is optimal: a primary sampling unit (PSU) is selected first, and then sub-sampled using secondary sampling units (SSUs). For example, we may select a random set of bogs (PSUs) and then sub-sample each with a series of plots or point sampling locations (SSUs).

Selection of Sites

This section describes the sampling approach recommended for selecting sampling units from the sample frame. In general, a **probabilistic** sampling design is recommended. In a probabilistic sampling design, all sampling units have a known probability of selection. When the probability of selection is un-known, there is potential that the data will be biased (i.e., certain segments of the population may be over- or under-represented). Common probabilistic designs include (US EPA 2006):

- **Simple random** sampling, in which sampling units are randomly selected, and each sampling unit has an equal chance of being selected. Simple random sampling is ideal when the target population is relatively homogenous. Simple random sampling provides unbiased estimates of target population parameters;
- **Systematic** sampling, in which sampling units are chosen according to a fixed interval (e.g., one might survey every 5th sampling unit), and the first sampling unit is randomly selected. Systematic sampling is logistically simple and facilitates broad coverage of the territory (in some simple random samples, sampling units may be clumped together). It may be biased if the fixed interval matches up with the natural periodicity of the sample frame (e.g., sampling every 2km along a river may be inappropriate if there is a natural riffle-pool sequence that is repeated every ~2km); and
- **Stratified** sampling, in which the sampling frame is first divided into non-overlapping groups or strata, and then each of the strata are sampled (stratified sampling described in further detail on page 12).

Probabilistic designs enable researchers to make inferences from the sample to the entire population of interest. Probabilistic designs are illustrated in Figure 4.

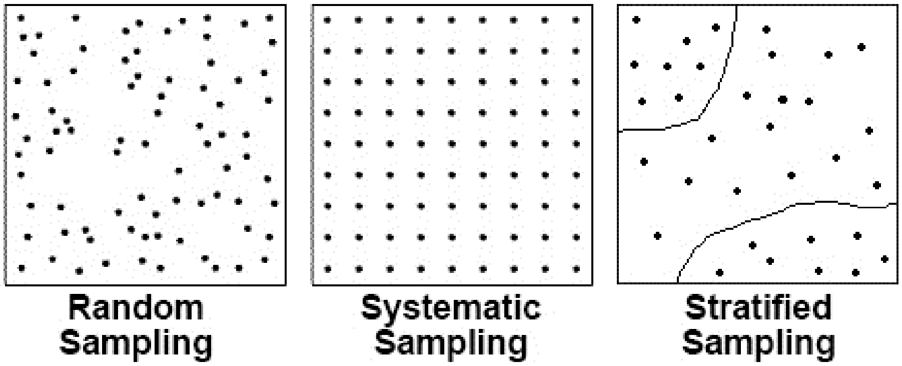


Figure 4. Illustration of the different ways to select sample sites. With simple random sampling, sampling units are selected randomly from the target population. With systematic sampling, sampling units are chosen according to a fixed interval. In a Stratified design, sampling units are first divided into groups (top left, middle, bottom right), and samples are taken from each group. Credit: Humboldt University.

While probabilistic designs are recommended, they are not mandatory. Sampling of sites based on **expert judgement** can be chosen, and additional important monitoring locations can be added to the sampling design (e.g., sites of high cultural value). However, in judgemental sampling, the selected sites cannot be used to make inferences about other parts of the region. In addition, judgemental sampling prohibits quantifying the variance, and may result in biases (US EPA 2006).

Sample Effort

Sample effort ultimately refers to the cost of sampling (inclusive of capital expenditures, maintenance, operations, and human resources costs, as well as the time it takes to conduct sampling). Effort is directly related to the number of sample units (PSUs and SSUs). In general, more samples give greater precision, however as the sample size increases there are diminishing returns (Figure 5). A well-designed probabilistic survey can provide almost as good information as a census for substantially less cost (Cochran 1977).

As a result, developing an **efficient** sampling design is ideal (i.e., increasing the value of each sample) (Figure 5). An efficient design is one which minimizes effort (e.g., cost, resources, time, etc.) while maximizing the precision and accuracy (and minimizing the bias) of the data.

Sampling effort will be influenced by the selected response design. For example, a cost-effective response design will allow a large number of samples, while an expensive response design will permit only a few samples.

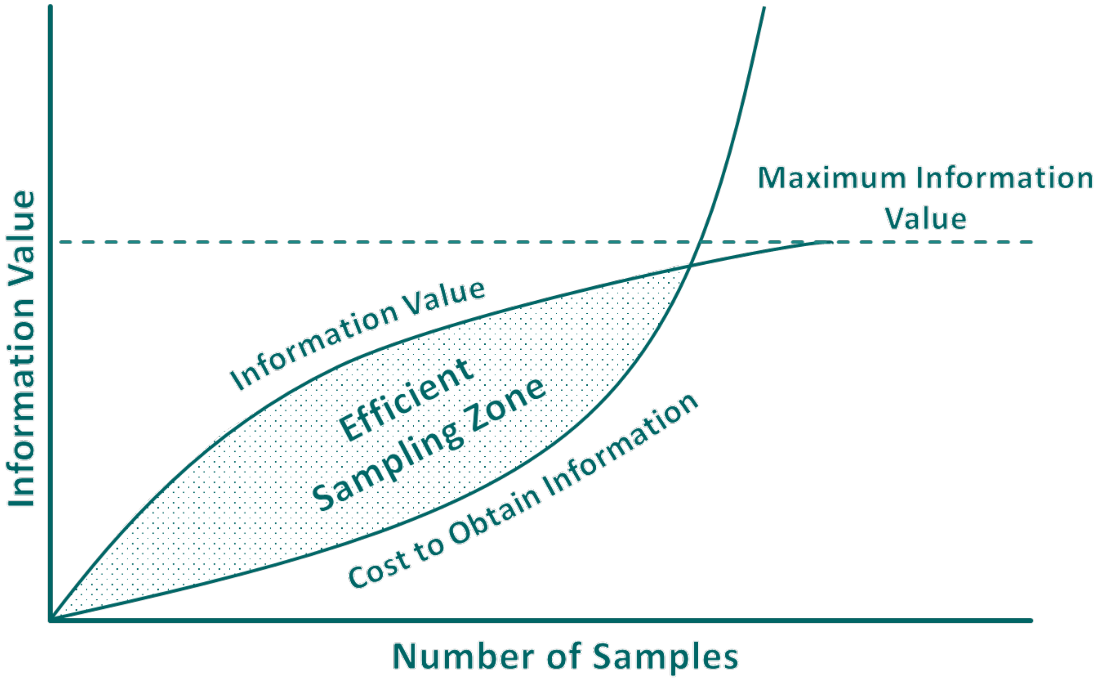


Figure 5. Simplified cost effectiveness of a monitoring program. Adapted from Plisnier et al. (2018).

Stratification

In a **stratified** monitoring design, the sampling frame is first divided into non-overlapping groups or strata (i.e., each sampling unit must belong to only one strata), and then each of the strata are sampled. Strata may be defined based on geography (e.g., elevation, distance from a given feature), time (e.g., seasons, or night and day) or other factors (e.g., limnology, waterbody type). Stratification is appropriate in several circumstances (US EPA 2006):

- If there is a requirement to have independent estimates for different strata (e.g., if the survey covers multiple jurisdictions, it may be necessary to develop independent samples for each jurisdiction);
- If the statistical efficiency of the design needs to be improved (i.e., maintaining precision while reducing sampling effort). Stratification is ideal when the variability within each group is low, and the variability between each group is high (see Figure 6). For example, it may be appropriate to stratify by wetland type (e.g., bogs, fens, marshes) if there is an expectation that parameters (e.g., pH, dissolved oxygen) would remain consistent within each wetland type, but differ between the wetland types;
- If some strata are rare and therefore unlikely to be sampled in a simple random sample (e.g., a culturally important plant may only grow in a certain wetland type which makes up only 1% of all wetlands in the territory); or
- If some strata are of particular importance, more effort can be allocated to those strata, which will increase the precision of statistical parameters.

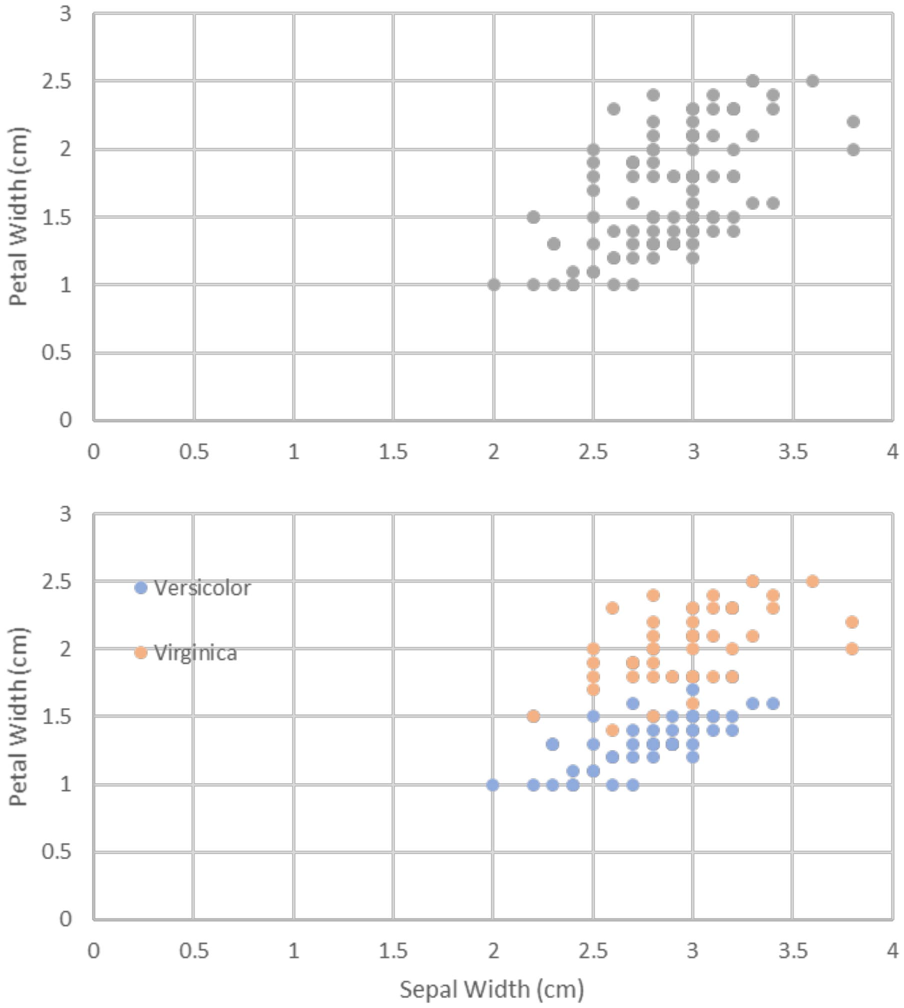


Figure 6. In this example, the variability of petal width among all sampled flowers is high (above). However, the variability within each species is low (orange and blue, at bottom).

Allocation of effort depends on the reason for stratifying. There are three basic strategies: (1) proportional allocation of sites based on the size of the strata; (2) equal allocation of sites to strata; and (3) optimal allocation which considers the variability within strata. Proportional allocation is equivalent to a simple random sample. In general, more effort should be allocated to strata which are most important (i.e., require greater precision) or where the variability is the highest (Thompson 2002). However, if variability of different strata is unknown, equal allocation of samples among strata is a sensible starting point. Stratification may not be appropriate if there is not sufficient information about the target population to consistently delineate strata (US EPA 2006).

Timing

The **timing** (at which point during the year) and **temporal frequency** (how often a sampling unit is visited) of sampling are critical components to the sampling design and will depend on the nature of the monitoring question. For each variable, the study objective and the assumed behaviour of the variable will influence the timing and frequency of sampling.

It is optimal to match the temporal frequency of sampling with the natural rate of variation in the system of interest. For example, an invasive species may be limited by cold wintertime temperatures (e.g., four days in a row below -20C) – in that case, monitoring temperature every minute is not necessary, simply measuring air temperature daily, at a consistent time of day will suffice. In the case of a variable that fluctuates with diurnal changes in temperature (e.g., snowmelt) it may be necessary to measure temperature on an hourly frequency.

Another consideration is whether to revisit the same sites year after year. Maintaining the same sampling units year after year minimizes the between site variability and therefore is optimal for the detection of long-term trends. However, the selection of different sites every year results in greater spatial coverage and is better for estimating the regional status of an indicator. In general, both status and trends are of interest. Panel designs (e.g., Table 3) represent a hybrid strategy where sites are revisited on different frequencies (McDonald 2002).

Table 3. Example sample design showing how a combination of revisit frequencies results in a greater overall sample size. If each panel consists of n=10 sample units, then in each year a total of 20 sample units are visited. After 4 years a total of 50 have been visited. After 12 years, 10 sites will have been visited every year and 40 sites will have been visited every 4 years for a total of 3 visits.

Year	Panel 1	Panel 2	Panel 3	Panel 4	Panel 5
1	**Sample**	**Sample**	-	-	-
2	**Sample**	-	**Sample**	-	-
3	**Sample**	-	-	**Sample**	-
4	**Sample**	-	-	-	**Sample**
5	**Sample**	**Sample**	-	-	-
6	**Sample**	-	**Sample**	-	-
7	**Sample**	-	-	**Sample**	-
8	**Sample**	-	-	-	**Sample**
Purpose	Long-term monitoring	Regional Status Monitoring			

3.5 Consider Data Analysis and Reporting Needs (how)

It is also important to consider how the data will be aggregated, analyzed, and reported during the planning phase. The analysis approach should be directly relevant to the questions of interest. Up front consideration of data analysis will help to ensure the correct data are collected and minimize the collection of irrelevant data (i.e., those which do not inform the analysis and management questions of interest). This step is also useful to provide a reality check on what analysis and inference are likely to be possible with the data collected. Data analysis and reporting considerations include:

- Type of data (e.g., qualitative, ordinal, binomial, count, continuous);
- Analytical approach (e.g., regression analysis, comparison among groups, trend analysis, simulation modeling);
- Thresholds (e.g., fixed vs. changes over time?); and,
- How the data will be reported (e.g., what graphs, figures, or maps do you expect to produce).

3.6 Consider Implementation Requirements (how)

This section describes important considerations for the implementation of monitoring programs. Though these may be the last among the list of components to consider, it is important to consider the linkages between these requirements and the other components, since implementation can influence the choices made among the other monitoring framework components. These considerations include (Pollock and Whitelaw 2005; Karr 2008; Plisnier et al 2018):

Governance Considerations

- Potential **implications for resource or stewardship office departments and programs** (e.g., assessing the skills or equipment necessary to undertake each monitoring activity tier);
- Where multiple agencies are involved, ensure that the **roles and boundaries** of the various agencies and partners are well defined. In such cases, ensuring clear communication between partners is key;
- **Links to established programs, or potential collaborators** (e.g., can two adjacent communities combine efficiencies and collaboratively monitor to resolve a common problem). In such cases, it is important to harmonize monitoring methods (and training) and data management systems to facilitate data sharing and increase the robustness of the data to inform management decisions; and
- Ensure **clear, concise, and culturally appropriate** (e.g., ensuring language translation is validated; avoiding disrespectful field protocols (e.g., ITK 2009)) **field-manuals and reporting procedures**.

Technical Considerations

- **Data management systems** (DMS) should be tailored to the specific monitoring activity (in cases where a DMS already exists, it may be necessary to tailor monitoring activities to the DMS). This will involve building a DMS that is optimized to store and process the types of observations that will be collected, tweaking the response and sampling design, or both. It is imperative that access to IT support, hardware (e.g., data storage, processing capacity, data security) and software (e.g., database software, data manipulation and analysis software, long-term storage capacity) is secured before monitoring is commenced, and that there is capacity to manage the DMS; and
- Ensuring that **maintenance of capital purchases** is included in monitoring budgets. Monitoring instruments must be properly maintained and calibrated; other hardware (e.g., IT, vehicles, facilities) will need regular maintenance as well.

Monitoring Design Considerations

- Semi-regular **check-ins with advising scientists** may assist ensuring that data quality standards are being met, that data archival is occurring, field-based-methods are being followed, instruments are calibrated, and may assist in periodically updating the monitoring program as new information is integrated.

4 Bringing it all Together

This section describes the steps required to pull together the individual components described in Section 3 and develop an overarching monitoring framework. The steps outlined here should not be interpreted as prescriptive but rather strategies which will help the user work through potentially difficult trade-offs.

4.1 Understand the Current Situation

There is a great diversity of Indigenous cultures and communities across Canada. Each Indigenous community holds a unique relationship to land, water and territory, shaped by both local and regional factors. Though there are some general principles that all monitoring programs should follow, it is important that monitoring be tailored to each community's context (Pollock and Whitelaw 2005; Cave et al. 2016). Developing a baseline understanding of a community's data needs, assets & resources, capacity, and existing or past monitoring initiatives is a critical first step in developing a monitoring framework. This information provides context that will ensure that a new monitoring program can make use of or expand on existing or past monitoring activities and integrate into decision making and planning processes (Plisnier et al. 2018).

It is important to identify these elements, and use the lessons learned from past monitoring activities to inform the new monitoring program (e.g., avoiding past mistakes, building on successes, avoiding cultural missteps, and understanding how information is used in decision making).

Key baseline information to collect includes (*inter alia*) (Cave et al. 2016; Plisnier et al. 2018):

- The scope of the issues that are facing a community, and what is known about them;
- A community's needs with regards to decision making (at multiple scales);
- Current and past monitoring activities, their relevance and rigour, and data management context (e.g., indicators); and
- Ties between data collection and decision making (e.g., information that can support negotiations, access to funding pools, for economic development, for on-the-ground activities, etc.), or a lack thereof. This step includes a gaps analysis and a review of opportunities to improve the current program.

Providing context to the issues and the community will assist in (Cave et al. 2016; Plisnier et al. 2018):

- Determining which existing questions may be addressed using existing data and information and which questions will require novel datasets, and the data that will be required to resolve those questions;
- Developing monitoring programs that piggyback off of existing or past efforts and existing data;
- Determining and prioritizing key community values (which can inform how questions are developed, and aid developing a tiered or prioritized monitoring framework); and
- Understand how decisions are made within a community, and how monitoring data can integrate into decision making.

4.2 Compile Suite of Potential Monitoring Components (why, what, where, when, how)

Using Section 3 as a guide, develop draft monitoring components for each priority question. At this stage there will be a variety of options from which to select. These preliminary options should be described along with their trade-offs before recommending the overall design:

- Develop and prioritize the key questions (why);
- Determine indicators and metrics for key questions (what);

- Identify and evaluate potential response and sample design alternatives and associated data analysis (where, when, how);
- Compile a suite of potential response and sample designs along with tradeoffs; and
- Identify any monitoring activities in common (e.g., handheld gauge may be used to collect data on multiple metrics).

Table 4. For each indicator and metric, describe the details of the response and sampling design options, as well as the capacity requirements.

Question	Indicator: Lake Health (Secondary)	
	Metric: Lake pH	**Metric: Dissolved Oxygen**
Response Design	• Equipment recommendations • Field protocols • Additional considerations	• Equipment recommendations • Field protocols • Additional considerations
Sample Design	• Sampling units • Strata • Site selection criteria • Frequency	• Sampling units • Strata • Site selection criteria • Frequency
Capacity Requirements	• Personnel requirements • Training needs • Equipment costs	• Personnel requirements • Training needs • Equipment costs

4.3 Develop a Master Sampling Frame and a Nested Design

Develop a Master Sampling Frame

The master sampling frame includes all potential sampling units (including strata), across all monitoring activities. Using the overall territory boundaries as the backdrop, overlay all potential sample units defined in the previous step. For a hydro-climactic monitoring program, this may include:

- Lakes;
- Streams;
- Wetlands;
- Biogeographic units (e.g., ecozone);
- Roads;
- Ice roads;
- Communities;
- Harvesting sites;
- Key habitats; and
- A spatial grid (if simple random sampling across an entire landscape is desired).

Develop a Nested Sampling Design

A master sampling frame will aid in nesting (co-locating) sites which may be associated with different questions or monitoring activities. Where possible, nesting is ideal, as it reduces the total cost of a monitoring program. In practice, this means employing multiple response designs at a single sampling unit. Though it is not necessary to nest, having some sampling units where multiple metrics may be measured can reduce costs (e.g., travel time). Take the scenario shown in Figure 7, for example. Indicator (protocol) 1 is to be collected at 50 sites, indicator 2 at 25 sites, and indicator 3 at 15 sites, in a nested design. Instead of 80 distinct sampling units (50+25+15), this design allows for 80 measurements using 3 protocols, using only 50 total sampling units. This scenario reduces the overall cost of sampling by reducing the need to travel to as many sampling sites; instead, one can monitor three parameters at one site. Another advantage of co-located sites is that it may be possible to relate data from different indicators to better inform the questions (e.g., using a regression analysis with environmental covariates).

Identify opportunities for nesting the sampling design by identifying cases where the same sample units (e.g., lakes) or monitoring activities (e.g., visual surveys) may be used to address multiple indicators.

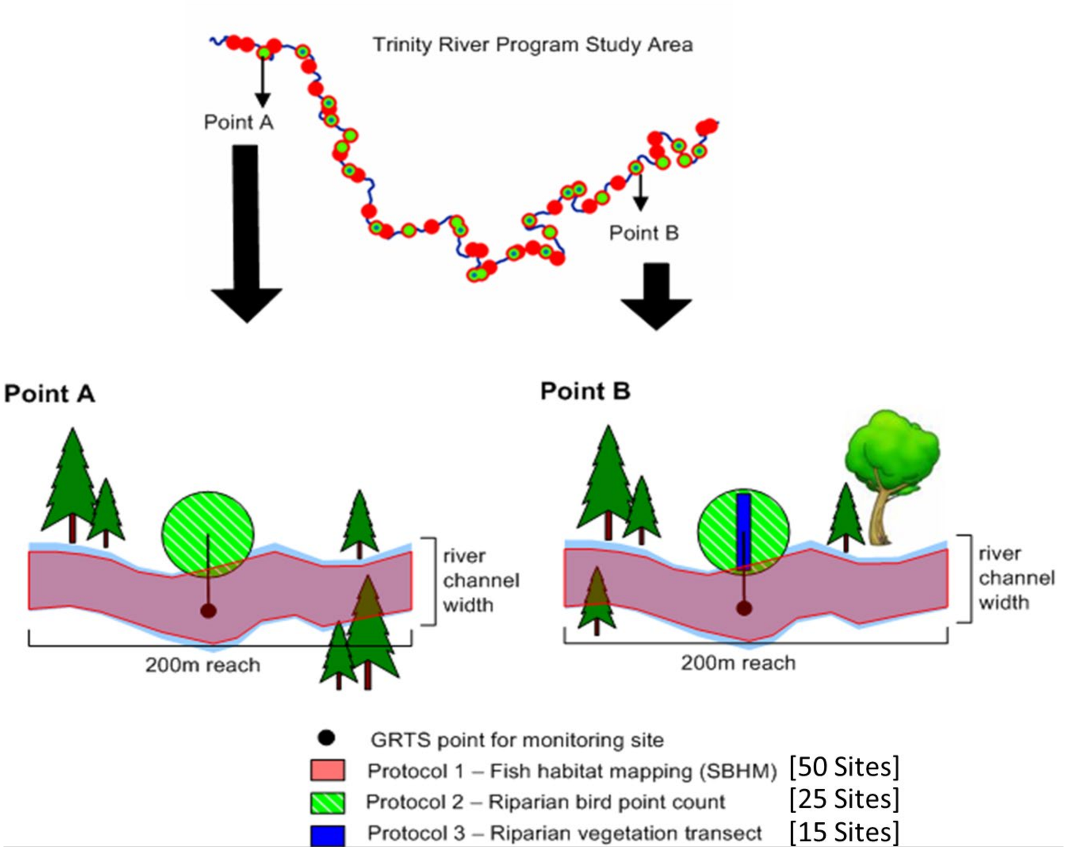


Figure 7. Example of co-located (nested) sampling units along a river, employing three response designs (protocols). Above, the colour of the sampling units (points) indicate the response designs to be implemented at each unit. All response designs are employed at 15 sites. At point A, sampling protocol 1 and 2 can be simultaneously conducted. At point B, sampling protocols 1, 2, and 3 can all be conducted. Co-locating sampling units across space and time can generate efficiencies (e.g., reducing travel costs). From TRRP and ESSA Technologies Ltd. (2009).

4.4 Allocate Monitoring Effort

There are unique considerations for monitoring programs which seek to address multiple questions. When addressing multiple questions, reducing costs by locating efficiencies is an important and worthwhile consideration. For example, selecting response designs which can collect information across multiple metrics (e.g., a hand-held probe may be able to measure pH, conductivity, dissolved oxygen, temperature, and turbidity) can reduce equipment purchasing costs. Efficiencies are compounded when sampling units are nested, and especially so when one metric can inform multiple questions.

Allocation of effort depends first on priority, but must also consider the practical cost-benefit trade-offs of different alternatives. We don't recommend a prescriptive approach but rather a series of considerations. In our experience, once the information gathered through Steps 1-3 (Sections 4.1-4.3) is summarized, the options are usually relatively obvious.

Which questions matter the most to the community?

When allocating monitoring effort among monitoring questions, it is important to establish the degree to which the monitoring question targets key uncertainties or reduces vulnerability of important environmental resources. At the end of the day, not all issues warrant equal concern; monitoring questions should be ranked in the order of "what matters most" to the community.

The prioritization of monitoring questions should factor in the risks to resource; an important resource that is not at risk may require less intensive monitoring activities than a vulnerable resource that a community may not be worried about (e.g., an endangered grass species). On the other hand, a site of utmost cultural importance may warrant monitoring, even if it is at low risk for known stressors.

The amount of uncertainty resolved by monitoring is another important factor to consider. Monitoring that resolves key uncertainties can provide more information than monitoring something that is already well known, especially if both monitoring activities will cost the same. However, it is important to weigh the amount of uncertainty that will be resolved against the value that the community places on the monitoring activity. Questions that directly address community concerns may rank as higher priorities than those which resolve scientific uncertainties (which may be **secondary** questions, ideal for partnership with an academic institution that can offer funding and capacity).

Which question(s) should be addressed first?

When considering how to sequence monitoring activities, there are a few factors that can help guide the choice. There may be a natural order to monitoring activities. For example, the results from one monitoring activity A may be required before monitoring activity B can begin. Priorities may change as new information is obtained and so the monitoring design itself should be revisited within an adaptive management loop. Collaborations with other communities or institutions (academic, government, other) may be a high priority, since the benefits of collaborations (e.g. potential for future collaborations, knowledge sharing, increased interest in monitoring among a community, etc.) are realized over time. Furthermore, monitoring activities which generate or sustain monitoring interest may be highly prioritized, especially if monitoring is not currently highly valued. Monitoring rainbow trout populations may generate interest among community members, even if the information generated is not of high value in the short term.

How many questions can each monitoring activity address?

Among monitoring activities, some will be able to inform multiple questions, while others will only be able to address one (e.g., Table 5). Assuming that the cost of two monitoring activities are equal, one which can address multiple questions can provide a higher value than one which can only address one question. When developing a monitoring framework, identifying monitoring alternatives and their cost will aid in prioritizing monitoring activities.

Table 5. Monitoring activities may inform one or more monitoring questions.

Monitoring Activity	Question 1	Question 2	Question 3	Question 4
Activity A	X	-	X	-
Activity B	X	X	-	-
Activity C	X	X	X	-
Activity D	-	-	X	X
Activity E	-	-	-	X

Altering the Cost of the Monitoring Framework

The framework is ultimately dependent on the budget available. The more affordable the framework, the more likely the long-term success (Plisnier et al. 2018; Jeffers et al. 2019). Depending on the budget available, there are three main ways to modify costs of the monitoring framework:

- **Indicator selection**. A variety of indicators can be used to answer a particular question. Indicators should be prioritized; core indicators should always be collected, while secondary or tertiary indicators should only be collected when there are sufficient resources, or if priorities change.
- **Response design**. Multiple response designs (tiers) may be used to collect data for the same indicator (e.g., remotely sensed soil moisture vs. a specialized soil moisture meter). Different tiers have varying costs and capacity requirements. Lower tiers are typically simpler and more affordable, while higher tiers are more resource intense. Typically, the increased cost will increase the precision and accuracy of the sample.
- **Sample effort**. The total sample size (i.e., number of strata and samples per strata) may be adjusted to according to capacity and other constraints. Reducing sample size will result in a loss of precision. However, it is important not to waste effort by sampling beyond what is required for the question of interest.

References

Aplin, P. 2005. Remote sensing: Ecology. Progress in Physical Geography, 29(1), 104–113. https://doi.org/10.1191/030913305pp437pr

Belfiore, S., J. Barbière, R. Bowen, B. Cicin-Sain, C. Ehler, C. Mageau, D. McDougall and R. Siron. 2005. A Handbook for Measuring the Progress and Outcomes of Integrated Coastal and Ocean Management. IOC Manuals and Guides, 46; ICAM Dossier, 2. Paris, UNESCO.

Carlson, T., and A. Cohen. 2018. Linking community-based monitoring to water policy: Perceptions of citizen scientists. Journal of Environmental Management, 219, 168–177. https://doi.org/10.1016/j.jenvman.2018.04.077

Cave, K., H. Switzman, and M. Nelitz. 2016. Indigenous Involvement in the Network of Networks: Enhancing Access and Use of Hydrometeorological Data for Water Management. Winnipeg, MB: Centre for Indigenous Environmental Resources

Cochran, W. G. 1977. Sampling techniques. John Wiley & Sons, New York, N.Y.

Cohn, J. P. 2008. Citizen Science: Can Volunteers Do Real Research? BioScience, 58(3), 192–197. https://doi.org/10.1641/b580303

Conrad, C. C., and K. G. Hilchey. 2011. A review of citizen science and community-based environmental monitoring: Issues and opportunities. Environmental Monitoring and Assessment. https://doi.org/10.1007/s10661-010-1582-5

Conrad, C. T., and T. Daoust. 2008. Community-based monitoring frameworks: Increasing the effectiveness of environmental stewardship. Environmental Management, 41(3), 358–366. https://doi.org/10.1007/s00267-007-9042-x

Crisp, D. J. 2004. The State-of-the-Art in Ship Detection in Synthetic Aperture Radar Imagery. Retrieved from https://apps.dtic.mil/dtic/tr/fulltext/u2/a426096.pdf

Danielsen, F., N. D. Burgess, and A. Balmford. 2005. Monitoring matters: Examining the potential of locally-based approaches. Biodiversity and Conservation (Vol. 14). https://doi.org/10.1007/s10531-005-8375-0

Douvere, F., and C. N. Ehler. 2011. The importance of monitoring and evaluation in adaptive maritime spatial planning. Journal of Coastal Conservation, 15(2), 305–311. https://doi.org/10.1007/s11852-010-0100-9

Ehler, C N. 2014. A guide to Evaluating Marine Spatial Plans. Paris, UNESCO, 2014. IOC Manuals and Guides, 70; ICAM Dossier 8.

Folke C, C. Fabricius, G. Cundhill, and L. Schulze. 2005 Communities, ecosystems and livelihoods. In: Capistrano D, Samper C, Lee M, Raudsepp-Hearne C (eds.), Ecosystems and human well-being: multiscale assessments. Volume 4. Island Press, Washington, DC pp 261–277

Hedge, P., F. Molloy, H. Sweatman, K.R. Hayes, J.M. Dambacher, J. Chandler, N. Bax, M. Gooch, K. Anthony, B. Elliot. 2017. An integrated monitoring framework for the Great Barrier Reef World Heritage Area. Marine Policy 77:90-96. https://doi.org/10.1016/j.marpol.2016.12.014

Inuit Tapiriit Kanatami [ITK]. 2009. Resolution on polar bear research methods, Annual Meeting, 11 June 2009. http://www.itk.ca/sites/default/files/private/2009-en-itk-agm- resolutions.pdf

Jackson, L.E., J.C. Kurtz, W.S. Fisher (Eds.). 2000. Evaluation Guidelines for Ecological Indicators. U.S. Environmental Protection Agency. Office of Research and Development, Research, triangle Park, NC, EPA/620/R-99/005.

Jeffers, V.F., F. Humber, T. Nohasiarivelo, R. Botosoamananto, L.G. Anderson. 2018. Trialling the use of smartphones as a tool to address gaps in small-scale fisheries catch data in southwest Madagascar, Marine Policy, Volume 99, Pages 267-274.

Johnson, N., A. Lynch, L. Alessa, A. Kliskey, C. Behe, F. Danielsen, S. Gearheard, P. Pulsifer, V. Gofman-Wallingford, E.-M. Krümmel, T. Mustonen, and M. Svoboda. 2015. The contributions of Community-Based monitoring and traditional knowledge to Arctic observing networks: Reflections on the state of the field. Arctic, 68(5), 1–13. https://doi.org/10.14430/arctic4447

Johnson, N., C. Behe, F. Danielsen, E. M. Krümmel, S. Nickels, and P. . Pulsifer. 2016. Community-based monitoring and indigenous knowledge in a changing arctic: a review for the sustaining arctic observing networks. Test, 1(1), 62. Retrieved from http://iccalaska.org/wp-icc/wp-content/uploads/2016/05/Community-Based-Monitoring-and-Indigenous-Knowledge-in-a-Changing-Arctic_web.pdf%0A

Kerr, J. T., and M. Ostrovsky. 2003. From space to species: ecological applications for remote sensing. Trends in Ecology & Evolution, 18(6), 299–305. https://doi.org/10.1016/S0169-5347(03)00071-5

Kosmala, M., A. Wiggins, A. Swanson, and B. Simmons. 2016. Assessing data quality in citizen science. Frontiers in Ecology and the Environment, 14(10), 551–560. https://doi.org/10.1002/fee.1436

Larsen, D.P., T.M. Kincaid, S.E. Jacobs, and N. S. Urquhart, 2001. Designs for Evaluating Local and Regional Scale Trends Vol. 51 No. 12. BioScience (51)12: 1069-1078.

Lemos, M. C., C. J. Kirchhoff, and V. Ramprasad. 2012. Narrowing the climate information usability gap. Nature Climate Change, 2(11), 789–794. https://doi.org/10.1038/nclimate1614

Mcdonald, Trent, L. 2003. Review of environmental monitoring methods: survey designs. Environmental Monitoring and Assessment, 85(3), 277–292.

MRAG. 2010. Monitoring the Vulnerability and Adaptation of Pacific Coastal Fisheries to Climate Change. Report Prepared for the Secretariat of the Pacific Community Marine Resources Division.

Paige, K., Darling, L.M. and D. Pickard. 2014. A Guide to Wildlife Resource Value Effectiveness Evaluations. Ecosystems Branch, Ministry of Environment, Resource Practices Br., Ministry of Forests, Lands and Natural Resource Operations. Victoria, BC. FREP Report 37. http://www.for.gov.bc.ca/hfp/frep/publications/index.htm

Pickard, D. and M. Porter. 2008. Monitoring and Evaluation Toolbox. Draft report prepared by ESSA Technologies Ltd., Vancouver, B.C. for Kathy Paige, Ecosystems Branch, B.C. Ministry of Environment, Victoria. 51 pp.

Plisnier, P. D., M. Nshombo, H. Mgana, and G. Ntakimazi. 2018. Monitoring climate change and anthropogenic pressure at Lake Tanganyika. Journal of Great Lakes Research, 44(6), 1194–1208. https://doi.org/10.1016/j.jglr.2018.05.019

Pollock, R. M., and G. S. Whitelaw. 2005. Community-based monitoring in support of local sustainability. Local Environment. https://doi.org/10.1080/13549839.2005.9684248

Porter, M., D. Pickard, S. Casley, N. Ochoski, K. Bryan and S. Huang. 2013. Skeena lake sockeye Conservation Units: habitat report cards. Report prepared by ESSA Technologies Ltd. for the Pacific Salmon Foundation. 111 p.

Rapport, D.J., and M. Hildén. 2013. An evolving role for ecological indicators: From documenting ecological conditions to monitoring drivers and policy responses. Ecological Indicators 28:10–15.

Reynolds, J. H. 2012. An overview of statistical considerations in long-term monitoring. Design and Analysis of Long-Term Ecological Monitoring Studies, 23–53. https://doi.org/10.1017/CBO9781139022422.005

Reynolds, J. H., M. G. Knutson, K. B. Newman, E. D. Silverman, and W. L. Thompson. 2016. A road map for designing and implementing a biological monitoring program. Environmental Monitoring and Assessment, 188(7). https://doi.org/10.1007/s10661-016-5397-x

Roy, P., É. Fournier, and D. Huard. 2017. Standardization Guidance for Weather Data, Climate Information and Climate Change Projections. Montreal, Ouranos. 52 pp. + Appendixes.

Savan, B., A. J. Morgan, and C. Gore. 2003. Volunteer environmental monitoring and the role of the universities: The case of Citizens' Environment Watch. Environmental Management. https://doi.org/10.1007/s00267-002-2897-y

Sharpe, A., and C. Conrad. 2006. Community based ecological monitoring in Nova Scotia: Challenges and opportunities. Environmental Monitoring and Assessment 113(1-3):395 – 409. http://dx.doi.org/10.1007/s10661-005-9091-7

Silvertown, J. 2009. A New Dawn for Citizen Science. Trends in Ecology and Evolution, 24(9), 467–471. https://doi.org/10.1016/j.chemosphere.2018.03.203

Soroye, P., N. Ahmed, and J. T. Kerr. 2018. Opportunistic citizen science data transform understanding of species distributions, phenology, and diversity gradients for global change research. Global Change Biology 24: 5281-5291. https://doi.org/10.1111/gcb.14358

Stalberg, H.C., R.B. Lauzier, E.A. MacIsaac, M. Porter, and C. Murray. 2009. Canada's policy for conservation of wild pacific salmon: Stream, lake, and estuarine habitat indicators. Can. Manuscr. Fish. Aquat. Sci. 2859: xiii + 135p.

Stevens D.L. Jr, and N.S. Urquhart. 2000.Response designs and support regions in sampling continuous domains. Environmetrics 11: 13–41.

Thomas, L., R. Williams, and D. Sandilands. 2007. Designing line transect surveys for complex survey regions. J. Cetacean Res. Manage. 9(1):1-13.

Thompson, S.K. 2002. Sampling. 2nd Ed. John Wiley & Sons, New York, N.Y.

Trinity River Restoration Program [TRRP] and ESSA Technologies Ltd. 2009. Integrated Assessment Plan, Version 1.0 – September 2009. Draft report prepared for the Trinity River Restoration Program, Weaverville, CA. 285 pp.

Turner, W., C. Rondinini, N. Pettorelli, B. Mora, A. K. Leidner, Z. Szantoi, G. Buchanan, S. Dech, J. Dwyer, M. Herold, L. P. Koh, P. Leimgruber, H. Taubenboeck, M. Wegmann, M. Wikelski, and C. Woodcock. 2015. Free and open-access satellite data are key to biodiversity conservation. Biological Conservation, 182, 173–176. https://doi.org/10.1016/j.biocon.2014.11.048

U.S. Environmental Protection Agency (US EPA). 2006. Guidance on Systematic Planning Using the Data Quality Objectives Process, (February).

Whitelaw, G. S., H. Vaughan, B. Craig, and D. Atkinson. 2003. Establishing Environmental, the Canadian Community Monitoring Network. Environmental Monitoring and Assessment, 88, 409–418

Appendix A – Hydro-Climatic Monitoring for Matawa

The Issue – Winter Roads

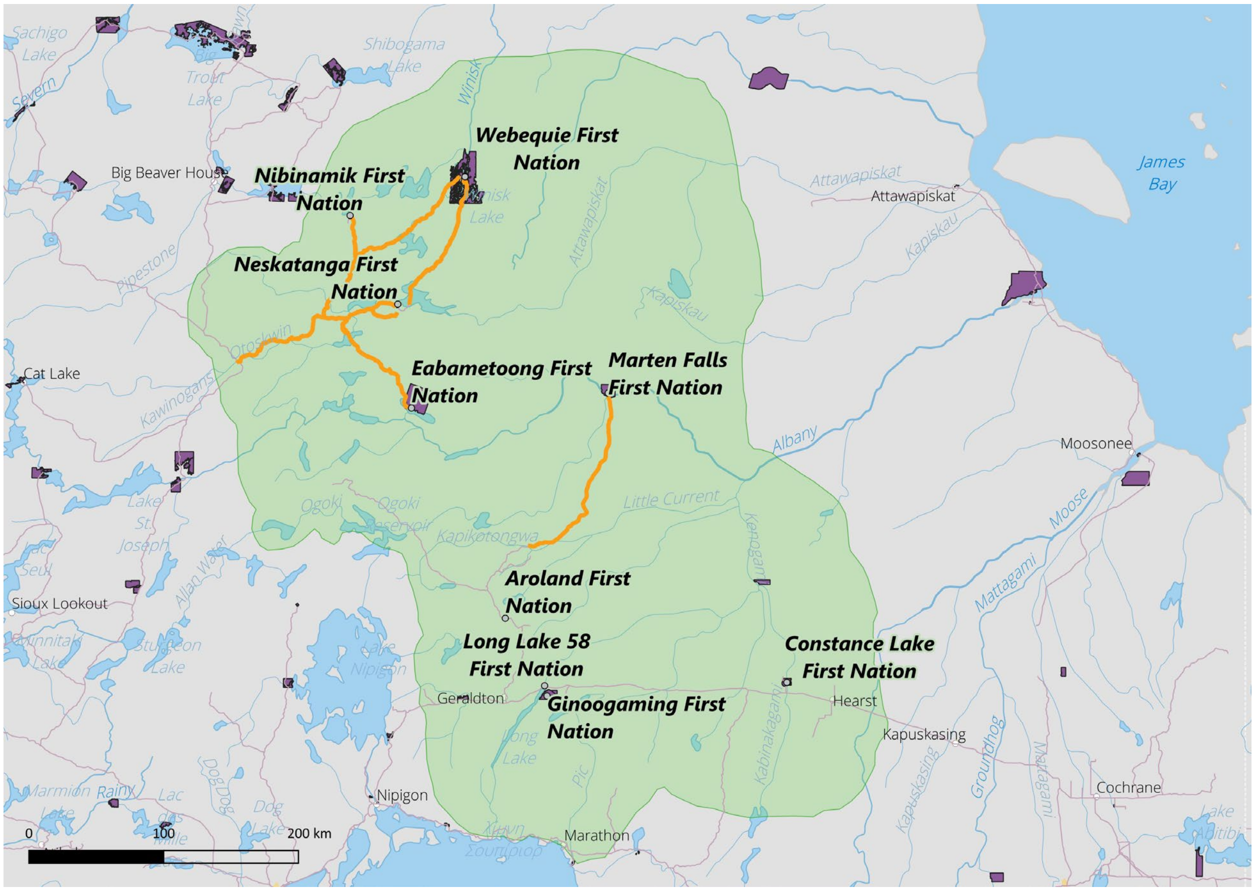


Figure 8. Member nations of Matawa First Nations Management showing Matawa Homelands. Winter roads (gold) connect five Matawa member First Nations to the provincial road network (purple).

Five Matawa member First Nations are remote, meaning that they are not accessible by road for most of the year. During the winter, once the ice is thick enough to support vehicles, winter roads are constructed which connect these communities to the provincial highway network (Figure 8). Winter roads facilitate travel between Matawa member First Nations and elsewhere, and significantly reduce the cost to bring goods (e.g., fuel, food, construction materials, etc.) to remote communities (IBI Group 2016). In fact, Perrin et al. (2015) estimate that shipping goods by winter roads costs 1/10th the price of using air transport. Remote Matawa member First Nations are accessible by two winter road corridors: the Webequie corridor, which services Eabametoong First Nation, Nibinamik First Nation, Neskantaga First Nation, and Webequie First Nation (see Figure 9), and the Marten Falls corridor, which services only Marten Falls First Nation (see Figure 10) (IBI Group 2016). Recently, members of Matawa member First Nations have noted that unseasonable warm weather in the shoulder season has reduced the viability of these roads. The monitoring in this section seeks to answer the following question: ***Will our winter roads remain safe and usable under a changing climate?***

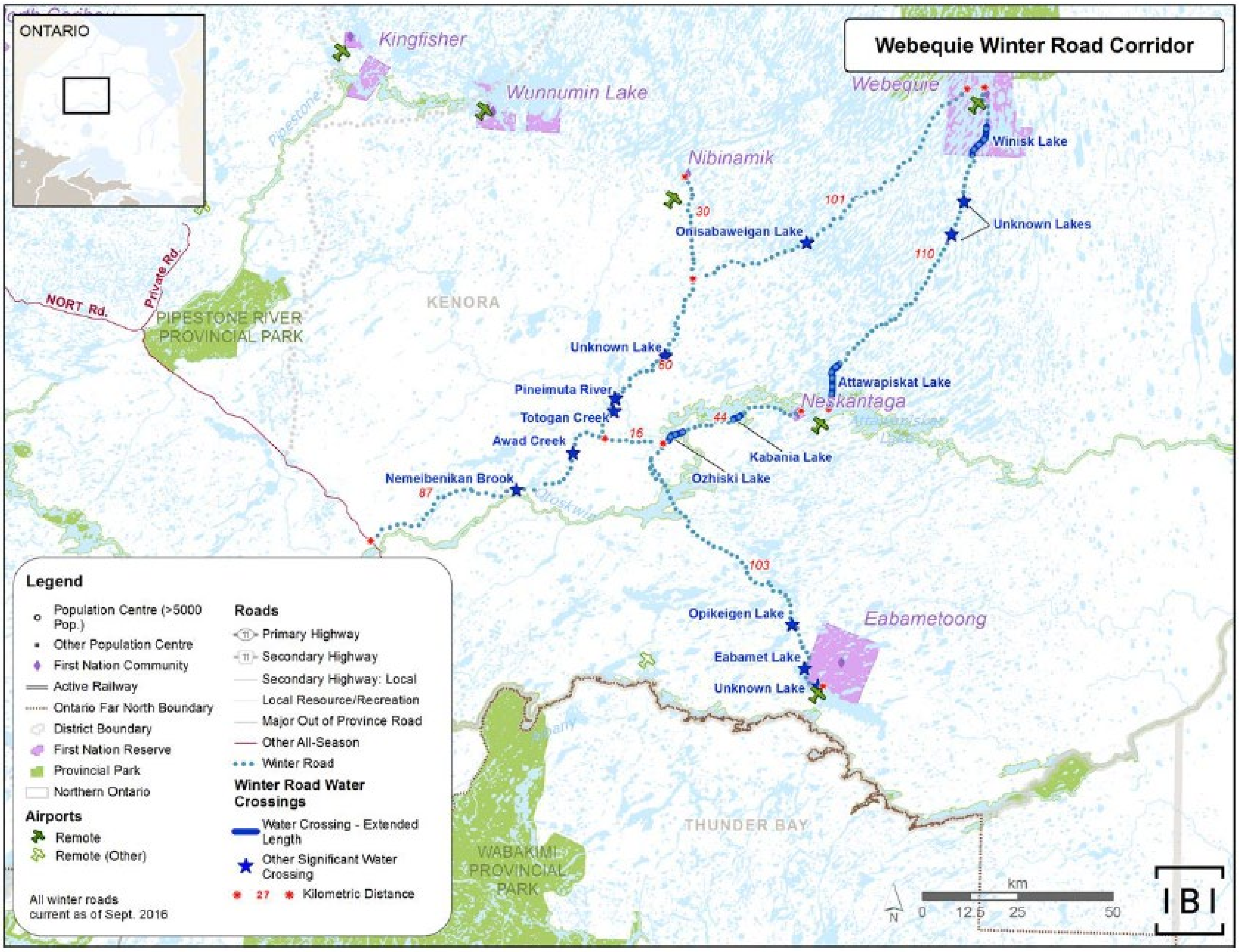


Figure 9. Webequie winter road corridor, showing extended length water crossings (sites of potential safety concern). Source: IBI Group (2016).

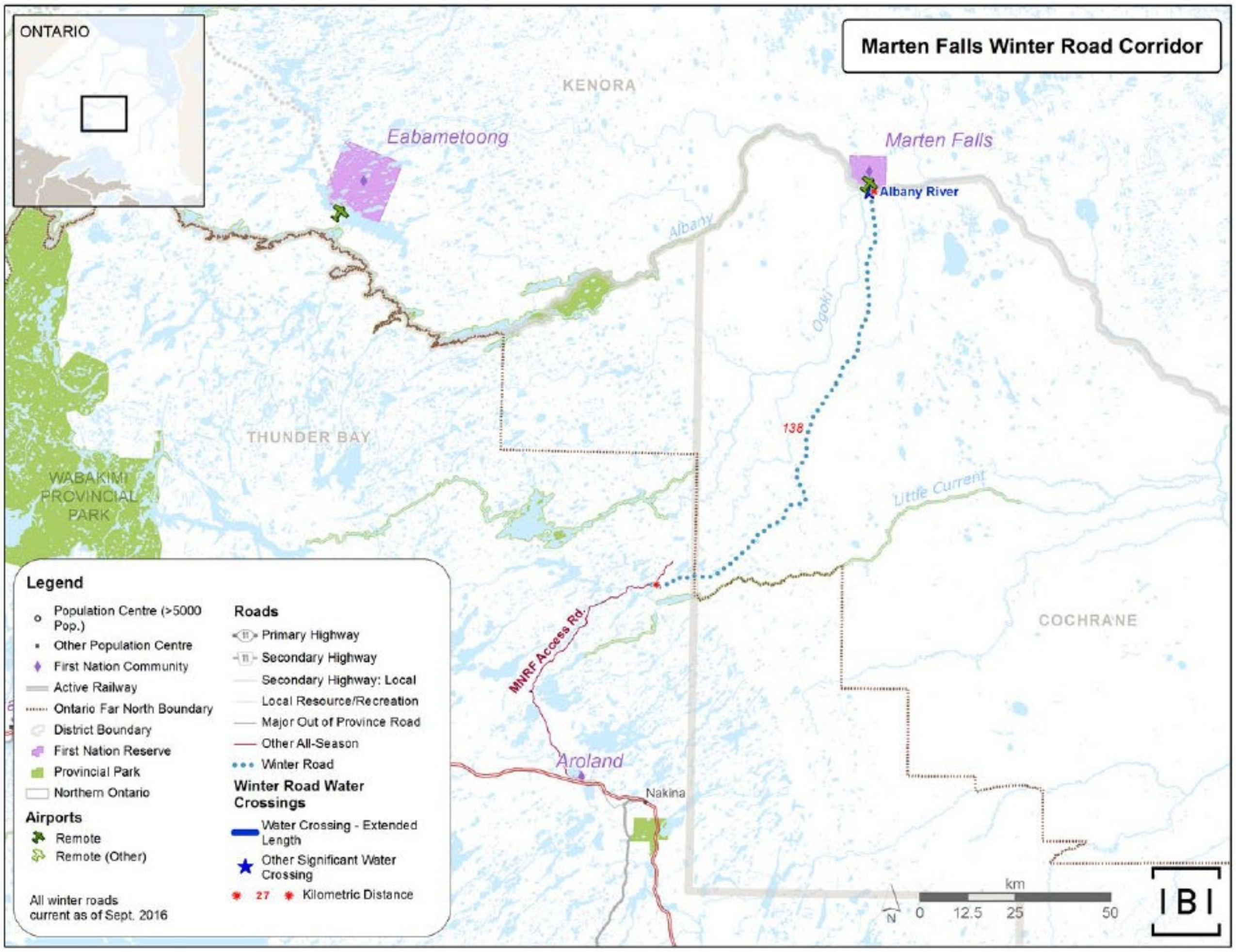


Figure 10. Marten Falls winter road corridor, showing extended length water crossings (sites of potential safety concern). Source: IBI Group (2016).

Indicators and Metrics

Primary Indicator: Length of Winter Road Operating Season

Metrics:

- Opening date of winter road;
- Closing date of winter road; and
- Average daily air temperature.

This indicator informs the usability of winter roads year over year. The length of a winter road's operating season is primarily driven by climatic variables – a colder winter will typically result in earlier freeze-up and later break-up, resulting in a longer operating season. In the fall, the opening of winter roads is largely determined by temperature and snowfall (snow acts as an insulator and slows ice growth) (Ashton 2011; Perrin et al. 2015; Proskin et al. 2011). In the spring, winter roads close when ice conditions thin, a process driven by solar radiation (i.e., sunlight) as well as warm temperatures (Ashton 2011; Perrin et al. 2015). In particular, freezing degree days (FDDs) are highly correlated with ice thickness and have been used to forecast the operating season of winter roads in future climate scenarios (Mullan et al. 2017). Although winter roads are engineered structures, and improvements in techniques and technologies have enabled them to open earlier and close later (Strandberg et al. 2014), they are still expected to have shorter operating seasons as temperatures warm (Mullan et al. 2017).

Secondary Indicator: Winter Road Condition

Metrics:

- Ice Thickness
- Ice Type
- Characterization of Cracks

The condition of winter roads is informed by three metrics: ice thickness, ice type, cracks in the ice. These metrics combine to paint a picture of the safety of winter road segments. Like the length of the winter road operating season, these indicators are influenced by climatic factors (in particular, ice thickness) but can be modified through road repairs and engineering design choices.

Ice Thickness

We recommend using this metric to inform the safety of ice-roads on a day by day basis. If ice is too thin, it will not be able to support weight. The maximum load which a winter road can bear (over water crossings) is governed by Gold's Formula (Barrette 2018):

$$P = A \times h^2$$

Where:

A is an empirically derived risk factor, which is typically set between 3.5 (low risk tolerance) and 6 (high risk tolerance);

h is the thickness of ice; and

P is the allowable load, in kilograms.

As a rule of thumb, the minimum ice thickness for typical loads is:

- 10 cm for foot traffic (120 kg)
- 18 cm for snow-machines (500 kg); and
- 38 cm for passenger vehicles (5000 kg) (assuming blue ice – different types of ice have different mechanical properties).

Ice Type

There are multiple types of ice that can form among winter roads, caused by different physical processes. Gold's Formula assumes that the ice is "blue ice," which is the strongest and thickest type of ice. Blue ice grows below surface ice and contains few bubbles. White ice forms above surface ice as snow is flooded (this can occur due to rain on snow or flooding). White ice contains a significant amount of bubbles and can support only half the load of blue ice. Slush ice or other types of ice with significant water content should not be included in ice thickness calculations (it should not be assumed to support any loads). Additional detail about the characterization of ice is given in Infrastructure Health & Safety Association (2014, p5).

Characterization of Cracks

Along with the thickness of ice in winter roads, cracks are indicative of the possible failure of a winter road (for sections over waterbodies), and thus are directly tied to road safety. Cracks may be caused by (Infrastructure Health & Safety Association 2014):

- Engineering design and operational factors:
    - Excessive Loads (when loads exceed the allowable load, or when the load is stationary for longer than the allowable limit)
    - Snowbanks (ice underneath snowbanks is typically thin, and the weight of snow can cause cracks)
    - Dynamic Waves (operating vehicles faster than permitted can cause dynamic waves that can cause cracks in weak-spots)
- Natural factors:
    - Differences in ice thickness and buoyancy
    - Thermal contraction or expansion of ice (ice cracks as a result of rapid changes in air temperature)
    - High winds (which can generate ridge formations)
    - Water level fluctuations

Ice cracks do not appear to be influenced by long-term climate conditions, although it is possible that a link exists but has not been determined. All cracks should be recorded and monitored. Wet cracks (those with the presence of water) indicate that cracks extend from the ice surface to the water below, and should prompt immediate action: loads should be removed and repairs should begin immediately (Infrastructure Health & Safety Association 2014). Dry cracks which are over ½ the thickness of ice should also be immediately repaired. Other cracks should be monitored, but are not considered as dangerous. Detailed information about how cracks alter load bearing capacity are given in Infrastructure Health & Safety Association (2014, p27).

Decision Making and Planning Processes

As northern Ontario's climate warms, members of Matawa member First Nations are concerned about the safety and long-term viability of winter roads. Already, individuals have reported that during the shoulder seasons, these roads are more unreliable due to unexpected warm weather or rain (e.g., from Neskatanga First Nation to Eabametoong First Nation) which can compromise ice conditions. If warming trends continue, the operating season of winter roads could significantly decline, even in the short term (e.g., Bush and Lemmen 2019; Mullan et al. 2017; Whalen et al. 2016). Important considerations with regards to winter roads in Matawa Homelands include:

- **Human health and safety.** There is a non-zero risk of failure for winter roads in areas where they cross waterbodies (lakes, rivers, and even muskegs). If winter roads are to fail (i.e., crack), members are at risk of personal harm, or may lose their vehicle. Monitoring ice conditions can potentially support emergency response planning, on hourly, daily, or longer time scales.
- **Economic activity and planning.** Winter roads significantly reduce the costs to ship goods to and from, and the costs for individuals to travel to and from remote communities (IBI Group 2016; Perrin et al. 2015). Winter roads also reduce the pressure on air transportation infrastructure, as they reduce the need for flights. Improved forecasting of winter road operating season length and conditions can facilitate infrastructure planning within community by providing more accurate knowledge when low-cost transportation will be available. While other cost-effective modes of transportation have been theorized as winter road replacements (e.g., hovercrafts; airships), none are currently feasible (Barrette 2018). Better knowledge about the how winter roads may be affected by climate change would help scope and prioritize climate change adaptation actions.

- **Negotiations with government.** Multiple lines of evidence suggest that winter road operating seasons will shorten, and freshwater ice will thin as the climate continues to warm (Brown and Duguay 2011; Bush and Lemmen 2019; Mullan et al. 2017). Evidence of the impacts of climate change on Matawa membercommunities (e.g., increased transportation costs, increased risks to safety) could be useful for negotiations with provincial and/or federal governments.
- **Referrals.** Baseline data about climate variables (e.g., current status, observed trends) can be of assistance when responding to referrals or impact assessment processes, or in negotiations with proponents. Better baseline knowledge about climate conditions may allow communities to better assess the potential impact of development activities.
- **Future developments.** Two all-season roads in Matawa Homelands are currently undergoing impact assessments, and a third is under consideration. As of the fall of 2019, an all-season road connecting Marten Falls to the Painter Lake road is undergoing an impact assessment; this would connect Marten Falls to the provincial highway network[1]. An all-season road between Webequie First Nation and a nearby mineral deposit is undergoing an impact assessment[2]. Finally, an all-season road in the Webequie winter road corridor has been under consideration for nearly a decade, and has gone through multiple rounds of community consultations. This road would link Webequie First Nation with the provincial highway network, although this project is not actively being considered.

Methodology and Sample Design Considerations

Sampling Design

Data for five of the six metrics (opening date and closing date of winter road, ice thickness, ice type, and characterization of cracks) should be obtained from winter road contractors. While data for air temperature is available from Environment Canada, it is recommended that additional data for this metric be collected, since data is only available at two locations – additional data would permit detection of climate trends at a finer scale. Sampling design for all metrics is provided in Table 6.

---

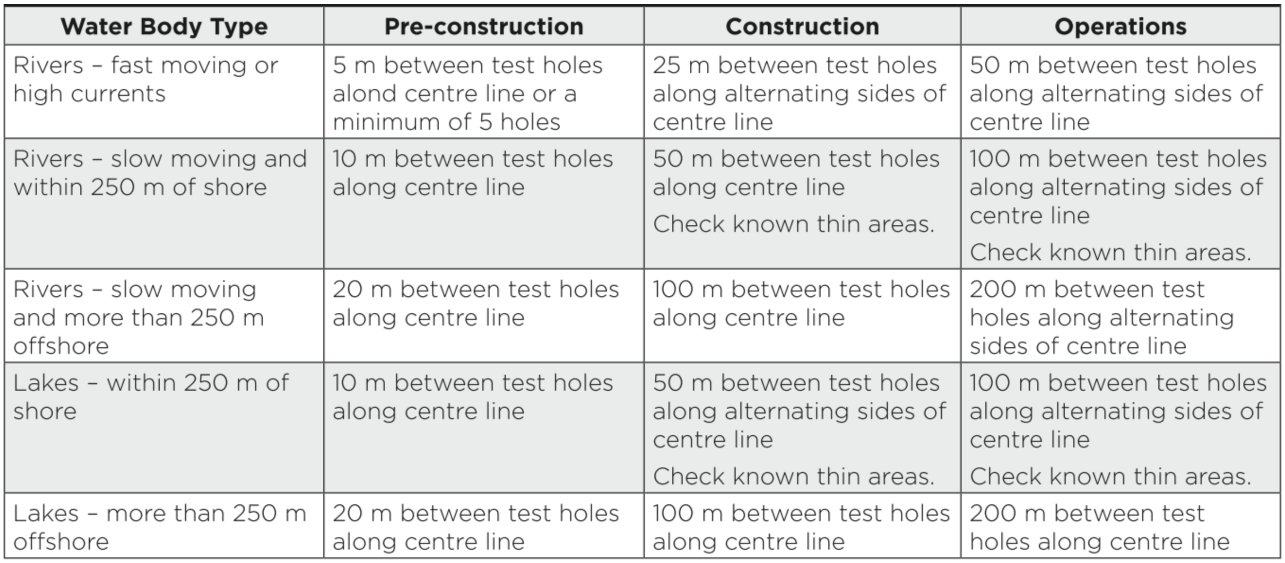
[1] https://iaac-aeic.gc.ca/050/evaluations/document/133156

[2] https://iaac-aeic.gc.ca/050/evaluations/document/133152

Table 6. Recommended sampling design for all metrics.

Indicator	**Length of Winter Road Operating Season**			**Winter Road Condition**		
Metric	**Date of Opening**	**Date of Closing**	**Average Daily Air Temperature**	**Ice Thickness**	**Ice Type**	**Characterization of Cracks**
Target Population	Winter roads in the Webequie and Marten Falls corridors.			Vulnerable water crossings on winter roads in the Webequie and Marten Falls corridors.		
Sample Frame	The sample frame would be the same as the target population.			The sample frame would be the same as the target population.		
Sample Unit	This method would use a census design (no stratification or site selection is necessary). Opening and closing dates for all road segments within both road corridors should be tracked, for all years.		Point location of temperature measurements, documented with GPS coordinates	Point location of ice condition measurements within the sample frame, documented with GPS coordinates.		
Stratification			Stratification is not recommended	The sample frame should be divided into crossings over rivers, and lakes. Ice thickness is highly variable over rivers, but is typically even across lakes. Increased sampling effort is suggested for rivers (see Table 7).		
Site Selection			Additional hourly air temperature monitoring should be conducted in Webequie, Nibinamik, and Eabametoong First Nations.	Ice thickness and condition should be measured systematically along the centreline of a winter road. Recommended maximum test-hole measurements are given in Table 7.		
Timing			Temperature should be recorded hourly.	In mid-winter, the variability of ice thickness is low, and sampling can be infrequent (Ashton 2011). In the fall and spring, ice thickness can change quickly in response to fluctuations in temperature and irradiance (Ashton 2011). This suggests that more frequent sampling should be done in the fall and spring, times at which roads are at high risk. Recommended sampling frequency is given in Table 8.		

Table 7. Recommended maximum spacing of auger test holes for measuring ice thickness. Additional measurements may be needed in thin areas. From Infrastructure Health & Safety Association (2014).



Water Body Type	Pre-construction	Construction	Operations
Rivers – fast moving or high currents	5 m between test holes alond centre line or a minimum of 5 holes	25 m between test holes along alternating sides of centre line	50 m between test holes along alternating sides of centre line
Rivers – slow moving and within 250 m of shore	10 m between test holes along centre line	50 m between test holes along centre line Check known thin areas.	100 m between test holes along alternating sides of centre line Check known thin areas.
Rivers – slow moving and more than 250 m offshore	20 m between test holes along centre line	100 m between test holes along centre line	200 m between test holes along alternating sides of centre line
Lakes – within 250 m of shore	10 m between test holes along centre line	50 m between test holes along alternating sides of centre line Check known thin areas.	100 m between test holes along alternating sides of centre line Check known thin areas.
Lakes – more than 250 m offshore	20 m between test holes along centre line	100 m between test holes along centre line	200 m between test holes along centre line

Table 8. Recommended minimum frequency of auger test hole measurements. More frequent measurements may be necessary when environmental changes (warmer temperatures, altered water currents), or load changes (heavier, or more frequent) are detected. From Infrastructure Health & Safety Association (2014).

Pre-construction	Construction	Operations
Check every 2-3 days to monitor ice growth until minimum ice thickness is achieved to deploy heavier pieces of equipment.	Check every 4-7 days or more frequently to monitor for specific ice requirements for construction equipment and operations.	Test entire route prior to increasing load limits. Monitor thin areas as recommended by ice cover supervisor (e.g., every 2-4 days).

Response Design

Primary Indicator: Duration of Winter Road Season

Metric: Open of Winter Road Season, Close of Winter Road Season

These data can be requested annually from the winter road operators (data collection and reporting is a required condition of funding). Winter road operators are contracted by Webequie First Nation (for the Webequie Winter Road Corridor) and Marten Falls First Nation (for the Marten Falls Winter Road Corridor). Opening and closing dates should be requested for each winter road segment (e.g., the Webequie Winter Road, the Nibinamik Winter Road, etc.). For each winter road segment, the opening and closing date for different vehicle categories should be requested.

Table 9 describes the recommended data fields for this metric (e.g., Marten Falls winter road, Nibinamik winter road). Additional columns could be added to include more winter road segments, and for additional years):

Table 9. Recommended data to collect for the opening and closing of the winter road season.

	Segment A – 2019/2020	Segment B – 2019/2020	Segment C – 2019/2020
Date Open to Light Traffic			
Date Open to Full Loads			
Date Closed to Full Loads			
Date Closed to All Traffic			

Metric: Average Daily Air Temperature

Average daily air temperature is calculated by averaging all hourly temperature recordings made on a given day.

Air temperature is collected by Environment Canada at locations within the Matawa Homelands, as described in Table 10. For each station, it is possible to download historical data in an excel compatible format (.csv).

Table 10. Location of select Environment Canada climate stations near Matawa winter roads.

Station Name*	Location	Data Link
Ogoki Post A	Marten Falls First Nation	https://climate.weather.gc.ca/climate_data/hourly_data_e.html?StationID=52898
Lansdowne House A	Neskatanga First Nation	https://climate.weather.gc.ca/climate_data/hourly_data_e.html?StationID=51237
Lansdowne House (AUT)	Neskatanga First Nation	https://climate.weather.gc.ca/climate_data/hourly_data_e.html?StationID=10244
* The locations in this table include only the Environment Canada climate stations which are currently collecting data, and are near to Matawa winter roads.		

For the collection of additional hourly air temperature in each community, a simple data logger that is capable of long-term data collection is recommended. Data loggers should be shaded from sunlight (ideally, encased in a radiation shield that still permits airflow), be kept at least 15 metres away from pavement, away from any other object that will radiate heat (i.e., not directly on the wall of a building), and at least 1.5 metres above ground level (Weather Underground n.d.).

Secondary Indicator: Ice Road Condition

Metrics: Ice Thickness and Characterization

Ice thickness can be measured in two ways: with an ice auger, or with ground penetrating radar (GPR) (Infrastructure Health & Safety Association 2014). Instructions for measurements with an ice auger are given here (instructions for GPR are provided in Infrastructure Health & Safety Association (2014)).

If ice is less than 30cm thick, an ice chisel or axe can be used, otherwise an ice-auger should be used. To measure the thickness of the ice, an ice thickness measuring stick (e.g., a marked pole) should be used. If multiple measurements are to be made, the distance between the sites should correspond with the phase of the winter road (pre-construction, construction, or operation), and the speed of the current underneath (on lakes, the distance can be substantially increased, although ice on lakes may thin towards the edges). If measurements are being used to assess the feasibility of the road, the thinnest measurement should be used to calculate the bearable load. Recommended data fields are described in the Data Storage, Analysis, and Reporting Considerations section of this document.

At all ice thickness measurement sites, the type of ice should be documented.

Suggested fields for data collection are presented in Table 11.

Metric: Ice Cracks

The presence and nature of ice cracks should be documented at all ice thickness measurement sites. Recommended data fields are described in the Data Storage, Analysis, and Reporting Considerations section of this document. Suggested fields for data collection are presented in Table 11 (additional ice cover inspection criteria for contractors are given in appendix F of Infrastructure Health & Safety Association (2014)):

Table 11. Recommended fields to record data about ice thickness, ice characterization, and cracks in ice.

	Site 1	Site 2	Site 3
Ice Thickness			
Snow Thickness			
Ice Type			
Water Depth			
Unusual or Deep Crack Starting?			
Water Visible in Crack?			
Crack Length			
Latitude			
Longitude			

Implementation Considerations

Safety

When sampling winter road conditions in the field (be it during the pre-construction, construction, or operation phase of the road), environmental monitors should ensure that they are following proper safety protocols. Winter roads can be dangerous, especially in the shoulder season, as the formation of ice may not be even, especially along rivers, where the behaviour of the river can influence ice thickness – some parts may be thick while others might be dangerously thin. Winter road testing protocols have been designed to ensure the safety of individuals in the field. A full set of safety protocols is given in Infrastructure Health & Safety Association (n.d., p24-25).

Ice Cracks

Cracks in the ice surface may appear in winter roads due to natural factors (e.g., rapid shifts in temperature), or as a result of the presence of loads (typically when vehicles travel too quickly, or when a load remains in place for too long). There are protocols in place that road operators already use to monitor and repair cracks. Segments of road with wet cracks should be closed off to use and immediately repaired. Protocols for monitoring and addressing cracks are documented in Infrastructure Health & Safety Association (n.d., p26-27).

Sample Frame and Stratification

With regards to ice thickness and the development of cracks, Matawa should be consulted about road segments which are known to be problematic. Winter road contractors should be notified of these locations. Should Matawa desire to do separate monitoring, these segments should be included in a separate strata with more comprehensive sampling.

Data Storage, Analysis, and Reporting Considerations

Annual Data Collection and Reporting

Data for all three indicators are collected by winter road operators. These contractors are hired Webequie First Nation (for the Webequie Winter Road Corridor), and Marten Falls (for the Marten Falls Winter Road Corridor) (Ken Coulter 2019, personal communication). Contractors should be able to provide data for these indicators upon request. Data for all indicators should be requested from contractors annually, and stored on Four Rivers' data server (historical data for all indicators should also be requested). Annual reports should summarize:

- The length of each road segment's operating season;
- The number temporary road closures for each road segment, and their cause;
- Maps highlighting problematic regions (e.g., areas where numerous closures occurred, areas where many ice cracks developed, areas with consistent thin ice);

  Graphs showing the long term trend in each road segment's operating season (for example, Figure 11 shows the length of the operating season for the Webequie, and Marten Falls winter road corridors (IBI Group 2016; Ken Coulter 2019, personal communication)).

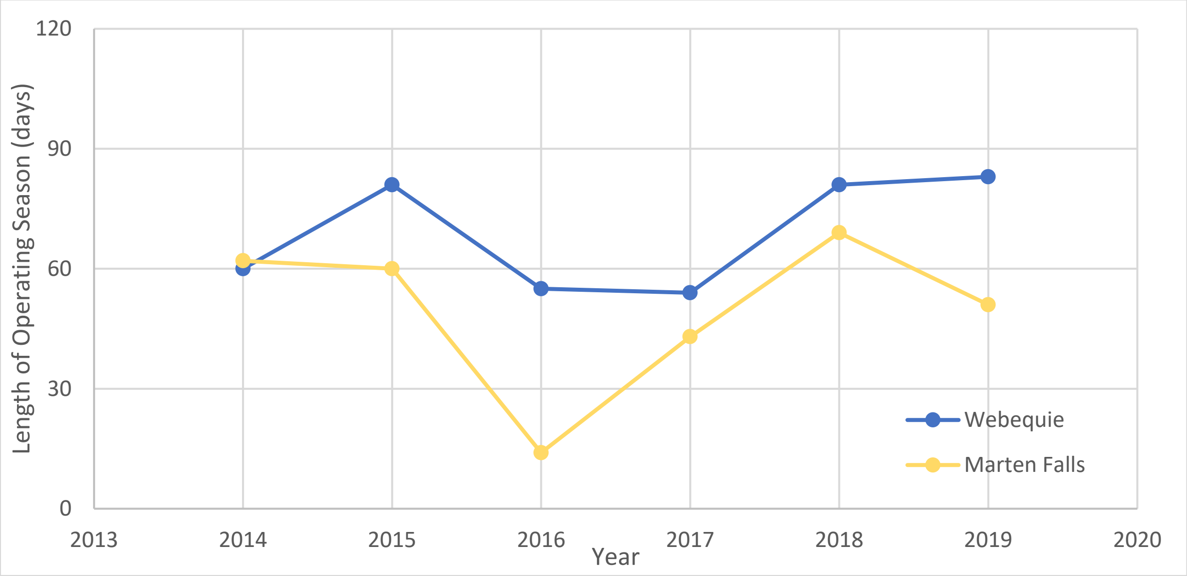


Figure 11. Length of operating season of the Webequie and Marten Falls winter road corridors (2014-2019) Source: IBI Group (2016); Ken Coulter (2019, personal communication)

Trend Forecasting

As the climate in Canada warms, lake ice is forecasted to freeze-up later, and break-up earlier (see Figure 12), leading to reduced operating season lengths for winter roads (Mullan et al. 2017; Perrin et al. 2015). Mullan et al. (2017) forecast that by 2100, a winter haul road in the NWT that connects several remote mines to the highway network may not develop sufficiently thick ice to accommodate heavy vehicles (and it will only be open to light vehicles for a fraction of the days it is currently open). Given that warming trends are expected to differ spatially in Canada, it is important that forecasts for each winter road be developed, accounting for local climatic conditions.

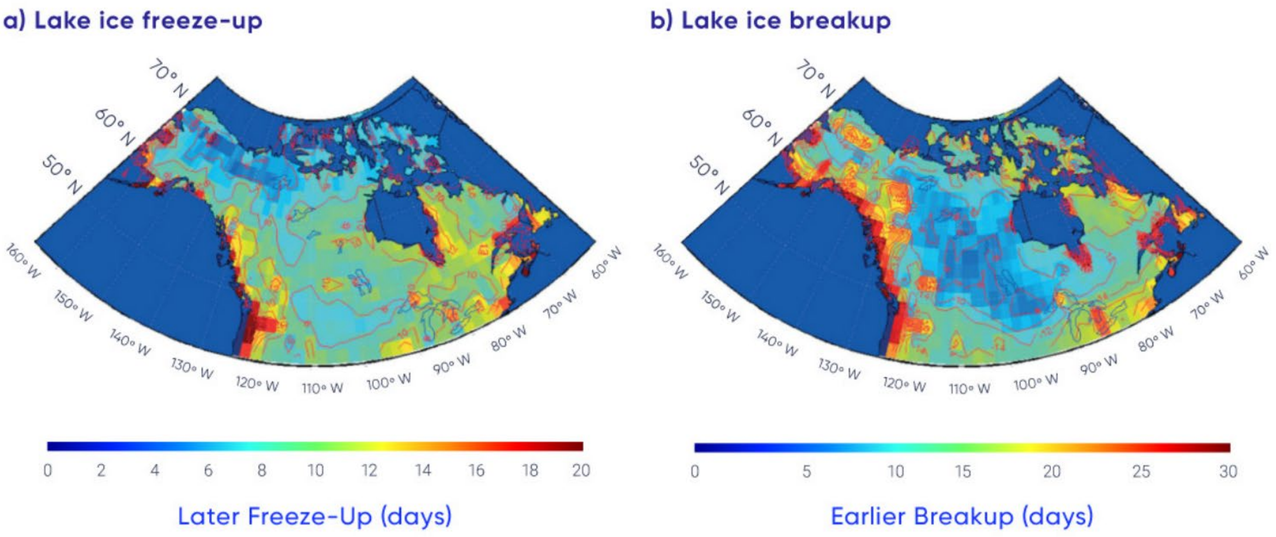


Figure 12. Forecasted change in lake ice freeze-up and breakup dates between the current (1961-1990) and future (2031-2070) climatic periods. Source: Dibike et al. (2012).

Methods to forecast winter road operating season length under future climate scenarios are described in Mullan et al. (2017) (Perrin et al. (2015) use a similar methodology but include additional environmental variables). Mullan et al.'s (2017) method is described below:

Step 1: Obtain baseline data

Collect baseline historic ice thickness and operating season length data for the winter road corridors from winter road operators.

Collect baseline historic climate data from climate stations in the vicinity of winter roads for the same time period for which you have baseline data about winter roads. Historic climate data can be obtained from the climate stations listed in Table 10, although it may only be necessary to use data from the warmest station (Mullan et al. (2017) use only the warmest climate station in their analysis, arguing that if the warmest part of the road is not usable, the entire road network is compromised). In the case of the Webequie winter road corridor, if the segment immediately north of the 808 highway is not usable, the link between Webequie, Eabametoong, Nibinamik, and Neskatanga First Nations and the provincial highway network will be broken.

Step 2: Determine the relationship between climate data and winter road operating conditions

Develop a statistical relationship between climate data indicators (predictor variables) and winter ice thickness and / or operating season length (response variables). This step will include pre-processing both datasets to ensure they are compatible. In their analysis Mullan et al. (2017) used daily cumulative FDDs (derived from daily temperature data) as a predictor of daily ice thickness (they make the assumption that ice thickness above a certain threshold will ensure that the winter road is open, acknowledging that in the real world, other factors will also affect winter road operations). Similarly, Perrin et al. (2015) also use annual FDDs as well as Melting Degree Days (MDDs) as predictor variables for total operating season length. Developing this relationship will require careful analysis of which environmental variables are best suited to predict winter road conditions.

Step 3: Obtain future climate data

Obtain climate data for future climate scenarios, in the Matawa homelands. Multiple datasets should be obtained (Mullan et al. 2017):

- Data should be obtained for different time periods of interest (either for individual years, or commonly used intervals like 2031-2050, 2051-2081, and 2081-2100);

- Data should be obtained for different climate scenarios (climate scenarios represent different pathways of greenhouse gas accumulation, ranging from low to high emissions scenarios); and
- Data should be obtained from multiple climate models, since each model is imperfect and will contain biases and errors (using multiple climate models allows you to account for some of the uncertainty involved in climate modeling).

Forecasted climate data for northern Ontario can be obtained from the Ontario Climate Data Portal (http://lamps.math.yorku.ca/OntarioClimate) as well as the Canadian Centre for Climate Services (https://www.canada.ca/en/environment-climate-change/services/climate-change/canadian-centre-climate-services/about.html). Climate data should be pre-processed to ensure its temporal resolution lines up with the baseline climate data. The data may need to be transformed to obtain variables of interest (e.g., FDDs).

Step 4: Use the statistical relationship to forecast future winter road operating conditions

Use the established regression relationship to develop projections for ice thickness and operating season length under future climate scenarios. Plug in projected climate values to estimate operating season length under a variety of future climate scenarios at different time periods. An example from (Perrin et al. 2015) is described below.

Perrin et al. (2015) developed the following equation to predict Road Operating Days from FDD Accumulation:

$$Road\ Operating\ Days = 0.0185 \times (Accumulated\ FDD) + 3.6313$$

By plugging in forecasted Accumulated FDD values under various climate scenarios and time periods, Perrin et al. (2015) were able to forecast changes in road operating season length (Figure 13).

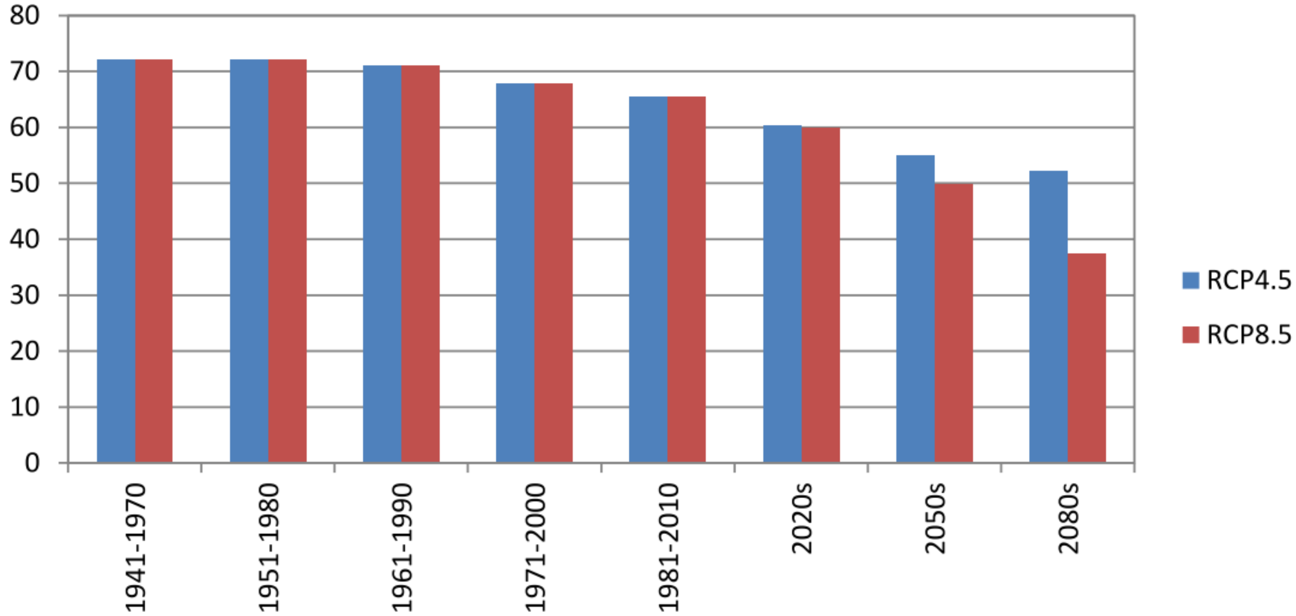


Figure 13. Forecasted operating season length of the Tibbitt to Contwoyto Winter Road based on FDD Accumulation, for RCP4.5 and RCP8.5 scenarios, based on an ensemble of climate models.

Linkages to Established Programs and Potential Collaborators

Federal Government

The federal government contributes money towards funding winter roads across Canada. Improving hydro-climatic data collection through numerous programs, including the Collaborative Monitoring Initiative is a federal government objective. Funding from federal government climate change adaptation programs may help Matawa respond to climate change.

Ontario Ministry of Natural Resources and Forests (OMNRF)

The OMNRF is the provincial authority responsible issuing permits for the operation and construction of winter roads. However, many permits are in effect permanent, having been in place for years.

Ontario Ministry of Energy, Northern Development, and Mines (OMENDM)

The OMENDM is responsible for funding the construction and maintenance of winter roads through the Northern Ontario Winter Roads Program. The program provides approximately $5 million per year to individual First Nations and contractors. Recipients (First Nations) may either construct and operate winter roads themselves or hire a contractor to do so.

Other First Nations Communities

Other northern Ontario First Nations communities are involved winter road construction and maintenance. Collaboration with other communities may help to better plan for winter road construction and operations. Contact information for First Nations involved with winter roads is given at: https://tinyurl.com/MNDM-IceRoad-FN-Contact.

References

Ashton, G. D. 2011. River and lake ice thickening, thinning, and snow ice formation. Cold Regions Science and Technology, 68(1–2), 3–19. https://doi.org/10.1016/j.coldregions.2011.05.004

Barrette, P. 2018. *Canadian winter road infrastructure and climate change adaptation : Prospective solutions through R & D*.

Brown, L. C., and C. R. Duguay. 2011. The fate of lake ice in the North American Arctic. Cryosphere, 5(4), 869–892. https://doi.org/10.5194/tc-5-869-2011

Bush, E., and D. S. Lemmen (Eds.). 2019. *Canada’s Changing Climate Report*. Ottawa, ON: Government of Canada.

Dibike, Y., T. Prowse, B. Bonsal, L. de Rham, and T. Saloranta. 2012. Simulation of North American lake-ice cover characteristics under contemporary and future climate conditions. International Journal of Climatology. https://doi.org/10.1002/joc.2300

IBI Group. 2016. *Draft Technical Backgrounder: Winter Roads*. *Studio One*.

Infrastructure Health & Safety Association. 2014. *Best Practices for Building and Working Safely on Ice Covers in Ontario*.

Mullan, D., G. Swindles, T. Patterson, J. Galloway, A. Macumber, H. Falck, L. Crossley, J. Chen, and M. Pisaric. 2017. Climate change and the long-term viability of the World’s busiest heavy haul ice road. Theoretical and Applied Climatology, 129(3–4), 1089–1108. https://doi.org/10.1007/s00704-016-1830-x

Perrin, A., J. Dion, S. Eng, D. Sawyer, J. R. Nodelman, N. Comer, H. Auld, E. Sparling, M. Harris, J. Y. H. Nodelman, and L. Kinnear. 2015. *Economic Implications of Climate Change Adaptations for Mine Access Roads in Northern Canada*.

Proskin, S., E. Groznic, D. Hayley, F. Mathison, R. McGregor, and V. Neth. 2011. *Guidelines for the construction and operation of winter roads*.

Strandberg, A., R. Wang, P. Spencer, and G. Strandberg. 2014. Ice Road Operation and Climate Change.

Weather Underground. n.d. Installing your Personal Weather Station. Retrieved December 14, 2019, from https://www.wunderground.com/pws/installation-guide

Whalen, D., P. Fraser, and D. L. Forbes. 2016. *Mackenzie Delta and Beaufort Coast spring breakup newsletter*. Ottawa, ON.

Appendix B – Hydro-Climatic Monitoring for Dehcho

The Issue – Water Levels & Navigability

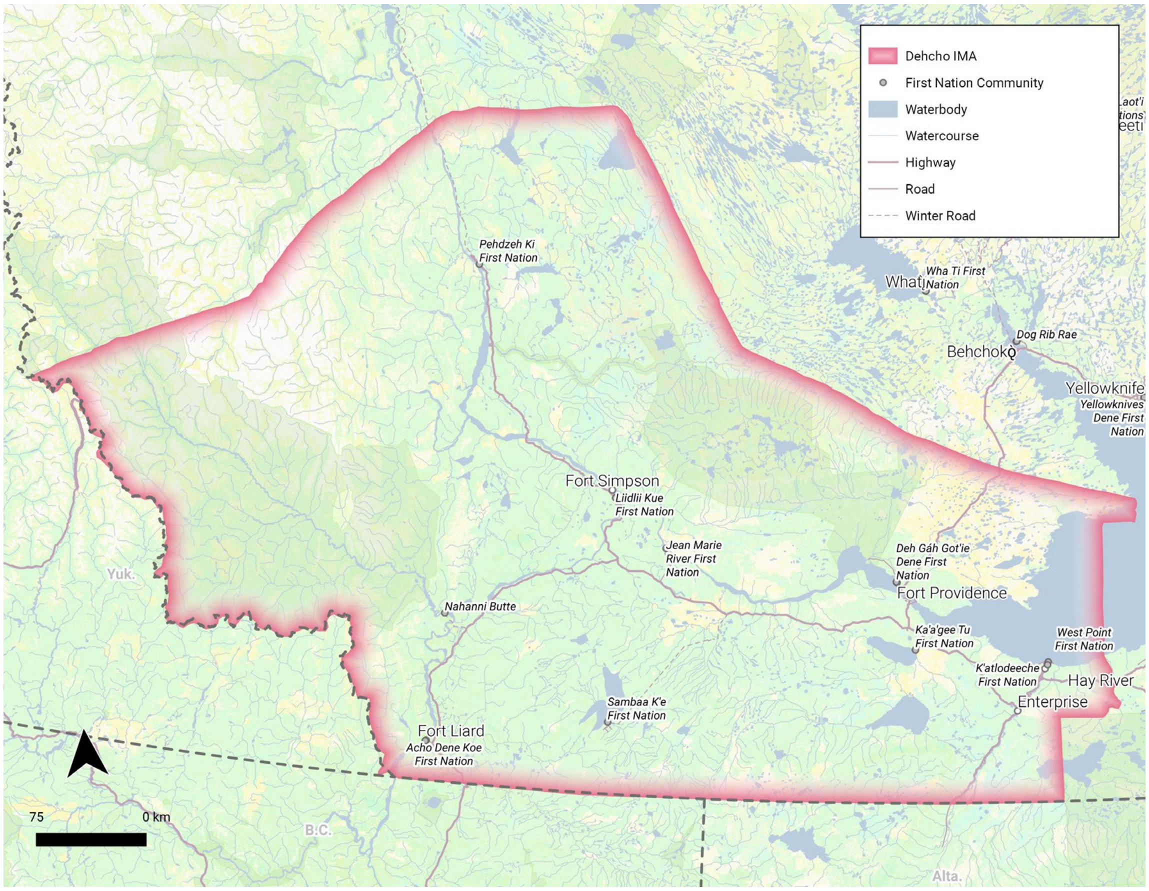


Figure 14. The Dehcho Interim Measures Agreement (IMA; red border) area within the Northwest Territories.

Dehcho First Nations (DFN) members have observed that average water levels within their traditional territory have been declining over the past decade (Mike Low, personal communication, 24 February 2020). DFN members note that water levels in the spring have remained normal, but that towards the end of the summer, water levels have been lower than normal, especially in tributaries.

Declining water levels in DFN traditional territory is not without consequences. First and foremost, DFN members are reporting that reduced water levels impede their ability to travel by boat on certain rivers, which prevents them from accessing preferred hunting and fishing areas. As a result of low water levels, when DFN members travel by boat, they are at increased risk of running aground, which could result in damage to their vessels or personal harm.

Reduced ability to access preferred hunting and fishing grounds may have consequences for food security among DFN members. If DFN members are unable to harvest country foods, this means they lose a precious source of high-quality food and will need to purchase more of their food from grocery store. Losing the ability to hunt and fish in preferred areas may also impact DFN members' mental wellbeing, sense of connection with the land, and ability to pass on their knowledge to younger generations.

Finally, there is concern that low water levels may have adverse impacts on fish stocks. Reduced water levels may impede fish from accessing spawning grounds, and the quality of rivers may change as a result of reduced water levels (for example, temperatures may rise above optimal temperatures).

The challenges described by DFN members can be described by two key questions:

What is the condition of water levels in DFN traditional territory?

What is the long-term trend in water levels in DFN traditional territory?

We propose two monitoring plans to resolve these questions.

What can the climate record tell us?

Canada has a long record of climate data, which has been extensively analyzed in academic climate change publications in recent decades. Data on variables including water levels, flow, temperature, and precipitation can shed light on temporal trends, and tell us if Dehcho First Nations' observations are consistent with the climate record.

Both temperature and precipitation have increased in the Dehcho Interim Measures Agreement (IMA). Increased temperatures will reduce water flows, while increased precipitation should increase water flows. Unsurprisingly, the hydrological record is inconclusive – no consistent trend in late summer flows have been observed in the Dehcho IMA.

Temperature

Higher temperatures will drive evapotranspiration, which will reduce flows and water levels in Canadian streams. Temperatures have already risen significantly in the Dehcho IMA. In the territories (Yukon, Northwest Territories, and Nunavut), has average annual temperatures increased by 2.3°C between 1948 and 2016 (Figure 15; Bush and Lemmen (2019). Notably, the strongest warming trend occurred during the winter (+4.3°C since 1948), while a weaker warming trend was observed over summer months (+1.6°C since 1948). Driven by warmer winter temperatures, snow cover duration has declined in the Northwest Territories, as has the annual maximum snow depth (Vincent et al. 2015).

Temperatures in the territories are forecasted to continue to rise. Under a "business as usual" scenario, average annual temperatures in the territories are forecasted to rise by an additional 2.7°C by 2031-2050, and 7.8°C by 2081-2100. Consequently, other temperature indices are also forecasted to become more severe. The number of hot days, the highest daily maximum and minimum temperature, and the length of the growing season are all expected to increase (Bush and Lemmen 2019).

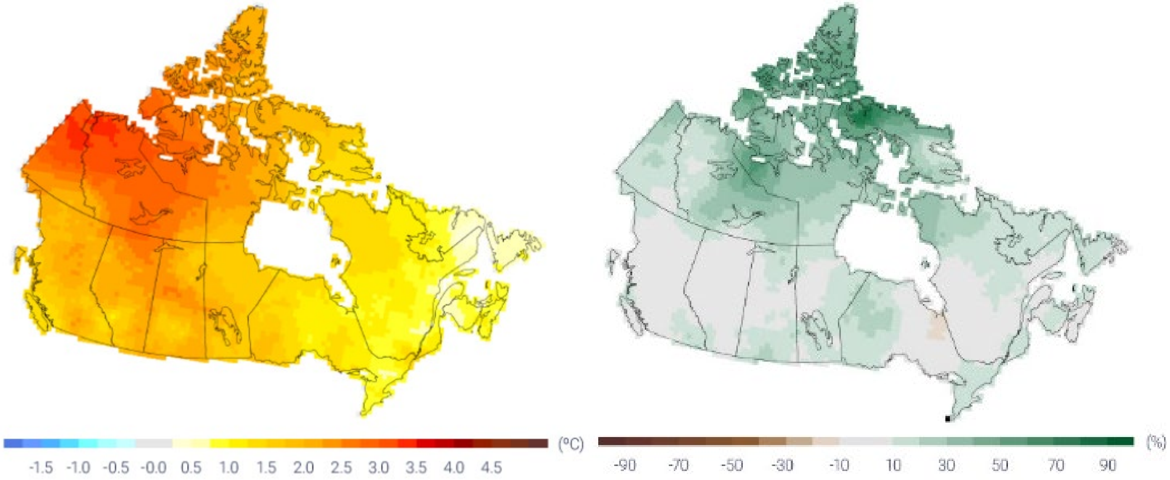


Figure 15. Left: change in average annual temperature, 1948-2016. Right: change in average annual precipitation, 1948-2012. Both courtesy of Bush and Lemmen (2019).

Precipitation

Changes in precipitation will affect water levels. The Dehcho IMA is a part of the larger Mackenzie watershed, which drains a large area of Canada. Increases in precipitation over the Mackenzie watershed will increase flows.

Between 1948 and 2012, annual precipitation in the territories rose by 32.5% (Bush and Lemmen 2019) although that has skewed by very large increases in the arctic archipelago (Figure 15). Annual precipitation is forecasted to continue to rise in the territories. Under a high emissions scenario, annual precipitation is forecasted to rise another 11.3% (by 2031-2050) and 33.3% (by 2081-2100) (Bush and Lemmen 2019). Precipitation increases will not be as strong in the upper Mackenzie Valley – precipitation in Fort Simpson is forecasted to rise by 11% between 2021-2050, by 19% for 2051-2080 and by 24% for the last 30 years of this century (ClimateData.ca 2020).

Freshwater

Across Canada, hydrology has changed in lockstep with warming temperatures. Warmer temperatures are causing earlier snowmelt, driving higher winter flows, and earlier spring flows (see Figure 16), although no trends in overall streamflow volume have been detected (Bush and Lemmen 2019). Under a high emissions scenario (business as usual) annual flows are forecasted to increase in most northern basins, due to increased annual precipitation (Bush and Lemmen 2019). Within the Dehcho IMA, the following trends have been reported:

- Rood et al. (2017) report that annual streamflow in the Liard and Mackenzie Rivers has increased over the past few decades (by 3.5% and 1.5% per decade between 1944-2013, respectively);
- Jacques and Sauchyn (2009) found that among 23 hydrological stations within the Mackenzie river basin, 7 showed statistically significant increases in annual flows, and 20 of 23 showed statistically significant winter increases in winter baseflow in the latter half of the 20th century. No declines in annual flows were observed;
- Yip et al. (2013) detected both increasing and decreasing trends in runoff and storage in the Mackenzie River Basin between (1961 and 2002), using two different datasets. Data from Environment Canada showed an overall decrease in modelled runoff, while data from the European Centre for Medium-

range Weather Forecasting showed an overall increase in runoff, while their analysis overall predicted an intensification of the hydrological cycle; and

- Burn et al. (2004) noted that winter flows in both the Athabasca and Liard River basins have increased over the years as have some spring flows, however, declines (not statistically significant) in summertime flows have been recorded. In the Liard, around 1 in 10 stations recorded declines in June, July, and August, between 1961-2000 (not statistically significant), and an earlier spring freshet date (with statistical significance).

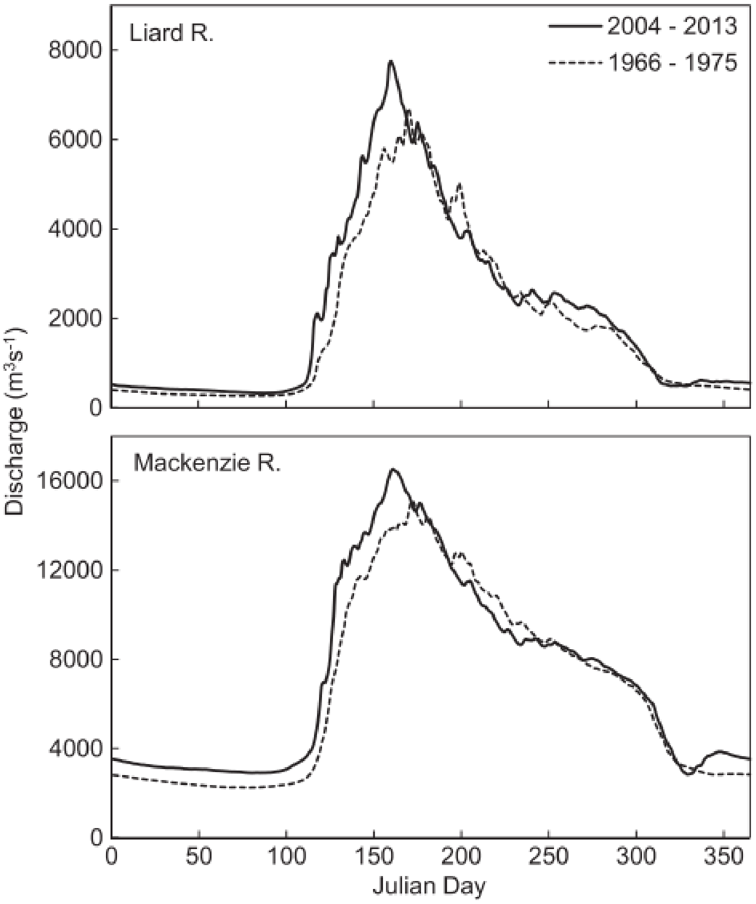


Figure 16. Slight shift towards earlier spring flows are observed in the Liard and Mackenzie river (Rood et al. 2017).

Plan 1: Broad Based Sampling Design

What is the condition of water levels in DFN traditional territory?

This sampling design aims to help collect evidence to resolve the above question. The idea of this sampling design is to conduct broad based sampling among rivers in the Dehcho IMA, in order to detect the proportion of rivers which are experiencing low flow late in the summer (i.e., to the point where navigation is impossible). With a random sampling design, the results from the sample could be extrapolated to the entire target population within the Dehcho IMA. Additional opportunistic sampling (by community members or field techs) can help by documenting conditions on streams that are important to community members (and which may be missed in a random selection).

Indicators and Metrics

The **indicator** for this sampling design is the overall condition of Dehcho IMA streams. This indicator will provide information about how common low water levels in the Dehcho IMA are. This will help determine whether the trends observed by DFN members are restricted to a select few channels (which happen to be high priority harvesting corridors / access routes), or whether the issue is prevalent across the IMA.

Two **metrics** will help inform the condition of Dehcho IMA streams.

Water Depth. For every stream to be sampled, water depth should be recorded at 1km intervals, beginning at the mouth of the stream, and upstream, either until the stream segment has been fully recorded, or until navigation is impossible due to too low water levels. Given that Dehcho hunters and fishers have different sized boats, navigability might vary for different boats, depending on their draft, as well a boater’s confidence in navigating potentially challenging waters. Most use aluminium Lund boats, 16- 18ft; although more and more people have jet boats which allow increased access but are very expensive. AAROM Guardians all use 18 ft Lunds, with the exception being Saamba K’e which operates a 22ft boat more suitable for large waterbodies.

This metric will inform a secondary metric, length of navigable channel. This metric is simply the distance traveled upstream until the depth is too low to be navigable. Should the same stream be sampled over multiple years, this metric can inform a directional trend in navigability (i.e., increasing length suggests navigability is improving, decreasing length suggests navigability is declining).

An optional metric to track is temperature. DFN members report concern that low water levels may have adverse impacts on fish stocks. Low water levels alone may impede fish from accessing spawning areas. In addition (and its not clear if data exists), rising temperatures could cause stress on fish populations. While depth is being recorded, temperature should be as well, to determine if temperatures are within, or outside of safe conditions for local fish stocks.

Methodology and Sample Design Considerations

Sampling Design

Target Population

The target population (the population we would like to know about) is a subset of the entire stream network in the Dehcho IMA. When it comes to determining which streams we want to sample from, a few rules can help to precisely specify which streams are in the target population:

- No very large streams. It is reasonable to assume that very large streams will always be navigable during late summer, year over year (e.g., the Mackenzie River, the Liard River, etc.);
- No very small streams. While water levels may be changing in these streams, there is no reason to expect them to ever be navigable (by motorboat), so they can be removed, eliminated from consideration; and
- No streams with pre-existing blockages (i.e., waterfalls, and rapids, etc.).

The target population is presented in Figure 17. For the purposes of this report, the target population was developed as follows: hydrology data for the Northwest Territories was obtained from CanVec (Government of Canada 2020b). CanVec data is distributed at three map scales: 1:50,000, 1:250,000, and 1:1,000,000. The 1:50,000, 1:250,000 is too fine, and includes many very small creeks that would not be navigable by motorboat[3]. The 1:1,000,000 Hydrology dataset was chosen for use because it allows us to easily eliminate very large streams[4], and does not include very small streams. Navigational blockages are represented by X's in Figure 17. Streams with existing blockages were overlaid on the dataset, allowing only navigable portions to be selected.

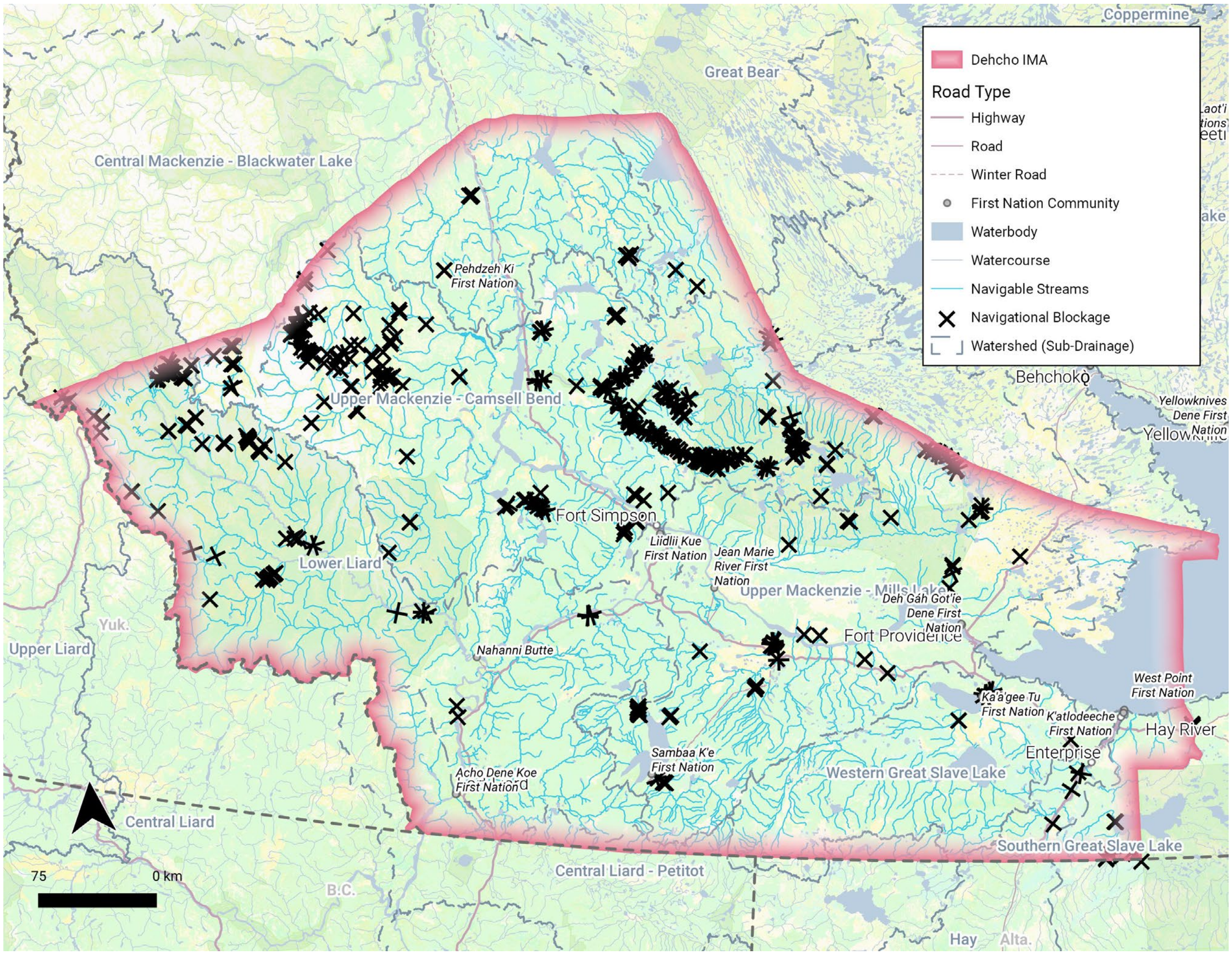


Figure 17. Navigable streams and navigational blockages within the Dehcho Interim Measures Agreement.

Sample Frame

The sample frame (all accessible sampling units in the target population) may differ from the target population. In theory, all streams in the target population should be accessible by boat, however, it may not be feasible to access some due to the high cost to travel to some of the more remote areas of the Dehcho IMA.

---

[3] CanVec data does not include stream order data. Stream order data attribute data would easily facilitate eliminating both very large (large stream order) and small (low stream order) streams. The GNWT is currently working on developing a model to assign stream order to all streams in the Mackenzie Valley (Evangelos Kirizopoulos, personal communication, 17 March 2020). Should that data become available, it should be used, as it could help more precisely define the target population.

[4] In the CanVec Hydrology 1:1,000,000 dataset, very large streams are represented by polygons, while other streams are represented by polyline data. All stream polygons have been removed from the target population.

Sample Unit

The sample unit (the unit of measurement) is the 1km reach of each stream, in which water depth (and temperature) is recorded.

Stratification

Stratification Option 1:

- Within the target population, stratification by watershed (Figure 17) will help determine if trends are the same or differ across the entire Dehcho IMA. For example, the presence of glaciers and late summer high elevation snow in the Nahanni watershed may mitigate declines in late summer flows relative to lower elevation watersheds. Watersheds can be successively sub-divided into smaller watersheds (in Canada, these are termed drainages, sub-drainages, and sub-sub drainages). For example, the Lower South Nahanni sub-sub-drainage is nested inside the Lower-Liard sub-drainage, which is nested inside Arctic drainage. Within the Dehcho IMA there are two drainages, nine sub-drainages, and 21 sub-sub-drainages. We recommend stratifying by sub-drainage. At this scale, watersheds can still be differentiated by environmental (e.g., glaciation, precipitation, temperature), and statistical power within each watershed can be maintained.

Stratification Option 2:

- A strata of culturally important streams should be established to prioritize coverage of streams that are actively used for fishing and hunting by Dehcho First Nations members. A preliminary set of streams identified by DFN include “direct tributaries to the Mackenzie and Liard Rivers including [the] Horn, Redknife, Axe Handle, Bouvier, Trout, Jean Marie River[s], Spence Creek, Upper Spence Creek, Netla River, Willlowlake River, Blackwater River, Kakisa River” (Mike Low, personal communication, 31 March 2020).

The level of effort allocated to each Stratirication Option should be informed by the desired level of inference. If DFN’s priority is to make inferences about all navigable streams in the Dehcho IMA, Option 1 should be prioritized. If the priority is to make inferences only about culturally important streams, then Option 2 should be prioritized. DFN may also opt to employ a hybrid approach and allocate effort among Stratification Options.

Site Selection

Among each watershed, a simple random sample should be used to select sites from the target population. A simple random sample will permit making inferences about the target population from the sample sites.

Sampling among the culturally important streams will come down to the availability of resources. If sufficient resources are available, it may be possible to sample all streams in each field season. If that is not possible, a simple random sample of sampling units (rivers) within this strata will still allow you to make inferences about all streams within this strata (however, it will not allow you to make inferences about all rivers in the Dehcho IMA).

Timing

Samples should be collected during the time period of interest: late summer (i.e., July and August). Within two months, one team could be expected to sample approximately 84[5] streams (roughly 2.6% of the target population). Across multiple years, a panel design could help detect long term trends while also ensuring a broad assessment of navigability within the Dehcho IMA is accomplished (Mcdonald 2003). A proposed panel design is suggested in Table 12. Each panel represents a randomly selected (non-overlapping) subset of the sample frame.

---

[5] One team, sampling two streams per day, for 42 business days (the amount of business days in July and August in 2020).

Table 12. Proposed panel design, incorporating both status and trend monitoring. In this design, each panel would include 21 sample units (totaling 84 samples per year). Panels 1 and 2 are revisited annually to detect long-term trends, while panels 3 through 10 are rotated in and out every 4 years to detect regional-scale trends. After four years, 210 unique sites can be visited.

Year	Panel									
	1	2	3	4	5	6	7	8	9	10
1	X	X	X	X						
2	X	X			X	X				
3	X	X					X	X		
4	X	X							X	X
5	X	X	X	X						
6	X	X			X	X				
7	X	X					X	X		
8	X	X							X	X
9	X	X	X	X						
10	X	X			X	X				
Purpose	**Long-term (trend) monitoring**		**Regional (status) monitoring**							

Response Design

All metrics for this sampling design are very easily measured.

There are a few options to measure water depth. For shallow (<3m depth) and slow streams, a **wading rod** (a long foldable rod) is a simple and inexpensive choice. Wading rods can measure inaccurately in soft-bottomed streams (e.g., muck or sand), as it can be difficult to precisely determine where the bottom is. Depth measurements with wading rods are made by visually inspecting the depth based upon depth markers inscribed on the rod (Turnipseed and Sauer 2010).

For deeper and faster streams, a **sounding reel** (or line) is recommended. A sounding reel consists of a long line connected to a mechanism to the line in or out at one end. The reeling mechanism can be used to track the length of line let out. If a sounding reel is not available, a line (with lengths marked at a regular interval) can be let out by hand, to test for depth. For both options, a weight should be affixed to the line to minimize drift of the line in the water, which can exaggerate depth measurements. However, some drift is to be expected. Turnipseed and Sauer (2010, p13-19) provide mathematical equations and look-up tables which can be used to correct for line drift.

A third option, a **sonic sounder** can be used and can be particularly useful in high velocity streams or where there is a of debris that may interfere with a sounding reel (Turnipseed and Sauer 2010, p12-20). Sonic sounders are highly accurate, but more expensive than the other two options.

To measure temperature of the water column, a standard water probe (e.g., a YSI sonde) can be used.

Additionally, other samples could be collected at sampling units. For example, water quality or biological sampling could be added to the field protocol to add value to the collection program.

In addition to depth and temperature, additional information should be collected for each sampling unit. These additional measures will ensure that these data are collected in a consistent manner:

- Name;

- Date;
- GPS location for every point along the stream;
- Air temperature;
- Weather conditions;
- Stream name;
- Distance up-stream; and
- Additional field observer's notes. This space can be used to document any remarks by the data collector that may provide additional context to the recordings (e.g., the nature of any navigational hazards).

Plan 2: Targeted Sampling Design

What is the long-term trend in late summer water levels in DFN traditional territory?

Additional hydrometric stations located at high concern rivers will assist DFN in developing a long-term record of hydrologic conditions (water levels and flows) within their territory. While there are 23 active hydrometric stations within the Dehcho IMA, most are alongside major waterways (e.g., the Mackenzie, Liard, and Hay rivers; see Figure 18). We recommend placing additional hydrometric stations placed in streams of concern to DFN to help develop long-term hydrometric monitoring in streams that are important to DFN members. We also recommend a review of existing hydrometric data to develop a baseline, which will help detect long-term trends in flows in the Dehcho territory.

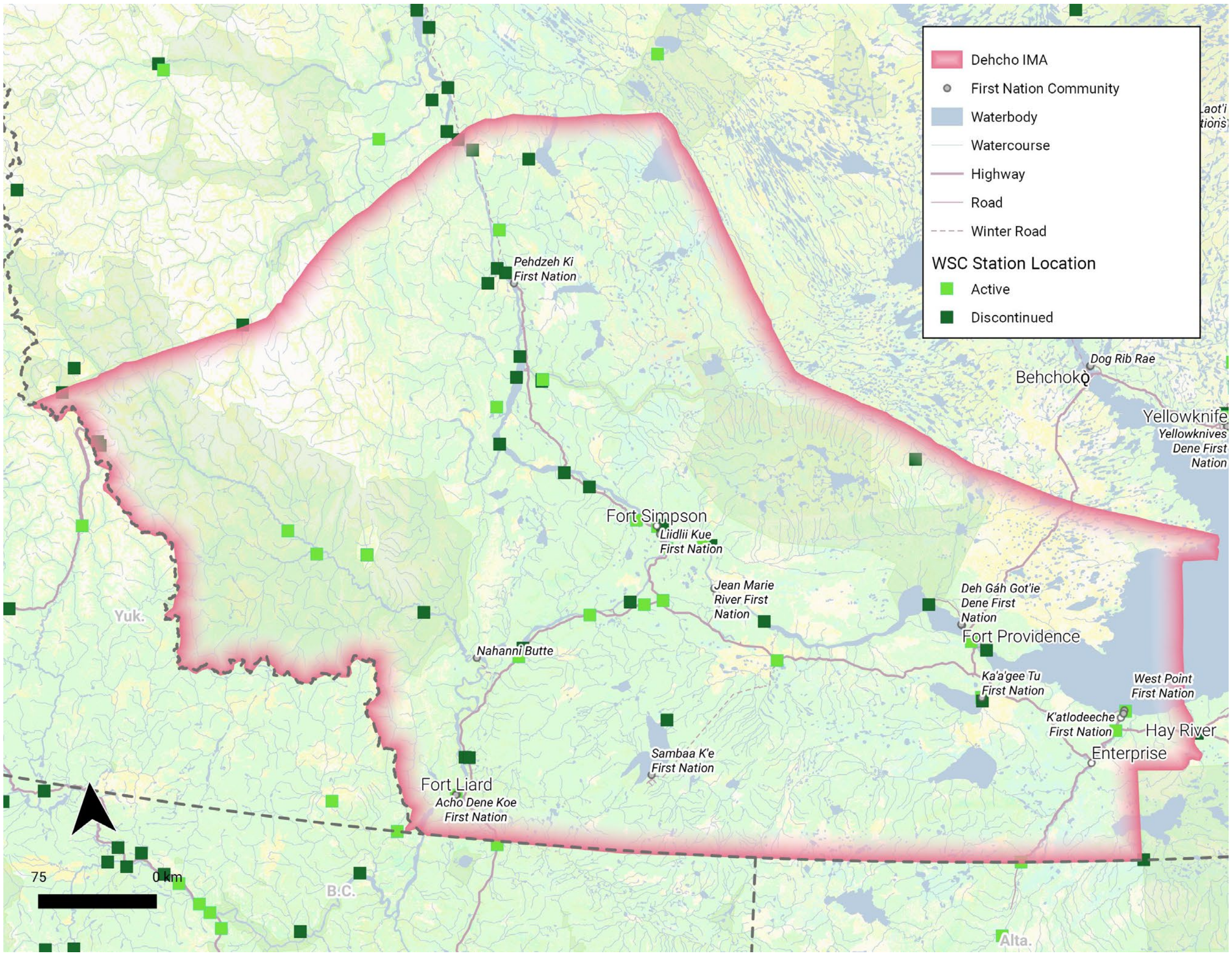


Figure 18. Location of active (light green) and discontinued (dark green) Water Survey of Canada sites in the Dehcho Interim Measures Agreement.

Indicators and Metrics

The **indicator** for this sampling design is the long-term trend in stage, discharge, and optionally, temperature among select streams in the Dehcho IMA. This indicator draws on data from both newly installed hydrometric stations, as well as a long-term dataset from existing hydrometric stations in the NWT (see Figure 18).

Multiple **metrics** will inform the long-term trend in stage and discharge. We recommend a few key metrics which are commonly reported in academic publications (Irving et al. 2018; Olden and Poff 2003).

Annual daily minimum discharge and stage tracks discharge (m^3/s) and stage (m) on the day with the lowest average flows, over a calendar year. Long term observation of this metric can help identify changes in extreme low flows, as well as whether the date on which minimum discharge and stage is advancing or regressing (e.g., as in Burn et al. (2004)).

Annual average summer discharge and stage tracks the average flow (m^3/s) and stage (m) across summer months (June, July, and August). This metric is similar to annual daily minimums in that it tracks changes in low flows year over year, but this metric should have less variability (one-day minimum flows will be highly influenced by extreme weather events). In addition to average summer discharge and stage, individual averages for the summer months can also be calculated, which can provide more information about specific periods of the year.

Stream temperature may optionally be measured at a hydrometric station. Stream temperatures can inform both long term changes in the environment due to climate change and can also be used to track potential adverse impacts to fish species. To track long term changes in climatic variables, commonly used metrics are average summer stream temperature, and 95th percentile summer temperature (Isaak et al. 2012; Vliet et al. 2013). To evaluate potential impacts to fish species, many compare observed (or forecasted) stream temperatures against species' thermal tolerances (e.g., > 19.9°C for Northern Pike embryos (Hokanson et al. 1973)). Two common metrics are the number of days in a year for which the 7 day average of the daily maximum temperature, or 7 day average temperature are above a species' threshold (Eaton and Scheller 1996; Mantua et al. 2010).

Methodology and Sample Design Considerations

Sampling Design

A probabilistic sampling design is not recommended for the addition of additional hydrometric stations. High per-station costs means that a well-designed probabilistic design would be extremely expensive. Costs for hydrometric stations range from $10,000 to $25,000 for installation, plus approximately $15,000 to develop a ratings curve, and ongoing annual costs between $9,000 to $20,000 (Okanagan Hydrometric Network Working Group 2008; Sutherland 2015). At the low end of those estimates are smaller streams, eliminating real-time data transmission, and measuring stream stage only (this would eliminate the need to develop a ratings curve).

Instead, it is recommended that DFN consult with its members to select rivers on which:

- DFN members have observed trends of declining mid-late summer water levels; and
- DFN members use for travel, harvesting, or other purposes, and / or have concern about the impact of low waters on fish populations.

Response Design

A hydrometric station can be used to calculate real-time (hourly) stage and discharge. A hydrometric station consists of a reinforced structure containing an instrument to measure stream level, as well as technology to store, and transmit data in real-time (Figure 19). Optionally, stream temperature can be monitored with a probe and data logger.

Discharge is not actively measured at a hydrometric station, but it is calculated from stage using a ratings curve. A rating curve is an equation that defines the relationship between discharge and stream stage.

Figure 19. A hydrometric station. Image courtesy of Environment and Climate Change Canada.

Stage

For permanent hydrological station, a stilling well is the most common method to measure stage (Rantz 1982; Turnipseed and Sauer 2010). Within the stilling well, a submersible pressure sensor may be used – these sensors use a flexible membrane to measure water pressure and convert it to a water level reading (i.e., metres above the river bottom). Stage can be stored in a data logger or transmitted via satellite or mobile telemetry. Stilling wells are advantageous in that they reduce turbulence, allowing for more accurate and precise measurements.

Discharge

Discharge is a product of the cross-sectional area of a stream, and the velocity of the water within it (Equation 1):

$$Q = A \times V \qquad \text{Equation (1)}$$

Where Q Total discharge (m^3/s)
A Cross sectional area (m^2)
V River velocity (m/s)

Due to real world constraints, it is rare that cross sectional area can be made in one measurement. For most streams, cross sectional area is typically derived by measuring depth at predetermined intervals across the river (see Figure 20). For each depth measurement, the stream velocity is measured as well (most field crews use a current meter) (Turnipseed and Sauer 2010). This allows one to measure discharge using Equation 2.

$$\mathrm{Q} = \sum_{i=1}^{n} \mathrm{A}_i \times \mathrm{V}_i \qquad \text{Equation (2)}$$

Where Q Total discharge (m^3/s)
A_i Cross sectional area of the i^{th} segment of a total n segments
V_i Mean velocity in the i^{th} segment.

A hydrometric station does not measure discharge directly. A ratings curve is used to infer discharge from stage.

A **ratings curve** is developed by measuring discharge across a broad range of river levels (from very low, to very high). The relationship between discharge and river level is then plotted (see Figure 22), which will allow one to derive discharge from stage (Turnipseed and Sauer 2010).

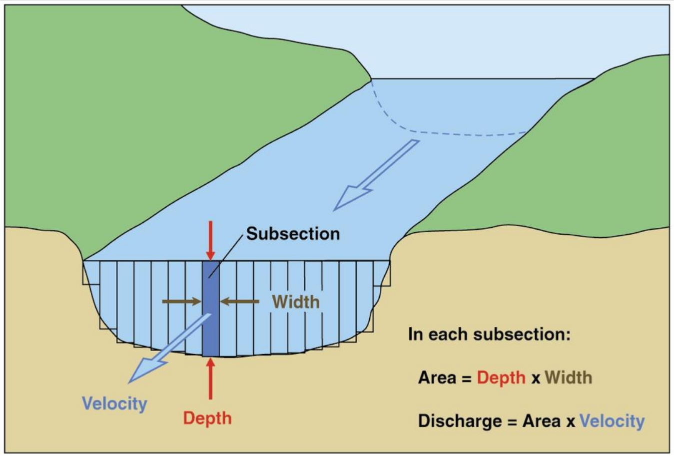


Figure 20. Cross-sectional area is calculated by measurements of area and velocity in multiple river subsections. Courtesy of the United States Geological Survey.

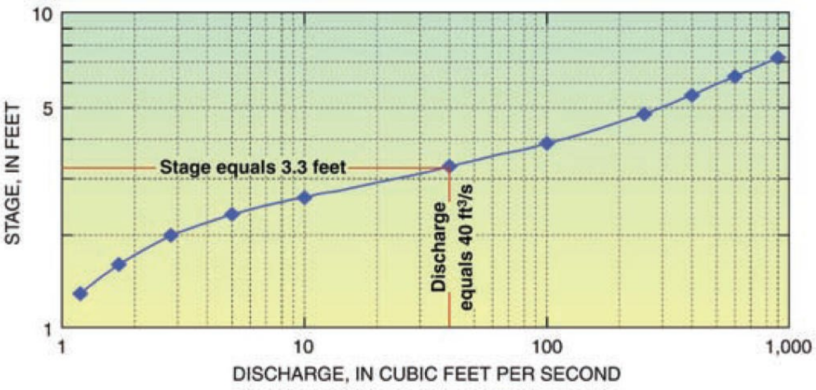


Figure 21. A ratings curve, showing the discharge – level (stage) relationship. Courtesy of the United States Geological Survey.

Discharge and stage data for archived and active hydrometric stations in the Dehcho IMA (and across Canada) can be obtained from the Water Survey of Canada (https://wateroffice.ec.gc.ca/). This data can be used to determine baseline conditions for the streams in the hydrometric network, which can then be compared against new observations.

Implementation Considerations

Site Selection

Rantz (1982) and Turnipseed and Sauer (2010) provide comprehensive guidance for selecting appropriate locations to install a hydrometric station. They provide the following guidance for site selection:

- Select a stretch of channel sufficiently downstream of an upper tributary, so that flow is uniformly distributed across the width of the stream, and sufficiently upstream of a lower tributary to avoid backwater and eddy effects;
- All flow should be restricted to a single channel, and the streambed should be free of obstructions that would create eddies. A smooth, mirror like water surface is indicative of uniform flow conditions;
- The streambed should have an easily measurable shape: roughly rectangular, trapezoidal, or parabolic;
- The cross-sectional profile should remain consistent year-round, and year over year. Stream banks should be unchanging, and the streambed should be free of scour or fill. If the cross-sectional area or profile changes, the ratings curve will need to be re-measured in order to calculate discharge accurately;
- The station should be placed in a relatively straight stream course – there should be no bends for 100m upstream or downstream;
- The site should be easily accessible, which will facilitate regular visits (to measure the ratings curve, and for necessary maintenance); and
- Discharge and stage should be measurable at both peak and minimal flow (the selected river should not run dry).

In the Northwest Territories, the presence of ice makes winter stage and discharge measurements unreliable (Government of Canada 2020a).

Data Analysis and Reporting Considerations

Data Analysis

To detect annual trends in hydrometric data, Burn et al. (2004) recommend using the Mann-Kendall test (Kendall 1975; Mann 1945), a non-parametric test that detects the presence of consistent (i.e., monotonic) increases or decreases in time-series data. For that reason, the Mann-Kendall test is particularly suitable for hydrometric time-series. Details about the implementation of this method is provided in Burn et al. (2004).

Reporting

Annual reporting for both plans should include updated data for all metrics (i.e., the number and proportion of streams with low water levels, trends in stage and discharge among streams of concern, and trends in temperature).

Reports should also include maps, which can help visually communicate trends in space. Maps showing the location of streams with low water levels will help determine if low water levels are consistent across the entire Dehcho IMA, or if they are constrained to a particular area or watershed. Trends in water levels or temperature can be mapped using icons to show the magnitude and direction of change (e.g., Figure 22).

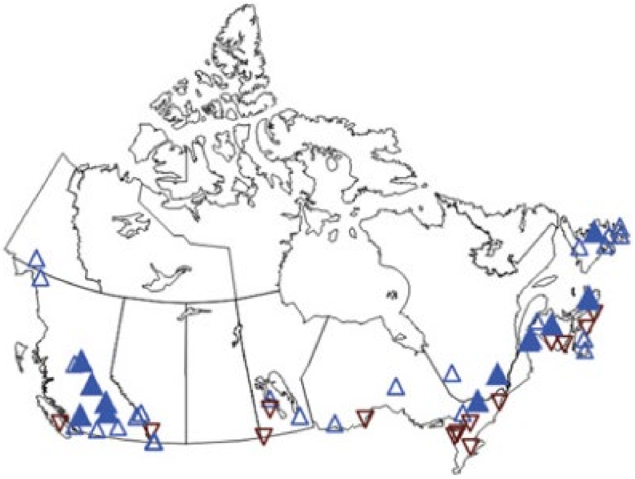


Figure 22. Trends in mean April mean streamflow. Triangle size is proportionate to trend magnitude. Solid triangles indicate statistical significance ($p < 0.05$) (Vincent et al. 2015).

Decision Making and Planning Processes

As the climate in the north continues to warm, declining summer flows in northern rivers are expected (Bush and Lemmen 2019). However, as a result of increased annual precipitation (especially in the winter) winter annual flows are expected to increase in both the Liard (Thorne 2011) and the Mackenzie (Vetter et al. 2017) rivers.

With changing water levels in the Dehcho IMA, DFN members are concerned about diminishing access to preferred harvesting sites, safely boat on formerly navigable river channels, and the health of fish populations. Systematically collecting information about the navigability of streams will be helpful in the following contexts:

- **Risks to human health, safety, and equipment**. If trends continue, travel on certain waterways in the Dehcho IMA may become risky. DFN members hold knowledge about which channels are and are not navigable. Should this knowledge become mismatched with the on-the-ground reality, risks to safety while traveling by boat may increase (e.g., due to running aground, becoming stuck, taking on water, etc.). It also may result in unintended damage to boats, which may require expensive fixes, or replacement.
- **Connection to the land**. The ability of DFN members to predict environmental conditions is tied to their own confidence. Decreased predictability of river navigability (among other environmental phenomena) impacts land-users' ability to rely on indigenous knowledge as a guide (be it in facilitating hunting and fishing, navigating, or remaining safe on the land). In some instances Indigenous peoples have reported increased anxiety and stress due to the experience of environment change and resulting loss of connection with the land (NWT Association of Communities 2019).
- **Negotiations with government.** Evidence of the impacts of climate change on DFN member communities (e.g., increased risks to safety and human health, evidence of adverse impacts to environment and species) could be useful for negotiations with territorial and/or federal governments.
- **Referrals and Impact Assessments.** Baseline data about climate variables (e.g., current status, observed trends) can be of assistance when responding to referrals or impact assessment processes, or in negotiations with proponents. Better baseline knowledge about climate conditions may allow DFN communities to better assess the potential impact of development activities in their territory on hydrological conditions.

Linkages to Established Programs and Potential Collaborators

Federal Government

The **Water Survey of Canada** (WSC) is a federal agency that collects, distributes, and analyzes Canadian hydrological data (Government of Canada 2018). The agency and its territorial and provincial partners maintain a network of 2500 active hydrometric sites, plus an archive of over 5,500 discontinued sites (Figure 18 shows the stations (23 active and 34 discontinued) in the vicinity of the Dehcho IMA). Hydrometric stations collect data on discharge (flow) and water level, which are used to inform irrigation and hydroelectric potential, to forecast floods, to inform civil engineering needs (e.g., road and pipeline design), as well as in scientific investigations of water quality, sediment transport, and climate change. The WSC partners with territorial and provincial agencies (in the Northwest Territories, the WSC partners with Environment and Natural Resources (ENR)).

Territorial Government

The NWT ENR collects water quality and quantity data throughout its monitoring network in the territory. They oversee multiple hydro-climatic data collection programs, which are summarized below:

Transboundary River Water Quality Monitoring Network. This program monitors water quality on river system at the NWT boundary, to monitor upstream water quality, as an early warning / detection system. This program has collected data that can serve as a baseline in case water quality should it shift in the future (e.g., in the case of upstream industrial development, or other sources of water quality issues). Monitoring takes place on the Liard, Hay, Peel, and Slave Rivers. Partners include Environment and Climate Change Canada, at Smith Landing, K'atl'odeeche, Gwich'in, and Liard First Nations, as well as Northern Alberta First Nations.

Liard River Environmental Quality Monitoring Program. This now-discontinued program measured water quality in the Liard river at the NWT / BC boundary between 1991 and 1995 (with periodic follow-ups until 2007), to assess the baseline status of the river, and to evaluate potential human health or aquatic habitat hazards.

NWT Water Stewardship Strategy. The NWT's water stewardship strategy was established to protect the water resources in the NWT and promote the stewardship of the NWT's waters. The strategy is implemented through 5-year action plans. The most recent plan is the NWT Water Stewardship Strategy: A Plan for Action, 2016-2020. The plans identify partners, and identify specific action items, deliverables, timelines, and monitoring mechanisms. The water stewardship strategy partners with Inuit, Metis, and First Nations partners through the Aboriginal Steering Committee, which helps to guide the implementation of the stewardship strategy.

Ecology North

Ecology North (EN) is a non-profit based in Yellowknife. EN organizes and supports initiatives that contribute to local environmental health and sustainability. One of EN's focal areas is contributing to water stewardship, in support of the NWT Water Stewardship Strategy.

EN supports and facilitates projects that contribute to effective, long-term stewardship of NWT water resources, and operates under the principles laid out in the NWT Water Stewardship Strategy.

Mackenzie Datastream

The Mackenzie Datastream is an open access online platform that amalgamates water quality data collected by over 30 partner communities within the Mackenzie River Watershed (including 5 DFN communities). The platform aims to facilitate knowledge sharing among communities, support informed decision making, enhance ecosystem health. The platform is open access and allows users to upload and share a wide variety of water resources data .

Tracking Change

The Tracking Change project is a multi-year social science research project to document Indigenous Knowledge in the Mackenzie River, Mekong, and Amazon watersheds. The project's overall goal is to support local governance of these ecosystems and support subsistence fishers. While the project does not collect quantitative data, the ongoing research can help inform ongoing monitoring needs and inform governance of water resources in the region.

Canadian Aquatic Biomonitoring Network

The Canadian Aquatic Biomonitoring Network (CABIN) is a national aquatic biomonitoring program that operates with a network of networks approach. CABIN facilitates inter-agency data collection and collaboration, with the focus on consistent reporting on fresh water quality indicators across Canada. Within the Dehcho IMA (plus a 50km buffer) there are over 250 CABIN data records.

References

Burn, D. H., O. I. Abdul Aziz, and A. Pietroniro. 2004. A Comparison of Trends in Hydrological Variables for Two Watersheds in the Mackenzie River Basin. Canadian Water Resources Journal. 29(4): 283–298. https://doi.org/10.4296/cwrj283

Burn, D. H., J. M. Cunderlik, and A. Pietroniro. 2004. Hydrological trends and variability in the Liard River basin. Hydrological Sciences Journal. 49(1): 53–67. https://doi.org/10.1623/hysj.49.1.53.53994

Bush, E., and D. S. Lemmen (Eds.). 2019. Canada's Changing Climate Report. Ottawa, ON: Government of Canada.

ClimateData.ca. 2020. Fort Simpson. Retrieved March 9, 2020, from https://climatedata.ca/explore/location/?loc=LAILM&location-select-temperature=tx_max&location-select-precipitation=rx1day&location-select-other=frost_days

Eaton, J. G., and R. M. Scheller. 1996. Effects of climate warming on fish thermal habitat in streams of the United States. Limnology and Oceanography. 41(5): 1109–1115. https://doi.org/10.4319/lo.1996.41.5.1109

Government of Canada. 2018. About the Water Survey of Canada. Retrieved March 4, 2020, from https://www.canada.ca/en/environment-climate-change/services/water-overview/quantity/monitoring/survey/about.html

Government of Canada. 2020a. Ice Conditions Warning. Retrieved March 9, 2020, from https://wateroffice.ec.gc.ca/ice_conditions_e.html

Government of Canada. 2020b. Topographic Data of Canada - CanVec Series. Retrieved March 20, 2020, from https://open.canada.ca/data/en/dataset/8ba2aa2a-7bb9-4448-b4d7-f164409fe056

Hokanson, K. E. F., J. Howard, and R. Jones. 1973. Temperature Requirements for Embryos and Larvae of the Northern Pike, Esox lucius (Linnaeus). Transactions of the American Fisheries Society. 102(1): 89–100. https://doi.org/https://doi.org/10.1577/1548-8659(1973)102<89:TRFEAL>2.0.CO;2

Irving, K., M. Kuemmerlen, J. Kiesel, K. Kakouei, S. Domisch, and S. C. Jähnig. 2018. A high-resolution stream fl ow and hydrological metrics dataset for ecological modeling using a regression model. Scientific Data. 1–14.

Isaak, D. J., S. Wollrab, D. Horan, and G. Chandler. 2012. Climate change effects on stream and river temperatures across the northwest U . S . from 1980 – 2009 and implications for salmonid fishes. Climatic Change. 113: 499–524. https://doi.org/10.1007/s10584-011-0326-z

Jacques, J. M. S., and D. J. Sauchyn. 2009. Increasing winter baseflow and mean annual streamflow from possible permafrost thawing in the Northwest Territories, Canada. Geophysical Research Letters. 36(1): 1–6. https://doi.org/10.1029/2008GL035822

Kendall, M. G. 1975. Rank correlation measures. Charles Griffin, London, 202, 15.

Kirizopoulos, E. 2020, March 17. Email communication.

Low, M. 2020, February 24. Email communication

Low, M. 2020, March 31. Email communication.

Mann, H. 1945. Mann Nonparametric test against trend. Econometrica.

Mantua, N., I. Tohver, and A. Hamlet. 2010. Climate change impacts on streamflow extremes and summertime stream temperature and their possible consequences for freshwater salmon habitat in Washington State. Climatic Change, 102(1–2), 187–223. https://doi.org/10.1007/s10584-010-9845-2

Mcdonald, Trent, L. 2003. Review of environmental monitoring methods: survey designs. Environmental Monitoring and Assessment. 85(3): 277–292.

NWT Association of Communities. 2019. Pulling Together to Tackle Climate Change. https://doi.org/10.4337/9780857939999.00022

Okanagan Hydrometric Network Working Group. 2008. Hydrometric Network Requirements for the Okanagan Basin.

Olden, J. D., and N. L. Poff. 2003. Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. River Research and Applications. 121: 101–121. https://doi.org/10.1002/rra.700

Rantz, S. E. 1982. Measurement and computation of streamflow: Volume 1. Measurement of stage and discharge.

Rood, S. B., S. Kaluthota, L. J. Philipsen, N. J. Rood, and K. P. Zanewich. 2017. Increasing discharge from the Mackenzie River system to the Arctic Ocean. Hydrological Processes. 31(1): 150–160. https://doi.org/10.1002/hyp.10986

Sutherland, C. 2015. Regional Climate and Hydrometric Monitoring Network Scoping Study.

Thorne, R. 2011. Uncertainty in the impacts of projected climate change on the hydrology of a subarctic environment: Liard River Basin. Hydrology and Earth System Sciences. 15(5): 1483–1492. https://doi.org/10.5194/hess-15-1483-2011

Turnipseed, D., and V. Sauer. 2010. Discharge measurements at gaging stations: U.S. Geological Survey Techniques and Methods. Retrieved from http://pubs.er.usgs.gov/browse/usgs-publications

Vetter, T., J. Reinhardt, M. Flörke, A. van Griensven, F. Hattermann, S. Huang, H. Koch, I. G. Pechlivanidis, S. Plötner, O. Seidou, B. Su, R. W. Vervoort, and V. Krysanova. 2017. Evaluation of sources of uncertainty in projected hydrological changes under climate change in 12 large-scale river basins. Climatic Change. 141(3): 419–433. https://doi.org/10.1007/s10584-016-1794-y

Vincent, L. A., X. Zhang, R. D. Brown, Y. Feng, E. Mekis, E. J. Milewska, H. Wan, and X. L. Wang. 2015. Observed trends in Canada's climate and influence of low-frequency variability modes. Journal of Climate. 28(11): 4545–4560. https://doi.org/10.1175/JCLI-D-14-00697.1

Vliet, M. T. H. Van, W. H. P. Franssen, J. R. Yearsley, F. Ludwig, I. Haddeland, D. P. Lettenmaier, and P. Kabat. 2013. Global river discharge and water temperature under climate change. Global Environmental Change. 23(2): 450–464. https://doi.org/10.1016/j.gloenvcha.2012.11.002

Yip, Q. K. Y., D. H. Burn, F. Seglenieks, A. Pietroniro, and E. D. Soulis. 2013. Climate impacts on hydrological variables in the Mackenzie River Basin. Canadian Water Resources Journal. 37(3): 209–230. https://doi.org/10.4296/cwrj2011-899