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Methods for Establishing Classification Schemes and Thresholds for Reporting on the State of Fish and Fish Habitat

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

The Fish and Fish Habitat Protection Program (FFHPP) in Ontario and Prairie Region has requested science advice on approaches that can be used to define classification schemes and associated thresholds for reporting on the State of Fish and Fish Habitat (SOFFH) in the Lower Great Lakes and East Slopes of Alberta reporting areas. Science advice for quantifying and assessing the SOFFH in these reporting areas was also requested. This document describes approaches that can be used to develop classification schemes, including schemes based on (i) functional relationships with management objectives, (ii) established thresholds, (iii) relative ranking and (iv) expert elicitation. A decision tree for selecting among the approaches, based on the availability of different types of information, is presented. In addition, we consider how information from multiple Metrics can be synthesized to report on the status of overarching Indicators, as well as how classification schemes can be established for the quality of data used in SOFFH reporting. Finally, key uncertainties related to the development of classifications schemes, are also discussed.

1. GLOSSARY

State of Fish (DFO 2022) is the diversity, composition, and abundance of fish relative to the naturally occurring community.

State of Fish Habitat (DFO 2022) is the ability of areas to support the life processes of aquatic organisms relative to the natural function of the area.

Indicators are physical and biological features of aquatic ecosystems used to describe the SOFFH. Based on DFO (2022), the primary Indicators of interest for the SOFFH Reporting within Ontario and Prairies Region will be Biodiversity, Water Quality, Connectivity, Land Use and Climate Change.

Metric(s) (DFO 2022) are variables that are directly measured to quantify an Indicator. Indicators may have one or multiple Metrics to describe them. For example, the Metric ‘dissolved oxygen’ may be used to support quantification of the Indicator ‘water quality’.

Classification schemes are categorical descriptions of state that are based on ‘binning’ an underlying quantitative measurement into categories (also known as ‘levels’). They can be binary (e.g., ‘good’ and ‘poor’), or have three (or more) categories, which are typically ordinal in nature (e.g., ‘excellent’, ‘fair’ and ‘poor’). Classification schemes can apply to both Metrics (i.e., based on underlying raw data) and Indicators (i.e., based on a synthesis of the categories of underlying Metrics specific to the Indicator).

Reporting thresholds are values of a Metric or Indicator used to define the upper and/or lower limits of categories used in classification schemes.

Ecological thresholds are values of a Metric or Indicator beyond which ecosystem function, structure, or composition changes rapidly or categorically. Ecological thresholds are sometimes referred to as ‘tipping points’ or ‘regime-shifts’.

Reporting Areas (DFO 2022) are the geographical areas of focus for reporting on the SOFFH

Assessment Units (DFO 2022) are the geographical area where Metrics are assessed against thresholds. The scale of the Assessment Units are dependent upon the scope and scale of the Reporting Area and data available. These units can range from individual lake or stream segments to entire watersheds (e.g., Tertiary Watershed level, HUC8, Ontario Watershed Boundaries).

2. INTRODUCTION

Reporting on the state of ecosystems is an increasingly common initiative for both governments and non-governmental organizations to communicate information on the presence, distribution, condition, and/or management of natural resources. This type of reporting helps to inform members of the public about the general structure and function of ecosystems near where they live, what the main pressures and stressors acting on ecosystems are, and how ecosystem condition is impacted by management activities. Furthermore, ecosystem reporting initiatives can help to establish priorities for conservation or restoration activities, identify gaps in monitoring, and help to identify and assemble datasets that could inform land use planning, development, project assessments, restoration and habitat protection.

In some cases, ecosystem reporting is also used to evaluate the impact of government policy or regulations on ecosystem condition, including evaluations of the effectiveness of commonly used ecosystem management measures. Developing ecosystem reports for this purpose is supported by the presence of clear ecosystem management goals, especially where those goals are stated in quantitative terms. Such goals may be generic across all ecosystems within a jurisdiction (e.g., the principle of ‘no net loss’; DFO 1986) or may be defined within management plans for individual ecosystems (e.g., within Integrated Fisheries Management Plans), and provide a clear rubric against which ecosystem state can be evaluated.

Fisheries and Oceans Canada (DFO) has committed to area-based reports on the SOFFH in Canada by March 31, 2023. While many previous reporting initiatives have focused on aquatic ecosystems in Canada (Table 1), none have done so with specific focus on DFO’s mandate to manage fish and fish habitat. Importantly, these reports will focus on fish and fish habitat in Canadian freshwater environments, and therefore complement other federal reporting initiatives such as the State of Canada’s Oceans reports.

Table 1. Examples of recent ecosystem reporting initiatives related to the SOFFH in Canada.

Organization	**Title**	**Year of most recent report**	**Reporting area**
World Wildlife Fund - Canada	Watershed report: A national reassessment of Canada’s Freshwater	2020	Canada
Environment and Climate Change Canada (ECCC) and U.S. Environmental Protection Agency	State of the Great Lakes	2022	Laurentian Great Lakes
Conservation Ontario	Watershed Report Cards	2018	Ontario
Ontario Biodiversity Council	State of Ontario’s Biodiversity	2021	Ontario
Government of Alberta	Handbook for State of the Watershed Reporting	Varies by Watershed Planning and Advisory Council	Alberta
Mackenzie River Basin Board	State of the Aquatic Ecosystem Report	2021	Mackenzie watershed
Fisheries and Oceans Canada	State of the Canadian Pacific salmon: Responses to changing climate and habitats	2019	Pacific watersheds in Canada
Fisheries and Oceans Canada	State of Canada’s Oceans	2020	Atlantic, Pacific and Arctic Ocean

As part of this initiative, the FFHPP in the Ontario and Prairie region have selected two priority areas to develop their own regional SOFFH reports: the Lower Great Lakes Area in Ontario, and the Eastern Slopes Region of Alberta. A previous Science Advisory meeting (held on June 29–30, 2021) discussed possible Indicators, Metrics, and data available for inclusion in the Ontario and Prairie regional SOFFH report (DFO 2022).

This document aims to provide the following information in support of the Ontario and Prairie regional SOFFH reporting:

- A review of the approaches used to categorize the status of Metrics within each Assessment Unit, including approaches to determine threshold values for reporting
- A review of approaches that could be used to categorize data quality for reporting on the SOFFH; and
- The identification of uncertainties and knowledge gaps with respect to methods that can be used for developing classification schemes for the SOFFH reporting.

This information corresponds with objectives 2-4 listed in the Terms of Reference for this Canadian Science Advisory Secretariat process. Further information in support of objectives 1 and 4 is provided in (Dey et al. in prep.[1]).

It is important to note that the development of reporting thresholds and classification schemes is not a requirement for reporting on ecosystem state. Many ecosystem reports are narrative and/or incorporate empirical data without specific thresholds and classification schemes. While reporting thresholds and classification schemes support objectivity, simplify communication with non-specialist audiences, and can help to integrate data from multiple jurisdictions, they are associated with drawbacks inherent to categorization. For example, categorization can exaggerate differences between data points that fall close to (but on opposite sides of) a threshold value and can therefore amplify small (and often ecologically irrelevant) differences among data points. Similarly, categorization can also lead to the erasure of differences among members of a category such that ecologically relevant intra-group variance may be ignored. As such, it may not be necessary or appropriate to develop classification schemes and reporting thresholds for all aspects of the SOFFH reports. A related issue is that independent categorization of Metrics and Indicators may misrepresent the overall ecosystem state. This may be especially problematic when the cumulative effects of multiple stressors act in a synergistic or antagonistic fashion, such that the realized impact of small amounts of degradation in each Metric or Indicator would differ from the additive predictions (Folt et al. 1999, Dey and Koops 2021). However, non-additive stressor interactions are not required for overall state to be poorly predicted by the independent evaluation of its component metrics, as such an issue can also arise when categorization schemes have poor resolution, or when the relative weight (i.e., importance) that different Metrics contribute to overall ecosystem state is not accounted for.

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[1] Dey, C.J., Matchett, S., Doolittle, A., Jung, J., Kavanagh, R., Sobowale, R., Schwartz., and Chu, C. In prep. Preliminary assessment of the State of Fish and Fish Habitat in Fisheries and Oceans Canada's Ontario and Prairies Region. Can. Sci. Advis. Sec. Res. Doc.

3. METHODS TO DETERMINE CLASSIFICATION SCHEMES FOR REPORTING ON THE SOFFH

This section describes methods for developing classification schemes, and their associated reporting thresholds, that could be used in the SOFFH reporting in Ontario and Prairie Region (Figure 1). We primarily focus on classification schemes for Metrics, however Indicators may also require classification schemes and many of the considerations outlined are relevant to both types of variables. Specific considerations for Indicator classification schemes are discussed at the end of the section.

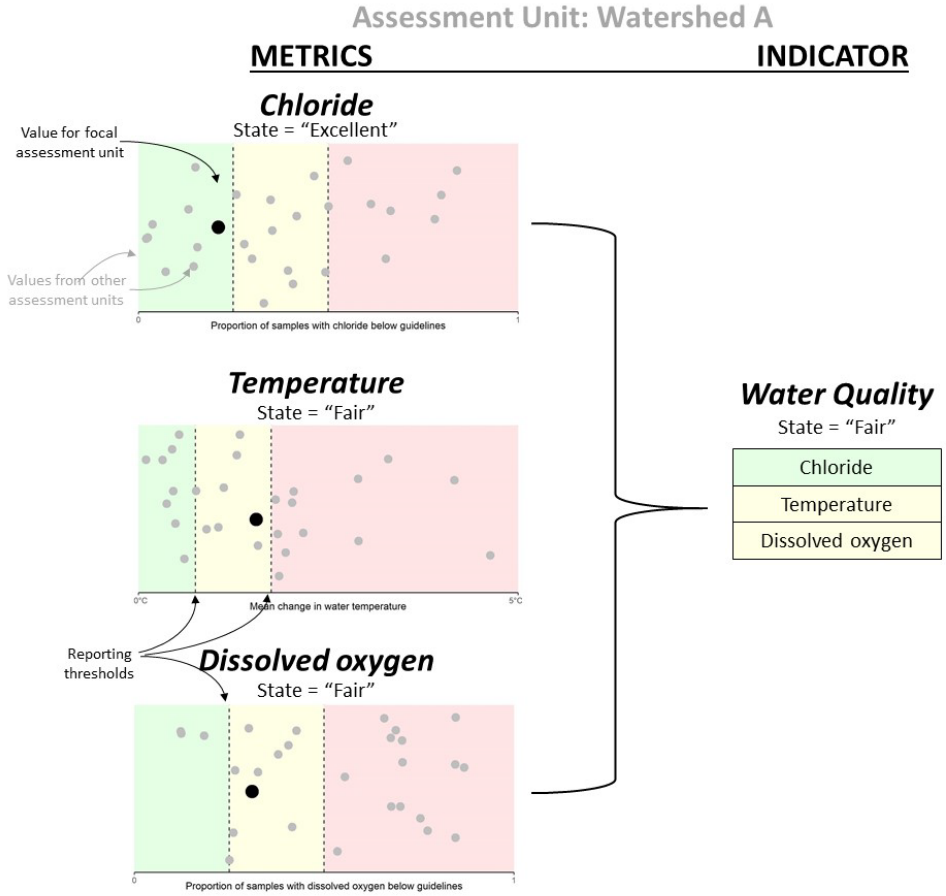

Figure 1. Illustration of classification schemes and reporting thresholds for Metrics and Indicators used in the SOFFH reporting. In this example, Metrics are associated with a three-level classification scheme, each of which is defined based on two reporting thresholds. The values of the Metric for the focal Assessment Unit are compared against the classification scheme to determine a state for each Metric, which are then synthesized to produce an assessment of state for the associated Indicator.

In addition, we focus on methods to establish classification schemes with two or more ordinal levels. In some cases, ecosystem reporting relies on non-ordinal classification schemes, for example when habitats are classified into types (e.g., river, lake, wetland). These classification schemes can provide descriptive value, but are not directly applicable to measuring the state of fish nor the state of fish habitat, as defined in DFO (2022). In most ecosystem reporting initiatives (e.g., Conservation Ontario 2018, ECCC and U.S. Environmental Protection Agency 2021, Ontario Biodiversity Council 2021), classification schemes contain 3–5 levels, ranging from levels describing systems in excellent or pristine condition, to those that are highly degraded or impacted. The greater number of levels that are included in a classification scheme, the more detailed reporting will be. However a greater number of levels also increases the challenge of defining meaningful reporting thresholds, and makes reporting results more complex to interpret.

In most cases, classification schemes will be based on setting quantitative reporting thresholds that define the (upper and/or lower) limits of a continuous measure that correspond with classification into each category. Thresholds used to define classification schemes can broadly be described as belonging to one of three types:

- **Absolute thresholds** are thresholds that define categories based on absolute values that are applicable across systems and species. They are attractive because of their broad applicability and provide a useful manner to evaluate the SOFFH based on snapshots of the state of focal systems or species in comparison to the threshold values. Setting appropriate absolute thresholds can be challenging because different ecosystems are differentially sensitive to stressors and ecosystem sensitivity can change across the annual cycle. However, absolute thresholds can be specific to a given system type, species or life stage. For example, separate thresholds for dissolved oxygen are set for early and late fish life stages, as well as for warm water and cold water systems in the Canadian Water Quality Guidelines for the Protection of Aquatic Life (Canadian Council of Ministers of the Environment 1999). As a result, absolute thresholds can be based on species-specific physiology and biology or habitat suitability indices (Terrell et al. 1982). Setting absolute thresholds does require considerations associated with risk across a mix of systems, and decisions to be made about whether thresholds should be precautionary (i.e., thresholds are developed with the most sensitive species or systems in mind) or not (e.g., thresholds represent the average system or species). Absolute thresholds are often single values, with systems classified into two categories (i.e., above or below the threshold), and are typically used to describe the state of the system (i.e., ‘good’ or ‘poor’).
- **Self-referent thresholds** are thresholds that define categories based on the amount of change within a given system. For example, a reporting threshold that considers the change in mean annual discharge of a river system could be used to help define the state of fish habitat in that system. Using self-referent thresholds addresses some issues associated with the variance and idiosyncrasies among ecosystems. However applying self-referent thresholds requires that both current and historical data are available for the system being assessed, which may not always be the case. Self-referent thresholds are typically used to describe trends in state (i.e., ‘improving’ or ‘worsening’), although self-referent thresholds can also describe the state (i.e., ‘good’ or ‘poor’) if the system can be assumed to have been in a pristine condition during the historical period.
- **Control-referent thresholds** are thresholds that define categories based on the difference between a given system and a (physically and geographically similar) reference system (i.e., the control system). For example, a threshold that considers the difference in turbidity between a developed and a pristine watershed within a region could be used to help define the state of fish habitat. Control-referent thresholds can also be defined in relation to a set of control systems by taking the average (or minimum, or maximum) value from multiple pristine systems. Applying control-referent thresholds requires that data are available for both the focal system and the control system(s). Control-referent thresholds are typically used to describe state (i.e., ‘good’ or ‘poor’) if the reference system can be assumed to be pristine, or to describe relative state (i.e., ‘best’ to ‘worst’) when reference systems are not pristine.

Where there are multiple data points from within a given Assessment Unit (e.g., samples from different areas of a watershed, or from different periods of time), a classification scheme must also determine how an overall category will be determined from a set of values. Typically, the overall classification would be based on some measure of central tendency (e.g., median or mean value), such that the overall classification of a Metric for a reporting represents the average/typical value across the Assessment Unit. These measures could be weighted to address issues associated with the distribution of habitat types across an Assessment Unit and could be corrected for spatial and temporal auto-correlation, if desired. Alternatively, in some cases it is reasonable to use extreme values to represent the state of the ecosystem (e.g., using the maximum recorded contaminant level as basis of categorizing a Metric for a reporting area), especially where extreme values have important impacts on fish and fish habitat. Where the underlying classification scheme is binary (e.g., over or under a single threshold value), a secondary classification scheme could also be established based on the proportion of samples exceeding the threshold within the Assessment Unit.

Determining the type of reporting threshold used, the number of levels in the classification system, and the values of the reporting threshold itself is non-trivial, and has important consequences for the overall message communicated in a report. In many cases, classification schemes have required iterative refinement to improve the transparency and validity of categorizations, which may require decades of focus from experts (e.g., IUCN Red List criteria). Below, we outline approaches to determining classification schemes and reporting thresholds for initial reporting on the SOFFH. These approaches are likely to be broadly applicable across Canada, and should be open to revision pending feedback on this reporting initiative.

3.1. CLASSIFICATION SCHEMES BASED ON FUNCTIONAL RELATIONSHIPS WITH MANAGEMENT OBJECTIVES

Where empirical data are available to understand the relationship between Metrics and variables of management interest (hereafter ‘management variables’), new classification schemes could be developed based on the values of the Metric that indicate whether management objectives will or will not, be met. Typically, ecosystem management focuses on maintaining or improving measures of ecosystems structure (Parks Canada 2017), function (Rice et al. 2015), or composition (ECCC 2020), or focuses more specifically on the direct management of Indicators (ECCC 2022). These management variables are related to Metrics through ‘functional relationships’, which may take on a variety of shapes (Figure 2).

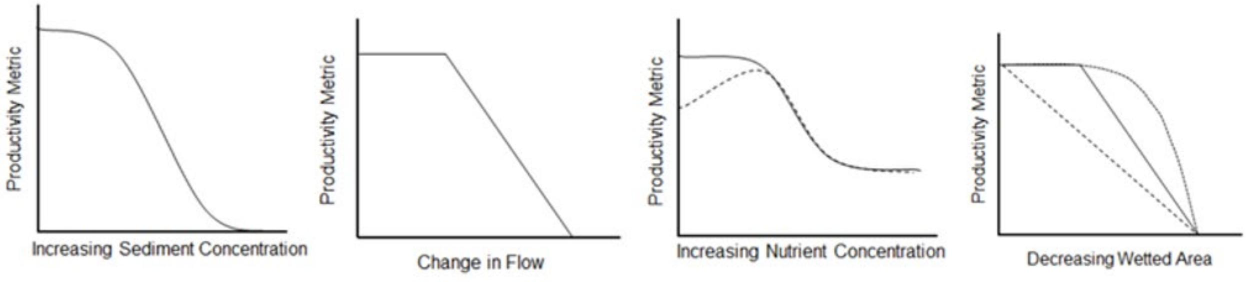

Figure 2. Examples of different functional relationships between a management variable (y-axis, productivity) and Metrics used to describe the SOFFH (x-axis). From DFO 2014.

Classification schemes (and associated reporting thresholds) can be set based on these functional relationships, using either empirical data reported in the literature or through data compiled for the SOFFH reporting process. In the simplest case, reporting thresholds can be set to the value of the Metric at which the functional relationship intersects the management objective, such that the classification scheme is strictly based on the value of the Metric associated with achieving or failing to achieve the management objective (Figure 3A).

Risk-based classification schemes could also be established to indicate when a measure of a Metric suggests that a management variable may be nearing, but has not yet reached, a management objective (e.g., Figure 3B). In this case, the classification scheme categories would focus on defining values of ecosystem state that would imply different levels of risk in failing to meet the management objective. This approach more implicitly acknowledges uncertainty in the measurement of ecosystem state by recognizing that data indicating that ecosystem variables are nearing management objectives do not provide strong evidence (either way) of whether management objectives will be realized, because both process and measurement error is inherent in the data collection. The distance at which a precautionary reporting threshold (Figure 3B) is established from the primary reporting threshold can be determined arbitrarily (e.g., the point on the curve at which the management variable is within 20% of the management objective), can be quantitatively determined using a ‘risk equivalency’ approach (e.g., Fulton et al. 2016, Duplisea et al. 2020) when data on process and measurement error are available, or can be informed by socioeconomic and institutional risks and interest (e.g., Rindorf et al. 2017).

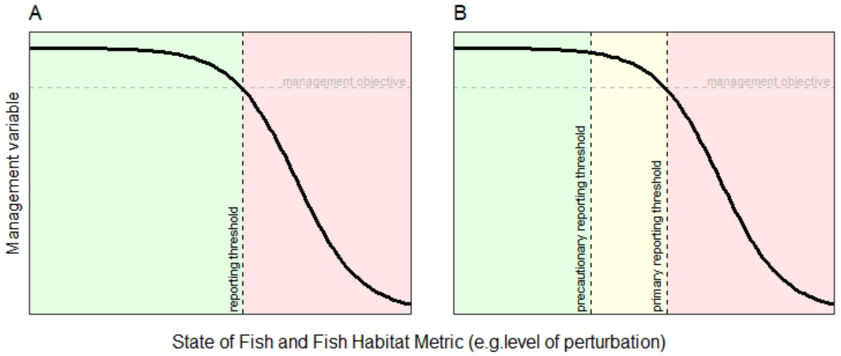

Figure 3. Hypothetical functional relationships between a management variable (e.g., productivity) and a Metric describing a stressor to an ecosystem (e.g., turbidity). In both cases, the establishment of reporting thresholds relies on pre-defined management objectives, which aim to keep a management variable within a certain favorable range. In A, a single reporting threshold is established at the point where the functional relationship indicates a management objective is no longer being met. In B, a secondary ‘precautionary’ reporting threshold is established to indicate when an ecosystem is nearing, but has not yet reached, a management objective.

Developing an empirical understanding of functional relationships for each Metric in each ecosystem would be infeasible, and therefore developing classification schemes and associated reporting thresholds will require the use of generalized functional relationships that are applicable across aquatic ecosystems. Fortunately, many of these generalized functional relationships have been described in the ecological literature, primarily through comparative research (e.g., Walker and Meyers 2004, Biggs et al. 2018), although mechanistic modelling can also be used (Enquist et al. 1998, Loreau 1998). In addition to previously published comparative analyses, it would also be possible for the SOFFH reporting process to conduct novel analyses to develop new generalized functional relationships, based on a subset of systems for which data on management variables and Metrics are available.

The drawback of applying generalized functional relationships is that individual ecosystems or ecosystem components vary in their response to changes in Metrics, and therefore the use of generalized functional relationships can mischaracterize the SOFFH in some ecosystems. This variation can be due to aspects of the ecosystem itself, such as the species present, the physical habitat, and the geography, or can be due to the history of disturbance on the ecosystem. Furthermore, individual ecosystems themselves vary in sensitivity to disturbance over time (Scheffer et al. 2015) and in relation to the suite of ongoing pressures acting on the system (e.g., in response to cumulative effects, see Appendix 1). The extent to which ecosystem variability is an issue for the use of generalized functional relationships depends on the amount of variability (among ecosystems and within ecosystems over time), and the extent to which the reporting aims to accurately characterize the state of each individual ecosystem or describe broader, regional or national trends.

In some cases, it may be possible to statistically characterize the variance around expected values for generalized functional relationships, and report on the confidence / uncertainty in ecosystem state associated with a given value of a Metric. When this is possible, a risk-based classification scheme could be developed based on threshold likelihoods of meeting management objectives. Additionally, the SOFFH reporting can aim to identify (in the narrative part of the documents) any recent pulse disturbances (e.g., extreme flooding events) that might disrupt the relationship between Metrics and management variables. In this way, the reports can recognize that while certain values of Metrics provide some information about the SOFFH, there are other, stochastic factors that also contribute to defining ecosystem state.

3.1.1. Reporting thresholds and ecological thresholds

Many comparative studies in which functional relationships have been described for aquatic ecosystems, have noted that the relationships are characterized by values of the state variables beyond which ecosystem function changes rapidly or categorically (Huggett 2005, Lindenmayer et al. 2005, Rosenfeld 2017). These change points are termed ‘ecological thresholds’, and have been identified for many different management variables and Metrics. For example, certain species require minimum habitat patch sizes to persist, and extirpation may occur below certain areal thresholds of habitat availability (Fahrig 2001). Additionally, rapid declines in water quality have been associated with thresholds for impervious surface cover (Liu et al. 2013), or deforestation in watersheds (Chow-Fraser 2006). Considerable research effort has focused on developing statistical methods to rigorously identify ecological thresholds from functional relationships (Table 2), with methods based on piecewise regression, discriminant function analysis, generalized additive models being most widely used (Scheffer and Carpenter 2003, Toms and Lesperance 2003, Scheffer et al. 2009, Toms and Villard 2015).

While many ecosystems demonstrate ecological thresholds, they are not ubiquitous and recent evidence suggests that they are challenging to detect even with large sample sizes (Hillebrand et al. 2020). Ecological responses can be gradual with changes in state, or ecosystems may be resistant to changes in state such that ecological responses are not present. Currently, there is not strong evidence about the types of ecosystem components, or the types of habitats, that should be associated with ecological thresholds versus those that typically exhibit non-threshold behaviours (but see Schallenberg (2020) for a typology of lakes having different functional relationships). As a result, non-threshold relationships are argued as the more appropriate null model in the absence of evidence of threshold behaviour (Hunter et al. 2009). For example, with regards to the productivity of aquatic ecosystems, DFO (2014) suggests that a linear decline in productivity with increasing perturbation, a functional relationship that does not include an ecological threshold, could be considered as the default relationship.

Table 2. Examples of statistical methods used to identify ecological thresholds

Method	Description	Key reference
Piecewise regression	Multiple, separate lines joined at breakpoints with options for smooth-transition functions	Toms and Lesperance 2003
Piecewise quantile regression	Breakpoints determined using quantiles of the conditional distribution of response variables	Tomal and Ciborowski 2020
Change point analysis	A set of methods to detect changes in the mean value of a time series	Andersen et al. 2009
Discriminant functions	Splits the response into two (or more) groups based on values of the driver.	Toms and Villard 2015
Threshold zones	Defines threshold region based on slope of response; requires both response and driver variable to be on the unit scale	Yin et al. 2017
Bayesian hierarchical modelling	Uses Gibbs sampling to identify changes in distribution parameters	Qian et al. 2003
Significant zero crossings (siZer)	Non-parametric, derivative-based method	Sonderegger et al. 2009
Fuzzy classification maximum likelihood breakpoint	Uses fuzzy class models to identify break points	Lu and Chang 2018

Importantly, ecological thresholds may also differ from reporting thresholds (Figure 4A–C). Consider a system which shows gradual (linear) degradation with increasing perturbation - this system does not have an ecological threshold but could still be classified into two or more categories based on reporting thresholds (Figure 4B). Additionally, ecosystem function may demonstrate a rapid shift associated with an ecological threshold but may still exceed a management objective even under high levels of perturbation (Figure 4C). In this case, reporting thresholds will be challenging to define and may not be aligned with ecological thresholds. Even when both reporting thresholds and ecological thresholds do exist, there may be additional policy reasons to define reporting thresholds differently than ecological thresholds, for example, to align reporting thresholds across jurisdictions or to take a precautionary approach to reporting.

Where ecological thresholds exist, they could be used to establish reporting thresholds when quantitative management objectives have not been specified. That is, ecological thresholds could be used as reporting thresholds under the assumption that crossing ecological thresholds increases the risk of failing to achieve high-level policy objectives such as the '*conservation and protection of fish habitat*' (DFO 2019) or avoiding '*harmful alteration, disruption or destruction of fish habitat*' (Fisheries Act s 35(1)). Specifically, changes in the character of ecosystem (e.g., a transition from an oligotrophic to a eutrophic system) caused by crossing ecological thresholds could be interpreted as a failure to conserve, or to prevent harmful alteration or disruption to, fish habitat.

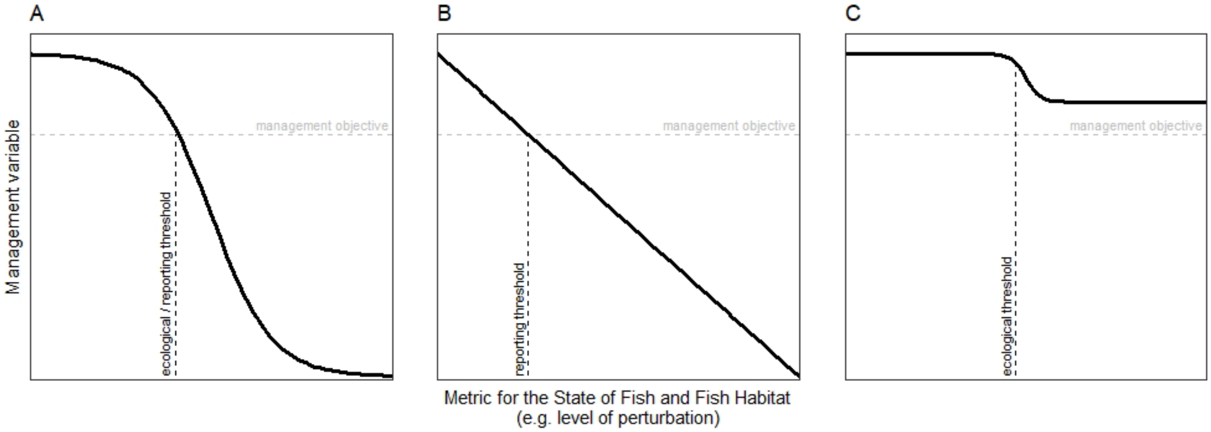

Figure 4. Hypothetical relationships between a Metric (e.g., level of perturbation) and a higher-level management variable (e.g., productivity) illustrating the difference between ecological thresholds and reporting thresholds. In A, ecosystem function declines rapidly associated with an ecological threshold. Exceeding the ecological threshold also causes productivity to fall below a hypothetical management objective, and therefore using the ecological threshold as the reporting threshold would be justified. In B, no ecosystem threshold exists as ecosystem function declines gradually with increasing perturbation. However, a reporting threshold could still be established as the value of the state variable at which ecosystem function declines below a management objective. In C, productivity declines rapidly associated with an ecological threshold, but does not fall below the management objective

However, it is important to reiterate that while ecological thresholds can be identified by scientific means, their application to classification schemes is a non-scientific consideration (Johnson and Ray 2021). The use of ecological thresholds as reporting thresholds constitutes a value-based decision to equate the two concepts, which may be reasonable in some circumstances. However, ecological thresholds may not always align with policy objectives and may also not be related to stakeholder values (Joseph 2020). As such, the use of functional relationships in defining classification schemes for the SOFFH reporting would be best supported by the presence of independently defined management objectives, rather than by identification of ecological thresholds.

3.2. CLASSIFICATION SCHEMES AND THRESHOLDS ESTABLISHED IN GUIDELINES, POLICY, REGULATIONS OR OTHER REPORTING INITIATIVES

For some Metrics, existing guidelines, policy, regulations or reporting initiatives may have already established classification schemes that could be leveraged for reporting on the SOFFH.

The primary value of leveraging established classification schemes (and their associated reporting thresholds) is that their use promotes consistency with other reporting initiatives, and provides information that is directly applicable to policy, regulations and/or legislation. Reports based on standardized classification schemes can enable comparisons among regions or across time, and therefore contribute to a greater holistic understanding of the state of ecosystems. In this way, leveraging existing classification schemes also contributes to the study of effectiveness of ecosystem management because it enables temporal and spatial comparisons between ecosystem state and management activities. Along a similar line, re-purposing established reporting thresholds could improve the efficiency of reporting, because relevant data are likely already being collected and analyzed with respect to these classification schemes.

Using established classification schemes and thresholds can have the benefit of leveraging previous work by expert groups to develop and refine those classification schemes. In many cases, reporting thresholds are established via formal mechanisms (e.g., Protocol for the Derivation of Water Quality Guidelines for the Protection of Aquatic Life, Canadian Council of Ministers of the Environment 2007) that integrate scientific advice with ecosystem management expertise, consider multiple sources of evidence, uncertainty, and variability among systems. When these approaches have been used, the thresholds themselves should already reflect a robust scientific understanding of the focal measure and have likely included some evaluation of risk management.

Additionally, where the Metrics used for ecosystem reporting are also management variables, and quantitative management objectives have been set for those management variables, classification schemes can be directly developed based on management objectives. Such ‘outcome-based’ thresholds avoid the complications associated with the (potentially non-linear) relationships between Metrics and management variables (see Section 3.1) and instead focus on the direct measurement of management variables to assess the state of ecosystems. For example, if ecosystem managers have an objective of maintaining ecosystem productivity above 90% of the natural system value, a classification scheme could be developed based on the direct measurement of productivity itself (i.e., using productivity as the Metric, and 90% of the natural productivity level as the reporting threshold).

Most thresholds established in policy, regulation and/or legislation are absolute thresholds, and are typically based on a binary classification system (i.e., systems are defined as either being above or below a single threshold value), although other classification systems are used (see, e.g., the self-referent, 3-level Fisheries Management Framework; DFO 2006). Furthermore, most thresholds established in other reporting initiatives are multi-level (4-5 level) classification systems, which may be based on a multi-level classification of an underlying state variable (see, e.g., Trophic Status classification scheme in the *Guide to Reporting on Common Indicators Used in State of the Watershed Reports*, reported in Table 3) or may be based on the proportion of sites/samples exceeding a binary threshold.

Table 3. Examples of thresholds established for guidelines, policy, and regulations that could be leveraged for reporting on the SOFFH in Canada.

Source	**Organization**	**Types of metrics**	**Example metric**	**Example threshold**
How much habitat is enough?	Environment Canada	Habitat availability and extent, land cover	Percent of stream length naturally vegetated	75%
State of Ontario’s Biodiversity Report	Ontario Biodiversity Council	Fragmentation, invasive species, water quality, ice cover, habitat extent, flow	Chloride in streams	120 mg/L
Canadian Water Quality Guidelines for the Protection of Aquatic Life	Canadian Council of Ministers of the Environment	Surface water contaminants, nutrients, dissolved gasses, debris, turbidity, colour, temperature	Dissolved oxygen in cold water systems	9.5 mg/L for early life stages 6.5 mg/L for other life stages
Ontario Provincial Water Quality Guidelines	Government of Ontario	Contaminants, pH, turbidity, contaminants in fish tissue	Turbidity	10% change from natural Secchi disc reading

Source	Organization	Types of metrics	Example metric	Example threshold
Canadian Sediment Quality Guidelines for the Protection of Aquatic Life	Canadian Council of Ministers of the Environment	Contaminants	Cadmium in freshwater	0.6 mg/kg dry weight
Watershed Reports	Conservation Ontario	Surface water quality, forest conditions, groundwater quality	% Riparian zone forested	> 57.5% = A 42.6–57.5 = B 27.6–42.5 = C 12.5–27.5 = D < 12.5 = F
Guide to Reporting on Common Indicators Used in State of the Watershed Reports	Alberta Environment and Sustainable Resource Development	Nutrients, bacteria, linear disturbance, fish community index	Trophic status (based on chlorophyll A concentration)	< 2.5 ug/L = Oligotrophic 2.5–8 ug/L = Mesotrophic 8–25 ug/L = Eutrophic > 25 ug/L = Hypereutrophic

3.3. CLASSIFICATION SCHEMES BASED ON RELATIVE RANKING

Where functional relationships are not known or management objectives are not quantitatively defined, relative ranking could be used to establish classification schemes (Figure 5). In this approach, Assessment Units are categorized along a gradient of 'best' to 'worst', based on their ranking relative to other Assessment Units under consideration.

Broadly, two classes of relative ranking classification schemes exist. First, categories can be established such that each level of the classification scheme includes an equal number of observations (i.e., Assessment Units). A simple example of such a classification scheme would be to categorize all Assessment Units as either being above or below the median (i.e., 50th percentile) value for the focal Metric. More detailed classification schemes could include different percentile breaks, for example a 4-level classification scheme would use the 25th, 50th and 75th percentiles as reporting thresholds.

Second, classification schemes can be established based on data clustering approaches that seek to identify natural breaks in the distribution of values. For example, Jenks' natural breaks classification method (Jenks 1967) attempts to minimize the average deviation between observations and the mean of their level, while maximizing deviation among the means of different levels, and has been previously used for environmental reporting. This method requires the *a priori* determination of the number of breaks to be used, which is advantageous for reporting purposes in that the number of breaks can be standardized across different Metrics to enhance consistency within the reporting initiative.

The downside of using relative ranking methods is that they do not provide direct information on the SOFFH and can complicate the interpretation of trends over time. For example, consider a report examining the state of Assessment Units in a region that has significant disturbance across all Assessment Units. Using a relative ranking scheme, some systems will be classified as having the 'best' value for a given Metric, even if that value represents significant degradation relative to the natural state of the system. Similarly, if all Assessment Units improve in a given Metric over time, their classifications will not change since their relative ranking will not have changed, and therefore the improvement in SOFFH will not be evident. These issues can be mitigated by applying relative ranking schemes only when the Assessment Units represent a breadth of ecosystem states (from pristine to highly degraded), such that relative rankings are more reflective of the full distribution of possible ecosystem states. In addition, reporting thresholds initially established through relative ranking can be maintained across time (i.e., adopting the approach outlined in 3.2) to better capture changes in the state of ecosystems rather than changes in the relative ranking of Assessment Units.

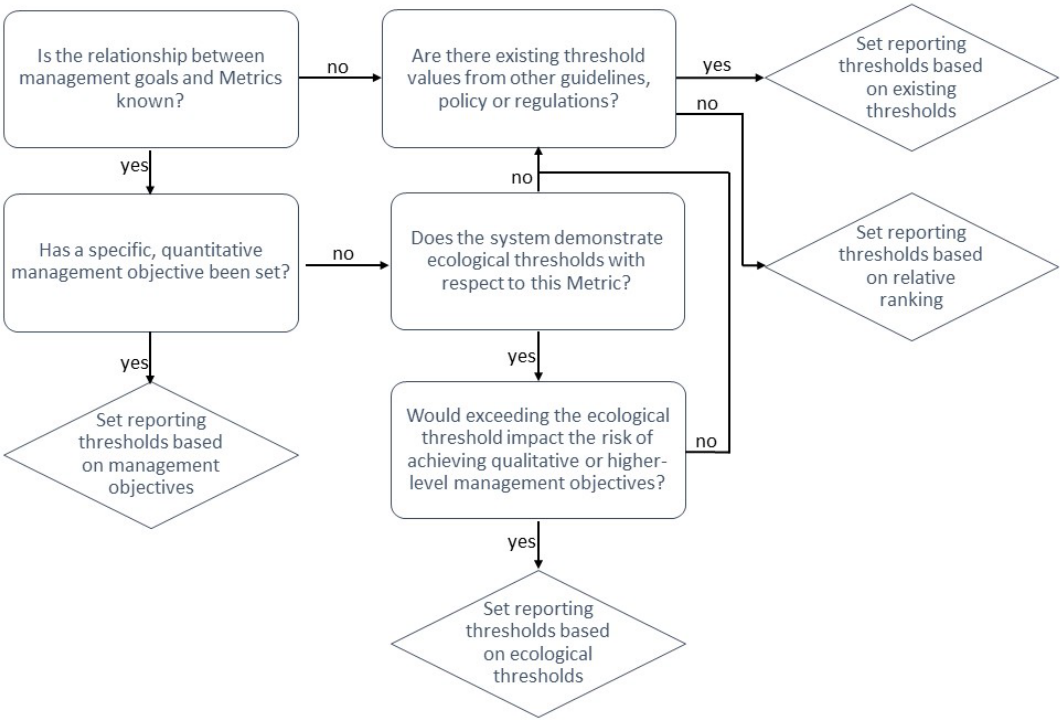

Figure 5. Example decision tree for selecting a method of developing classification schemes and associated reporting thresholds. Note that the method of developing classification schemes based on expert elicitation (Section 3.4) can be combined with other methods or serve as an alternate approach to the data driven approach outlined in this figure.

3.4. CLASSIFICATION SCHEMES BASED ON EXPERT ELICITATION

The development of classification schemes, as well as the assignment of Assessment Units to levels within those schemes, could also be based on expert opinion. A suite of structured methods has been developed for eliciting, aggregating and summarizing qualitative and quantitative expert opinion on ecological and environmental issues (e.g., Choy et al. 2009, O'Leary et al. 2009, James et al. 2010, Sutherland et al. 2011, Hemming et al. 2018), and these methods are being widely applied to a suite of different projects, including ecosystem reporting (e.g., AE and IEG 2021). Application of these methods for reporting on the SOFFH could address gaps where limited empirical data exist or strengthen inference by being combined with empirical data analyses (e.g., via Bayesian analyses with priors informed by expert opinion; Choy et al. 2009). In addition, these methods would enable the direct participation of a broader group of experts in the reporting process, including Indigenous knowledge holders and community members with expertise in local aquatic ecosystems (e.g., anglers, naturalists, municipal government staff).

For the assignment of Assessment Units to levels of a classifications scheme in the SOFFH reporting, methods such as the Delphi approach or 'IDEA' protocol (Mukherjee et al. 2015, Burgman 2016, Hemming et al. 2018), could be straightforward to apply with a set of local or regional experts on fish and fish habitat. In these methods, individual experts are queried for their estimate (and confidence) in an unknown quantity (e.g., the overall quality of surface water in a watershed). The estimates from all experts are then aggregated and presented back to each expert (with or without a period of discussion), after which each expert is able to revise their estimate based on their personal knowledge and the aggregated knowledge of the group.

Under classic Delphi approaches, the iterative process (of seeking individual feedback, aggregating, and sharing aggregated data with each expert to refine their estimate) would be repeated either until a pre-established consensus threshold has been reached, or until a pre-determined number of iterations has been completed, while under the IDEA protocol, only one iteration is typically conducted. Many versions of these processes retain anonymity among experts, which helps to avoid social pressures associated such as the dominance of ‘authoritative’ group members and halo effects (Nisbett and Wilson 1977), while the iterative nature of the process helps to work towards group consensus. These methods can also be conducted remotely and asynchronously (e.g., Dey et al. 2022), which may be advantageous when larger groups of experts are involved.

The primary downside of expert elicitation-based classification is the perception that expert opinion is less reliable than ‘objective’ empirical data because of issues associated with bias. However, as Martin et al. (2012) indicate, empirical data may also contain biases, inadequacies and errors, and it is not the case that empirical data are necessarily closer to the truth than expert opinion. Additional downsides associated with expert elicitation is that many such methods are relatively time consuming and logistically challenging. For example, Delphi and IDEA approaches may have high dropout rates if experts do not feel sufficiently engaged, or if the processes themselves take too long. These issues would be exacerbated if the same set of experts is asked to provide input on multiple Metrics. However, it is not clear that expert elicitation methods would always be more onerous than empirical data compilation and analyses, depending on the existence and organization of open data and databases.

3.5. CLASSIFICATION SCHEMES FOR INDICATORS

In addition to classification schemes for Metrics, higher-level Indicators could also have classification schemes to support the SOFFH reporting.

Classifications schemes for Indicators are different from those for Metrics in that they must combine multi-dimensional data (i.e., from multiple Metrics) to produce a synthetic categorization. If the classification schemes developed for each of the underlying Metrics are consistent (i.e., have the same number of levels and the same labels), then the distribution of categorizations could be used to produce a categorization for the Indicator. In this case, the considerations are similar to those for the combination of multiple data points into a single categorization for a Metric, in that the multi-dimensional data has been collapsed to a single dimension (the categorizations of each of the component Metrics).

In some cases, a measure of central tendency (e.g., median or mean value) or an extreme value (e.g., the minimum or maximum) can be used. This approach however, would implicitly weight each of the component Metrics as an equally important contributor towards the state of the Indicator, a situation which may not accurately reflect reality as Indicators (and overall levels of the health of ecosystems) are often drive more strongly by particular variables. As such, classification schemes for Indicators may wish to weight the contributions of different Metrics according to their level of importance in determining the state of the Indicator. Such an approach requires the development of a weighting scheme, which could be derived from expert opinion (see Section 3.4) or be based on statistical approaches in rare cases where sufficient data are available. However, different weighting schemes may need to be developed for different reporting areas, or different habitat types – as the importance of different Metrics may vary across systems.

Alternatively, multivariate approaches based on variable reduction could be applied directly to the underlying multi-dimensional data to classify Indicators. Here, raw data from each of the contributing Metrics can be combined to produce a single, synthetic ‘index’ describing the State of Fish or Fish Habitat with respect to the Indicator. For example, Chow-Fraser (2006) used principal component analysis (Jollife and Cadima 2016) to combine up to 12 variables into a synthetic Water Quality Index (a continuous value). Similarly, a Riparian Health Assessment Index, ranging from 0 to 63 (or transformed to a percentage-based score) has been developed by the Alberta Riparian Habitat Management Society (i.e., 'Cows and Fish' program) as a synthetic score that combines measures of habitat alteration, vegetation composition, canopy cover, presence and distribution of invasive species and flow alteration in riparian areas (Ambrose et al. 2009). In this framework, each variable receives a score (with differing maximum values reflecting the weighting of each variable towards the final index), which is then combined through simple addition to create the final index value. Classification schemes for Indicators based on multivariate indices can then be established by setting reporting thresholds for the indices, through the methods described above (i.e., Sections 3.1–3.4).

Finally, classification schemes and categorizations for Indicators could also be produced through expert opinion. In this approach, groups of experts would decide upon categorizations for Indicators based on (structured or unstructured) discussion, supported by data and/or the weighting of component Metrics. While more 'subjective', this approach may better accommodate challenges associated with varying data quality (see Section 4), and the importance of different Metrics towards categorizations of Indicators. Typically, consensus-based approaches are used for categorization (e.g., ECCC and U.S. Environmental Protection Agency 2021), however experts could also be surveyed, and the final categorizations based on statistical aggregation techniques.

3.6. CLASSIFICATION SCHEMES FOR DATA QUALITY

In addition to developing classification schemes and reporting on the state of ecosystems, many environmental reporting initiatives also provide information on the quality of data used to derive estimates of state. This 'value added' component of reports helps readers to contextualize the (un)certainty that the report authors have in their estimates, as well as identifies data gaps that could be prioritized for future research and monitoring initiatives.

Most reporting on data quality is based on the assessment of datasets against checklists of criteria that indicate high quality environmental data. For example, WWF's State of the Watershed report considered the recency of data, the temporal range of data and the geographic precision to assign data as 'sufficient', 'moderately sufficient, 'partially sufficient' or 'insufficient' (WWF-Canada 2020). Similarly, the State of the Great Lakes 2019 report includes a 5 item checklist for data quality related to whether data have gone through quality assurance and validation processes, have appropriate geographic coverage, and are accompanied by estimates of uncertainty (ECCC and U.S. Environmental Protection Agency 2019). These data quality scores are typically reported for each Metric, although may also be reported at the level of Indicators.

Importantly, these classification schemes typically include a minimum threshold for data quality required to produce an estimate of the state of the ecosystem. Where data quality did not meet this threshold, the associated Metric or Indicator can be deemed 'data deficient' and no state reported. Such a threshold functions as an upper limit on the amount of uncertainty that should be tolerated when reporting on ecosystem state. In general, a higher level of data quality (and corresponding lower level of uncertainty) should be required to report on ecosystem state when information is shared with the public, as lay audiences will often have a poorer understanding of the impact of uncertainty on outcomes than experts (Gregory et al. 2012).

While not typically used in ecosystem reporting initiatives, estimates of the state of ecosystems in data deficient regions could still be made based on regional patterns of the state of watersheds (i.e., using statistical imputation methods, or Bayesian approaches with priors derived from regional patterns). That is, even in the absence of Assessment Unit specific data, some overall estimate of the SOFFH could be produced based on a combination of the limited available data and the general spatial and temporal patterns of stressors. Regardless of the approach used (setting a minimum threshold of data quality for reporting on state, or providing the best available estimate of state even when data are limited), sharing information about the amount of uncertainty in estimates of ecosystem state would help readers to understand gaps and limits in the available data.

While some components of data quality scores could be supported by quantitative analyses (e.g., spatial comparisons of the coverage of data with waterbodies in the Assessment Unit, power analyses to quantify the ability to detect trends through time), qualitative assessments are less technically demanding and align with other data quality assessments in ecological science (Brilis et al. 2000, Wilkinson et al. 2016, Birigazzi et al. 2019).

4. KEY UNCERTAINTIES

Per the definitions list in the Glossary, the assessment of the SOFFH requires knowledge of the natural state of fish communities, and the natural function of fish habitat as baseline states against which systems are evaluated. However, it is arguable whether any fish communities and fish habitat remain in pristine conditions in Canada. Even in areas in which there has been little industrial development, aquatic ecosystems are impacted by pressures acting at a distance, such as climatic changes and the long-distance spread of pollutants. Furthermore, in many cases native keystone species / ecosystem engineers have been extirpated for long periods of time, increasing uncertainty about how ecosystems were structured and how they functioned in pristine conditions.

Many authors have written about the dangers of shifting baselines in natural resource management (e.g., Pauly 1995, Pinnegar and Engelhard 2008), and this issue also applies to reporting. If reporters perceive the SOFFH characteristics that existed at the start of their career as the unaffected, reference condition then environmental reporting may grossly mischaracterize the natural characteristics of ecosystems (Humphries and Winemiller 2009). Issues of shifting baselines are magnified when data on ecosystem state postdates the onset of ecosystem stressors, which is typically the case for freshwater ecosystems in Canada.

A related issue to shifting baselines, non-stationarity, describes the fact that natural ecosystems are not maintained in a single stable state, but instead are constantly changing in response to geological, climatic and evolutionary processes (Rollinson et al. 2021). As such, characterizing the natural state and function of fish and fish habitat, as is required for assessing the SOFFH, is complicated by the fact that natural ecosystems are not stable. Furthermore, non-stationarity complicates the links between Indicators and overall ecosystem state because the impact of Indicators on overall state may be overwhelmed by the fundamental non-stationarity of ecosystems. For example, catastrophic events such as landslides may degrade the SOFFH despite improvements in Indicators.

An additional uncertainty relates to emerging stressors for aquatic ecosystems, and how they can be accommodated in ecosystem reporting initiatives. By definition, emerging stressors have a short history of impacting aquatic ecosystems and are therefore likely to be associated with significant data gaps, including gaps in understanding of functional relationships, limited (or no) existing thresholds, and a lack of historical data. These data gaps provide significant challenges for ecosystem reporting, including challenges associated with identifying particular emerging stressors to include in reporting initiatives from the suite of possible stressors.

Furthermore, because different stressors and pressures can interact in complex ways (Crain et al. 2008, Jackson et al. 2016, Dey and Koops 2021), it is unclear how the state of different Metrics and Indicators relates to an overall SOFFH. The cumulative effects of small amounts of degradation in multiple habitat components can lead to severe degradation in overall ecosystem state, even when each habitat component falls within a ‘good’ or ‘excellent’ level. Furthermore, different Metrics and Indicators may contribute different amounts towards the overall ecosystem state, such that overall state may more closely reflect the condition of a small number of key Metrics and be poorly predicted by an evaluation of a broader set of Metrics. Understanding how different stressors interact, and how to weight different Metrics and Indicators when producing overall measures of SOFFH, could improve future iterations of the SOFFH reports.

Finally, the development of classification schemes and reporting thresholds has been based on quantitative scientific information. However, there is a wealth of expert knowledge (including Indigenous knowledge and local knowledge) of aquatic ecosystems that could also inform the SOFFH reporting. While methods for expert elicitation, including the compilation and synthesis of Indigenous knowledge, are well established (Carothers et al. 2014, Runk 2014, Thompson et al. 2020) – weaving information from multiple knowledge systems to produce ecosystem reports is not common practice. However, it could be possible to adapt approaches based on ethical space (Ermine 2007) and/or two-eyed seeing (Reid et al. 2021) to bring together Indigenous and scientific data for reporting purposes. If appropriate methods could be developed, such approaches could make a significant contribution towards addressing informational gaps present in any single knowledge system, enhancing the understanding of historical ecosystem states (and thereby addressing shifting baselines), and strengthening support for the overall SOFFH reporting initiative.

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5. APPENDIX

5.1. RESPONSE OF FUNCTIONAL RELATIONSHIPS TO CUMULATIVE IMPACTS OF MULTIPLE STRESSORS

Some have argued that different species and ecosystems demonstrate general functional relationships, and that knowledge of these general relationships can both inform management activities and reduce the need to study the response of individual populations within each study area (e.g., Guénette and Villard 2005, Rompré et al. 2010, Lade et al. 2021). However, others have noted that ecological responses vary considerably, even when comparing the response of similar taxa (or similar ecosystems) to similar stressors (Rhodes et al. 2008, Swift and Hannon 2010). While some of the variance is associated with methodological differences among studies, the shapes of functional relationships themselves are impacted by the cumulative effects (i.e., the combination of past and present stressors) acting on ecosystems.

In particular, stressors continue to cause impacts on species and ecosystems, even after the stressors have been removed. As such, historical stressors can alter functional relationships by disrupting ecosystem processes, even when measured attributes (e.g., Metrics) have returned to baseline conditions. The rate of recovery of an ecosystem following an impact is described as ecosystem resilience (Eno et al. 2013), and is thought to be related to factors such as connectivity, functional redundancy, and environmental heterogeneity (Van Looy et al. 2019). Relatedly, exposure to multiple stressors can also alter ecosystem resistance, defined as the ability of an ecosystem to maintain function in the face of temporary or prolonged disturbance. Ecosystem resistance (and therefore functional relationships) is impacted by the nature of interactions between stressors, which may exceed the additive effect of the stressors in acting in isolation – sometimes dramatically so.

Through their impacts on ecosystem resistance and resilience, cumulative effects can impact the SOFFH in a manner that is not directly captured through the independent assessment of Metrics. That is, ecosystems can show significantly reduced productivity, richness or abundance even when no single Metric indicates a high degree of degradation.