Fisheries and Oceans Canada / Pêches et Océans Canada
Ecosystems and Oceans Science / Sciences des écosystèmes et des océans

GEOSPATIAL MAPPING TOOLS, INDICATORS, AND METRICS FOR FISH HABITAT IN THE PACIFIC REGION

Context

On August 28, 2019, a new *Fisheries Act* came into force with restored protections and modernizations to help safeguard fish and fish habitat. To implement the modernized Act, the Fish and Fish Habitat Protection Program (FFHPP) has more capacity to work with communities, partners, and stakeholders in freshwater, coastal and marine environments to undertake activities that will improve outcomes for fish and fish habitat through conservation, protection, and restoration. FFHPP plans to improve how it reports to Canadians on both its own activities related to fish and fish habitat protection and the important related work of partners and stakeholders. Modern tools and approaches to track and assess the health or state of fish and fish habitat are needed to support responsive and integrated regulatory, planning, partnership and monitoring activities by FFHPP and to demonstrate improved outcomes for sustainability of fish and fish habitat.

Fisheries and Oceans Canada's (DFO) Fish and Fish Habitat Protection Program requested that Science Branch review geospatial tools to identify freshwater-related indicators and metrics (i.e., representative measures) to assess and report on the status of threats and state of fish habitat, including but not limited to those listed in the Fish and Fish Habitat Protection Policy Statement (DFO 2019) and the Interim Risk Management Guide for the Protection of Fish and Fish Habitat (DFO 2019b). The threats listed in the policy are habitat degradation, habitat modification, aquatic invasive species, pollution, and climate change. Those listed in the guide are sedimentation, deleterious substances, and change or loss of riparian zone, aquatic habitat and vegetation, fish passage, dissolved oxygen, and nutrients. The overexploitation of fish and provincially managed species, and change in food supply, noise, light, and electromagnetic field are beyond the scope of this request.

Public facing geospatial tools that provided indicators of human activities and threats to fish habitat and watersheds in the Pacific Region were reviewed alongside key habitat threats of DFO-managed freshwater and anadromous species as identified by the FFHPP threats listed above and the Committee on the Status of Endangered Wildlife in Canada (COSEWIC). For example, existing tools for British Columbia and the Yukon included the Pacific Salmon Explorer, World Wildlife Fund Watershed Reports and British Columbia (BC)'s Stewardship Baseline Objectives Tool. In total, thirteen geospatial tools were assessed and compared using Pathways of Effects diagrams. Global Threats to Human Water Security and River Biodiversity and World Wildlife Fund-Canada were the highest ranking tools in terms of the number of threats they addressed that have been identified as important to fish and fish habitat by both FFHPP and COSEWIC.

This Science Response results from the Science Response Process of July 27, 2022 on Geospatial Mapping Tools, Indicators, and Metrics for Fish Habitat in the Pacific Region. The assessment and advice will be used to inform FFHPP Pacific Region activities associated with the implementation of the modernized *Fisheries Act*, including being able to articulate how FFHPP Pacific is working to develop habitat status or health indicators. This advice will also inform planning for future reporting in part by identifying gaps and uncertainties in effectively identifying habitat status.

Background

Geospatial tools used to estimate and map human activities and associated threats across land and seascapes are becoming prevalent to help determine where biotic communities are most impacted, and to guide prioritization of management and conservation efforts. Direct measures of human impacts (e.g., pollutant loading) are often unavailable across regions, whereas geospatial human activity and land use information is much more accessible and can be used to develop indicators (i.e., proxies) of potential impacts for large spatial extents. Many geospatial tools address multiple activities or threats and combine them to create cumulative effects scores, as it is well-recognized that ecosystem degradation and declines in species populations are influenced by multiple factors. The advent of publicly available geospatial datasets and increased use of GIS software and web platforms has led to many spatially overlapping efforts to map human activities and threats. The application of these tools are often for a specific purpose, or 'focal value', and many have different approaches, resolutions, and methods of indicator and cumulative effect development. This Science Response compiles and compares existing geospatial tools in the Pacific Region that may be used to evaluate threats to fish habitat.

Comparison of geospatial tools and cumulative effect assessments requires standardized conceptual frameworks and terminology. Indicators developed by geospatial tools vary in whether they directly represent human activities, or are a combination of activities and environmental parameters used to estimate a stressor or effect. Given the different terminology applied across tools, it can be difficult to distinguish what each tool is representing and how they compare. Identifying the conceptual framework of a tool enables determination of how closely indicators are linked to threats and how indicators are combined when there are final cumulative effect scores. Pathways of Effects (PoE) frameworks are conceptual models that aid in identifying relevant human activities, links to associated stressors and effects, and the focal value or ecological component (Murray et al. 2020) (Fig. 1). For instance, in a PoE framework, the presence of dams (human activity) leads to habitat fragmentation (effect) that may be detrimental to fish habitat (focal value/ecological component). We follow the definitions described in Murray et al. (2020) where a 'stressor' is a human related driver that causes an undesired change in a focal value, and an 'effect' is a deviation from the expected range of the focal value. In terms of fish habitat as a focal ecological component, a human derived change in nutrients is a stressor to fish habitat, and the subsequent decrease in dissolved oxygen concentrations is an effect on fish habitat. In addition, the term 'pressure' can be used synonymously with human activities (e.g., as in the Pacific Salmon Explorer), which is defined as an agent exerted by human activities to elicit an effect (Oesterwind et al. 2016; Murray et al. 2020). However, 'pressure' is used in FFHPP PoE diagrams to represent the stressor or effect of a human activity. Inconsistent use of these terms is a problem across freshwater and marine fields (Oesterwind et al. 2016). Therefore, we combined stressors and effects under the umbrella term of 'threats' to match the language used by COSEWIC and the FFHPP Policy Statement (DFO 2019), and avoided using the term pressure. FFHPP has four consolidated PoE frameworks to represent human activities that are land-based, water-based, produce noise and energy, or affect flow (DFO 2021). These PoE frameworks are meant to focus on a single activity for regulatory review and identify a full suite of potential threats (termed 'pressures' in the PoE) to the productivity of fisheries. Many activities that are reviewed by FFHPP and noted in the four PoE frameworks are not currently amenable to GIS analysis (e.g., explosives, dredging, etc.). In addition, the FFHPP PoE diagrams only include DFO managed activities (i.e., within the riparian zone or in water), whereas the tools reviewed here generally sought to encompass many human activities across the landscape that lead to threats to fish habitat and watersheds, often for the purpose of cumulative effect assessment. Thus, we applied a modified PoE framework based on cumulative effect focused frameworks (Murray et al. 2020) to the compiled tools so that we could identify the level of indicator analysis and to enable standardized comparison across tools.

There were several criteria used to determine the suitability of existing geospatial tools for reporting on the status of threats and the state of fish habitat. The following were identified as optimal characteristics of a tool for such purposes:

1. includes a relatively comprehensive number of human activity and environmental indicators and used these to estimate threat indicators as more directly related proxies of impacts to fish and fish habitat,
2. estimates indicators that are relevant to many (ideally all) of the threats identified as important by FFHPP and COSEWIC, including climate change,
3. is directly relevant to fish habitat,
4. covers the extent of the Pacific Region (British Columbia and Yukon),
5. has a stream reach or fundamental watershed resolution that can be aggregated, or an intermediate scale such as the 1:20,000 Freshwater Atlas Assessment Watersheds that is easier for reporting but is not so coarse as to lose ecological meaning,
6. incorporates water flow and downstream effects for relevant indicators for more accurate estimates of threats,
7. includes a final cumulative effect or risk score for identifying high priority areas for management actions that is created using binning or summation methods that are based on quantified biological responses or expert opinion, to the extent possible, and maintain the original structure of the data, and
8. conducts re-assessments of indicators to evaluate change in status over time.

Analysis and Response

Available geospatial tools for evaluating and summarizing the state of fish habitat

We conducted an online search for BC and Yukon public facing, interactive geospatial tools (or global tools that include BC and Yukon), as well as publicly-available BC provincial reports from the Ministry of Forests, Lands, Natural Resource Operations and Rural Development (FLNRORD), that may be used to evaluate and summarize the state of habitat for DFO-managed freshwater and anadromous species (salmon, species at risk [SAR]) and watersheds. We found 13 relevant tools (Table 1) that spanned:

- BC watersheds (8):
  - BC Oil and Gas Commission Area-Based Assessment (‘Oil and Gas’) (2018)
  - Pacific Salmon Explorer (‘PSE’) (2021)
  - Stewardship Baseline Objectives Tool for Forested Watershed Condition (‘SBOT’) (2022)
  - Skeena Sustainability Assessment Forum’s State of the Value Report for Fish and Fish Habitat (‘Skeena’) (2021)

- Elk Valley Aquatic Ecosystems Cumulative Effects Assessment Report ('Elk Valley') (2018)
- Howe Sound Cumulative Effects Framework ('Howe Sound') (2018)
- Southern Interior Watershed Assessment Protocol ('SIWAP') (2016)
- Pollutants Affecting Whales and Their Prey Inventory Tool ('PAWPIT') (2022)

- Yukon watershed (1)
  - Yukon River Inter-Tribal Watershed Council IGAP Map ('IGAP') (year unknown)
- Canada (1)
  - World Wildlife Fund - Canada Watershed Reports (hereafter, 'WWF-Canada') (2015)
- Global (3)
  - Global Forest Watch Interactive World Forest Map and Tree Cover Change ('Global Forest') (2022, ongoing)
  - Global Threats to Human Water Security and River Biodiversity ('Global Water') (2010)
  - HydroATLAS (2019)

The focal ecological components of the tools included watershed health or quality, aquatic ecosystems, fish and fish habitat, salmon, biodiversity, and forest cover; the latter, from Global Forest, was included as within scope because many of the included human activities and intermediate indicator groupings (e.g., 'hydrology') were relevant to fish habitat, and were assessed within river basins (Table 1).

Table 1. Geospatial tools relevant to assessing and reporting on the status of threats to the state of fish habitat in the Pacific Region. Abbreviation is for the Ministry of Forests, Lands, Natural Resource Operations and Rural Development (FLNRORD).

Tool name, organization	Spatial extent	Resolution/ scale	Cumulative scoring approach	Ecological component
Peace River Area-Based Assessment, BC Oil and Gas Commission	Peace River, BC	Water Management Basins; FLNRORD Natural Disturbance Units	None	Riparian habitat, old growth forest, wildlife habitat
IGAP Map, Yukon River Inter-Tribal Watershed Council	Yukon River Watershed, Yukon	Yukon River Watershed	None	Water quality and fish
Pacific Salmon Explorer, Pacific Salmon Foundation	BC salmon watersheds (Haida Gwaii, Nass, Skeena, Central Coast, Fraser, Vancouver Island and Mainland Inlets)	1:20,000 Freshwater Atlas Assessment Watersheds	Rolled-up score	Pacific salmon
Watershed Reports, World Wildlife Fund-Canada	Canada	Water Survey of Canada sub-drainage area	Rolled-up score	Watershed health
Howe Sound Cumulative Effects Framework, FLNRORD	Howe Sound, BC	1:20,000 Freshwater Atlas Assessment Watersheds	None	Aquatic ecosystems

Tool name, organization	Spatial extent	Resolution/ scale	Cumulative scoring approach	Ecological component
Elk Valley Aquatic Ecosystems Cumulative Effects Assessment Report, FLNRORD	Elk Valley, East Kootenay Region, BC	1:20,000 Freshwater Atlas Assessment Watersheds	Rolled-up score	Aquatic ecosystems (riparian habitat, Westslope Cutthroat Trout)
State of the Value Report for Fish and Fish Habitat, Skeena Sustainability Assessment Forum	Skeena, Nass and Nechako, BC	1:20,000 Freshwater Atlas Assessment Watersheds	None	Fish and fish habitat
Stewardship Baseline Objectives Tools for Forested Watershed Condition, FLNRORD	South Coast Region, BC	1:20,000 Freshwater Atlas Assessment Watersheds and Fundamental Units	Rolled-up score	Watershed condition
Southern Interior Watershed Assessment Protocol, FLNRORD	Thompson-Okanagan, BC	1:20,000 Freshwater Atlas Assessment Watersheds	Rolled-up score	Water quality, fish and aquatic ecosystem health
Pollutants Affecting Whales and Their Prey Inventory Tool, Environment and Climate Change Canada	Fraser Basin, Vancouver Island and coastal areas in Killer Whale habitat, BC	Air emissions: 2.5 km grid; Surface runoff: sub-basins (within Fraser Basin only); Point source emissions: point locations	Sum of pollutants	Chinook Salmon, Southern and Northern Resident Killer Whales
HydroATLAS, World Wildlife Fund-US	Global	15 arc-second grid (~ 500 m at the equator)	None	River characteristics
Global Threats to Human Water Security and River Biodiversity, Environmental CrossRoads Initiative	Global	0.5° grid (~ 55 km)	Weighted sum	Human water security, biodiversity
Global Forest Watch Interactive World Forest Map, Global Forest Watch	Global	Data dependent, many with a 30 m grid or point locations	No cumulative scoring	Forest cover

Relevant fish habitat indicators and metrics

From the 13 tools above, we identified the available indicators that are relevant to Pacific salmon and Species at Risk habitat. We developed and applied a standardized template based on cumulative effect PoE frameworks to compare across tools (Fig. 1). The template identified five divisions: human activity indicators, environmental indicators, threat indicators, cumulative scores, and the focal ecological component. Some tools combined human activity and/or environmental indicators to create threat indicators; in a standard PoE this would be represented by an arrow. We did not show all of the metrics and data that went into the estimation of an indicator as this was not the primary focus of the PoE application (but see details on development of each indicator in Iacarella and Potapova 2022), and instead used a dashed arrow to show which indicators were combined into categories or cumulative scores, and a solid arrow linking final groupings or scores to the ecological component. Intermediate groupings were indicated when used to quantitatively combine human activity and/or environmental indicators before creating threat indicators or when used to qualitatively link indicator categories.

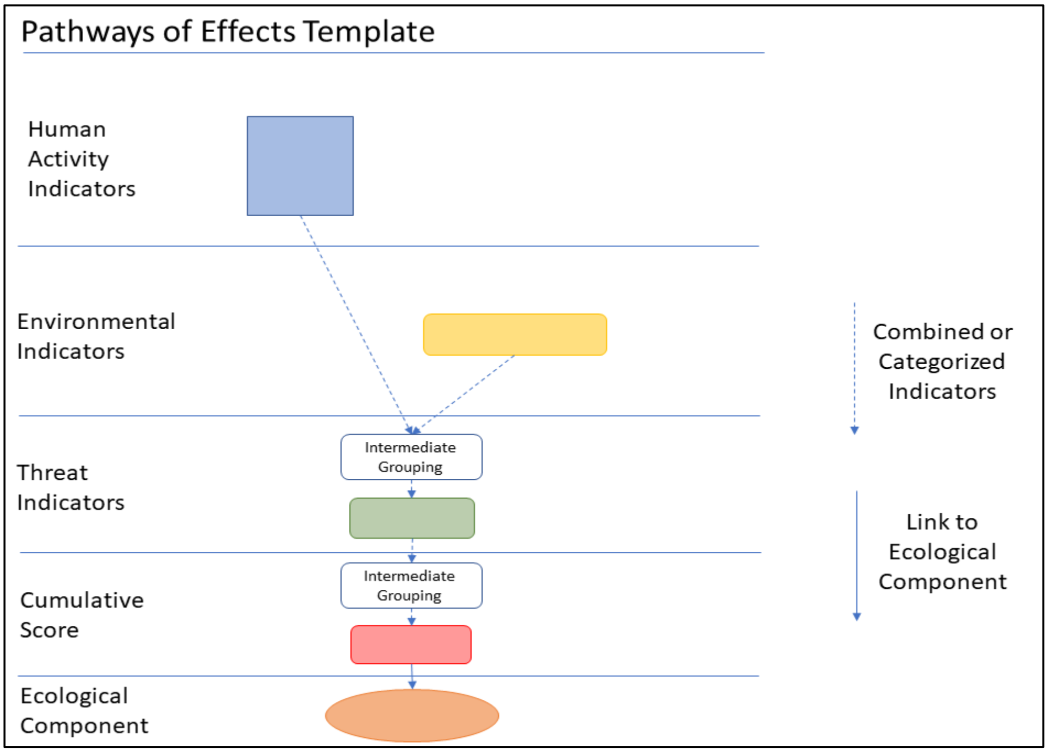


Figure 1. Modified Pathways of Effects template for assessing and comparing geospatial mapping tools. Human activity indicators (blue square) represent development and landscape disturbances (e.g., 'equivalent clearcut area'), and environmental indicators (yellow rectangle) identify features that lead to greater susceptibility to impacts (e.g., proportion of lakes and wetlands) or climate-related characteristics (e.g., changes in flow). Both types of indicators can be used to develop threat indicators (green rectangle) that represent stressors or effects (e.g., high flow hazard) on the ecological component (e.g., fish habitat or watersheds; orange oval). In some cases, different intermediate groupings (white rectangle) were used to quantitatively combine human activity and/or environmental indicators before creating the threat indicator (e.g., 'surface flow attenuation ranking'), or were used to conceptually identify indicator categories (e.g., 'watershed pressures') (dashed arrow). Multiple indicators may then be quantitatively grouped into a final cumulative effect or risk score ('cumulative score) (red box, dashed arrow) that is spatially associated with the ecological component (solid arrow). If indicators were conceptually grouped, but not assigned a final score then this was considered an intermediate grouping.

Though some indicators were similar across tools, many were calculated using different metrics. In particular, the threats of pollution, sedimentation, and riparian disturbance were represented by a couple of tools, but each were calculated with different sub-indicators, metrics, or benchmarks for scoring (Appendix 1, Table A1; Iacarella and Potapova 2022). For instance, the sediment threat indicator was calculated by SBOT using three metrics based on road lengths, road-stream crossings, and disturbance within the riparian zone, and by SIWAP using two related but different road length metrics, logging on slopes, and three environmental characteristic metrics. Notably, these tools used different criteria for distances from streams and steep slope cut-offs to calculate road metrics. PAWPIT and Global Water also estimated total suspended solids (a measure of sediment loading), though this was identified by the tools as a type of pollutant. PAWPIT estimated classes of pollutants including total suspended solids from point source effluent releases and from surface runoff across different landcover types (i.e., agricultural, urban, and non-urban), whereas Global Water used a combination of human population density, vulnerability to water erosion, and published erosion rates to estimate annual water erosion rates as a proxy (Appendix 1, Table A1; Iacarella and Potapova 2022). Each of these tools captured different human activities and environmental characteristics that lead to sedimentation, and it is likely some combination of them that would result in the most comprehensive estimate.

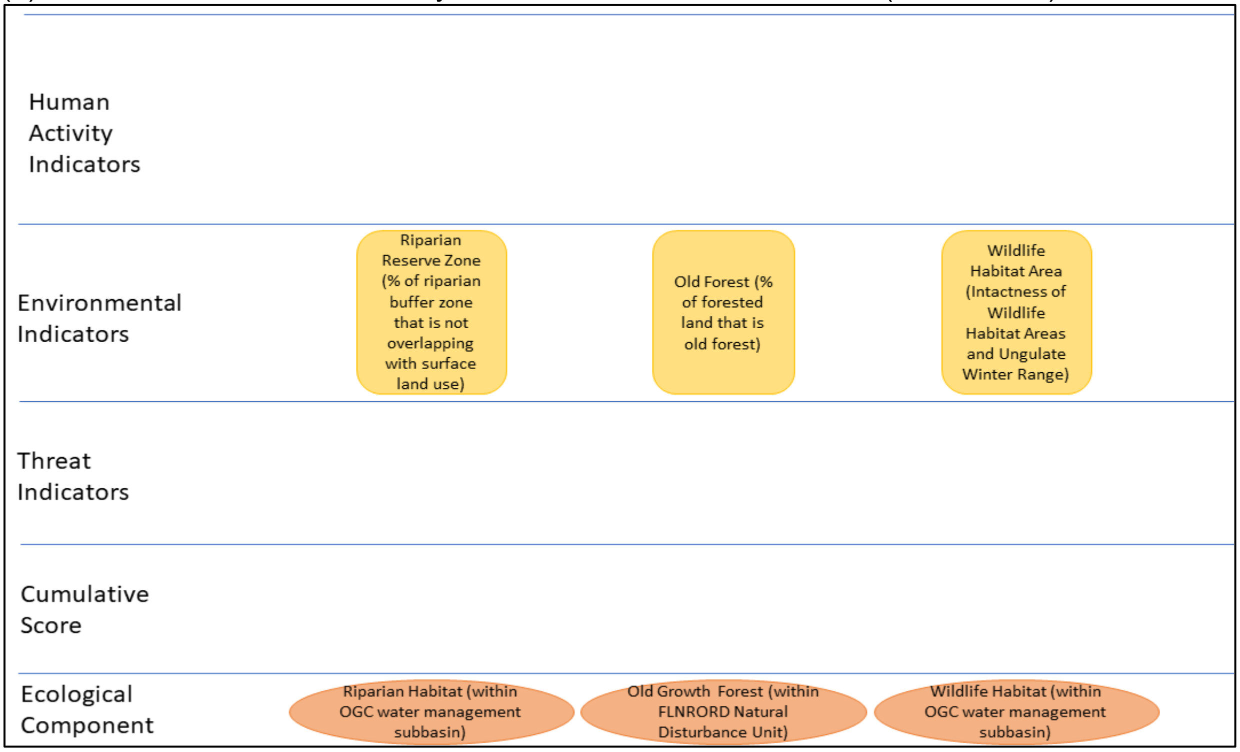
The tools also relied on a variety of data sources, though the majority (except for global tools) used data from the provincial BC Data Catalogue or federally-developed national sources. Data quality may vary. For instance, some data sources used by the tools were outdated, and many represent different time periods (Pacific Salmon Foundation 2021). Thus, the accuracy of indicators in estimating a threat depends on the relevance of the metric, the comprehensiveness across metrics, and the quality of the data sources. This also extends to cumulative effect scores which can be greatly influenced by data with high uncertainty (Halpern and Fujita 2013). There is clearly a lack of consensus on which metrics (and to some extent, data sources) are best for developing threat indicators; attempting to determine this was outside the scope of the review, but was identified as a need for further evaluation. However, some literature review and expert elicitation have been conducted to compile the most likely human-related causes of different threats for indicator estimation (e.g., Stalberg et al. 2009, Boyd et al. 2022). *In situ* validation is a next step that would greatly advance our understanding of the suitability of metrics and data for threat indicators, though this is currently lacking for all of the existing tools except for PAWPIT's contaminant load analysis. PAWPIT's analysis revealed their indicators underestimated *in situ* pollution despite a comprehensive review of point source pollution and surface runoff inputs, and highlighted a need for better quality data (PAWPIT 2022).

Owing to the complexity and variety of indicators and metrics across the 13 tools, we focused the rest of the review at the level of indicators. The presentation of tools below is based on spatial extent (i.e., region, global) and author organization (i.e., non-profit, government) as tools within these categories were most similar in methodology.

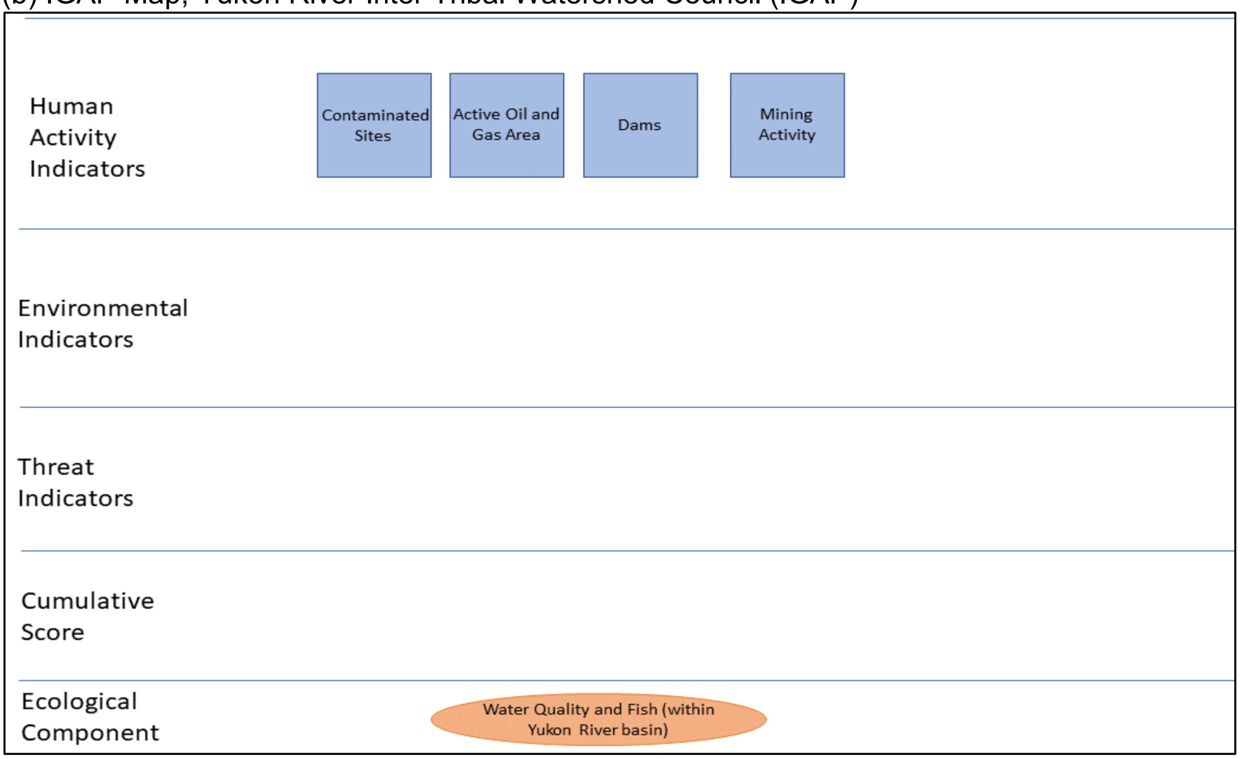
Regional tools from non-government organizations and industry

The application of the standardized PoE model showed the level of indicator analysis used by each tool. All of the tools, except the Peace River Oil and Gas tool, identified human activity indicators. Oil and Gas only included environmental indicators (n = 3), whereas the Yukon-based IGAP tool only included human activity indicators (n = 4) (Fig. 2a-b). PSE largely focused on several mapped human activity indicators (n = 11) rather than threat indicators (n = 2) for BC's salmon-bearing watersheds (Fig. 2c). The activity indicators were combined into general categories relevant to salmon habitat (e.g., 'human development index, 'water quantity') and then rolled up into a cumulative effect score. WWF-Canada had more of a threat indicator focus, with human activity (n = 10) and environmental indicators (n = 4) used to estimate five threats rolled into a threat score relevant to watershed health (Fig. 2d). Some of the human activity indicators used by WWF-Canada are unique to the tool, for instance transportation incidents were used to approximate pollution.

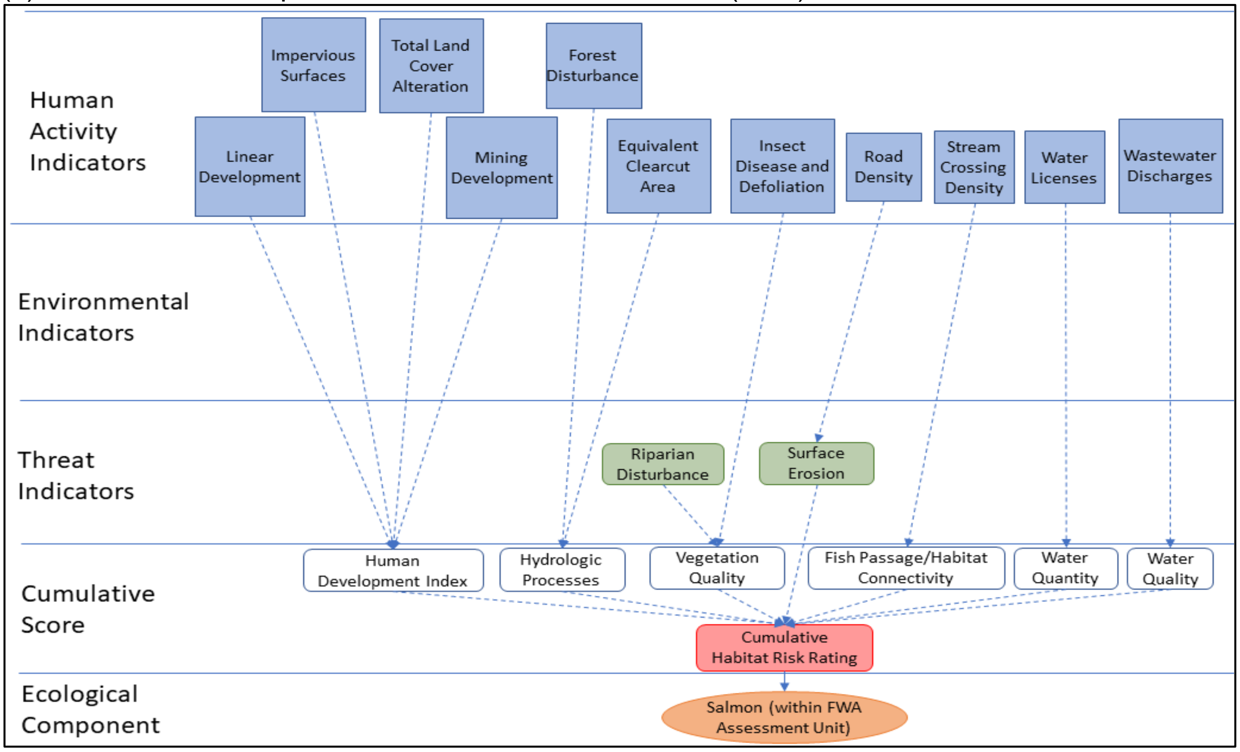
(a) Peace River Area-Based Analysis, BC Oil and Gas Commission (Oil and Gas)



(b) IGAP Map, Yukon River Inter Tribal Watershed Council (IGAP)



(c) Pacific Salmon Explorer, Pacific Salmon Foundation (PSE)



(d) Watershed Reports, World Wildlife Fund-Canada (WWF-Canada)

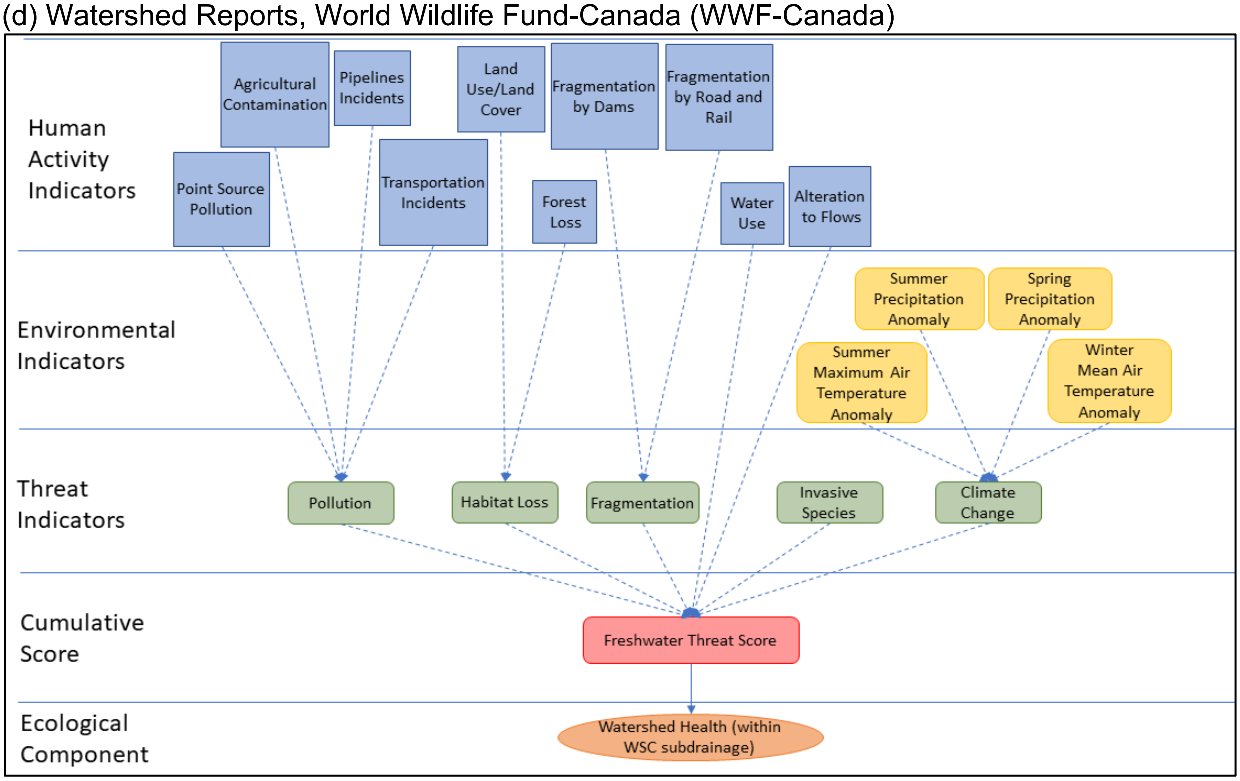


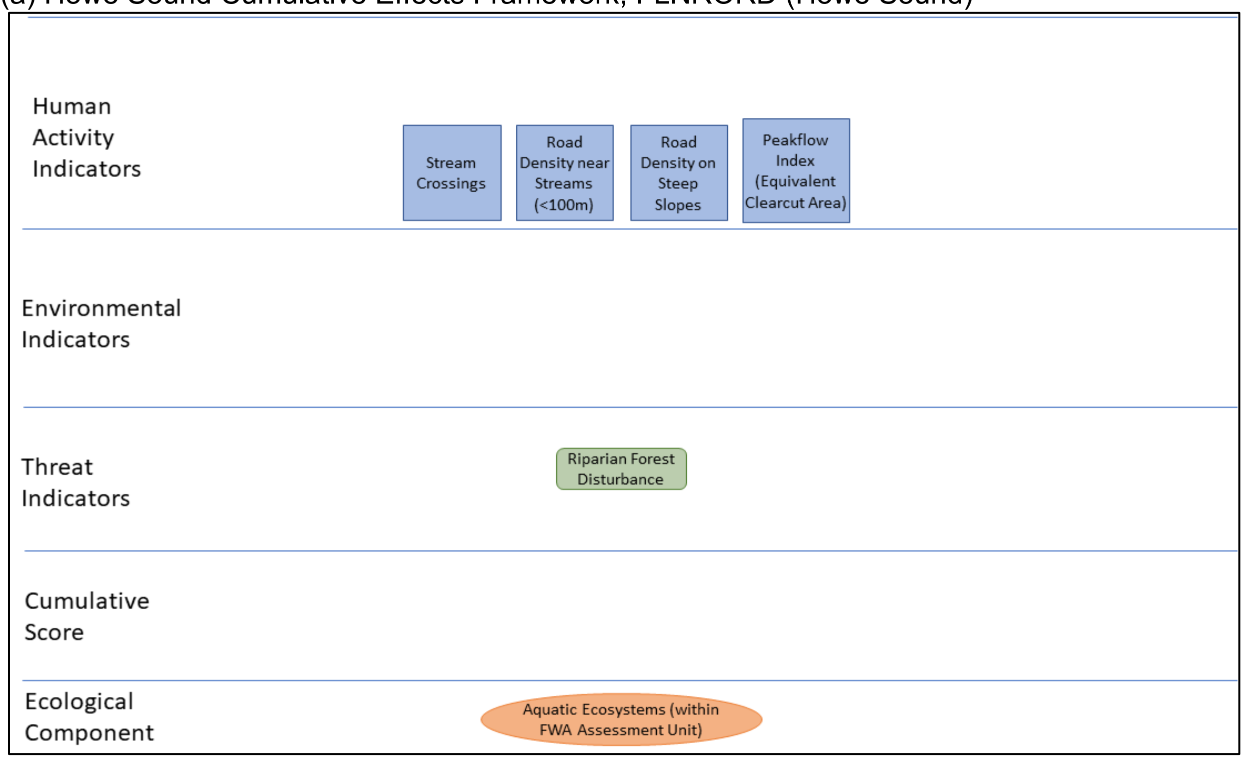
Figure 2. Regional geospatial tools from non-government organizations and industry. Abbreviated names are in parentheses. Acronyms are Oil and Gas Commission (OGC), Ministry of Forests, Lands, Natural Resource Operations and Rural Development (FLNRORD), Freshwater Atlas (FWA), Water Survey of Canada (WSC).

Regional tools from government organizations

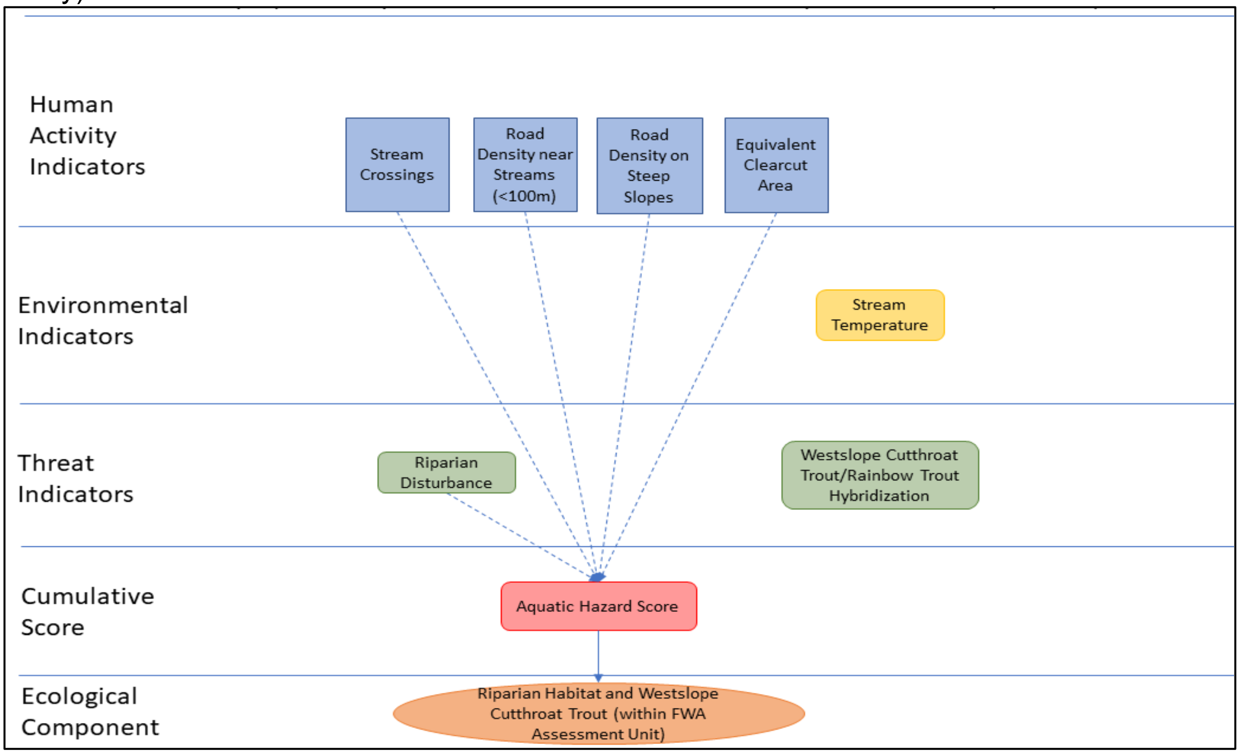
The five BC provincial tools included many of the same human activity indicators as PSE (the data sources largely being developed by the province). Howe Sound and Elk Valley were the simplest tools with 4 human activity indicators, whereas Skeena contained the most human activity indicators (n = 12), which were largely categorized as 'watershed pressures' (Fig. 3a-c). SBOT for South Coast BC was the most interactive online tool from the province, and grouped human activity (n = 5) and environmental indicators (n = 4) into three hazard scores (high flow, sediment, and riparian hazards) relevant to watershed condition based on a series of rankings and inputs (i.e., intermediate metrics) (Fig. 3d). SIWAP for the Thompson-Okanagan Region used the same hazard groupings as SBOT, with some variation on indicator inputs and intermediate metrics (Fig. 3e).

PAWPIT, from Environment and Climate Change Canada, focused on pollutants that affect Chinook Salmon in the Fraser Basin, Vancouver Island, and coastal watersheds (Fig. 3f). A comprehensive list of human activity indicators chosen for their pollution potential (n = 11, including a grouped 'other commercial' category) were used to develop estimates for different types of pollution threats (i.e., point source and three categories of surface runoff [Fraser Basin only]); an air emission threat was assembled directly from emission data.

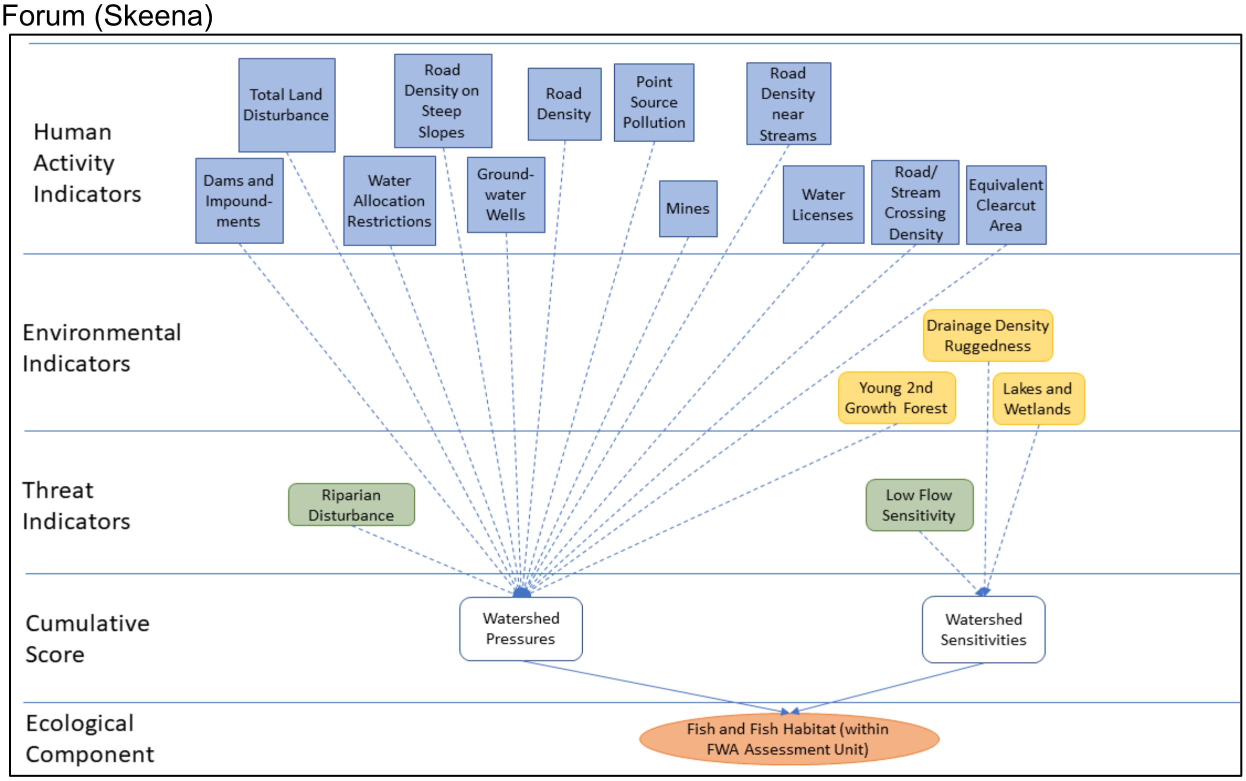
(a) Howe Sound Cumulative Effects Framework, FLNRORD (Howe Sound)



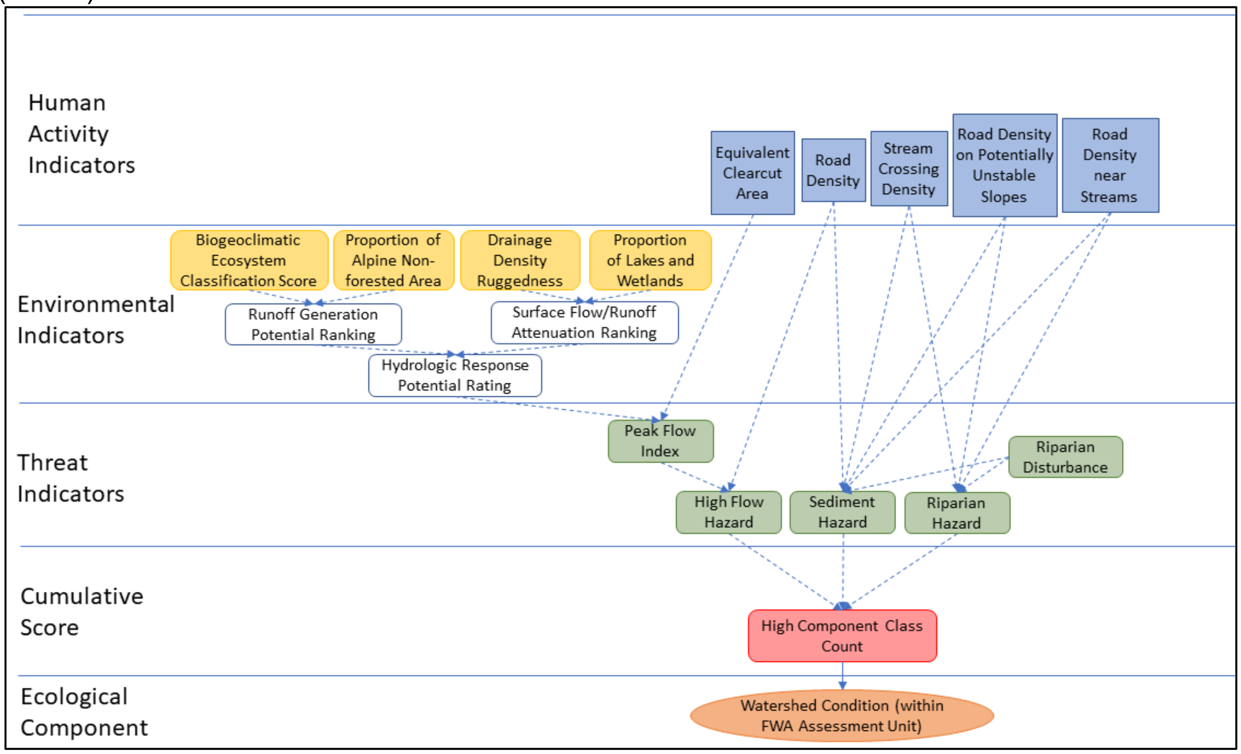
(b) Elk Valley Aquatic Ecosystems Cumulative Effects Assessment Report, FLNRORD (Elk Valley)



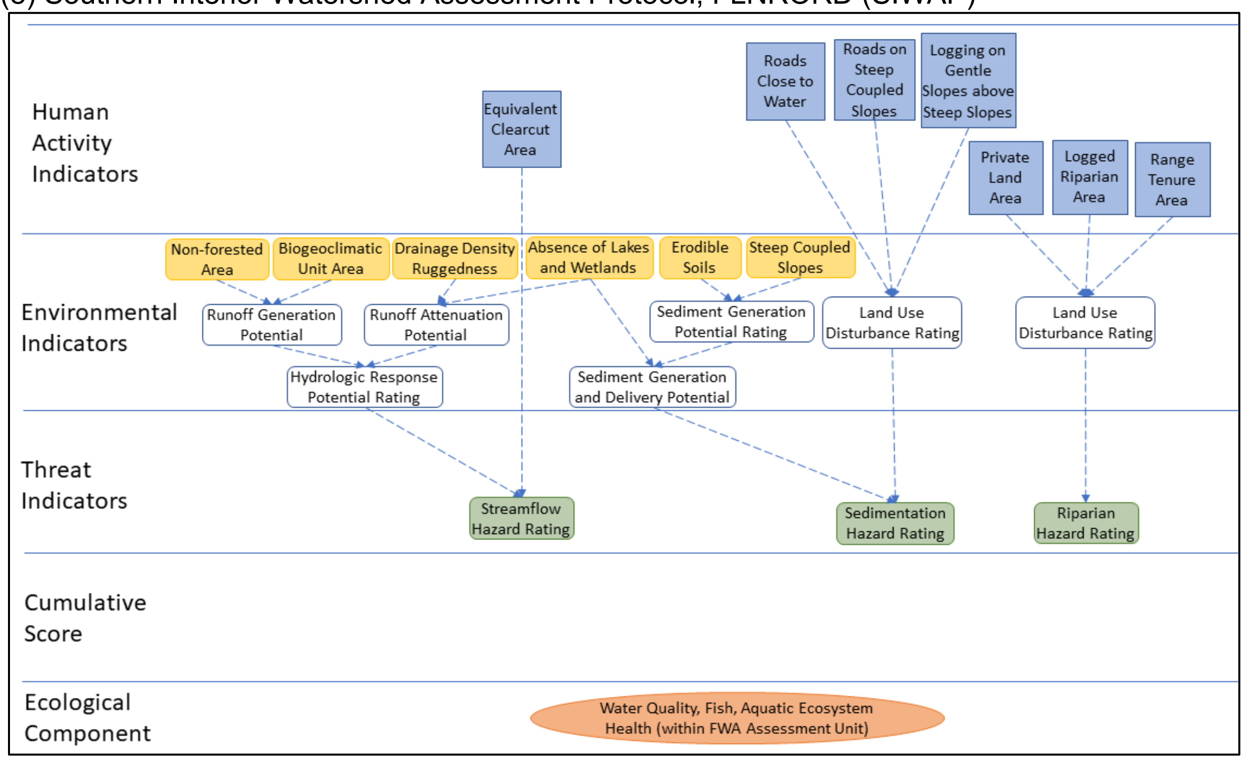
(c) State of the Value Report for Fish and Fish Habitat, Skeena Sustainability Assessment Forum (Skeena)



(d) Stewardship Baseline Objectives Tools for Forested Watershed Condition, FLNRORD (SBOT)



(e) Southern Interior Watershed Assessment Protocol, FLNRORD (SIWAP)



(f) Pollutants Affecting Whales and Their Prey Inventory Tool, Environment and Climate Change Canada (PAWPIT)

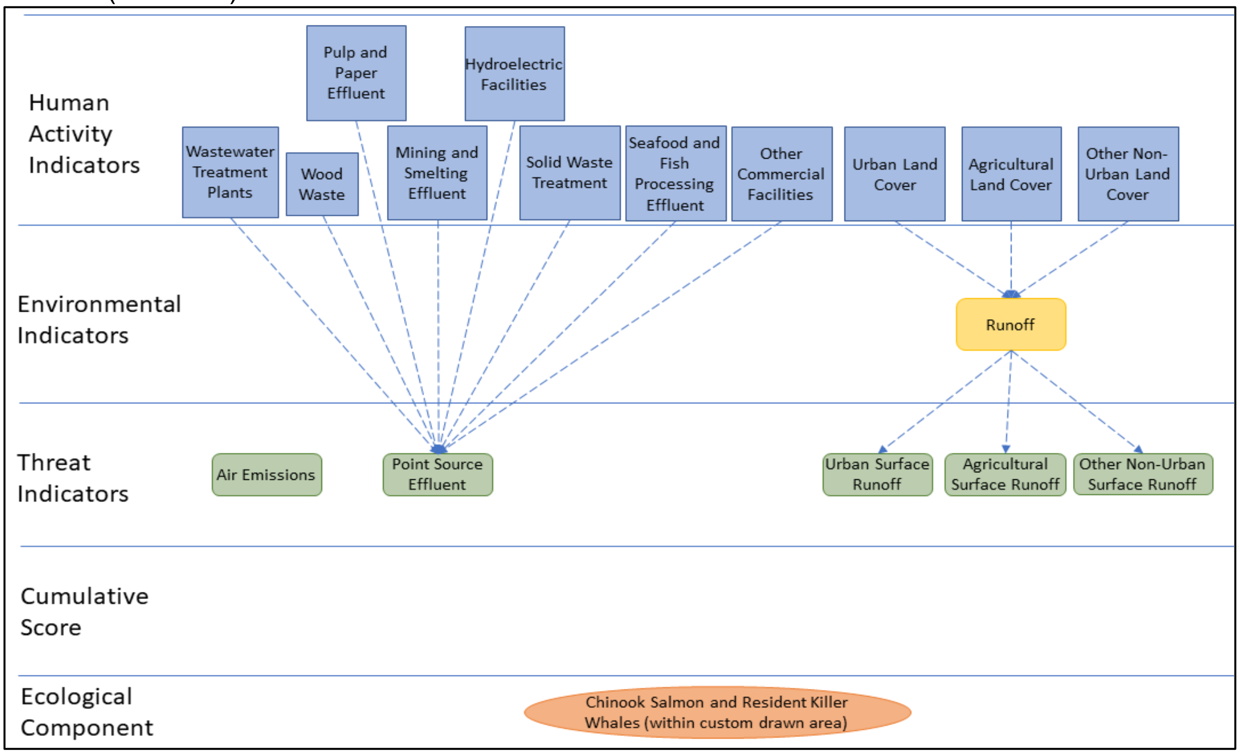
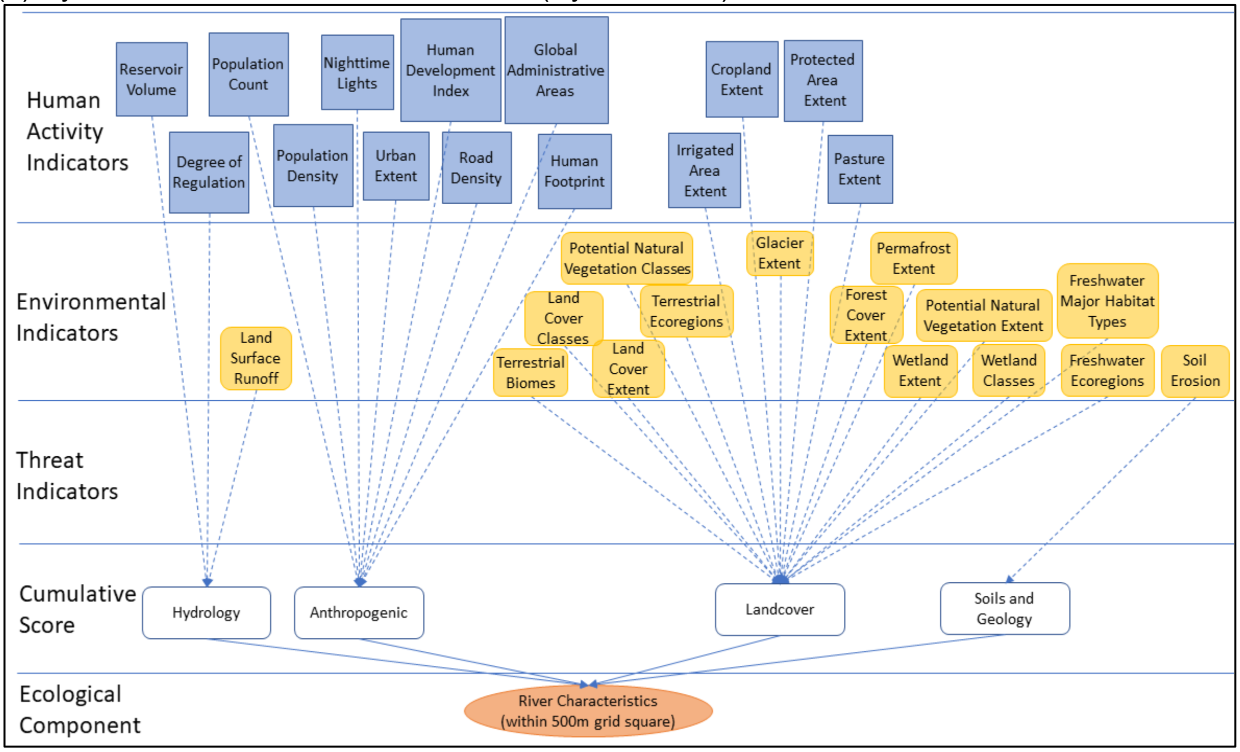


Figure 3. Regional geospatial tools from government organizations. Abbreviated names are in parentheses. Acronyms are for Freshwater Atlas (FWA).

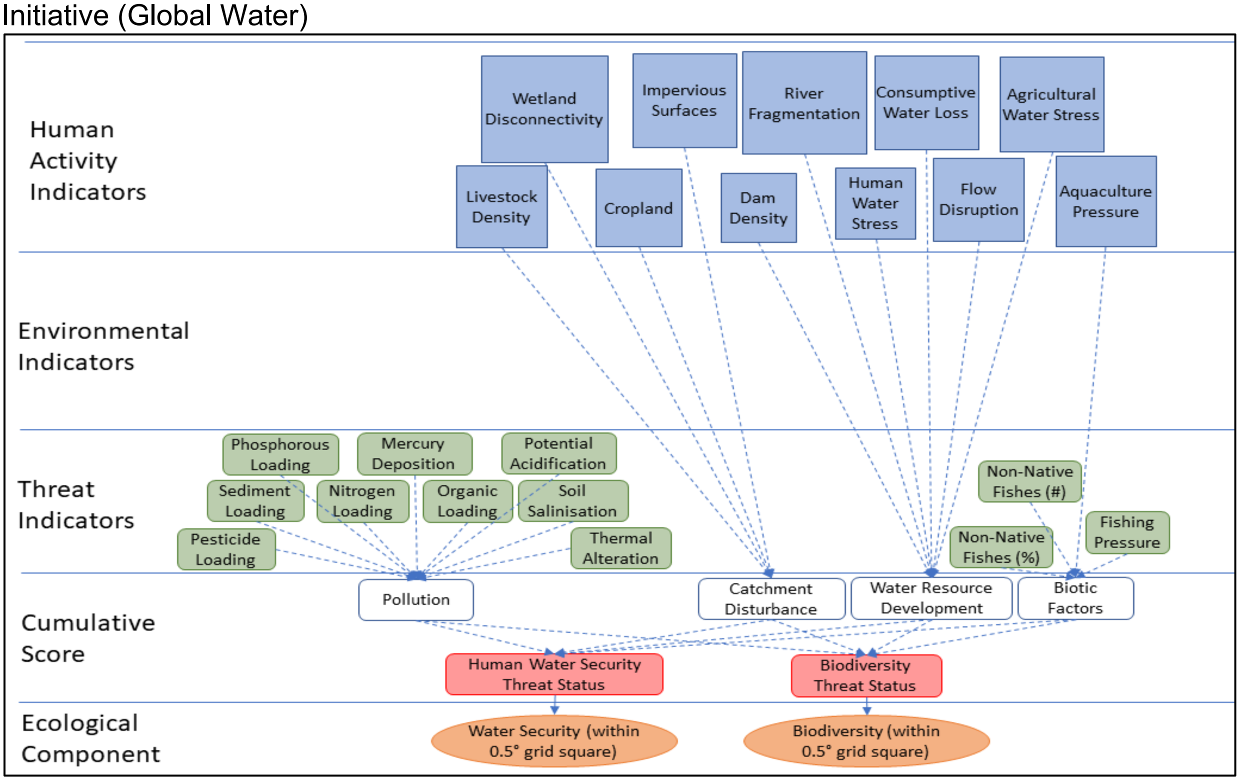
Global tools

HydroATLAS had the most extensive environmental indicators available (n = 13), and also a number of human activities (n = 12) (Fig. 4a). These layers were spatially associated with rivers, but the threats from these activities were not identified and vary in relevance to fish habitat. Global Water had an extensive number of human activity (n = 11) and threat indicators (n = 12; 9 were rolled into a pollution threat indicator) (Fig. 4b). These were grouped into intermediate metrics and then into threat status scores for human water security and biodiversity. Global Forest provided a suite of human activity indicators (n = 8) largely related to a land use category, and extensive environmental indicators (n = 16) related to land cover, forest change, and climate (Fig. 4c).

(a) HydroATLAS, World Wildlife Fund-US (HydroATLAS)



(b) Global Threats to Human Water Security and Biodiversity, Environmental CrossRoads Initiative (Global Water)



(c) Global Forest Watch Interactive World Forest Map, Global Forest Watch (Global Forest)

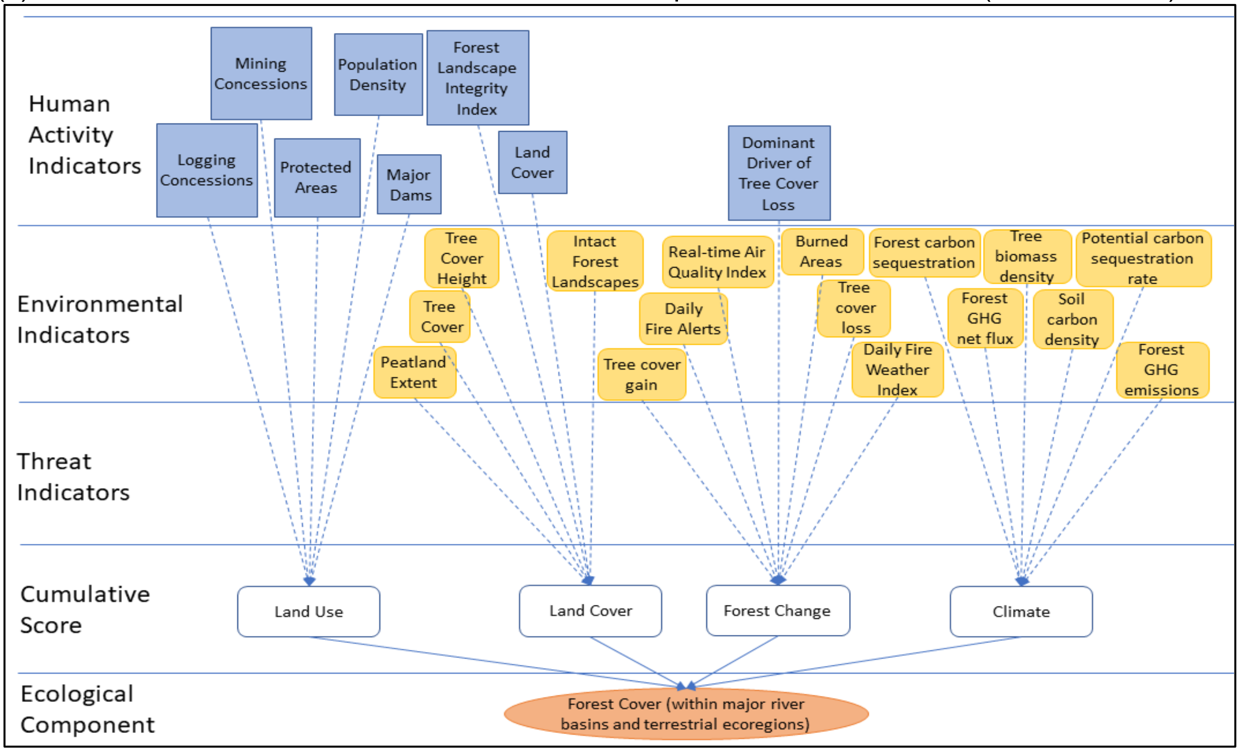


Figure 4. Global geospatial tools. Abbreviated names are in parentheses. HydroATLAS had additional indicators for soil and geology, hydrology, physiography, and climate listed in Iacarella and Potapova (2022).

Methods used to develop indicators

We reviewed the methods used by the geospatial tools to create the indicators, including spatial analysis approaches, resolutions, spatial extents, cumulative effect scoring methods (thresholds, binning, and summation rules), if applicable, and any temporal components to assessing indicators.

Spatial analysis approaches

There are a variety of approaches that can be taken to approximate threats of human activities to freshwater habitat. The simplest approach uses direct overlays of geospatial data and accounts for the amount of activity within a given area of interest. This is a widely used approach for land and seascape geospatial stressors analyses, and was employed by nine of the tools. However, considering flow direction is important for freshwater habitat assessments, and especially for stream network-level analyses. Depending on the extent of dilution, impacts to downstream habitats may be underestimated if flow is not considered for human activities with downstream effects (e.g., pollution from mines). The two primary methods that accounted for downstream effects included using pour points (points on the surface at which water flows out of an area) of catchments or sub-basins to account for increased impacts downstream (HydroATLAS, 19 indicators; WWF-Canada, 1 indicator), and a flow accumulation approach that accounted for human activity inputs along a stream network with defined flow direction and the volume of discharge to account for dilution (Global Water, 14 indicators). SBOT and SIWAP also used elevation of watershed units to estimate indicators within high flow (both) and sedimentation hazards (SIWAP only) within a watershed. PSE identified ‘zones of influence’ as areas of land that drain into important salmon habitat, which uses a direct overlay of activities that are then bounded by watershed units. This accounts for the influence of human activities that are not directly nearby a stream, as do other tools that use watersheds as their spatial resolution (see ‘Resolution’ section below), but does not estimate downstream accumulation (or dilution) for habitats within a watershed.

The contribution of runoff to some threats (e.g., pollution, sedimentation) is another important consideration for freshwater habitat. This was only addressed by PAWPIT, which used modelled surface water runoff and landcover categories (agricultural, urban, and non-urban) to estimate pollutant contributions from these landcover types.

Resolutions and spatial extents

The resolution needed to identify and manage threats to fish habitat is likely different than the resolution needed to report on overall intensity of estimated impacts to fish habitat across a large region. The majority of tools reviewed applied input data to a watershed-level resolution, which is amenable to mapping and highlighting areas across a landscape that are estimated to be more at risk. Six of the tools (PSE and the 5 BC provincial tools) used the 1:20,000 scale Freshwater Atlas (FWA) Assessment Watersheds, which have an average area of 0.3 km^2 (on par with a 0.55 km grid). These units were developed by the province to delineate as many watersheds as possible that fully contained the area of land drained by an interior stream to a point at the watershed boundary with no upstream areas draining into it.

In addition, Oil and Gas used Water Management Basins and WWF-Canada used Water Survey of Canada sub-drainage areas.

HydroATLAS and Global Water gridded their data inputs and applied them to global freshwater systems. Specifically, HydroATLAS used a 15 arc-second grid (~ 0.5 km at the equator) and applied it to sub-basins (‘BasinATLAS’) and river reaches (‘RiverATLAS’). Global Water used a 0.5° grid (~ 55 km) applied to stream networks.

The remaining three tools do not roll up or apply indicators to a freshwater unit. Instead, they mapped point data (IGAP), different resolutions of gridded data (Global Forest), or represented indicators as a heat map (PAWPIT). The latter two, Global Forest and PAWPIT, were effective visualizations of human activity and threat gradients at a finer resolution than watershed units, but did not directly provide summary statistics that may be useful for reporting efforts.

As listed above, WWF-Canada extended across Canada, PSE and SBOT spanned several basins important to salmon in BC, six tools were specific to major watersheds or sub-basins in BC, and three tools were global. IGAP was the only tool specific to the Yukon.

Cumulative effect scoring

Seven of the tools combined indicators into a type of cumulative effect score:

- PSE used two types of methods for each of their indicators to first bin values into low, moderate, and high categories. Eight of the indicators were binned based on statistical delineations (e.g., percentiles, outliers), and four were binned based on literature or expert opinion. Indicators were then grouped into different impact categories (e.g., ‘vegetation quality’, ‘water quality’) and rolled-up into within category low, moderate, high risk bins based on the number of indicators with low/moderate/high rankings (e.g., if 2 of 4 indicators are high, then the risk is high). The final cumulative score was then based on another, similar series of roll-up rules.
- WWF-Canada used four statistical methods to bin indicator values into 3-6 threat levels (e.g., no threat up to very high threat) using percentiles, Jenks natural breaks, standard deviations, or categories from the literature. These binned threats were then assigned

values (e.g., very low threat = 1) and a percentage was calculated based on the total number of levels. The maximum or average was then taken of the percentage threat scores within an indicator category (e.g., ‘pollution’, ‘habitat loss’), and the median across all indicator categories was used as the final cumulative score.

- Elk Valley standardized each continuous indicator from 0-1 (excluding hybridization and stream temperature indicators). The average score across the 5 of 7 applied indicators was then binned into low, moderate, and high hazard scores. Low, moderate, and high scores were also developed for each indicator using literature and expert opinion, though these were not used for the cumulative effect score.
- SBOT used statistical and expert-based approaches to bin each indicator into low, moderate, and high categories based on thresholds from the BC Cumulative Effects Framework (Provincial Aquatic Ecosystems Technical Working Group 2020). For the ‘peak flow index’ threat indicator, SBOT used scoring matrices for each intermediate indicator grouping from the BC Cumulative Effects Framework adapted from SIWAP. The scoring matrices pair indicators so that the value of one indicator influences the risk category of the indicator it is paired with. For example, the peak flow index of a watershed with an equivalent clearcut area of 40% could be rated as either low or high depending on whether the ‘hydrological response potential’ is low or high. Each hazard category (i.e., ‘high flow’, ‘sediment’, and ‘riparian’) was then assigned a low, moderate, or high risk rating based on the highest rating across the relevant indicators. The highest rating across the hazard categories was then selected as the overall cumulative score.
- SIWAP developed the original approach used by SBOT and the scoring matrices within the BC Cumulative Effects Framework (Provincial Aquatic Ecosystems Technical Working Group 2020). SIWAP assigned final values to each hazard category, as above, but did not combine the hazards for an overall cumulative score.
- PAWPIT’s pollution indicators were all calculated in units of kg/year and were directly summed for a cumulative effect of pollutants measure.
- Global Water standardized each indicator value to a continuous 0-1 scale. Indicators were then grouped into intermediate metrics, weighted by importance based on expert opinion, and summed. These metrics were then similarly grouped, weighted by importance, and summed into cumulative effect scores for ‘human water security threat’ and ‘biodiversity threat’. Weights for an indicator or intermediate metric that went into more than one group were different based on importance to that group. For instance, river fragmentation contributed more to ‘biodiversity threat’ (weight = 0.3) than to ‘human water security threat’ (0.03).

As is evident from the variety of approaches used in the above tools, there is currently little consistency or agreement on setting thresholds for binning values, or for roll-up or summation methods for the final cumulative effect score. Ideally, binning is based on ecologically meaningful values such as those measured by stressor-response curves through laboratory experiments (e.g., temperature thresholds; U.S. Environmental Protection Agency 2003) or field observations (DFO 2019b; Iacarella 2022). Secondarily, binning thresholds would be based on expert opinion and literature review. Stalberg et al. (2009; discussed in more detail in ‘other approaches and tools’) provide provisional benchmarks for a number of indicators based on expert opinion and note that these may be further customized for different Pacific salmon Conservation Units or on a watershed basis. The Environmental Protection Agency has also conducted extensive literature reviews on experimental and field temperature responses of salmonids in the Pacific Northwest to create standards for temperature thresholds (U.S.

Environmental Protection Agency 2003). Conversely, binning based on data structure (e.g., percentiles, outliers, deviations) does not account for non-linear and threshold responses, which are ecologically common, and creates indicator scores that are only relevant to the assessed area.

Many iterations and a variety of binning methods and roll-up rules for a single tool can make the final cumulative effect score far removed from the original data. In particular, binning indicator values at the beginning stage of a series of roll-up rules for assigning low, moderate, and high risk levels can prematurely reduce the information provided by continuous data. A more common approach in cumulative effect literature is to standardize scores and sum them before categorizing final scores into risk levels (Halpern and Fujita 2013). This maintains the resolution of the data up to the point of the final scoring method. In addition, it is recommended that any skew in indicator scores is maintained as this represents real differences across the landscape, and to standardize scores based on the highest observed value within the region plus an additional 10% to capture short term increases in threats (Halpern and Fujita 2013). Scores are then often weighted based on expert opinion which aids in giving emphasis to more impactful threats. However, this cumulative effect approach assumes linear and additive responses, which is likely inaccurate but currently widely accepted owing to insufficient information (Halpern and Fujita 2013). An alternative approach used by SBOT and SIWAP, as further detailed in the BC Cumulative Effects Framework (Provincial Aquatic Ecosystems Technical Working Group 2020), is the most conservative as it assigns high risk wherever a high indicator value exists. This is more risk-adverse than statistical (e.g., averaging, summing) or counting (e.g., number of indicators with a certain value) approaches.

Temporal component

The ideal of assessing the state of fish habitat is to update evaluations to determine how threats change over time with the progression of human activities and disturbance across the landscape, and with restoration and conservation actions. Of the tools reviewed, only Global Forest had a temporal component, with the years compared depending on the indicator (and dataset used). For instance, ‘tree cover loss’ was mapped as a time lapse from 2001-2021, whereas ‘intact forest landscapes’ showed the baseline in 2000 and patches of subsequent loss from 2000-2013 and 2013-2016. As in other tools, human activities such as mining were only provided as a single snapshot in time.

It was not within scope to determine whether and how frequently the human activity data sources for the Pacific Region are updated to enable a temporal component (but for a list of data sources for each tool indicator see Iacarella and Potapova 2022). However, PSE indicated that many of the BC provincial layers are not currently updated and some of the layers used by regional tools are quite outdated. For instance, the ‘Aggregate Mining Inventory’ used by PSE was published in 2004 (see Appendix 7 in Pacific Salmon Foundation 2021). In general, the human activity data sources with the best temporal component are forestry layers which in some cases have annual information, as evidenced by the global layers used by Global Forest. Land cover layers are also updated by Natural Resources Canada every five years. Climate data used to develop stream temperature and flow indicators can also provide a daily temporal resolution (e.g., Pacific Climate Impacts Consortium Explorer described in ‘Other approaches and tools informally reviewed’). However, given limited updates to data and different temporal extents of each dataset, the reviewed tools currently provide threat estimates as a single snapshot in time.

Indicators linked to threats in the FFHPP Policy Statement, Interim Risk Management Guide, and COSEWIC reports

We identified which indicators from the geospatial tools were linked to the threats listed in the Fish and Fish Habitat Protection Policy Statement (DFO 2019) and to pressures identified in the Interim Risk Management Guide for the Protection of Fish and Fish Habitat (DFO 2019b) to determine whether these tools addressed some aspect of the threats deemed important by FFHPP. We further determined which tools included indicators related to threats listed by COSEWIC. To do this, we compiled key threats reported in COSEWIC documents to be impacting populations of Pacific salmon and freshwater SAR in the Pacific Region. We reviewed 28 COSEWIC reports for 26 Chinook DUs, one Coho DU, 24 Sockeye DUs, and 25 SAR. We extracted and grouped freshwater threats into 14 categories: avalanches and landslides, high flow, low flow, high temperature, habitat degradation, habitat fragmentation, hatchery enhancement, interactions with invasive species, interactions with problematic native species, changes in pathogen transmission from high temperatures, pollution, recreation (i.e., canoeing noted as a threat to stickleback), riparian habitat loss, and sedimentation. Finally, we identified whether COSEWIC-reported threats were encompassed by the Policy Statement (DFO 2019) and Interim Risk Management Guide (DFO 2019b) to evaluate if there were any key threats that may need further consideration by FFHPP.

We note that some FFHPP and COSEWIC-listed threats have many different aspects, for instance habitat degradation and modification, and the geospatial tools may only address some of them. For instance, dredging is a human activity that leads to habitat degradation and modification, but was not included in the tools. The human activities and threats represented in the tools tended to be those that have readily available spatial data. Each tool provided different indicators that were relevant to FFHPP and COSEWIC threats, and as noted previously, these were comprised of a variety of metrics. The quality of the indicators can be better evaluated by comparing the metrics used, as in Appendix 1, Table A1 and in Iacarella and Potapova (2022); for instance, point source pollution estimates from PAWPIT and Global Water were much more developed than the count of pollutant sources included in Skeena. We provided Tables 2-4 to show which indicators from each tool were related to FFHPP and COSEWIC threats (as identified by the tools) to provide an overview. This again highlighted the variety of indicators that may be used to assess a threat, and enabled high-level, relative comparisons of the comprehensiveness of the evaluations by the tools and of the priority threats. We note that ‘addressing’ a threat does not imply that all aspects of the threat have been estimated.

The FFHPP Policy Statement (DFO 2019) threats of habitat degradation and modification were commonly addressed by the geospatial tools (n = 11 tools for both), whereas aquatic invasive species (n = 2), pollution (n = 5), and climate change (n = 2) were more often missing (Table 2). WWF-Canada was the only tool that addressed some aspect of all of these threats, and Global Water had links to all but climate change. PSE, Howe Sound, SBOT, SIWAP, HydroATLAS, and Global Forest all evaluated habitat degradation and modification threats, but none of the other threats. WWF-Canada and Elk Valley were the only tools that incorporated some aspect of climate change.

The Interim Risk Management Guide (DFO 2019b) threat of fish passage change or loss was addressed the most frequently by the geospatial tools (n = 10), whereas aquatic vegetation change, changes in food supply, and dissolved oxygen were not evaluated by any of the tools (Table 3). Many of the tools (n = 8) had indicators relevant to at least 3 of the 8 threats, with Global Water connected to the most threats with 4.

Similar to the FFHPP threats, habitat degradation and fragmentation were the most commonly evaluated COSEWIC threats by the geospatial tools (n = 11, n = 10, respectively) (Table 4).

Hatchery enhancement, pathogen transmission, and recreation were not addressed by the tools, and avalanches/landslides (SBOT, SIWAP) and interactions with problematic native species (Elk Valley) were infrequently included. Global Water evaluated the most COSEWIC threats (n = 8), followed by WWF-Canada, Elk Valley, and Skeena (n = 7 for all three).

COSEWIC-reported threats that are not currently accounted for in the FFHPP Policy Statement (DFO 2019) or Interim Risk Management Guide (DFO 2019b) are avalanches/landslides, hatchery enhancement, interactions with problematic native species, changes in pathogen transmission from high temperatures, and recreation (Table 5). The COSEWIC threat of pollution matched up with the most threats listed by FFHPP (pollution, deleterious substances, dissolved oxygen, nutrients). In particular, eutrophication (i.e., excess nutrient inputs) and anoxia (i.e., low dissolved oxygen) are noted by COSEWIC as pollution threats.

Table 2. Indicators assessed by geospatial tools that are relevant to evaluating threats listed in the Fish and Fish Habitat Protection Policy Statement (DFO 2019). Indicators were only included under listed threats when the tool identified the link to the threat; for instance, if a tool included road density as an indicator but did not state it was included as a proxy for sedimentation, we did not make the link ourselves.

	FFHPP Policy Statement Threats				
Tool	**Habitat degradation**	**Habitat modification**	**Aquatic invasive species**	**Pollution**	**Climate change**
Oil and Gas	-	-	-	-	-
IGAP	Mines, Oil and gas	Dams	-	Contaminated sites	-
PSE	Equivalent clearcut area, Impervious surfaces, Linear development, Mines, Total land cover alteration	Equivalent clearcut area, Stream crossings, Water licenses	-	-	-
WWF-Canada	Dams, Forest loss, Land use/Land cover, Road and rail crossings	Alteration to flows, Dams, Road and rail crossings, Water use	Invasive species	Agricultural contamination, Pipeline incidents, Point source pollution, Transportation incidents	Spring precipitation anomaly, Summer maximum air temp. anomaly, Summer precipitation anomaly, Winter mean air temp. anomaly
Howe Sound	Equivalent clearcut area, Road density indicators, Stream crossings	Equivalent clearcut area, Stream crossings	-	-	-
Elk Valley	Equivalent clearcut area, Road density indicators, Stream crossings	Equivalent clearcut area, Stream crossings	-	-	Stream temp.
Skeena	Dams, Equivalent clearcut area, Mines, Road density indicators, Stream crossings, Total land disturbance	Dams, Equivalent clearcut area, Groundwater wells, Water allocation restrictions, Water licenses, Stream crossings	-	Point source pollution	-
SBOT	Equivalent clearcut area, Road density indicators	Equivalent clearcut area, Stream crossings	-	-	-
SIWAP	Equivalent clearcut area, Road density indicators	Equivalent clearcut area	-	-	-

	FFHPP Policy Statement Threats				
Tool	**Habitat degradation**	**Habitat modification**	**Aquatic invasive species**	**Pollution**	**Climate change**
PAWPIT	-	-	-	Air emissions, Point source effluent, Urban, non-urban, and agricultural runoff	-
HydroATLAS	Cropland, Human footprint, Pasture, Roads, Urban extent	Degree of regulation, Irrigated area extent, Reservoir volume	-	-	-
Global Water	Cropland, Dams, Impervious surfaces, River fragmentation, Wetland disconnectivity	Consumptive water loss, Dams, Flow disruption, River fragmentation Water stress	Non-native fishes	Mercury deposition, Nitrogen, Organic loading, Pesticide loading, Phosphorous, Sediment, Potential acidification, Soil salinisation, Thermal alteration	-
Global Forest	Dams, Dominant driver of tree cover loss, Forested landscape integrity index, Land cover, Logging, Mines	Dams	-	-	-

Table 3. Indicators assessed by geospatial tools that are relevant to evaluating threats listed in the Interim Risk Management Guide for the Protection of Fish and Fish Habitat (DFO 2019b). Indicators were only included under the listed threats when the tool identified the link to the threat; for instance, if a tool included road density as an indicator but did not state it was included as a proxy for sedimentation, we did not make the link ourselves. Aquatic vegetation change, changes in the food supply, and dissolved oxygen were not addressed by any of the tools so were not included in the Table.

	FFHPP Interim Risk Management Guide Threats				
Tool	**Riparian change**	**Fish passage change or loss**	**Sedimentation**	**Deleterious substances**	**Nutrients**
Oil and Gas	Riparian reserve zone	-	-	-	-
IGAP	-	Dams	-	Contaminated sites	-
PSE	Riparian disturbance	Stream crossings	Surface erosion	-	-
WWF-Canada	-	Dams, Road and rail crossings	-	Pipeline incidents, Point source pollution, Transportation incidents	Agricultural contamination
Howe Sound	Riparian forest disturbance	Stream crossings	Road density indicators	-	-
Elk Valley	Riparian disturbance	Stream crossings	Road density indicators	-	-
Skeena	Riparian disturbance	Stream crossings	Road density indicators	Point source pollution	-
SBOT	Riparian disturbance	Stream crossings	Road density indicators	-	-
SIWAP	Riparian hazard	-	Road density indicators	-	-
PAWPIT	-	-	Point source effluent, Urban, non-urban, and agricultural runoff	Air emissions, Point source effluent, Urban, non-urban, and agricultural runoff	Point source effluent, Urban, non-urban, and agricultural runoff
HydroATLAS	-	Degree of regulation, Reservoir volume	Soil erosion	-	-
Global Water	-	Dams, River fragmentation	Sediment loading	Mercury deposition, Pesticide loading, Potential acidification, Soil salinisation	Livestock density, Nitrogen loading, Organic loading, Phosphorous loading
Global Forest	-	Dams	-	-	-

Table 4. Indicators assessed by geospatial tools that are relevant to evaluating threats reported by COSEWIC for salmon Designatable Units and Species at Risk in the Pacific Region. Indicators were only included under listed threats when the tool identified the link to the threat; for instance, if a tool included road density as an indicator but did not state it was included as a proxy for sedimentation, we did not make the link ourselves. Hatchery enhancement and changes in pathogen transmission from high temperatures were not addressed by any of the tools so were not included in the Table.

	COSEWIC Threats										
Tool	**Avalanches/ Landslides**	**High flow**	**Low flow**	**High temperature**	**Habitat degradation**	**Habitat fragmentation**	**Invasive species**	**Problematic native species**	**Pollution**	**Riparian habitat loss**	**Sedimentation**
Oil and Gas	-	-	-	-	-	-	-	-	-	Riparian reserve zone	-
IGAP	-	-	-	-	Mines, Oil and gas	Dams	-	-	Contaminated sites	-	-
PSE	-	Equivalent clearcut area	Water licenses	-	Impervious surfaces, Linear development, Mines, Total land cover alteration	Stream crossings	-	-	-	Riparian disturbance	Surface erosion
WWF-Canada	-	Alteration to flows, Forest loss	Alteration to flows, Water use	Summer max air temp. anomaly, Winter mean air temp. anomaly	Forest loss, Land use/Land cover	Dams, Road and rail crossings	Invasive species	-	Agricultural contamination, Pipeline incidents, Point source pollution, Transportation incidents	-	-
Howe Sound	-	Equivalent clearcut area	-	-	Road density indicators	Stream crossings	-	-	-	Riparian forest disturbance	Road density indicators

COSEWIC Threats											
Tool	**Avalanches/ Landslides**	**High flow**	**Low flow**	**High temperature**	**Habitat degradation**	**Habitat fragmentation**	**Invasive species**	**Problematic native species**	**Pollution**	**Riparian habitat loss**	**Sedimentation**
Elk Valley	-	Equivalent clearcut area	-	Stream temp.	Road density indicators	Stream crossings	-	WCT/ RBT hybridiz-ation	-	Riparian disturbance	Road density indicators
Skeena	-	Equivalent clearcut area	Groundwater wells, Low flow sensitivity, Water allocations, Water licenses	-	Road density indicators, Total land disturbance	Dams, Stream crossings	-	-	Point source pollution	Riparian disturbance	Road density indicators
SBOT	Roads on unstable slopes	Equivalent clearcut area	-	-	Road density indicators	Stream crossings	-	-	-	Riparian disturbance	Road density indicators
SIWAP	Logging above steep slopes	Equivalent clearcut area	-	-	Range tenure area, Road density indicators	-	-	-	-	Riparian hazard	Road density indicators
PAWPIT	-	-	-	-	-	-	-	-	Air emissions, Point source effluent, Urban, non-urban, and agricultural runoff	-	Point source effluent, Urban, non-urban, and agricultural runoff

	COSEWIC Threats										
Tool	**Avalanches/ Landslides**	**High flow**	**Low flow**	**High temperature**	**Habitat degradation**	**Habitat fragmentation**	**Invasive species**	**Problematic native species**	**Pollution**	**Riparian habitat loss**	**Sedimentation**
HydroATLAS	-	Land surface runoff	Land surface runoff	-	Cropland, Human footprint, Pasture, Road density, Urban extent	Degree of regulation, Reservoir volume	-	-	-	-	Soil erosion
Global Water	-	Impervious surfaces	Consumptive water loss, Flow disruption, Water stress	Thermal alteration	Cropland, Impervious surfaces, Wetland disconnectivity	Dams, River fragment-ation	Non-native fishes	-	Acidification, Pesticide, Phosphorous, Mercury, Nitrogen, Organic loading, Soil salinisation, Thermal alteration	-	Sediment loading
Global Forest	-	-	-	-	Dams, Driver of tree cover loss, Forested landscape index, Land cover, Logging, Mines	Dams	-	-	-	-	-

Table 5. Comparison of threats reported by COSEWIC for salmon Designatable Units and Species At Risk in the Pacific Region versus threats listed in the Fish and Fish Habitat Protection Policy Statement (DFO 2019) and Interim Risk Management Guide for the Protection of Fish and Fish Habitat (DFO 2019b).

	COSEWIC Threat													
FFHPP/ Interim Risk Management Guide Threats	**Avalanches/Landslides**	**High flow**	**Low flow**	**High temperature**	**Habitat degradation**	**Habitat fragmentation**	**Hatchery enhancement**	**Invasive species**	**Problematic native species**	**Pathogen transmission**	**Pollution**	**Recreation**	**Riparian habitat loss**	**Sedimentation**
Habitat degradation	-	-	-	-	✓	✓	-	-	-	-	-	-	-	-
Habitat modification	-	✓	✓	-	✓	✓	-	-	-	-	-	-	-	-
Aquatic invasive species	-	-	-	-	-	-	-	✓	-	-	-	-	-	-
Pollution	-	-	-	-	-	-	-	-	-	-	✓	-	-	-
Climate change	-	✓	✓	✓	-	-	-	-	-	-	-	-	-	-
Riparian change	-	-	-	-	-	-	-	-	-	-	-	-	✓	-
Aquatic vegetation change	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fish passage change or loss	-	✓	✓	-	-	✓	-	-	-	-	-	-	-	-
Sedimentation	-	-	-	-	-	-	-	-	-	-	-	-	-	✓
Deleterious substances	-	-	-	-	-	-	-	-	-	-	✓	-	-	-
Changes in the food supply	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Dissolved oxygen	-	-	-	-	-	-	-	-	-	-	✓	-	-	-
Nutrients	-	-	-	-	-	-	-	-	-	-	✓	-	-	-

Other approaches and tools informally reviewed

We identified ten other geospatial approaches and tools that are useful for assessing and reporting on the state of fish habitat. These were not within scope for the full review because they were not public facing and online, or were for areas outside of the Pacific Region. This is not a comprehensive list of other approaches and tools, but these were collated during our search for tools and through discussions with DFO and FLRNORD. In addition, there are many studies on relationships between human activity and threat indicators and fish responses, as well as on cumulative effects on freshwater fish, that can be useful for large scale management and reporting. These were not fully reviewed here because they are not currently framed or developed as accessible geospatial tools, or they applied tools reviewed here (e.g., Chen and Olden 2020 used HydroATLAS; Iacarella 2022 used PSE). However, some notable methods provided that were lacking from the existing geospatial tools were (1) assessment of change in climate- and human activity-associated threats over time (Chu et al. 2015; Chen and Olden 2020), (2) use of stressor-response curves for creating non-linear, fish abundance-based cumulative effect scores (DFO 2019c), and (3) application of models on non-linear responses of fish diversity to create cumulative effect scores (Iacarella 2022).

Two indicator approaches that are focused on fish and fish habitat but not yet developed as online tools are from DFO. Stalberg et al. (2009) developed an approach for monitoring and managing salmon habitat in freshwater and estuaries that identified key pressure (i.e., threat) and state (e.g., water quality) indicators through working group and expert discussions. For streams, they focused on 5 pressure indicators (total land cover alteration, road development, water extraction, riparian disturbance, permitted discharges), 6 state indicators (sediment, water quality, salmon rearing temperature, spawning migration temperature, stream discharge, benthic invertebrates), and 2 habitat quantity indicators (accessible stream length, spawning area length). They provided recommended metrics of measurement, methods for measurement, and risk thresholds relevant to salmon based on literature and expert opinion. Many of the tools reviewed above address similar indicators as the pressure indicators Stalberg et al. (2009) identified, though Elk Valley and WWF-Canada are the only ones that have incorporated some of the indicators relevant to states of stream temperature and discharge. The other DFO approach focused on freshwater threat assessment for salmon and SAR habitat is detailed in Boyd et al. (2022). This geospatial tool focused on 7 threats reported by COSEWIC for species within the Fraser Valley Region as an in initial proof of concept. Spatial analysis and mapping was conducted at a stream reach resolution (1st order streams using a 25 m grid), and downstream accumulation of relevant human activities were accounted for using flow accumulation analysis. A final cumulative effect score was calculated by standardizing each indicator and summing values for a continuous score applied across stream reaches and within habitat patches. State indicators including stream temperature and discharge under different climate scenarios are to be incorporated in the next iteration (Boyd et al. 2022).

The Pacific Northwest has similar geospatial assessment and reporting needs for salmon habitat and has a variety of online tools, some of which have indicators not yet included in Pacific Region tools, as well as incorporation of Indigenous knowledge. Another tool that has been used by FLNRORD in developing SBOT is from Minnesota. The tools are briefly summarized below:

1. State of Salmon in Watersheds 2020: Washington State Recreation and Conservation Office – Governor's Salmon Recovery Office
    a. Largely qualitative assessment of the state of salmon and salmon habitat across Washington using six key indicators: salmon, funding for restoration projects, habitat, water quality and quantity, harvest, and hatcheries.

   b. Displays quantitative data for salmon population abundance and harvest, as well as some high-level data for habitat indicators aggregated for Washington.
   c. Geospatial component only includes mapping out locations of water quality monitoring sites and hatcheries.
   d. On a regional basis, indicators are discussed using "case studies" that highlight habitat restoration and salmon recovery efforts, and assessments of hatchery and hydropower management across each region.

2. State of Our Watersheds 2020: Northwest Indian Fisheries Commission
   a. Web map delineating Areas of Interest for 20 Tribal Chapters across Western Washington, linked to regional reports on habitat indicators relevant to each Tribe's Area of Interest.
   b. Indicators include shoreline armoring, impervious surfaces, forest cover, riparian forest cover, culverts, water quality, water wells, invasive species, water quality for shellfish, road density and crossings, streamflow, ocean conditions, and others chosen as locally relevant by specific Tribal Chapters.
   c. Relevant indicators are mapped (non-interactive) across each Area of Interest, and some have been quantified at the local sub-watershed scale and have been assigned risk categories based on benchmark values.
   d. Reporting has been carried out every four years since 2012 (2012, 2016, 2020) with an assessment of each indicator's improvement or deterioration since the last report.
3. Puget Sound Watershed Characterization Project: Washington Department Fish and Wildlife, Habitat Program, Olympia, Washington
   a. Interactive geospatial tool for the Puget Sound Basin that maps the relative conservation value of local sub-watershed units based on cumulative indices, with a focus on salmonid habitat and land use planning.
   b. Indicator groups made up of sub-indicators included water flow, water quality, and fish and wildlife habitats. Some indicators account for downstream effects (e.g., downstream salmonid habitat).
   c. Water flow and quality indicators are further broken down into assessments of each sub-watershed's contribution to natural flows and sediment/nutrient delivery processes, as well as their levels of anthropogenic degradation, and protection and restoration.
4. Mackenzie River Basin Board State of the Aquatic Ecosystem Report: Mackenzie River Basin Board
   a. Web-based aquatic ecosystem assessment for the Mackenzie-Great Bear, Peel, Liard, Great Slave, Peace and Athabasca watersheds, combining multiple knowledge systems (Indigenous knowledge and scientific information based on environmental monitoring).
   b. Ecosystem integrity was assessed using "signs and signals" organized into four indicator groups containing sub-indicators: water quantity, water quality, habitat and species, and health and wellbeing.
   c. Assessment was based on an extensive literature review of both scientific and Indigenous knowledge, and basin-wide data analysis.

   d. Qualitative health index ratings (minimal or no change, moderate change, and significant change) were assigned for each indicator across both knowledge systems and findings were presented and discussed collectively across knowledge systems.
   e. Past reporting included 2003 and 2012, but 2021 was the first year that includes Indigenous knowledge.

5. Minnesota Department of Natural Resources Watershed Health Assessment Framework: Minnesota Department of Natural Resources.
   a. Interactive geospatial tool for the State of Minnesota used to assess watershed health at multiple watershed scales using a cumulative 'ecological health score'.
   b. The Ecological Health Score is calculated as the mean of five indicator groups made up of sub-indicators: hydrology, geomorphology, biology, connectivity, and water quality.
   c. Indicator scores were scaled from 0-100, with some indicators (e.g., impervious surfaces) binned into impact categories.
   d. Outputs PDF "Report Cards" with summary data for each major watershed.

Finally, approaches and tools with specific foci on state indicators relevant to fish habitat that have useful geospatial layers and indicator classification methods are the Pacific Climate Impacts Consortium Explorer, the California Environmental Flows Framework (California Environmental Flows Working Group 2021), and the Environmental Protection Agency Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards (U.S. Environmental Protection Agency 2003). The Pacific Climate Impacts Consortium Explorer is a mapping tool for gridded (30 km^2) climate data and modelled hydrological data under historical and future climate change scenarios. The current extent of gridded hydrological outputs are for the Peace, Fraser, and Columbia basins. The Pacific Climate Impacts Consortium is collaborating with DFO to extend these models to coastal watersheds, as well as to produce hydrologic-based stream temperature models at the same resolution. The California Environmental Flows Framework provides an approach for standardizing environmental flow monitoring and suggests several important metrics of flow including fall pulse flow, wet-season baseflow and peak flow, spring recession flow, and dry-season baseflow. The EPA Water Quality Standards provide guidelines for temperature thresholds that are suitable for salmonid habitat specific to life-stage and based on extensive review of literature on lab- and field-based temperature responses of salmonids. These resources can be used to help fill the gap in many of the Pacific Region tools for evaluating stream temperature and flow indicators.

Conclusions

Suitability of the tools for describing threats to fish and fish habitat

We assessed the reviewed geospatial tools against eight key criteria that would make a tool best suited for evaluating and reporting on threats to fish and fish habitat. We identified the highest performing tools based on an average of high-level rankings across the tools for each of these criteria. The top three tools, in order, were WWF-Canada, Global Water, and Skeena (Table 6).

Table 6. Criteria for an optimal geospatial tool were applied to each reviewed tool using a couple of metrics to provide high-level rankings (ranking, (metric)). Criteria #1-2 were ranked based on counts of indicators and threats, and criteria #3-8 were rated on a scale of does not meet (-), moderately meets (+), and meets the criteria well (++). The number of indicators (# 1) counted from PoE diagrams (Figs. 2-4) included human activity and environmental indicators (a), and threat indicators counted separately (b), but did not include intermediate groupings. The number of threats addressed (#2) were counted separately across Tables 2-4, though there was some overlap between the FFHPP Policy Statement, FFHPP Interim Risk Management Guide, and COSEWIC threats. Note, rankings for criteria #1-2 do not account for the quality or comprehensiveness of the indicators and metrics used. The final ranking was an average across all criteria rankings, and top three rankings were bolded for each.

Tool criteria	**Oil and Gas**	**IGAP**	**PSE**	**WWF-Canada**	**Howe Sound**	**Elk Valley**	**Skeena**	**SBOT**	**SIWAP**	**PAWPIT**	**HydroATLAS**	**Global Water**	**Global Forest**
(1) Numerous human activity and/or environmental indicators (a) used to estimate threat indicators (b)	11 (3)	10 (4)	7 (11)	4 (14)	10 (4)	9 (5)	**3** (15)	8 (9)	5 (13)	6 (12)	**1** (29)	7 (11)	**2** (24)
	6 (0)	6 (0)	4 (2)	**2** (5)	5 (1)	4 (2)	4 (2)	**2** (5)	**3** (3)	**2** (5)	6 (0)	**1** (12)	6 (0)
(2) Addresses threats identified by FFHPP and COSEWIC	11 (2)	8 (7)	5 (11)	**2** (15)	6 (10)	4 (13)	**3** (14)	5 (11)	7 (9)	9 (6)	7 (9)	**1** (16)	10 (5)
(3) Relevant to fish habitat	2 (+)	2 (+)	**1** (++)	**1** (++)	2 (+)	**1** (++)	**1** (++)	**1** (++)	**1** (++)	**1** (++)	2 (+)	2 (+)	2 (+)
(4) Covers extent of Pacific Region	3 (-)	3 (-)	2 (+)	**1** (++)	3 (-)	3 (-)	3 (-)	3 (-)	3 (-)	3 (-)	**1** (++)	**1** (++)	**1** (++)
(5) Fine or intermediate, hydrologically-relevant resolution	3 (-)	3 (-)	**1** (++)	3 (-)	**1** (++)	**1** (++)	**1** (++)	**1** (++)	**1** (++)	2 (+)	**1** (++)	3 (-)	2 (+)
(6) Accounts for flow direction and downstream effects	3 (-)	3 (-)	3 (-)	**1** (++)	3 (-)	3 (-)	3 (-)	2 (+)	2 (+)	2 (+)	**1** (++)	**1** (++)	3 (-)
(7) Estimates cumulative score using data structure-preserving, biologically meaningful methods	3 (-)	3 (-)	2 (+)	2 (+)	3 (-)	2 (+)	3 (-)	2 (+)	2 (+)	**1** (++)	3 (-)	**1** (++)	3 (-)
(8) Includes a temporal component or re-assessment of indicators over time	2 (-)	2 (-)	2 (-)	2 (-)	2 (-)	2 (-)	2 (-)	2 (-)	2 (-)	2 (-)	2 (-)	2 (-)	**1** (+)
Final ranking	12	11	6	**1**	10	8	**3**	5	5	7	4	**2**	9

Most importantly, the tool should include a suite of relevant human activity indicators, and environmental indicators as needed, to estimate threat indicators, and in so doing, link to many or all of the threats identified as important by FFHPP and COSEWIC. In this regard, Global Water was the highest ranking tool in terms of the number of FFHPP and COSEWIC-identified threats for which it had relevant indicators. The next most well-developed tool from this review was WWF-Canada based on their application of several human activity and environmental indicators that were used to estimate five important threats relevant to fish habitat and watershed health. This was also one of the few tools to begin addressing the threat of climate change. Skeena also presented many indicators that had relevance to FFHPP and COSEWIC threats. Tools that presented a comprehensive analysis of select indicators and may be useful for compiling together with other tools are SBOT, SIWAP, and PAWPIT, which collectively cover threats based on high flow levels, sedimentation, riparian change/loss, and pollution.

Relevance to fish habitat and Pacific Region extent were criteria that were not optimized in any single tool. The global tools were the only ones that spanned the full Pacific Region, but these did not have a specific fish habitat focus. In particular, the focal ecological component of Global Water (water security and biodiversity) was not the same that would be used by DFO for reporting on the state of fish habitat, though many of the indicators and methods developed were highly relevant. Conversely, PSE had the strongest association with fish habitat as it was directly developed for assessments and reporting on Pacific salmon and salmon habitat. PSE currently spans Pacific salmon bearing watersheds in BC, but the tool was not ranked as highly in this review in part because it combined human activity indicators into intermediate groupings that were broad categorizations (e.g., ‘human development index’) rather than estimating specific threat indicators. This made the tool further removed from the connection to threats to fish habitat, which was reflected in the lower number of FFHPP threats it addressed. However, the human activity indicators PSE developed have been useful for identifying drivers of fish species compositional turnover across Assessment Watersheds in the Fraser Basin (Iacarella 2022).

Fine or intermediate resolution and incorporation of flow direction and downstream effects for relevant indicators were additional criteria. Global Water used the most sophisticated geospatial analysis approach by accounting for downstream effects with indicators directly associated with stream networks and flow directionality, though the resolution (55 km grid) was coarser than most regional tools. Boyd et al. (2022) used a similar approach to Global Water in accounting for downstream effects, with a fine resolution applied to known Pacific salmon and SAR habitat and developed threat indicators reported by COSEWIC for the focal fish species. Six of the tools (PSE and 5 FLRNORD associated tools) used an intermediate resolution of 1:20,000 Freshwater Atlas Assessment Watersheds for estimating indicators. The Assessment Watersheds were specifically designed for freshwater assessments and maintain a fairly high resolution for reporting. SBOT provided the ability to view summary information at both the Assessment Watershed and Fundamental Unit scale, which represents the area that drains directly into a stream reach. Conversely, the resolution of WWF-Canada (i.e., basins and major watersheds) may be overly coarse for reporting within the Pacific Region. The level of detail provided by PAWPIT and Global Forest maps can be effectively used to visualize and highlight gradients of threats and cumulative effects. However, reporting applications tend to focus on coarser outputs that provide simplified ‘healthy’ and ‘unhealthy’ categories of the state of fish habitat and watershed condition, which may be easier for public dissemination. The Minnesota Department of Natural Resources balances the two by providing online, interactive maps at two resolutions and PDF report cards for each major watershed.

The base criteria of creating a cumulative effect or risk score was met by seven of the tools. However, the additional criteria of binning and/or summing indicator scores based on response curves, literature review, or expert opinion, as well as maintaining data structure in the scoring, was mixed across and within the tools. Even within many of the tools, the variety of methods used to categorize different indicators into low, moderate, and high threat levels made the meaning of the final score unclear and removed from the original data. Conversely, the method used by Global Water to standardize the indicators on a continuous scale and sum using weights based on expert opinion was simple, directly connected to the data, and in line with cumulative effect methods in the literature (Halpern and Fujita 2013). PAWPIT also had a clear summation method for scoring, which was enabled by their focus on pollution and standardized units across different types of pollutants. The method used by SBOT and SIWAP provided another useful cumulative scoring approach that is more risk adverse by focusing on the highest rated threats, though its application involves a lot of rules that become removed from the original data.

The final criteria for tools to conduct re-assessments of indicators over time was only met for select indicators by Global Forest. Many of the data sources were limited for time series largely because they are not updated regularly. However, a couple data sources are updated, such as forest and land cover. Provided data availability, any of these tools could be extended to include temporal replication.

Data gaps and uncertainties

- Determining which metrics and data sources are best for developing different threat indicators needs further evaluation and will likely continue to need updating as research advances. *In situ* measures of water quality related threats (e.g., pollution, sedimentation) would help test the accuracy of the metrics used. Similarly, *in situ* measures of habitat and fish responses are needed to validate the accuracy of relative cumulative effect scores.
- The variety of binning methods and threshold cut-offs used by the reviewed tools to assign indicators low, moderate, and high scores presented a high degree of uncertainty in the designated scores. Ideally, these scores would be based on species and life-stage specific responses, rather than statistical methods, though these responses can be difficult to determine. A more fulsome review is needed to determine appropriate responses and thresholds for different threats.
- Similarly, the cumulative effect scoring methods differed greatly across tools, and many contained a complicated series of binning and roll-up rules. These different approaches will lead to different results using the same data and indicators. The best approach for cumulative effect scoring, and the implications for selecting various methods, needs further assessment.
- There was a significant data gap for tools to be able to iteratively assess the state of fish habitat over time. To address this gap, there needs to be consistent effort and support to maintain and update human activity related datasets, and to clearly identify timestamps of when the human activity occurred or when the data was collated.

Recommendations

- We recommend DFO develops an approach to reporting on the state of fish habitat that incorporates the strengths of the variety of tools reviewed here, with the aim to achieve the eight criteria identified for an optimal geospatial tool. As a first pass, Global Water and WWF-Canada provide the best starting point as they developed the most indicators that were associated with FFHPP and COSEWIC priority threats. Both tools would be improved by re-analyzing the indicators at the finer resolution, 1:20,000 Freshwater Atlas Assessment Watersheds scale. The SBOT and SIWAP tools were the most comprehensive for three threat indicators (high flow, sedimentation, and riparian disturbance), and PAWPIT was the best source for regional pollution estimation (including sources contributing to sedimentation). Given PSE has a platform that focuses on Pacific salmon and salmon habitat, it may be further developed by incorporating the strong suits of these other tools and adding indicators to address FFHPP and COSEWIC threats that currently have little or no assessment.

- There is a need to better address changes in threats to fish habitat over time. A first step would be to delineate which datasets have timestamps and temporal components, and at a minimum, the time range that the dataset captures. Data needed to estimate various threats can then be matched based on the time range and delineated into year spans depending on the temporal resolution and extent across datasets. Evaluating changes over time may be more achievable by evaluating timeseries of threats separately as not all threats may be comparable across time with different requisite data inputs.
- Other approaches and tools would be beneficial to draw upon. For instance, Stalberg et al. (2009) and EPA Water Quality Standards (2003) collectively provide suggested binning values and thresholds for a variety of indicators. Tools such as the Minnesota Department of Natural Resources Watershed Health Assessment Framework provide other useful ways to visualize and report on the state of fish habitat, in this case through multiple resolutions provided as interactive maps and report cards. In addition, the State of Our Watersheds 2020 and Mackenzie River Basin Board State of the Aquatic Ecosystem Report are examples of tools that incorporate Indigenous ecological values and knowledge. Iterative review of relevant freshwater tools, as well as of assessments for specific threats, is recommended to continue improving tools used for Pacific Region evaluation and reporting.

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Appendix 1

Table A1. Indicators, metrics, and benchmarks for three primary threat indicators (or intermediate indicator groupings) that were shared among tools: pollution, sedimentation, and riparian disturbance. Tools used a variety of (1) sub-indicators to estimate the threat (identified as threat or human activity indicators depending on the structure of the tool, see Pathways of Effects diagrams for each tool), (2) metrics to estimate the indicators, and (3) benchmarks to bin the metrics for final cumulative effect or risk scoring. The common threat (i.e., pollution, sedimentation, riparian disturbance) had to be identified by the tool to be noted here; for instance, if a tool included road density as an indicator but did not directly tie it to one of the shared threats, we did not make the link ourselves. Also, note that some indicators identified by tools as pollution threats were highly relevant to sedimentation (e.g., total suspended solids measured by PAWPIT through point source emissions and surface runoff, and sediment loading by Global Water).

Shared threat indicator	Tool	Sub-indicators	Metric	Benchmark
Pollution	WWF-Canada	Risk of agricultural contamination: Nitrogen	Risk of contamination from ‘soil landscape classification’ (unitless)	Percentiles
		Risk of agricultural contamination: Pesticides	Risk of contamination from ‘soil landscape classification’ (unitless)	Percentiles
		Risk of agricultural contamination: Phosphorus	Risk of contamination from ‘soil landscape classification’ (unitless)	Percentiles
		Pipeline incidents	Spill volume (L)	Percentiles
		Point source emissions	Land and water releases (metric tonnes)	Percentiles
		Transportation incidents	Number of incidents with spills or leaks of dangerous goods (#)	Jenks Natural Breaks
	Skeena	Point source pollution	Number of pollutant point sources (#)	None
	PAWPIT	Air emissions (divided into classes of pollutants)	Air emissions (kg/yr)	None
		Point source emissions (divided into classes of pollutants)	Effluent releases, leachates, PCB releases (kg/yr)	None
		Surface runoff (divided into classes of pollutants)	Agricultural, urban, non-urban (kg/yr)	None
	Global Water	Mercury deposition	Present-day vs. pre-industrial ($g/km^2/yr$)	None
		Nitrogen loading	Present-day vs. pre-industrial ($N/km^2/yr$)	None
		Organic loading	Labile carbon from nitrogen loads (Biological Oxygen Demand/km^2/yr)	None
		Pesticide loading	Pesticide application to cropland ($kg/km^2/yr$)	None
		Phosphorous loading	Point source, non-point source, and atmospheric deposition ($P/km^2/yr$)	None

Shared threat indicator	Tool	Sub-indicators	Metric	Benchmark
Pollution	Global Water	Potential acidification	SOx and NOx deposition (H+ equivalents/km²/yr)	None
		Sediment loading	Estimated annual erosion rates (metric tonnes/km²/yr)	None
		Soil salinization	Electrical conductivity of soils (dS/m)	None
		Thermal alteration	Return flow of thermal power stations (millions of m³/yr)	None
Sedimentation	SBOT	Road density	Length of roads by watershed area (km/km²)	Expert opinion based on available science
		Road density near streams	Length of roads within 100 m of a stream by watershed area (km/km²)	Expert opinion based on available science
		Road density on potentially unstable slopes	Length of roads on steep slopes (> 60%) by watershed area (km/km²)	Expert opinion based on available science
		Stream crossing density	Number of road-stream crossings by watershed area (#/km²)	Expert opinion based on available science
		Riparian disturbance	Length of streams within 30 m of disturbance by length of streams within watershed (km/km)	Expert opinion based on available science
	SIWAP	Road density near streams ('roads close to water')	Length of roads within 50 m of a stream by watershed area (km/km²)	Expert opinion
		Road density on potentially unstable slopes ('roads on steep coupled slopes')	Length of roads on steep slopes (> 50%) within 50 m of a stream ('steep coupled slopes') (km/km²)	Expert opinion
		Logging on gentle slopes above steep slopes	Percent watershed area with logging on gentle slopes (< 50%) above steep slopes (> 50%) (%)	Expert opinion
		Absence of lakes and wetlands	Area-weighted proportion of watershed covered by lakes and wetlands (unitless)	Expert opinion
		Erodible soils	Percent watershed area covered by erodible soils (%)	Expert opinion

Shared threat indicator	Tool	Sub-indicators	Metric	Benchmark
Sedimentation	SIWAP	Steep coupled slopes	Percent watershed area with steep slopes (> 50%) where base of slope is within 50 m of a stream (%)	Expert opinion
Riparian disturbance	PSE	None	Percent watershed area altered by human activity within 30 m of freshwater bodies (%)	Expert opinion and science-based
	Howe Sound	None	Percent streams disturbed within watershed (%)	Expert opinion and science-based
	Elk Valley	None	Percent disturbed area per riparian area delineated using Digital Elevation Models (%)	Taken from BC Cumulative Effects Framework
	Skeena	None	Percent of area within 30 m of streams with recent human or natural disturbance (%)	Taken from PSE
	SBOT	Riparian disturbance	Length of streams with disturbance within 30 m by length of streams within watershed (km/km)	Expert opinion based on available science
		Road density near streams	Length of roads within 100 m of a stream by watershed area (km/km^2)	Expert opinion based on available science
		Road density on potentially unstable slopes	Length of roads on steep slopes (> 60%) by watershed area (km/km^2)	Expert opinion based on available science
		Stream crossing density	Number of road-stream crossings by watershed area ($\#/km^2$)	Expert opinion based on available science
	SIWAP	Private land area	Percent stream length overlapping private land (%)	Expert opinion
		Range tenure area	Percent stream length overlapping range land (%)	Expert opinion
		Logged riparian area	Percent stream length with harvesting within 30 m (%)	Expert opinion

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