Exploring monitoring design options and scenarios for a provincial flowing waters monitoring program

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Exploring monitoring design options and scenarios for a provincial flowing waters monitoring program

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Summary

Rivers and streams are complex ecosystems with considerable socio-economic value. However, they are increasingly pressured by anthropogenic activities and climate change. Responding to these pressures requires understanding ecological status and trends in rivers and streams (collectively known as *streams*) at landscape scale. Developing a landscape scale monitoring program is a complex, iterative, process that requires expertise from a range of disciplines such as statistics and ecology. In this report, we apply the principles and practices of monitoring program design to explore a range of hypothetical scenarios for a provincial stream monitoring program in Ontario, Canada. Our aim is to provide examples to stimulate discussion, highlight knowledge gaps, and visualize complex design principles. We explore six monitoring scenarios varying in complexity and spatiotemporal scope. These scenarios illustrate a range of potential design decisions relating to access challenges, the costs of sampling uncommon stream types and difficult to access streams, and the logistical and methodological challenges associated with monitoring streams at provincial scale.

Résumé

Exploration des options et des scénarios de conception de la surveillance pour un programme provincial de surveillance de l'eau

Les rivières et les ruisseaux sont des écosystèmes complexes dont la valeur socio-économique est considérable. Toutefois, les activités anthropiques et le changement climatique exercent une pression de plus en plus forte sur eux. Pour répondre à ces pressions, il faut comprendre l'état et les tendances écologiques des rivières et des ruisseaux (collectivement appelés cours d'eau) à l'échelle du paysage. L'élaboration d'un programme de surveillance à l'échelle du paysage est un processus complexe et itératif qui nécessite des compétences dans diverses disciplines telles que les statistiques et l'écologie. Dans ce rapport, nous appliquons les principes et les pratiques de la conception des programmes de surveillance pour explorer une série de scénarios hypothétiques pour un programme provincial de surveillance des cours d'eau en Ontario, au Canada. Notre objectif est de fournir des exemples pour stimuler les discussions, mettre en évidence les lacunes dans les connaissances et visualiser des principes de conception complexes. Nous explorons six scénarios de surveillance dont la complexité et la portée spatio-temporelle varient. Ces scénarios illustrent une série de décisions de conception potentielles concernant les difficultés d'accès, les coûts d'échantillonnage des types de cours d'eau peu courants et difficiles d'accès, ainsi que les défis logistiques et méthodologiques associés à la surveillance des cours d'eau à l'échelle provinciale.

Acknowledgements

We thank Rob Mackereth, Dak de Kerckhove, Scott Reid, Adam Challice, Paul Finigan, and Nolan Pearse all from the Ministry of Natural Resources, and Anurani Persaud from the Ministry of the Environment, Conservation, and Parks for helpful discussions and reviews of earlier drafts.

Contents

1| Introduction

Rivers and streams (hereafter referred to collectively as *streams*) are complex ecosystems that hold considerable cultural and socioeconomic value (de Groot et al. 2002, Strayer and Dudgeon 2010). In Ontario, streams support a variety of aquatic biota and provide fresh water for human consumption, recreation, navigation, irrigation, industrial use, and energy production (Chu et al. 2022). Streams across North America are increasingly pressured by anthropogenic activities and climate change, threatening the ecological and economic integrity of these valuable ecosystems (Strayer and Dudgeon 2010, Chu et al. 2022). Responding to these pressures effectively requires an understanding of ecological status and trends in streams to inform resource management.

Ontario is a large province covering more than one million square kilometres. Nearly 15% of the province is covered by fresh water, with some 500,000 kilometres of stream spanning the width and breadth of the province. Nearly 70% of these streams flow through a relatively undisturbed landscape on the Canadian Shield, while southern streams have limited natural cover remaining (Jones et al. 2019). A lack of roads makes it challenging to access northern streams, limiting our understanding of their aquatic ecology and condition. The massive scale of this resource makes it impractical to monitor and manage streams individually. Instead, a landscape-scale approach is needed, consistent with the ministry's existing approach to management (e.g., the Provincial Fish Strategy) and a core principle of the ongoing provincial inland lakes broad-scale monitoring program (Lester et al. 2003, 2021).

In this report, we apply the principles and practices of monitoring program design (Sutton and Jones 2023) to explore a range of design scenarios for a provincial stream monitoring program. We do not aim to design a monitoring program that can be implemented in practice, but rather to provide illustrative examples to stimulate discussion, highlight knowledge gaps, and visualize potentially complex design principles and decisions. Specifically, the goal of this report is to: (1) provide illustrative examples of potential design decisions and the effects on the possible scope of inference and sampling costs, (2) highlight the unique challenges, and possible solutions, that might be faced when developing a landscape-scale stream monitoring program for Ontario, and (3) explore the relative costs of different monitoring designs through hypothetical scenarios.

2| A review of monitoring program design

Designing a monitoring program is a complex, iterative, process that requires stakeholder input and experience from a range of disciplines including statistics and ecology (Figure 1; Sutton and Jones 2023). Clear goals and objectives defined in collaboration with stakeholders are essential. The goals and objectives inform the spatial (where to sample), temporal (when to sample), and statistical (how much to sample) aspects of the design. Early drafts of a monitoring program are often too costly or resource intensive to be feasible in practice. As a result, goals and objectives must evolve to match sampling realities and resource constraints. An inadequate design will fail to detect relevant changes and trends, leading to an incorrect understanding of the condition of a resource and inappropriate or ineffective management actions. As such, monitoring programs that cannot achieve their goals and objectives, even with revisions, should not be implemented.

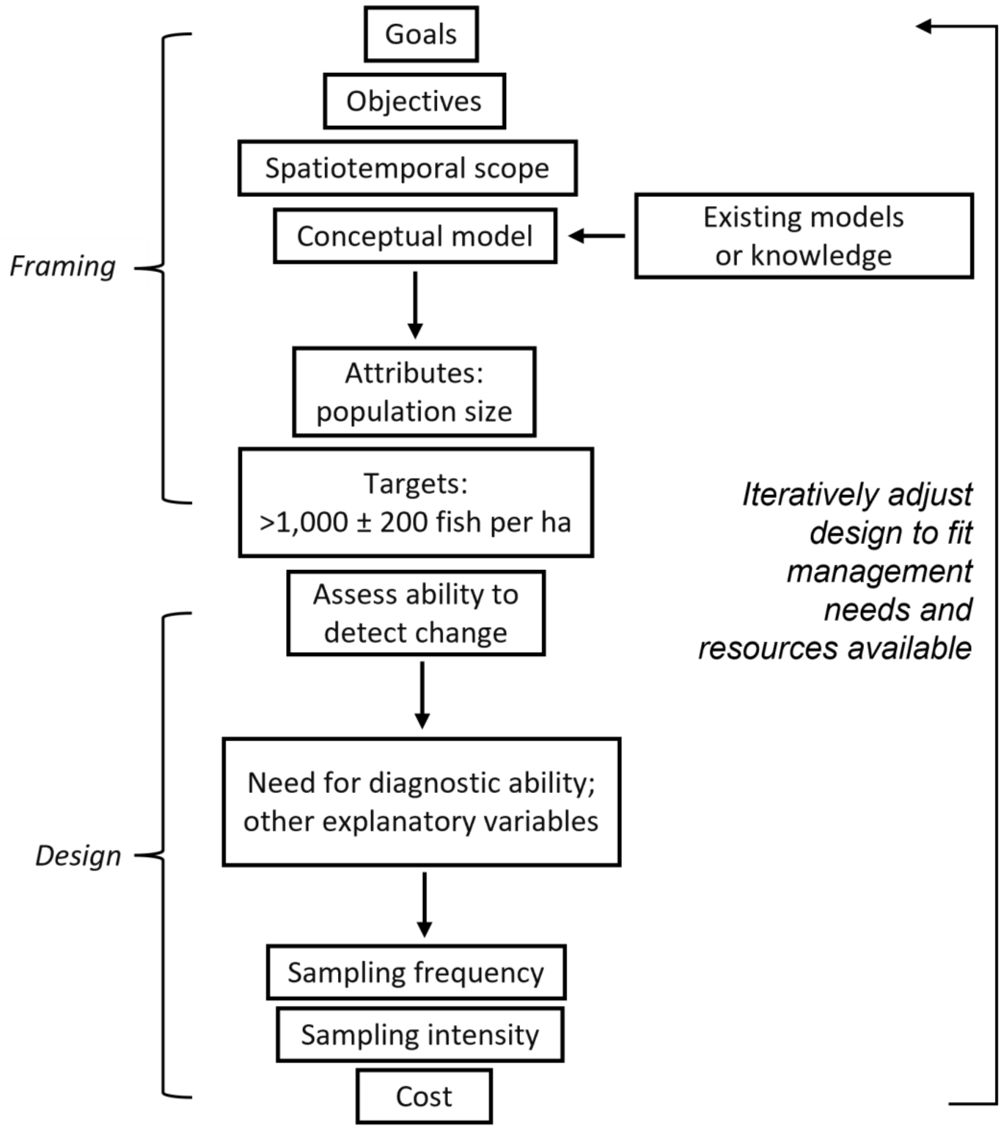

Figure 1. The iterative process of designing a monitoring program. Goals identify the reason for monitoring, while objectives provide measurable targets. Together, goals and objectives define the spatiotemporal scope for the monitoring program (i.e., regions and time frames over which inferences are needed). A conceptual model representing major drivers of ecosystem dynamics and function is then developed. Attributes associated with variables of interest are then chosen for monitoring. Targets are then defined for each attribute and evaluated to understand natural and observational variability, and the ability to detect change for a given sampling methodology and intensity. The need for diagnostic power (i.e., the power to understand why changes occur) is then determined in consultation with stakeholders. Monitoring costs are estimated based on the chosen design. If the cost is too high the goals, objectives, and scope must be adjusted, and alternative monitoring designs must be explored. Adapted from Reynolds et al. (2016).

In general, monitoring programs are developed to assess status or trends, and sometimes both. Status assessments provide a *point in time* understanding of ecosystem condition by comparing observations to predefined expectations or benchmarks (e.g., a water quality guideline). Trends are assessed by tracking changes in status through time. The goal of landscape-scale monitoring is to make inferences about the many by sampling the few. Scientifically credible inferences are only possible when samples (the few) accurately represent the population (the many). Sampling sites are usually chosen probabilistically (at random) to limit selection biases that may influence representativeness. Sampling restrictions such as resource constraints, access challenges, and a lack of suitable sampling methods also affect sample representativeness. Invalid inferences and incorrect conclusions will occur when selection biases and sampling restrictions are prevalent.

The goals and objectives of a monitoring program define its spatiotemporal scope and, in turn, when and where sampling occurs. Monitoring programs must provide insight at scales relevant in resource management. Common considerations include the geographic extent of monitoring (e.g., provincial vs. regional), the smallest scale of interest (e.g., watersheds vs. subwatersheds), and relevant analysis and reporting timescales. Spatiotemporal scope is often limited to specific habitats (e.g., wadeable streams) and species (e.g., salmonids), and for practical reasons such as resource constraints, methodological deficiencies, and access challenges. Spatiotemporal scope determines what can be reported on by a monitoring program.

Monitoring programs are usually designed to detect changes in a few key variables determined by the objectives. Statistical power is necessary to detect changes and trends when they truly exist. However, detecting changes and trends does not require understanding of why they are occurring. Identifying the drivers of changes and trends requires diagnostic power. The levels of statistical and diagnostic power needed must be defined when specifying goals and objectives. Committing limited resources to collecting diagnostic information may be inefficient where the same resources could be used to sample more sites at a broader scale or detect changes faster. Nevertheless, investment in a broad-scale monitoring program may help to support and inform site selection for smaller-scale diagnostic studies.

Deciding which variables to monitor is a challenging task that largely depends on the goals and objectives. Key features of useful variables are that they can be measured directly, are stable over time, are easy to interpret, and respond strongly to stressors and disturbance. There are two major paradigms in environmental monitoring: stressor-based and effects-based. The stressor-based approach seeks to quantify potential biological effects by measuring physical, chemical, and biological stressors. The effects-based approach measures biological responses to stressors. The stressor-based approach can provide an *early warning* before changes occur, while effects-based monitoring may reveal unanticipated cumulative, interactive, or legacy effects. The goals and objectives determine the appropriate approach, and most monitoring programs will benefit from a combination of stressor- and effects-based monitoring.

Monitoring programs are implemented following a survey design, which is developed based on the goals, objectives, scope, and variables of interest. Approaching survey design from a statistical perspective is necessary to ensure scientifically credible inference. Minimizing variability is crucial in efficient trend detection. Stratification, the division of a population into homogenous subpopulations, is a powerful tool that partitions variation and provides a basis for comparisons within subpopulations. It can be challenging to detect changes and trends without stratification because population-level heterogeneity may mask subpopulation trends. Variability can also be minimized by using simple, repeatable, sampling methods.

The spatiotemporal design defines when and where sampling occurs. A key decision is whether to sample the same sites through time or select new sites for each sampling event. Resampling designs, where sites are revisited over time, are typically used for trend detection because they eliminate variability introduced by changing sampling sites. Reallocation designs, where new sites are chosen before each sampling event, are often used in status assessments because they provide broader spatial coverage and limit potential biases from repeated sampling at the same locations. Split panel designs combine reallocation and resampling, but at the cost of increasing sampling and analytical complexity.

Streams are in constant flux, transitioning from one set of equilibrium conditions to the next. As such, it is necessary to standardize the timing of sampling to avoid confounding the detection of changes and trends with naturally occurring phenomenon. Monitoring must account for cyclical processes (e.g., seasonal, diurnal) and sampling must occur at the same point in each cycle. The variable or attribute being monitored often dictates the timing of sampling. Sampling frequency depends on the stability of the variables being monitored and the program objectives. Variables that are stable at interannual timescales require less frequent sampling than variables that vary daily or annually. If effects are expected to be large and rapidly occurring, infrequent sampling can be insufficient because irreversible damage could occur before changes are detected.

It is essential to conduct formal power analyses and sample size calculations when developing a monitoring program to ensure effort is sufficient to achieve the goals and objectives. Balancing the risk of failing to detect changes (false negatives) against the risk of falsely detecting changes (false positives) is crucial. Failing to detect changes may be damaging for a resource, and it is often acceptable to increase the risk of false positives to increase the power to detect changes. Increasing sampling effort is the primary method of increasing statistical power, and it may be necessary to accept that monitoring will only detect very large changes when effort is limited by resource constraints. Formal power analyses are not trivial, requiring simulation and knowledge of expected variability, except in the simplest cases. Program designers are strongly encouraged to consult a practicing statistician during program development to ensure their design can meet monitoring goals and objectives given available resources and natural variability.

3| Design options and scenario development

3.1| Rationale and approach

A needs assessment completed by the River and Stream Integrated Monitoring Framework task team (Chu et al. 2022) included a survey of staff across the ministry to identify program areas that would benefit from standardized stream monitoring. A broad objective statement was also created to guide future monitoring program development. It states:

> "[The] objective of [a provincial stream monitoring program is to] monitor and report on the status and trends of riverine ecosystem health, particularly fish biodiversity and their physical, chemical, and biological environment."

This objective statement and the needs assessment results informed our exploration of a range of design options and scenarios. The next step in monitoring program design would be to define the monitoring objectives and scope. However, we chose not to pre-specify objectives or scope because our goal was to assess the effect of various design decisions on monitoring costs and possible scope of inference. We define objectives as needed for illustrative purposes, while scope is addressed in-depth in the following section on program and the discussion. In practice, the objectives and scope would be defined through consultation with internal stakeholders.

The needs assessment conducted by the task team identified numerous variables of interest for a provincial monitoring program (Table 1). Given these results and the ministry's business areas the need to monitor fish is clear. However, monitoring fish will be a costly endeavour due to the natural variability of fish populations and communities. The concern about cost is particularly true for stream environments that are much more variable than lakes (Resh et al. 1988), which are currently monitored via the provincial broad-scale monitoring program. However, much can be learned about stream conditions by measuring physical and chemical variables. Indeed, we envision a tiered monitoring program with field-based sampling as the final tier. Generally, this monitoring pyramid would consist of:

1. **Remote sensing** which can be used to monitor the broad-scale stressors known to affect stream health (e.g., Wang et al. 2011, Jones et al. 2019). This approach is currently taken in the ministry's state of the biodiversity reports, indicating capacity and expertise exists to implement such assessments. Further, remote sensing can aid in the interpretation of field-based data sets by providing information on meaningful covariates (e.g., land use). Remote sensing is a powerful tool because monitoring can occur on private land and in remote areas, allowing complete coverage of a study region. Monitoring using remote sensing is contingent on regular (e.g., every 10 years) updates to the base data.

2. **Data loggers** have a pivotal role in monitoring because they can provide high-resolution temporal data over broad geographic areas. Indeed, much can be learned by monitoring stream temperatures and flows (Poff et al. 1997, Metcalfe et al. 2013). Thermal and flow regimes affect many biological processes, and monitoring changes in these variables can provide insights into ecosystem conditions. Automated data loggers are not restricted to monitoring temperature or flows, and a range of chemical and physical variables such as turbidity and water quality can be monitored. This type of data is collected continuously and can be reported on at different intervals (e.g., annually or after several years).

3. **Field-based sampling** would comprise the final monitoring tier because it is the costliest and most logistically challenging to implement. Field-based monitoring provides a direct understanding for many variables of interest (e.g., biodiversity) that can only be inferred via other monitoring tiers. Nevertheless, the increased costs and resource requirements are not always justifiable given the information gains. Field-based sampling is infrequent (e.g., every 5 years).

This tiered approach is consistent with the principles of landscape ecology (i.e., "the valley rules the stream"), while providing incremental information increases that mirror monitoring costs. A distinction is drawn between using data loggers and field-based sampling, even though both are field-based methods, because they differ substantially in ongoing implementation effort. We mainly focused our efforts on exploring design options for the last two tiers because they are costly and challenging to implement. However, remote sensing will be integral in any provincial monitoring program, and we address its use in the discussion.

Table 1. Candidate variables to monitor and report on provincial stream conditions identified by the River and Stream Integrated Monitoring Framework task team and ministry staff as part of a needs assessment for a provincial monitoring program in Ontario.

Theme	Variable	Description/metrics	Frequency	Tier*
Thermal and flow regime	Flow	Flow regime metrics	Continuous	2
	Flow alteration	Timing and flashiness of flows	Continuous	2
	Water temperature	Thermal regime metrics	Continuous	2
Chemical	Chlorophyll *a*	Concentration	Continuous	2/3
	Conductivity	Concentration	Continuous	2/3
	Chlorine	Concentration	Continuous	2/3
	Dissolved organic carbon	Concentration	Continuous	2/3
	Total dissolved solids	Concentration	Continuous	2/3
Biological	Large-bodied fishes	Presence/absence; abundance	At sampling	3
	Small-bodied fishes	Presence/absence; abundance	At sampling	3
	Large-bodied fish tissues	Mercury contaminant analysis	At sampling	3
	Deformities, erosions, lesions, and tumours	Presence/absence	Incidental	3
	Species-at-risk	Presence/absence	Incidental	3
	Invasive species	Presence/absence	Incidental	3
	Macroinvertebrates†	Biodiversity; abundance	At sampling	3
Habitat and stressors	Climate	Temperature and precipitation	Continuous	1
	Land cover/land use	Land cover composition	As needed	1
	Riparian habitat	Riparian buffer width	As needed	1
	Channel form/substrate	Sinuosity; mean depth ratio	As needed	1
	Fishing pressure	Fishing effort or harvest	As possible	1/3
	Aquatic connectivity	Count of barriers and crossings	As needed	1
	Water taking	Count of water taking sites	As needed	1
	Point source pollution	Count of point source sites	As needed	1

*1=remote sensing, 2=data loggers, 3=field-based sampling; †identified as optional

3.2| Spatial framework and monitoring design

The Aquatic Ecosystem Classification

The provincial Aquatic Ecosystem Classification (AEC; Jones and Schmidt 2022) is recommended as a spatial framework for future monitoring projects. The AEC (Figure 2) is a science-based tool that groups streams using their physical (e.g., temperature, flow) and watershed (e.g., drainage area, geology) characteristics. The AEC provides a powerful monitoring foundation because the stream classes (Table 2) reduce complexity and partition variability. The spatial unit of interest

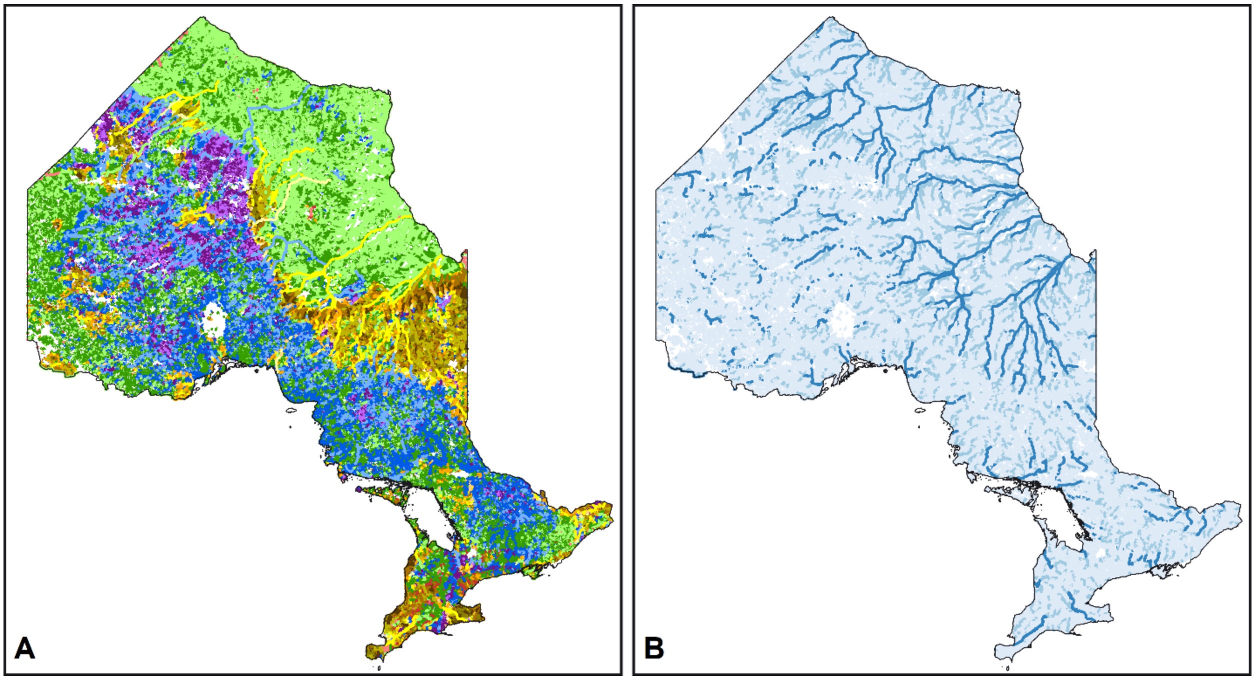

Figure 2. The Aquatic Ecosystem Classification (AEC) Version 1 showing (A) 16 classes of streams and (B) three stream size classes based on drainage area: (1) wadeable (<200 km^2, light blue), (2) semi-wadeable (≥200 km^2 to <2000 km^2, medium blue), and (3) non-wadeable (≥2000 km^2, dark blue). A legend describing the AEC stream classes shown in panel A is provided in Table 2.

Table 2. Aquatic ecosystem classification stream classes and variables used to classify streams. Clear streams are in the top half of the table and turbid stream in the bottom half. The clarity of the water is defined during summer low flow conditions. Class code descriptors are: VH=very high, M=moderate, L=low, C=clear, T=turbid, F=fast, S=slow.

Symbol	Class code	Baseflow index	Channel slope (%)	Stream length (km)
Clear streams (C) *				
	VHCF	≥0.65 (very high)	≥0.1 (fast)	34,952
	VHCS		<0.1 (slow)	9,480
	HCF	≥0.51 and <0.65 (high)	≥0.1 (fast)	68,337
	HCS		<0.1 (slow)	30,160
	MCF	≥0.35 and <0.51 (moderate)	≥0.1 (fast)	136,983
	MCS		<0.1 (slow)	92,157
	LCF	<0.35 (low)	≥0.1 (fast)	7,177
	LCS		<0.1 (slow)	1,586
Turbid streams (T)*				
	HTF	≥0.51 (high)	≥0.1 (fast)	3,929
	MTF	≥0.35 and <0.51 (moderate)		16,684
	LTF	≥0.20 and <0.35 (low)		23,645
	VLTF	<0.2 (very low)		20,170
	HTS	≥0.51 (high)	<0.1 (slow)	2,081
	MTS	≥0.35 and <0.51 (moderate)		12,826
	LTS	≥0.20 and <0.35 (low)		11,411
	VLTS	<0.2 (very low)		4,351

is the stream segment — a group of flow-connected, ecologically homogenous, stream reaches. The segments provide standardized monitoring units, while the classes are a consistent unit for reporting. Ancillary information (e.g., drainage area) can inform sampling methods and provide covariates for analyses. Indeed, the variables that shape the AEC (e.g., turbidity, channel slope) affect our ability to safely and reliably sample physical, chemical, and biological attributes. As a result, the AEC can also support the selection of appropriate sampling methods for each stream class. We discuss additional applications of the AEC to monitoring throughout this section.

Spatial, temporal, and statistical design

Although there is a clear need for provincial-scale monitoring, it is also necessary to identify the smallest spatial scale of interest to stakeholders that is practical to monitor. It is always possible to scale from small spatial scales to larger ones (e.g., regional to provincial) because the amount of data increases as it is aggregated at larger spatial scales. In contrast, studies designed at large spatial scales may not be useful to answer small-scale questions because monitoring sites are too dispersed to provide adequate sample sizes. Tertiary watersheds and fisheries management zones (FMZs) are candidates for sub-provincial inferences because they align with the ministry's existing planning and management framework (FMZs) and reporting products, including state of the biodiversity reports and watershed report cards (tertiary watersheds). Monitoring FMZs will cost less than tertiary watersheds because FMZs are less numerous. However, monitoring FMZs may prevent inferences at the tertiary watershed scale because the number of sites in each tertiary watershed may be too small for reliable inferences (Figure 3). In contrast, monitoring at the tertiary watershed scale will lead to more precise estimates at FMZ and provincial scales. For these scenarios, we explored FMZs and tertiary watersheds as spatial scales of interest, with sampling restricted to FMZs (15) and tertiary watersheds (178) that contain streams.

With the spatial scope of monitoring determined, the next step in monitoring program design is to specify the target population and sampling design. For these scenarios, we defined the target population as all streams represented in the provincial AEC and located within Ontario. The AEC segments provide a convenient sampling unit, while the stream classes provide the basic unit of stratification. Segments were further stratified into three size classes based on catchment area: wadeable (<200 km^2), semi-wadeable (≥200 and <2,000 km^2), and non-wadeable (≥2000 km^2; Figure 2). Segments were also stratified by spatial units (either FMZ or tertiary watershed based on the scenario). The strata define a hierarchical classification that allows data to be aggregated across several scales. The task team determined that the Winnipeg River and streams in FMZ 12 (Ottawa River) would be monitored as part of the provincial inland lake broad-scale monitoring program because they are effectively lake chains (Chu et al. 2022). As such, these spatial strata were excluded from our monitoring scenarios. In total, there are 472 strata at the FMZ scale and 3,190 strata at the tertiary watershed scale (Figure 4). Note that each spatial stratum does not contain each stream and size class combination, and the total number of strata is not simply the product of the number of stream classes, size classes, and spatial strata.

Sampling was assumed to follow the 5-year monitoring cycle recommended by the task team to align monitoring with the ministry's existing management and reporting timelines. A resampling design (i.e., the same sites sampled through time) was assumed for simplicity, but a reallocation approach (i.e., new sites at each sampling event) may be equally valid depending on monitoring objectives. A resampling design is indicative of the minimum sampling cost because reallocation approaches require larger sample sizes to detect trends due to increased variability and the use of less powerful unpaired statistical tests. We discuss reallocation approaches where needed to illustrate key differences between resampling and reallocation designs.

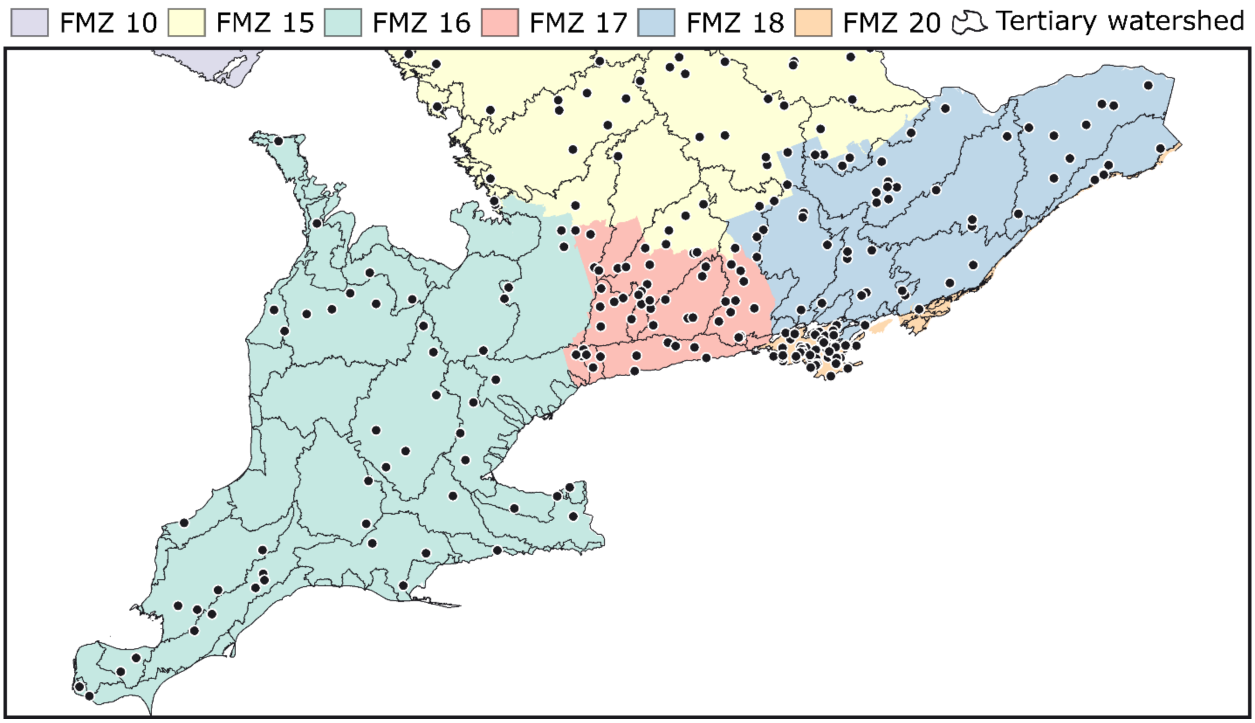

Figure 3. An illustrative example of the effects of spatial scale on survey design, site allocation, and the possible scope of inference. In this example, monitoring was designed to report on stream condition at a fisheries management zone (FMZ) scale with a minimum sample size of 50 stream segments per zone. Note that some tertiary watersheds are sampled extensively, while others are unsampled or have sample sizes too small to generate reliable inferences or provide statistical power.

With few exceptions, it is impractical to sample the entirety of a resource. In turn, the challenge for landscape-scale monitoring is to produce scientifically credible inferences over broad spatial scales from a small subset of locations sampled in the field. A random stratified sampling design was used in these scenarios because it eliminates selection biases that can occur when sites are chosen manually. Selection biases (e.g., over- or under representation of certain stream types or stressors) can lead to invalid inference because the population represented in the sample is not representative of the true stream population. Manually selecting representative sites is difficult because scientists and resource managers do not have experience with every stream across the landscape, and information about potential stressors is often incomplete. Subconscious biases may also mean that some streams are never considered. As such, it is possible that streams selected for monitoring will systemically differ from other streams in unknown ways. Randomly selecting sites minimizes the potential for systematic biases because each stream has the chance of being chosen. In the scenarios, sites were selected in each stratum using simple random sampling. However, restricted randomization approaches (e.g., generalized random tessellation stratified) are often used in practice because they produce samples with minimal spatial autocorrelation.

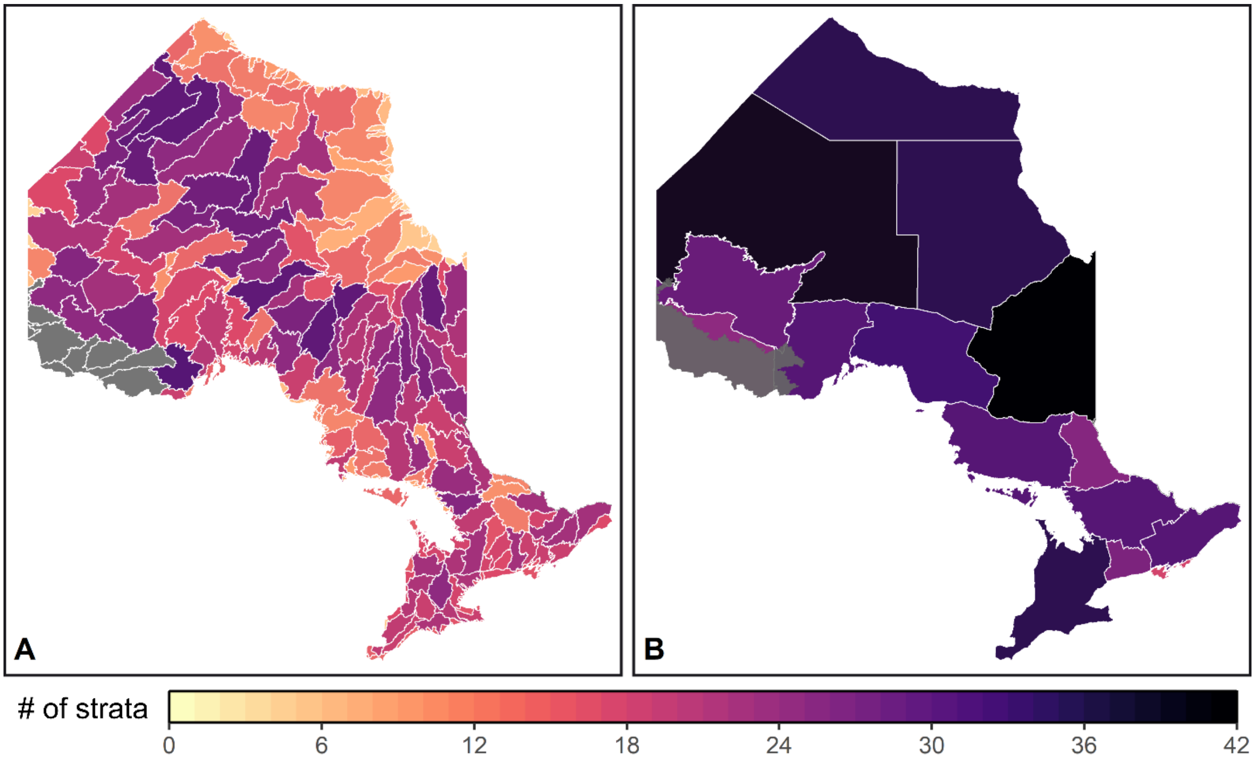

Figure 4. Spatial strata explored in monitoring scenarios: (A) tertiary watersheds and (B) fisheries management zones. Colours indicate the number of stream classes (stream size by class strata) present in each spatial stratum. The dark grey shaded regions identify watersheds and fisheries management zones ineligible for inclusion in a provincial monitoring program.

Monitoring challenges and opportunities

A provincial monitoring program will have several unique technical challenges that will influence its design and sampling costs. First, the density of streams and heterogeneity of stream types in Ontario generates a considerable number of strata to monitor (figures 2–4). There are many rare stream classes, often representing <5% of total stream length, that will be costly to sample (Figure 5). Indeed, the three rarest classes (HTF, HTS, and LCS) combined represent <2% of total stream length. However, these classes represent about 16% of strata at the FMZ scale and 12% of strata at the tertiary watershed scale because they are widely distributed across Ontario and among size classes. In contrast, the three most common classes (HCF, MCF, and MCS) represent roughly 60% of total stream length, and 27% or 30% of strata at the FMZ and tertiary watershed scales, respectively. In turn, if effort is distributed evenly across strata, monitoring <2% of Ontario's streams would take half as much effort as monitoring 60%.

Limiting sampling to common stream types may be necessary to make monitoring feasible. The task team proposed restricting sampling to stream classes that represent ≥10% or ≥25% of total stream length in each spatial stratum. Applying cut-offs in spatial strata is necessary to ensure adequate monitoring in strata with diverse or rare stream types (Figure 6). For example, limiting monitoring to stream classes that represent ≥10% of provincial stream length will cause

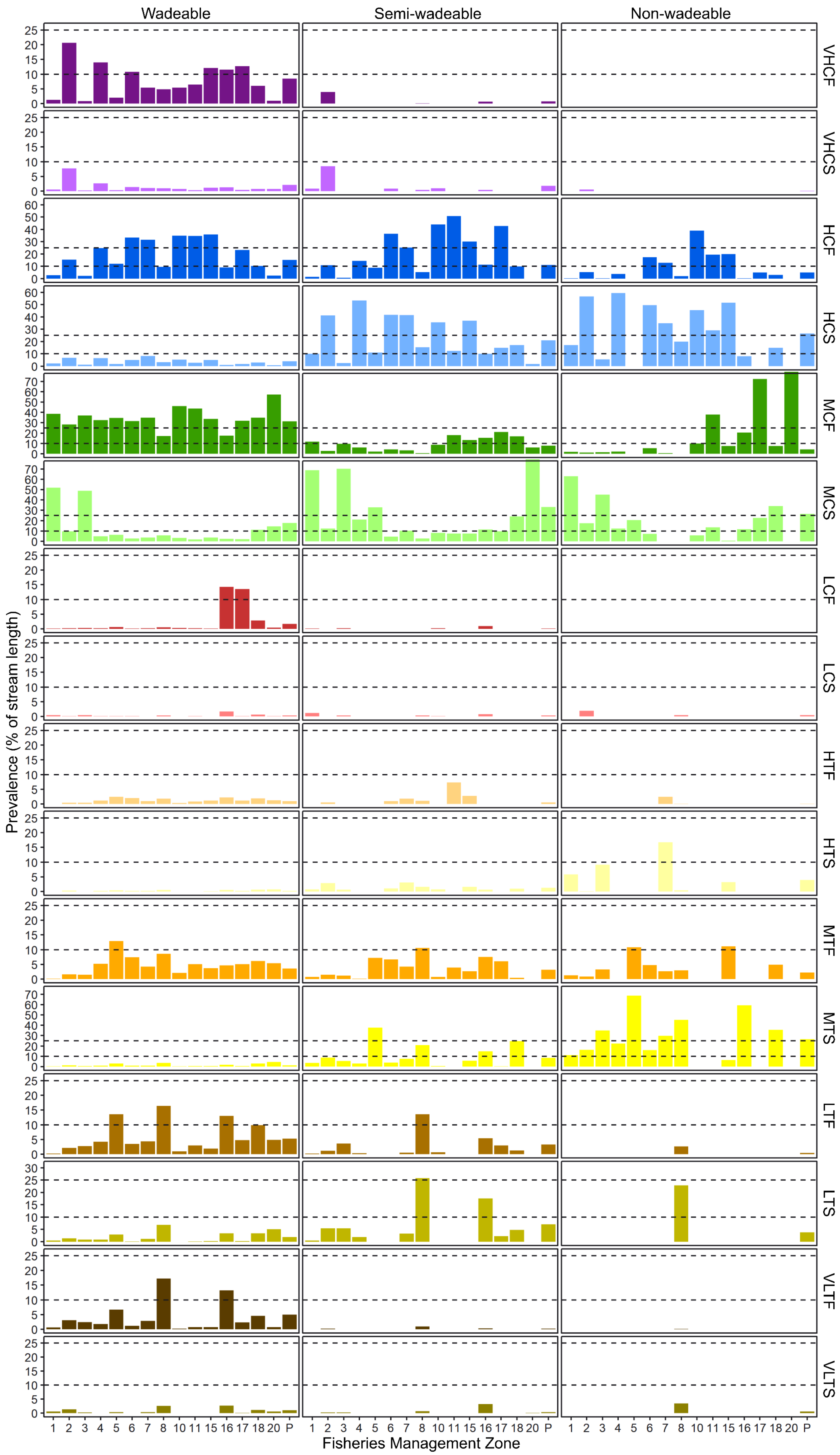

Figure 5. Prevalence of Aquatic Ecosystem Classification stream classes by size class and Fisheries Management Zone in Ontario. P is the overall provincial prevalence. The horizontal dashed lines represent the cut-offs of ≥10% and ≥25% proposed by the task team.

Table 3. Monitoring methods available to estimate fish presence/absence, species index, index of abundance, absolute abundance, and population and population structure and dynamics in Ontario streams by Aquatic Ecosystem Classification (AEC) stream class and size stratum. Cell shading indicates the availability of sampling approaches for each stratum: green=available, orange=methods must be adapted, red=no existing methods. Adapted from Jones et al. (2021). For an in-depth review of methods for sampling fish and their habitats in flowing waters, see Millar et al. (2023). The AEC stream and size class codes are defined in Figure 2 and Table 2. NA=not applicable.

AEC class		Electrofishing	Seine netting	Hoop/ fyke net	Minnow trap	Gill net	Nordic netting	Fall walleye index netting*	Angling
Wadeable	VHCF	1a, 2, 3, 5, 6a	1, 2, 3, 5b	1, 2, 3, 4	1, 2, 3, 4; e	NA	NA	NA	1, 3; d
	VHCS	1a, 2, 3, 5, 6a	1, 2, 3, 5b	1, 2, 3, 4	1, 2, 3, 4; e	NA	NA	NA	1, 3; d
	HCF	1a, 2, 3, 5, 6a	1, 2, 3, 5b	1, 2, 3, 4	1, 2, 3, 4; e	NA	NA	NA	1, 3; d
	HCS	1a, 2, 3, 5, 6a	1, 2, 3, 5b	1, 2, 3, 4	1, 2, 3, 4; e	NA	NA	NA	1, 3; d
	MCF	1a, 2, 3, 5, 6a	1, 2, 3, 5b	1, 2, 3, 4	1, 2, 3, 4; e	NA	NA	NA	1, 3; d
	MCS	1a, 2, 3, 5, 6a	1, 2, 3, 5b	1, 2, 3, 4	1, 2, 3, 4; e	NA	NA	NA	1, 3; d
	LCF	1a, 2, 3, 5, 6a	1, 2, 3, 5b	1, 2, 3, 4	1, 2, 3, 4; e	NA	NA	NA	1, 3; d
	LCS	1a, 2, 3, 5, 6a	1, 2, 3, 5b	1, 2, 3, 4	1, 2, 3, 4; e	NA	NA	NA	1, 3; d
	HTF	NA	1, 2, 3, 5b	1, 2, 3, 4	1, 2, 3, 4; e	NA	NA	NA	1, 3; d
	HTS	NA	1, 2, 3, 5b	1, 2, 3, 4	1, 2, 3, 4; e	NA	NA	NA	1, 3; d
	MTF	NA	1, 2, 3, 5b	1, 2, 3, 4	1, 2, 3, 4; e	NA	NA	NA	1, 3; d
	MTS	NA	1, 2, 3, 5b	1, 2, 3, 4	1, 2, 3, 4; e	NA	NA	NA	1, 3; d
	LTF	NA	1, 2, 3, 5b	1, 2, 3, 4	1, 2, 3, 4; e	NA	NA	NA	1, 3; d
	LTS	NA	1, 2, 3, 5b	1, 2, 3, 4	1, 2, 3, 4; e	NA	NA	NA	1, 3; d
	VLTF	NA	1, 2, 3, 5b	1, 2, 3, 4	1, 2, 3, 4; e	NA	NA	NA	1, 3; d
	VLTS	NA	1, 2, 3, 5b	1, 2, 3, 4	1, 2, 3, 4; e	NA	NA	NA	1, 3; d
Semi-wadeable	VHCF	1a, 2, 3, 5, 6a; g	1, 2, 3, 5b; g	1, 2, 3, 4; g	1, 2, 3, 4; e, g	NA	NA	NA	1, 3; d
	VHCS	1a, 2, 3, 5, 6a	1, 2, 3, 5b; g	1, 2, 3, 4	1, 2, 3, 4; e, g	1, 2, 3; c, h	1, 2, 3, 5a; f, h	1, 2, 3, 5; f, h	1, 3; d
	HCF	1a, 2, 3, 5, 6a; g	1, 2, 3, 5b; g	1, 2, 3, 4; g	1, 2, 3, 4; e, g	-	-	-	1, 3; d
	HCS	1a, 2, 3, 5, 6a	1, 2, 3, 5b; g	1, 2, 3, 4	1, 2, 3, 4; e, g	1, 2, 3; c, h	1, 2, 3, 5a; f, h	1, 2, 3, 5; f, h	1, 3; d
	MCF	1a, 2, 3, 5, 6a; g	1, 2, 3, 5b; g	1, 2, 3, 4; g	1, 2, 3, 4; e, g	-	-	-	1, 3; d
	MCS	1a, 2, 3, 5, 6a	1, 2, 3, 5b; g	1, 2, 3, 4	1, 2, 3, 4; e, g	1, 2, 3; c, h	1, 2, 3, 5a; f, h	1, 2, 3, 5; f, h	1, 3; d
	LCF	1a, 2, 3, 5, 6a; g	1, 2, 3, 5b; g	1, 2, 3, 4; g	1, 2, 3, 4; e, g	-	-	-	1, 3; d
	LCS	1a, 2, 3, 5, 6a	1, 2, 3, 5b; g	1, 2, 3, 4	1, 2, 3, 4; e, g	1, 2, 3; c, h	1, 2, 3, 5a; f, h	1, 2, 3, 5; f, h	1, 3; d
	HTF	NA	1, 2, 3, 5b; g	1, 2, 3, 4; g	1, 2, 3, 4; e, g	-	-	-	1, 3; d
	HTS	NA	1, 2, 3, 5b; g	1, 2, 3, 4	1, 2, 3, 4; e, g	1, 2, 3; c, h	1, 2, 3, 5a; f, h	1, 2, 3, 5; f, h	1, 3; d
	MTF	NA	1, 2, 3, 5b; g	1, 2, 3, 4; g	1, 2, 3, 4; e, g	-	-	-	1, 3; d
	MTS	NA	1, 2, 3, 5b; g	1, 2, 3, 4	1, 2, 3, 4; e, g	1, 2, 3; c, h	1, 2, 3, 5a; f, h	1, 2, 3, 5; f, h	1, 3; d
	LTF	NA	1, 2, 3, 5b; g	1, 2, 3, 4; g	1, 2, 3, 4; e, g	-	-	-	1, 3; d
	LTS	NA	1, 2, 3, 5b; g	1, 2, 3, 4	1, 2, 3, 4; e, g	1, 2, 3; c, h	1, 2, 3, 5a; f, h	1, 2, 3, 5; f, h	1, 3; d
	VLTF	NA	1, 2, 3, 5b; g	1, 2, 3, 4; g	1, 2, 3, 4; e, g	-	-	-	1, 3; d
	VLTS	NA	1, 2, 3, 5b; g	1, 2, 3, 4	1, 2, 3, 4; e, g	1, 2, 3; c, h	1, 2, 3, 5a; f, h	1, 2, 3, 5; f, h	1, 3; d
Non-wadeable	VHCF	NA	NA	NA	NA	NA	NA	NA	1, 3; d
	VHCS	1a, 2, 3, 5, 6a	NA	1, 2, 3, 4	NA	1, 2, 3; c	1, 2, 3, 5a; f	1, 2, 3, 5; f	1, 3; d
	HCF	-	NA	-	NA	-	-	-	1, 3; d
	HCS	1a, 2, 3, 5, 6a	NA	1, 2, 3, 4	NA	1, 2, 3; c	1, 2, 3, 5a; f	1, 2, 3, 5; f	1, 3; d
	MCF	-	NA	-	NA	-	-	-	1, 3; d
	MCS	1a, 2, 3, 5, 6a	NA	1, 2, 3, 4	NA	1, 2, 3; c	1, 2, 3, 5a; f	1, 2, 3, 5; f	1, 3; d
	LCF	-	NA	-	NA	-	-	-	1, 3; d
	LCS	1a, 2, 3, 5, 6a	NA	1, 2, 3, 4	NA	1, 2, 3; c	1, 2, 3, 5a; f	1, 2, 3, 5; f	1, 3; d
	HTF	NA	NA	-	NA	-	-	-	1, 3; d
	HTS	NA	NA	1, 2, 3, 4	NA	1, 2, 3; c	1, 2, 3, 5a; f	1, 2, 3, 5; f	1, 3; d
	MTF	NA	NA	-	NA	-	-	-	1, 3; d
	MTS	NA	NA	1, 2, 3, 4	NA	1, 2, 3; c	1, 2, 3, 5a; f	1, 2, 3, 5; f	1, 3; d
	LTF	NA	NA	-	NA	-	-	-	1, 3; d
	LTS	NA	NA	1, 2, 3, 4	NA	1, 2, 3; c	1, 2, 3, 5a; f	1, 2, 3, 5; f	1, 3; d
	VLTF	NA	NA	-	NA	-	-	-	1, 3; d
	VLTS	NA	NA	1, 2, 3, 4	NA	1, 2, 3; c	1, 2, 3, 5a; f	1, 2, 3, 5; f	1, 3; d

*Replaced by riverine index netting (RIN; Jones and Yunker 2009)

1=presence/absence; 2=species richness; 3=relative abundance; 4=absolute abundance; 5=population structure (i.e., size, age); 6=population dynamics (i.e., reproduction, mortality)

a=should be used in conjunction with other methods; b=habitat specific; c=a passive method for use in shallow waters, but may be used actively from a boat; d=for target species, e=for small species and juveniles, f=may be difficult to set nets in habitats with soft bottoms; g=wadeable only; h=non-wadeable only

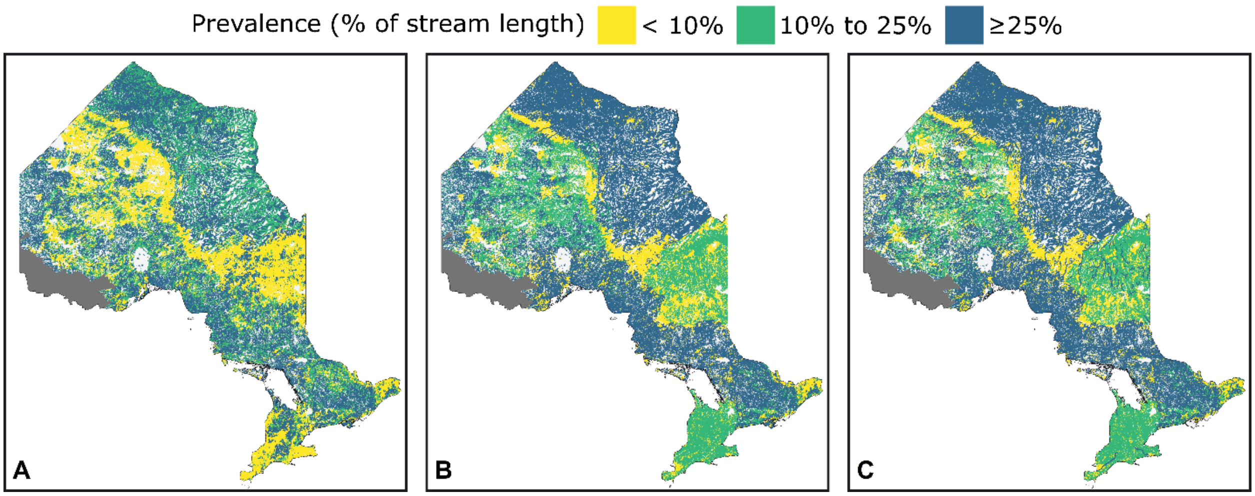

Figure 6. Distribution of stream segments representing <10%, 10% to 25%, and ≥25% of stream length at A) the provincial scale, B) in each fisheries management zone, and C) in each fisheries management zone by size class combination. Segments shown in yellow correspond to rare stream classes, and these segments will not be assessed if prevalence thresholds are used. Segments shown in blue represent common classes, and these segments will be assessed under all proposed prevalence thresholds. Dark grey shaded regions identify watersheds and fisheries management zones ineligible for inclusion in a provincial monitoring program.

71% of the stream length in FMZ 8 to be unassessed, while applying the 10% cut-off in FMZ 8 leaves 54% of the stream length unassessed. Prevalence-based cut-offs must also account for stream size because small streams are more numerous and differ in character from large rivers. Indeed, the distribution of stream classes varies considerably across stream sizes, and few large rivers would be sampled if prevalence calculations are not stratified by size (Figure 5). For these monitoring scenarios, prevalence-based cut-offs were applied in the combined spatial (e.g., FMZ or tertiary watershed) and stream size strata. That is, the prevalence of each stream class was calculated for each size class based on the total stream length in that size class in each spatial stratum, and any cut-offs were applied to these stratified prevalence values.

Inferences cannot be made in unsampled strata. As a result, the decision to exclude strata must be carefully evaluated and its effect on the ability to achieve monitoring objectives understood. For example, excluding rare stream classes may be problematic if biodiversity assessment is the goal because these rare classes are often biodiversity hotspots. Conceptually, strata are distinct subpopulations that are sampled and analyzed independently. Aggregating subpopulation data allows inferences about the broader target population. Excluded subpopulations (strata) shrink the target population. However, because the strata are distinct analytical units, choosing not to sample a stratum does not prevent inferences in the remaining strata. As an example, excluding remote streams in FMZ 1, 2, and 3 due to their high monitoring costs does not prevent analyses for the remaining FMZs — it simply restricts inference to the 246,344 stream kilometres (53% of the total) in the remaining FMZs.

The diversity of stream types makes it challenging to choose appropriate sampling techniques. Upwards of 88% of Ontario's streams by length are small wadeable streams for which we have well developed methods (Table 3; Jones et al. 2021). Streams that are too large to safely wade and too small to safely boat (semi-wadeable streams) are difficult to sample, and few methods exist. While existing methods could be adapted to these streams, more research is needed to develop standard approaches. Methods are also lacking for larger high gradient systems, where strong water currents and high turbidity make it challenging to travel and sample safely. Larger low gradient systems can be sampled using many of the same methods used in lakes. Although there are relatively few large rivers, they are often of greater interest in resource management than the more numerous small streams that flow into them and determine their condition. As a result, developing sampling methods for larger semi-wadeable and non-wadeable rivers may be a high priority. With existing methods, 90% of Ontario's total stream length could be monitored (Figure 7). However, method availability varies with stream size, with 12% of non-wadeable and 100% of semi-wadeable streams lacking methods.

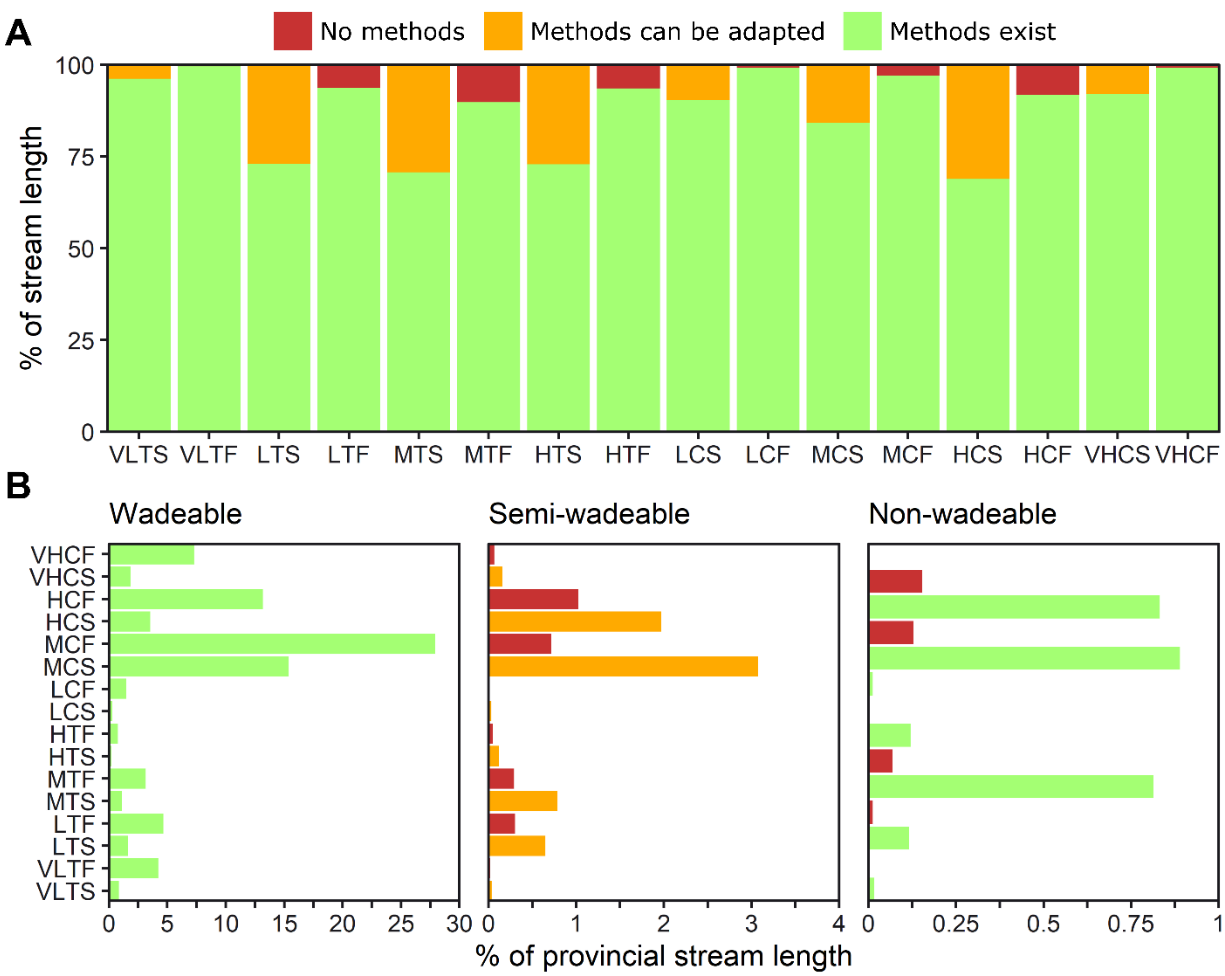

Figure 7. Suitability of existing sampling methods for Ontario streams by (A) Aquatic Ecosystem Classification (AEC) stream class and (B) stream size. The AEC stream and size class codes are defined in Figures 2 and Table 2.

A key challenge for provincial-scale monitoring will be accessing streams to sample. Southern Ontario has limited public land due to population growth and associated development (Figure 8). Although much of the land in the north is public, access is challenging because streams are remote. In Ontario, nearly 86% of streams are entirely on public land, but with considerable regional variation. For example, only 5% of stream kilometres in southern Ontario (represented by the Mixedwood Plains Ecozone) are entirely on public land, compared with 97% of stream kilometres in the north. We compiled data available on Ontario GeoHub to determine the distribution of public lands across Ontario (Table A1.1). However, this data set underestimates public lands, particularly in the south (Figure 9). As such, it is difficult to constrain monitoring site selection, and the number of stream segments that can be accessed is underestimated. Comprehensive mapping of public land (e.g., parks, conservation areas) in southern Ontario is needed as this information is not currently available in a single data set. Monitoring on private land is problematic in a resampling design because long-term access to the same monitoring sites is not guaranteed. A reallocation design can be better suited to regions with extensive private land, but the program needs to be adequately designed to accommodate inaccessible sites. Considerations around private land largely do not apply in non-wadeable systems because they are boatable, thus access depends only on the availability of a public launch point.

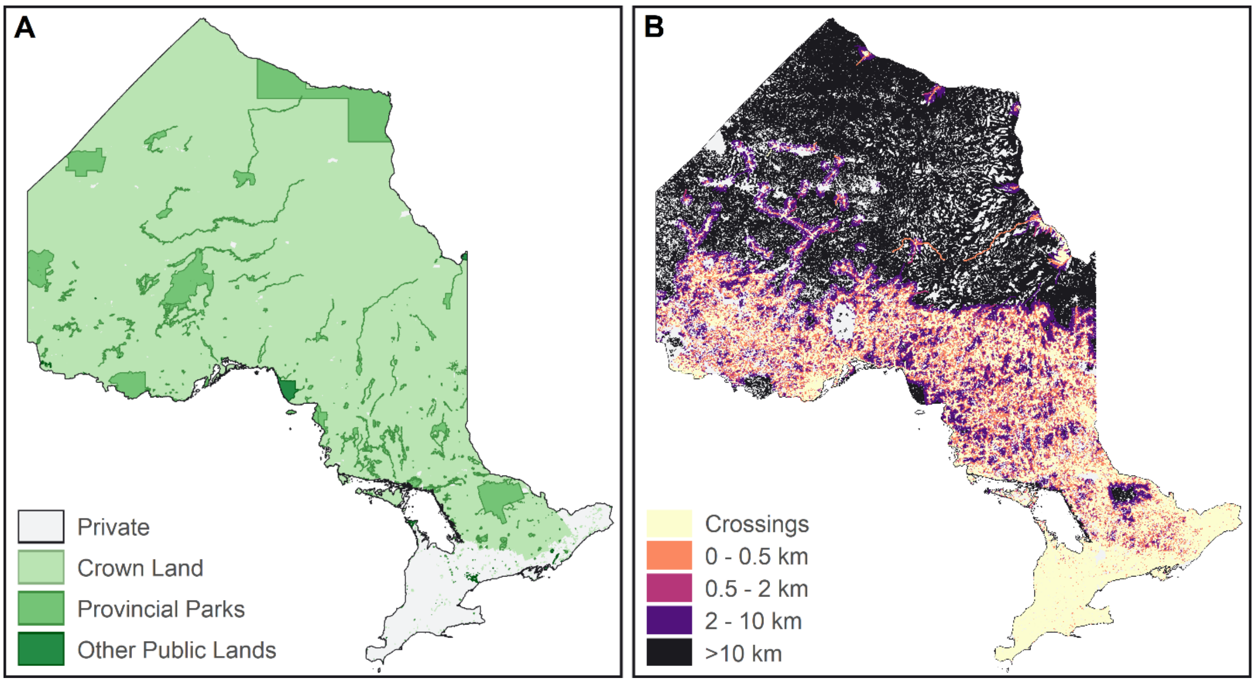

Figure 8. Factors influencing stream accessibility in Ontario: (A) the distribution of public lands and (B) the minimum distance to the nearest road.

Proximity to a road influences stream accessibility and sampling costs considerably. As distance increases, access becomes more difficult and sampling costs increase due to reduced field crew productivity and the need for alternative forms of transportation (e.g., boats or aircraft). In this study, we assumed 500 metres represents a rough boundary beyond which it becomes increasingly impractical to transport equipment and access sites on foot. Across Ontario, 24% of stream segments are within 500 metres of a road. Road crossings can also represent convenient locations to collect point samples (e.g., environmental DNA, water chemistry) and to install data loggers (e.g., automated flow or temperature loggers), although careful consideration must be given to confounding effects.

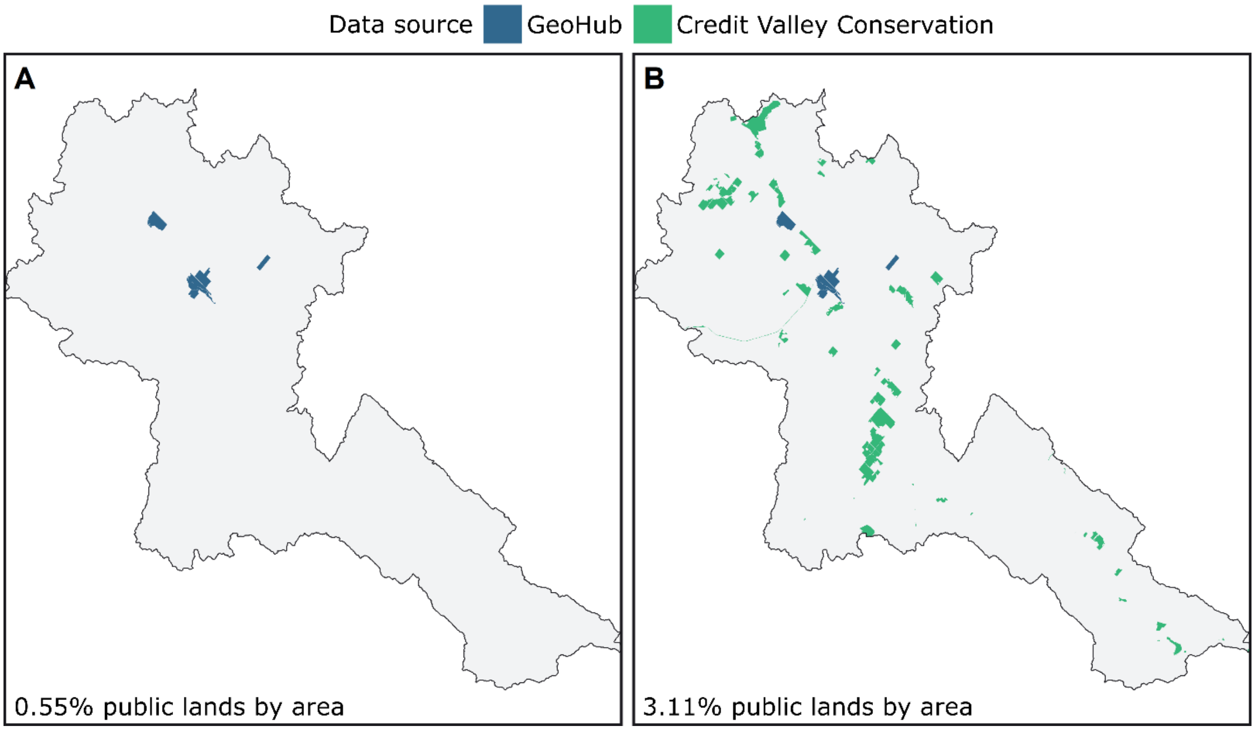

Figure 9. Example of limitations in existing public lands data sets for assessing the distribution of public lands in Ontario. Panel A shows the distribution of public lands across the Credit River watershed based on Ontario GeoHub data (see Appendix 1). Panel B supplements this GeoHub data with public lands identified by Credit Valley Conservation. The augmented data represents nearly a 5-fold increase in the amount of public land available for monitoring site selection.

3.3| Scenarios, sample sizes, and relative costs

We developed several monitoring scenarios to explore the effects of various design options and sampling realties on monitoring program costs and the possible scope of inference:

- **Scenario 1** was an unrestricted scenario that included all segments regardless of rarity, sampling method availability, or access difficulty.
- **Scenario 2** restricted monitoring to common stream classes that represent ≥10% of the total stream length in each combined spatial and size class stratum (hereafter we refer to stream classes representing <10% of total stream length with each combined spatial and size class stratum as *rare* stream classes for simplicity).
- **Scenario 3** considered sampling method availability, limiting sampling to stream size and class combination with existing suitable sampling methods (see Table 2).
- **Scenario 4** explored access challenges, limiting sampling to segments within 500 metres of a road for wadeable and semi-wadeable streams and 10 kilometres of a road for non-wadeable streams. Sampling for wadeable and semi-wadeable streams was also limited to segments with a minimum of 300 metres of continuous stream length on public land. In many sampling protocols, 300 metres is the minimum site length necessary to assess

fish biodiversity. No public land restriction was used in non-wadeable streams because it was assumed they could be accessed by boat from a public access point.

- **Scenario 5** assessed the full range of possible restrictions, excluding rare stream classes, streams without suitable sampling methods, and inaccessible segments.

- **Scenario 6** illustrates a brook trout monitoring program for southern Ontario.

Scenarios 1 to 5 are presented for both candidate spatial scales as Part A (tertiary watersheds) or Part B (fisheries management zones). For example, Scenario 1A shows the relative costs and inferences possible from unrestricted monitoring at the tertiary watershed scale. Scenarios are summarized regionally (Far North, Near North, and southern Ontario) to evaluate differences in monitoring costs across Ontario. The Far North was defined using the Far North Plan Boundary, while southern Ontario was defined by the Mixedwood Plains Ecozone. Any segments between these boundaries were classified as Near North in these analyses. Segment crossing boundaries was assigned to the region containing most of their length (i.e., 50%).

The sixth monitoring scenario evaluated the cost of a smaller-scale brook trout monitoring program for southern Ontario. Brook trout are a highly valued and sought after game fish that are also indicators of clean healthy streams. In southern Ontario, the range of brook trout has decreased nearly 50%, and these declines are expected to continue over the coming century (Jones et al. 2020, Sutton and Jones 2021). Brook trout mainly inhabit small wadeable streams that can be sampled using existing methods, and recent work has produced a habitat suitability model that could help guide monitoring design and interpret sampling results. As such, a brook trout monitoring program is achievable using existing tools and methods. This scenario focused on wadeable streams within quaternary watersheds that contain suitable brook trout habitat in the habitat suitability model developed by Jones et al. (2020). In this scenario, access challenges were not considered because we assumed a reallocation design would be used to track changes in occupancy and distribution over time. As a result, sampling on private land is not problematic because new monitoring sites are visited at each timestep, eliminating the need to ensure long-term access to the same monitoring sites.

Detailed power analyses and sample size calculations were beyond the scope of these analyses because they require prior knowledge of expected natural and observational variability, and an understanding of the analytical approach to be used. Further, power analyses are only valid for a specific objective (e.g., to detect a 25% decline in brook trout abundance), but the goals and objectives of a provincial monitoring program are not yet defined. For illustrative purposes, we used the sample size of 25 segments per stratum as recommended by the task team (Chu et al. 2022). Although this sample size is based on assumptions that may be inaccurate, it provides a useful starting point to compare the relative cost of different monitoring scenarios. In the brook trout scenario, sites were allocated within quaternary watersheds without stratifying by class or size because we assumed the objective would be to monitor changes in brook trout occupancy at small spatial scales.

The three main factors affecting field-based monitoring costs are: (1) equipment capital costs, (2) staff salaries, and (3) site access costs. Estimating the capital costs of equipment was beyond the scope of this study, while staffing costs are largely fixed. In turn, access costs were the main input available to estimate the cost of different monitoring scenarios. Access costs are affected by several factors including the material costs of site access (e.g., fuel, equipment) and the time needed to reach a site (i.e., lost productivity). These costs are largely driven by site remoteness, which is, in turn, mainly determined by the distance to a road (Figure 9). To explore the relative cost of the different scenarios, segments were assigned to three access cost classes:

- **Class 1** was used as a reference class and included segments crossing a road at some point along their length — these segments will be the cheapest and easiest to monitor.
- **Class 2** included segments that passed within 500 metres of a road without crossing. These segments were assigned a relative cost of 2x (i.e., 2x more costly to sample than a segment in the reference class) because of increased equipment costs (e.g., the need for off-road vehicles or watercraft to reach sites) and time lost while travelling to a site.
- **Class 3** included segments farther than 500 metres from a road. These segments were assigned a relative sampling cost of 10x because it is impractical to reach these segments without costly air travel or lengthy boat trips in large streams.

Although a fully costed program would require consideration of a range of additional costs, the purpose of this analysis was to explore the relative costs of different monitoring scenarios. As a result, these access cost classes provide a consistent base for such comparisons. Cost estimates are presented without units.

The probabilistic nature of the proposed monitoring design makes it possible for sampling costs to vary considerably in each design scenario depending on the spatial allocation of sites. As such, costs were calculated by averaging 1000 samples randomly drawn under each scenario to avoid bias. To understand how design decisions affect the scope of inference, we calculated the number of stream kilometres sampled (i.e., the stream length directly assessed) and monitored (i.e., the stream length characterized by the sample for which inferences can be made) for each monitoring scenario.

4| Results and discussion

Monitoring costs and possible scope of inference varied considerably among scenarios (Table 4; Figure 10). In all scenarios, tertiary watersheds were substantially more expensive to monitor because the watersheds (178) greatly outnumber fisheries management zones (15). Monitoring was consistently more expensive in the Near North and Far North because their large area required more sample sites than the south and access costs were higher due to the remoteness of streams. Excluding rare stream types (Scenario 2) achieved large cost savings, ranging from 58% at the tertiary watershed scale to 70% at the fisheries management zone scale. However, inferences were limited to 80% and 73% of provincial stream length at the tertiary watershed and fisheries management zone scales, respectively, due to the exclusion of smaller strata in the diverse south and northwest, and at the border between the Ontario Shield and Hudson Bay Lowlands (Figure 10). Restricting monitoring to stream sizes and classes for which sampling methods exist (Scenario 3) limited inference to 90% of provincial stream length with minimal overall cost reduction. Cost savings were primarily realized because streams lacking sampling methods are mostly in the north where access costs are high. Restricting sampling to accessible segments (Scenario 4) limited the scope of inference to less than one-quarter of provincial

Table 4. Summary metrics for monitoring scenarios analyzed to assess the influence of monitoring design decisions and sampling realties on monitoring costs and the possible scope of inference in Ontario. Reported costs and stream lengths are averaged over 1000 simulated sample draws from each sample frame to account for spatial variability in monitoring costs. Stream kilometres sampled refers to the length of stream characterized by sampling and not the physical stream length sampled. Stream kilometres monitored refers to the total stream length for which inferences are possible. Monitoring costs are a unitless measure designed to facilitate comparison of the relative costs of different monitoring scenarios and do not reflect actual costs. For detailed descriptions of the monitoring scenarios and methods used to produce cost estimates, refer to Section 3.3.

	Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5		Scenario 6
	A	B	A	B	A	B	A	B	A	B	
Far North											
Cost per site	9.91	9.88	9.86	9.80	9.92	9.90	2.58	3.40	2.63	3.94	NA
Sampling cost	121,695	17,494	57,498	4,813	99,564	11,162	1,365	821	1,105	591	NA
Stream length sampled (km)	48,162	13,031	34,552	6,483	27,725	7,396	4,122	2,687	3,471	1,962	NA
Stream length monitored (km)	210,862	210,862	180,671	166,654	186,343	186,343	4,210	4,210	3,558	3,340	NA
Stream length monitored (%)	100.00	100.00	85.68	79.03	88.37	88.37	2.00	2.00	1.69	1.58	NA
Near North											
Cost per site	6.55	5.75	6.39	5.43	6.71	6.02	1.73	1.77	1.77	2.51	NA
Sampling cost	145,134	27,296	56,783	8,623	128,268	20,530	25,113	8,707	10,580	2,393	NA
Stream length sampled (km)	40,485	12,735	25,237	7,007	24,856	6.042	38,629	15,622	14,223	3,945	NA
Stream length monitored (km)	193,768	193,768	150,555	134,332	176,886	176,886	90,952	90,952	60,531	53,542	NA
Stream length monitored (%)	100.00	100.00	77.70	69.33	91.29	91.29	46.94	46.94	31.24	27.63	NA
Southern Ontario											
Cost per site	2.10	2.23	1.89	1.86	2.14	2.41	1.40	1.41	1.41	1.48	2.36
Sampling cost	19,561	3,880	6,218	1,086	18,855	3,318	1,516	990	662	347	2,124
Stream length sampled (km)	21,958	6,264	10,606	3,534	18,157	3,240	3,707	2,853	1,874	1,235	1,684
Stream length monitored (km)	58,135	58,190	40,147	38,297	54,324	54,379	5,475	5,475	3,201	2,879	48,776
Stream length monitored (%)	100.00	100.00	69.06	65.81	93.44	93.45	9.41	9.41	5.51	4.95	83.90
Provincial											
Cost per site	6.55	5.89	6.70	5.46	6.50	5.92	2.88	1.99	1.80	2.49	2.36
Sampling cost	286,390	48,670	120,498	14,522	246,687	35,009	46,458	10,517	12,347	3,331	2,124
Sites sampled (#)	43,722	8,257	17,998	2,662	37,972	5,912	16,116	5,280	6,864	1,339	900
Classes sampled (#)	16	16	16	12	16	16	16	16	14	12	16
Stream length sampled (km)	110,605	32,030	70,395	17,024	70,738	16,678	1,678	381	19,569	7,141	1,684
Stream length monitored (km)	462,766	462,820	371,373	339,284	417,554	417,608	100,637	100,637	67,291	59,761	48,776
Stream length monitored (%)	100.00	100.00	80.25	73.31	90.23	90.23	21.75	21.74	14.54	12.91	10.54

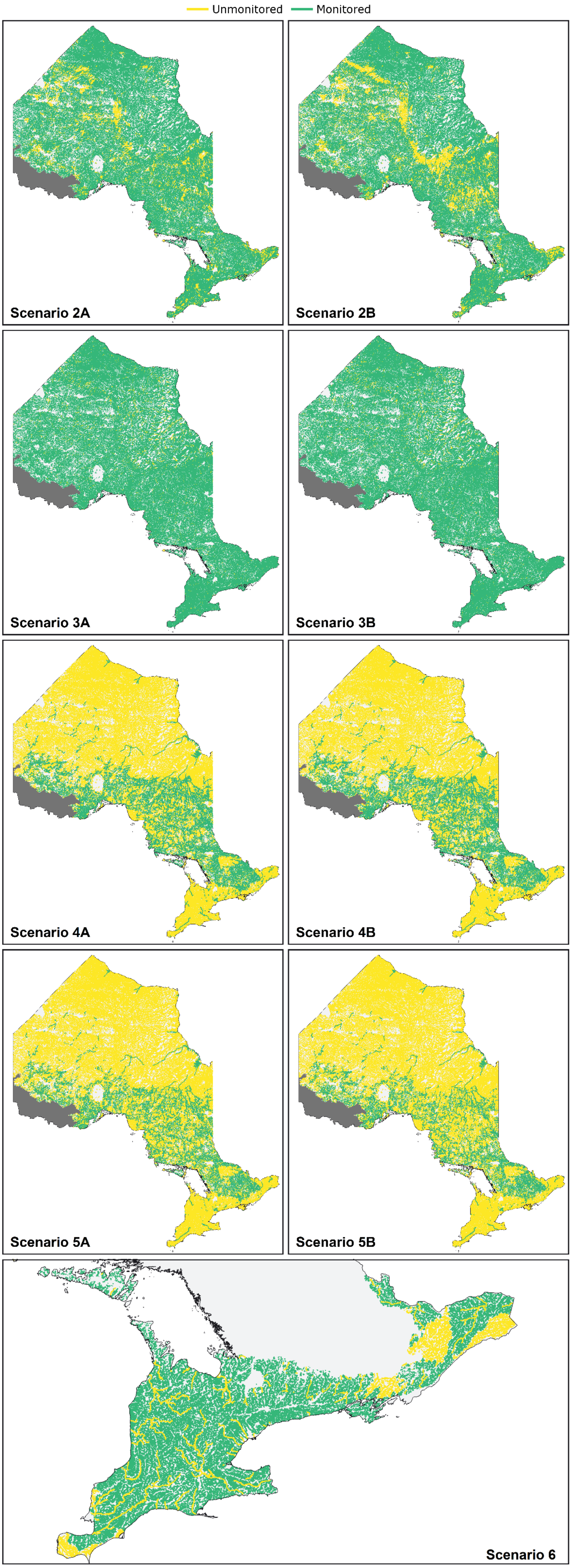

Figure 10. Distribution of stream segments assessed in the Ontario monitoring scenarios. Inferences are only possible for segments shown in green. Dark grey shaded regions show watersheds and fisheries management zones ineligible for inclusion in a provincial monitoring program. For detailed descriptions of the monitoring scenarios, refer to Section 3.3.

stream length. The Far North and southern Ontario became effectively unmonitored, and inference was possible for less than 10% of the stream length in each region. Combining restrictions and sampling realities (Scenario 5) illustrated the most realistically achievable provincial-scale monitoring program given existing sampling methods and knowledge of which segments are accessible. In this scenario, inferences would be limited to 14.5% of provincial stream length at the tertiary watershed scale and 12.9% of provincial stream length at the fisheries management zone scale.

The monitoring designs explored in these scenarios are suitable to assess changes and trends in stream condition at a landscape scale. They can provide a landscape-scale understanding of the associations between stream status and broadscale stressors (e.g., land use change). Inferences are possible at a provincial, sub-provincial (tertiary watersheds or fisheries management zones), and stream class scale. Local (i.e., segment-scale) inferences are only possible for segments that are randomly selected for sampling as part of the study design. Provincial monitoring cannot be used as a substitute for local targeted monitoring, which may still be needed to address science and management concerns for stressors that act at small scales (e.g., waterpower, mining, Ring of Fire) or where inferences are needed at smaller (e.g., subwatershed) spatial scales. Deviating from the random design to address localized concerns violates fundamental assumptions of the statistical design and affects the validity of inferences. Provincial monitoring should not be used as a substitute for an inventory in data-poor systems (e.g., the Far North). While monitoring can improve understanding in data-limited systems, inventories are designed to address knowledge gaps and are often needed to resolve fundamental questions about distribution and variation in a resource before monitoring begins (Reynolds et al. 2016). A key difference is that an inventory focuses on understanding the spatial distribution, abundance, and structure of a variable, while monitoring aims to detect changes or trends in the status of a variable to support management. Nevertheless, data collected as part of a monitoring program can be used to inform local issues by generating benchmarks and condition expectations. For example, the Stream Evaluator Tool (https://www.mcgi.state.mi.us/smdt/index.html) created by Michigan's Department of Natural Resources (Wills et al. 2006) leverages long-term monitoring data to generate benchmarks that allow users to evaluate the condition of any stream sampled using their standardized protocols.

The monitoring scenarios revealed considerable regional differences in the costs and challenges associated with implementing a provincial monitoring program. A lack of public land is the main impediment in the south, while the cost and difficulty of accessing remote streams is an issue in the north. At the same time, there are stark contrasts in the type and degree of stressors across Ontario (Jones et al. 2019). While southern Ontario is heavily developed with little natural cover (e.g., forests and wetlands) remaining, much of northern Ontario is relatively undeveloped. Indeed, roughly 68% of the north is forested, while lakes and wetlands cover a further 23% of the land area. The main stressors in southern Ontario are built-up community infrastructure and agriculture. In the north, major stressors include forestry, mining, roads and stream crossings, and waterpower. In terms of land area, southern Ontario covers 9% of the province's land area, but contains 92% of the population (Ontario Biodiversity Council 2010). The north covers 91% of the province's land area and contains just 8% of the population. As such, it can be argued that available monitoring resources should be directed to areas that are most affected. For example, sampling in the Far North can comprise upwards of 42% of total sampling costs (Scenario 1A), with a cost per site one-third higher than that in the Near North and nearly four times that in southern Ontario, yet stressors are less prevalent than in the south. Indeed, the cost of unrestricted monitoring at the tertiary watershed scale (Scenario 1A) in the Far North (sampling 10.5% of its 117,058 segments on average) would allow each of the 28,653 segments in southern Ontario to be sampled twice. The inland lakes broad-scale monitoring program already encountered these challenges, with fisheries management zones in the Far North (FMZ 1, 2, and 3) removed from the program after the first monitoring cycle due to the high costs of monitoring in those strata (Lester et al. 2021).

Resource requirements are not the only barrier to implementing provincial monitoring. Even if resources were available to sample every stream segment across the province, it would still be impossible because of inadequate sampling methods and poor understanding of where it is possible to sample. Current methods do not reliably characterize fish communities in 12% of non-wadeable and 100% of semi-wadeable streams. As such, inference is limited to the 90% of total stream length represented by wadeable streams and non-wadeable streams that can be sampled with current methods. Uncertainty in where monitoring is possible also impedes the implementation of a provincial monitoring program, particularly in southern Ontario. Indeed, the proposed resampling design may not be feasible in southern Ontario due to uncertainty in the location and quantity of public lands. Existing knowledge of the location of public lands suggests that, if private lands are not sampled, <6% of stream length in southern Ontario would be accessible. However, analyses in the Credit River watershed suggest existing provincial-scale data may underestimate the area of private lands by 465% (Figure 9). Even if this relationship held true across southern Ontario, inference would still be restricted to <50% of its total stream length. Further, public lands are usually in the lower reaches of a watershed where river valley parks exist. As such, restricting monitoring to public land may fail to adequately monitor more numerous headwater streams, which suggests that a resampling design may not be feasible in southern Ontario, and that a more costly reallocation design may be necessary. Regardless of the design, it is impossible to develop and cost a monitoring program without an understanding of where sampling is possible because the physical location of the monitoring sites determines accessibility and costs. As such, compiling detailed information about the location of public land across Ontario needs to be completed before a monitoring program can be developed. It is not feasible to have field crews go door to door seeking access permission when a sample site is on private land.

A benefit of the stratified sampling designs proposed in these monitoring scenarios is the ability to add and remove strata through time. For example, monitoring could be initiated in wadeable streams alone, allowing time to develop adequate sampling methods for the remaining stream types. A program limited to wadeable streams may still provide useful inferences because 88% of Ontario’s total stream length is wadeable. Subsequent monitoring cycles could integrate missing strata as methods are developed, gradually increasing scope to the entire province. The flexibility to add or remove strata can also help monitoring remain viable in the face of resource constraints and changing objectives. Strata that become too resource intensive to sample can be removed, while strata that become the focus of emerging management concerns may be added if they are not already sampled. Adding or removing strata should only occur when necessary to meet monitoring objectives or accommodate resource restrictions.

The challenge of implementing a comprehensive field-based monitoring program at a provincial scale highlights the importance of a tiered monitoring approach such as that described above. Remote sensing, the first monitoring tier, avoids many of the challenges associated with field-based monitoring because it characterizes all streams on the landscape. This approach removes the need for a statistical design because a complete census is achieved. Further, remote sensing allows sampling in regions that are costly (e.g., the Far North) and challenging (e.g., private land in southern Ontario) to access. Monitoring via remote sensing applies pre-existing relationships between environmental covariates (e.g., climate, land use) and ecosystem condition to monitor changes and trends in status through time (Goetz and Fiske 2008, Wang et al. 2011, Peterson et al. 2013, Dauwalter et al. 2019). In addition, remote sensing can guide field-based sampling and direct effort to regions where change is likely to occur. Remote sensing is a separate standalone cost, and monitoring using remote sensing data is predicated on the existence of prior research establishing relationships between environmental covariates and ecosystem condition. Remote sensing represents the basic level of monitoring in a provincial monitoring program.

The disadvantage of the remote sensing tier is that status is inferred and not directly measured. Indeed, field-based sampling will be necessary where direct understanding of ecosystem status is required. However, monitoring biota (e.g., fish, macroinvertebrates) is resource intensive and logistically challenging, which results in data collected at a low temporal resolution (e.g., once in 5 years). Data loggers can provide data at a higher temporal resolution (e.g., sub-daily), often at a lower cost per site than sampling biota. As such, monitoring using data loggers (e.g., stream temperature and flow) forms the second tier of a provincial monitoring program. It is logistically and financially impossible to install a logger in every segment across Ontario and, as such, many considerations discussed in relation to the monitoring scenarios apply. For example, a statistical perspective is needed to allow inference about the broader stream population, while the ability to access streams influences possible inference. As a result, data loggers have a narrower scope than remote sensing. However, scope is broader than sampling biota (e.g., the third monitoring tier) because data loggers can be used anywhere streams can be accessed (e.g., road crossings). This approach is particularly relevant in the south where the prevalence of private land makes it difficult to access sufficient stream lengths for biological monitoring (e.g., electrofishing or kick-netting). However, many streams will still be inaccessible for logger-based sampling, reinforcing the need for remote sensing for comprehensive monitoring of the province’s streams.

Uncertainties around the goals and objectives of a provincial stream monitoring program are considerable, particularly given the realties of monitoring (e.g., costs, access difficulties, lack of sampling methods) evaluated here. Until these uncertainties are addressed, it is impossible to design or implement an effective monitoring program. Effective monitoring requires clear goals and objectives (e.g., to detect a 50% decline in brook trout abundance) because they affect the statistical, spatial, and temporal design (Vos et al. 2000, Yoccoz et al. 2001, Reynolds et al. 2016). Monitoring that lacks clear goals and objectives is costly and wasteful because data is collected that may be useless for management. For example, the resampling design used in these scenarios can provide an understanding of changes and trends in variables like biomass and abundance but is less useful for detecting changes in distribution because the same sites are visited repeatedly. If detecting changes in species distribution is an objective, the proposed resampling design will be inappropriate. Improved clarity around goals and objectives will also allow analysis of the trade-offs among monitoring cost, complexity, and scope. These scenarios clearly showed the high costs of monitoring in the north, but it is impossible to evaluate the consequences of redirecting resources from the north to other areas because it is unclear if the north must be sampled to achieve monitoring goals and objectives.

The definition of clear goals and objectives should trigger a review of the variables proposed for provincial monitoring (Table 1). Variables chosen for monitoring must be justified in the context of specific objectives to ensure monitoring is cost effective (Sutton and Jones 2023). Monitoring "laundry lists" of variables often leads to program failure because the variables monitored have no direct value in management while increasing sampling costs.

Spatial scope should also be re-evaluated, and it is likely that both spatial stratifications used in these scenarios are inappropriate for a provincial monitoring program. Streams are hierarchically structured, directional systems influenced by their surrounding landscapes and reaches further upstream. As such, streams should be managed as one unit from headwaters to mainstem. Fisheries management zones can cross watershed boundaries, which does not make sense from an ecological perspective. In addition, fisheries management zones were designed to manage harvest by allowing fishing season lengths and catch limits to be set by zone (OMNR 2005). However, it is unclear whether harvest is an important stressor in Ontario streams. Tertiary watersheds provide spatial strata that respect that spatial structure of streams, but their number makes them expensive to monitor, limiting their suitability. Further, it may be challenging to design, implement, and evaluate management actions for each watershed. The inability to access much of each watershed in the south may also present inferential challenges because sample sizes for many stream classes will be insufficient. Future work could explore larger spatial strata such as secondary watersheds or amalgamations of tertiary watersheds based on sampling costs and scope of inference.

Implementing a simpler, small-scale, monitoring program with available sampling methods may be a good learning opportunity. The brook trout monitoring program explored in Scenario 6 can be realistically achieved with existing sampling methods, while the occupancy model developed by Jones et al. (2020) provides tools to interpret data collected in the field. The narrow scope of this program reduces implementation costs, which are lower than the least expensive provincial program (Scenario 5B). At the same time, Scenario 6 comprehensively monitors southern brook trout populations, while Scenario 5B monitors <5% of southern Ontario's total stream length. In turn, a brook trout monitoring program may be more valuable in management. The small scope of a brook trout monitoring program provides an opportunity to develop capacity and expertise in monitoring, while proper stratification could allow data from this program to be incorporated in a provincial monitoring effort when knowledge and resources are available to implement it.

5| Conclusions, recommendations, and next steps

Before a provincial stream monitoring program can be developed several issues must be addressed. Knowledge gaps, including a lack of sampling methods for non-wadeable and semi-wadeable streams and uncertainty in the location of public land, makes it impossible to design a full monitoring program or estimate cost. Investment is needed to decrease these uncertainties and improve our knowledge of Ontario's streams. There is also considerable uncertainty around monitoring goals and objectives that must be resolved for a monitoring program to be effective. Assembling a team of stakeholders to clarify monitoring goals and objectives is a necessary step in developing a provincial monitoring program. This analysis has advanced our understanding of what we know, where investments are needed, and the relative costs of various monitoring designs.

We envision a tiered monitoring design consisting of: (1) remote sensing to monitor the broad-scale stressors known to affect stream health (e.g., urbanization), (2) data loggers that provide high-resolution temporal data (e.g., stream flow and water temperature) over large geographic areas, and (3) field-based sampling to provide the most direct assessment of stream condition. However, the field-based sampling tier will be the costliest and most logistically challenging to implement. The expertise and capacity to use remotely sensed data exists in the ministry, and several recent examples of using this data to assess stream condition are available (e.g., Jones et al. 2019). Similarly, the ministry has previously reported on stream flows as part of the state of the resource and biodiversity reporting.

In the short term, it is possible to design and implement a smaller-scale field-based brook trout monitoring program for southern Ontario using existing knowledge and sampling methods. The reduced scope of this program makes it much less expensive than a provincial-scale monitoring program, while providing an opportunity to develop monitoring capacity and expertise that will benefit future provincial monitoring efforts. This program could be the beginning of a stream monitoring program to be expanded as research and development allows monitoring of missing stream types and sizes (e.g., a building blocks approach). A natural progression would involve research and development to enable monitoring of brook trout streams in northern Ontario. Specifically, methods are needed to sample large systems (e.g., the Nipigon River) that are often inhabited by brook trout in northern Ontario. Research is also needed to develop a brook trout occupancy model for northern Ontario, similar to the southern Ontario model, that would help guide where to sample on the landscape.

Monitoring program costs are directly related to resource managers' needs. For example, evaluating stream health has a different cost than evaluating fisheries status. Spatial scope and extent also have a large role in defining costs. If information is needed at small scales (e.g., individual streams vs. watersheds) or across large geographic areas (e.g., regional vs. provincial) sampling costs will increase. As the extent (geographic area) of a monitoring program increases, decisions are needed about whether to monitor remote areas that may be considerably more expensive to sample (e.g., 10x more than estimated here). Stream size and type also affects costs. Small wadeable streams are relatively inexpensive to sample, and well established sampling methods are available. Methods are not well established for larger rivers and sampling is more expensive. Decisions around goals and objectives and the spatial scope and extent of sampling are driven by management. The role of science begins after these decisions are made, providing input on suitable sampling approaches, or conducting power analyses to determine the power to detect change and meet management objectives.

Several relevant aspects of monitoring, such as developing reference models and benchmarks and implementing a data management and analysis framework, were beyond the scope of this analysis. Nevertheless, they are essential components of monitoring and require sufficient resources to be allocated for their development. Sampling is only a small part of monitoring and collecting data that cannot be interpreted or applied in resource management has little practical benefit.

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Appendix 1. Public land data sets

Table A1.1. Data sets used to summarize the distribution of public land in Ontario.

Data set	Source
Crown land use planning atlas	geohub.lio.gov.on.ca/datasets/lio::clupa-overlay
Crown game preserves	geohub.lio.gov.on.ca/datasets/lio::crown-game-preserves
Land use plan area[1]	geohub.lio.gov.on.ca/documents/lio::land-use-plan-area-mnr
Federal protected areas	geohub.lio.gov.on.ca/datasets/lio::federal-protected-areas/
Non-government agency nature reserve	geohub.lio.gov.on.ca/documents/87f2b8a3accd4610b848a293b922b10c/
Municipal parks	geohub.lio.gov.on.ca/datasets/54e66313574848488e69dfa676d6f6fe_3

[1] The Far North Plan Area was used to represent public lands in the North.

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