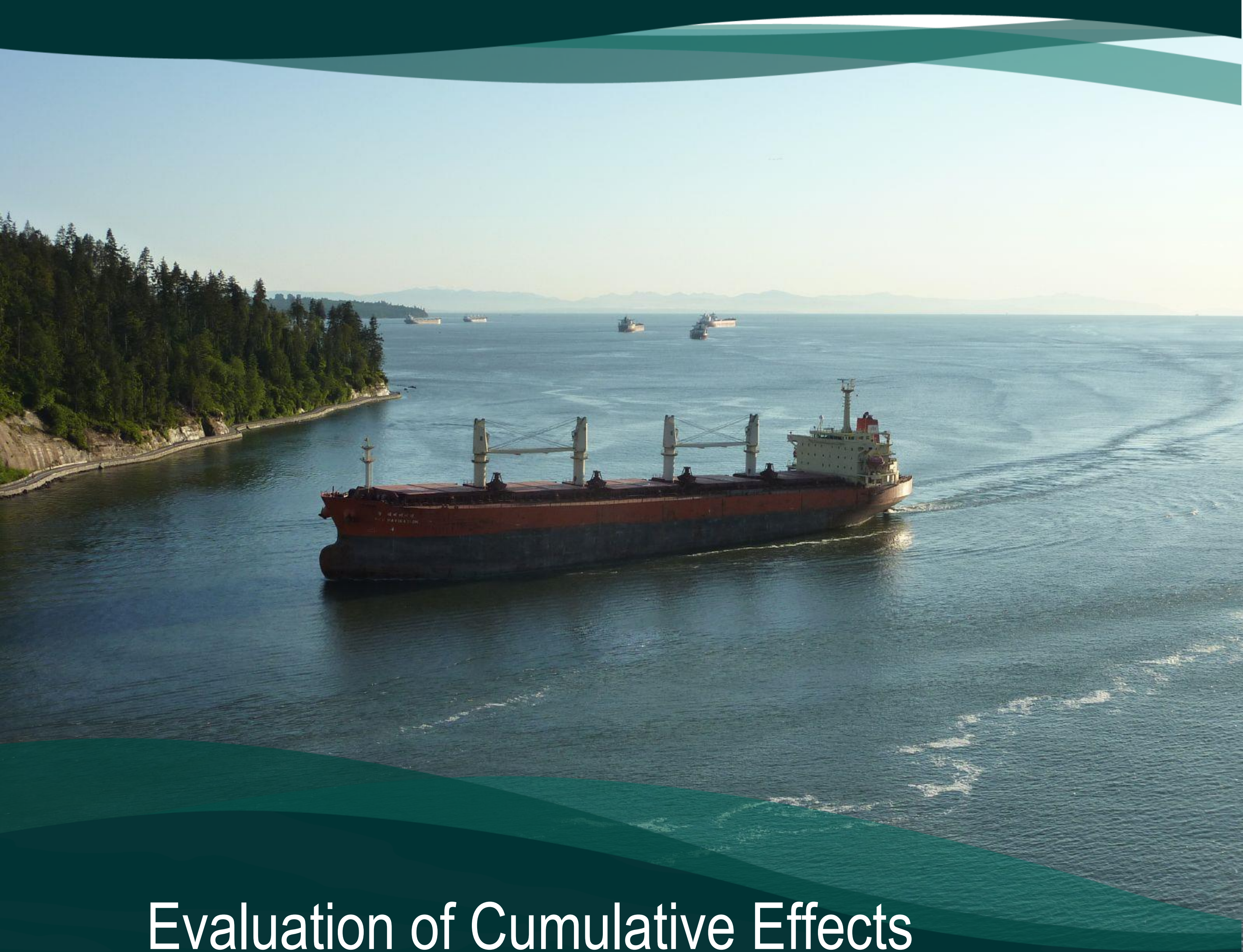

Evaluation of Cumulative Effects Assessment Methodologies for Marine Shipping

Final Report

March 25, 2019
Prepared for Transport Canada

Project #: T8080 - 180068

Transports Canada Transport Canada

ESSA

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Prepared for:

Transport Canada

Contact:

Jeff Campagnola

Jeff.campagnola@tc.gc.ca

1.613.990.5796

Contact:
Darcy Pickard
dpickard@essa.com
(613) 376-9903

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

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We would sincerely like to thank everyone who contributed.

1 Introduction

1.1 Purpose

The purpose of this project is to evaluate and compare potential assessment methodologies for cumulative effects assessment in the context of the Transport Canada led Cumulative Effects of Marine Shipping initiative (CEMS) under Canada's Ocean Protection Plan. The report provides recommendations as to which categories of methodology are most applicable under different scenarios. This information will help inform the assessment step within the CEMS initiative.

1.2 Background

On November 7, 2016, the Prime Minister launched a $1.5 billion national Oceans Protection Plan that improves marine safety and responsible shipping, protects Canada's marine environment, and offers new possibilities for Indigenous and coastal communities. The Oceans Protection Plan has four main priority areas:

- Creating a world-leading marine safety system that improves responsible shipping and protects Canada's waters, including new preventive and response measures;
- Restoring and protecting the marine ecosystems and habitats, using new tools and research, as well as taking measures to address abandoned boats and wrecks;
- Strengthening partnerships and launching co-management practices with Indigenous communities, including building local emergency response capacity; and,
- Investing in oil spill cleanup research and methods to ensure that decisions taken in emergencies are evidence based.

The CEMS initiative is under the restoring and protecting the marine ecosystem pillar of the Oceans Protection Plan. The goal of the initiative is to develop a cumulative effects assessment framework focused on current and potential marine vessel activity. The initiative has prioritized six pilot sites[1] covering all three of Canada's coasts. The first year of the initiative has involved scoping the concerns related to marine vessel **activities** as well as identifying the **stressor**s of concern for each pilot site.

Outreach and engagement are core principles of this initiative, and Indigenous peoples, local stakeholders, and coastal communities are involved in all aspects of the initiative. Regional workshops have been used to identify the specific activities of concern and the ways that those activities are affecting the marine environment and traditional use. Identification of **Valued Components** (VCs), linkages between the stressors and VCs (i.e., pathways of effect), and indicators to inform the relative impact of different pathways is currently underway. This report is part of Phase 2 (Figure 1.1) and was recommended by Lerner 2018 to 'develop an assessment toolkit' which will inform the assessment step within the overall CEMS initiative.

[1] Northern, British Columbia; Southern, British Columbia; St. Lawrence River, Quebec; Bay of Fundy, New Brunswick; Placentia Bay, Newfoundland; Cambridge Bay, Nunavut

Concurrently, Transport Canada is identifying potential data sources to inform priority indicators. Once finalized Transport Canada will apply the framework to the six pilot sites. Information gathered from the implementation of the pilots will inform the management and response toolkit. Evaluation and improvement of the framework will occur on an ongoing basis, along with continued communication with Indigenous peoples, local stakeholders, and coastal communities.

Activity: An action that may impose one or more stressors on the ecosystem being assessed. [Thornborough et al. 2018 (DFO)]

Stressors: Any physical, chemical, or biological means that, at some given level of intensity, has the potential to negatively affect a valued component. [Thornborough et al. 2018 (DFO)]

Valued Components: Refer to environmental features that may be affected by an activity and that have been identified to be of concern by the proponent, government agencies, Indigenous peoples, or the public. The value of a component not only relates to its role in the ecosystem, but also to the value people place on it. For example, it may have been identified as having scientific, social, cultural, economic, historical, archaeological, or aesthetic importance. [Definition is adapted from CEAA 2012]

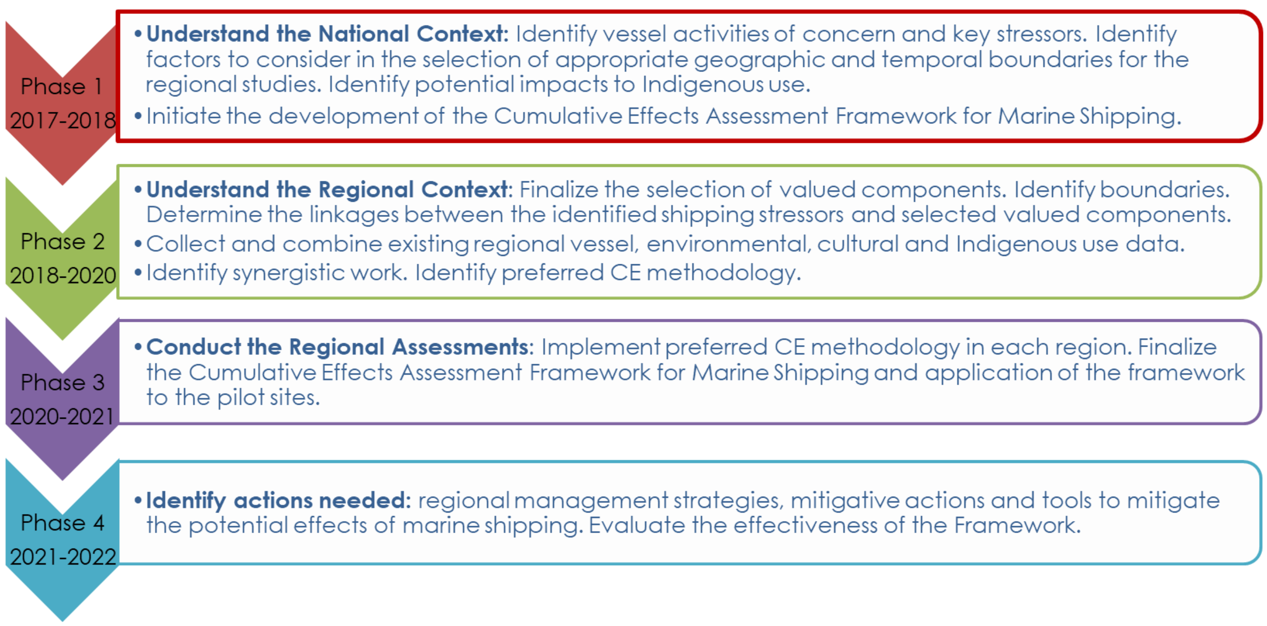

Figure 1.1. Phases in the process to develop a cumulative assessment framework as outlined in the Transport Canada Ocean Protection Plan Cumulative Effects of Marine Shipping presentation.

1.3 What is Cumulative Effects Assessment?

In order to complete the evaluation of assessment methodologies, we must first define what is meant by Cumulative Effects Assessment (CEA). The Canadian Council of Ministers of the Environment (CCME) provides the following definitions:

Cumulative effect is a change in the environment caused by multiple interactions among human activities and natural processes that accumulate across space and time.

Cumulative effects assessment is a systematic process of identifying, analyzing, and evaluating cumulative effects.

Cumulative effects management is the identification and implementation of measures to control, minimize or prevent the adverse consequences of cumulative effects.

Although these definitions are useful for making clear what is meant by these foundational terms, the definitions alone do not provide sufficient detail about what the assessment steps entail. Similarly, Transport Canada's five phase process and Lerner (2018)'s eight steps do not provide detail about what occurs within an 'assessment' step.

Ideally, CEA involves a series of methods that assess the condition of the environment, describe the causal pathways that link stressors and cumulative effects, and predict the risks and benefits associated with alternative scenarios (Jones 2016). Although there is consensus on the general steps of the CEA process (Jones 2016), there is debate in terms of the methods that should be used at each of these stages (Jones 2016, Stelzenmüller et al. 2018). It is important to understand the structure of the overall cumulative effects framework within which the method will be applied (Greig et al. 2013). In other words, what is the scope of the assessment and what management strategies are being informed by the outcome of the assessment?

No single method is sufficient to address all aspects of cumulative effects assessment (Canter 2008, Stelzenmüller et al. 2018). Ultimately, the selection of a method depends on data availability, ease of use, and, fundamentally, on the questions that the assessment seeks to answer (Greig et al. 2013). In practice, various methods and associated tools are usually applied in combination through the cumulative effects assessment process (CEQ 1997) so that specific questions can be addressed (Greig et al. 2013).

There are multiple worldviews that can influence the selection of methods and associated tools and how they are applied. CEA inherently acknowledges the holistic and interconnected nature of complex socio-ecological systems; however, assessment methods can be applied differently based on different worldviews. This report summarizes the range of assessment methodologies available and considerations in selecting different methods. It does not include details about how different types of knowledge should inform those methods or how methods should be applied based on different worldviews.

We created a diagram that displays important elements in a CEA framework in order to show our understanding of how the assessment step supports the broader framework in the context of the Transport Canada led CEMS initiative (Figure 1.2). This figure builds on the general stages identified by Jones (2016) as well as the more detailed good practice handbook provided by the International Finance Corporation (IFC, 2013). Sections 1.3.1 to 1.3.5 provide a brief discussion of each of the components in the generic CEA framework.

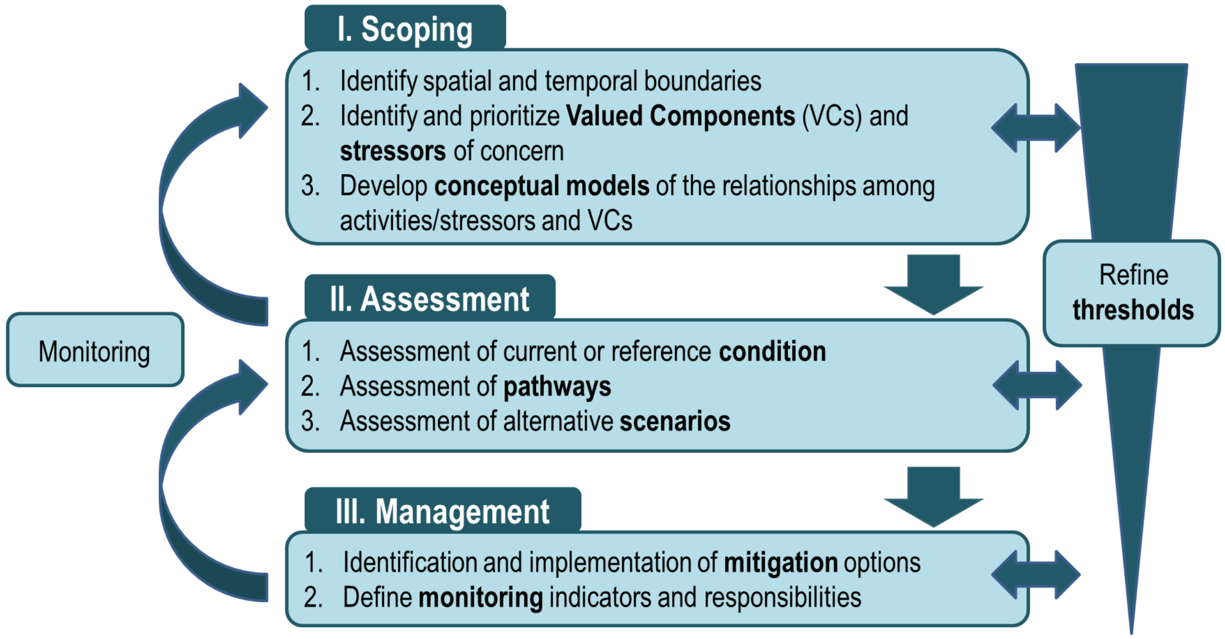

Figure 1.2. This figure shows how the assessment step fits within a broader CEA framework. The Scoping step is underway concurrently, led by Transport Canada and informed by regional workshops. This report focuses on potential methods for the Assessment step. The Management step is will be addressed in Phase 4 of the CEMS initiative.

1.3.1 Scoping

A poorly defined problem is one of the most common reasons for studies to flounder (Reynolds et al. 2016). In the CEA context the scoping step is necessary to focus efforts on a smaller more manageable set of critical stressors and priority VCs over a well-defined spatial and temporal scope. However, it is useful to begin with a broadly defined scope and identify all potential stressors and VCs before narrowing the scope. This approach is useful to ensure nothing is inadvertently missed, to communicate and justify the scoping decisions, and to allow for adjustment in priorities as context changes (e.g., if priority VCs change over time or if new data suggests a different stressor is of greater concern). In this case, this step will involve clarification over what is meant by 'Marine Shipping', identification of potential stressors and VCs of interest, development of conceptual models (i.e., pathways of effects in Appendix A), and finally prioritization of VCs and identification of stressors and pathways of greatest concern.

The spatial and temporal scale of the assessment is important. It should be based on the spatial scale of the VC while also taking into account the scale(s) of the activities acting on the VC and the scale that mitigation activities can be implemented. If multiple scales are relevant a nested approach may be useful (Rebecca Martone, pers. comm). For example, an assessment of current condition in the Skeena estuary, used salinity zones nested within the larger estuary (Pickard et al., 2015). In the case of the CEMS initiative, regions are nested within the broader national initiative. There may be additional nesting required within regions. In terms of temporal boundaries, a difficult decision is how to characterize the reference condition. Should it represent historical conditions or is it sufficient to evaluate current condition? Lack of historical data is a common challenge and deciding how to define the reference condition can be a road block to getting started (Kelly Munkittrick, pers. comm.).

1.3.2 Assessment

The assessment phase of any CEA framework involves three main steps: (1) assessment of the current or reference condition; (2) assessment of the impact pathways; and (3) assessment of alternative scenarios. Each of these stages is important and a combination of methods and associated tools may be necessary to address all stages.

Assessment of current or reference condition:

This step begins with compiling and evaluating the quality and spatial/temporal extent of the best available data. In some cases, Indigenous Knowledge may be available to support the assessment. Expert elicitation may also be used where no empirical[2] information exists. Indicators need to be developed to represent both stressors and VCs. Indicator selection generally involves evaluating alternative indicators against a set of criteria such as: relevance, responsiveness, and feasibility (Pickard et al. 2018). Finally, the current or reference condition of priority VCs and stressors of concern are summarized using the best available data for each indicator selected. Information gaps are often identified at this stage.

Assessment of pathways

The purpose of this step is to understand the cause-effect relationships between stressors and VCs. This includes understanding the magnitude of effects as well as the shape of the functional relationship between stressors and VCs (e.g., linear, exponential, optimum range). Additionally, it is useful to understand which pathways are most important (i.e., what are the relative drivers of the system?).

In most CEA frameworks this step isn't broken out separately but is an implied necessary step to evaluate alternative scenarios and to enable threshold definition. It can also be useful to iteratively refine the scope of the assessment to focus on the primary drivers of the system. For the purpose of this report we felt it was useful to explicitly discuss this step as different methods will be relevant depending on whether the task involves quantifying relationships or evaluating alternative scenarios.

Assessment of alternative scenarios

Given an understanding of the current or reference condition and the relationships among stressors and VCs, it is possible to evaluate alternative future scenarios. This step can be difficult but is what makes CEA valuable to informing decisions. This step also requires an understanding of the management context which defines relevant future scenarios. These may include management levers which are available to mitigate impacts of stressors as well as future development or climate scenarios.

1.3.3 Management

It is important to understand the management context as one designs the assessment step. What are the management objectives? What management decisions will be informed by the assessment? For example, decisions around alternative development scenarios (e.g., port expansions) or decisions around how to mitigate current activities (e.g., oil spill response, timing/location of vessel movement). If one objective is to minimize cumulative effects on VCs resulting from marine shipping, it makes sense to focus on those effects where there is the greatest potential to make a change. This may differ depending on who is implementing

[2] Empirical: "originating in or based on observation or experience" Merriam-Webster [https://www.merriam-webster.com/dictionary/empirical]

the initiative. A common challenge of CEA is that VCs are affected by stressors that fall under a variety of jurisdictional authorities (e.g., DFO, Transport Canada, Provincial or Territorial, or local governments). In this case, mitigation opportunities will be collaboratively identified in partnership with all levels of jurisdiction.

Clearly defined management objectives will help to scope the assessment and will help to inform the selection of assessment methodologies. Identifying management decisions up front will help to characterize alternative scenarios of interest. Likewise, the assessment step will help us to better understand the current condition, cause-effect relationship between stressors and VCs, relative drivers of the system, and potential outcomes of alternative scenarios, thus informing management decisions.

Finally, there is another link between management decisions and what society determines is acceptable. This is discussed further in the following section on thresholds.

1.3.4 Thresholds

We define thresholds to be levels at which a particular stressor or VC exceeds a level of concern resulting in an alternative management regime. Thresholds are informed by a combination of technical understanding and a socially defined level of acceptable change (Hegmann et al. 1999). Pressures (e.g., noise) resulting from activities (movement underway) cannot be interpreted as stressors without first defining thresholds. Assessment of impact pathways is a critical scientific input to developing meaningful thresholds.

In practice, thresholds are often best guesses to start and are refined throughout the CEA process. In absence of thresholds, it may be possible to first identify whether the current condition is ‘acceptable or unacceptable’. As functional relationships are quantified, thresholds can be informed by these empirical relationships. Models can also be used to inform thresholds by evaluating likelihood of survival under different conditions.

1.3.5 Monitoring

Monitoring is necessary to inform cumulative effects assessment and enable good cumulative effects management (CCME unpublished). One of the outcomes of initial scoping and subsequent assessment is to identify knowledge gaps. While preliminary assessments may be completed based on expert knowledge, it is important to verify hypotheses with empirical evidence. Monitoring should be used to address the greatest uncertainties for the most important pathways. In this way monitoring enables continuous improvement within the framework.

1.3.6 Iterative learning

While there is a natural sequence to the generic CEA framework described in Figure 1.2, in practice, implementation is iterative. Selection of an assessment methodology depends on the outputs from other components within the framework and may also change with future iterations through the framework (i.e., as we refine scope or as new data become available).

The first iteration through the assessment step may involve limited empirical information. The first iteration helps to define the scope using best available data or expert opinion and may identify information gaps and critical uncertainties. As these uncertainties are addressed the level of understanding improves and the scope may be adjusted or refined. Selection of methodologies will tend to shift from simple to complex as the scope is refined and more data are available.

1.4 Report Structure

There are a large variety of methodologies which have been applied to CEA. Most of these are not sufficient on their own to accomplish a CEA but are useful for supporting a CEA. Usually a suite of methods and associated tools are needed to accomplish a CEA, with selection depending on context. In conducting this evaluation, we do not provide a comprehensive review of all possible methods but rather discuss higher level categories of methods with information on specific methods and associated tools provided to support the discussion. The report includes 8 sections plus a series of appendices:

- Section 1 provides important background context which clarifies the nature of this report.
- Section 2 describes our approach to completing the evaluation.
- Section 3 describes the screening phase of our evaluation.
- Section 4 provides the detailed evaluation, including a description of possible methods and associated tools and an evaluation of their relevance, rigour, and feasibility.
- Section 5 presents a comparative analysis across methods and introduces a number of case studies that illustrate the application of these methods and how they could be used in the context of the Cumulative Effects of Marine Shipping initiative.
- Section 6 discusses crosscutting methods relevant to CEA, including: Indigenous knowledge, expert elicitation, and decision support tools.
- Section 7 introduces examples of CEA frameworks and how the assessment step fits into the broader context.
- Section 8 provides overall conclusions, including insights from the evaluation and the Technical Workshop, how to use the assessment toolkit, and next steps for the CEMS.
- Appendix A describes additional context that has informed our evaluation. In particular, we provide a brief summary of the: status of marine shipping pathways of effects model development, regional context in the pilot sites, and data availability.
- Appendix B includes short summaries of key review papers on cumulative effects assessment methods and tools.
- Appendix C provides additional detailed feedback from participants of the Technical Workshop (Ottawa, 20-21 February 2019).
- Appendix D is the Technical Backgrounder that was shared with participants, as a brief summary of this report, prior to the Technical Workshop.

2 Methods

2.1 Overview

The assessment of cumulative effects is a complex problem requiring consideration of multiple factors, disciplines and stakeholders' views. In order to account for this complexity in a transparent and systematic manner, we have structured our review into two phases; first a broad screening of potential assessment methodologies (**Tier 1**) followed by a detailed review of the most promising methods (**Tier 2**).

This approach allowed us to conduct an evaluation with enough breadth to cover the majority of methods in the literature potentially relevant for marine shipping and with enough depth to assist Transport Canada in the selection of the most appropriate methods. Concurrently to Tier 2, our team conducted research into contextual themes that helped us inform and frame our evaluation, specifically: Transport Canada's management context; the current understanding of the Pathways of Effects for marine shipping; the geographic and cumulative effects (e.g., human activities, valued components, main concerns) context for the six pilot regions; and the relevant data sources that Transport Canada has identified to date. The detailed evaluation of Tier 2 was also supplemented with the insights from a series of interviews we conducted with key experts. Figure 2.1 illustrates the evaluation framework and process.

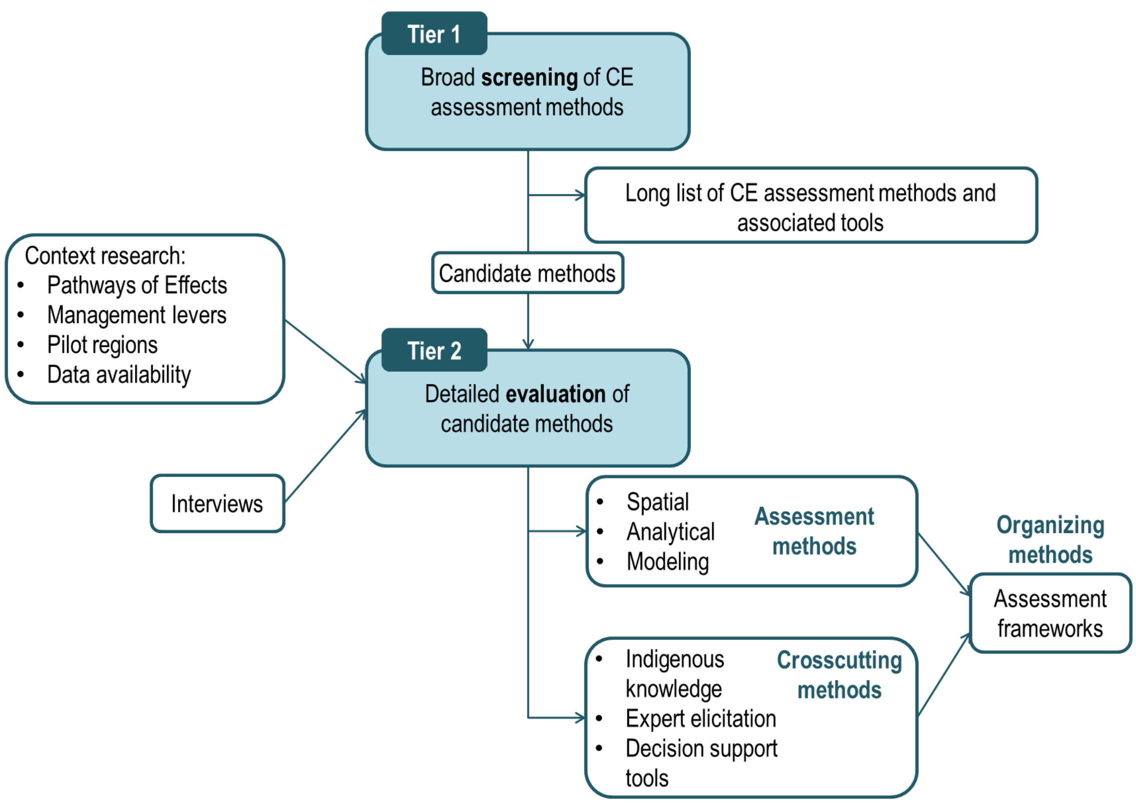

Figure 2.1. Evaluation framework showing the flow of information and key outputs.

2.2 Screening Phase

2.2.1.1 Literature review

As a first step in the development of the evaluation framework, our team undertook a broad desktop search of cumulative effects assessment methodologies and associated tools. In addition to the references included in key background material, such as the literature review by Lerner (2018), we conducted a high-level desktop and web search to identify cumulative effects assessment approaches which have been applied in a context relevant for marine shipping. Specifically, we searched academic sources (e.g., Google Scholar, Science Direct) and other thematic and grey literature databases (e.g., Fisheries and Oceans Canada, International Association of Impact Assessment) for the following key words:

- “Cumulative effects/impacts assessment” + “(marine) shipping”
- “Cumulative effects/impacts assessment” + “marine environment/ecosystems/habitats”
- “Cumulative effects/impacts” + “(marine) shipping” + “modeling”
- “Cumulative effects/impacts assessment” + “(marine) shipping” + “tools”
- “Cumulative effects/impacts” + “assessment toolkit” + “marine environment/ecosystems/habitats”
- “(marine) shipping” + “impacts/effects assessment”

The purpose at this stage was not to research and document in depth any specific approach but to get an understanding of the range and types of existing cumulative effects assessment methodologies and tools. These initial searches were supplemented by literature summarized in review papers, provided by experts, or familiar to our team.

2.2.1.2 Tabular summary

The outcome of the preliminary screening was a long list of cumulative effects assessment methods and associated tools, as well as relevant review papers or reports dealing with multiple approaches. This preliminary list has been documented in an Excel spreadsheet (Table 2.1). The spreadsheet organizes the information for each entry using the following headings:

- Citation: Full citation
- Type of document: Paper, report, case study or tool
- Overview: Brief description of the content of the document
- CE method/tool: we grouped the table entries into the three main categories evaluated in Tier 2: (i) spatial, (ii) analytical, (iii) modeling approaches
- Geographic scope: Scale and place at which the assessment was conducted (e.g., Pacific North-BC)
- Stressors: Specific marine shipping stressors that were included in the analysis
- VCs: valued components that were addressed in the analysis.

Table 2.1. An excerpt from the preliminary Tier 1 summary spreadsheet is shown here to illustrate the organizational structure of the Tier 1 evaluation.

	Citation	ype of docume	Overview - not original writing	Website (if applicable)	Link to the file in Dropbox	Method/tool	CE assessment category	Geographic scope	Stressor (PoE)	Stressor Details	VC Category	VC Details
4	Clarke Murray, C., Mach, M.E., & Martone, R.G. (2014) Cumulative effects in marine ecosystems: scientific perspectives on its challenges and solutions. WWF-Canada and Center for Ocean Solutions. 60 pp.	Report	In this review we discuss four components of cumulative effects science and application: (1) how cumulative effects manifest in ecosystems as a result of multiple human activities; (2) challenges in applying scientific knowledge in cumulative effects assessment, including defining spatial and temporal scales, baselines, reference points, indicators, and identifying significant changes in the face of uncertainty and natural environmental variability; (3) models and tools that have been developed to assess cumulative effects; and (4) priorities for science and management of cumulative effects		https://www.dropbox.com/home/d_global/Projects/EN2500to2599/EN2511%20Transport%20Canada/References?preview=Murray+et+al+2014+Cumulative+effects+in+marine+ecosystems.pdf		Review of multiple methods/tools					
7	Center for Ocean Solutions. 2011. Decision Guide: Selecting Decision Support Tools for Marine Spatial Planning. The Woods Institute for the Environment, Stanford University, California	Report	This Decision Guide, produced by the Center for Ocean Solutions (COS), is intended to assist practitioners in selecting appropriate decision support tools (DSTs) that can help them conduct marine spatial planning in their own jurisdictions		https://www.dropbox.com/home/d_global/Projects/EN2500to2599/EN2511%20Transport%20Canada/References?preview=Center+for+Ocean+Solutions+2011+Selecting+DST+for+marine+spatial+planning.pdf		Review of multiple methods/tools					
12	Pınarbaşı K., I. Galparsoroa, A. Borja, V. Stelzenmüller, C.N. Ehler, A. Gimpel.2017. Decision support tools in marine spatial planning: Present applications, gapsand future perspectives. Marine Policy 83: 83-91	Paper	The main objective of this review is to: (i) characterize and analyse the present use ofthe DSTs in existing MSP implementation processes around the world, (ii) identify weaknesses and gaps ofexisting tools, and (iii) propose new functionalities both to improve their feasibility and to promote	http://dst.azti.es/	https://www.dropbox.com/home/d_global/Projects/en2500to2599/en2511%20transport%20canada/References?preview=Pinarbasi_et_al_2017+Decision+support+tools+in+marine+spatial+planning.pdf		Review of multiple methods/tools					
15	Ban N.C., H.M. Alidina, J.A. Ardron. 2010. Cumulative impact mapping: Advances, relevance and limitations to marine management and conservation, using Canada's Pacific waters as a case study. Marine Policy 34: 876–886	Paper	38 human activities were considered, with each broken down according to stressor types and a range of spatial influences. 4 categories of information were combined: (1) spatial data on the location of activities and their intensities if known;(2)types of stressors resulting from these activities; (3) relative impact of		https://www.dropbox.com/home/d_global/Projects/EN2500to2599/EN2511%20Transport%20Canada/References?preview=Ban_et_al_2010_+CE+Mapping+Canada+Pacific.pdf	Method	Spatial approaches	Exclusive economic zone (EEZ) of Canada's Pacific coast	Multiple stressors	The analyses were undertaken at the activity level. For transportation, two activities were	Biological	Habitat types: benthic, shallow pelagic and deep pellagic
16	Clarke Murray C., S. Agbayani, H.M. Alidina, N.C. Ban. 2015. Advancing marine cumulative effects mapping: An update in Canada's Pacific waters. Marine Policy 58: 71–77	Paper	The paper describes the third iteration of cumulative effects mapping in the Canadian Pacific Coast, based on updated spatial data. The spatial location of human activities and habitats weighted by their vulnerability to each activity were combined in a GIS model to map cumulative effects following methods developed by Halpern and colleagues		https://www.dropbox.com/home/d_global/Projects/EN2500to2599/EN2511%20Transport%20Canada/References?preview=Murray_et_al_2015_Advancing+marine+CE+mapping.pdf	Method	Spatial approaches	Regional (Canada's Pacific marine waters)	Multiple stressors	47 human activities including recreational boating and shipping (large vessels)	Biological	Multiple habitat types
26	Moore S.E., Randall R. Reeves, Brandon L. Southall, Timothy J. Ragen, Robert S. Suydam, and Christopher W. Clark. 2012. A New Framework for Assessing the Effects of Anthropogenic Sound on Marine Mammals in a Rapidly Changing Arctic. BioScience 62: 289–295 doi:10.1525/bio.2012.62.3.10	Paper	We propose a new assessment framework that is based on the acoustic habitats that constitute the aggregate sound field from multiple sources, compiled at spatial and temporal scales consistent with the ecology of Arctic marine mammals		https://www.dropbox.com/home/d_global/Projects/EN2500to2599/EN2511%20Transport%20Canada/References?preview=Moore+et+al+2012+Framework+sound+effects+on+marine+mammals.pdf	Method	Spatial approaches	Arctic	Noise (movement underway)			
27	Coll, Marta & Piroddi, Chiara & Albouy, Camille & Lasram, Frida & Cheung, William & Christensen, Villy & Karpouzi, Vasiliki & Guilhaumon, Francois & Mouillot, David & Paleczny, Michelle & Palomares, M L D & Steenbeek, Jeroen & Trujillo, Pablo & Watson, Reg & Pauly, Daniel. (2012). The Mediterranean Sea under siege: Spatial overlap between marine biodiversity, cumulative threats and marine reserves. Global Ecology and Biogeography. 21. 465 - 480. 10.1111/j.1466-8238.2011.00697.x.	Paper	We first identified areas of high biodiversity of marine mammals, marine turtles, seabirds, fishes and commercial or well-documented invertebrates. We mapped potential areas of high threat where multiple threats are occurring simultaneously. Finally we quantified the areas of conservation concern for biodi- versity by looking at the spatial overlap between high biodiversity and high cumu- lative threats, and we assessed the overlap with protected		https://www.dropbox.com/home/d_global/Projects/EN2500to2599/EN2511%20Transport%20Canada/References?preview=Coll+et+al_2011_The+Mediterranean+Sea+under+siege.pdf	Method	Spatial approaches	Mediterranean Sea	Multiple stressors	Multiple stressors including shipping	Biological	Multiple species: mammals, turtles, seabirds, fishes and invertebrates
28	Vries, P. de, J.E. Tamis, J.T. van der Wal, R.G. Jak, D.M.E. Slijkerman and J.H.M. Schobben (2011). Scaling human-induced pressures to population level impacts in the marine environment; implementation of the prototype CUMULEO-RAM model. Wageningen, Wettelijke Onderzoekstaken Natuur & Milieu, WOt-werkdocument 285. 80 p. 10 Figs.; 7 Tabs.; 47	Report	This report presents a generic framework for Cumulative Effect Assessment (CEA). It assumes that effects are a function of the intensity of pressures resulting from human activities and the sensitivity of ecosystem components to those pressures. The generic framework above is implemented as the prototype CUMULEO-RAM model		https://www.dropbox.com/home/d_global/Projects/EN2500to2599/EN2511%20Transport%20Canada/References?preview=de+Vries+et+al+2011+Scaling+human+pressures+to+population+level+impacts.pdf	Method	Modeling approaches	Wadden Sea (Netherlands)	Multiple stressors	26 activities but limited the pressures to only abrasion and visual disturbance	Biological	Oystercatcher, common eider, heart urchin, Baltic tellin, common mussel, common cockle
29	Micheli F, Halpern BS, Walbridge S, Ciriaco S, Ferretti F, et al. (2013) Cumulative Human Impacts on Mediterranean and Black Sea Marine Ecosystems: Assessing Current Pressures and Opportunities. PLoS ONE 8(12): e79889. doi:10.1371/journal.pone.0079889	Paper	Quantification and mapping of the cumulative impact of 22 drivers to 17 marine ecosystems reveals that 20% of the entire basin and 60–99% of the territorial waters of EU member states are heavily impacted, with high human impact occurring in all ecoregions and territorial waters. Less than 1% of these regions are relatively unaffected. This high impact results from multiple drivers, rather than one individual use or stressor, with climatic drivers (increasing temperature and UV, and acidification), demersal fishing, ship traffic, and, in coastal areas, pollution from land accounting for a majority		https://www.dropbox.com/home/d_global/Projects/EN2500to2599/EN2511%20Transport%20Canada/References?preview=Micheli+et+al+2013+Cumulative+impacts+Mediterranean+and+Black+Sea.PDF	Method	Spatial approaches	Mediterranean and Black Sea	Multiple stressors	22 anthropogenic drivers	Biological	17 marine ecosystem types

2.2.1.3 Review papers

Besides literature on specific methods and tools, we included in our screening 14 review papers that document and compare multiple cumulative effects assessment methods or tools. Although the purpose of these reviews differs from the focus of this evaluation (i.e., cumulative assessment methodologies applicable to marine shipping), reviewing and comparing various organizing structures of review papers helped us in defining our evaluation framework, as well as providing an overview on the state of practice of cumulative effects assessment methodologies.

2.3 Detailed Evaluation

We grouped methods into three categories: spatial, analytical and modeling and reviewed each against a consistent set of criteria (Table 2.2). These criteria inform about attributes of the methods which are especially important in selecting an approach: the **relevance** of the method in relation to the CEMS initiative; the **rigour** of the approach in terms of how well established it is in CE practice, the level of information supporting the assessment and the treatment of uncertainty; and its **feasibility** as a general estimation of how easy it would be to implement the assessment approach.

Table 2.2. Evaluation criteria.

Category	Criterion (rating)	Description
Relevance (Low/medium/high)	Spatial and temporal scale	• Is the method applicable at the national and/or regional scale? • Can the method be applied at different spatial and temporal spatial scales?
	Indigenous knowledge[3]	• Could the approach incorporate knowledge from Indigenous communities or First Nations?
Rigour (Low/medium/high)	Application of the method	• Are there multiple publications of applications of the method? • Is the method considered 'best practice'?
	Level of underlying data/information	• Is the method based on expert judgement, literature of studies in other similar places, site-specific data, and/or derived using a model?
	Uncertainty	• Does the method clearly account for and state uncertainties and assumptions?
Feasibility (Low/medium/high)	Complexity	• How complicated/sophisticated (e.g., requires special skill sets, takes a lot of time, etc.) is the method?
	Data requirements	• How much and what types of data or information are needed?

[3] Note: we attempted to rank whether the method could be used in conjunction with Indigenous knowledge. Whether and how this would occur requires working with the Indigenous knowledge holders and communities in all parts of assessment process.

Category	Criterion (rating)	Description
	Data flexibility	• Can the method incorporate multiple types of data? (e.g., geospatial and tabular) • Can the method incorporate data not specifically gathered for the assessment method? • Are there steps that can be taken if data do not exist? • Can the method incorporate more data as they become available?
	Accessibility	• What is the extent of user knowledge required to conduct the method? • Is there a User's Guide, training session, support network?
	Cost	• How expensive is it to undertake conducting the method? Are the tools used in this method freely available or must they be purchased?
	Interpretability and communicability	• How easy are the outputs to interpret? And to communicate? Do the outputs require extra processing?

2.3.1.1 Concurrent tasks

Simultaneously to the desktop research for Tier 2, we conducted additional research (summarized in Appendix A) into a number of topics that provide fundamental context regarding the assessment of cumulative effects of marine shipping:

- Pathways of Effects: Fisheries and Oceans Canada (DFO), with input from Transport Canada, is developing the Pathways of Effects model that articulates the cause-effects relationships between activities associated to marine shipping and their effects, via stressors, on the Valued Components (VCs) of the environment. This information is important because the specific stressors and VCs being considered can influence the choice of the assessment method. For instance, we aimed, as part of the screening in Tier 1, to cover assessment methodologies for the specific activities under marine shipping (e.g., anchorage, movement underway, etc.).

- Management Context: The assessment of cumulative effects is nested and informed by specific management context and objectives. As part of the background research, our team reviewed relevant documentation on the scope and nature of Transport Canada's management mandate over marine areas and resources.

- Regional Context: The pilot sites differ in their geography, concerns regarding cumulative effects, specific stressors and valued components of special importance, etc. Based on the information gathered to date by Transport Canada, our team developed brief regional profiles discussing these regional differences and particularities.

- Data Availability: Transport Canada is currently in the process of identifying relevant data sources potentially relevant for cumulative effects assessment. The choice of assessment method is dependent on the types of data available.

The desktop research for each method was also supplemented by interviews with key experts. In total, we have interviewed 8 experts, including:

- Natalie Ban, Associate Professor in the School of Environmental Studies of the University of Victoria (British Columbia)
- Claude Comtois, Professor of Geography at the University of Montreal
- Roland Cormier, President of Ecorisk Mgmt Inc.
- Peter Duinker, Professor in the School for Resource and Environmental Studies of Dalhousie University
- Mike Elliott, Professor of Estuarine and Coastal Sciences at the Institute of Estuarine and Coastal Studies of the University of Hull
- Rebecca Martone, Marine Biologist with Marine and Coastal Resources, government of British Columbia
- Robert Stephenson, scientist with DFỎs St. Andrews Biological Station and a visiting Professor at the University of New Brunswick
- Villy Christensen, lead developer of Ecopath/Ecosim/Ecospace software for modeling food web interactions.

2.4 Challenges

There are several challenges we encountered during the implementation of this project:

Apples to oranges. The suite of candidate assessment methodologies we were asked to consider included a combination of methods, tools, and case studies, making it difficult to compare directly. For the purpose of this report we defined these terms as follows:

Methodology: The collective body of methods employed by a particular field, in this case cumulative effects assessment.

Method: A procedure or process for attaining an object, in this case the assessment of cumulative effects. In some cases, tools may exist to support the method, but a method may exist in absence of a tool.

Tool: A means to an end, an instrument or apparatus used in performing an operation. In this case tools are designed to support one or more cumulative effects assessment methods. Tools range in specificity from specific applications (e.g., ECCC's Marine Emission Inventory Tool) to generic software (e.g., ArcGIS).

Case study: The specific application of one or more methods and associated tools. These tend to be one-off examples which employ a combination of the methods discussed in this report to achieve a particular end.

Another challenge was that methodologies varied in terms of their function, i.e., how they could support CEA. Through the course of the screening phase, we developed a consistent organizing structure that we believe helps to address this challenge and distinguish among methods (Section 4.1). We also narrowed our detailed evaluation to focus on methods using examples of associated tools or case-studies where helpful.

National versus regional. A common challenge for national initiatives is the need to develop a national approach which is still relevant at the regional scale, and ideally is flexible enough to account for regional context. Finding a balance is difficult. A compromise may be to develop a national approach focused on aspects that are broadly applicable and can also be readily integrated with regional initiatives.

Data availability. Transport Canada is currently in the process of collecting existing coastal environmental data and regional marine shipping data for the six pilot sites. Data availability will influence the selection of assessment methodologies. Given that this task is still underway it is not possible to make specific recommendations at this time.

Timing of scoping. Development and implementation of the national Cumulative Effects of Marine Shipping initiative is being informed by engagement with Indigenous peoples and stakeholders in each of the six pilot sites across Canada. As with any work requiring engagement, this will take time. Since Transport Canada is using a collaborative process in choosing valued components, priority VC's have not yet been solidified at the time of writing this report. This inhibits making specific recommendations about which methods may be most appropriate. Instead we provide general guidance about what methods are appropriate under different conditions.

3 Screening of Assessment Methodologies

3.1 Overview

This section presents the main findings of Tier 1 of the evaluation process, which consisted of a high-level screening of cumulative effects assessment methods relevant for marine shipping. We reviewed in total 181 references including papers about specific methods/tools, review papers, assessment frameworks, key background documents, etc. The documents reviewed cover a variety of types of sources, from academic papers, reports, texts, case studies, websites and presentations. Figure 3.1 shows the distribution of references according to the theme or aspect of the evaluation that they inform. Half (50%) of the references are papers related to one of the assessment categories (i.e., spatial, analytical and modeling approaches). It should be noted that the distinction between methods is not always obvious and there are some methods described in the references that include elements of multiple approaches. However, we decided to classify the references based on their predominant assessment methodology (e.g., if a modeling method includes a spatial analysis component we would still classify it under the ‘modeling approaches’ category).

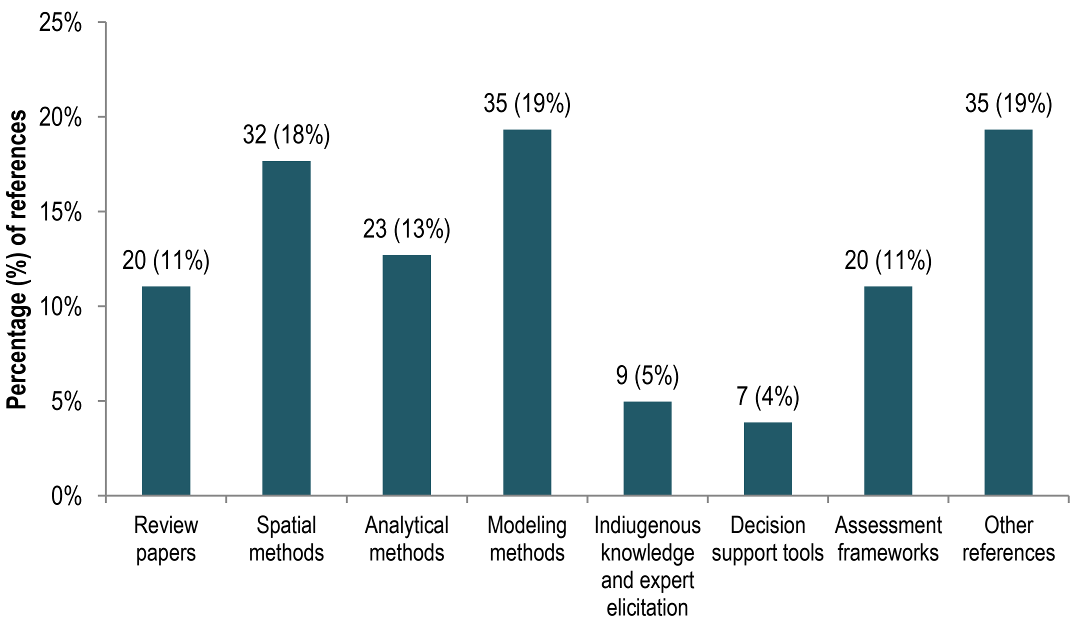

Figure 3.1. Distribution of literature reviewed per theme.

This screening phase was used to help identify the most relevant methods for Transport Canada. Insights from this review also helped form the organizational structure employed in the more detailed Tier 2 evaluation (Section 2.3).

3.2 Overall Findings

This section summarizes the main findings from the review papers looking into cumulative effects assessment methodologies. Appendix B presents a set of summaries of the most relevant review papers for this report.

In general, authors group the methods according to either the methodological nature of method or the function that the method and associated tool supports in the assessment process. Figure 3.2 shows various categorizations of CEA methods that we have found in the literature.

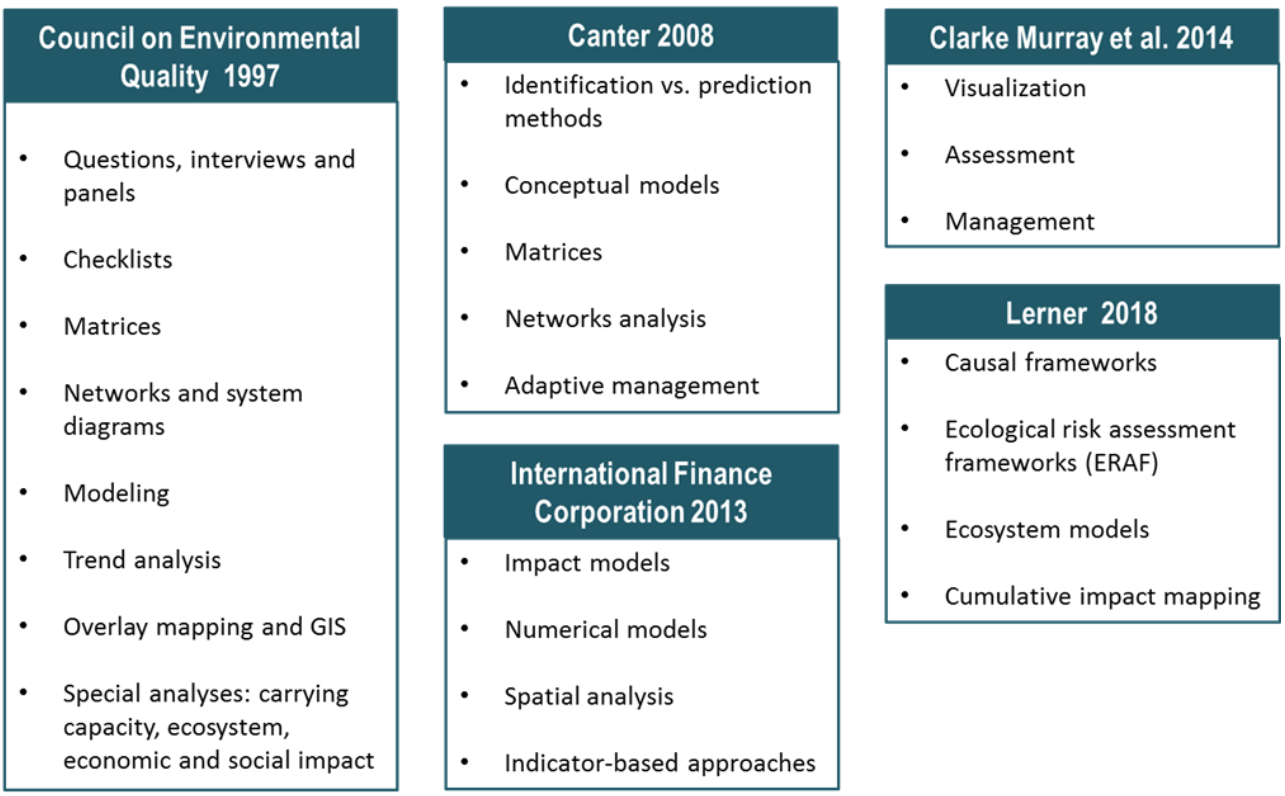

Figure 3.2. Examples of categorizations of cumulative effects assessment methods from the literature

Some authors have specifically looked at the methods used for CEA in marine environments. Willsteed et al. (2017) found a high variability, both conceptually and methodologically, in the approaches that have been used. The authors found that this disparity in methodological approaches does not contribute to improving regional understandings of cumulative environmental change.

Other specific challenges of CEA in marine environments (Stelzenmüller et al. 2018) are a consequence of the openness and high connectivity of marine ecosystems and the heterogeneity and uncertainty in biophysical processes, which are in some cases less well understood than in terrestrial ecosystems.

Main challenges and limitations in the practice of CEA include: limited scope of the studies (Korpinen and Andersen 2016) that does not include all pathways, lack of benchmark or thresholds for stressors (Korpinen and Andersen 2016) and ecosystem components (Jones 2016), uncertainty (Clarke Murray et al. 2014), and identifying baselines (Clarke Murray et al. 2014, Foley et al. 2017).

Uncertainty is unavoidable in CEA (Jones 2016). Although uncertainty is acknowledged in most CEAs, it is rarely addressed in terms of how it affects the result of the assessment (Stelzenmüller et al. 2018). Usual methods to address uncertainty in the context of these assessments include the use of Bayesian Belief Networks and expert elicitation (later discussed in Section 4.4).

CEAs are complex assessments and defining impacts, baseline, scale, and significance are still major challenges in CEA practice according to Foley et al. (2017). Despite the recent advances in CEA science and in the tools and methods available, practitioners are still struggling to put scientific approaches (e.g., quantitative assessments, use of numerical models, etc.) in practice. There is also inconsistency in how baselines are defined and how the effects and their significance are assessed.

To date, the predominant method for cumulative effects assessment has been some variation of spatial analysis (Korpinen and Andersen 2016). This type of approach involves combining spatial information on the intensity of the pressures/stressors with data on the distribution and characteristics of the valued components under study. Although spatial approaches can help with the formulation of the problem (Judd et al. 2015), this type of analysis alone does not provide an assessment (quantification) of the impacts.

CEQ (1997) points to two aspects of CEA that require special analysis, and therefore special methods: the need to address resource sustainability and the focus on both ecosystems and human communities.

4 Detailed Evaluation of Assessment Methodologies

4.1 Organizational Structure

At the outset of this exercise we used the four categories defined by Lerner (2018) in her review of cumulative effects frameworks: causal frameworks, ecological risk assessment frameworks (ERAFs), ecosystem models, cumulative impact mapping. As we progressed with the screening we found it useful to group the methods from the literature into three new categories in terms of the nature of the assessment: spatial, analytical and modeling methods. These categories roughly align with the steps described in the assessment step (Section 1.3): **spatial methods** are often used to evaluate the condition of VCs and stressors, **analytical methods** aim to quantify the functional relationships for impact pathways, and **modeling methods** enable the evaluation of alternative scenarios. Using the Pathways of Effects model (Appendix A) as a reference, we have further divided the methods according to the portion of the system that the assessment focuses on (Figure 4.1); e.g., stressors, VCs or pathways.

Methods do not divide perfectly into mutually exclusive categories. In some cases, one method may be an input for another method. In other cases, there is some overlap in approaches discussed in two different methods (e.g., many methods have a spatial component). We have divided methods based on their primary characteristics acknowledging that there is some overlap among methods. In addition, several supporting methods were identified (i.e., Indigenous knowledge, expert elicitation, and decision support tools) and are documented in Section 6.

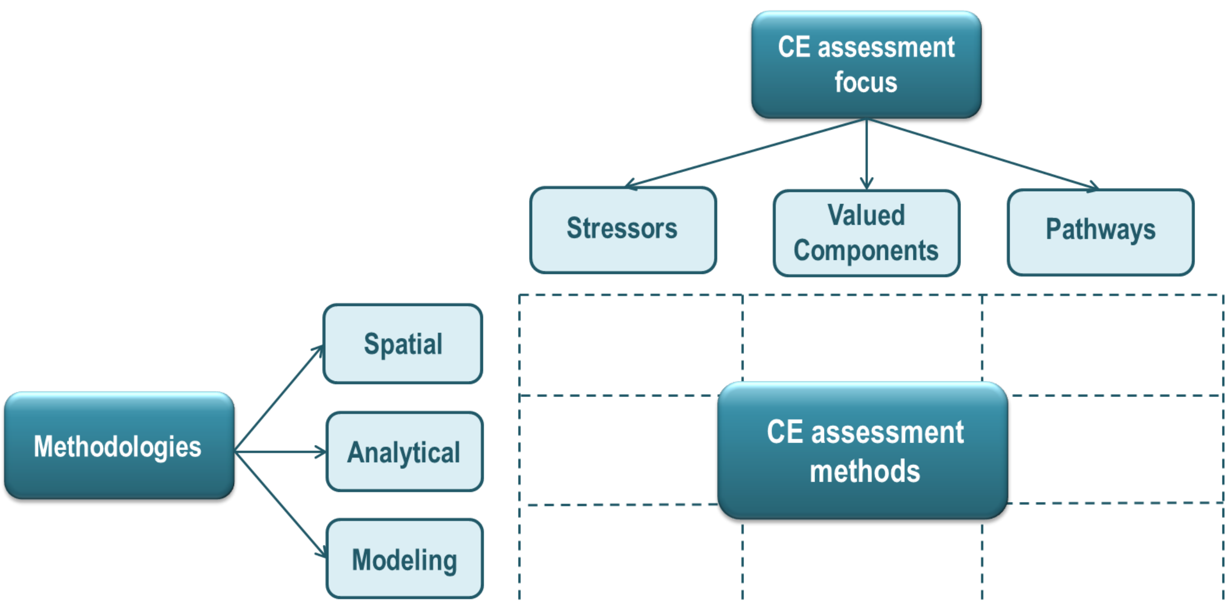

Figure 4.1. Organizational structure for the evaluation of cumulative effects assessment methods

4.2 Spatial Methods

4.2.1 Overview

Spatial methods to assessing cumulative effects involve identifying the locations of stressors and VCs to understand how VCs are being exposed to stressors (i.e., geographical overlap) and the way that exposure results in different levels of effect. Spatial approaches can entail simply mapping locations to understand where there are different types of stressors and VCs as well as using characteristics about the stressors and VCs along with analytical approaches or modeling to better understand the magnitudes of effect. In this way, spatial approaches are not distinct from analytical and modeling methods but rather complementary.

Spatial methods are often conducted early in a CEA process as they can highlight geographical areas to focus on (e.g., areas with many stressors acting on VCs) and priority pathways (e.g., a pathway where the stressor and VC are often interacting). In this section, we focus on spatial approaches related to mapping, which is essentially one method that can be used alone or with other analytical or modeling methods, described in Sections 4.3 and 4.4.

Mapping human activities and VCs involves identifying locations and associated characteristics (i.e., a spatial representation of the stressor or VC condition). For example, for an ecological VC, this can include identifying areas in which the species has been observed and the population levels within each of those areas. Mapping multiple activities and/or VCs brings together single activity and single VC maps by overlaying activities and values to highlight areas where different VCs are exposed to different activities.

4.2.1.1 Stressors

Identifying locations for human activities is often easier than for VCs because data collection can be built into the activity. For example, the Automatic Identification System (AIS) is a tracking system that collects vessel movement information while vessels are operational using a global positioning system receiver (GPS) (Marine Traffic 2018). With data collection occurring while vessels are underway, AIS data are constantly being gathered and can easily be used for a variety of purposes. One way in which AIS data are often used in assessments of cumulative effects is to produce maps of vessel traffic density (Figure 4.2). Vessel traffic density information can then be useful in conjunction with analytical or modeling methods to estimate the magnitude of a stressor (e.g., with noise propagation models as discussed in Section 4.4.1) and/or the ultimate effect on a VC (e.g., effect of noise on nearby cetaceans).

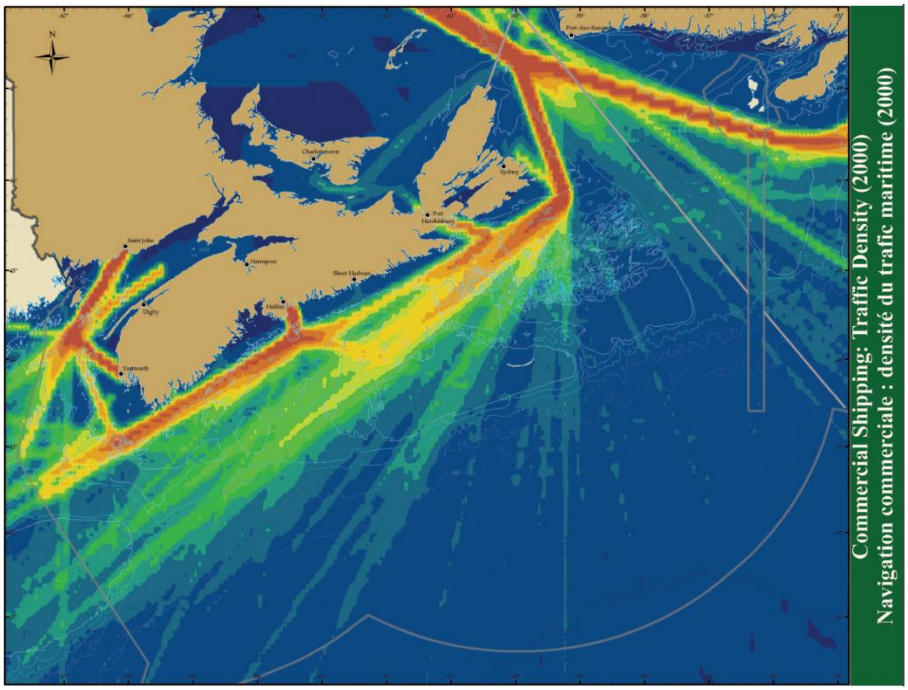

Figure 4.2. Heat map illustrating intensity of vessel traffic from The Scotian Shelf: An Atlas of Human Activities (DFO 2005).

For cases in which it is not possible to build data collection into the activity, data can be collected in the field. Data collection in the field requires monitoring using appropriate methodologies (i.e., how to collect the data) and sampling designs (i.e., where, when and how often to collect the data). A methodology often useful for human activities is surveys, whereby observations of activities are recorded in a systematic way by repeatedly recording observations along specific transects. In designing this type of monitoring, a statistician should be consulted to ensure a robust design.

However, field monitoring can be costly and so it may be more efficient to compile estimates through engaging people involved in the activity. This is often done using surveys to ask individuals about where and when they were in different places and what they were doing. An example of this is creel surveys that are conducted with fishers as they return from fishing. In these surveys, fishers are asked where they were fishing, how long they were fishing, and what they caught, which provides location and magnitude data related to the fishing stressor (i.e., location and magnitude).

Additionally, locations and characteristics of human activities can be estimated based on Indigenous knowledge or expert opinion, both of which are further discussed in Section 6.

4.2.1.2 Valued components

Mapping ecological, cultural, and socioeconomic VCs can be conducted using multiple methods, including field-based monitoring, eliciting expert opinion, and engaging with Indigenous knowledge holders.

Mapping ecological VCs can be difficult, especially in aquatic environments, because they can be difficult to detect thereby requiring sampling techniques to determine their locations. The type of sampling method to employ depends on the VC. Although it is out of scope to identify the monitoring methods for all potentially relevant VCs, some examples include: Monitoring for cetaceans by conducting surveys along predetermined transects; and monitoring for crabs through deployment of crab traps. In addition, some methods may allow for monitoring multiple VCs (e.g., underwater SCUBA surveys can be used to collect data related to multiple different species).

Locations and characteristics of ecological, cultural, and socioeconomic VCs can also be estimated through engaging with Indigenous knowledge holders (further discussed in Section 6.1). In some cases, Indigenous communities may have already undertaken initiatives to document this information. For example, in Haida Gwaii, British Columbia, the Haida Marine Traditional Knowledge (HMTK) project was initiated in 2007 by the Haida Fisheries Program to research and document Haida culture, traditions and knowledge related to the Haida Gwaii marine area (CHN 2011a). As part of this project, interviews were conducted with community members and significant sites, fishing areas, and ecological features were mapped. Figure 4.3 displays part of a large map that was produced to complement multiple reports (CHN 2011b).

Locations and characteristics of ecological and socioeconomic VCs can also be estimated using expert opinion. This method is further discussed in Section 6.2.

Upon mapping the locations and characteristics of VCs, maps can be overlaid with maps of stressors to identify priority pathways (e.g., ones in which a VC is highly exposed to a specific stressor) and priority geographical areas (e.g., where VCs are exposed to multiple stressors). Risk assessment discussed in Section 4.3 builds on this kind of spatial analysis. This information can then be used to support analytical and modeling methods which further explore the magnitude and nature of the effects on different identified VCs.

Figure 4.3. Part of the Haida Ocean & Way of Life Map produced as part of the Haida Marine Traditional Knowledge Study.

4.2.1.3 Pathways

One method that has connected stressors and VCs and is heavily focused on mapping is cumulative impact mapping (Halpern 2008 Ban et al. 2010, Micheli et al. 2013, Clarke Murray et al. 2015, Depellegrin et al. 2017, Mach et al. 2017, Andersen and Stock 2013, Korpinen et al. 2012). At its most basic level, cumulative impact mapping is stressor focused as it involves identifying the multiple activities occurring across a space and using information about the activities (i.e., types and levels of stressors) to make inferences about the levels of cumulative pressures occurring in the space. However, cumulative impact mapping builds upon that, using information about the sensitivity and vulnerability of VCs from expert elicitation to assess how the cumulative pressures in the space may be affecting the VCs (Halpern et al. 2008). Ban et al (2010) applied this approach on the western coast of Canada.

4.2.2 Evaluation Criteria

4.2.2.1 Relevance

Usefulness

Type and intensity of vessel traffic differs spatially along Canadian coasts. These differences result in different types and intensities of stressors, which then act on different suites of values. Identifying and mapping the suites of stressors occurring in different spaces allows for identifying hotspots of concern or areas where management efforts can be focused (Ban et al. 2010). Further identifying and mapping suites of VCs allow for highlighting spaces where specific management actions may be applied to reduce effects on specific values. In addition, mapping activities and VCs can be used along with other methods to either highlight areas where more detailed methods should be used, or to make spatially explicit the inferences that result from the other methods.

Spatial & temporal scale

Mapping locations and characteristics of stressors and VCs has been undertaken at global, regional, and local scales. Mapping has occurred for particular stressors (e.g., PSF 2015), for specific valued components (e.g., CHN 2011a), and for examining how stressors can cumulatively impact the ecosystem using the cumulative impact mapping approach developed by Halpern et al. (2008) (Ban et al. 2010, Mach et al. 2017). Smaller scale assessments are able to present results with more geographical specificity. For example, Halpern et al. (2008) conducted a global assessment and highlighted global areas of concern, whereas Ban et al. (2010) focused specifically on the British Columbia coastline and highlighted areas specific to British Columbia (Figure 4.4).

Although mapping cumulative impacts can be conducted at multiple spatial scales, it is important to note the spatial scale of the data being used and assumptions embedded within those datasets, so that inferences are not made at scales that are finer than the datasets allow. In determining the best spatial scale to conduct an assessment, consideration should be given to the scale of the different types of human activities and VCs as well as the spatial scale of how management activities can be implemented. When these considerations lead to multiple relevant scales (e.g., different VCs require different scales), assessments need to be conducted at multiple scales, which can be undertaken using a nested approach (R. Martone, pers. comm.).

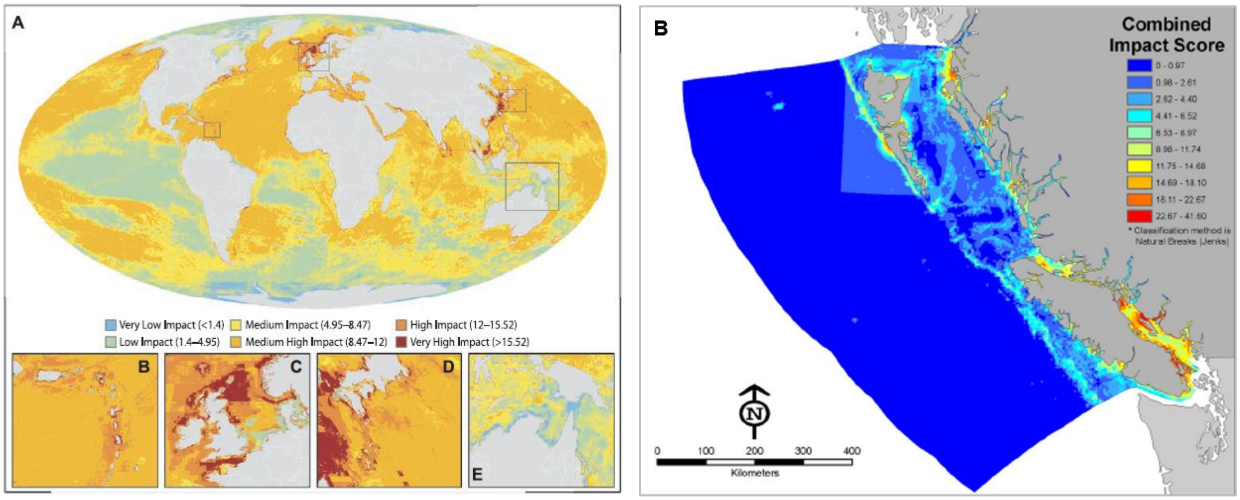

Figure 4.4. (A) Map of global cumulative human impact across 20 ocean ecosystem types as well as four maps of highly impacted regions (from Halpern et al. 2008), and (B) impact scores for areas along the British Columbia coastline (from Ban et al. 2010).

Indigenous knowledge

Indigenous knowledge has been widely used to document specific characteristics about ecosystems as well as cultural places and uses (CHN 2011a). For examining cumulative impacts in a spatially explicit way, Indigenous knowledge is valuable for providing insight into the type and intensity of human activities and the status of ecological and cultural components in the past, how they have changed over time, and the way that they may change into the future under various scenarios (N. Ban, pers. comm.). Indigenous knowledge is further discussed in Section 6.1.

4.2.2.2 Rigour

Application of method

There are many applications of mapping human activities and valued components (e.g., CHN 2011a, PSF 2015). For human activities, this includes documenting footprints for permanent activities, such as coastal industries (e.g., government tenure data), and tracking for activities that spatially change through time. For example, combining data from all AIS equipped vessels within an area over a particular time can provide spatially explicit information about the intensity of AIS equipped vessel traffic within the space given the time period. For valued components, locations and characteristics can be identified based on scientific research, Indigenous knowledge, or local knowledge.

Datasets about multiple human activities and VCs are often combined within global information systems (e.g., ArcGIS, QGIS) to understand how activities and ecosystem components spatially interact. Sometimes this information is further incorporated into a web-based mapping platform. For example, the Marine Plan Partnership (MaPP) Marine Plan Portal is an interactive map-based program that uses the SeaSketch platform to allow users to view multiple layers within the MaPP area (MaPP 2018). For further information about this refer to the case study detailing it in Section 6.3.2.

Overlaid spatial information can further be used with other types of approaches to better understand impacts that may be occurring on valued components. One approach that has been undertaken many times is combining spatially explicit information with expert based estimates of ecosystem vulnerability, using the cumulative impact mapping approach (Halpern et al. 2008,). Using this approach, categories of human activities are mapped and expert judgement is used to estimate ecosystem-specific levels of impact for the categories so that cumulative impacts can be estimated in a spatially explicit way. Other methods that can be spatially explicit or complemented using spatially explicit information are discussed in the analytical and modeling methods sections (Sections 4.3 and 4.4).

A spatially explicit approach is beneficial for understanding how human activities and VCs are exposed to each other, and for highlighting areas with concerning overlaps. Combining spatially explicit information with another approach (e.g., a model) is beneficial when there is a need for greater understanding about the relationship between activities and/or components.

Level of underlying data/information

Mapping human activities and VCs can incorporate multiple types of information, including empirical data from scientific research, Indigenous knowledge, or local knowledge, as well as inference-based information from models or expert estimations. Because mapping for cumulative effects inherently requires data for multiple human activities and/or VCs, it is often challenging to collect or acquire empirical data for all of the data required. Furthermore, it is especially challenging when there is a need to estimate how stressors dissipate as they move further from the activity of origin and how that stress then impacts specific VCs. Because of this, there is often a reliance on data collected elsewhere in the world and/or expert knowledge (N. Ban, pers. comm.). This information is then often used for further analytical analyses (see Section 4.3) or in the development of simulation models (see Section 4.4).

Uncertainty

Mapping human activities and VCs can involve accounting for uncertainty when applicable. Data about human activities are often census based (i.e., data collection designed to capture all of the activity), as is the case with AIS data (i.e., it captures all of the movements of the AIS equipped boats). However, when human activity or VC data are collected based on sampling only a portion of the activity or component, then confidence intervals can be included. Because human activities can usually be measured more easily than VCs, which need sampling, it is generally easier to collect data with less uncertainty for activities than VCs.

When mapped information is used in combination with another method then any uncertainties associated with the other approach also exist. For example, if a model is used to estimate a level of impact on a VC from a specific stressor, estimates of the level of impact will involve uncertainty based on the data used to inform that relationship in the model. Some cumulative impact mapping undertakings have worked to explicitly account for uncertainties (Figure 4.5) (Gissi et al. 2017). Whether uncertainties are quantified or reduced, it is ultimately important to be explicit about where uncertainties exist and/or where assumptions have been made (N. Ban, pers. comm.).

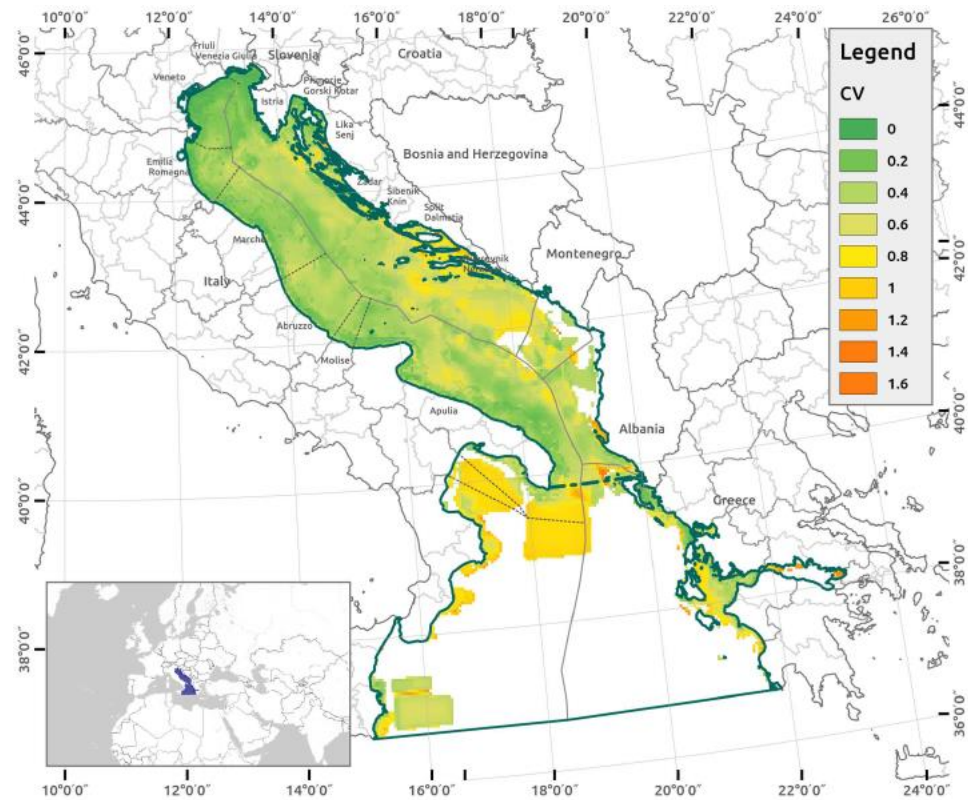

Figure 4.5. Coefficient of variation (CV) resulting from the Monte Carlo simulation of the four input factors used in the uncertainty analysis in Gissi et al. (2017).

4.2.2.3 Feasibility

Complexity

Spatial approaches can vary in complexity. Mapping that makes explicit the locations and characteristics of human activities or VCs can be relatively low in complexity. This type of mapping and analyzing overlaid information requires GIS capabilities (e.g., ArcGIS or QGIS) and knowledge related to analyzing different types of datasets (e.g., boat tracks, species habitat use, etc.). Complexity can increase when combining mapped information with other assessment methods (e.g., modeling) depending on the complexity of the other approach.

Data/information requirements

Data or information requirements depend on the number of human activities and/or VCs that are included in the scope of the assessment. The more human activities or VCs in the assessment, the greater the data requirements.

In order to assess the cumulative pressure from the comprehensive suite of human activities within a space, spatially explicit data are required related to all of the human activities within the space of interest. To subsequently assess the stressors that are produced by those human activities, information is required about which activities produce which stressors and in what ways (e.g., information about noise dissipates with distance from the source vessel; see Section 4.4 for how single stressor model can be used to simulate this type of information). To assess the exposure of VCs to activities and stressors, spatially explicit data are required about the distribution of VCs within the space of interest (see Section 4.3 for analytical methods to estimating distributions).

A complimentary analytical or modeling method can be beneficial for estimating how the VCs are affected by the stressors. In doing so, information is required about how stressors affect components of the system and how multiple stressors and components interact (e.g., whether the effect from two stressors on a component is additive, synergistic, or antagonistic). Data and information requirements associated with analytical and modeling methods are further discussed in Sections 4.3 and 4.4.

In the absence of quantitative data, Indigenous knowledge (Section 6.1) or expert judgement (Section 6.2) may be useful for filling data gaps. Alternatively, assumptions may be used, so long as the assumptions are made explicit (N. Ban, pers. comm.).

Data flexibility

Because mapping human activities and VCs inherently incorporates multiple types of information, including empirical data and inference-based information, there is a large degree in the flexibility related to incorporating data not specifically gathered for a cumulative effects assessment and for using data from expert judgement in the absence of empirical data. In fact, cumulative impact mapping often relies on datasets collected for other purposes (Halpern et al. 2008, Ban et al. 2010), which can include human activity data tracked on an ongoing basis (e.g., AIS data) or as part of a specific research project (e.g., species population data gathered for a PhD thesis). If mapping of activities and VCs is combined with another approach, further data limitations may exist according to the flexibility of the other approach.

Accessibility

Because mapping of locations of human activities and VCs has been conducted many times, information about methods for doing so are accessible. Furthermore, GIS software systems (i.e., ArcGIS, QGIS) used to undertake mapping are commonly used and there is a wide support network of people to support the use of these systems.

Cost

Undertaking mapping activities varies depending on the scope of the assessment, availability of data, and availability of software and human resources. Undertakings can be scoped based on gathering specific human activity and/or specific VC data (e.g., only examining vessel traffic related to ferries as opposed to multiple types of vessels) and scoped based on different spatial and temporal scales. In addition, cost will vary depending on data availability, as cost will greatly increase with the need to gather empirical data, conduct expert elicitation exercises, or engage Indigenous knowledge holders.

Interpretability & communicability

Maps are beneficial for communicating and interpreting information, and this includes maps of locations of human activities and VCs. When combining mapped information with other methods, results may become more complicated to communicate depending on the complexity of the other method. In general, if ease of communication and interpretability is important, using a spatially explicit approach will allow for presenting results on maps, which aids communication.

4.3 Analytical Methods

4.3.1 Overview

This section does not capture the vast literature on statistical methods. Rather it identifies a few key methods that are relevant in the context of the CEMS initiative. This section differs from the other sections in that the methods focus on how to use **empirical information[4].** Specifically, we describe how to evaluate the spatial distribution of Valued Components, characterize risk, and quantify functional relationships for hypothesized pathways.

4.3.1.1 Stressors

The condition or magnitude of activities (e.g., movement underway) can usually be measured directly and relatively easily as it is the thing we are actually in control of. Quantifying the stressors (e.g., noise) resulting from a given activity is more difficult. In general, the stressors are quantified using mechanistic models (refer to Stressor models Section 4.4.1) based on empirical data for the related activity. While there may be some exceptions, there is limited value in further exploring analytical methods for quantifying stressors.

4.3.1.2 Valued Components

Methods for monitoring and evaluating the condition of VCs (e.g., abundance of whales) are more complex than for activities. This is because VCs are not directly within our control, they tend to be found across broad spatial scales making a sampling approach necessary, and they are often difficult to detect. There are a variety of methods which may be applicable including: capture-recapture studies, radio-tracking, or visual surveys. Collectively the combination of sampling design and field methodologies can be referred to as monitoring design, which is beyond the scope of this report. In general, a statistician should be consulted to design a robust monitoring program.

There are, however, a few analytical methods associated with identifying the spatial distribution of VCs which are likely to be of particular use to the CEMS initiative and are discussed further in this section.

Home-range Estimation

Summary

Identification of home-ranges or areas which are most important to VCs during different life-stages or times of year. These distributions could be overlaid with corresponding maps of stressors to identify exposure hotspots.

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[4] Empirical: "originating in or based on observation or experience" Merriam-Webster [https://www.merriam-webster.com/dictionary/empirical]

Description

Utilization distributions are defined as the distribution of an animal's position in the plane (Worton 1989). Estimating the utilization distribution is useful for identifying home-ranges or critical habitat for different species or life-stages. There are a variety of methods in the literature for estimating home-ranges. In general, they require empirical information about where the species of interest is found. This information can take a variety of forms including: radio-tracked animals, indirect or direct signs of presence, or visual surveys (Cominelli et al. 2018). The frequency of observations is then analyzed spatially to identify the utilization distribution. These distributions can be plotted on a map to illustrate the areas which are most frequently used by the species or life-stage of interest. There are both parametric[5] and non-parametric approaches for estimating these distributions. Worton (1987) provides a review of methods for home-range estimation. These methodologies are fairly simple in concept and a variety of freely available software tools exist to support them. A combination of GIS and moderate statistical expertise are required.

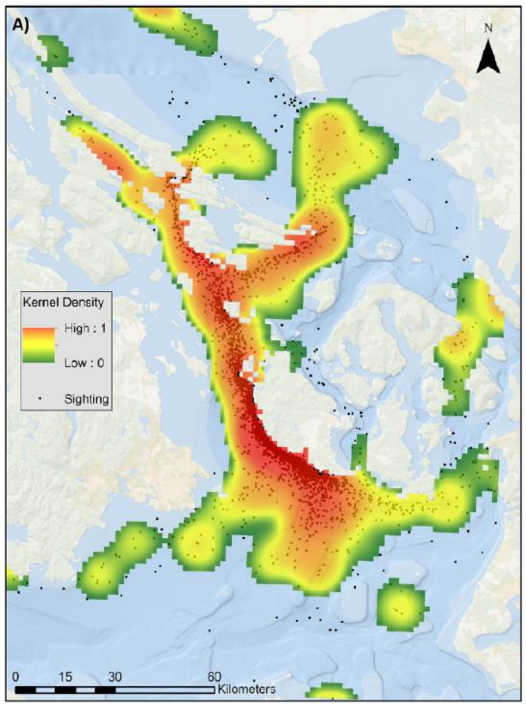

Figure 4.6. Example of the summer core habitat of Southern Resident Killer Whales estimated using kernel density estimation, a non-parametric method (Worton 1989), to estimate utilization distributions (Figure replicated from Cominelli et al. 2018).

[5] Parametric approaches involve an assumption about distribution of the data, most commonly that the data are normally distributed. Non-parametric approaches do not make any assumptions about the distribution of the data, but in general it is more difficult to make statements about the probability or confidence of the results.

Habitat Suitability Models (HSM)

Summary

Similar to home-range estimation, habitat suitability models are useful for estimating spatial distributions of VCs. The additional benefit of habitat suitability models is that future distributions may be predicted under different habitat scenarios. HSM are a useful tool to support spatially explicit simulation models (Section 4.4).

Description

Habitat suitability modeling (HSM) is a method for predicting the quality or suitability of habitat for a given species based on known affinities with habitat attributes such as habitat structure, habitat type and spatial arrangements between habitat features (e.g., depth, substrate, cover type, etc.). This information can be combined with maps of those same habitat attributes to produce maps of expected distributions of species and life stages. Unlike home-range estimation HSM requires information about both **habitat** and **species occurrence or abundance** and habitat data must be collected at locations where the species does not occur as well as where it does. The basic idea is that when habitat resources are used disproportionately to their availability, the species is preferentially selecting the resource (Manly et al. 2002).

HSM typically relies on regression techniques to quantify the relationship between habitat and species occurrence or abundance. In data-poor situations, a literature review of the available information or expert opinion may be used to develop the initial models. Once suitability index values have been calculated for the habitat characteristics, by one or another of the methods described above, they can be mapped individually and combined into a composite map. The resultant map will show the expected distribution of habitat suitability for each species and/or life stage included in the analysis. HSM vary in generality and precision, due in part to the sometimes limited quantitative and often qualitative nature of existing information. Once the relationship between habitat and the species of interest is quantified, that relationship can be used to predict distributions in places where no direct observations of the species exist or to predict distributions under alternative future scenarios.

These methodologies are still simple in concept although the analysis is slightly more involved. Like home-range estimation there are a variety of freely available software tools to support HSM (Guisan et al. 2017). A combination of GIS and moderate statistical expertise are required.

4.3.1.3 Pathways

This section describes methods for quantifying the functional relationships between stressors and VCs (i.e., the pathways in the PoE model, Appendix A) and determining the relative importance of different pathways. Functional relationships between one stressor and one VC may take a variety of forms (e.g., linear or exponential). Analysis may be completed for a single pathway but also for multiple pathways simultaneously. Effects of multiple stressors may be additive or synergistic. Understanding the nature, magnitude, and relative importance of different pathways can help to focus the scope of the assessment, inform thresholds, parameterize models, and ultimately inform management actions.

Risk Assessment

Summary

Risk assessment may be useful to the CEMS initiative as a way of identifying locations where exposure to stressors may be the greatest in each region and also which impacts (e.g., stressor-VC pathways) are most likely.

Description

Risk assessments evaluate the exposure of some entity (e.g., VC) to a stressor (or multiple stressors), and determine the consequence of this adverse exposure. For example, an analysis involving risk assessment may examine the overlap of a species' range with a particular stressor and, therefore, its exposure to that stressor (Murray et al. 2014). Risk is typically defined as the probability of occurrence of a stressor, or **hazard**, and the magnitude of its consequences; hazard is defined as something that has the potential to cause harm (Manuilova 2003). Risk is often portrayed along two axes, with the **exposure** of a valued component (VC) to a stressor on the x-axis, and its **sensitivity** to that stressor on the y-axis.

Some studies estimate the severity of a list of potential stressors of relevance by consulting with experts in the field, often through the use of surveys (Halpern et al. 2007, Grech et al. 2008, Stelzenmuller et al. 2010). Similarly, some studies made use of a phased, screening framework to iteratively assess the risk to VCs given under different stressor scenarios. The screening approach can be in the form of a multi-criteria analysis[6] (Stelzenmuller et al. 2010, Hobday et al. 2011, Furlan 2017), or a computer-based programs (Manuilova 2003, DFO 2012, DFO 2014).

Impact scores may be generated for VCs through application of stringent criteria with threshold values (Wood et al. 2012, Lawson and Lesage 2013, O et al. 2015, and Herkul et al. 2017). The risk impact scores are the product of exposure and consequence scores, determined through analysis of quantitative data within a qualitative criteria framework.

Several studies have applied a geospatial analysis of the distribution of activities, stressors, and valued components of concern to graphically depict areas of highest risk, and aid management decisions (Halpern et al. 2007, Grech et al. 2008, Stelzenmuller et al. 2010, Parravicini et al. 2012). An advantage of geospatially-focused assessments is that larger areas can be analyzed at the synoptic level, allowing data-scarce systems to still be broadly assessed. However, one issue with geospatial analyses is that stressors are typically site-specific, and broad extrapolation of their effects at larger spatial scales can be difficult (Parravicini et al. 2012).

Regression Analysis

Summary

Regression analysis is a general class of analysis which can be used to quantify the relationships between stressors and VCs based on empirical data. This approach can be used to determine the direction, shape and magnitude of the functional relationship between a given stressor and a VC. It can also be used to help determine the relative importance of different pathways for a given VC. Additional environmental covariates

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[6] GIS-based **multi-criteria analysis (MCA)** is a tool that generates alternate outcomes based on how input parameters, such as the rank order of the stressor, are altered. Any simulated outcome from the MCA that is considered to have a higher level of risk associated with it should flag for decision makers that alternate human-activity scenarios should be considered.

can be considered to help distinguish between impacts due to the stressor and those due to environmental conditions.

Description

Regression analysis is a fundamental statistical tool used to estimate relationships between one or more response variables and one or more explanatory variables using observed data. Anyone who has taken at least one university level statistics course is likely familiar with the concept of fitting a straight line to observed data. This basic concept can be extended to a variety of more complex scenarios including: more explanatory variables, linear and non-linear functional relationships, interactions, and different types of response variables (e.g., categorical, binary, continuous). Generalized Linear Models (GLMs) represent the generic form of regression analysis.

$$E(Y) \quad = f(\beta_0 + \beta_1 X_1 + \cdots + \beta_p X_p + Zu) + \varepsilon \quad \text{Equation 1}$$

Equation 1 describes the basic structure for any GLM analysis: Y represents the response variable, and the expected value of Y is given by some function *f* of a linear combination of the explanatory variables, X. The β's represent the coefficients estimated from the analysis, Z_u represent the random effects, and ε represents the remaining error. In this case the response variable Y would be the VC, and the stressors would be the explanatory variables (X). Random effects may be appropriate in cases where there are repeated measurements on the same experimental units (e.g., when the same whale is observed multiple times within the study).

An important part of regression analysis is model selection. It may be possible to fit many different models[7] given enough data, and it can be challenging to determine which model is best. There is a trade-off between model fit and predictive ability. A model that fits the observed data extremely well may not be very good at predicting future outcomes. Model selection involves looking at a variety of possible models which vary in terms of the number of explanatory variables, the functional form, and whether or not interaction terms are included. In general, the 'best' model is the simplest one that adequately describes the data.

There are a number of different approaches to model selection. We recommend the Burnham and Anderson (1998) hypothesis driven approach. This approach requires a-priori specification of likely models based on biological hypotheses and builds nicely on the conceptual pathways of effects models in development.

There are many variations on this overarching methodology and numerous texts on the subject, depending on the details (Dobson 1990; Draper et al. 1998). This method is relatively complex and requires advanced statistical expertise.

Classification and Regression Trees and Forests

Summary

These methods provide a non-parametric alternative to regression analysis that can be used to determine the nature of functional relationships between stressors and VCs as well as identifying the most important

[7] In this context model refers to the regression model (e.g., the generic form is shown in Equation 1).

pathways. They don't have the same restrictive assumptions about distribution and may be better able to address large numbers of potential stressor pathways.

Description

Classification and Regression Trees (CART) are a non-parametric alternative to regression analysis. Classification refers to the case where the response variable is categorical and regression trees are used otherwise. They are a form of binary recursive partitioning. Beginning with the full data set, the software determines which variable is the best to split the dataset and at what value of the variable. Now the data is split into two nodes based on a rule for a single variable. Then for each of the nodes the best splitting variable is chosen until the full tree is built and no more splits are possible. There are generally options available to limit the extent of the tree. The splitting criteria are chosen to maximize the reduction in heterogeneity, in other words to split the data so that the response variables within each node are similar. A weakness of simple regression trees is that they can be unstable (i.e., highly dependent on the particular set of observations). Regression Forests essentially replicate the regression tree process many times using a new subset of the data every time. Final predictions use the average findings across all observed trees. This method may be useful when there is a lot of data and limited prior knowledge about the system.

These methods are relatively easy to implement using freely available canned software tools such as: rpart or randomForestSRC (R Core Team). Brieman et al. (1984) provides detailed guidance on implementation.

Principal Components Analysis

Summary

Principal Components Analysis (PCA) could be a useful method for determining which stressors or combinations of stressors are most important for a particular VC. This would provide valuable focus for subsequent analysis and modeling efforts.

Description

Data reduction and interpretability are the primary goals of a PCA. This is particularly useful when there are a large number of potential explanatory variables (stressors in this case) some of which may be correlated. PCA is a mathematical procedure which transforms the larger number of possibly correlated variables into a smaller number of uncorrelated variables called '*principal components'*. Components are linear combinations of the original variables. The nature of the linear combination can give insight into the combined effect of multiple variables. The idea is to try and determine which components explain the majority of the total system variability. Although you may need many variables to describe all of the variability, it is often the case that only a few principal components are needed to account for most of the variability in the system (Johnson and Wichern 2002). This method is often used in exploratory analysis and may provide inputs to a multiple regression or cluster analysis.

Weight of evidence

Relevance

Understanding the relative importance of different pathways on a VC helps to focus research and management strategies. In practice however, it is difficult to quantify the functional relationships of one pathway let alone the relative importance of many. This is particularly true when data are limited or varied in nature as is often the case in Cumulative Effects Assessments. Weight of evidence methodologies use multiple lines of evidence to make statements about the relative likelihood of different hypotheses or in this case pathways.

Description

The term Weight of Evidence has been widely used in the literature but there is no agreed upon definition (Weed 2005). Burkhardt-Holm and Scheurer (2007) outline an approach that evaluates the: plausible mechanism, exposure, correlation/consistency, thresholds, specificity, and experimental evidence through a series of questions. Marmorek et al. (2011) simplified and adopted this approach (Figure 4.7) to evaluate the relative likelihood that each of 13 potential stressors was responsible for the decline in Fraser River Sockeye.

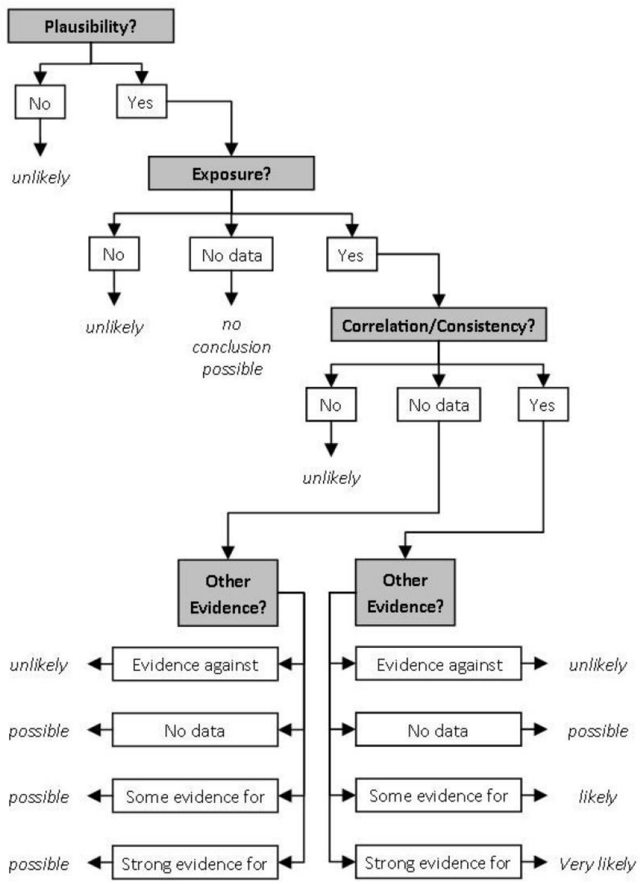

Figure 4.7. This flow diagram shows the weight of evidence approach used to determine the relative likelihood each particular stressor was responsible for the decline of Fraser River sockeye. This is replicated from Marmorek et al. 2010.

4.3.2 Evaluation Criteria

4.3.2.1 Relevance

Usefulness for the CEMS initiative

The marine ecosystem is incredibly complex and there are many unknowns. A critical component of the assessment step (Figure 1.2) is to quantify and validate hypotheses about impact pathways using empirical information. These empirically based assessments can then be used to support evaluation of alternative scenarios using a variety of modeling methodologies (Section 4.4). The analytical methods described in this section describe how the CEMS initiative can:

- Determine the spatial distribution of VCs of interest.
- Develop habitat suitability models so distributions can be predicted based on habitat characteristics.
- Complete risk assessments to identify high priority areas or pathways where the exposure and consequence are high.
- Quantify the magnitude and nature of the functional relationships between stressors and VCs (i.e., pathways).
- Identify the relative importance of different pathways (i.e., the drivers of the system).

Spatial & temporal scale

While the methods described here are broadly applicable, analytical efforts are likely best applied at regional or local scales. It may be possible to analyze data from different regions simultaneously, but it is likely not useful given the regional differences in VCs. In addition, data availability differs greatly by region. It would be easier to tailor the analytical details to the available data.

Indigenous knowledge

Indigenous knowledge (IK) can comprise empirical information that can be used in conjunction with analytical approaches. Potential applications of IK with analytical approaches include informing the location of species generating an index of relative abundance, conducting home-range estimation, undertaking regression analysis, and informing risk assessment. Additionally, weight of evidence approaches are particularly well suited to incorporating multiple lines of evidence as may be provided when using Indigenous knowledge alongside other types information. Any application of IK must be done by or with IK holders and communities. Indigenous knowledge is further discussed in Section 6.1.

4.3.2.2 Rigour

Application of method

In general, the analytical methodologies are well established and have a strong technical foundation. There is extensive literature on both the theory and practice of quantitative methods. In terms of their application to cumulative effects assessment, there are quite a few examples which involve determining the spatial distribution of VCs and assessing risk. However, there are relatively few examples of pure quantitative methods being applied to quantify the functional relationships between stressors and VCs. This is likely because the methods can be intimidating, the underlying relationships are likely very complex (particularly when multiple pathways are considered), and data are often limited making it difficult to draw concrete conclusions. Weight of evidence approaches which enable multiple lines of evidence to be considered (e.g., risk assessment, correlation analysis, and Indigenous knowledge) are a possible compromise.

Level of underlying data/information

These methods rely on empirical information. If data do not exist, then spatial methods (Section 4.2) based on expert elicitation (Section 6.1) or models may be generated based on current hypotheses (Section 4.4), but ultimately some form of observed data are necessary to validate our understanding of the system.

Uncertainty

An advantage of traditional parametric statistical methods is the fact that findings always include a measure of confidence or uncertainty. Non-parametric methods do not make assumptions about the underlying distribution and therefore do not directly generate estimates of uncertainty. However, with advances in computing power, bootstrap[8] methods can easily be used to generate confidence intervals. Risk assessment and Weight of Evidence methods do not explicitly address uncertainty although some authors may use ad-hoc approaches to account for uncertainty.

4.3.2.3 Feasibility

Complexity

The methods discussed here can be relatively complex for the lay person. There are a number of details that depend on the specifics of the particular dataset. In general, a statistician should be consulted when analyzing quantitative data. The simplest concept is likely the idea of estimating exposure (i.e., where the stressor and the VC overlap). Evaluating a single pathway (i.e., the correlation between one stressor and one VC) should also be familiar to anyone who has taken a university statistics class. The weight of evidence approach has intuitive appeal and is conceptually simple. The rest of the methods are likely new to someone who has limited analytical background.

Data/information requirements

In general, these methods are very data intensive, as they strictly rely on empirical information. The modeling methods may also be data intensive, but we often rely on expert opinion to initially parameterize models until we have a better understanding of the quantitative relationships. In this context of the CEMS initiative, there is likely to be more information about the stressors than the VCs. This will limit which analyses are possible in each region.

Data flexibility

As described in the previous paragraph, these methods are limited to the available data. There may be methods that could utilize expert opinion, but for the purpose of this report, the focus of this category of methods is specifically on making use of empirical information. Different analyses are possible if you have information on: stressor only, VC only, or both. Spatial information enables additional options. Caution should be employed when combining information from different studies, particularly when evaluating the pathways. Methods for estimating spatial distributions are the most flexible in terms of data inputs.

Accessibility

As described in the complexity section, these methods are less accessible than some of the others discussed in the report. Risk assessment may be an exception as there are a number of tools that have

[8] The term bootstrap is derived from the idea of 'pulling oneself up by the bootstraps'. This methodology relies on computing power to do the 'heavy lifting' and is a relatively recent development [Efron and Tibshurani, 1994]. Bootstrapping essentially involves simulating the findings many times to produce a distribution of outcomes from which confidence intervals can be extracted.

been developed to support this approach (e.g., EcoFate and EUSUS). For moderately experienced analysts, R (https://www.r-project.org/) is a free open source statistical package which provides tools for all of the statistical methods discussed here. Weight of evidence methodologies are in their own class as they require human integration of ideas, difficult for a computer to implement but relatively intuitive for a human.

Cost

The most expensive aspect of utilizing these methods is collecting the data in the first place. A relatively small investment in analytical support to help set up the analyses also makes sense. We strongly recommend using R, for implementation of statistical analyses. Where necessary, R is able to interact with other software (e.g., ArcGIS, QGIS, or MS Access).

Interpretability & communicability

The results for the spatial methodologies are likely easiest to communicate. Presenting spatial distributions or exposure in the form of a map is extremely intuitive and is appealing to many audiences. The rest of the methods are more difficult to communicate effectively, and the results of the quantitative analyses will often require additional processing to help the reader digest.

4.4 Modeling Methods

4.4.1 Overview

The common characteristic of the methods discussed in this section is that they all address cumulative effects assessment from a modeling perspective. Models can be defined as tools for the abstraction and simplification of natural systems (USGS) which allow for the analysis of the system and making predictions about its behaviour. Models vary widely in their purpose, format (e.g., software tools), level of complexity, data requirements, predictive capacity, etc.

Specifically, for the marine environment, a broad range of modeling approaches have been used to model cumulative effects (Clarke Murray et al. 2014); from conceptual models describing the system and the interactions among stressors and Valued Components (VCs) to complex quantitative predictive models assessing the effects of specific pathways or stressors. As part of the cumulative assessment process, models can be used for a variety of purposes and at various stages; from conceptual models that articulate the cause-effects linkages of the system and help identify key components or pathways to quantitative models that provide an estimation of the magnitude of the impacts and that can be used to explore management scenarios. A key functionality of modeling methods is their ability to test ‘what if’ scenarios (Heinänen et al. 2018) and thus link the evaluation of cumulative effects to management or mitigation actions.

This section covers relevant methods that use a modeling approach for this range of functions by providing insights into one component of a system (i.e., a stressor or a valued component), multiple components, or one or multiple pathways (Figure 4.8).

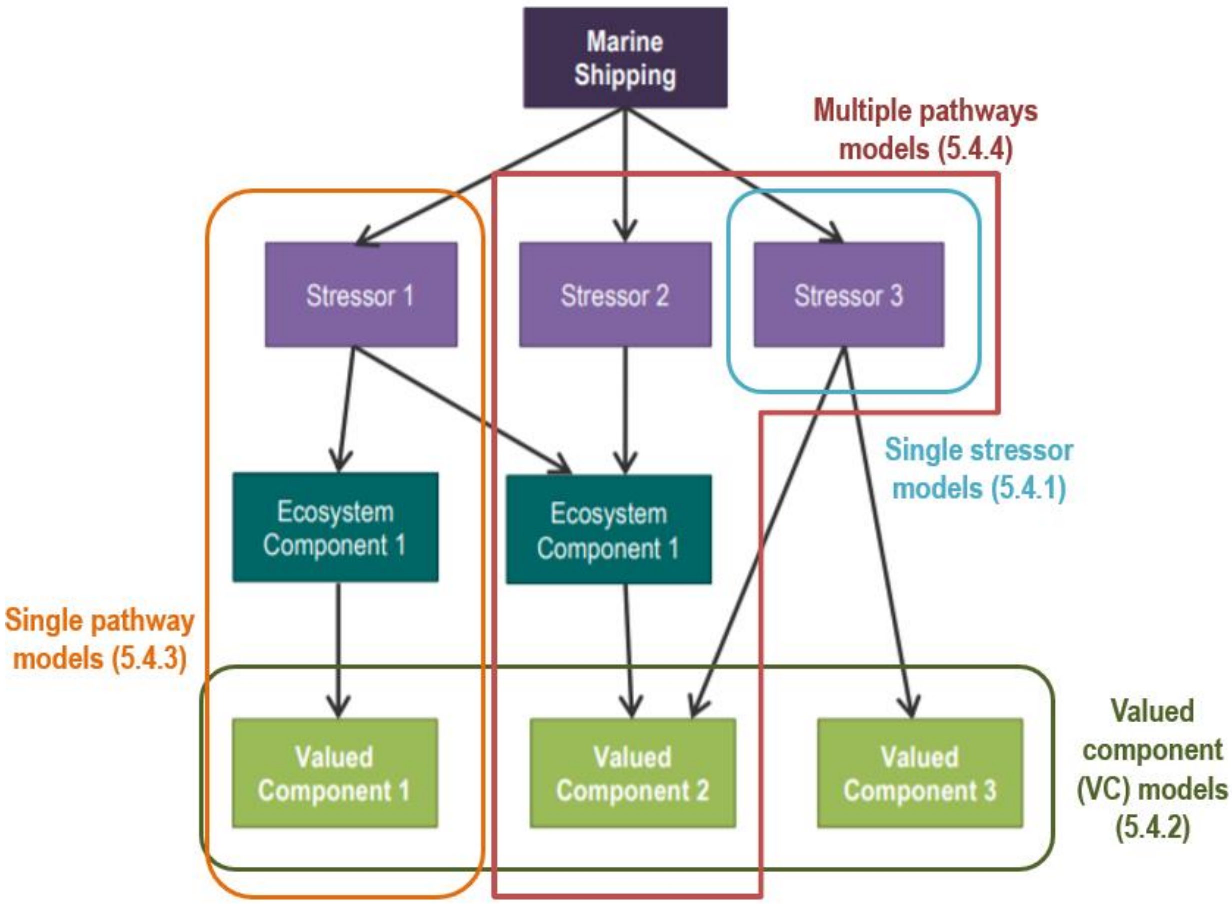

Figure 4.8. Modeling methods as they apply to the Pathways of Effects model.

4.4.1.1 Stressors

The preliminary Pathways of Effects model for marine shipping (see Appendix A) includes 35 stressors associated to seven shipping activities: in-water works, anchoring, grounding/wrecking, operational and accidental discharge, movement underway and harvesting.

Based on the results of Tier 1 screening, we found that most of the stressor modeling efforts related to marine shipping have focused on quantifying the effects of underwater noise, oil spills and, to a lesser extent, the risk of strikes, especially for cetaceans, with vessels.

Underwater noise

In terms of underwater noise, which is a particular concern for marine mammals, noise propagation models have been developed for the Pacific region (Erbe et al. 2012, O'Neill et al. 2017, Cominelli et al. 2018), the Arctic (Aulanier et al. 2017, Halliday et al. 2017), and the Saint Lawrence estuary (Chion et al. 2017).

All of these studies rely on simulating noise levels using a numerical acoustic propagation model, which incorporates ship traffic information (e.g., cumulative hours, vessel types, etc.), characteristics of the water column (Aulanier et al. 2017), and bathymetry data (Erbe et al. 2012), to estimate how anthropogenic noise propagates in the marine environment. Automatic Identification System (AIS) data are the shipping traffic data usually used in these noise prediction models. However, since this registry only provides information for vessels of a certain size, areas in which small vessels are the predominant ship type are not well represented by the AIS records (Erbe et al. 2012).

Multiple acoustic model tools have been developed which could potentially be used in this type of assessment: Range-dependent Acoustic Model (RAM), Research Ambient Noise Directionality (RANDI), Marine Operations Noise Model (MONM) developed by JASCO (O'Neill et al. 2017), Underwater Acoustic Simulator (UAS) developed by the DHI Group. The cumulative MONM noise model was developed by JASCO Applied Sciences for the Noise Exposure to the Marine Environment from Ships (NEMES) project.

The output of these models is usually in the form of sound intensity maps (Figure 4.9), which can then be overlaid with habitat ranges or distribution maps of sensitive species (Section 4.3) to complete the assessment of exposure to this stressor.

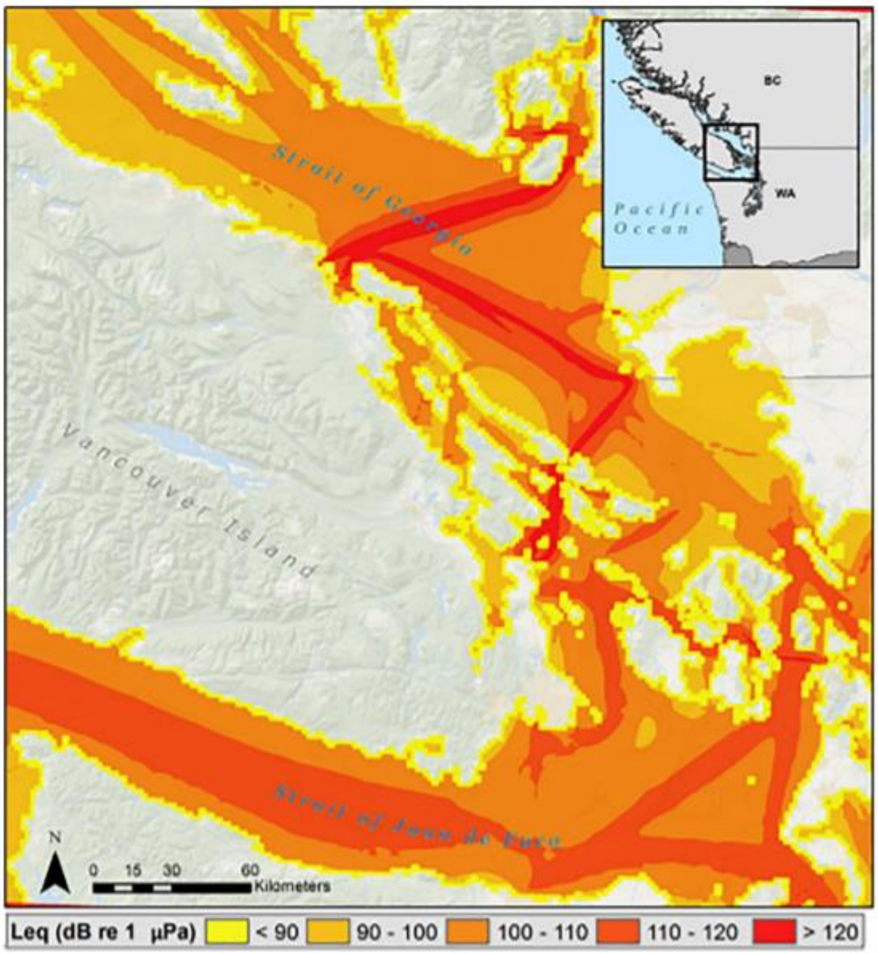

Figure 4.9. Output of the cumulative noise model developed by JASCO Applied Sciences. The map shows the cumulative Leq - equivalent sound level in decibels - values relative to the ship categories combined (Source: Cominelli et al. 2018).

Oil spills

Oil spill models are used to predict the trajectory of oil spills (due to accidental discharges) large accidental ones, not operational ones) in seas. These complex numerical models (Spaulding 2017) have intensive data requirements, including high resolution oceanographic (e.g., currents, waves) and meteorological information (Alves et al. 2016), information on the time and location of the spill, and information about the characteristics of the oil. Various 3-D hydrodynamic oil dispersion models have also been developed. For instance, in the Mediterranean there are currently four models: MOTHY, MEDSLIK, MEDSLIK-II, POSEIDON-OSM (MEDESS 2018).

The output of these models is usually in the form of maps and graphs (Figure 4.10) showing the spatial evolution of the oil spill in the days following the spill event. These oil dispersion models are usually applied in the context of risk analysis (see a more detailed discussion of risk assessment frameworks in Section 7), as well as contingency and response planning.

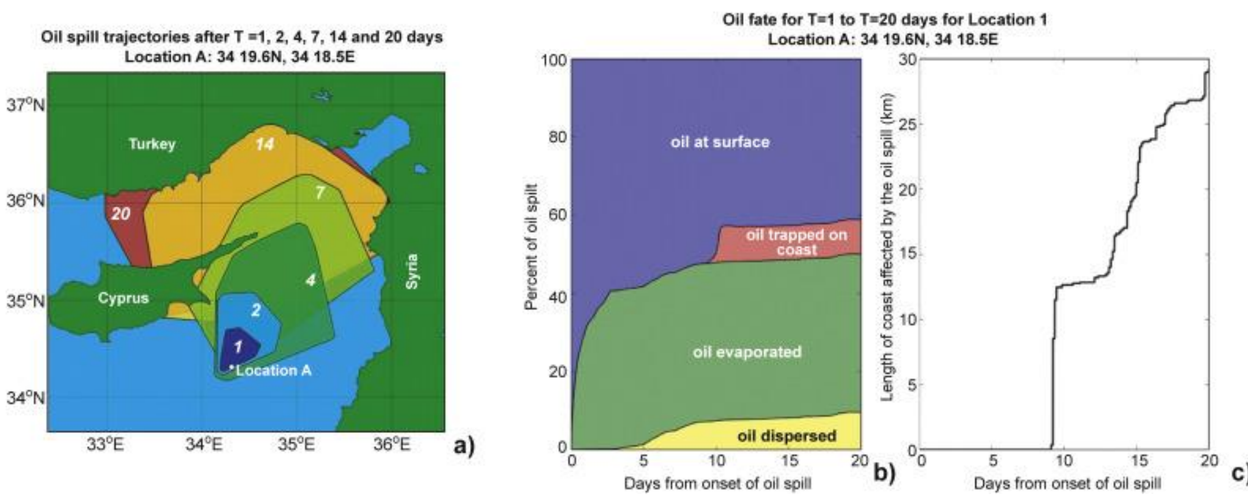

Figure 4.10. Example of MEDSLIK oil spill simulations (Source: Alves et al. 2015).

It should be noted that Transport Canada, as part of its Regional Risk Assessment (RRA) program for the Northern Shelf Bioregion, is building its internal capacity to perform risk assessments that evaluate the probability and potential consequences of marine ship-source oil spills. Some of the software tools being considered as part of this process include the following:

- **SAMSON** (Safety Assessment Models for Shipping and Offshore in the North Sea) from the Maritime Research Institute of Netherlands (MARIN): This is a software package that uses a maritime traffic database (AIS), various environmental conditions such as wind and current and different mathematical models to calculate the probabilities of certain 'dangerous' events (i.e., oil spills). Its modeling functions can provide support for decision making (e.g., port location).
- **H3D** (3D Hydrodynamic Model) is a three-dimensional model developed by Tetra Tech to compute the transport and diffusion of temperature, salinity and various introduced contaminants such as dissolved oil fractions.
- **SPILLCALC**, also developed by Tetra Tech, is a time stepping model that computes the motion and weathering of liquid hydrocarbon spills.

Substrate disturbance

The impact of anchoring on the seafloor biota is poorly understood, especially in deeper waters where conducting biological assessments is costly (Davis et al. 2016). Based on AIS data, Davis et al. (2016) attempted to evaluate the impact of anchoring off the coast of New South Wales (Australia). Changes in currents, tides, and wind make vessels swing on their anchors, creating distinctive arc shapes on the seafloor. These arcs delineate areas of the sea bottom subject to scoring and they represent the footprints of the anchoring activity. In port areas which have been receiving vessels for decades there can be substantial areas subjected to repeat scoring.

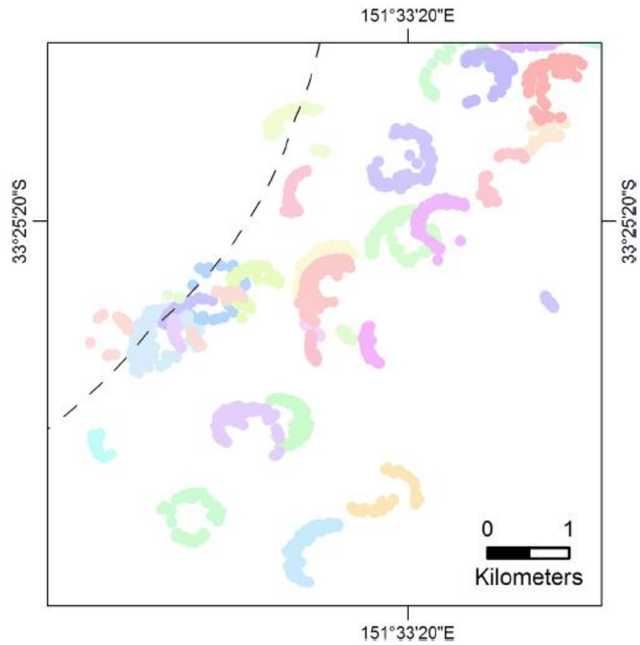

Figure 4.11. Anchor arcs based on AIS vessel tracking data near the Port of Newcastle (Australia). Different shades denote individual vessels (Source: Davis et al. 2016).

Emissions

Commercial ships are an important source of air pollutants and greenhouse gases. The Marine Emissions Inventory Tool (MEIT) is the primary source of marine emissions data in Canada[9] and it can be used to assess changes in marine emissions (and fuel consumption). MEIT data can inform air quality models, GHG projections, and emissions inventories.

9 https://www.green-marine.org/wp-content/uploads/2018/06/Monica-Hilborn.pdf

4.4.1.2 Valued Components

These models focus on assessing the state and the interactions among ecological[10] components of the environment. The main application of these models is to understand the status and potential responses of ecological VCs to changes in their environment.

It is important to note that ecological VCs can be conceptualized and modeled at different levels; single species (e.g., sea otter), multiple species (e.g., marine mammals in a given area) or whole ecosystems (e.g., estuaries). This section discusses these modeling options.

Single-species models

Single-species models have been the predominant modeling approach in fisheries assessments (Plagányi 2007). Individual-based models (IBMs) and OSMOSE are single-species model examples that study trophic or predation rules at the individual level with implications at the population level.

Another example which has been used outside of the fisheries sector is **Population Viability Analysis** (PVA), which uses demographic models to assess population level effects as one or more demographic parameters (e.g., fecundity) are varied (Lacy et al. 2017). Detailed PVA models depend on: availability of estimates for demographic rates (e.g., fecundity, survival, and the variability in such rates); confidence that observed past rates are predictors of ongoing demography, or that trends can be foreseen; data for quantifying effects of threats on demographic rates; and a population model that adequately captures the key demographic, social, genetic, and environmental processes that drive the dynamics of the population of concern.

PVA can be used to explore how multiple stressors affect a wildlife population. Where stressors can be linked to specific demographic variables, PVA can be used to evaluate the risks from one or more stressors to wildlife populations. Lacy et al. (2017) applied a PVA method to the southern resident killer whale population to explore the cumulative effect of multiple human stressors, including noise, ship strikes and oil spills from shipping.

Multi-species models

Multispecies models focus on understanding the trophic interactions among species or functional groups (Piroddi et al. 2015). Specifically, they address predator–prey interactions in marine communities. These models have often been developed in the context of fisheries management although some have also been used to simulate environmental changes (e.g., water temperature and pH, nutrient concentration, etc.). Numerous multi-species models have been developed (Plagányi 2007, Piroddi et al. 2015) covering different species groups and trophic interactions. Some of these include Spatial Multi-species Operating Model (SMOM), Stochastic Multi-Species model (SMS), and Population-Dynamical Matching Model (PDMM).

Ecosystem models

Ecosystem models address the whole ecosystem and describe the relationships between functional groups in a system using fundamental assumptions about the mass-balance of a system over a period of time. In

[10] It is important to note that although this section is focused on ecological models, valued components can also be cultural or socioeconomic.

recent years, with a move toward ecosystem-based management, ecosystem models have been gaining attention (Smith et al. 2016).

There are a range of ecosystem models with varying degrees of complexity (Smith et al. 2016) which can be applied at the pathway or multiple pathway level. Some models focus on a specific aspect of marine ecosystems, such as fisheries (Plagányi 2007), while other more recent model developments address the whole socio-ecological system (i.e., "end-to-end" models).

ECOPATH with ECOSIM (EwE) and ATLANTIS are trophic ecosystem modeling frameworks which assess trophic flows at the whole ecosystem scale. These models have mainly been applied in fisheries management. Compared to EwE, ATLANTIS is much more data-intensive, takes much more effort to set up and calibrate, and does not have a simple user interface.

EwE has been extensively applied in Canada (Figure 4.12) with examples in the Arctic, Pacific and Atlantic coasts. Although its primary application has been in the field of fisheries management, EwE is increasingly being applied to different ecosystem types and subjects, including pollution, aquaculture and marine protected areas (Colleter et al. 2014). For example, Vasslides et al. (2016) recently looked at literature on the use of EwE to assess the impacts eutrophication and other stressors affecting coastal ecosystems.

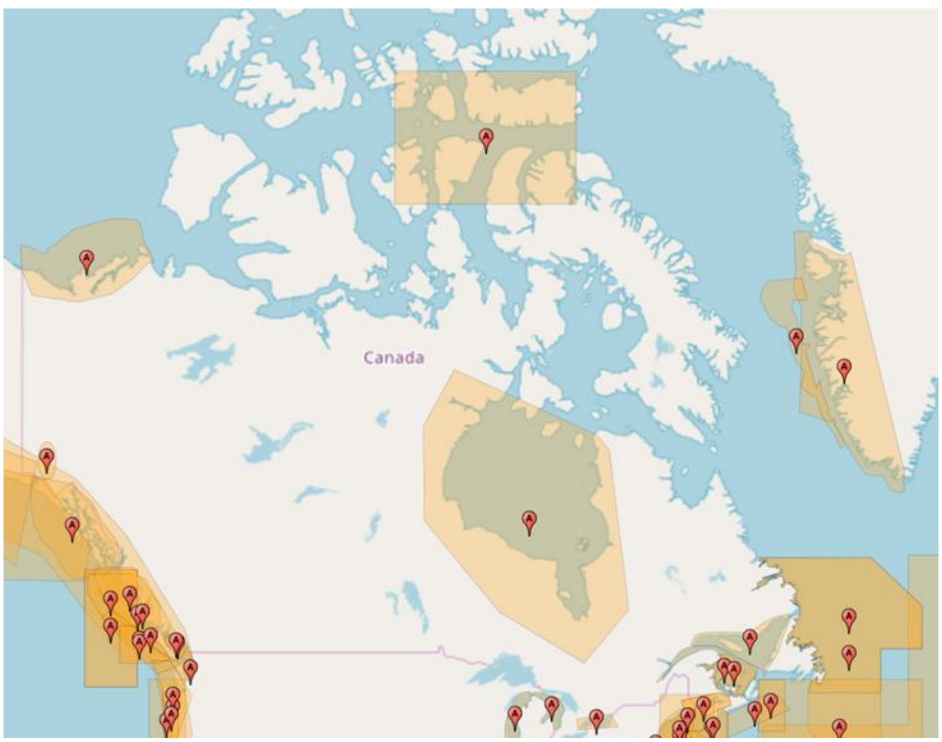

Figure 4.12. Location of EwE model applications in Canada.

Raoux et al. (2017) applied EwE to assess the impacts of wind farm development on the trophic structure of the benthic community; a pathway that could be appropriate to assess the effects of anchorage or wreckage.

A recent study by Harvey (2018) explored possible response functions to anthropogenic noise on a population of harbour porpoises using EwE. Using a spatially-explicit modeling approach with Ecospace (see more details in the spatially-explicit simulation models sub-section below), this study mapped the spatial distributions of shipping density and identified ‘hotspots’ where cetacean populations and shipping coincide. It then modeled the impact that noise levels have on predation behavior of these cetacean species and how these effects can manifest in their biomass and trophic interactions with other species in the community.

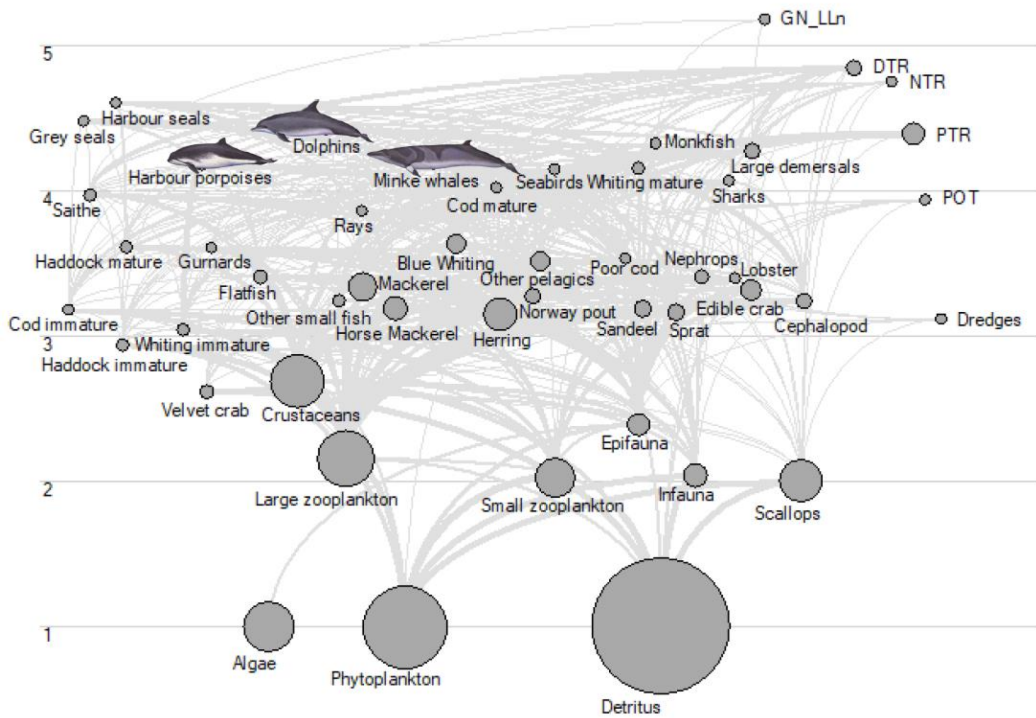

Figure 4.13. Ecopath model used in Harvey 2018. Nodes represent functional groups or organisms in the model, scaled to the biomass of the organism within the ecosystem. Trophic levels are shown on the y-axis (Source: Harvey 2018).

4.4.1.3 Single Pathway

These models link stressors to specific VCs by simulating the process by which effects occur from one linkage to the next along a specific pathway.

Underwater noise

To assess pathways related to **noise**, outputs from noise prediction models have been combined with information about the abundance and distribution of species of concern. This type of assessment can be done for one species, such as the study by Cominelli et al. (2018) which looked at the exposure of Southern Resident Killer Whales (SRKW) to cumulative noise in the Salish Sea, or multiple species, such the assessment Erbe at al. (2014) conducted for 11 marine mammal species found off the coast of British Columbia. Understanding the vulnerability of a given species to various noise levels is a key component in these models. For instance, Erbe et al. (2014) developed audiogram-weighted maps reflecting the noise threshold for the studied species, based on the available literature.

Noise models can also be integrated with other models simulating ship-wildlife interactions. For instance, Chion et al. (2017) implemented an underwater acoustic sub-model (i.e., Research Ambient Noise Directionality model – RANDI) in the agent-based 3MTSim model to assess the effectiveness of various protection measures (e.g., reduced vessel speed, delimitation of no-go areas) for the endangered St. Lawrence beluga whale population.

Ship strikes

Marine mammals, especially cetaceans, are the species group most at risk of ship strikes. Challenges exist in quantifying mortality based on reported collisions and quantifying the effects of both lethal and sub-lethal collisions at the population level. Because of the concentration of cetaceans in the Pacific coast, several studies (William and O'Hara 2009, DFO 2017) have focused on assessing ship strike risk for whale populations in British Columbia. These approaches are spatially-explicit models which combine spatial information on species abundance with shipping data (using AIS or other marine traffic data sets) to estimate the relative probability of whale-vessel encounter using generalized additive models (GAMs). Although this type of model cannot predict quantitative effects of strike mortality at the population level, it can be useful for identifying hotspot areas where high density of cetaceans coexists with intense marine traffic (Figure 4.14) (Williams and O'Hara 2009).

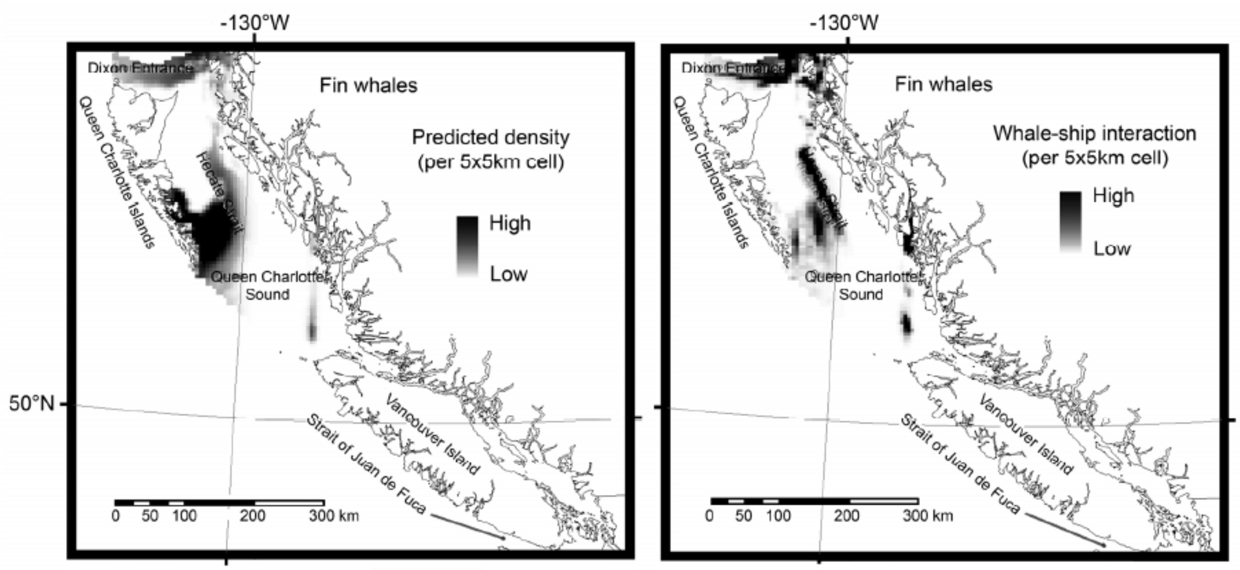

Figure 4.14. Density (left) and intensity surface (right; a result of whale density x marine traffic vessel intensity) for fin whale (Source: Adapted from Williams and O'Hara 2009).

The 3MTSim is a socio-ecological model, developed for the Saint Lawrence estuary (Chion et al. 2017), that simulates the movements of individual boats (2D) and marine mammals (3D). The main application of this model is to evaluate how alternative traffic management scenarios can impact the marine mammals and shipping activities in the area. For these alternative scenarios, the model calculates transit times, frequency of encounters between marine mammals and boats, and the risk of lethal ship strikes.

Oil spills

As discussed previously, a large number of oil models have been developed in recent years to predict the trajectory and fate (i.e., how oil evolves in the marine environment) of oil spills at sea. By coupling these models with an evaluation of the effects of oil spills on the components of the environment, it is possible to assess this pathway. The Spill Impact Model Application Package, SIMAP^{TM}, is a commercial software tool which includes two sub-modules: one physical model that simulates oil trajectory and fate, and a biological effects model which includes algorithms to quantify the impact of oil on habitats, aquatic organisms (fish, invertebrates, aquatic plants, plankton), and wildlife (birds, mammals, reptiles). French-McCay (2004) provides an overview of this model and applies it to the Exxon Valdez oil spill as a validation case study. This study found that this model provides overall reasonable results. The physical model component requires wind and current information. The estimation of biological effects involves a higher degree of uncertainty since sensitivity to oil hydrocarbons is not well known for all species (French-McCay 2004) and the movement patterns and migratory behaviors of some species (e.g., sea birds) complicate the assessment of wildlife population exposure to oil.

4.4.1.4 Multiple Pathways

Conceptual modeling: Pathways of effects

Understanding the causal links between activities and stressors and their effects on the components of the environment underlies, to varying degrees, most of the cumulative assessment methods and tools discussed in this report.

Conceptual models can be defined as descriptions or abstractions of the general functional relationships among essential components of an ecosystem (Fischenich 2008). In the context of cumulative effects assessment, conceptual models are representations of the linkages or causal relationships between activities and stressors and their impacts on the components of the socio-environmental system under analysis (Canter 2008, Antony et al. 2013). The output of conceptual models is usually in the form of a descriptive narrative and/or graphical representation of the cause-effect linkages identified for the system. Conceptual models are a pre-requisite for all numerical models (Smith et al. 2016).

Conceptual models can be considered identification methods (Canter 2008) which can help with scoping VCs, establishing spatial and temporal boundaries, selecting indicators, and identifying the most relevant pathways.

Pathways-of-effects (PoEs) models are one type of conceptual model consisting of a graphical representation of the predicted relationships between activities, pressures or stressors and valued components. By visually illustrating the complexity of ecosystems and their interactions with human activities, PoEs are excellent communication tools (Stephenson and Hartwig 2009).

Stephenson and Hartwig (2009) used a Pathways of Effects model to determine what activities might have a potentially negative effect in the marine ecosystems of the Beaufort Sea in the Yukon North Slope. The application of the PoE model in this case resulted in the identification of oil and gas development as the main threat for the marine ecosystems in this region. Pathways of Effects conceptual models for marine shipping are currently being developed by DFO, and those will be used as a foundational component of the Transport Canada led CEMS initiative (Appendix A).

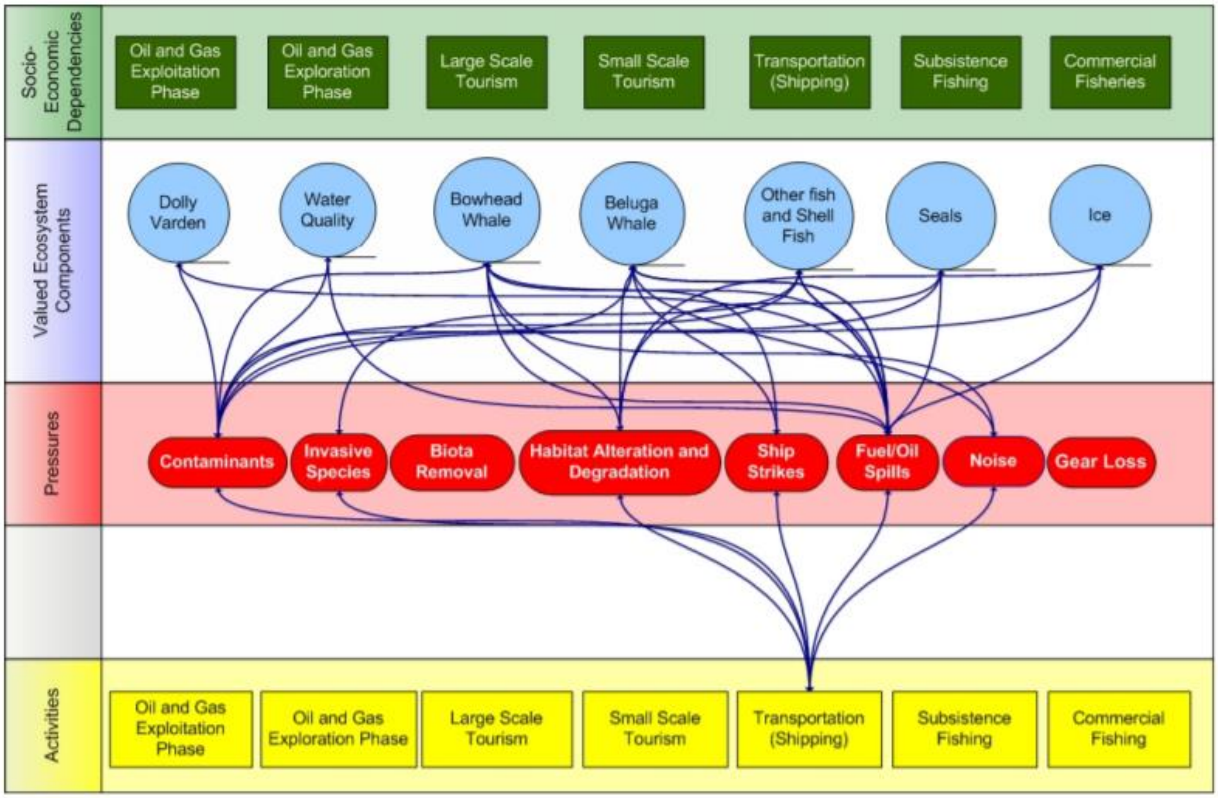

Figure 4.15. Example of a single activity Pathways of Effects diagram for marine transportation (Source: Stephenson and Hartwig 2009).

Drivers-Pressures-State-Impact-Response (DPSIR) models

The DPSIR (Drivers-Pressures-State-Impact-Response) approach is a problem-structuring framework which can be used to assess the causes, consequences and responses to change (Elliott et al. 2017). This approach derives from the Pressure-State-Response (PSR) conceptualizing frameworks, which have been used in marine ecosystems risk analysis and management since the 1990s (Patrício et al. 2016).

The DPSIR model is policy-oriented (Patrício et al. 2016) since it describes the system in terms of drivers (e.g., development and economic activities) which cause pressures (e.g., abrasion, increase in marine noise, over-fishing) that, in turn, affect the state of the ecosystems (e.g., habitat quality, population size, etc.) and require a response in the form of a management action.

For use in coastal and marine ecosystems, the original DPSIR has been adapted and modified into 23 derivative approaches (Figure 4.16) (Patrício et al. 2016). Some of these modified approaches seek to include the evaluation of ecosystems services in the DPSIR framework. Kelble et al. (2013) developed a Driver, Pressure, State, Ecosystem service, and Response (EBM-DPSER) conceptual model and applied it to the Florida Keys and Dry Tortugas marine ecosystem.

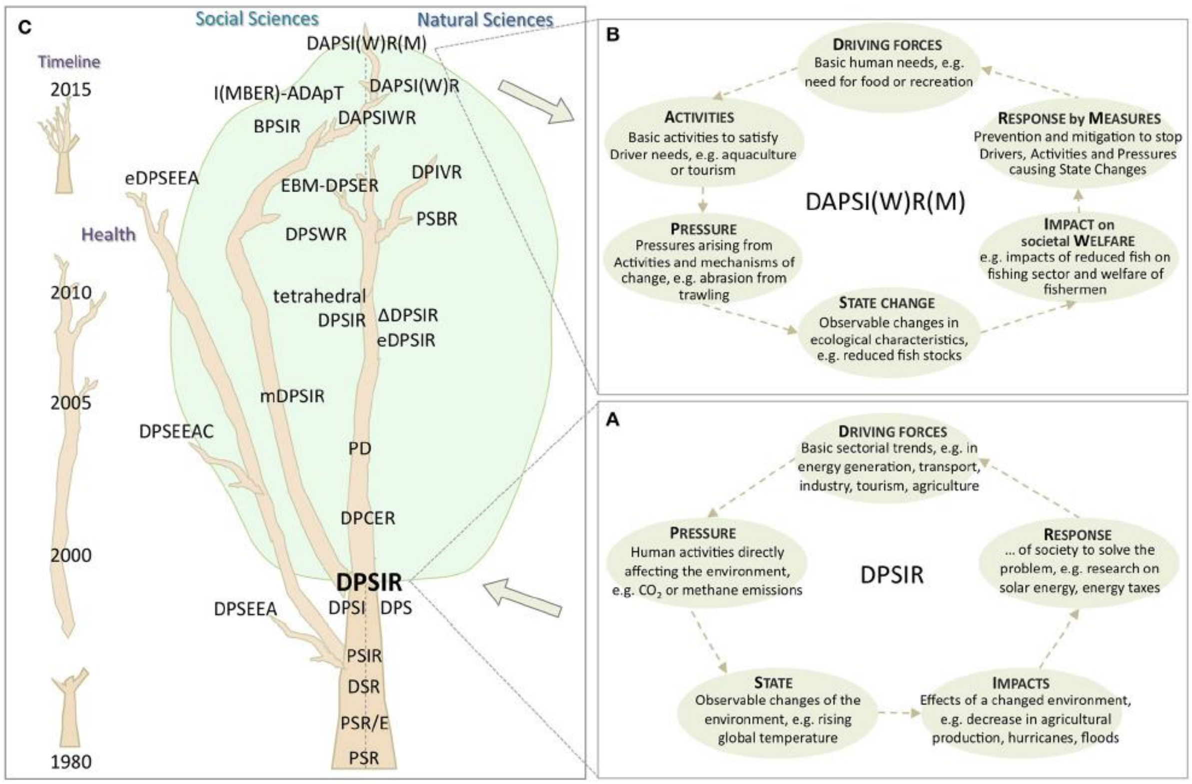

Figure 4.16: Conceptualizations of the DPSIR model: A) original DPSIR model, redrawn from the original EU framework (EC 1999), B) recent DAPSI (W)R(M) model (Elliott et al. 2017), and C) timeline and development/relationship of DPSIR and derivatives (Source: Adapted from Patrício et al. 2016).

At the core of the DPSIR frameworks there is an understanding of the interactions and relationships between stressors and VCs. Furlan (2017) utilized the DPSIR framework to delineate relationships between sources of stressors and their consequences for VCs and habitats and further broke pressures and impacts into four hazard categories: biological impacts, physical impacts, chemical impacts, and climatic impacts (Figure 4.17).

One of the common critics to DPSIR models is the variability in the interpretation and use of the main components of the methodology (i.e., Drivers-Pressures-State Change-Impact-Response) (Patrício et al. 2016). This is reflected in the multiple derivatives of the model which have come up in the last decades.

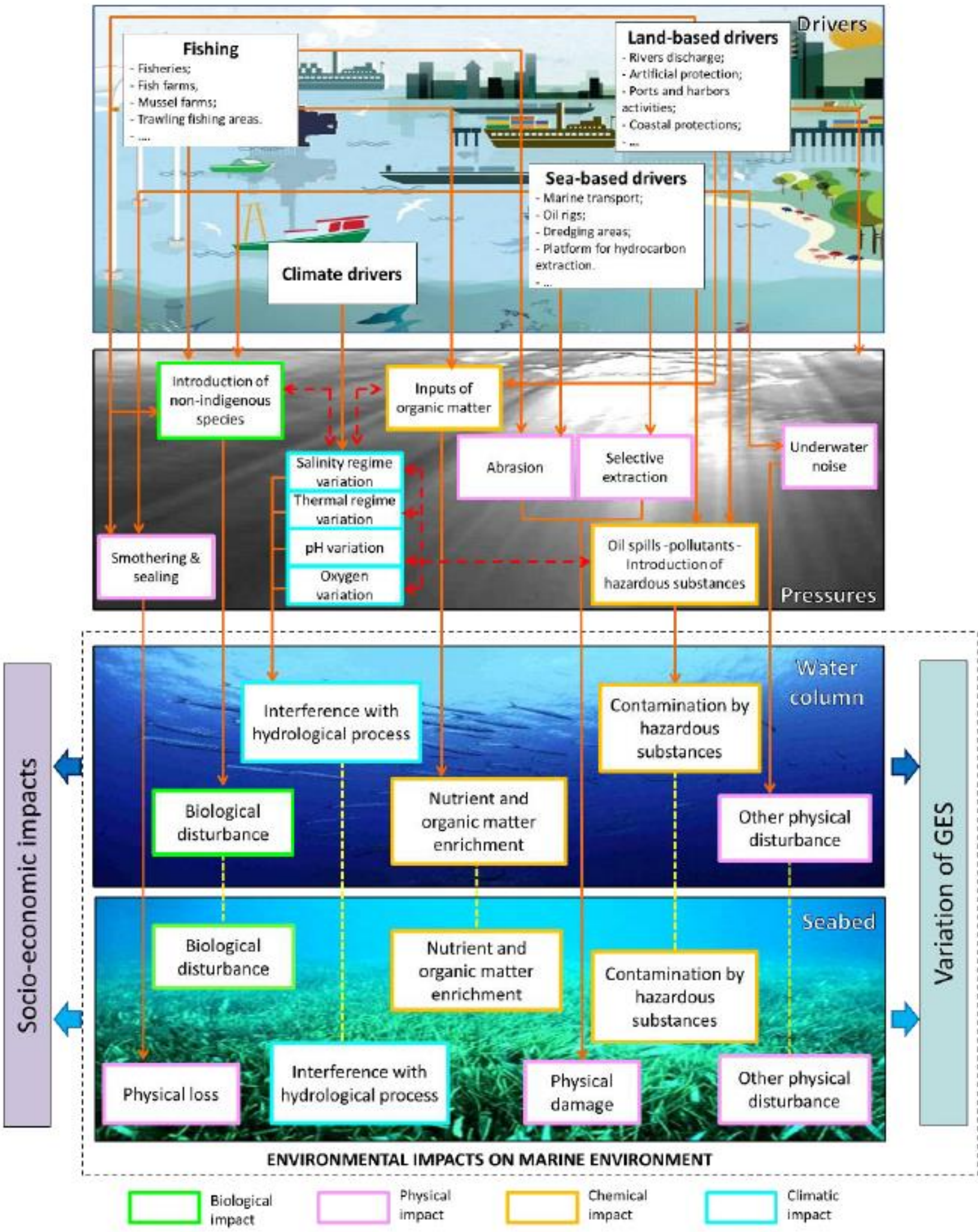

Figure 4.17. Conceptual model of stressors and valued components, and their identified linkages. This model is used to inform the risk assessment method (Source: Furlan 2017)

Bayesian Belief Networks

Bayesian Belief Networks (BBNs) are graphical and probabilistic models that represent the correlative and causal relationships among variables (McCann et al. 2006). In the context of environmental and ecological analysis, this type of model is usually applied to situations where there are substantial uncertainties about the system under study (Smith et al. 2016). Common uncertainties in cumulative effects assessment include absence or incomplete knowledge of the stressors-VCs relationships and uncertainty about the combined effect of multiple stressors (Ban et al. 2014).

Especially relevant for natural resources management, BBNs can predict the response of ecological variables to different management alternatives (McCann et al. 2006). This feature makes this modeling method especially suitable for its application in the adaptive management of complex socio-ecological systems (Ban et al. 2014, Smith et al. 2016).

Unlike mechanistic modeling approaches, BBNs do not require explicit understanding of the process linking two variables in the system because they calculate the likelihood of change in the state of a given variable based solely on probabilities (Langmead et al. 2007). Additionally, BBNs are flexible in terms of the input data and can perform calculations based on expert opinion if empirical data are not available. They can model uncertainty while also accounting for sensitivity in the system (Lawson and Lesage 2013, Goerlandt and Montewka 2015).

Graphically, BBNs are networks which represent the causal relationships among nodes (state variables) and other components of the system through a box and arrows scheme. The links between components are based on the understanding of the underlying processes (Smith et al. 2016). Each node is associated with a function that gives the probability of the variable dependent on the upstream/parent nodes (Smith et al. 2016). To date, the application of BBNs to marine assessments has been limited (e.g., Langmead et al., 2007; Ban et al. 2014; Stelzenmüller et al. 2010 and 2015; Uusitalo et al., 2015). Ban et al. (2014) applied a BBNs approach to study the effects of multiple stressors, and multiple water management alternatives, to coral reefs in the Australian Great Barrier Reef. The main interest in this study was to understand the relative effects of the stressors.

Stelzenmüller et al. (2010) combined BBNs and Geographical Information Systems (GIS) in order to generate a spatial representation of the model-based management scenarios. The BBN model (Figure 4.18) represents the overall level of vulnerability within the study area as a function of the intensity of three example human activities, and the type of marine landscapes and their sensitivity to those activities.

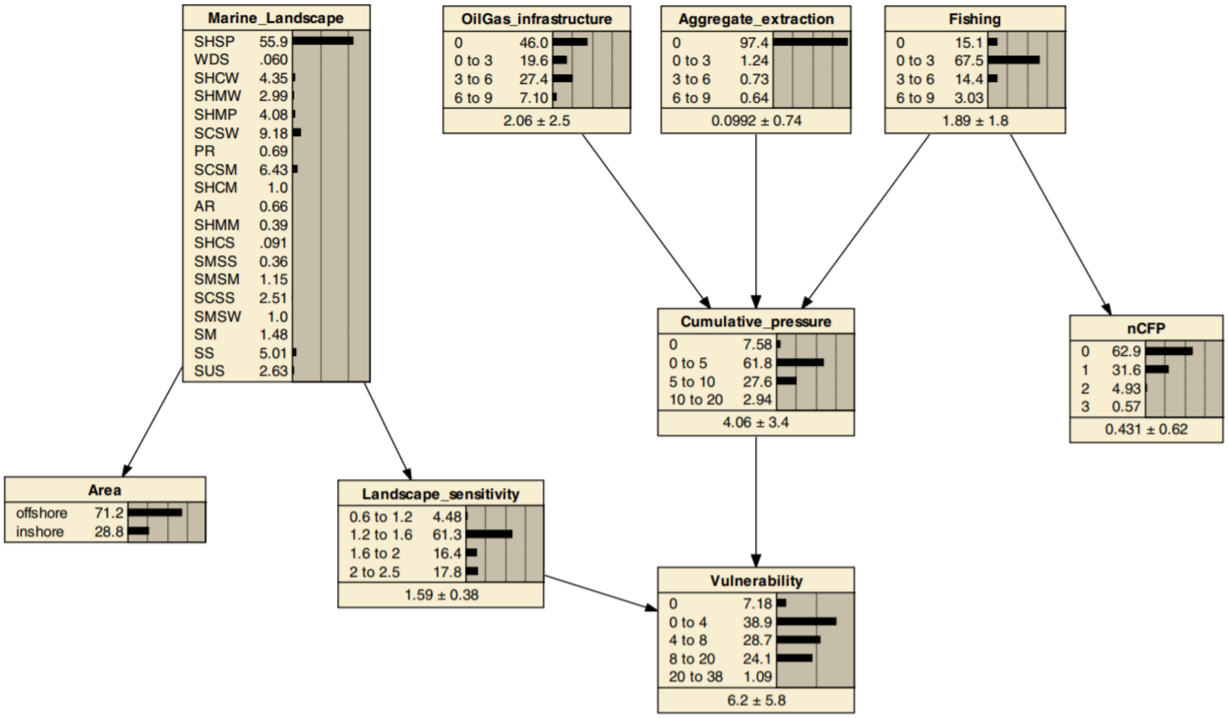

Figure 4.18. Conceptual model and baseline scenario showing the key variables used to predict the overall level of vulnerability of UK marine landscapes and the values for the probabilities (%) for defined categories of the respective nodes. Source: Stelzenmüller et al. 2010.

Spatially-explicit simulation models

With the movement toward ecosystem-based management of marine areas, models that allow the assessment of spatially and temporally explicit cause-effect relationships are gaining attention (Fulton et al. 2015). Combining multiple modeling techniques under a spatially explicit predictive framework enables a holistic assessment of the system and facilitates the identification of monitoring and management actions (Bastos et al. 2017).

These models are the ultimate cumulative effects assessment tool (Peter Duinker, pers. comm.) and where the modeling practice is headed. They require an understanding of the quantitative relationships between stressors and VCs (4.3.1.3) and a baseline or starting state condition. From there, impacts are predicted spatially and over time for the area of interest. Using this information, they allow for the evaluation of alternative scenarios over time and space. They are most relevant at the regional scale.

Ecospace is an example of a spatially-explicit ecosystem model which can predict impacts on marine ecosystems based on the Ecopath mass-balance approach. Ecospace has been applied to evaluate marine protected areas and fisheries management (Walters et al. 1999). Ecospace can generate future predictions of spatial biomass patterns for several hundred grid cells and for several species. Although it cannot provide detailed quantitative predictions, this model is useful as a policy screening tool (Walters et al. 1999).

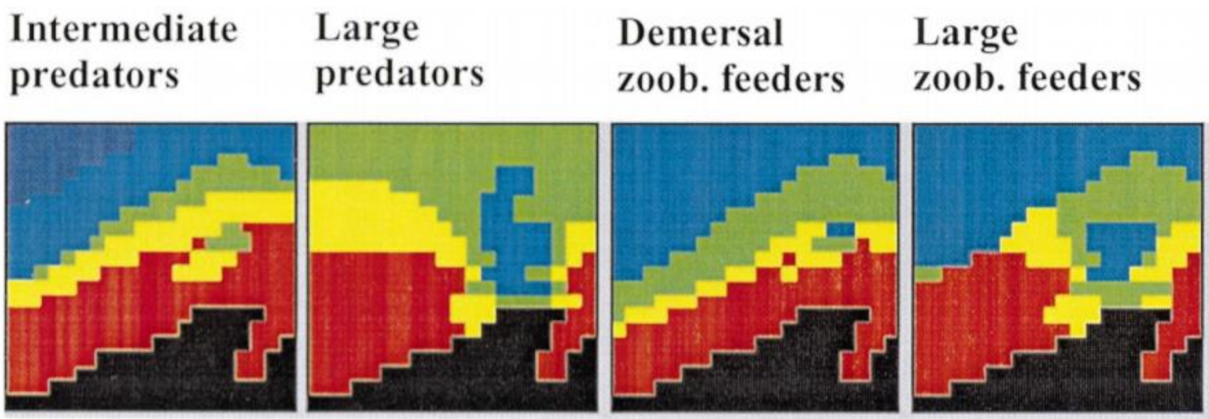

Figure 4.19: Example of biomass distribution maps predicted by Ecospace for the coast of Brunei Darussalam, Southeast Asia, with red indicating high and blue indicating low deviations from the Ecopath baseline for each functional group (Source: Walters et al. 1999).

The approach used by Harvey (2018) to assess the impacts of noise on cetaceans also applied an EWE/Ecospace modeling approach.

Johanson et al. (2017) applied the spatially-explicit model **SPRAT** to analyze the historical change in the eastern Scotian Shelf; a cod-dominated area which shifted to a herring-dominated ecosystem. SPRAT is a fish stock prediction tool that models in 3D the flow of energy or biomass through the ecosystem. It can simulate the effect of both environmental (e.g., water temperature) and biological (e.g., species interactions) drivers affecting the fish stock of interest and the implications for the ecosystem of planned management interventions.

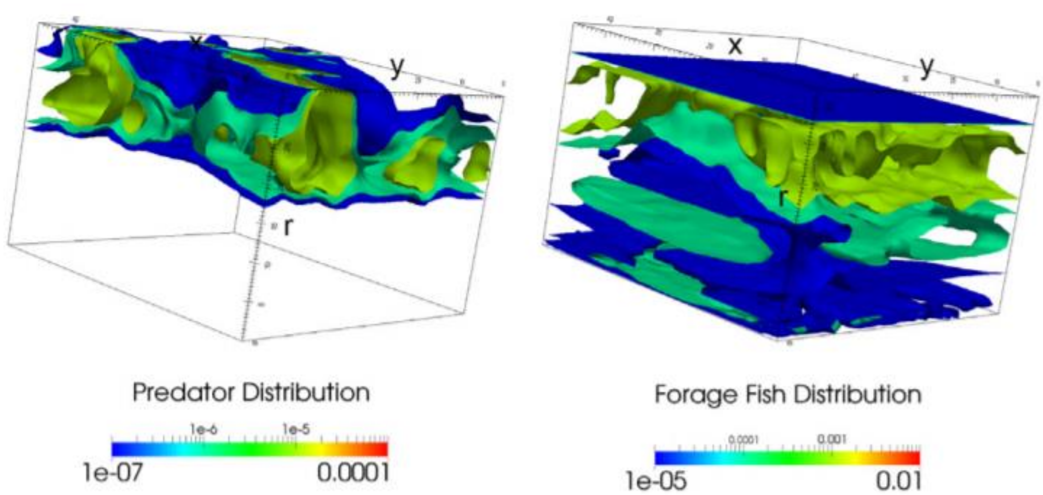

Figure 4.20: Graphic model outputs from SPRAT showing biomass distributions for the predator (left) and forage fish (right) functional groups (Source: Johanson et al. 2017).

Agent-based models (ABMs) simulate dynamic networks of many interacting agents in a spatial and temporal explicit manner. This approach differs in that the receivers (in this case, VCs of interest) are not considered static. Instead these models stochastically predict the behaviour of multiple agents (agents can be individual animals or groups, such as fish schools) when faced with stressors (e.g., noise) or different habitat conditions. For instance, Heinänen et al. (2018) used an ABM approach to develop a realistic physiology-based migration model for mackerel in the Norwegian Sea. This study applied an integrative modeling framework by linking high resolution hydrodynamic models, correlative species distribution models and ABM in order to understand and predict the spatio-temporal distribution and movements of Atlantic mackerel. This modeling framework was then used to understand the impacts of noise (seismic surveys) on mackerel migration patterns and density distribution (Figure 4.21). This approach could be applied to any mobile VC of interest to Transport Canada (e.g., fish, birds, cetaceans).

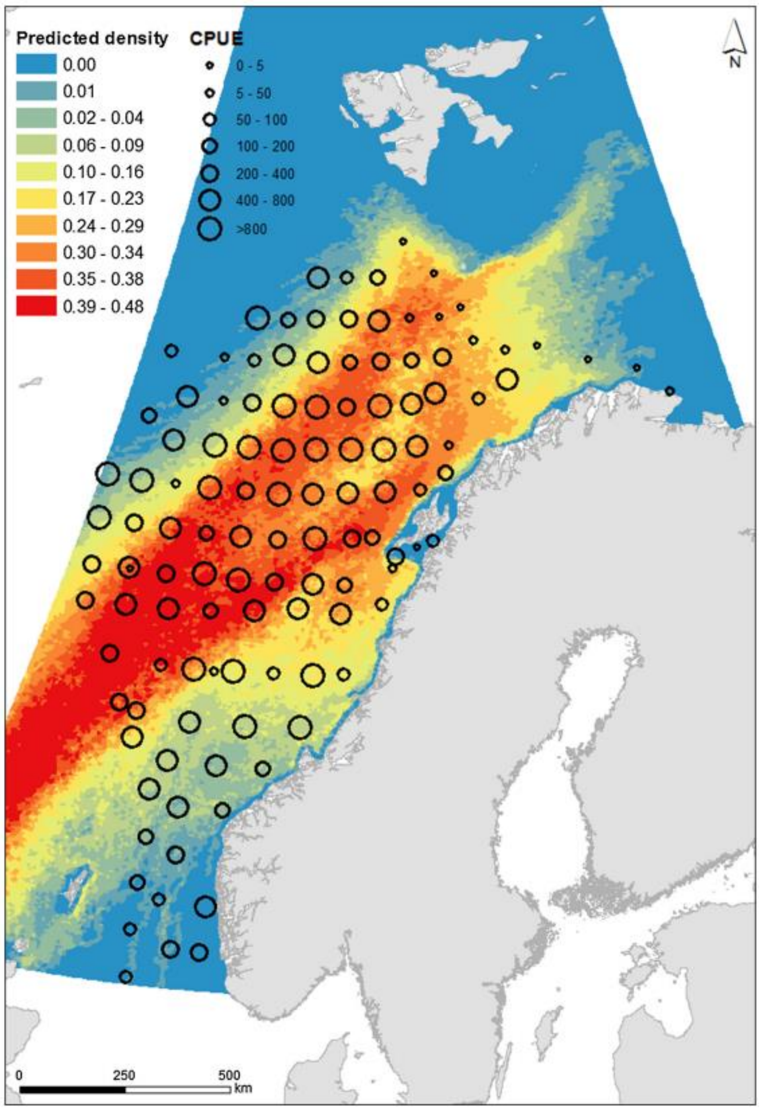

Figure 4.21: Mean predicted density of agents (km^2) in comparison to observed values represented by catch per unit effort (CPUE, [kg nmi^{-1}]) for the same period (Source: Heinänen et al. 2018).

4.4.1.5 Integrated Modeling

Many different modeling tools have been applied to one or more aspects of the pathways of effects (i.e., stressors, VCs, or pathways). However, the real power of modeling in the CEA context is when several of these models are integrated. For example, most of the examples of spatially explicit simulation models involve a combination of physical and biological models linked together and applied over space/time. The best models also leverage analytical methods (e.g., habitat suitability models or regression analysis to inform input parameters).

It is possible to integrate multiple sub-models simulating the physical (e.g., currents, water temperature and salinity) habitat conditions with species-specific preferences (i.e., habitat suitability indices) derived from empirical data. Likewise stressor models can be linked to population models to predict the population level response to stressor driven changes in key demographic variables. The Mobile Animal Ranging Assessment Model for Biological Studies (MARAMBS), developed by the DHI Group to understand the impacts of the oil and gas industry in the Barents Sea, is an example of this integrative modeling approach (Figure 4.22) in which a hydrodynamic model is combined with a statistical habitat model and an ABM to analyze the presence and movement of vulnerable species marine mammal species in the region.

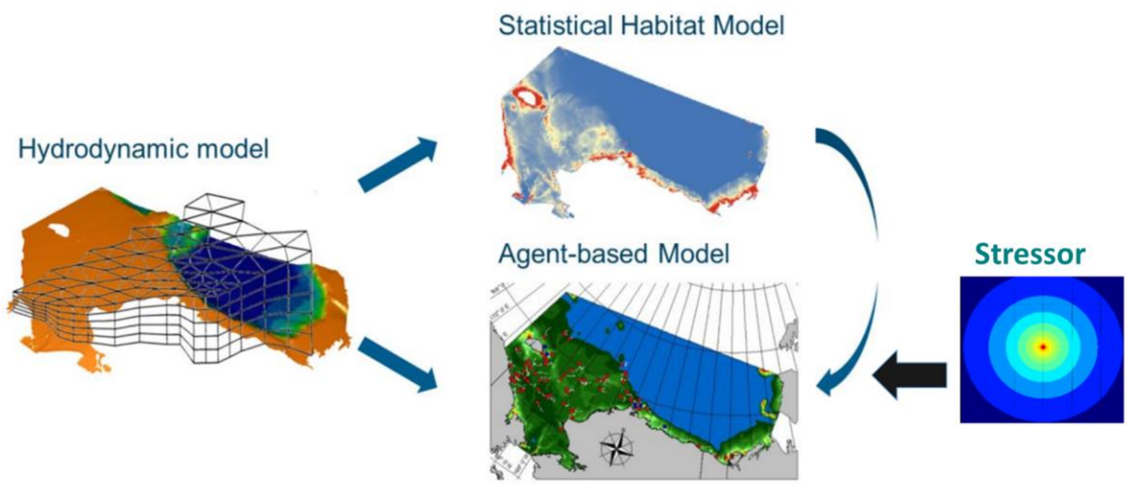

Figure 4.22: Conceptual diagram of MARAMBS (Source: Frank Thomsen, DHI)

4.4.2 Evaluation Criteria

4.4.2.1 Relevance

Usefulness for the CEMS initiative

Modeling methods can support the assessment of cumulative effects in various ways. Models can assist in articulating hypotheses, scoping, quantifying the intensity of stressors (stressor models), assessing the state and interactions among the components of the environment (valued component models), linking the stressors with their effects on valued components (single pathway models) and in studying how multiple pathways can have impacts on one or more valued components (multiple pathways models).

Stressor	Stressor models are useful for quantifying spatial scale and magnitude of a specific stressor based on information about the related activity. However, it should be noted that modeling stressors is not enough to assess cumulative effects and the outputs of these models need to be compared to thresholds or combined with other models that assess the impacts of these stressors on valued components. The development of these models has focused on certain stressors (i.e., underwater noise and oil spills) for which there are a variety of tools and options available. For other stressors associated with shipping, such as substrate disturbance, there are relatively few examples.
Valued Component	Single-species models are relevant to understand how specific species might respond to cumulative stressors to project population changes (Lacy et al. 2017) and explore management scenarios. Multi-species models have a narrower focus on simulating trophic/predation interactions and their use to study anthropogenic stressors has been very limited. Ecosystem models expand the scale to study trophic interactions at the ecosystem level. Although ecosystem models have been primarily applied to answer questions pertaining to fisheries management, they are increasingly applied to study the response of ecosystems to other types of stressors (e.g., impact of noise on marine mammals as studied by Harvey 2018) and show a good potential as a regional modeling tool.
Pathway	These models provide an opportunity to gain a more in-depth understanding of a pathway of interest (i.e., effects of given stressor on a priority VC). Most importantly, they can be used to test alternative scenarios or management actions and their effects on the interactions between stressors and valued components. For instance, Chion et al. (2017) used the 3MTSim model to estimate how shipping restriction measures affect the beluga population in the St. Lawrence.
Multiple pathways	Multiple pathways models are problem-structuring frameworks and can be applied to any combination of stressors and valued components (Patrício et al. 2016). Their application to marine environments has been limited (Smith et al. 2016). However, as conceptual models they can be adapted to the specific problem and system under study. These models can also be part of broader decision support frameworks.

Spatial & temporal scale

Model methods are best applied at the regional scale because they are precise enough at finer scales and at larger than regional scales the uncertainty in the processes modeled and the outputs increases significantly. Multiple pathways methods used in marine policy, such as DPSIR, have also been applied at a larger scale by linking various marine systems.

Stressor	Regarding spatial and temporal scale, stressor models are best suited to be applied at the regional scale because predictive ability decreases significantly at finer (local) and broader

	scales. However, some of the modeling tools may be able to be replicated in different regions as marine shipping activities tend to be similar across regions.
Valued Component	Ecological models can be applied to a range of spatial and temporal scales. However, they are usually applied at the regional level (e.g., habitat or ecosystem distribution in a specific region). VCs tend to differ by region.
Pathway	Because they combine information about the stressor and the distribution range or habitat use of one or more species, pathway models are best applied at the regional level.
Multiple pathways	Multiple pathways modeling can be applied for different VCs across ecosystem types (e.g., coastal, marine) and various geographical scales. The DPSIR model can also link marine systems and show the connectivity between adjacent systems (Patrício et al. 2016). This connectivity can be visualized by several interlinked DPSIR cycles (Smith et al. 2016). This connectivity makes DPSIR models especially useful for larger scales.

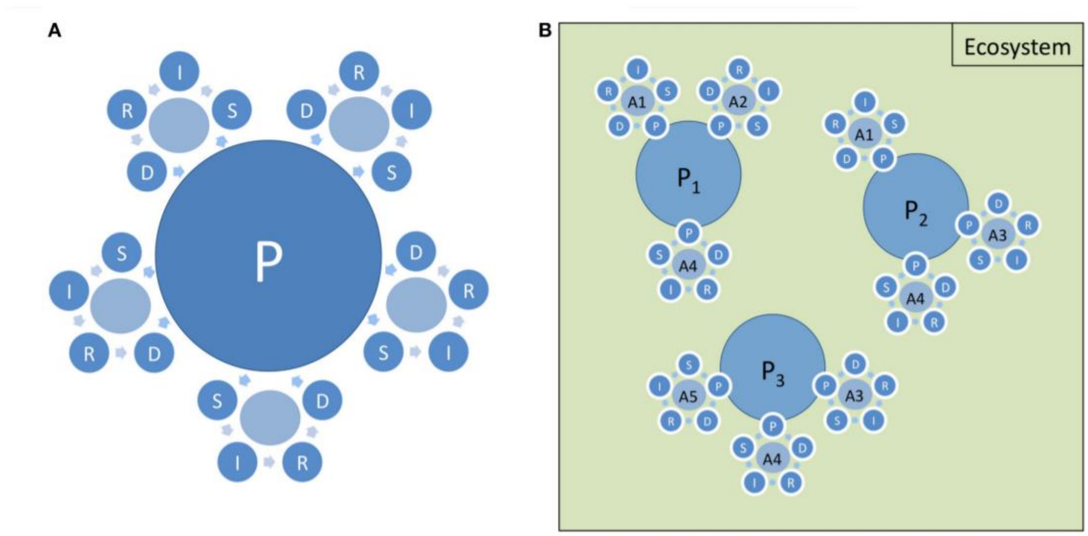

Figure 4.23. Multispace DPSIR cycles: A) Separate DPSIR cycles linked through a common Pressure element (e.g., abrasion pressure from the activities of benthic trawling, anchoring, dredging, etc.); B) Example of linked DPSIR cycles in a particular ecosystem with individual separate Pressures (P1-P3), each associated with discrete Activity types (A1-A4) (Source: Adapted from Smith et al. 2016).

Indigenous knowledge

Stressor	Indigenous knowledge (IK) can be used in conjunction with modeling methods. For instance, IK could be used to inform parameter estimates or validate and contrast the outputs of the models. An example of this is work undertaken by First Nations on the central coast of British Columbia who used IK along with field-based data to model Dungeness crab fishery dynamics and better
Valued Component	
Pathway	

Multiple pathways	understand the status of both the population and fishery (case further detailed in Section 6.1.2.1). IK is particularly helpful for informing conceptual modeling approaches (i.e., PoE, DPSIR and BBN) . Antony et al. (2013) developed conceptual and BBNs models for the Great Barrier Reef in Australia using results from an extensive participatory process that included experts and stakeholders. In doing so, use of IK needs to be done with IK holders. Indigenous knowledge is further discussed in Section 6.1.

4.4.2.2 Rigour

Application of method

Model methods are well documented in the academic literature. In the case of multiple pathways models, one shortcoming is the fact that many of these models have only been applied conceptually.

Stressor	Stressor models have frequently been applied in research studies, impact assessments, and other instances. Applications have been documented in the literature (multiple papers). Noise models have been developed and studied extensively in Canada. There are multiple examples of their applications across regions (e.g., Arctic, Pacific and Atlantic regions). There is a range of choices in terms of specific tools and applications for each stressor.
Valued Component	The development and application of these models is well established in the literature with multiple academic papers describing the use of these models in different geographic and ecological contexts.
Pathway	The development and application of pathway models is well established in the literature, especially for pathways that have received more attention, such as the effects of underwater noise on marine mammals.
Multiple pathways	Many of these models are applied at a conceptual level. For instance, Patrício et al. (2016) found in their review that the links between pressures and state changes are not usually quantified in DPSIR frameworks but analyzed conceptually. Spatially-explicit models are usually documented in applications or case studies.

Level of underlying data/information

Models tend to rely on quantitative empirical information as input data however preliminary models can be developed in absence of empirical information. More policy-oriented and scenario-based models such as DPSIR or BBN are particularly well suited to incorporating other types of information, including qualitative data and expert opinion.

Stressor	Stressor models are based on research and the current scientific understanding of the processes and mechanisms by which the stressors manifest (e.g., underwater noise models are based by the physics involved in noise propagation under the sea). The output of these models is generally quantitative data displaying the results of simulations

Valued Component	For the modeling of species or functional groups, these models rely on the scientific knowledge available (e.g., life cycle, population dynamics, predation behavior, etc.) and also on observational data (e.g., spatial distribution of a certain species).
Pathway	These methods rely on the scientific knowledge about the species or ecosystems being modeled, as well as on the understanding of the cause-effect relationships by which stressors impact these components (Section 4.3). In the absence of empirical data (e.g., for the distribution of a certain species), input data can be complemented with expert knowledge but, to a large extent, these models rely on scientific data.
Multiple pathways	These models rely on a variety of data sources; from quantitative empirical data to qualitative information or expert judgement (Smith et al. 2016).

Uncertainty

Most modeling methods document the uncertainty associated with their simulations, at least in terms of data input quality and information gaps.

Stressor	Uncertainty is explicitly captured and accounted for as part of the model calculations.
Valued Component	The application of these methods is usually documented in a systematic manner, including uncertainties in the knowledge base of the model (e.g., uncertainties about certain parameters) or the prediction scenarios.
Pathway	Uncertainty associated with the sources of data and model outputs are usually formally documented in the case studies or applications.
Multiple pathways	Bayesian Belief Networks treat uncertainty explicitly (Ban et al. 2014) and systematically as part of the evaluation of probabilities. The rigour in treatment of uncertainty is more variable in the other methods. For instance, DPSIR models usually incorporate many types of data and this can lead to uncertainty not being systematically accounted for (Smith et al. 2016).

4.4.2.3 Feasibility

Complexity

Models are complex assessment methods that require specific, and often expert, knowledge about the processes and VCs under study.

Stressor	The complexity of stressor models requires model users to have a good level of understanding of the science of the processes simulated by the model (e.g., noise propagation, oil spills), good quantitative skills, and capacity to interpret numerical and graphical outputs.
Valued Component	Ecological models are complex and require specific skills, most notably knowledge about the ecology of the target species. The implementation of these models can be a long process involving: the set of the model (defining boundaries, selecting parameters and indicators, etc.), collecting the necessary data sets, calibration and running the model for multiple scenarios.
Pathway	These models are complex and require users with expert knowledge on multiple disciplines. They can involve, and therefore require knowledge about how to implement, a sequence of sub-

	models in which the stressor is modeled first and then outputs are incorporated in an ecological or biological model to assess the effects on the valued component.
Multiple pathways	There is a wide range of complexity in these models. Depending on the specific objectives of the assessment and the characteristics of the system, the models can be simple or complex and part of a nested modeling approach.

Data/information requirements

Data requirements are significant for all model methods with the exception of pathways of effects.

Stressor	In regard to data/information requirements, development of stressor models requires extensive data sets and specific site-specific data for their calibration and validation.
Valued Component	In general, these models are intensive in terms of data requirements. PVA models, for instance, require a sound understanding of the life cycle and population dynamics of the target species (Lacy et al. 2017). Ecopath models require input data of six key parameters (Harvey 2018): biomass, production/biomass ratio, consumption/biomass ratio, 'other mortality', diet composition, and catches. Although they can rely on estimates for these parameters, Ecopath and other ecosystem models are data intensive.
Pathway	Data requirements are substantial and specific. Because they address different processes along the pathway of effects, both information on the stressor and on the valued component needs to be collected to run these models.
Multiple pathways	Data requirements vary widely for these models. The application of DPSIR models relies on having not only indices of change but also baselines, thresholds and targets against which to judge that change (Smith et al. 2016). Spatially-explicit models are more demanding in terms of data than the other approaches.

Data flexibility

Models are generally not flexible in terms of their data needs. Some of the multiple pathways models, such as DPSIR, allow for certain flexibility in terms of the quantity and quality of information needed for running them.

Stressor	These models have specific data requirements and cannot run on types of data other than what they are designed for.
Valued Component	As more data become available, specific interactions in the ecosystems can be better quantified (Lacy et al. 2017). In the absence of empirical data, models can use expert elicitation to estimate parameter values, or can use sensitivity analysis[11] to bound the problem. However, the parameters themselves are fixed (e.g., biomass, growth and predation rates, etc.).

[11] "Sensitivity analysis is the study of how the uncertainty in the output of a mathematical model or system can be apportioned to different sources of uncertainty in its inputs." [Wikipedia accessed Jan 12, 2019] When data are limited, the model may be manipulated to evaluate the outcome under alternative hypothetical scenarios.

Pathway	The combination of different sub-models restricts the data flexibility of the models. They require specific ecological information and data about the stressor and the mechanism of impact.
Multiple pathways	One of the strengths of BBNs is that probabilities in the model can be combined and quantified using different types of data: empirical data, statistical associations, mathematical representations, and probabilistic quantities derived from expert knowledge (Stelzenmüller et al. 2010). In general models allow the information to be easily updated with improved data (Smith et al. 2016)

Accessibility

Stressor	Stressor model accessibility *(medium)* depends on the model. There are some publicly available simulation tools (e.g., MEDSLIK-II) for which case studies and user manuals may exist. However, many models are not provided in a way that allows for the public to easily use.
Valued Component	Users of ecological models need specific knowledge and training. Most of their applications are carried out in academic contexts or by scientists working for entities involved in the management of marine resources. There is ample documentation (e.g., technical and academic references) for these models. For instance, Ecobase is a publicly available database developed by EwE users which includes over 400 EwE models with their metadata and over 190 models available for download.
Pathway	Implementing these models requires knowledgeable users with technical expertise in different fields (e.g., underwater noise and ecology of cetaceans).
Multiple pathways	Conceptual models are easily accessible by stakeholders with various levels of technical and expert knowledge. Spatially-explicit simulation models require users with extensive modeling expertise.

Cost

Stressor	Costs may involve purchasing software licenses and/or datasets and might also involve the collection of site-specific data for validation. Implementation costs also include the time effort of multidisciplinary teams of experts.
Valued Component	Implementation costs of these models can be substantial. Personnel with specific skills and knowledge are required, often in a multi-disciplinary context, and the process of setting up and running the model takes time.
Pathway	Implementation of these models can be costly as they tend to involve setting up and running several sub-models.
Multiple pathways	The costs in developing and implementing these models can vary significantly depending on the type of model. Compared to the other modeling approaches discussed in this section, implementation of conceptual models is less costly. Spatially-explicit models might have additional costs for things such as specific software and data requirements.

Interpretability & communicability

Stressor	Most stressor models are spatially-explicit with outputs that are in the format of maps, which are relatively easy for interpretability and communicability.
Valued Component	Ecological model outputs can be difficult to interpret by non-expert audiences. There is a variety in the format of the outputs, including graphs (Figure 4.24), maps for those which are coupled with GIS applications, tables, etc. All these outputs consist of quantitative information and projections into the future.
Pathway	Outputs are usually in the form of maps, which are generally useful for interpretability and communicability. Because of their focus on the evaluation of scenarios, the relevance of these applications is more obvious.
Multiple pathways	Conceptual models can be developed in consultation with mixed groups of scientists, managers and stakeholders and provide a platform for discussing the structure and key elements of the system of interest. DPSIR and PoE models can be useful as a visualization tools for complex interactions (Patrício et al. 2016) and are valuable for communicating among many stakeholders. One of the common critics to DPSIR models is the variability in the interpretation and use of the main components of the methodology (i.e., Drivers-Pressures-State change-Impact-Response) (Patrício et al. 2016). This is reflected in the multiple derivatives of the model which have come up in recent years. Spatially explicit simulation models are difficult to implement but generate spatially explicit predictions (i.e., maps) which are intuitive to interpret.

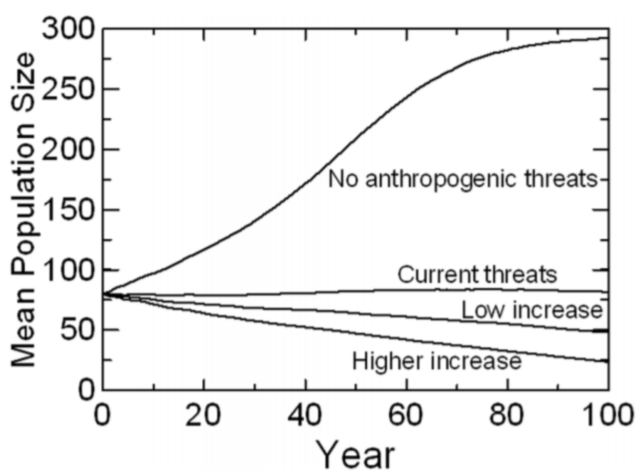

Figure 4.24. Example of a single-species model output. Mean projected Southern Resident Killer Whale (SRKW) population sizes for scenarios with (from top to bottom): no anthropogenic noise or contaminants; current Chinook abundance, noise, and PCBs; reduced Chinook, increased noise, and additional threats of oil spills and ship strikes as estimated for low level impacts of future industrial development; and these increased and additional threats with higher level impacts of development (Source: Lacy et al. 2017).

5 Comparative Analysis

5.1 Comparison across assessment methods

Section 4 provides a detailed evaluation of each of the three assessment methods (i.e., spatial, analytical and modeling), this section presents a higher-level comparative overview across methods (Table 5.2). We have qualitatively ranked the methods for the three main evaluation criteria: relevance, rigour and feasibility as described in Table 5.1. Relevance refers to the general usefulness of the method (i.e., relevant spatial scale, ability to incorporate Indigenous knowledge), rigour provides an overall evaluation of the strength of the method in terms of how well established and justified the method is and the quality of their inputs and outputs. Lastly, feasibility provides an estimation of how easy it would be to implement the method (e.g., skills and resources required, complexity of the method, etc.).

Table 5.1. Qualitative ranking of methods according to the evaluation criteria.

Evaluation criteria	High	Medium	Low
Relevance	All methods discussed in the detailed review are relevant or they would not have been removed at the screening phase. However, some methods were considered more useful than others to the specific CEMS context. The rating of high, medium, or low reflects this assessment.		
Rigour	Well documented in academic papers, case studies, etc. Quantitative assessments that account for uncertainty	Methods which have been documented but they are less standardized or are more recent applications	General lack of documentation. The method is not supported by a well-established application
Feasibility	The method is easy to understand and interpret. There is flexibility in data requirements and accessible tools	Moderately complex, some expertise required. Some flexibility in data needs.	Data-intensive complex methods which require expert knowledge for their implementation.

Given that we identified the most promising methods during the screening phase, it is not surprising that most of the methods rank from medium to high for the three criteria. The analytical methods regression and principal component analysis rank 'low' on feasibility because of their complexity and requirement for expert statistical skills. Multiple species and ecosystem models were evaluated as 'low' for both relevance and feasibility because of their indirect applicability to marine shipping and their high demands in data and expert skills for their implementation.

Table 5.2. Comparative evaluation of assessment methods (coloring indicates low = red, medium = orange, and high = green)

Category			Evaluation criteria		
		Method	Relevance	Rigour	Feasibility
Spatial Methods	Stressors	Mapping	Useful for understanding the spatial variability of different types of stressors, especially given that the type and intensity of vessel traffic differs spatially in Canadian waters. Can use Indigenous knowledge with this method. High	Methods for mapping stressors are well documented in peer-reviewed papers. High	The method is intuitive in application and interpretation. It can incorporate multiple types of data, which are relatively easy to collect. Compilation of data requires skills and tools that are widely used. High
	Valued components	Mapping	Useful for understanding the spatial condition of VCs, and along with stressor information, the exposure of VCs to different stressors. Can use Indigenous knowledge with this method. High	Methods for mapping stressors are well documented in peer-reviewed papers. High	The method is intuitive in application and interpretation. It can incorporate multiple types of data, and compilation of data requires skills and tools that are widely used. Data collection can be costly if they do not already exit. High
	Pathways	Cumulative impact mapping	A spatially explicit way to connect stressors to effects on the underlying ecosystem using limited data. May be useful depending on the assessment need. Although not common with other applications, could use Indigenous knowledge with this method. Medium	Cumulative impact mapping has been applied in many places with an approach that is well documented in peer-reviewed papers. Data needs are high, which result in data limitations that require assumptions to draw conclusions. Medium	There are multiple documented applications to follow in applying it. However, with high data requirements requiring assumptions, there is complexity in the nuance of the application. It also requires conducting expert elicitation. Medium
Analytical Methods	Stressors	Not Applicable. Can typically be directly measured or estimated through single stressor models (see Section 4.4).			
	Valued components	Home-range estimation	Identify critical habitats. Medium	Well documented use in academic papers. Can account for uncertainty. High	The method is intuitive in application and interpretation. It is relatively flexible in terms of data requirements and can incorporate a variety of sources of varying degrees of precision. At a minimum the method requires georeferenced observations for the VC of interest. There are a variety of freely available software tools to support this method. High
		Habitat Suitability Modeling	Identify critical habitats and predict species distributions. High	Well documented use in academic papers. Can account for uncertainty. High	The method is intuitive in application and interpretation. The analysis and data requirements are more intensive than for home-range studies. In addition to georeferenced observations of the VC, data are also required for habitat at locations with and without the VC

Category		Method	Relevance	Rigour	Feasibility
			Evaluation criteria		
					present. Users require moderate statistical knowledge. Medium
	Pathways	Risk Assessment	Useful for identifying high priority pathways where the exposure and consequence are high. As a scoping and prioritization tool, this method is highly relevant. It is not well suited to quantifying the actual functional response of a VC to an activity or stressor. Medium – High	Well documented use in academic papers, however the method is less standardized and less quantitative than many of the other analytical methods. Ad-hoc methods are sometimes used to address uncertainty. Medium	The method is intuitive in application and interpretation. It is relatively flexible in terms of data requirements and can incorporate a variety of sources of varying degrees of precision. High
		Regression analysis	Assess magnitude and nature of functional relationships between stressors and VCs as well as identify the relative importance of different pathways (i.e., the drivers of the system). High	The most established analytical method discussed in this report. Well documented use in academic papers. Can account for uncertainty. Given sufficient data this is the preferred method to quantify relationships. High	Data intensive. Implementation and interpretation are challenging. Users require significant statistical knowledge. Application to a single pathway is less challenging (i.e., requires less data and is easier to implement and interpret) than trying to evaluate the relative importance of many stressors on a particular VC. Low
		Classification and Regression Trees or Forests	Assess magnitude and nature of functional relationships between stressors and VCs. High	A more recent development in the literature but this approach is still well documented in academic papers. Bootstrap methods are used to account for uncertainty. Medium	This approach is more data intensive than regression analysis. The method is relatively easy to implement and interpret through use of freely available software tools. It may be useful when there are a relatively large number of potential stressors and uncertainty in terms of the nature of the relationships. There are a variety of freely available software tools to support this method. Users require moderate statistical knowledge. Medium
		Principal Components Analysis	Identify the relative importance of different pathways (i.e., the drivers of the system). Primarily useful in this context to help refine scope. Medium	Well documented use in academic papers. Can account for uncertainty. High	Data intensive. Implementation and interpretation can be intimidating without statistical expertise. Low or medium?
		Weight of Evidence	Identify the relative importance of different pathways (i.e., the drivers of the system). High	Well documented use in academic papers, however the method is less standardized and less quantitative than many of the other analytical methods. Uncertainty may be addressed quantitatively or using ad-hoc	This method has intuitive appeal and is conceptually simple yet can incorporate more rigorous information where available. The method can incorporate a variety of data sources varying in quality and quantity. High

Category		Method	Evaluation criteria		
			Relevance	Rigour	Feasibility
				approaches within some lines of evidence and not others. Medium	
Modeling Methods	Stressors		Highly relevant for studying the intensity of specific stressors (noise, oil spills) and explore management scenarios. Models exist for a few stressors associated to marine shipping. High	These models are the outcome of well-established research. They are well documented. Explicitly address uncertainty. High	Extensive and specific data requirements. Users need quantitative skills and subject knowledge. Costs may include purchase of specific software. Medium
	Valued components	Single species	Useful for exploring scenarios and understand the response to stressors of a species of special importance (priority VC). Medium	Well documented use in academic papers. High	Requires extensive knowledge and data of the target species. Users need quantitative/statistical skills. Medium
		Multiple species	These models focus on simulation trophic/predation interactions. Unclear link to anthropogenic pressures. Low	There are multiple case studies and academic papers documenting the applications of these models. Rigorous data treatment and explicit consideration of uncertainty. High	Requires extensive knowledge and data of the target species. Users require significant statistical knowledge to model the species interactions. Low
		Ecosystems	Primarily used for fisheries management, these models are starting to be applied to account for other human activities. However, it is unclear how it would apply to CEMS initiative unless the VC itself is an ecosystem. Medium	Extensive literature on these models. Many tools and methods available with specific documentation. Uncertainties are usually documented. High	In general, these are data intensive models requiring large data sets to calibrate and run the simulations. Low
	Single pathway		These models establish the interactions between stressors and VCs and can be used to evaluate alternative scenarios. High	Well documented in the literature. Uncertainties (in the knowledge base and the predictions of the model) are well documented. High	Extensive and specific data requirements. Multi-disciplinary teams with expert knowledge. Costs may include purchase of specific software. Medium
	Multiple pathways	PoE	An explicit understanding of the cause-effect linkages between stressors and components should underlie any model. High	PoEs are considered best practice. The quality of the evidence supporting the links determines the level of uncertainty of the model. Medium	PoE models can be developed by a range of stakeholders based on the data and knowledge available. High
		DPSIR	Flexible problem-structuring approach that can be applied to a variety of contexts. Policy-oriented model. High	Limited practical application; most assessments are semi-quantitative. Medium	This model is data flexible and it can be adapted to the available resources. High

Category		Method	Evaluation criteria		
			Relevance	Rigour	Feasibility
		BBN	Limited application to marine problems but these models are emerging as a solution in data-limited contexts. High	Uncertainty explicitly addressed. High	BBN models can combine empirical data and expert knowledge. High
		Spatially explicit	Holistic modeling approach that assesses the implications of cumulative effects over space. High	Case studies well documented in the literature. Uncertainty usually documented. High	These models require specific skills (spatial and stochastic modeling) and are more data-intensive than other multiple pathways models. Medium

5.2 Application to the Cumulative Effects of Marine Shipping Initiative

5.2.1 Overview

This section describes how methods could be applied to the Cumulative Effects of Marine Shipping (CEMS) initiative. Table 5.3 provides an overview of the application of the evaluation methods. Under the column 'Generic Application' we have documented the general intended use of the method. In order to provide more concrete and relevant examples of application for Transport Canada we have included a 'Specific example of how the CEMS initiative might use methods in each category'. These are hypothetical instances in which methods could be applied in the assessment of cumulative effects of shipping in Canada. Finally, the last column to the right provides examples of specific methods and associated tools.

Table 5.3. Overview of the application of the evaluated assessment methods

Category		Generic Application	Specific example of how the CEMS initiative might use methods in each category	Methods and associated Tools
Spatial	Stressor	Map the location and intensity of marine shipping stressors	Using AIS data, vessel density information can be used to identify in a spatially explicit way the magnitude of various stressors associated with movement underway. By connecting this spatially explicit data with models related to stressors, estimated stressor magnitudes can then be examined along with locations of VCs to identify geographical areas of concern. For example, underwater noise could be modeled based on the density of traffic, and that information can then be overlaid with information about the distribution of marine mammals.	Tools: ArcGIS, QGIS, SeaSketch
	Valued Component	Map the location of observations	Related to the stressor example in the row above, maps of locations of marine mammal observations and marine mammal critical habitat (as identified by DFO) could be overlaid with vessel density information to identify geographical areas of concern. This information can then inform where further work may be needed to monitor and/or model effects.	Tools: ArcGIS, QGIS
Analytical	Valued Component	Determine the spatial distribution of VCs of interest. Develop habitat suitability models so distributions can be predicted based on habitat characteristics.	Observations on sea otters could be used to identify their home ranges during different times of the year and during different times in their life-cycle. This information could be used to inform vessel movement decisions/restrictions temporally during the most vulnerable periods. If data allowed or funding could be secured for monitoring, additional habitat information could be used to generate a habitat suitability model. This would allow researchers to make predictions about spatial distributions in locations without direct observations or under alternative future scenarios.	Methods: Utilization distribution, Habitat Suitability Modeling Tools: R programming language, USGS HSI software
	Single Pathway	Complete risk assessments to identify high priority areas or pathways where the exposure and consequence are high.	The CEMS initiative could undertake risk assessments for priority VCs in each region to identify the stressor-VC pathways where the risk is the greatest. This would enable regions to focus more extensive monitoring and modeling efforts on a smaller subset of priority VCs which are most vulnerable to the stressors observed in each region. For example: • In the Arctic a risk assessment could be used to determine which of the concerns (e.g., increased vessel traffic impacts to food security) raised by Indigenous peoples and stakeholders are most at risk due to current or increased shipping activity. • In the Bay of Fundy, risk assessment could be used to determine which species of concern are most at risk to oil spill events, a leading cause for concern in this region.	Methods: Risk assessment Tools: EcoFate

	Single Pathway	Quantify the magnitude and nature of the functional relationships between stressors and VCs (i.e., pathways).	Quantifying the impact of movement underway on breeding bird colonies would help to inform decisions around how much is too much. In many cases the functional relationship between a stress and an observed response in a VC is non-linear, i.e., there may be tipping points. In this example, it is possible that there is a certain number of disruptions that are tolerated before a nest is abandoned. Once these functional relationships are quantified they can be incorporated into simulation models which relate alternative stressor scenarios to population or ecosystem level responses.	Methods: Regression Tools: R programming language
	Multiple Pathways	Identify the relative importance of different pathways (i.e., the drivers of the system).	A weight of evidence approach could be used to identify the pathways of greatest concern to beluga populations in the Saint Lawrence River. This would involve collecting the best available data on potential stressors (e.g., noise, collisions, oil spills, tourism, vessel wastewater, climate change) and beluga populations. If one or two stressors stand out, these can then be prioritized in future monitoring and modeling efforts. In addition, any information about the magnitude and nature of the functional relationship could be incorporated into future modeling or mitigation efforts as described in the single pathway example.	Methods: Regression, CART, Forests, PCA, WoE Tools: R programming language
Modeling	Stressor	Modeling the magnitude or distribution of the stressor associated with a particular activity.	The impact of anchoring in Northern BC could be investigated by first modeling the substrate disturbance or 'anchoring footprint' for individual boats under different conditions (e.g., tide, wind, current) and then using this to assess the current disturbance as well as alternative future scenarios. This information could later be overlaid with VC or habitat distribution information to inform the magnitude of the impact (i.e., single pathway assessment).	Noise models: RAM, RANDI, NONM, NEMES Oil spills modeling: MOTHY, MEDSLIK, MEDSLIK-II, POSEIDON-OSM, SAMSON, H3D, SPILLCALC Emissions: MEIT
	Valued Component	Simulate how a stressor or multiple stressors can affect an ecological component of the environment at the species, habitat or ecosystem scale.	A life cycle model for salmon could be generated to inform population viability analyses. In other words, various life cycle parameters (e.g., juvenile survival) could be adjusted to evaluate the long-term impacts on the population. This model could later be linked to stressor models to evaluate population level responses to alternative management scenarios (i.e., single or multiple pathway models).	Method: Population Viability Analysis (PVA) Method/tools: ECOPATH with ECCOSIM (EwE), Atlantis
	Single Pathway	Link stressors to specific components by simulating the process by which effects occur from one linkage to the next along a particular pathway.	A single stressor model could be generated which describes the position and movement of tankers at different times of the year in order to identify areas which are effectively no-longer available for fishing. This could then be related to a second model which describes theoretical fishing opportunity (i.e., spatial and temporal openings or traditional use areas). The combination of these two models could be used to assess current lost fishing opportunities and possible future scenarios under different mitigation options.	Method: linkage of single stressor and VC models Tools: 3MTSim model, Spill Impact Model Application Package (SIMAP)

			Similarly, a pathway model can combine an underwater noise propagation model with a distribution model of sensitive cetaceans to assess the potential impacts of increased noise due to marine traffic. Vessel strike models operate in a similar way, combining traffic data with the distribution of certain species to assess the risk of collisions.	
	Multiple Pathway	Problem-structuring frameworks that can be applied to any combination of stressors and valued components to understand the combined effect of multiple pathways and their relative importance	Under a DPSIR or BBN framework, multiple shipping impact pathways (noise, risk of strikes, discharge, etc.) could be conceptualized and study to assess their relative importance and test various management options.	Methods: DPSIR, BBN, PoE, Spatially explicit models

5.2.2 Case-studies

We have selected relevant examples from the literature that illustrate the application of the assessment methods in a context relevant for Transport Canada. Table 5.4 provides a list with a short description of these 30 cases studies. Most case-studies use a combination of methods to achieve their objectives. This is not meant to be a comprehensive list but rather a list of relevant examples provided to help clarify how the methods could be applied in practice.

Table 5.4. Selected case studies relevant for the CEMS initiative

Case Study	Category	Focus	Title	Description	Short Citation
1	Spatial	VC	Haida Marine Traditional Knowledge Study	The Haida Marine Traditional Knowledge (HMTK) project was initiated to research and document Haida culture, traditions and knowledge related to the Haida Gwaii marine area (CHN 2011a). Interviews were conducted with individuals in the communities, most of whom were Haida elders with long histories of fishing and gathering as well as strong roots in Haida traditions. Interviews were recorded, transcribed, and the information was entered into a database. Spatially explicit information was mapped and digitized. Maps were created that compiled information from multiple interviewees about significant sites, fishing areas, and ecological features. The result was reports with a plethora of information about traditional harvesting areas, seasonal harvest patterns, sites of cultural and historical importance, and observations about species abundance and population trends.	CHN 2011b
2	Spatial	VCs	Mapping of ecological and socioeconomic VCs	The Marine Plan Partnership (MaPP), a co-led process between 17 First Nations and the Government of the Province of British Columbia, created the MaPP Marine Plan Portal to support discussions and decisions related to marine planning on the coast of British Columbia. Data was compiled related to ecological and socioeconomic activities/stressors and VCs (e.g., species populations, habitats, human activities, etc), and mapped in a way that allows for overlaying activities/stressors and VCs to understand areas of overlap. The MaPP Marine Plan Portal is further discussed in Section 6.3.2.	MaPP 2019
3	Analytical	VC	First Nations monitoring of cultural sites on the coast of British Columbia	Coastal First Nations in British Columbia participate in a Regional Monitoring System (RMS) in order to systematically collect data of interest to the Nations across the broader region. As part of the RMS, the Nations have developed monitoring protocols, one of which is for documenting the condition of and changes to cultural sites. The methods for assessing cultural sites are aimed at documenting the location and characteristics of the site, impacts that occur to the site across time, and threats to the site. Methods are consistent with those developed by the Province of British Columbia for inventory of archeological sites, and allow for qualitative and quantitative measurements of condition and change.	Hoshizaki 2016 BC Archeology Branch 2015 BC 2000
4	Spatial / Analytical	Pathways	Cumulative Impact Mapping in Canada's Pacific Waters	This study was undertaken to advance the understanding of multiple stressors along British Columbia's coastline. Existing regional human use data that was used included locations and intensities of human activities, types of stressors resulting from the activities, relative impact of activities on habitats, and distances the effects occur over. In addition, expert judgement was used to estimate vulnerability scores that allowed for linking the level of impact from stressors to specific habitat types. Using methods from Halpern et al. (2008), a cumulative impact score was produced for three habitat classes (benthos, shallow pelagic, and deep pelagic) as well as a combined score. The authors discussed how cumulative impact maps can be used to prioritize areas for protection or restoration and inform potential management interventions.	Ban et al. (2010)
5	Spatial / Analytical	VC	Summer core range for Southern Resident Killer Whales	This study uses observations of Southern Resident Killer Whales from the British Columbia Cetacean Sightings Network to estimate the summer core range using a non-parametric approach known as kernel density estimation (Worton 1989). They then overlay information from a regional noise model on top of the summer core area to identify where exposure to noise is greatest.	Cominelli et al. 2018

Case Study	Category	Focus	Title	Description	Short Citation
6	Spatial / Analytical	VC	Habitat suitability model for salmon in the Salish Sea	The Pacific Salmon Foundation is in the process of developing a habitat suitability model for salmon in the Salish Sea.	Villy Christensen, pers. comm.
7	Analytical	VC	USGS Habitat suitability index software	USGS provides canned Habitat Suitability Index (HSI) software to compute HSI values for selected species from field measurements of habitat variables. They have published HSI values for numerous species.	https://pubs.er.usgs.gov/publication
8	Spatial / Analytical / Modeling	Pathways	Risk assessment of VCs to PCBs in the San Francisco Bay	The San Francisco Bay Food-Web Bioaccumulation Model for PCBs calculates the spatial distribution of polychlorinated biphenyls (PCBs) concentrations within a number of organisms (fish, mammals, birds, and invertebrates) that inhabit the San Francisco Bay. The results of this model can then be compared to threshold concentrations to establish instances of exceedance, and determine the associated exposure risk faced by VCs, and the bioaccumulation-related health risks humans and other species at higher trophic levels may face.	Gobas et al. 2010
9	Analytical / Modeling	Pathways	Risk assessment tool to evaluate exposure of VCs to air pollution	The European Union System for the Evaluation of Substances (EUSUS) is a computer-based ecological risk assessment program that carries out air pollution assessments in a systematic way. It first performs an exposure assessment based on estimates of concentrations that may impact valued components, including models that account for the properties of the emitted substance, its distribution, and the direct exposure of valued components to it. Second, it performs an effects assessment comprised of hazard identification and the relationship between the dose of the substance and the severity of its impact on the VCs. Finally, it characterizes the risk based on the outputs from the model-based steps 1 and 2.	Manuilova 2003
10	Spatial / Analytical	Pathways	GIS-based risk assessment applied to marine ecosystems	The Plan4Blue project (SYKE Finnish Environmental Institute) utilizes a GIS-based risk assessment method that cumulatively assesses risk given the distribution and sensitivity of VCs, and the distribution of anthropogenic pressures. The objective of the project is to identify best practices for the sustainable use of marine ecosystems and resources.	Herkul et al. 2017
11	Analytical / Modeling	Pathways	EcoFate, a computer-based software tool for ecosystem-based risk assessment of chemical emissions on aquatic ecosystem	EcoFate is a computer-based software that integrates an ecosystem-based risk assessment of chemical emissions into a cumulative effects framework. The software can simulate point, and non-point source emissions in freshwater and marine ecosystems (including lakes, rivers, and inlets). It assesses the impact of a specified concentration of pollutants on the whole aquatic ecosystem (water, sediment, and biota), based on that concentration's exceedance of a set of environmental criteria. The model also considers food-web bioaccumulation, human health risks, and can be run using time-dependent and steady-state scenarios.	Gobas et al. 1998
12	Analytical	Pathways	Regression analysis and Weight of Evidence approach to evaluate effect of a variety of stressors on sockeye	The Cohen Commission Enquiry into the decline of Fraser River sockeye used a multiple regression analysis to relate each of 13 different stressors to different life-stages of sockeye. A series of plausible models were generated a-priori to evaluate alternative functional relationships and potential interaction effects. The regression analysis was used within a larger weight of evidence approach to evaluate the likelihood that each of the stressors was responsible for the decline.	Marmorek et al. 2011

Case Study	Category	Focus	Title	Description	Short Citation
13	Analytical	Pathways	Random forest algorithm to identify dominant stressors on fish in European estuaries	Teichert et al (2016) used a random forest algorithm to evaluate the influence of multiple stressors on fish ecological quality in European estuaries. The approach enabled them to identify the dominant stressors in the estuaries as well as investigate the nature of the relationships (e.g., additive, synergistic, or antagonistic).	Teichert et al (2016)
14	Analytical	Pathways	Weight of Evidence approach to evaluate impacts of Run-of-River hydroelectric projects on salmonids	The Pacific Salmon Foundation used a weight of evidence approach to evaluate Run-of-River Hydroelectric Projects and their Impacts on Salmonid Species in British Columbia.	Connors et al. 2014
15	Analytical/ Modeling	Pathways	Impact of marine vessel traffic on access to fishing opportunities	AIS data on marine vessel traffic was analyzed to quantify the location and size of areas which were no longer available for fishing due to vessel traffic at different times of the year. This was then compared to fishery openings (defined by space and time) within the traditional territory of the Musqueam First Nation. Regression analysis was used to quantify the magnitude of the impacts to Musqueam fishing opportunities for salmon, crab, and prawn. Quantification of these relationships allowed the authors to both characterize the current condition of impacts and evaluate potential impacts under alternative development scenarios. The analysis also allowed the authors to assess the relative impacts associated with different types of vessels. This improved knowledge of the historical, current, and potential future conditions is critical to enabling the Musqueam to make informed decisions about future activities.	Nelitz et al. 2018
16	Modeling	Stressor	Cumulative underwater noise	This study used a cumulative noise modeling procedure to determine the contribution of vessel noise to the ambient sound level distribution in the Salish Sea. Modeled (using the MONM model developed as part of the NEMES project) sound levels were calculated to evaluate the sound exposure of Southern Resident Killer Whales (SRKW) and other marine fauna in the Salish Sea.	O'Neil et al. 2017
17	Modeling	Stressor	Assessing and mapping underwater noise impacts	This case study presents a probabilistic model and mapping framework (RANDAM) which integrates the intrinsic variability and uncertainties of shipping noise and its effects on marine habitats. It was applied to assess the effects of changes in the soundscape on Arctic marine habitats	Aulanier et al. 2017
18	Modeling	Stressor	Impacts from cumulative underwater noise on killer whales	Based on a simple sound transmission model and ship track data (AIS), this study evaluated the cumulative underwater acoustic energy from shipping in the west Canadian Exclusive Economic Zone, showing high noise levels in critical habitats for endangered resident killer whales.	Erbe et al. 2012
19	Modeling	Stressor	Assessing substrate disturbance from anchoring	Using AIS data, this study attempted to evaluate the impact of anchoring off the coast of New South Wales (Australia) by analyzing the footprints in form of arcs left by long-term anchoring activity on the seafloor	Davis et al. 2016
20	Modeling	VC (single species)	Understanding cumulative effects at the population level for South Killer Whales	This paper describes a population viability analysis of resident South Killer Whales in the western Pacific to explore possible demographic trajectories and the relative importance of anthropogenic stressors.	Lacy et al. 2017
21	Modeling	VC (ecosystem)	Effects of substrate disturbance on benthic communities	Raoux et al. (2017) applied Ecopath to assess the impacts of wind farm development on the trophic structure of the benthic community; a pathway that could be appropriate to assess the effects of anchorage or wreckage.	Raoux et al. 2017

Case Study	Category	Focus	Title	Description	Short Citation
22	Modeling	VC (ecosystem)	Impacts of underwater noise at the ecosystem level	This study used a spatially explicit model (EwE/Ecospace) to simulate the impacts of underwater noise from shipping on predation behavior of harbor porpoises and to evaluate how these effects can manifest in their biomass and trophic interactions with other species in the community.	Harvey 2018
23	Modeling	Single pathway	Predicting impacts of vessel strikes for whales in the Pacific	Spatially-explicit model that combines spatial information on species abundance with shipping data (using AIS or other marine traffic data sets) to estimate the relative probability of whale-vessel encounter using generalized additive models (GAMs).	Williams and O'Hara 2009
24	Modeling	Single pathway	Assessing the risk of ship strikes in the Saint Lawrence estuary	The 3MTSim is a socio-ecological model, developed for the Saint Lawrence estuary (Chion et al. 2017), that simulates the movements of individual boats (2D) and marine mammals (3D). The main application of this model is to evaluate how alternative traffic management scenarios can impact the marine mammals and shipping activities in the area	Chion et al. 2017
25	Modeling	Single pathway	Evaluating the impacts of oil spill across functional species groups	This study applied the Spill Impact Model Application Package (SIMAP) modeling tool - a coupled oil fate and effects model has been developed for the estimation of impacts to habitats, wildlife, and aquatic organisms resulting from acute exposure to spilled oil - to the Exxon Valdez case study.	French-McCay 2004
26	Modeling	Multiple Pathways	Identifying relative importance of pathways using PoE	Stephenson and Hartwig (2009) used a Pathways of Effects model to determine what activities might have a potentially negative effect in the marine ecosystems of the Beaufort Sea in the Yukon North Slope.	Stephenson and Hartwig 2009
27	Modeling	Multiple Pathways	Assessing multiple pathways using a conceptual and probabilistic model based on expert opinion	This framework combines the development of conceptual models with the application of Bayesian Belief Networks to describe the linkages between environmental drivers, human activities and resulting pressures on ecosystem values for two key marine ecosystems in the Australian Great Barrier Reef World Heritage Area: coral reefs and seagrasses.	Anthony et al. 2013
28	Modeling	Multiple Pathways	Modeling impacts on marine ecosystem services	Kelble et al. (2013) applied a Driver, Pressure, State, Ecosystem service, and Response (EBM-DPSER) conceptual model to the Florida Keys and Dry Tortugas marine ecosystem as a case study to illustrate how it can inform management decisions.	Kelble et al. 2013
29	Modeling	Multiple Pathways	Using Bayesian Belief Networks to assess multiple pathways	Ban et al. (2014) applied a Bayesian Belief Networks method to study the effects of multiple stressors, and multiple water management alternatives, to coral reefs in the Australian Great Barrier Reef.	Ban et al. 2014
30	Modeling	Multiple Pathways	A Bayesian Belief Network–GIS framework as a practical tool to support marine planning	Stelzenmüller et al. (2010) combined a BBNs method and Geographical Information Systems (GIS) to visualise relationships between cumulative human pressures, sensitive marine landscapes and landscape vulnerability, to assess the consequences of potential marine planning objectives, and to map uncertainty-related changes in management measure.	Stelzenmüller et al. 2010

6 Crosscutting methods

Although this report is designed to focus on assessment methods (Assess Information box in Figure 6.1) there are several methods applicable to CEA more generally, and potentially applicable to all of the assessment methods detailed in Section 4.

Indigenous knowledge (IK) can be empirical data (e.g., direct observations by IK holders), expert information (e.g., inferences based on and IK holder's cumulative body of knowledge), and ways that knowledge should be used within assessment processes (e.g., how empirically derived IK should be used on its own in conjunction with approaches such as spatial, analytical, or modelling approaches). The subsection below provides a brief summary about IK as it relates to CEA, and highlights how Indigenous communities and knowledge holders should be included in the assessment process.

Expert elicitation is often used as an information input in CEA processes due to the fact that CEA have large data requirements to meet the need for information about the multitude of components within a socio-ecological system. The subsection below includes a brief summary of how expert elicitation is relevant to CEA. Expert elicitation techniques are also related to IK as IK holders are experts about the systems in which they live.

Results from cumulative effects assessments are used to make decisions, which can include the use of decision support tools. The subsection below briefly summarizes how DSTs are relevant to CEA and a subset of DSTs that may be of interest to the CEMS initiative.

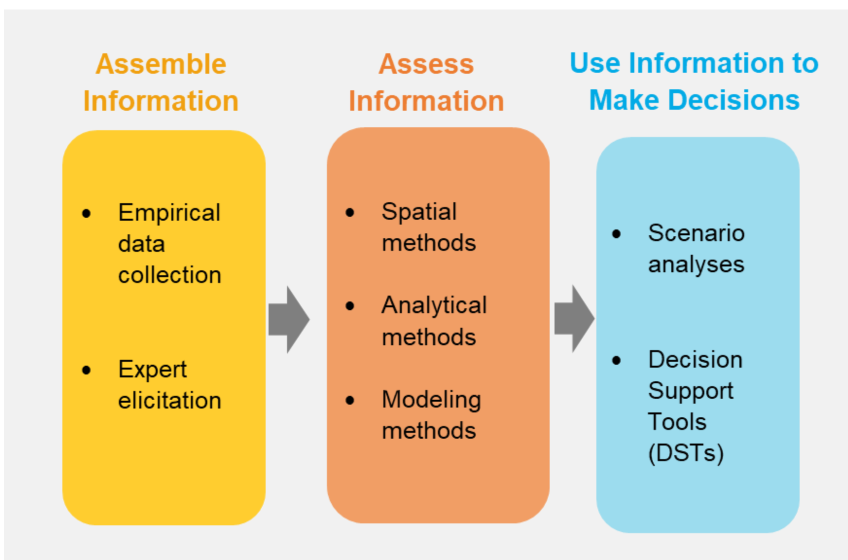

Figure 6.1. A conceptual diagram, highlighting how a framework can help organize how we assemble information, assess information, and use information to arrive at management decisions. Cumulative effects frameworks encompass all of these steps, and more.

6.1 Indigenous Knowledge

6.1.1 Overview

Indigenous knowledge (IK) is derived from a multitude of experiences and traditions that are passed down orally or by shared practical experiences of people who have lived within and as part of the natural environment for hundreds or thousands of years (Berkes 2000; Berkes 2018; Huntington 2000; Houde, 2007). It encompasses knowledge, practices, and beliefs that are interconnected with culture, spirituality, tradition, and worldview of a group of people and their landscape (Figure 6.2) (Ban et al. 2018; Berkes 2018; Houde 2007). Additionally, IK is both what is known (i.e., the information) as well as the ways of knowing (i.e., the process).

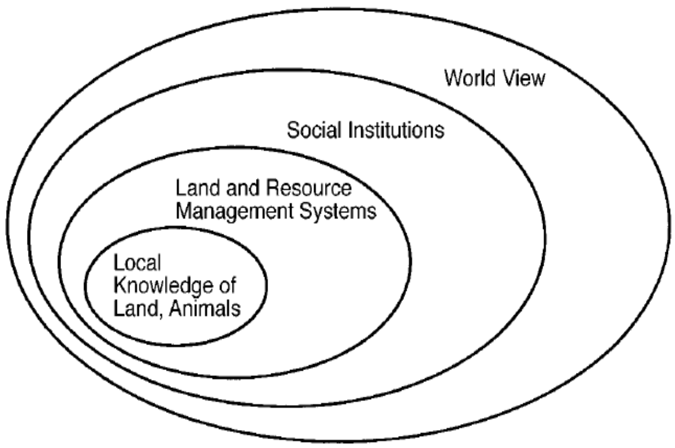

Figure 6.2. Indigenous knowledge encompasses local knowledge, management systems, social institutions, and worldviews (Berkes 2018).

IK can be qualitative (e.g., why a species prefers a specific habitat) or quantitative (e.g., habitat locations on a map). It can be empirical (i.e., direct observations or experiences) or inference-based (i.e., conclusions based on reasoning). For example, empirical information could be identified locations from a person who observed a particular species in a specific place; whereas inferences could be information about the type of habitat characteristics a species prefers based on a person's cumulative body of knowledge (Berkes 2018; Kalland 2003). In this way, IK holders are experts about the systems within which they live.

As Indigenous communities have lived within and as part of ecosystems for thousands of years, the knowledge gained and passed down through generations is deeply rooted in their place and community (Ban et al. 2018; Berkes 2018; Nazarea 2010). Given this close connection to place, IK is uniquely valuable for informing how the ecosystems in the place function, assessing the health of those ecosystems, and informing decisions to promote desired outcomes within those ecosystems (Berkes 2018). In addition, IK is unique in that it is embedded within moral and ethical contexts (Ban et al. 2018; Berkes 2018). Thus, in acknowledging the value of IK, it is important that the application or use of IK is done by or with the Indigenous people (Berkes 2018).

IK is valuable as a sole source of knowledge as well as can be valuable when used in conjunction with other forms of knowledge. Different forms of knowledge (e.g., IK and western science-based knowledge) entail unique strengths and limitations. For example, IK can provide information across long time scales but may be limited by human memory (e.g., things deemed more important or significant events may be more likely to be remembered and passed on), whereas western scientific information from oceanographic devices may be shorter-term but operate 24 hours a day to collect fine-scaled data (Ban et al. 2018; Lewis et al. 2009). Information from multiple methodologies with differing and potentially complementary strengths and limitations can provide stronger insights than from one method alone, ultimately increasing the weight of evidence for findings (Gadgil et al. 1993; Huntington et al. 2004; Salomon et al. 2007; Tengö et al. 2014; and refer to Section 4.3.1.3 for details about weight of evidence methods) When IK is combined or braided with western science information and/or methodologies, differing strengths can be used in complementary ways to improve inferences (Ban et al. 2017). However, there is a risk of institutionalizing IK into existing western scientific structures and so it is important that these processes are conducted with IK holders and communities (Berkes 2018; Mistry and Berardi 2016).

6.1.2 Relevance for the CEMS initiative

Coastal Indigenous communities have lived along Canada's shores since time immemorial. Over this long period of time, they have acquired a rich historical knowledge about the places in which they have been a part and developed locally-relevant marine resource management practices (Ban et al. 2017, Ban et al. 2018). This IK entails uniquely valuable information relevant to identifying valued components of the ecosystem and determining how marine shipping may be connected to those components. How this IK should be applied as a sole source of information or how it could be used in conjunction with other forms of knowledge will be dependent on the type of IK that exists within the communities and how they see it best being applied.

When working with Indigenous communities to determine how to assess cumulative effects and the ways IK could be applied, one example of a potential application is identifying VCs and understanding how different components of the system are connected. Another example relevant to examining the relationship between components is as part of a Bayesian Belief Network (BBN) approach (Section 4.4.1.4). BBNs allow for integrating Indigenous and expert knowledge (as priors) with field-based data to determine predictions about system behavior, which allows for more informed results than using field-based data alone (Ban et al. 2014). An example that relates to the use of CEA in decision making is the Mauri Model, which is a DST developed with an Indigenous worldview, and further discussed in Section 6.3. Another example related to understanding the status of components is a specific case undertaken on the central coast of British Columbia by Ban et al. (2017) (detailed below).

6.1.2.1 Case Study

In response to concerns about declines in First Nations Dungeness crab catches and Fisheries and Oceans Canada requests that First Nations provide evidence of a problem in satisfying their food, social, and ceremonial (FSC) needs, First Nations on the central coast of British Columbia undertook a study to document IK with Indigenous fishers and model the probabilities of experiencing successful FSC harvests (Ban et al. 2017).

Interviews were conducted with Indigenous fishers, within which they were asked about crab catches and abundance across their lifetime, gear types used, the number of crabs they desire to eat per year, and the catch rate necessary for them to consider a FSC trip successful. Responses were then used along with local abundance data derived from recently collected field-based data to conduct computer simulations and estimate the probabilities of experiencing successful FSC trips at different sites under current levels of abundance. Results indicated that fishers have experienced changes in abundance across their lifetime and that the probabilities of experiencing a successful FSC trip were low at all sites except one.

This study provides an example of working with Indigenous knowledge holders to apply their IK in a way that can inform improving management. Specific to assessing cumulative effects, it provides an example of how IK can be used to better understand the status of a VC (i.e., Dungeness crab) and where important thresholds exist (i.e., number of crabs needed for FSC fishery).

6.2 Expert Elicitation

6.2.1 Overview

In the absence of empirical evidence on how different ecosystems respond to multiple stressors, marine managers have looked to the use of expert elicitation methods in order to estimate both the absolute and/or relative impacts of stressors on Valued Components (VCs). In doing so, approaches have used expert elicitation to identify components important for inclusion in assessment, including what human activities should be included, what stressors result from which activities, and what components of the socio-ecological system are important to include. Expert elicitation has also been used to quantify the relationship between the different components within the system. For example, the cumulative impact mapping approach developed by Halpern et al. (2008) involves eliciting expert judgement to estimate ecosystem-specific levels of impact for multiple anthropogenic drivers of ecological change.

The use of expert elicitation allows for identifying key knowledge gaps (e.g., where priority VCs have limited data), comparing estimates of impacts across different stressors and VCs, and prioritizing areas where management efforts should be focused.

Methods of documenting expert knowledge include hosting workshops, conducting interviews, and performing surveys (Longhurst 2003, Halpern 2007).

6.2.2 Relevance for the CEMS initiative

Cumulative effects assessments require data related to multiple human activities and how they relate to the multiple components within the system. With these multiple dataset requirements assessments frequently encounter the issue of data availability and paucity. Expert knowledge derived from elicitation can supplement temporally-restricted data by providing a proxy for long-term field data (Singh et al. 2017).

In the absence of data collected from scientific studies or Indigenous knowledge, expert knowledge has been used to identify important elements in a socio-ecological system and estimate how they are related. Because cumulative effects assessments inherently involve examining multiple stressors and multiple valued components, there are often large data needs, and associated data gaps, which lead to reliance on expert knowledge.

6.2.2.1 Case Study

An expert elicitation procedure has been applied to understand the impact of human activities on marine ecosystem services (Singh et al. 2017) in the coastal areas of Tasman and Golden Bays (New Zealand). Through an iterative interview procedure, experts on each of the ecosystem services under analysis were asked to derive impact scores and pathways for each designated activity or stressor, characterizing uncertainty parameters for each resulting 'impact profiles'.

One of the outcomes of this analysis was the mapping of the mechanistic pathways by which drivers and stressors impact ecosystem services. The information provided by experts through interviews was organized in the following way to create the pathways: Driver → Stressor → Impact on Ecosystem Service.

Impact profiles and pathways were then combined to calculate cumulative effects and develop networks of causal impact pathways.

This study used a "weight of expertise" approach by which the number of experts describing a specific pathway was recorded, as well as the number of times a specific link was mentioned. This quantitative information informed the development of 'hive' diagrams (Figure 6.3) which organize the cause-effect networks along axes (i.e., human activities, stressors or ecosystem services).

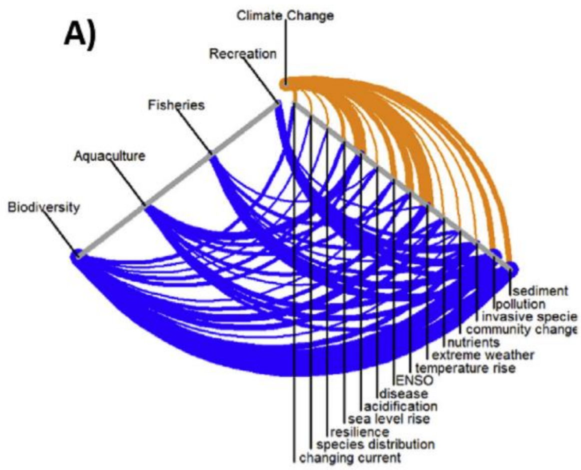

Figure 6.3: Example of hive diagrams representing networks of pathways of impact from a) climate change and b) commercial fishing commercial fishing. These plots show drivers of impact (top axis) leading to various stressors (lower right axis, connected with orange lines) and impacting ecosystem services (lower left axis, connected with blue lines). The thickness of each line represents how many experts mentioned each link. The nodes along each axis are organized by ranking the nodes with the highest number of linkages to the lowest (highest number of links on the outside). Source: Singh et al. 2017

This approach for cumulative effects assessment links causes and consequences and makes a distinction between direct and indirect effects. It investigates all pathways and can assist in determining which are the most prominent drivers or pathways. This is especially important to guide management and monitoring efforts. The fact that effects are not quantified, and the assessment is not spatially explicit are the main shortcomings of this approach.

6.3 Decision Support Tools

6.3.1 Overview

Decision support tools are computer-based models that assist the user in identifying and reaching management decisions by evaluating alternative scenarios or trade-offs. They can be spatially-explicit, incorporate data from ecological, economic, and social systems, and assess progress towards reaching management goals (Center for Ocean Solutions 2011). Commonly, DSTs can be implemented at a number of stages within the overall framework, and particularly at these steps: alternative scenario development, alternative scenario evaluation, evaluation of management objectives, and during the refinement stage for these objectives.

6.3.2 Relevance for the CEMS initiative

Decision support tools (DSTs) can support the assessment of cumulative effects of marine shipping in various ways; including combining and visualizing multiple data sets, assessing the impacts of marine traffic on ecosystems services, etc. This section highlights some of these tools developed for marine contexts.

Many DSTs have been developed for the marine environment that aid decision-makers in utilizing the results from cumulative effects analyses in a systematic way, such that conclusions about the optimal path toward reaching management objectives can be discerned. Several of these tools are web-based, allowing people to quickly view, share and conduct new analyses. They can be spatially-explicit, and incorporate data from ecological, economic, and social systems. DSTs that may be of interest to the CEMS initiative include ATLANTIS, SeaSketch, Marxan, and Cumulative Impacts, MIMES, and Coastal Resilience. Most of these DSTs have been developed specifically for addressing cumulative effects analyses and management in the marine environment (ATLANTIS, SeaSketch, Marxan, and Cumulative Impacts). Others, like MIMES, ARIES, and Coastal Resilience, may be applicable to marine ecosystems, even if they are not explicitly designed for such areas. For example, MIMES can apply broadly to any ecosystem of interest, including to marine ecosystems as long as there is established knowledge about the ways in which marine shipping impacts the provision of ecosystem services to communities.

The advantages and weaknesses of the various DSTs depend on the data available to the user, the scope of work being undertaken, and the complexity of the model being used. Some DSTs require minimal technical expertise, while others are geared towards expert users. Figure 6.4 provides an overview of some of the DST tools mentioned, and their ease of use.

Minimal training or technical expertise	Minimal training and expertise but process objectives must be set in advance	Expert users
InVEST	ARIES	ARIES
MarineMap	Coastal Resilience	Atlantis
Multipurpose Marine Cadastre	Cumulative Impacts	InVEST
	Marxan with Zones	Marxan with Zones
	MIMES	MIMES

Figure 6.4. Expertise required for use of various decision support tools. Figure taken from Center for Ocean Solutions (2011)).

The **Multi-scale Integrated Models of Ecosystem Services tool (MIMES)**, developed by AFORDable Futures, is a GIS-based model that valuates ecosystem services and quantifies the flow of benefits to communities who are provisioned by those services. Once ecosystem services have been valuated, it is then possible to quantify the extent to which adverse impacts to the ecosystem, such as land and sea-use changes, will culminate in impacts to the community, in a trade-off style analysis. MIMES can be applied to ecosystems at any scale between local and global.

Marxan with Zones, developed by The Ecology Centre (University of Queensland), is a popular DST, and an extension of the widely-used Marxan software. The main use of the tool is for identifying priority marine conservation areas from a suite of potential sites and meeting user-defined biodiversity targets based on multiple ecological, social, and economic values, and at the lowest possible cost (Game and Grantham 2008). It does so by assessing "reserve design" problems via exact algorithms and non-exact algorithms (heuristics) to produce optimal and near-optimal solutions. The Marxan with Zones extends the analysis by allowing for various levels of protection to be allocated to identified conservation areas (Watts et al. 2008).

SeaSketch is a participatory, web-based marine mapping tool that allows users to generate, share, and discuss several spatially-explicit alternative management plans or conservation zones. The tool has the ability to integrate other decision support tools such as Marxan analyses and Cumulative Impacts models (Section 4.2) so that the spatial distribution of priority areas can be assessed with regard to cumulative effects. Feedback reports generated from maps of user-defined zones of interest provide information on protected habitats, socio-cultural and economic cost-benefit analyses, and more (www.SeaSketch.org).

The **ATLANTIS ecosystem model**, developed by Commonwealth Scientific and Industrial Research Organization (CSIRO), is a sophisticated simulation model that can assess different environmental scenarios such as climate change, human impacts, land use changes, pollution distributions, and the effects of wind and wave farms on marine ecosystems (Kaplan et al. 2014). It uses spatially-explicit information on physical, chemical, biological, and socio-economic data to simulate food-web relationships, hydrographic processes, habitat interactions, and more. It is intended to be used as a long-term decision-making tool (Center for Ocean Solutions 2011).

The **Mauri Model** is a decision-making tool that quantitatively assesses the impact of stressors on four dimensions of 'mauri', or, an entity's inherent value. The model has been developed under the belief that decisions regarding the value of an entity are not sustainable if only economic valuation is considered. Instead, it assigns values based on a combination of ecosystem, community, cultural, and economic mauri (Peacock et al. 2012). These categories may be equally weighted or allow for a redistribution of weight depending on the perspectives or biases of the stakeholders. The model is capable of addressing some of the typical issues identified in CEAs such as comparison of indicators in the absence of complete datasets and can be implemented to assess current and future scenarios.

Other examples of decision support tools of relevance for the marine environment include:

- The **Coastal Resilience** DST is another web-based mapping tool, developed by The Nature Conservancy. It provides users with spatially-explicit information on coastal ecosystems, socio-economic considerations, and community vulnerabilities for current and future scenarios (Centre for Ocean Solutions 2011).
- **Artificial Intelligence for Ecosystem Services (ARIES)** is a tool that maps and quantifies environmental assets, as well as impacts to these assets arising from climate change, or land use/cover changes (Center for Ocean Solutions 2011). Ecosystem service flows and pathways are spatially and temporally modeled, which enables users to identify critical intersections between pathways. The model works by using a suite of approaches including Bayesian networks (Section 5.4), machine learning, and pattern recognition (Center for Ocean Solutions 2011).

- **InVEST**, developed by the Natural Capital Project, is a set of open-source, GIS-based models that map the value of ecosystem services, and performs a trade-off analysis to evaluate how proposed developments might impact the ecosystem and alter the flow of ecosystem-derived values. Outputs from this tool are provided in biophysical or economic terms.

6.3.2.1 Case Study

The Marine Plan Partnership for the North Pacific Coast (MaPP) is a project aimed at developing and implementing marine use plans for the North Coast of Canada, through collaborative work between 18 First Nations and the Government of British Columbia (www.mappocean.org, Marine Plan Partnership Initiative 2015). The goal is to provide recommendations for achieving healthy ecosystems, socio-cultural wellbeing, and economic development using a marine ecosystem-based management (EBM) framework (Marine Plan Partnership Initiative 2015).

MaPP uses the SeaSketch decision support tool by first integrating a Marxan analysis to inform the placement of areas of high conservation value within the maps generated through SeaSketch (www.seasketch.org). The resulting “marine planning portal” was used to assess multiple layers of data to provide a holistic view of planning options, given valued components such as species, habitats, First Nations cultural sites, and more (www.coastalfirstnations.ca).

Using data assembled from literature reviews, workshops, and expert elicitation, Marxan was run offline for over 170 spatially-explicit datasets of relevant ecological information to produce maps which provide solutions to the identified management problem. The results were uploaded to the web-based SeaSketch tool. Users of the online SeaSketch tool were then able to establish and prioritize candidate conservation areas based on the level of protection, assigned through the Marxan analysis, of the underlying layers Marxan. The output of this integration is both a map of priority-ranked conservation areas, and quantitative scores for user-defined zones, based on the level of protection assigned to the areas.

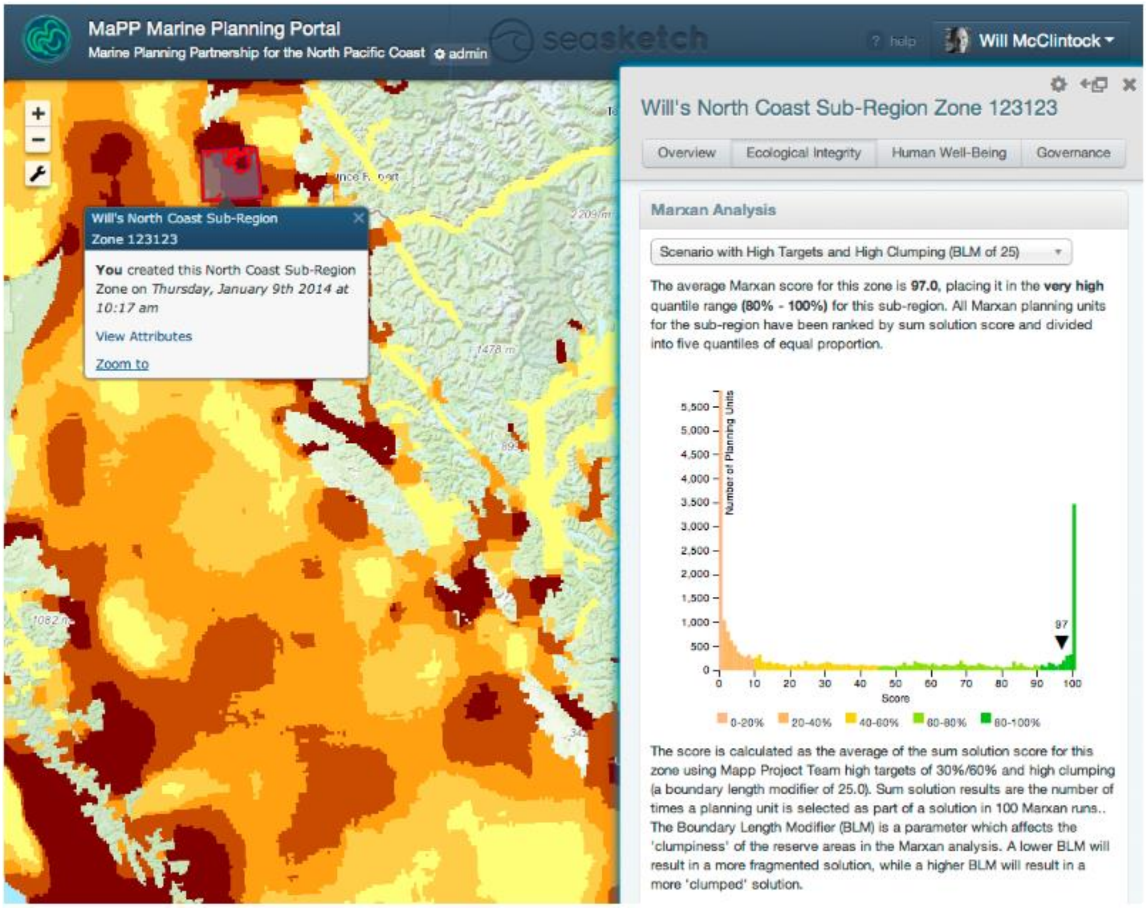

Figure 6.5. Example output from the "Marine Planning Portal" showing both the SeaSketch map, and the integrated Marxan analysis report. Image taken from https://www.seasketch.org/case-studies/2013/04/05/mapp.html.

Because the marine planning portal decision support tool is web-based, outputs are shareable, allowing for real-time collaboration and discussions between stakeholders (www.SeaSketch.org).

7 Organizing methods: CEA Frameworks

7.1 Overview

Frameworks bring together the various spatial, analytical, and modeling strategies discussed throughout this report, and assemble them in a way to address the objectives of a given initiative (see Figure 6.1). The CEA framework for the CEMS initiative should help to clarify which tools to use, when, and at what stage of the analysis. While analysis of potentially useful frameworks is technically beyond scope of the project, it is helpful to think about how the methods discussed in this report may be used in combination. Some examples of frameworks which could be incorporated into the cumulative effects analysis (CEA) include scenario analysis, management strategy evaluation, and risk assessment (Rebecca Martone pers. comm).

Scenario analysis is a process that identifies and analyses several potential future outcomes, rather than identifying a single, precise future outcome. It utilizes one set of assumptions to arrive at multiple alternative scenarios (Hassani 2016). Scenario analysis is incorporated in assessment Step 3 (Figure 1.2). **Management strategy evaluation** (MSE) assesses the effectiveness of different combinations of data collection approaches, analysis methods, and processing in achieving desired management goals (Punt et al., 2014). Decision support tools (DSTs) may be of use when evaluating management strategies (Figure 7.1). This approach is useful in determining which management strategy, from a set of candidate strategies, best meets the established objectives. This concept becomes relevant as Transport Canada moves into phase 4 of the initiative and starts to consider explicit linkages to management levers.

The following subsections outline several examples of frameworks that may be considered in development of a framework for the CEMS initiative. The first two examples, the “EU Marine Strategy Directive” and the “BC Cumulative Effects Framework”, may provide useful templates. The third example, “risk assessment” is a generic framework.

7.2 Examples of CEA frameworks

7.2.1 EU Marine Strategy Directive

The Marine Strategy Directive outlines a framework, called The Marine Strategy Framework, which seeks to protect, preserve, and restore marine environments under the jurisdiction of the European Union (European Commission 2010). The Directive (2008) defines the objectives and approaches by which the framework operates including consultation, monitoring, program of measures, and reporting (European Parliament 2008). A series of descriptors of “good environmental status” for marine ecosystems is provided, with broadly applicable indicators such as species distribution and population size, outlined. The framework directly addresses cumulative effects within *Article 8* (Assessment). Provided below is an overview of the framework, broken into its constituent chapters, and with emphasis placed on specific Articles of relevance to this project:

Chapter 1: General Provisions (*Articles 1-7*)

Articles 1-4 within this chapter focus on collecting data, defining the scope, and identifying the regions of study. *Articles 5-7* set out to develop regional marine strategies, garner regional cooperation, and designate regional authorities to oversee progress. *Article 5* is particularly useful, as it aims to delineate the overall strategy of the initiative, including environmental assessment, the establishment of environmental targets, implementation of the program, and the establishment of a program of measures to ensure objectives are met.

Chapter 2: Marine Strategies: Preparation (*Articles 8-12*)

This chapter deals with assessment, defining healthy environments, and establishing targets for environmental condition. Of note is *Article 8* which is aimed at assessing the relevant marine regions and performing cumulative effects assessments to identify predominant stressors. *Article 10*, in which environmental targets associated with identified indicators are established, is also of relevance. *Article 11* focuses on the establishment of monitoring programs to facilitate the ongoing assessment of the environmental status of the marine areas of study.

Chapter 3: Marine Strategies: Programmes of Measures (*Articles 13-16*)

This chapter identifies regional programs of measures to ensure environmental objectives are being met (*Article 13*), identifies scenarios in which exceptions to management objectives may be made, including time constraints (*Article 14*), establishes recommended community actions for each region (*Article 15*), and outlines the need for governing bodies to assess whether the framework meets the requirements of the Directive (*Article 16*).

Chapter 4: Updating, Reports and Public Information (*Articles 17-23*)

This chapter describes keeping strategies up to date, writing interim reports, allowing public consultation periods, the role of communities financing the marine strategies, and the need for a review of the Directive by 2023).

Chapter 5: Final Provisions (*Articles 24-28*)

Chapter 5 outlines the logistical considerations to be made by relevant governing bodies regarding the Directive and the objectives therein.

The focus of the framework on the marine environment, and at the regional and community scale is of direct relevance to CEMS initiative. However, its strength lies in its broad applicability beyond its intended scope (Roland Cormier, pers. comm.).

7.2.2 BC Cumulative Effects Framework

The province of British Columbia developed a robust cumulative effects framework to address the issue of sustainable resource management through assessment of the activities and natural processes that may result in potential consequences to economic, social, and environmental values (Government of British Columbia 2017). The framework organizes identified ecological values into three tiers (general provisions, cumulative effects assessment, and cumulative effects management), ranging in scale from coarse values (such as entire ecosystems) to fine values (like specific species of concern). An associated policy document describes the four-step process the framework operates under; (1) the development of assessment protocols for the VC (including data collection, conceptual model development, and identification of indicators and benchmarks), (2) assessment of how collected data compares to outlined benchmarks, (3) identification of management responses, and (4) reaching management decisions (Figure 7.1) (Government of British Columbia 2017).

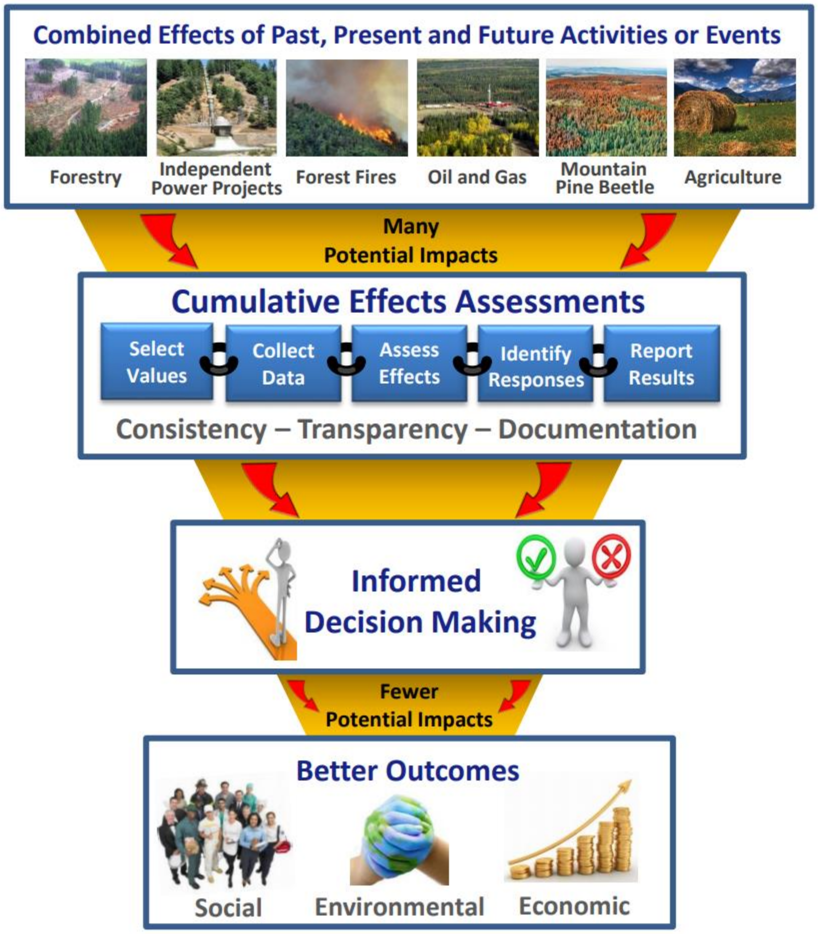

Figure 7.1. The cumulative effects framework (Government of British Columbia 2017).

Broad objectives and specific objectives are considered separately within this framework. Broad objectives are established in relation to identified benchmarks, while management triggers are used to assess specific management objectives. Management triggers guide shifts between management classes, given the impact to the VC and the cumulative changes occurring in the region (see Figure 7.2 below).

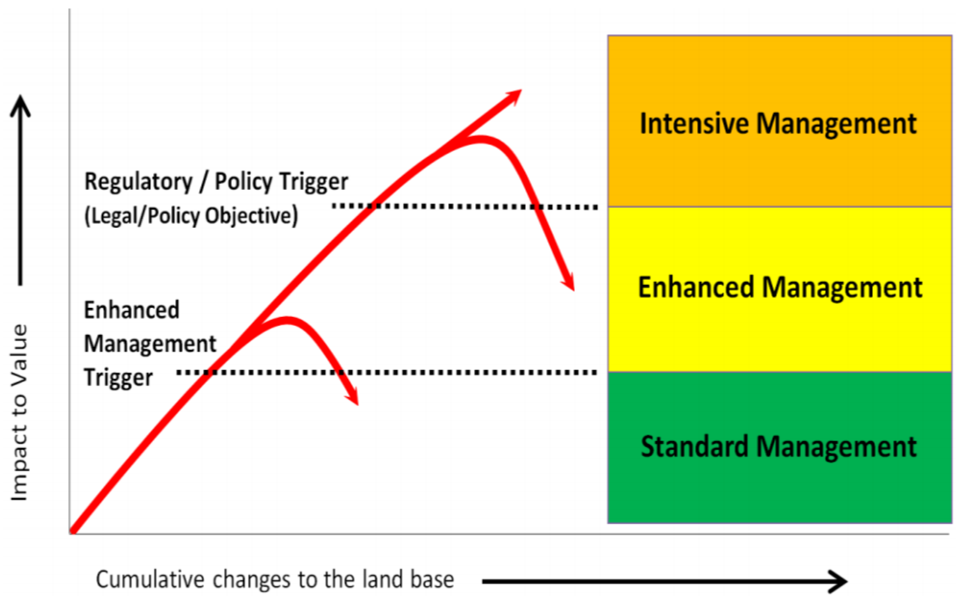

Figure 7.2. Illustration of Management Triggers as defined by the BC Cumulative Effects Framework, interim policy (Government of British Columbia 2017).

While the framework has been developed for use in BC's terrestrial environment, the underlying framework could be adapted for use in the marine environment, and for any region of interest. The Marine Plan Partnership built their cumulative effects framework to be consistent with the BC template.

7.2.3 Risk Assessment

Within a broader cumulative effects framework, the process of risk assessment, as stated by The International Organization for Standardization (ISO), includes the identification of risk sources, the analysis of their consequences, and the evaluation of relevant management options (see also Figure 7.3).

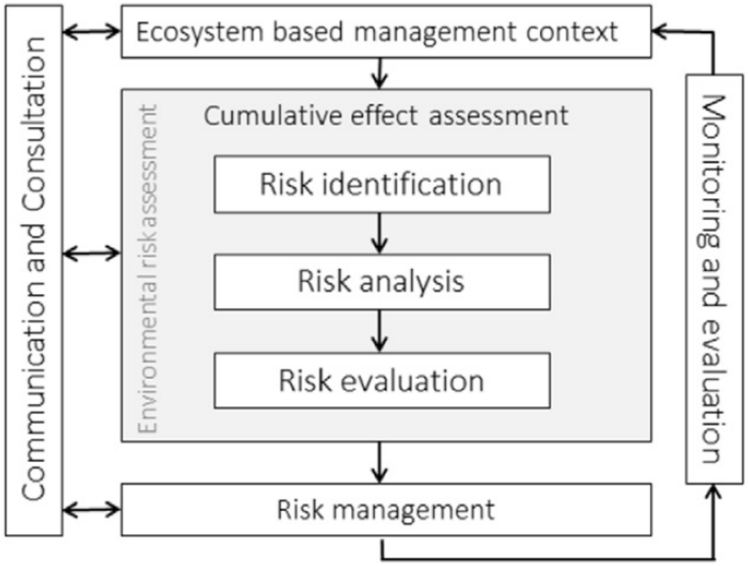

Figure 7.3. A conceptual diagram of how cumulative effects assessments can be embedded into a standard risk assessment framework. Figure taken from Stelzenmuller et al. 2018.

The "risk identification" stage involves identification of stressor sources (e.g. shipping), stressors (e.g. noise), and VCs within the area(s) of concern. This is followed by the establishment of the relationships between each of those components using a causal framework often paired with geospatial information. Finally, levels of risk for each VC are evaluated using a scoring system which assigns risk to VCs based on a set of criteria. This is usually accomplished via models that use thresholds and criteria to evaluate and map risks to VCs under different scenarios, or through the use of qualitative data and expert knowledge (Stelzenmuller et al. 2018).

The next stage is "risk analysis" wherein the level or probability of risk is determined, and the cumulative effects of those risks are established. Most risk assessments that operate within a CEA framework accomplish this through GIS mapping and modeling, such as the "bow-tie" modeling approach; The bow-tie method depicts the multiple pathways of risk of an event, and the multiple consequences of that event taking place (see Figure 7.4) (Cormier et al. 2018). Robust analyses at this risk analysis stage will further account for the effectiveness of implemented management decisions (Stelzenmuller et al. 2018).

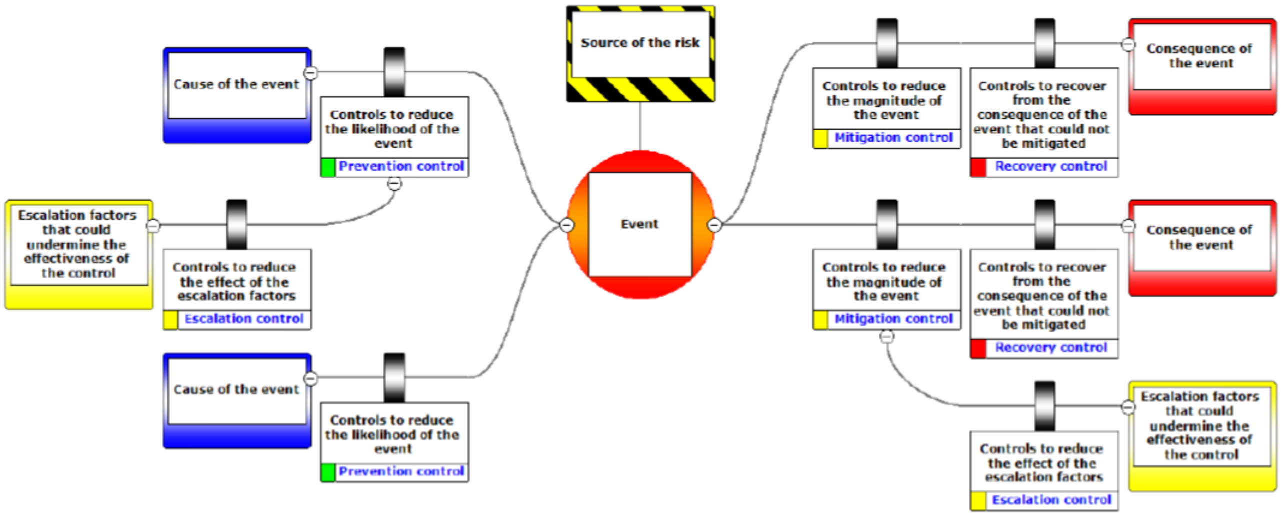

Figure 7.4. Example conceptual diagram of the "bow-tie" approach. Image taken from Cormier et al. 2018.

The final stage, "risk evaluation" compares the results of the risk analysis with existing criteria and thresholds to determine the level of risk that stakeholders are willing to tolerate. This stage also involves the re-assessment of risk tolerance after management decisions, that have altered risk levels, have been implemented.

A number of risk assessment frameworks directly address particular species, actions, or other specified VCs within the broader ecosystem (see Grech et al 2008, Gobas et al. 2010, DFO 2012, and Lawson and Lesage 2013). These approaches usually involve a combination of spatial modeling and semi-quantitative estimates of the impacts of the stressors. In contrast, several risk assessment frameworks have been applied more generally to many ecological components (see Gobas et al. 1998, Halpern et al. 2007, Stelzenmuller et al. 2012, Hobday et al. 2011, Samhouri et al. 2012, O et al. 2015, Herkul et al. 2017, Furlan 2017). O et al. (2015) notes that conducting a broad-based assessment is useful for screening out less significant VCs, stressors, and sources, and allowing subsequent semi-quantitative and quantitative analyses to be more focused.

Most risk assessment studies that occur within a cumulative effects framework tend to apply a combination of spatial analysis, analytical and modeling methods at some point in their risk assessment. For example, Furlan (2017) used a GIS mapping, multi-criteria analysis, and expert surveys to arrive at spatially-explicit, qualitatively and quantitatively-informed risk values. DFO's ecological risk assessment framework (ERAF) and the methods outlined in Stelzenmuller et al. (2010) provide similar examples.

A common issue faced by several cumulative effects analyses is the issue of uncertainty in the ecological system, particularly in the cause-effect relationships (Stelzenmuller et al. 2018). The application of risk assessment to these analyses has been shown to greatly reduce this uncertainty, by accounting for the lack of knowledge or limited data in the level of risk prescribed to a VC (Stelzenmuller et al. 2010, Hobday et al. 2011).

7.2.3.1 Examples

Attribution of risk is generally achieved via computer-based tools and models, criteria-based qualitative assessment, or a combination of the two. This section lists a number of candidate tools and methods.

The **Ecological Risk Assessment Framework (ERAF)** (DFO 2012, DFO 2014, O et al. 2015) systematically and thoroughly identifies cumulative risks to VCs. It operates within a broader Adaptive Management (AM) framework in place in Canada. It applies a tiered approach, adopted from Hobday et al. (2011), that progressively arrives at risk estimates through qualitative, semi-quantitative, and highly quantitative stages. While the ERAF was developed for biological VCs, non-biological VCs are suitable for analysis, so that risks to socio-cultural components can be assessed (O et al. 2015).

The **bow-tie approach** takes into account all of the stressor sources, stressors, and VCs, their spatio temporal distributions, and the exposure, status, and sensitivities of VCs and habitats to assess the extent to which a hazard scenario would impact those VCs and habitats, and their compounding effects (based on links established in the causal framework stage). It aims to identify preventative measures to reduce the risk of an event occurring (on the left side of the bow-tie), and the mitigation and recovery strategies that can take place if the event occurs (right side of the bow-tie) (see Figure 7.4 above) (Cormier et al. 2018). The approach can be implemented through the use of software such as **BowTieXP** (Cormier et al. 2018).

7.2.3.2 Relevance to Marine Shipping

Gimpel et al. (2013) notes that given the spatial context of marine shipping and its impacts on VCs, methods that examine risk from a geospatial prospective are needed to accurately characterize linkages between vessel activity and VCs of interest. Most of the methods and associated tools presented in Sections 4.2, 4.3, and 4.4 could potentially be applied in a marine shipping context, and a few examples have been developed to consider shipping-related risks.

The method outlined in Furlan (2017) explicitly considered marine shipping as one stressor source. Lawson and Lesage (2013) also specifically considered marine shipping in their risk assessment; they developed a cumulative risk assessment framework to determine the risk of impact to marine mammals from marine development-related noise, strikes, and invasive species. The framework employs a 'probability of impact' analysis which considers marine mammal population size, seasonal densities in the specified region, conservation status, habitat use, and sensitivity to the stressors. Gimpel et al. 2013 analyzed risk of conflicts between vessel traffic, marine protected areas, fisheries, and off-shore wind development under current and future management scenarios in the German waters of the North Sea. Goerlandt and Montewka 2015 used Bayesian Belief Network (BBN) modeling to probabilistically assign risk to different tanker collision-related oil spill scenarios in the Gulf of Finland.

While not directly addressing shipping-related risk, many analyses consider risk assessment in the marine environment, more generally: Grech et al. 2008, Stelzenmuller et al. 2010, Hobday et al. 2011, DFO 2012, Samhouri et al. 2012, Wood et al. 2012, Cormier et al. 2013, Lawson and Lesage 2013, DFO 2014, O et al. 2015, and Herkul et al. 2017.

8 Conclusions

8.1 Key insights from the evaluation of CE assessment methodologies

8.1.1 Overarching insights

- **The CEMS initiative will require a combination of assessment methods.** Section 4 summarizes a variety of methodologies which have been applied to CEA. On their own, most of these methods are insufficient to complete a full assessment; however, most of them have potential to be useful to the CEMS initiative. Our review suggests that all three categories of methodologies (spatial, analytical, and modeling) play an important role, and can be linked to one of the assessment steps identified in Figure 1.2.
    - **Spatial** methods are most useful for evaluating the *reference condition* of either activities/stressors or VCs as well as understanding how VCs are spatially exposed to activities/stressors [assessment step 1, in Figure 1.2].
    - **Analytical** methods based on empirical data are useful for interpreting spatial data to inform our understanding of key habitat requirements, evaluating risk, and *quantifying the relationships* between stressors and VCs (i.e., pathways) [assessment step 2, in Figure 1.2].
    - **Modeling** methods build on the previous two categories and are necessary for evaluating *alternative scenarios* [assessment step 3, in Figure 1.2].
- **Several crosscutting methods will also be useful to the CEMS initiative**
    - **Indigenous knowledge** is invaluable in conducting a CEA. It is important to work with communities during all steps in the process of conducting a CEA.
    - **Expert elicitation** methods will be critical to the initiative, particularly where data are limited.
    - **Decision support tools,** which make use of the outcome of the assessment step, are beyond the scope of this project but will need to be considered in later steps of the initiative.
- **Existing CEA frameworks may provide useful templates for the CEMS initiative.** In general, frameworks allow decision-makers to integrate a suite of assessment methods and tools to thoroughly evaluate the cumulative effects of stressors and link the CEA to management contexts.
    - **Risk assessment frameworks** provide a means of qualitatively and quantitatively evaluating the exposure of a valued component to a stressor, and its sensitivity. The framework can utilize spatial and analytical assessments, Indigenous knowledge, expert elicitation, causal relationships, and model outputs to assess the relative impact of various stressors on valued components.
    - Frameworks such as the **EU Marine Strategy Framework** and the **BC Cumulative Effects Framework** permit CEA's to explicitly address management concerns by clearly

defining objectives and thresholds (i.e., what is considered "good environmental status"), and allow analyses to occur at broad or fine scale resolution by introducing scale-specific objectives.

- **Examples addressing social VCs were less prevalent in the evaluation however many of the insights apply to both ecological and social VCs.** Although applications of assessment methods have largely focused on ecological VCs, the three categories are relevant for assessing cultural and socioeconomic VCs. For example, the Haida Marine Traditional Knowledge Study (Table 5.4) involved spatially identifying locations of culturally valued components (e.g., traditional harvest sites). Indigenous communities on the Coast of British Columbia use analytical methods as part of their Regional Monitoring System (Table 5.4) to document changes to cultural sites. In addition, there are decision support tool models, such as MIMES, the Mauri Model, AIRES and InVEST (Section 6.3.2), that consider social values related to ecosystem services and provide outputs in economic terms. Cultural and socioeconomic effects are also often associated with ecological VCs. For example, culturally important traditional harvesting can be affected by changes in the population of the species being harvested. In these cases, results from assessment of ecological VCs may be inputs into assessments of cultural or economic VCs.
- **Marine shipping activities are relevant nationally, whereas VCs and impact pathways may differ by region.** It may be possible to select a single modeling tool for stressors of concern (e.g., oil or noise) and replicate these across multiple regions. This would improve efficiency, build capacity, and enable results to be more easily compared across regions. However, it is likely that different methods will be required to assess VCs and impact pathways in each region depending on the nature of the VCs, the intensity of stressors, the local data availability and capacity.

8.1.2 Spatial insights

- Spatial methods are **one of the most common approaches** observed in our evaluation and are expected to be a key method for the CEMS initiative.
- Spatial assessments may be particularly **useful during early iterations** to refine scope (e.g., identify geographical hotspots) and to identify information gaps.
- Although there are many ways to collect spatial data, and many ways resulting spatial information can be used, at the foundation of spatial approaches is **a single conceptually simple method**: Mapping locations and characteristics of activities/stressors and VCs.
- Inferences should not be made at **spatial scales** that are finer than the datasets allow.
- Data related to activities/stressors are often easier to gather/collect than data related to VCs, which can result in **greater uncertainties for inferences related to VCs**.
- In light of large data requirements, assessments often require **assumptions where little or no information is available**. When spatial assessment involves complementary analytical or modeling approaches, assumptions related to those methods also apply.

8.1.3 Analytical insights

- Assessment of the functional relationships between stressors and VCs using **empirical evidence is a critical component of cumulative effects assessment**. This step is essential to: validate the nature of hypothesized pathways, refine the scope by identifying the most important pathways, improve the accuracy of models used to evaluate alternative scenarios, inform development of meaningful thresholds, prioritize mitigation activities, and quantify uncertainty.

- The analytical methods described in this report are highly dependent on **data availability and data quality**.
- **Risk assessment** is anticipated to be a useful scoping method for the CEMS initiative to help refine the priorities in each region.
- **Weight of evidence** is anticipated to be a useful method for the CEMS initiative to evaluate the relative importance of different pathways in each region. This is particularly expected to be the case in early iterations of the initiative assuming that the data are limited and varied in nature as is typical for any new initiative.
- More **complex and data rich methods** should be invested in for priority pathways where uncertainties and potential benefits are high. This includes **supporting monitoring** to address critical data gaps.
- **R statistical software** is freely available, well documented, accepted in academic setting, and has readily available tools to support most of the analytical methods discussed.

8.1.4 Modeling insights

- A key distinction of modeling methods is that they can be used to test **alternative scenarios** or management options, the third component of the assessment step (Figure 1.2).
- Unlike analytical methods, **models can be developed in absence of empirical data**. This usage can test alternatives using expert knowledge and current hypotheses about the system. Sensitivity analysis can help to bound the problem and identify the most sensitive parts of the system. Pathways with the greatest influence or uncertainty in terms of their impact on the VC can then be prioritized in terms of data collection.
- **Stressor models**, such as underwater noise or oil spill models, are well-established methods and extremely useful in predicting the intensity of the stressor of concern. Where possible, existing stressor models should be leveraged to support the CEMS initiative.
- **Single species models** that evaluate population level effects resulting from changes to various life-cycle parameters are expected to be very useful to the CEMS initiative and should be developed for at least a small set of top priority VCs in each region. If the VC is the whole ecosystem, **ecosystem models** may be appropriate.
- **Spatially explicit simulation models which relate stressors to VCs and enable evaluation of alternative scenarios are the ultimate CEA method**. However, the level of data, effort, and expertise required for their implementation, makes spatially explicit models best suited at regional scales for a sub-set of highest priority VCs and pathways of greatest impact and potential for improvement.
- **Integrated modeling**, involves linking one or more sub-models together (e.g., linking physical and biological models) and is the preferred approach for more complex models such as spatially explicit simulation models.

8.2 Selection of Assessment Methods

Selecting specific methods and associated tools within each category depends on the: relevance (e.g., priority VCs), rigour (e.g., data availability), and feasibility (e.g., capacity/funding) of different options within the category (Table 5.2). Section 5.2 provides detailed examples of how each category of method could be applied to the CEMS initiative (Table 5.3), as well as a list of relevant case studies (Table 5.4) that demonstrate how multiple methods can be used in combination to achieve a particular objective. We propose a series of guiding questions for consideration when selecting assessment method(s). These should be used along with the tables in Section 5. The questions are not meant to be prescriptive in their application as there is not one 'correct' method or combination of methods for each possible scenario. Some questions may depend on the regional context. Preliminary information for each pilot region is provided in Appendix A: Regional Context.

In general, early iterations of the assessment step tend to use simpler less data intensive methods and are more focused on refining scope and identifying knowledge gaps. Whereas later iterations involve more complex methods applied to a narrower scope (e.g., the most important pathways).

8.2.1.1 Relevance

What stage of the assessment process are you in?

Different methods apply to different stages of the assessment process (Figure 1.2). In general, spatial methods are used to assess current or reference condition, analytical methods are used to quantify impact pathways, and modeling methods are used to evaluate alternative scenarios. Initial iterations will tend to use simpler methods and later iterations will increase in complexity as the scope is refined and new information is acquired.

Have the most important pathways been identified?

If starting from scratch, risk assessment (informed by spatial analyses of stressors and VCs) should be considered to help identify the most important pathways. Indigenous knowledge and expert elicitation may be used to support a risk assessment. If sufficient data are available this should be followed up with analytical assessments to quantitatively assess the relative importance of pathways identified in the risk assessment for each priority VC. If the most important pathways have already been identified, then selected methods can focus on evaluation of those pathways using both analytical and modeling methods.

What management decisions are informed by the CEA?

Identifying the management objectives and levers that scope the CEA process is an important consideration for prioritizing VCs and pathways as well for determining what alternative scenarios should be evaluated in step 3 of the assessment step. Although beyond the scope of this report, this will be important because it can be more useful to further analyze and develop predictive models for impact pathways with clear mitigation opportunities.

8.2.1.2 Rigour

What level of information is available for priority VCs and stressors?

How much information is available over space and time? What are the strengths and limitations of the available information (e.g., different spatial/temporal resolution)? Information can be in various forms including Indigenous knowledge and scientific data. Knowledge and information availability vary across the different regions and communities. Methods vary widely in their data requirements and flexibility (see discussions on 'Data requirements' in Sections 4.2.2, 4.3.2 and 4.4.2).

Ideally, there is empirical information about the VCs and the stressors so more sophisticated quantitative spatial, analytical, and modeling methods can be used. In absence of quantitative data spatial methods leveraging qualitative information is a good place to start. Risk assessment and weight of evidence methods are well suited to using qualitative information.

Is it possible to supplement the available information with expert knowledge?

Section 6.2 provides insights on how to use and integrate expert knowledge in CEAs. These methods are particularly valuable early in the process in absence of empirical information. For example, models may be used to articulate the current understanding of the system using expert knowledge and complete preliminary sensitivity analyses.

Is it possible to collect new data?

Monitoring is one of the costlier elements of CEAs however it is a valuable tool for reducing uncertainties. It is important to identify if there are opportunities to supplement existing information (e.g., collaborate with others to collect data). If not, methods will be limited by current data availability.

8.2.1.3 Feasibility

What is the general knowledge and skill level of the team conducting the CEA?

The skills of the team conducting the CEA are critical for the selection of a method as when all else is equal it is more efficient to use methods that the team already has the capacity to conduct. Likewise, if input from experts outside the team is needed, it is best to identify these requirements early in the CEA process. Some methods require the use of specific modeling software or an expert level of knowledge about a VC or area. The 'feasibility' column in Table 5.1 and, in more detail, the discussion of the 'complexity' and 'accessibility' evaluation criteria for the different methods in Sections 4.2.2, 4.3.2 and 4.4.2 provide useful context for answering this question.

What are the resources (e.g., time, money) available for conducting the CEA?

Costs vary across methods. Collecting new data is usually the most expensive cost for all method. Additionally, conducting expert elicitation exercises, engaging Indigenous knowledge holders or purchasing specific software or analytical tools will add to the costs. More complex methods with higher costs may be required as priorities are explored in deeper detail. A brief discussion on costs for the different methods can be found under the 'cost' criterion in Sections 4.2.2, 4.3.2 and 4.4.2.

Are there existing applications of methods or tools for priority VCs, stressors of concern, or impact pathways?

In cases where there are existing applications of methods or associated tools these should be leveraged rather than starting from scratch. Potential examples of existing applications of methods or tools include:

- there are a number of existing models to quantify stressors associated with marine shipping such as noise, oil, and emissions;
- there is a recent paper documenting the summer range of Southern Resident Killer Whales;
- a series of habitat suitability models are under development by DFO through related OPP initiatives

Who are the key stakeholders and what is the best way to communicate the results?

It is important to foresee how the results of the CEA will be communicated, depending on the needs and preferences of the stakeholders involved. Spatially-explicit methods that generate maps are usually easier to interpret than graphs or numerical outputs of quantitative analyses. The discussion under 'Interpretability and communicability' for the various methods in Sections 4.2.2, 4.3.2 and 4.4.2 provides more information for this consideration.

8.3 Technical Workshop Insights

8.3.1 Workshop Summary

As part of the CEMS initiative, Transport Canada held a two-day technical workshop (20-21 February 2019) in Ottawa with the following objectives:

- Share the results of this report;
- Gather input from participants on the assessment methods and tools and on recommendations for regional work and path forward.
- Provide an opportunity to build and strengthen relationships and learning between federal governments and Indigenous Nations, territorial and provincial government departments, environmental non-government organizations, academia and marine industry stakeholders.

Representatives from all six pilot sites were present at the workshop, including Indigenous representatives, subject matter experts, academic representatives, personnel from provincial government, environmental non-government organizations, marine industry, and a number of federal government representatives from Transport Canada, Fisheries and Oceans Canada, and the Canadian Environmental Assessment Agency (CEAA), and Crown-Indigenous Relations and Northern Affairs Canada (CIRNAC).

The workshop report (Stratos 2019) summarizes the main outputs and ideas discussed during the two-day event. This section provides additional insights and information generated through the workshop discussions that complement this report.

8.3.2 Workshop Insights

Overarching Feedback

- Transport Canada should **prioritize creation of a first draft national framework** for CEA of marine shipping using a small group of experts. This draft could then be refined using a group similar to those at the Feb workshop.
- There is a need to **acknowledge and incorporate different worldviews and types of knowledge in all aspects of the initiative**. Indigenous communities need to be involved at all stages of the CEA. It is important Indigenous knowledge is not simply forced into western science methods. Having communities and knowledge holders as part of the process at all stages ensures that relevant knowledge is identified, assessment methods are informed by Indigenous worldviews, and Indigenous knowledge is used appropriately.

- There were concerns raised about the focus of this **initiative being limited to a single sector**.
- Practitioners should **consider Ecosystems as VCs as well as or instead of single species VCs.**
- Activities do not necessarily imply stresses and so we need to **use caution when using measures of the intensity of the activity rather than the stressor** (E.g., vessel traffic instead of noise).
- **Uncertainty in CEA is a critical concept**. Decisions get made with or without data and with or without information about uncertainty. Decisions can be improved if uncertainty is clearly addressed. There are many sources of uncertainty including: spatial and temporal variability, sampling error, measurement error, modeling assumptions etc. These errors can propagate through the methods described in this report and if not explicitly accounted for can result in poor decisions. Sections 4.2.2.2, 4.3.2.2 and 4.4.2.2 discuss uncertainty with respect to each of the methods.
- A suggestion from the workshop was that it would be helpful for the National Framework to **provide some guidance on setting baselines and thresholds** and that this should be done through some form of **co-development**.
    - **How to define baselines?** There was extensive discussion on this topic at the workshop. Typical options include comparing to current condition or comparing to some historical condition. Evaluating current condition is generally considered a useful exercise to help determine what changes from current are acceptable. This does NOT necessarily imply that current condition should be used as the baseline or target. This discussion is a common road block to CEA (Section 1.3.1). Ultimately, what is considered acceptable is a social decision.
    - **How much is too much?** While this question is informed by the assessment methods, setting thresholds depends on what is considered socially acceptable (Section 1.3.4). This question leads to questions about what management levers are available to Transport Canada (e.g., could you run more ships through the Strait of Georgia if they were all quieter?). These issues are outside the scope of this report but must be addressed in the framework.

Methods

- A key outcome of the workshop was that participants agreed with the report conclusion that **a combination of all three categories of methods will be necessary** and that selection of said methods will depend on context.
- There was **consensus on the value of spatial methods** particularly in early stages of the assessment. Maps were considered useful for evaluating exposure but their limitations were acknowledged: limited ability to illustrate effects which are more complex than a simple overlay of VCs and stressors; varied scales of information (e.g., points, polygons, grids of different sizes); lack a temporal component; and reliance on data availability.
- **Modeling methods were acknowledged to be a powerful tool when used appropriately** but there was also concern that models are only as good as the data and assumptions going into them and so that there needs to be open and transparent development and communication of models to avoid competing models or distrust from stakeholders. Other comments included:

- The need for clearly communicated information on uncertainty of both input parameters and assumptions.
- The need for models to be co-developed with impacted communities to ensure sufficiency and relevance of models, for example 'modeling with a participatory approach' Diana Lewis (Indigenous Studies, University of Dalhousie).
- There were questions about how to incorporate socio-cultural aspects in models.

National Framework

Development of a National Framework is outside the scope of this report but was the subject of extensive discussions at the workshop. Development of such a framework to provide consistent guidance at a National level was a clear recommendation from the workshop. The workshop report (Stratos 2019) summarizes these findings in detail. In particular, they provide a useful list of "Considerations" and they provide a "Summary of common VCs and Stressors across Canada". This section provides a few additional thoughts from workshop participants:

- While there are regional differences, there was a **long list of common stressors and VCs identified across Canada** which provides a potential focus for the National Framework.
- There was consensus that **the framework should involve an iterative approach**. Adaptive management was discussed as a potential approach and received general support with the caveat that it was actually implemented, not just used to 'check a box'.
- Some participants advocated for a **tiered approach to ensure at least a minimum common level of information** is collected across all components. With the potential to dig deeper where necessary.
- The framework should **consider alternative governance strategies** to facilitate the collaborative development of the initiative. Section 8.3.3 provides some examples for consideration.

8.3.3 Additional information

During and after the workshop, participants shared additional information and suggested relevant case studies based on their experience. This section highlights these additional examples that complement those presented in Section 5.2.2.

Marine spatial planning

Planning in the marine environment involves making management decisions (e.g., zoning) for marine areas with multiple uses and users in order to achieve certain sustainability or ecological status goals, such as the case of the European Marine Strategy Framework Directive (Elliott et al. 2018). Cumulative impacts are a core element of marine spatial planning although their consideration is multi-sectoral and, therefore, broader in scope than the assessment of cumulative effects associated exclusively to marine shipping.

Methods and approaches used for marine planning can be relevant for cumulative effects assessment in the context of the CEMS initiative. These additional case studies document the use of expert judgement and spatial analysis to support the assessment of multiple stressors in a planning context.

- Elliott M., S.J. Boyes, S. Barnard, Á Borja. 2018. Using best expert judgement to harmonise marine environmental status assessment and maritime spatial planning. *Mar Pollut Bull*. 133:367-377. https://doi: 10.1016/j.marpolbul.2018.05.029

Elliott et al. 2018 explored the use of best expert judgement to determine the environmental footprint of multiple activities on marine ecosystems and their cumulative effect on regional ecological status (Elliott et al. 2018).

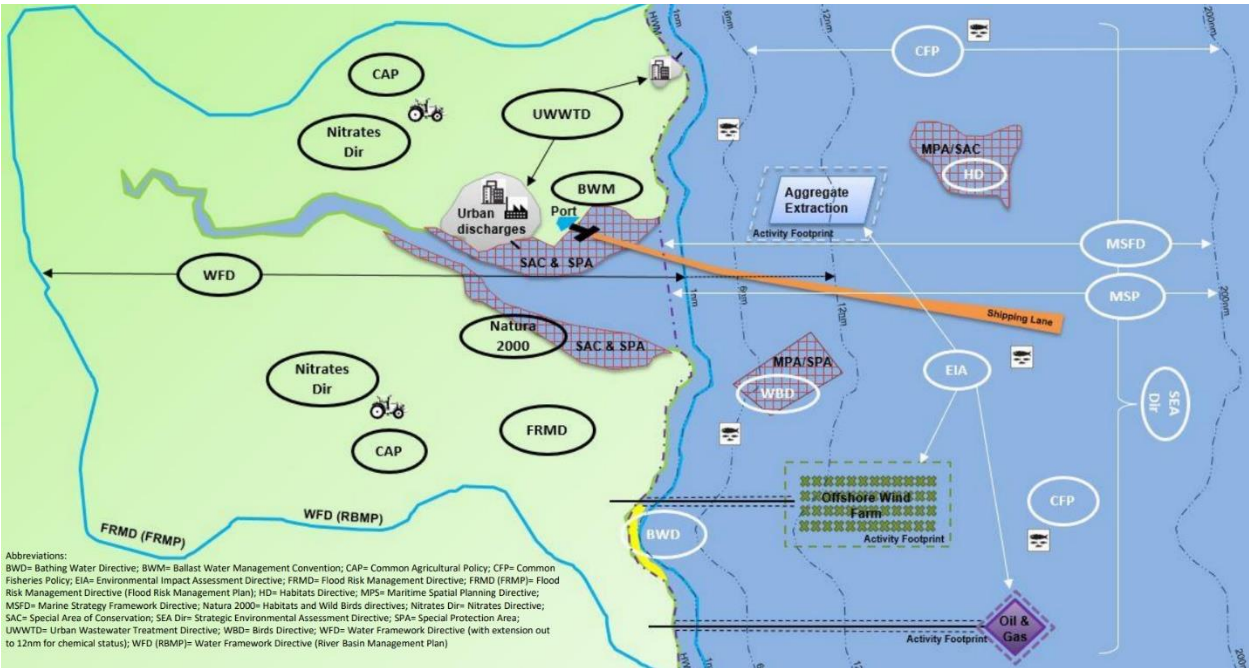

Figure 8.1. Conceptual representation of the multiple pressures, land and marine-based, affecting the coastal and marine ecosystems under the jurisdiction of the European Marine Strategy Framework Directive (Source: Elliott et al. 2018)

- Boyes S.J., M. Elliott, S.M. Thomson, S. Atkins, P. Gilliland. 2007. A proposed multiple-use zoning scheme for the Irish Sea.: An interpretation of current legislation through the use of GIS-based zoning approaches and effectiveness for the protection of nature conservation interests. *Marine Policy* 31 (3): 287-298 https://doi.org/10.1016/j.marpol.2006.08.005

A GIS-based scenario approach was used in this case study to test a zoning scheme proposed for the Irish Sea. This approach allows to visually and qualitative the potential impacts of various zoning scenarios permitting different combinations of legally permitted activities.

Governance

Our review has focused on methods for assessing cumulative effects, but any assessment is embedded in a governance and management framework. A discussion on best governance arrangements at the regional and national levels is out of scope of this report but the following case studies provide relevant insights to inform the development of governance mechanisms.

- Bodin, Ö. Collaborative environmental governance: Achieving collective action in social-ecological systems. *Science* 357

This paper reviews case studies on environmental governance and draws conclusions on how to achieve effective collaborative governance.

- Boyes S.J. and M. Elliott. 2015. Marine legislation--the ultimate 'horrendogram': international law, European directives & national implementation. Mar Pollut Bull. 2014 Sep 15;86(1-2):39-47. doi: 10.1016/j.marpolbul.2014.06.055

This study discusses the problem of compartmentalisation as created by superimposed legislation that affects the management of marine areas. Taking the example of EU marine legislation, the authors analyze the complexity of the legal landscape and its consequences for marine management.

- Weber, M., N. Krogman, and T. Antoniuk. 2012. Cumulative Effects Assessment: Linking Social, Ecological, and Governance Dimensions. *Ecology and Society* 17(2): 22

This study proposes a multidisciplinary framework for the use of cumulative effects assessment in land use planning. Specifically, the authors explore the application of a scenario analysis approach in data-limited regions and how to incorporate social dimensions and Indigenous knowledge.

Appendix C provides additional insights into governance, specifically on examples of Government to Government (i.e., G2G) arrangements.

Management context

The assessment of cumulative effects happens within a management framework and is influenced by the specific management levers available to mitigate impacts. The selection of CE assessment methods and tools depends on the management goals for marine ecosystems in a given region. Our review did not consider in detail the management context. The following case studies provide useful insights to take into consideration for the development of the Framework.

- Clarke Murray C., J. Wong, G.G. Singh, M. Mach, J. Lerner, B. Ranieri, G. Peterson St-Laurent, A. Guimaraes, K.M.A. Chan. 2017. The Insignificance of Thresholds in Environmental Impact Assessment: An Illustrative Case Study in Canada. Environmental Management 61: 1062–1071

Determining the significance of impacts is a key outcome of environmental impact assessments. This paper reviews the approaches taken to assess significance in a number of impact assessments from British Columbia. The authors conclude there is a need for clear and defensible significance determinations, including collaborative approaches.

- Elliott M. 2013. The 10-tenets for integrated, successful and sustainable marine management. *Mar Pollut Bull*. 74(1):1-5. doi: 10.1016/j.marpolbul.2013.08.001

The multiplicity of stressors, users, agencies, etc., as well as the large spatial scales and moving baselines for marine ecosystems make marine management extremely complex. Drawing from the business literature, Elliott (2013) proposes in this paper ten tenets for the management of any marine environmental stressor or combination of stressors.

CEA frameworks

Assessment of cumulative effects happens within a framework that also includes scoping and management considerations. These case studies complement the examples of organization methods discussed in Section 7.

- Cormier R. M. Elliott and J. Rice. 2019. Putting on a bow-tie to sort out who does what and why in the complex arena of marine policy and management. *Science of The Total Environment* 648: 293-305

This paper discusses the application of bow-tie analysis as part of a DAPSI(W)R(M) conceptual framework to study endogenous and exogenous pressures on marine ecosystems. The authors conclude that this approach bridges systems analysis and ecosystem complexity and provides a rigorous, transparent and defendable system of decision-making for the marine context.

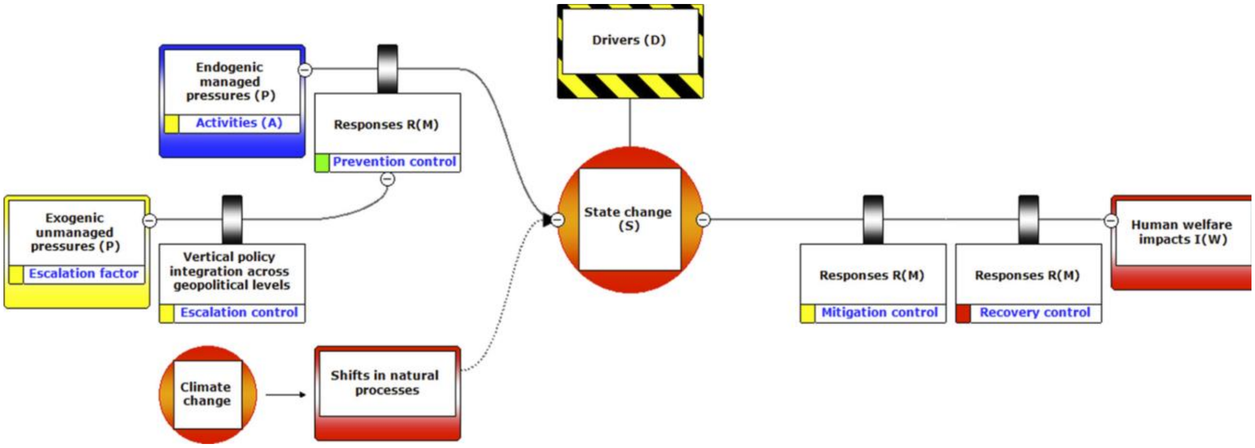

Figure 8.2. Representation of a bow-tie analysis framework to study the influence of endogenic managed and exogenic unmanaged pressures (Cormier et al. 2019)

- DFO. 2012. Assessment of the Laurentian Channel Area of Interest: A Risk Characterization

This report describes the assessment process undertaken for the Laurentian Channel Area of Interest (AOI) as part of the potential designation as a Marine Protected Area (MPA) under the Oceans Act. The assessment involves the systematic analysis of each conservation objective and the quantification of stressors from human activities, including the identification of activities that are incompatible with the planned MPA.

- Clear Seas Centre for Responsible Marine Shipping (Clear Seas) is an independent not-for-profit research centre that supports safe and sustainable marine shipping in Canada. This organization has commissioned several studies relevant for cumulative effects assessment and management. One of these studies is the Vessel Drift and Response Analysis for Canada's Pacific Coast which used a scenario and risk-based approach, Nuka Research & Planning Group, LLC (Nuka Research) to analyze how the location and availability of Emergency Tow Vessels (ETVs) or rescue tugs might influence the potential for a disabled vessel to drift aground along the west coast of Canada.

- Aleutian Islands Risk Assessment: This multi-phase risk assessment of marine transportation in the Bering Sea and the Aleutian Archipelago was conducted from 2010 to 2015 to identify measures to reduce the risk of oil spills from large vessels operating in the region.

- The Department of Ecology of the State of Washington (United States) has conducted a series of oil spill prevention risk assessments, such as the Grays Harbor Vessel Traffic Risk Assessment. The risk identification process follows a workshop-based participatory approach.

Use of remote imagery for the characterization of VCs and stressors

Satellite images can support and complement the information sources used for the characterization of valued components and stressors. Especially relevant for remote locations or in situations where there are significant gaps in baseline information. The use of commercially available satellite images and image analysis can be combined with Indigenous knowledge and other sources of empirical data to obtain a more comprehensive characterization of the natural features or stressors affecting a region. By using archived data it could be also possible to expand the baseline into the past, for instance to analyze changes in the coastline.

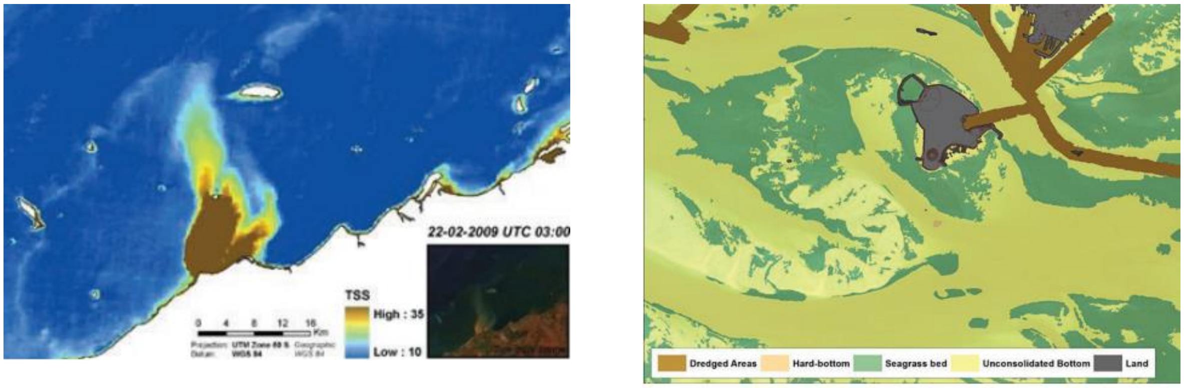

Figure 8.3. Examples of use of satellite images for the study of a sediment plume originating from a river after a heavy rainfall (left) and the characterization of marine habitats (right). Source: DHI GRAS

8.4 Path Forward

In this section we provide a suggested path forward based on the combined findings of the evaluation and the February 20-21, 2019 workshop.

8.4.1 ESSA Recommendations

Develop the CEMS Framework

We agree with the workshop recommendation to formally develop the CEMS Framework in the near future. As noted in the outset of this report, it will be difficult to move forward with the assessment step without a clear understanding of the broader context. We also agree that the most efficient approach is likely to have a small group of experts draft a broad framework and then to collaboratively refine this draft with the regions. Completion of a 'straw dog' is expected to be a relatively quick exercise. There is substantial information summarized in this report to support this effort:

- ESSA's draft framework presented in Figure 1.2;
- Section 7 which provides a brief overview of frameworks applied elsewhere;
- The workshop report (Stratos 2019) which summarizes participant thoughts around a National Framework;
- A series of additional references provided by workshop participants (Section 8.3.3);
- And the draft checklist provided by Mike Elliott and Roland Cormier (Appendix C).

Complete first iteration of the scoping phase in collaboration with the regions

Transport Canada is moving into Phase 2 of the CEMS initiative (Figure 1.1) which involves working with the pilot regions to refine the scope of the assessment. This step is necessary to inform the selection of methodologies in each region and to identify opportunities where Transport Canada can make the most beneficial contributions (e.g., investing in a methodology or tool to assess a common pathway across regions). Key outcomes of this scoping phase include:

- Setting clear objectives
- Defining the spatial and temporal boundaries
- Scoping down to a smaller set of priority VCs and stressors of most concern (reduce from the 100s of candidate VCs to 10s of priority VCs)
- Develop pathways of effects conceptual models for the priority VCs (Section 4.4.1.4)
- Identify and assemble the best available information

NOTE: It is important for all involved to recognize that this is an iterative process. Choices made at this stage can be revisited. Trying for perfection in early iterations can severely impede progress. It is our recommendation to focus on the areas of agreement and then proceed through the next phases using the best available information before circling back and addressing information gaps.

Identify most promising management levers

Phase 4 of the CEMS initiative includes identification of potential actions to mitigate the potential effects of marine shipping. We recommend that a preliminary review of potential management levers occurs earlier in the process. The intent of an earlier review would be to identify how different activities could be managed or mitigated to reduce the stressor to VC effect. Potential management levers will differ in their effectiveness and feasibility (e.g., cost and legislative authority). The most promising management levers can then be formally explored using modeling methods to evaluate alternative scenarios. Given that such modeling methods are relatively complex and may be too costly to implement for all pathways, it will be important to focus on the most promising management levers.

Some management levers will be Nationally relevant (e.g., through National or International legislation) others will be regionally specific and may differ depending on the governance structure of the region.

Key questions to consider when evaluating management levers:

- How effective would the management lever be in reducing the impact?
- How feasible is it to ‘turn the dial’ on the management lever?

There is Canadian legislation or International agreements already in place for a number of activities and associated stressors (e.g., oil spills, ballast water, biofouling, discharge, air emissions, grounding/wrecking, and anchoring). Our preliminary findings suggest that the management lever with the greatest untapped potential is associated with vessel movement (e.g., where and when vessels of different types travel, and how many are allowed over what period).

Identify thresholds

The CEMS initiative does not explicitly address when and how they will define thresholds for acceptable levels of impact to VCs. This is a very complex task which can be informed by the assessment step which will help to quantify the functional relationships between stressors and VCs and which will ideally enable evaluation of alternative scenarios. However, determining what is the preferred scenario and what level of impact is acceptable is a social decision (Section 1.3.4). Setting thresholds is also expected to be an iterative process as illustrated in Figure 1.2. Our recommendation would be to begin this discussion during the scoping phase by asking the regions whether or not the current level of impact is considered acceptable. From there thresholds can be revisited with regions as the assessment step proceeds and a better understanding of the exposure, functional impact relationships, and alternative scenarios are achieved. It may be helpful for the CEMS framework to include some general guidance about how to develop and incorporate thresholds or management triggers into the overall initiative. The British Columbia Cumulative Effects Framework and the European Union Marine Strategy Directive may provide useful templates (Section 7).

Address key information gaps

The initial iteration of the CEMS initiative will proceed using the best available information. However, it is likely that a variety of information gaps will be identified for stressors, VCs, and pathways (e.g., outright gaps in space/time, information that is not readily available, poor quality information). Uncertainties may be reduced by addressing key information gaps in later iterations. Collecting new data is generally quite costly and efforts should be focused on those gaps which are most critical to informing management decisions. In some cases, it may be possible to obtain new information without on the ground field monitoring. Other information sources include Indigenous knowledge as described in Section 6.1 and privately held datasets (e.g. industry or research organizations). In addition, there may be opportunities to further mine available data using emerging remote sense approaches (Section 8.3.3).

How to proceed with the Assessment step?

In order to determine which combination of methods and associated tools are most appropriate nationally as well as within each region, it is necessary to complete a first iteration of the scoping phase as described above. In this section we propose a possible approach for implementation of the Assessment phase of the CEMS initiative, assuming the initial iteration of the scoping phase is complete. However, these steps should not be taken as prescriptive and are instead provided as a starting point for discussion with the regions to help the CEMS move forward. We assume that the CEMS framework will be iterative and we expect early iterations of the assessment step to use simpler less data intensive methods focused on refining scope and identifying knowledge gaps. Whereas we expect later iterations involve more complex methods applied to a narrower scope (e.g., the most important pathways). Section 8.2 provides guidance on how to use the content of this report to help determine the most appropriate approach for each region in each of the tasks outlined below.

Figure 8.4 illustrates a possible path forward moving from broad to narrow scope as the complexity increases. The first column refers to the Assessment Steps (Figure 1.2). The second column describes the proposed Tasks for implementation of the Assessment phase of the CEMS initiative. The third column refers to the appropriate methods section in the report. Indigenous knowledge will be an important source of information and will inform the detailed approach taken in each of the Tasks. Expert elicitation may be used to supplement the methods in absence of empirical information. Tasks 1 & 2 involve a coarse assessment of **where the stressors are occurring** (using Spatial Methods) and **where VCs are found** using a combination of Spatial Methods and if possible Analytical Methods (Home range estimation and Habitat suitability models). The intent of Task 3 is first to identify **where potential impacts may occur** (i.e., where VCs are exposed to stressors) and, if possible, to identify the **key drivers** of the system (i.e., the relative importance of different stressors to different VCs using Analytical Methods). We anticipate that in the early iterations risk assessment and weight of evidence approaches which can readily incorporate a range of information types will be more feasible, but as quantitative data are collected some of the more data intensive Analytical Methods (e.g., Principle Components Analysis or Regression) may be useful. At this point we believe it will be necessary to **further reduce the scope** to a smaller set of 2-3 priority pathways for each region. Tasks 4 & 5 would then focus on this small set of high priority pathways. Step 4 involves using the best available empirical information to **quantify the functional relationships** between the stressor and VC using Analytical Methods. In early iterations, this step may be cursory at best. However, in later iterations as new data are collected to address key gaps, this step will be important to help reduce uncertainty in model parameter inputs. Task 5 involves **developing a modeling framework to evaluate alternative management scenarios** (e.g., how would the impacts to VCs change as we dial different management levers up or down). The preferred approach here would be to develop a spatially explicit simulation model which integrates several smaller modules as necessary to link changes in the activity (via management levers) to changes in how the stressor propagates through time and space, to changes in key behavioural or life history components of the VC of interest, which ultimately can be translated into a population level or ecosystem level response through a population model or ecosystem model. This preferred approach may require a significant investment of time and therefore should be applied in priority order to those pathways with the greatest risk and greatest opportunity for management intervention. **Explicitly describe the uncertainty** at all stages including assumptions, data inputs, model parameterization, and outputs.

Transport Canada should consider supporting Task 5 (Developing a modeling framework) for one or more pathways which are identified as priorities across all regions. This could be used by all regions, with appropriate adjustments to regionally specific parameters (e.g., local habitat availability). This could also be used as a template for regions to develop additional pathways of interest. Alternatively Transport Canada could focus on one or two modeling components which are broadly relevant. For example: it is likely that several activity-stressor linkages will be common priorities (e.g., activity-noise; or activity-oil). The population level response modules will likely need to be regionally specific even if the species are similar.

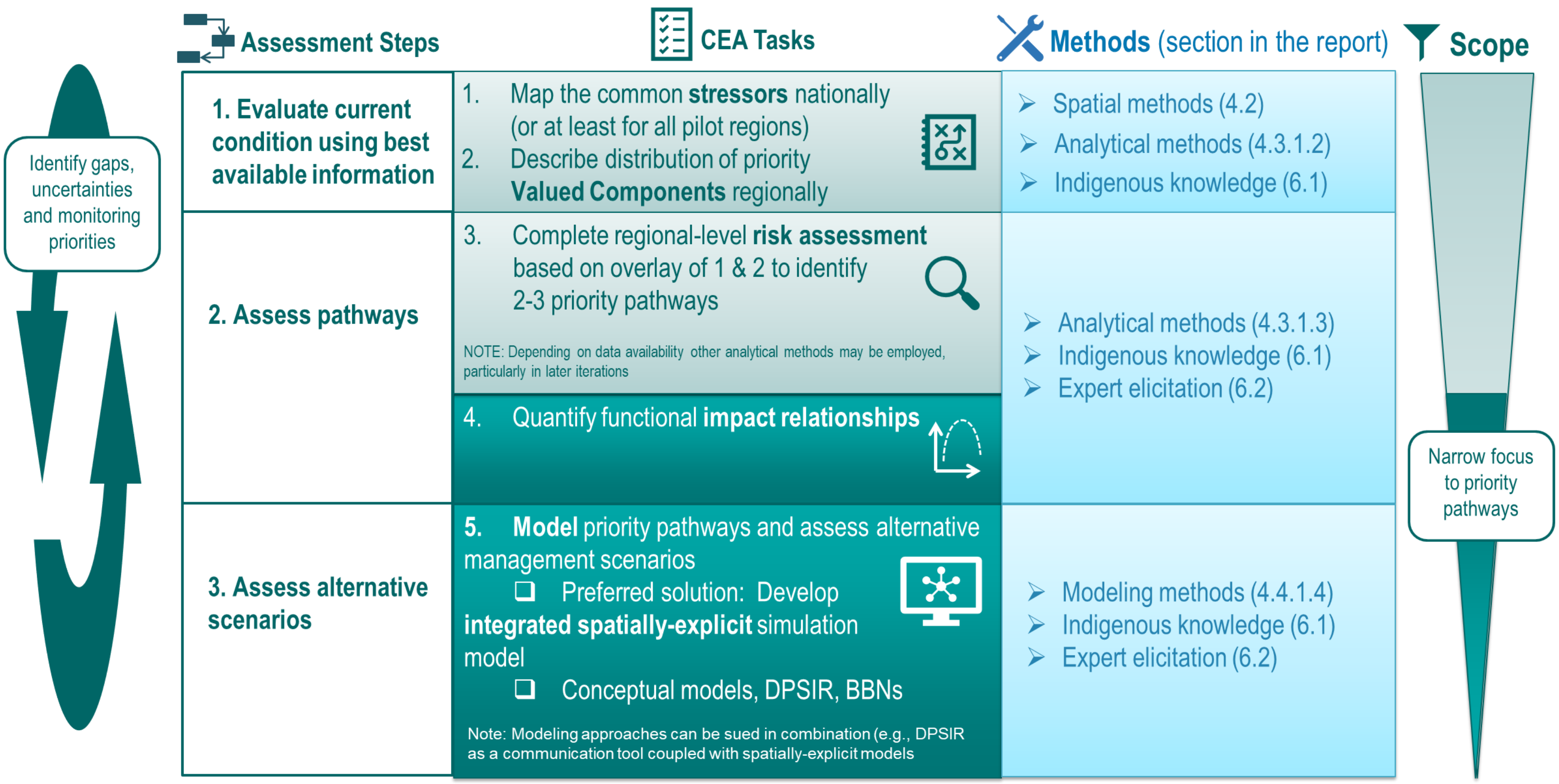

Figure 8.4. Possible path forward for the assessment phase of the CEMS initiative.

8.4.2 Guiding Principles

Table 8.1. Guiding principles for implementation of the assessment step of the CEMS initiative. describes a preliminary set of guiding principles which emerged from the evaluation, including the literature review, interviews with experts, and discussions during the Feb 20-21, 2019 workshop. These are not meant to be an exhaustive list but represent some of the important principles which were identified during this project. Additional principles may be added as they are identified.

Table 8.1. Guiding principles for implementation of the assessment step of the CEMS initiative.

Principle	Description
Identify the management objectives early in the process	Identifying management decisions up front will help to characterize alternative **scenarios** of interest. Identifying mitigation opportunities which are within control of the CEMS initiative will also help to focus assessment efforts.
Focus on the essential	It is not possible to assess everything. Scoping to a manageable set of **priority VCs** (e.g., less than 10), **stressors of concern**, and most important pathways is critical to successful implementation of the assessment step. The CEMS initiative is currently in the process of collaboratively refining the scope in each region. The process for prioritization and resulting decisions should be documented. Scope refinement is expected to continue iteratively as the assessment progresses. In general, early iterations of the assessment step are likely to use simpler less data intensive methods more focused on refining scope and identifying knowledge gaps. Whereas later iterations may involve more complex methods applied to a narrower scope (e.g., the most important pathways).
Build on existing work	Where possible leverage existing work rather than starting from scratch. There are a number of related initiatives which could be employed to support different aspects of the CEMS initiative. This can include everything from: CEA frameworks, existing modeling tools, analyses quantifying pathways, thresholds, monitoring and data management systems.
Explicitly identify uncertainties	This may include model assumptions, data gaps or data uncertainty. Uncertainty may be expressed quantitatively or qualitatively.
Keep it simple	Models are complex assessment methods and this complexity increases as the scope of the model increases (e.g., pathways instead of single stressors or VCs). • To avoid unnecessary complications, the simplest model that achieves the objectives of the assessment should be selected. • We recommend coupling several smaller and simpler models rather than creating a single all-encompassing model (e.g., linking a stressor model for noise to a separate life cycle model for beluga populations). This approach is better able to leverage existing work, builds upon the strengths of subject matter experts, and reduces complexity. • In general, we recommend only considering one VC at a time, although multiple stressors and pathways should be considered simultaneously. The added complexity of modeling multiple VCs simultaneously is not expected to be fruitful except perhaps in cases where there are clear trophic level interactions between VCs (e.g. marine mammals and forage fish). Even so, these would likely be questions for later iterations as specific uncertainties are identified.

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Appendix A: Cumulative Effects and Marine Shipping in Canada: Overall Context

Marine Shipping Pathways of Effects

Pathways of Effects (PoE) are conceptual models that represent the cause-effect linkages between stressors and their effects on valued environmental, cultural, and socioeconomic components (Government of Canada 2012). PoE models consist of components that represent the different parts of the system (i.e., activities, stressors, valued components) linked by impact pathways (generic example displayed in Figure A. 1) that represent the interactions that lead to direct or indirect effects on the valued components. PoEs are usually accompanied by rationales that detail the supporting evidence for the relationships represented in the model.

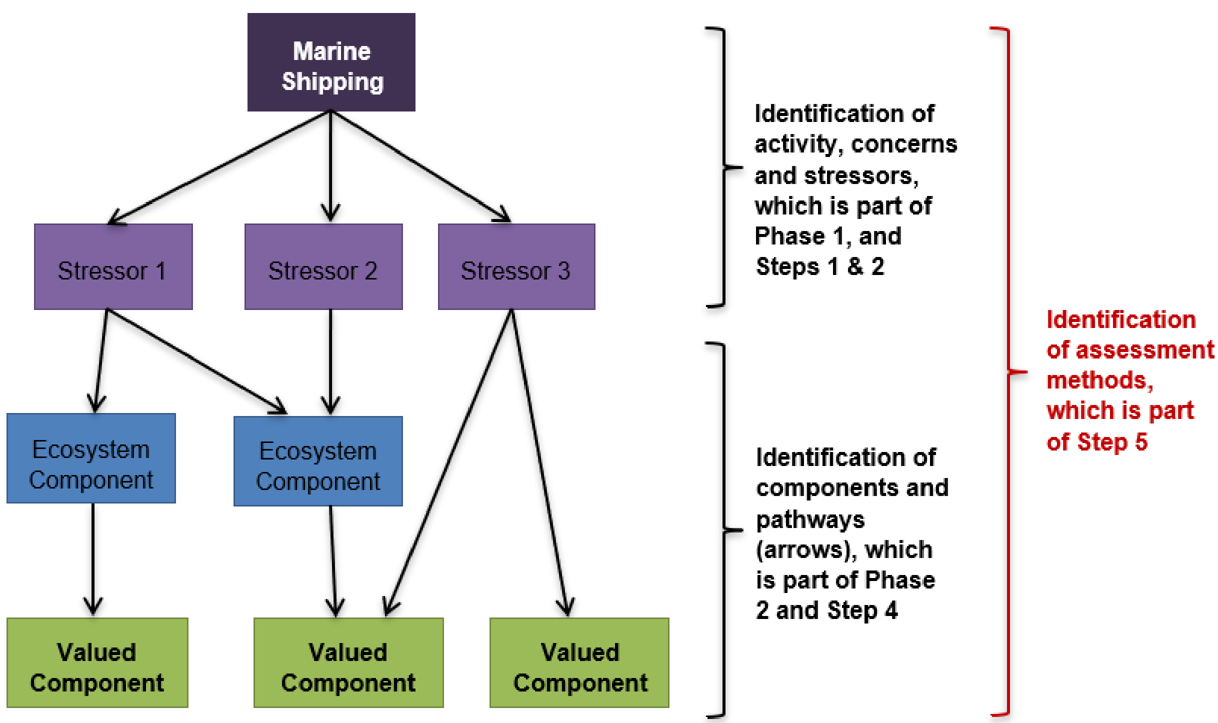


Figure A. 1. The value of using a simple Pathways of Effects conceptual model as a basic organizing structure for the cumulative effects framework is illustrated by aligning this generic model with the phases and steps identified in the CEMS initiative. Note that valued components can be ecological, cultural or socioeconomic.

PoE models are useful communication tools as they explicitly articulate the current understanding of the system, providing a common understanding from which to facilitate discussions and make decisions. PoE models are an important step in any cumulative effects assessment framework, regardless of assessment approaches that are utilized.

DFO is currently leading the development of PoE models for marine shipping. The final PoE diagrams will be informed by previous work as well as through expert opinions/literature review conducted through a Canadian Scientific Advisory Secretariat process.

Current undertakings as part of Phase 2 (2018-2020) involve identifying valued components for six pilot regions, mapping the linkages between stressors and the valued components, and identification of assessment methods, which is the focus of this report. Figure A. 2 displays activities and stressors as identified during recent Transport Canada engagement and from the science advisory report by DFO (2015).

When asked how marine shipping could affect the environment or traditional uses of environmental resources, Indigenous Nations, coastal communities, and other stakeholders identified seven broad categories of activities, including log booming/dredging, anchoring, grounding/wrecking, discharges both operational and accidental, movement underway and harvesting (i.e., the effects of fishing vessels specifically associated to vessel movement). These activities result in multiple stressors (Figure A. 2) on ecological and social valued components.

A total of 778 potential valued components (VCs) have been identified for the six pilot regions, including biological, physical and social components (Figure A. 3). This list of VCs, derived mainly from environmental and social impact assessments, will be further developed and priority VCs will be identified as part of the upcoming regional engagement in Phase 2.

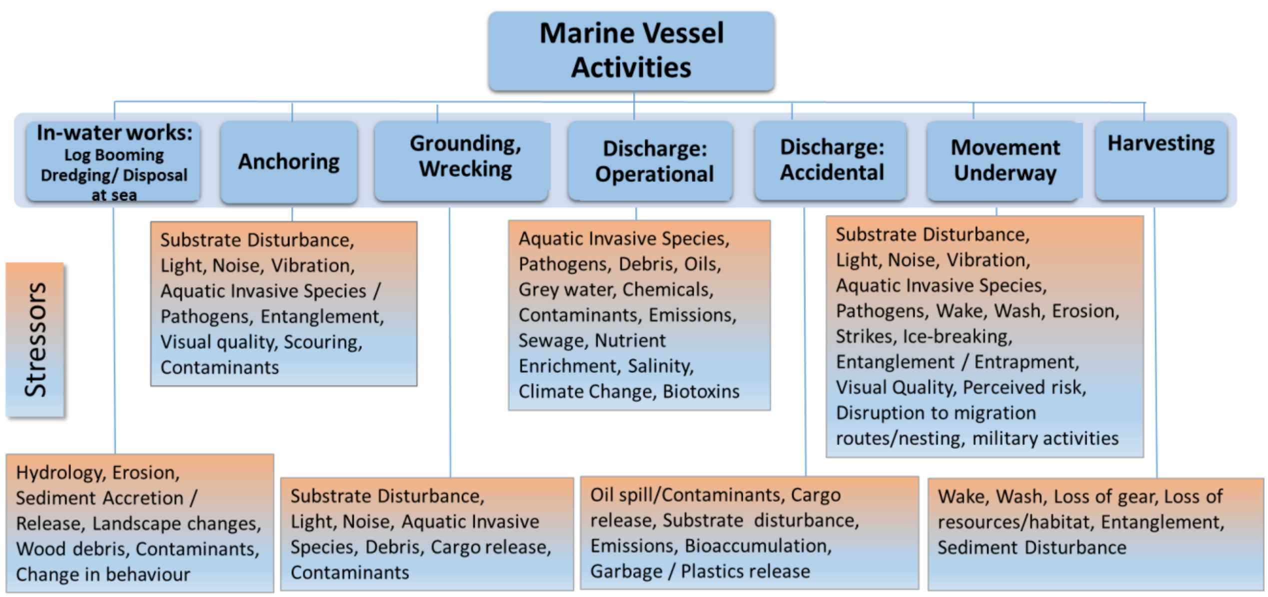


Figure A. 2. Activities and stressors identified during recent Transport Canada engagement and from the science advisory report by DFO (2015)

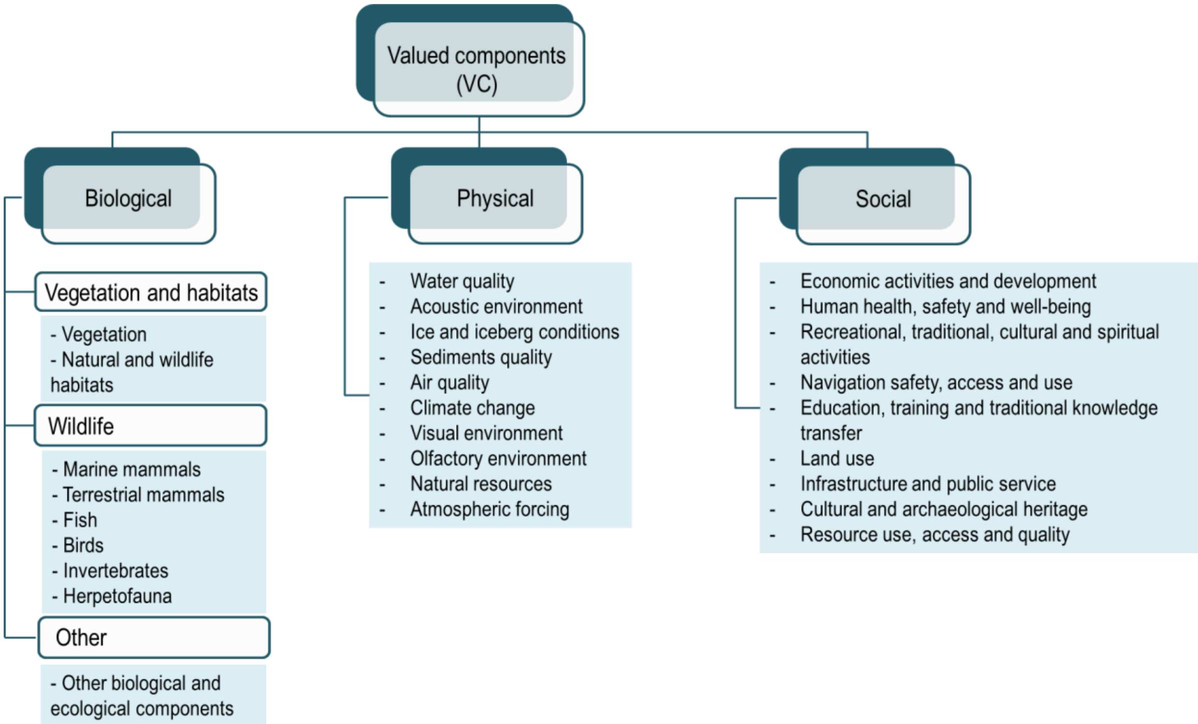


Figure A. 3. General categories of valued components identified for the six pilot regions

Regional Context

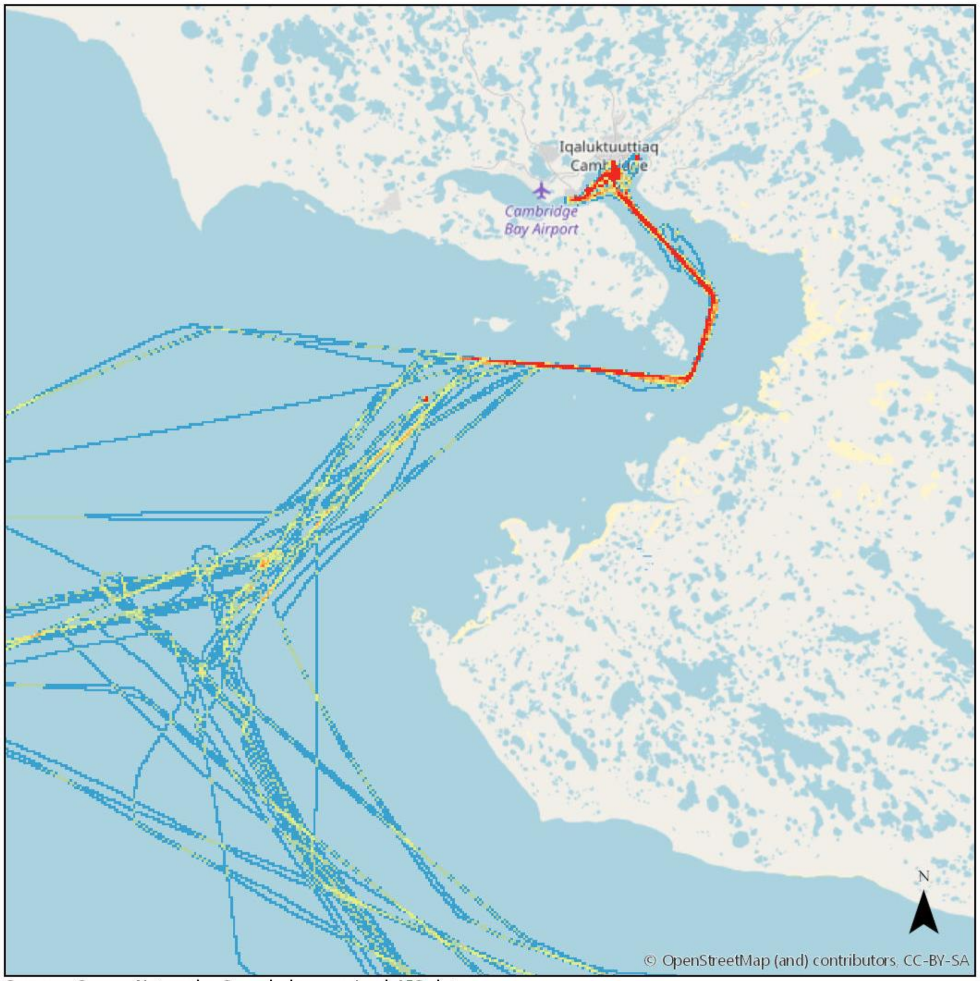
This section introduces the six regions of relevance for the CEMS initiative, concerns stakeholders have for each of these regions, characteristic vessel types and activities prevalent in the area, the valued components which have been identified so far, as well as any recent or ongoing cumulative effects initiatives implemented for the regions. Regional data availability is summarized as part of the Data Availability section in this Appendix.

Arctic

Marine traffic

Different communities expressed different concerns associated with marine shipping. Marine vessel traffic and mining are two activities that have been identified as having an impact on the community of Iqaluit. At a May 2018 workshop in Cambridge Bay, participants identified “super barges” as a particularly concerning type of vessel due to its disturbance of wildlife, warming of waters, and the introduction of invasive species (Government of Canada 2018a). During a June 2018 workshop in the Inuvik, NWT, participants identified specific types of vessels of greatest concern for the Inuvialuit Settlement Region, namely cruise ships, yachts, recreational vessels, and tourism crafts (IGC 2018).

Cambridge Bay
Vessel Transits - All Vessel Types, Sept 2018



Source: Ocean Networks Canada harmonized AIS data

Figure A. 4. Vessel transit heat map for the Cambridge Bay area. Map provided by Transport Canada. Note: information about vessel activity is based on Automatic Identification System (AIS) data, and therefore vessels that do not use the AIS system (e.g., small recreational boats) are not represented in this map.

Concerns

During an Oceans Protection Plan (OPP) meeting in Iqaluit in 2017, stakeholders voiced their highest priority concerns regarding their marine environment. A big concern was that of marine areas and marine food sources Inuit depend on being degraded by garbage pilings from mining, and from shipping (OPP 2017a). Increased marine vessel traffic impacts on marine mammals, vessel-induced ice breakage, vessel waste water pollution, oil spills, noise, and physical impacts on the sea beds from anchorage were identified concerns. Increased frequency of anchorage and longer anchorage time have been identified as a concern to residents in the region (letstalktransportation.ca). A loss of walrus and a decline in Beluga whales, changing currents, invasive species, and garbage in fishing nets and on beaches around the Belcher Islands was raised as a local-scale concern (IGC 2018, OPP 2017a).

At an October 16-18, 2017 Transport Canada-hosted workshop in St. John's, Newfoundland focused on shipping through Arctic corridors, participants expressed apprehension about several marine-shipping related possibilities. These included oil spill response capacity (including equipment, legal gaps, irregular maintenance and access to equipment, and storage and disposal resources), mass rescue capabilities, and the effects of climate change on increased marine shipping and sailing traffic through the arctic regions potentially impacting haul outs and feeding areas of narwhals, belugas, and seals (Government of Canada 2017a). Community access to hunting of narwhal through the Mary River where voyager and tanker traffic is high was also a concern. Several of these concerns were also echoed at a June 2018 workshop in the Inuvik, NWT (IGC 2018).

During a May 2, 2018 workshop in Cambridge Bay, participants identified food security, increased tourism-related vessels traffic, interference of ships during the hunting season, pollution, oil spills, noise, grey water, changing migration patterns of marine mammals, effects of ice-breakers on hunting access and caribou migration, and an inability to track smaller vessels around the community to be of concern (Government of Canada 2018a).

Valued Components

Several biological VCs have been identified for this region: 19 marine mammals (including walruses, narwhals, Beluga and Bowhead whales), 12 terrestrial mammals (including polar bears, muskox, Arctic hares, and moose), 25 fish species, 11 birds, 13 invertebrates, 5 plants, 16 habitats, and 5 other ecological components are included under this category.

Physical VCs include water quality (6), acoustic environment (3), ice conditions (1), sediment quality (4), air quality (3), climate change (1), and visual environment (1).

The Arctic region has a significant number of socio-economic VCs of relevance. These include economic activities and development (7), human health, safety and well-being (9), recreational, traditional, cultural and spiritual activities (7), navigation safety, access and use (4), education, training and traditional knowledge transfer (3), land use (2), infrastructure and public service (2), and cultural and archeological heritage (2).

Current state of CE practice within the region

Cumulative effects work has been undertaken for the Arctic region in and around Cambridge Bay by several groups including the Beaufort Sea Partnership, the Northwest Territories Cumulative Impacts Monitoring Program (CIMP), the Inuvialuit Game Council (IGC), and the World Wildlife Fund (WWF) (Beaufort Sea Partnership 2009, Campagnola, J. pers. comm, IGC 2018, NWT 2018a). Since 2008, The Northwest Territories Water Stewardship Strategy has been working on an initiative to outline a water strategy, including the assessment of the cumulative effect of anthropogenic water and land use, and waste deposits on the watershed (NWT 2018b). The Arctic Corridors group (www.arcticcorridors.ca), in partnership with Northern Voices has studied and written many reports about subjects such as climate change, the effects of pleasure craft tourism, and the cumulative effects of marine shipping (Arctic Corridors and Northern Voices 2018). Environmental assessment studies have been performed by the Nunavut Impact Review Board and collaborative efforts through the Beaufort Regional Strategic Environmental Assessment initiative (https://rsea.inuvialuit.com/).

Newfoundland

Marine traffic

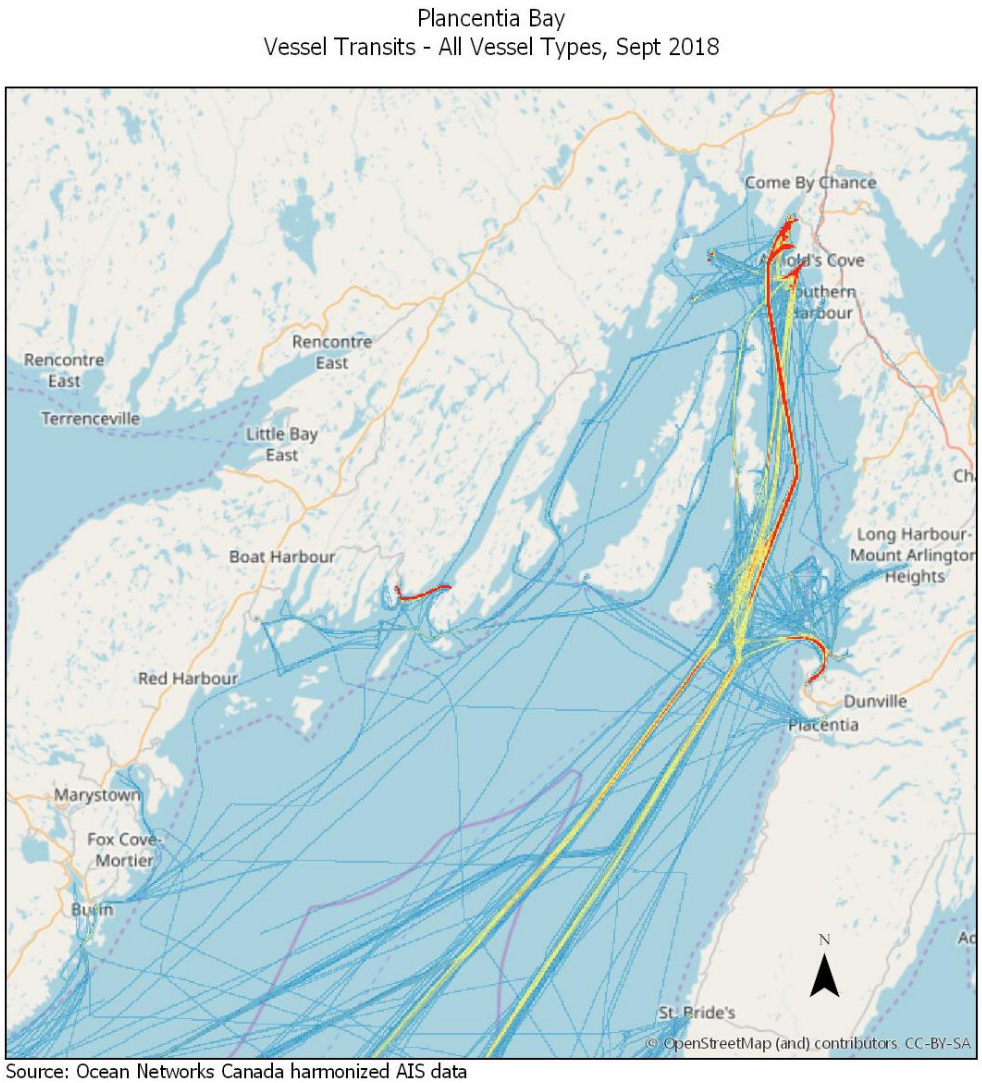


Figure A. 5. Vessel transit heat map for the Placentia Bay area. Map provided by Transport Canada. Note: information about vessel activity is based on Automatic Identification System (AIS) data, and therefore vessels that do not use the AIS system (e.g., small recreational boats) are not represented in this map.

Concerns

General concerns about environmental protection, oil spills, lack of information related to wind and wave conditions, safety, inclusion of Indigenous groups in initiatives, and the protection of traditional knowledge, cultures, and socioeconomics were voiced during the Oceans Protection Plan (OPP) engagement session in St. John’s, Newfoundland on March 28, 2018.

Process-based concerns raised by participants included the balance between economic opportunities and protecting community resources, and that traditional knowledge is included in initiatives. Participants were concerned about ensuring that adequate time is allocated to any initiatives such that thorough analyses can be achieved, that privacy be considered, and that risks of marine traffic are properly considered (Lorne Pike & Associates 2018).

Valued Components

Four marine mammals including cetaceans, otters, and pinnipeds, 1 terrestrial mammal, 11 fish species including bluefin tuna, and Atlantic cod, 14 birds, 10 invertebrates, 1 herpetile (sea turtles), 4 aquatic and terrestrial plants species, and 7 aquatic and terrestrial habitats have been identified so far as biological valued components category for Newfoundland.

Physical VCs include 4 water quality considerations, and 1 each of acoustic environmental, sediment quality, air quality, climate change, and visual environmental considerations.

Social VCs include 1 economic activity (commercial fisheries), recreational, traditional, cultural and spiritual activities (3), navigation safety, access and use (1), land use (1), infrastructure and public service (1), and cultural and archeological heritage (1).

Current state of CE practice within the region

A recent draft plan for a regional assessment of offshore oil and gas exploration drilling East of Newfoundland and Labrador has been released, which will seek to assess the current and anticipated cumulative effects of such operations in combination with other physical disturbances that may result (Government of Canada 2018b).

New Brunswick

Marine traffic

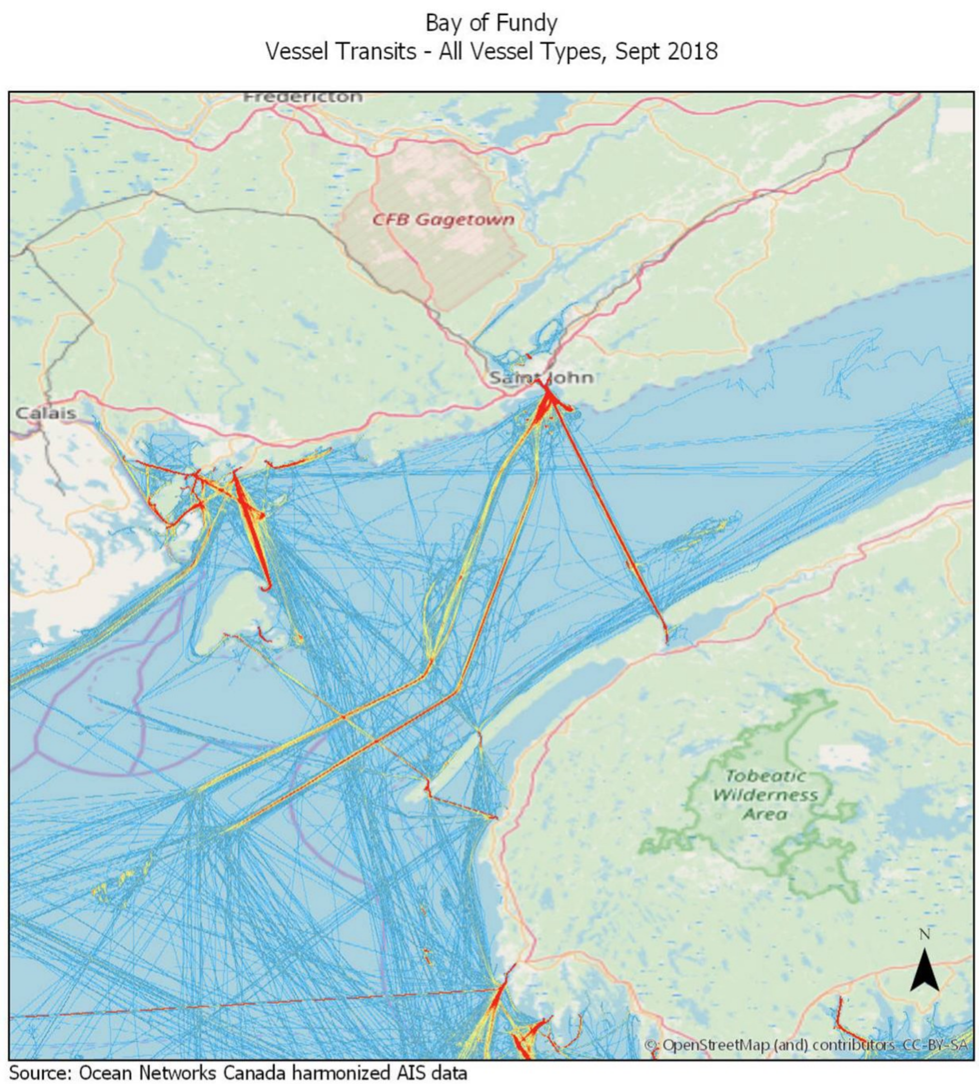


Figure A. 6. Vessel transit heat map for the Bay of Fundy area. Map provided by Transport Canada. Note: information about vessel activity is based on Automatic Identification System (AIS) data, and therefore vessels that do not use the AIS system (e.g., small recreational boats) are not represented in this map.

Concerns

A workshop was hosted by Transport Canada on January 25th, 2018 in Moncton, New Brunswick to elicit feedback on, and generate ideas regarding components of the Ocean Protection Plan that are relevant for the area. The leading cause for concern regarding the cumulative effects of increased vessel traffic was that of oil and pollution leaks from vessels, and the resulting impacts on coastal areas and species. Participants also expressed concern about the environmental impacts of sunken ships, and the increased risk of collisions between marine fauna and fishing gear.

Valued Components

Seven plant species/communities, 9 habitats, 3 marine mammals including the Northern Right Whale, 10 terrestrial mammals including moose and lynx, 12 fish including halibut, 5 birds, and 5 invertebrates have been identified as biological VCs for this region.

Physical VCs of focus for the region include 4 water quality considerations, and one each of acoustic environmental, ice conditions, sediment quality, air quality, climate change, and visual environmental considerations.

Social VCs include 1 economic activity/development (commercial fisheries), 6 human health, safety and well-being, 5 recreational, traditional, cultural, and spiritual activities, 1 land use activity, and 1 cultural and archaeological heritage consideration.

Current state of CE practice within the region

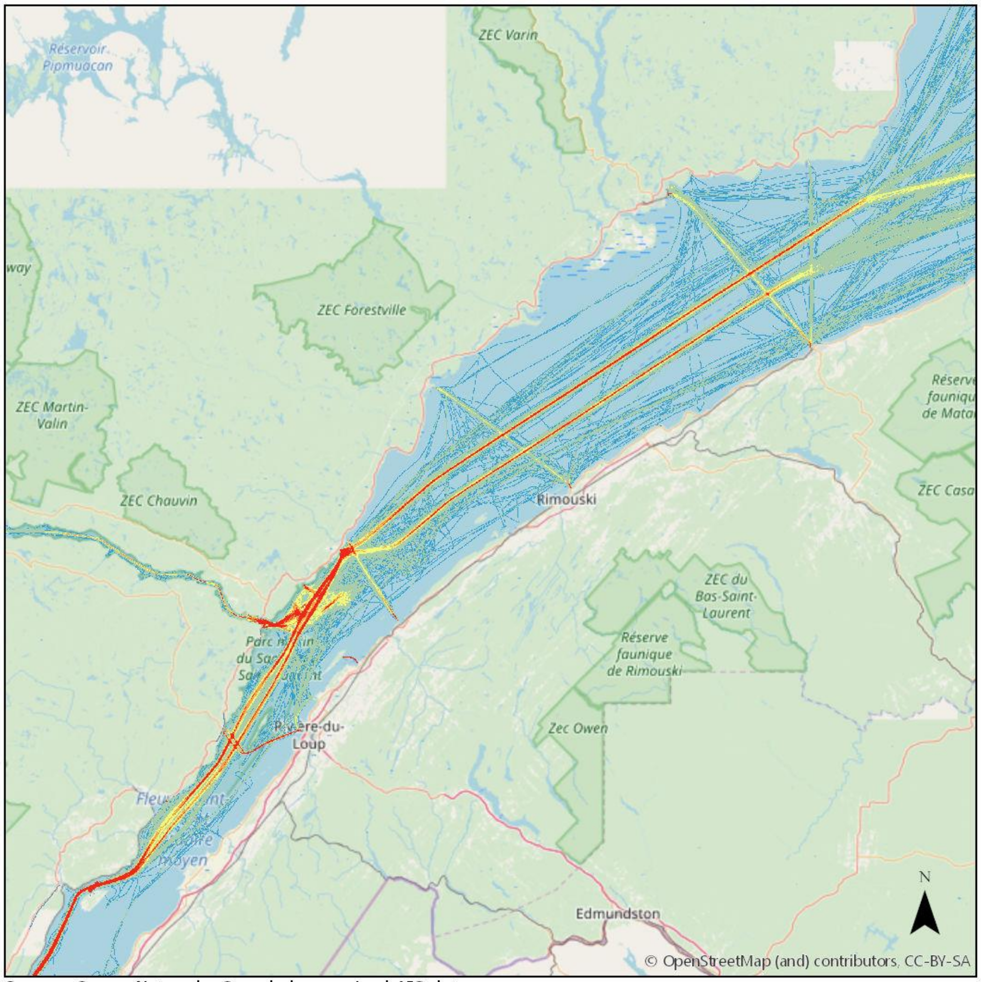
The Canadian Government's Area Response Planning (ARP) initiative, which ran between 2014 and 2017, sought to help the Bay of Fundy develop oil spill response plans for four pilot areas using a risk assessment methodology. The program included an evaluation of environmental sensitivities (https://www.tc.gc.ca/eng/marinesafety/oep-ers-arp-4473.html).

Quebec

Marine traffic

Marine vessel traffic, cruise ship anchorage close to the bays, and coast guard vessel traffic were some identified activities of concern for the region.

St. Lawrence River
Vessel Transits - All Vessel Types, Sept 2018



Source: Ocean Networks Canada harmonized AIS data

Figure A. 7. Vessel transit heat map for the St. Laurence River. Map provided by Transport Canada. Note: information about vessel activity is based on Automatic Identification System (AIS) data, and therefore vessels that do not use the AIS system (e.g., small recreational boats) are not represented in this map.

Concerns

Several concerns relating to marine vessel activities were specified during the engagement sessions held in Quebec City on November 7 (First Nations only), and November 8 (stakeholders only), 2017. Of note, stakeholders voiced their concern about the effects of increased marine vessel traffic in terms of noise effects and on, and collisions with Beluga Whales and other marine mammals, the risk of oil spills, light pollution, marine heritage sites, vessel wastewater, climate change, the capacity of the St. Lawrence, dredging, effects of anchorage on wildlife, issues relating to abandoned vessels, invasive species introductions, and shoreline erosion from vessel wakes, among others (Government of Canada 2017b, IDDPNQL 2017). Overfishing of lobster with the onset of more visiting vessels to the Gaspe Peninsula is of worry (Government of Canada 2017b). The fact that different stressors would pertain to different valued components in distinct areas within the region was raised; For example, vessel traffic may predominantly affect fisheries in one area, while shoreline erosion is of priority concern in another area. Participants were also concerned about ensuring cumulative effects studies consider existing regional studies, and follow the framework of the Environmental Assessment Act (IDDPNQL 2017). Stakeholders asserted that water intakes, wastewater discharges, and their effects of erosion be considered (Government of Canada 2017b).

There was concern that increased vessel traffic through the Seaway would lead in increased conflicts, safety, and access issues with the First Nations that utilize the areas near the river for fishing and recreation. Ensuring a balance is struck between mitigation efforts, like reduced vessel speed, and the ability of First Nations to engage in activities like fishing was raised. Impacts on First Nations' crab fishing was also highlighted. It was recommended that information and data be collected with engagement of First Nations, and from several different communities to ensure varying points of view are accounted for (IDDPNQL 2017).

Stakeholders were concerned about the spatial extent of the region of focus, suggesting that the fluvial areas of the St. Lawrence and Lake Saint-Pierre be included in analyses as these are areas in which significant port development is occurring, and that years prior to the construction of the St. Lawrence Seaways (1954) also be included in any temporal analyses. It was also suggested that a site in the Nunavik and/or Eeyou-Istchee Baie-James areas be added to the roster of sites, but not included with the St. Lawrence site. They also recommended that the entire system be considered rather than just a portion of it (IDDPNQL 2017, Government of Canada 2017b, Transport Canada 2018).

Valued Components

Biological VCs identified for this region include: 14 aquatic and terrestrial plant species/communities, 16 habitats including salt marshes, eelgrass beds, and protected areas, 4 marine mammals including Beluga whales, 5 terrestrial mammals including caribou, the rock vole, and the least weasel, 17 fish, 8 birds, 8 invertebrates including coral and sponges, and 7 herpetiles including different species of turtles.

One each of water quality, acoustic environment, ice conditions, air quality, and climate change, as well as 3 sediment quality, and 3 visual environment valued components make up the physical VC category.

Various social VCs are of relevance for this region, namely: 3 economic activities and development including tourism and commercial fisheries, 5 human health, safety and well-being considerations, 7 recreational, traditional, cultural and spiritual activities including birdwatching and recreational fisheries, 2 navigation safety, access, and use considerations, education, training and traditional knowledge transfer (1), land use (1), infrastructure and public service (1), cultural and archeological heritage (2), resource use, access, and quality (1).

Current state of CE practice within the region

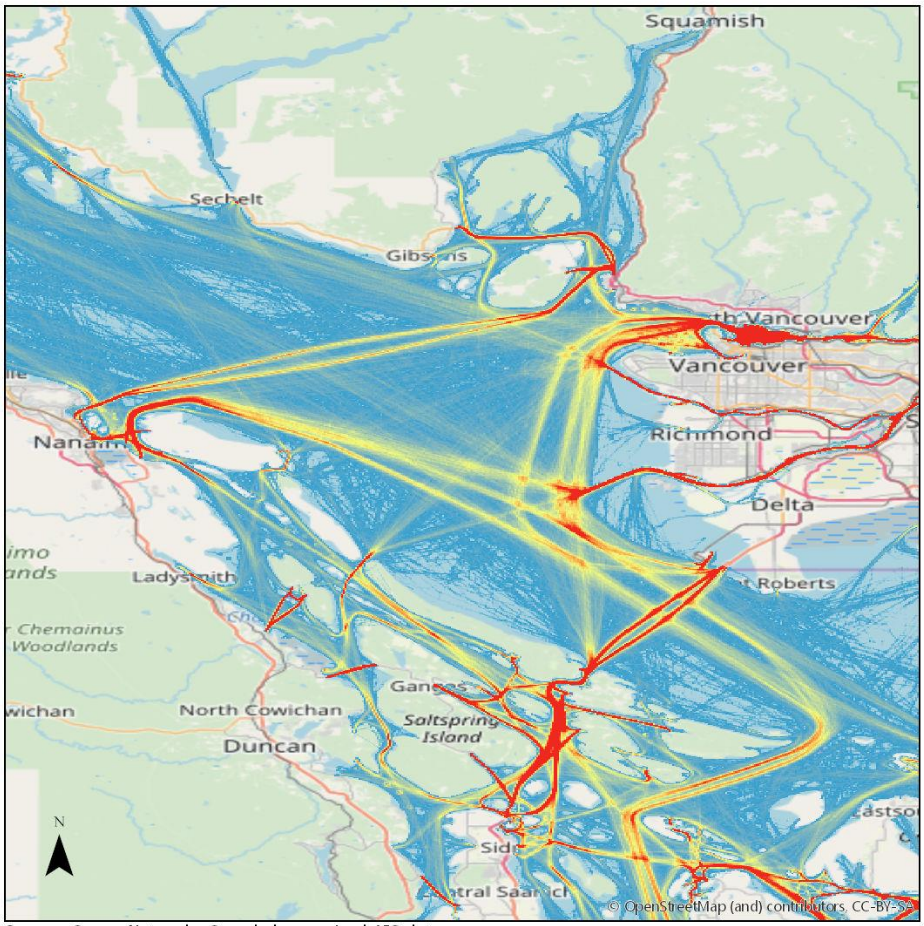
Cumulative effects initiatives that have been or are currently being implemented in Quebec include phase 1 of the multi-year characterization of coastal ecosystems work, which focuses on data collection in the marine estuary pilot zone, and the Canadian National Action Plan's initiative to reduce the impacts of vessel noise and collisions with whales in the Gulf of St. Lawrence (Government of Canada 2017b, Government of Canada 2018d).

Southern BC

Marine traffic

High amounts of marine vessel traffic and increased vessel speed, which are linked to population growth and the associated increase in the number of pleasure boats and ferries, were noted as activities of great concern (One World Inc. 2017a). Dredging and fish farming are other noted activities of concern to stakeholders in the 2017 Vancouver forum (One World Inc. 2017a).

Vancouver Area
Vessel Transits - All Vessel Types, Sept 2018



Source: Ocean Networks Canada harmonized AIS data

Figure A. 8. Vessel transit heat map for the Vancouver area. Map provided by Transport Canada. Note: information about vessel activity is based on Automatic Identification System (AIS) data, and therefore vessels that do not use the AIS system (e.g., small recreational boats) are not represented in this map.

A workshop held on October 23 and 24, 2018 in Victoria, BC, asked participants to identify the types of vessel activities they deemed to be most relevant. They identified accidental and operational discharges, grounding/wrecking, movement underway and monitoring/sampling as the activities vessels contributed to the most across all the sectors of discussion (ferries, government and research vessels, shipping, military, tug and barges, commercial fishing, sports fishing, cruise ships, whale watching vessels, and recreational boats) (McWhinnie et al. 2018).

Concerns

During the South Coast Dialogue Forum in Vancouver (One World Inc. 2017a), stakeholders were most concerned about pollution from vessel emissions and vessel accidents (air emissions, oil spills, waste water discharges, vessel paint residuals, and natural disaster-related pollution from vessels), noise and light pollution, and physical disturbances of the shoreline and sea beds (shoreline erosion from vessel wakes) on human, environment, and endangered species health. Physical disturbances and pollution from dredging and commercial development, viral transmissions from fish farms, invasive species, litter from vessels, climate change, Southern Resident Killer Whale impacts from vessel strikes and effects to their food sources, and impacts of heightened vessel traffic on whale watching tours were also highlighted (One World Inc. 2017a).

Concern about the spatial extent of the Port of Vancouver pilot site was also mentioned, and it was recommended that spatial boundaries extend beyond administrative boundaries, to include northern and southern coasts or even encompass the range of the Southern Resident Killer Whale (One World Inc. 2017a).

Ensuring First Nations maintain traditional territories and fishing rights, and reducing any economic impacts on First Nations and commercial fisheries were also mentioned.

Process-related concerns voiced during the Vancouver forum included ensuring that coastal community knowledge is incorporated during data collection, that areas beyond Vancouver's port be included in any baseline data collection to account for pollution levels already present in the area, and that the climate change effects might obscure interpretation of baseline measures made. Ensuring seasonality is reflected in collected data was also voiced (One World Inc. 2017a).

Activities

Valued Components

A total of 140 individual biological valued components have been identified for Southern BC, the largest number of all six regions of focus. 40 fish including salmonids, 15 birds, 13 invertebrates including corals, sponges, and echinoderms, 32 plants, and 22 habitats contribute significantly to this number. Marine mammals (6) including several species of whale such as the Southern Resident Killer Whale, terrestrial mammals (3), and herpetiles (4) make up the rest.

Physical VCs include water quality (6), acoustic environment (3) including vibrations and underwater/airborne noise, sediment quality (3), air quality (1), visual environment (4) including the visual effects of shipping, and landscape beauty, and natural resources (1).

Six economic activities and development including tourism and commercial fisheries, 5 human health, safety and well-being considerations, 5 recreational, traditional, cultural and spiritual activities including recreational fisheries, 4 navigation safety, access, and use considerations, 1 education, training and traditional knowledge transfer, 3 land use, 8 infrastructure and public service, and 4 cultural and archeological heritage social valued components are of relevance for this region.

Current state of CE practice within the region

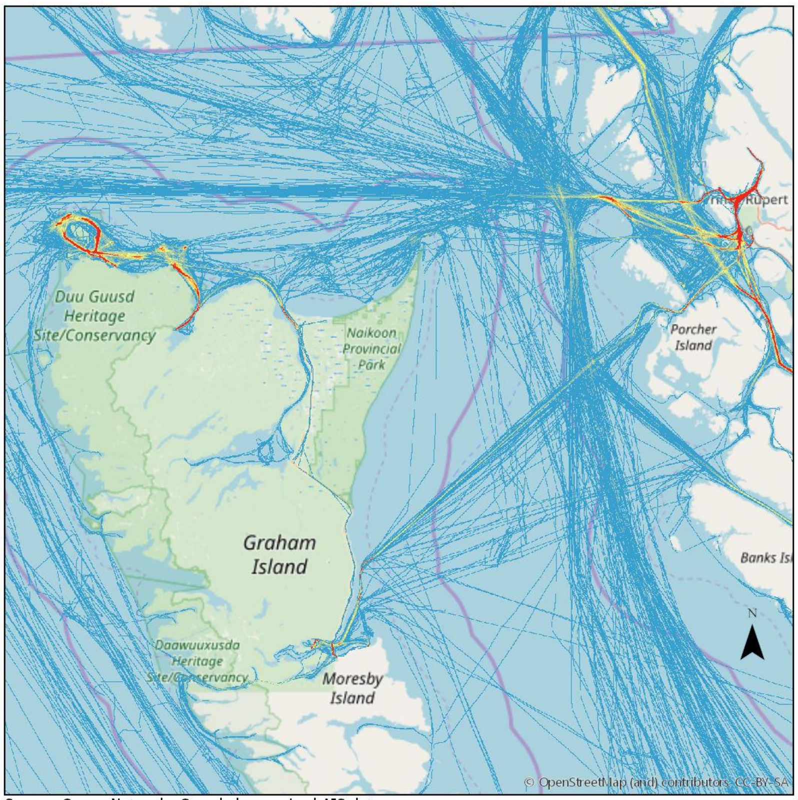
The Tsleil-Waututh Nation has performed cumulative effect assessments for the region, and have also commented on the adequacy of CE work and Marine Shipping Addendum (MSA) proposed for the Robert's Bank Terminal 2 Project (Smith 2016) as well as the TransMountain Pipeline project. The Musqueam Indian Band have recently completed an assessment of the impacts of marine vessel traffic on access to fishing opportunities (Nelitz et al. 2018). Additional CE work has been undertaken in Howe Sound (Campagnola, J. pers. comm).

Northern BC

Marine traffic

Marine vessel traffic was the greatest activity of concern noted by the stakeholders during the North Coast Dialogue Forum held in Prince Rupert (One World Inc., 2017b). Boating, ferries, commercial fishing vessels, and shipping were the priority listed forms of marine vessel traffic that was of greatest concern.

Prince Rupert Area
Vessel Transits - All Vessel Types, Sept 2018



Source: Ocean Networks Canada harmonized AIS data

Figure A. 9. Vessel transit heat map for the Prince Rupert area. Map provided by Transport Canada. Note: information about vessel activity is based on Automatic Identification System (AIS) data, and therefore vessels that do not use the AIS system (e.g., small recreational boats) are not represented in this map.

Concerns

Concerns about the effects of vessel-related water and air pollution, oil spills, vessels carrying liquefied natural gas (LNG), vessel noise and light, physical disturbances (vessel whale strikes, shore erosion from vessel wakes, anchorage scouring, invasive species), dredging, log booming, and climate change impacts on the wellbeing of human and marine life, as well as the health of the ecosystem as a whole were of highest priority for Prince Rupert (One World Inc., 2017b, OPP 2018a).

Interactions between increased large vessel anchorage and First Nations fishing harvest and salmon wellbeing, abandoned vessels, and interactions of large vessels with smaller vessels, like fishing vessels, was also outlined as a concern for the region. Similarly, large vessel interference with First Nations Food, Social, and Ceremonial (FSC) fisheries near the Skeena estuary was articulated as an issue (One World Inc., 2017b). Another notable concern for the region was that cumulative effects analyses should encompass a greater geographic area, following the ecological boundaries rather than administrative boundaries, including the Skeena estuary, and extending to Haida Gwaii, the Southern tip of Alaska, and inland to lakes and rivers (One World Inc., 2017b).

In addition to ecological and social concerns, process-related concerns regarding collecting data in a manner that is reproducible, engages First Nations, considers seasonality, and considers different community priorities for collection were also raised. It was also noted that historically collected data be included in cumulative effects assessments (One World Inc., 2017b). First Nations raised concerns regarding sensitivities when considering socio-economic aspects of studies in which they are engaged (OPP 2018a).

Valued Components

114 Biological VCs have been identified for northern BC, including the following: 38 aquatic and terrestrial plant species/communities including liquorice fern, bog cranberry, and several evergreen tree species, 18 habitats, 4 marine mammals, 5 terrestrial mammals including grizzly bears and moose, 9 fish, 9 birds, 18 invertebrates, and 9 reptiles.

Physical VCs include water quality (4), acoustic environment (1), sediments quality (3), air quality (3), visual environment (2), and atmospheric forcing (2).

In terms of social VCs, 3 economic activities and development, 4 human health, safety and well-being considerations including disease and drug consumption, 4 recreational, traditional, cultural and spiritual activities including shellfish farms, 2 navigation safety, access, and use considerations, 3 land use, 9 infrastructure and public services such as power infrastructure and waste management services, and 1 cultural and archeological heritage consideration are of relevance.

Current state of CE practice within the region

There are multiple cumulative effects initiatives that have been undertaken or are currently being undertaken along British Columbia's north coast.

The Marine Plan Partnership (MaPP) developed a MaPP cumulative effects framework, and is working to continue to develop and refine it in the MaPP North Coast sub-region (MaPP 2017). As part of this work, the MaPP cumulative effects coordinator has worked within other cumulative effects initiatives, including the Cumulative Effects Monitoring Initiative (CEMI), the Metlakatla Cumulative Effects Management Initiative, and the Environmental Stewardship Initiative (ESI) - North Coast Cumulative Effects Demonstration Project (MaPP 2017). Also as part of this work, in 2018 a North Coast water quality monitoring strategy was developed, which is in the initiation and implementation stage (OPP 2018a).

Through the federally initiated Cumulative Effects Monitoring Initiative (CEMI) in the Prince Rupert area, a 2016 draft interim plan, and a detailed monitoring proposal were developed for the region (OPP 2018a). Beginning in 2014, the Metlakatla First Nation began the Metlakatla Cumulative Effects Management Initiative, which has involved characterizing priority values and associated indicators, establishing management benchmarks, and monitoring for the 10 identified values.

The North Coast ESI project is focused on priority values within the Skeena region. It is one of five pilot ESI projects across the Province of BC, and the only one focused on the marine environment. It is a collaboration that includes North Coast First Nations, the Provincial government (Ministry of Energy, Mines and Petroleum Resources, and the Ministry of Forests, Lands, Natural Resource Operations and Rural Development), and the Marine Plan Partnership. To date they have developed pathways of effects models, indicators based on management goals, preliminary approach to assessment (including identification of thresholds) and have begun data collection using a preliminary monitoring plan.

Previous initiatives to assess cumulative effects in the Skeena estuary include the Pacific Salmon Foundation's Skeena River Estuary Assessment (Pickard et al. 2015), and the World Wildlife Foundation Skeena Cumulative Effects Assessment (WWF 2018).

Summary of available data

Types of data used in Cumulative Effects Assessments

The assessment of cumulative effects requires data connecting the activities and stressors to the Valued Components (VCs). Data requirements depend mainly on the type of assessment method being used. Data availability thus influences the choice of the assessment method. Strongly quantitative CEAs, such as those involving complex statistical models, require large and complex input datasets (Jones 2016). In addition, these datasets might need to be analyzed from various spatial and temporal scales.

A wide range of types of data can be used in cumulative effects assessments, including quantitative or qualitative information, georeferenced data, traditional knowledge data, etc. These various data types come from a variety of sources, including: studies and reports, workshops, monitoring programs, field studies, outputs of modeling exercises, etc.

Spatial data (i.e., points, lines and polygons) in the form of georeferenced information on the location and intensity of pressures (e.g., density of vessel traffic) and on the occurrence of ecosystem components (e.g., polygons representing the habitat distribution of a given species) are routinely used in spatial cumulative effects assessments (Korpinen and Andersen 2016). Even if the assessment is not spatially-explicit, some form of spatial data is usually included in most assessment methods.

Lack of empirical information on stressors-receptors interactions is a common problem in cumulative effects assessments. One way to overcome this lack of data is by eliciting expert knowledge on certain aspects of the assessment; such as determining the vulnerability of marine ecosystems to multiple anthropogenic stressors (Teck et al. 2010) or analyzing the pathways of effects and assigning impact scores (Singh et al. 2017). Expert knowledge is usually collected through surveys and/or technical workshops; usually in an iterative manner (refer to Section 6.2)

Indigenous knowledge (IK), refers to the knowledge held by Indigenous groups who have a long relationship with the territories where they live, and the resources found in these areas. This type of knowledge is valuable, especially for providing a historic perspective in the absence of long-term scientific data. Specifically, one of the shortcomings of the ecological baselines in cumulative assessments is that the available data are usually recent and reflect the environment in a degraded condition as affected by historical impacts (Clarke Murray et al. 2014, Korpinen and Andersen 2016). In this context, traditional and local ecological knowledge can contribute to understanding ecological trends or define the reference or pre-development conditions of the VCs (Clarke Murray et al. 2014).

Data available for the CEMS Initiative

Transport Canada is currently in the process of identifying data sources and collecting data sets that will inform and support the development and implementation of the CEMS initiative. This process is at a preliminary stage and the final data sets will be defined once the spatial and temporal boundaries and the priority Valued Components (VCs) have been established for each pilot region.

So far Transport Canada has compiled a list of potential data sources based on a preliminary screening of available information (e.g., reports, contacts, other government departments and initiatives, etc.), data sources lists which have been compiled for other initiatives under the Ocean Protection Plan, such as the Marine Regional Response Planning (RRP) initiative; a regional strategy for marine pollution incident response planning and preparedness implemented by MaPP in the Pacific region. This preliminary list includes information sources potentially relevant for characterizing the VCs (e.g., habitat ranges, wildlife studies, protected areas, data sets on physical attributes such as ice cover and tides, etc.) and stressors (mainly vessel traffic data).

Some of the data sources identified for the Arctic include information on shipping trends and culturally significant marine areas, as well as socio-economic values from the monitoring committees. The Ocean Networks Canada has a monitoring station in Cambridge Bay from which data are made available online (Campagnola, J. pers. comm.).

There are some initiatives at the national level that could provide data related to marine shipping, such as the Clear Seas Center for Responsible Marine Shipping, the Marine Environmental Observation, Prediction and Response Network (MEOPAR), or Ocean Networks Canada, which monitors ecological, physical and marine use parameters in both the East and Western coasts and in the Arctic.

In general, data sources on social VCs are not well represented across regions as compared to biological or physical VCs.

Through the engagement process with stakeholders in the pilot regions, potential additional sources of data are being identified. For example, the Green Marine Initiative in Quebec and the Working Group on Marine Traffic and Protection of Marine Mammals in the Gulf of the St. Lawrence (G2T3M) could provide useful insights related to the effects of underwater noise. The coastal ecosystem data collected through the current “characterization of coastal ecosystem” study will be available on the St. Lawrence Global Observatory website (https://ogsl.ca/en).

Stakeholders from the Pacific region identified a number of entities that could have relevant data for the South Coast of BC during a South Coast Dialogue Forum in Vancouver (One World Inc. 2017a). These entities include the Canadian government, the British Columbian government, the United States Coast Guard, Islands Trust, the Port of Vancouver, the David Suzuki Foundation, Streamkeepers, the Vancouver Aquarium, Universities, and Indigenous stewardship groups, among others (One World Inc. 2017a). Potential data sets from these sources include water quality data, vessel incidents, fish, wind and tides, climate change, and watercraft effects.

For the Northern BC Coast, a number of data sources were identified during the North Coast Dialogue Forum held in Prince Rupert (2017). Data from the Canadian government, the British Columbian government, First Nations fisheries departments and traditional knowledge, the Tsimshian Environmental Stewardship Authority, the Marine Plan Partnership for North Pacific Coast (MaPP), the T Buck Suzuki Foundation, and other NGO’s are included on this list (One World Inc., 2017b). A long-term Port of Prince Rupert initiative to collect water, air, wind, and noise data in 31 areas using emission stations around the Port, and through a partnership with ONC has been ongoing for some years (One World Inc., 2017b). Many of the data sources identified during this forum pertained to water and air pollution, fish stocks, noise, and historical data.

Vessel traffic data

Vessel traffic data are essential for assessing cumulative effects. This type of information is used as a measure of marine shipping activity in many assessment methods. It is also a critical input for various modeling approaches, such as for models predicting underwater noise propagation, oil spills or strikes with wildlife.

The **automatic identification system** (AIS) is a global tracking system that allows vessels to view traffic in their area and also to be seen by other ships. The information automatically transmitted by the vessels includes their location, speed and dimensions. Terrestrial and space-based receivers can also record AIS data. Canadian Coast Guard has a network of terrestrial stations for live vessel tracking within a distance of a few nautical miles. Current and historical AIS data can also be purchased from corporations who own constellations of satellites that record this information.

Being fitted with an AIS tracker is a requirement[12] for ships bigger than a certain size (e.g., for ships over 300 tons engaged on international travel and for ships over 500 tons that are not engaged on international travel). Fishing vessels and most recreational and research boats are therefore not covered as part of the AIS network (Figure A. 4 - Figure A. 9).

Figure A. 10. AIS coverage across Canada (Source: Canadian Coast Guard).

In areas where small vessels are the predominant type of ship, AIS data are not available. Erbe et al. (2012) identified this limitation for noise models that rely exclusively on AIS. In their study of cumulative noise in the west Canadian Exclusive Economic Zone, they use the Vessel Traffic Operation Support System (VTOSS) program of the Marine Communications and Traffic Services (MCTS) of the Canadian Coast Guard as an alternative source of information on marine traffic.

Transport Canada has recently proposed amendments[13] to the navigation safety regulations, including the requirement of AIS technology for passenger ships that carry more than twelve passengers or vessels that are more than eight meters in length and are certified to carry passengers.

[12] http://www.ccg-gcc.gc.ca/eng/CCG/Maritime-Security/AIS#guidelines

[13] https://letstalktransportation.ca/navigation-safety-regulations

Appendix B: Summary of Review Papers

As previously discussed, as part of Tier 1 we screened 20 review papers which compare and contrast specific methods and tools. Although these reviews have a different scope and goal than the present evaluation, it was informative to understand how other studies have framed and analyzed cumulative effects assessment methods and tools and the lessons that emerge from the literature. This section presents the key findings from the thirteen papers most relevant for this evaluation.

Reference: **Lerner, J. 2018. Review of cumulative effects management concepts and international frameworks. Prepared for Transport Canada under Contract T8080-170062.**

Overview: At the request of Transport Canada, Lerner (2018) conducted a literature review of international cumulative effects management frameworks, including the assessment of CE, with a focus on marine shipping and coastal contexts. The literature review covered 262 documents, including academic papers, grey literature and seven case studies of implemented cumulative effects management systems (3 Canadian and 4 international).

Key insights: This study groups models and tools usually applied to analyze the cause-effect linkages between activities and valued components into four categories: causal frameworks (e.g., DPSIR, Pathways of Effects); ecological risk assessment frameworks (ERAFs); ecosystem models (e.g., Ecopath with Ecosim, Atlantis) and cumulative impact mapping. These four categories are not explicitly evaluated, but Lerner provides a set of qualitative criteria for assisting in the selection of a specific assessment method. These criteria include: resources available (i.e., data, time and cost), manageability, generality, realism and precision.

Reference: **Stelzenmüller, V., Coll, M., Mazaris, A. D., Giakoumi, S., Katsanevakis, S., Portman, M. E., Ojaveer, H. 2018. A risk-based approach to cumulative effect assessments for marine management. Science of the Total Environment, 612, 1132-1140**

Description: The authors review the common shortcomings and the challenges of cumulative effects assessments undertaken in marine environments, focusing specifically on the treatment of uncertainty in these studies. The authors reviewed 154 studies regarding their input data, methods and tools applied in the respective risk management process. They proposed a modified risk-based approach for CEA.

Key insights: Each step of the CEA process demands different scientific analyses and expertise and, therefore, CEA studies usually involve a selection of methods adequate for each of the steps.

Reference: **Foley, M. M., Mease, L. A., Martone, R. G., Prahler, E. E., Morrison, T. H., Murray, C. C., & Wojcik, D. 2017. The challenges and opportunities in cumulative effects assessment. Environmental Impact Assessment Review, 62, 122-134.**

Description: Foley et al. (2017) conducted a comparative study, through expert survey, to assess the state of CEA practice in marine and coastal environments in four jurisdictions with advanced environmental regulatory frameworks: California (USA), British Columbia, (Canada), Queensland (Australia) and New Zealand. The premise of the authors is that even though there have been significant scientific advances in tools and methods for cumulative effects analysis, practitioners are still faced with significant challenges when implementing CEAs. The purpose of this review is to identify the main challenges and point to ways in which CEA practice could align with the best available science.

Key insights: The main shortcomings affecting current CEA practice are, according to Foley et al. (2017): scoping impact metrics, identifying baselines, defining spatial and temporal boundaries and determining significance of the effects. The results of the expert survey indicate that CEA processes are complex across the four jurisdictions and practitioners struggle to find the data and tools they need to complete thorough assessments.

Reference: Korpinen S. and Andersen J.H. 2016. A Global Review of Cumulative Pressure and Impact Assessments in Marine Environments. Front.Mar.Sci. 3 (153).

Overview: This review aims to provide an overview of the methods and practices used in cumulative effects assessment in marine environments. The authors analyzed the similarities among approaches, the emerging best practices, and the ways in which these studies addressed common CEA criticisms. The review covered 40 international cumulative effects assessments which had been published after 2000 and included, at least, two stressors.

Key insights: The predominant assessment method of cumulative effects is spatial analysis based on the approach developed by Halpern et al. (2008) and involving the combination of spatial information on the intensity of the pressures/stressors with data on the distribution and characteristics of the ecosystem components. According to Kornipen and Andersen (2016) some of the key limitations in the current practice include the lack of benchmarks or thresholds for the pressures, which prevents adequate estimation of impacts, and the limited scope of the studies which do not cover the full array of pressures on marine ecosystems. 25% of the reviewed studies build on a conceptual model that systematically identifies all the linkages between human activities and impact on ecosystem components.

Reference: Jones, F.C. 2016. Cumulative effects assessment: theoretical underpinnings and big problems. *Environ. Rev*. 24: 187–204.

Overview: In this review paper Jones (2016) assesses current practice in cumulative effects assessment (CEA) and documents with evidence from the literature the theories supporting (CEA) and the main challenges and problems found in implementation.

Key insights: Jones (2016) argues that there is consensus on the steps of the CEA process. However, there is no agreement in terms of the best methods and tools to complete those steps. Science has advanced significantly in the CEA space. There are numerical models available for the assessment of effects. The reasons why CEA studies are still, for the most part, qualitative are not related to the state of the science but perhaps to the regulatory and administrative frames in which these studies are undertaken.

Reference: Smith C.J., Papadopoulou K.N., Barnard S., Mazik K., Elliott M., Patrício J., Solaun O., Little S., Bhatia N.and Borja A. 2016. Managing the Marine Environment, Conceptual Models and Assessment Considerations for the European Marine Strategy Framework Directive. Front. Mar.Sci.3:144.

Overview: Smith et al. (2016) reviewed the use of conceptual models as part of the studies done under the European Marine Strategy Framework Directive. They focused specifically on the Driver-Pressure-State-

Impact-Response (DPSIR) framework, which has been extensively used in Europe, and analyzed if this approach is relevant to organize and focus assessments in real marine situations.

Key insights: The authors identified a number of challenges that prevent conceptual models turning into actual assessments: lack of data to validate the causal links between stressors and components, accounting for the interactions among stressors (e.g., synergistic, antagonistic, additive, etc.), pervasive uncertainty and low level of confidence in the predictions. The paper discusses other assessment approaches complementary to DPSIR: matrices, ecosystem models, Bayesian Belief Networks, and bow-tie approaches.

Reference: Judd A.D., T. Backhaus, F. Goodsir. 2015. An effective set of principles for practical implementation of marine cumulative effects assessment. Environmental Science & Policy 54: 254–262.

Overview: Judd et al. (2015) discussed the various definitions and conceptual framings of cumulative effects assessments and proposed an assessment framework based on the principles of environmental risk assessment. This risk-based approach involves screening the pathways according to their likelihood of exposure.

Key insights: Methods based on spatial analysis or the mapping of cumulative pressures can help with the formulation of the problem, but they are not in themselves comprehensive cumulative effects assessments. The output of CE assessments should include the identification and evaluation of management options to address cumulative risks.

Reference: Clarke Murray, C., Mach, M.E., & Martone, R.G. 2014. Cumulative effects in marine ecosystems: scientific perspectives on its challenges and solutions. WWF-Canada and Center for Ocean Solutions. 60 pp.

Purpose: This review of the state-of-the-art knowledge and practice of cumulative effects assessment and management in marine ecosystems explores common challenges in cumulative effects assessment and discusses the models and tools developed to conduct this type of assessments.

Key insights: The authors distinguish between *models*, which are specialized and more science-focused, and *tools*, which are designed for a broader audience and generally applied to management decisions. Both are used to estimate changes in ecosystems based on known relationships between stressors and components. Depending on the main function they provide, Clarke Murray et al. (2014) distinguish among three categories of models and tools: i) visualization, including pathways of effects and spatial analysis methods; ii) assessment, as used to evaluate how stressors affect the valued components (e.g., oil spill models, ecological models, simulation tools, etc.); and iii) management tools and models, including tools that enable the assessment of alternative scenarios (e.g., EcoPath with Ecosim, MIMES, InVEST, etc.).

Pervasive uncertainty and dynamic baselines are two of the main challenges in cumulative effects assessment. All assessments involve uncertainty, especially in terms of how stressors interact with each other (e.g., synergistic effects) and in distinguishing the relative contribution of stressors/activities to the impacts on receptors. There is a need for more research and systematic analyses at multiple scales to reduce or quantify this uncertainty.

Setting the baseline according to current conditions is also problematic since it can lead to measuring change against an already degraded system. Clarke Murray et al. (2014) suggest eliciting traditional and local knowledge to define the pre-development or reference state of the ecosystem.

Reference: Center for Ocean Solutions. 2011. Decision Guide: Selecting Decision Support Tools for Marine Spatial Planning. The Woods Institute for the Environment, Stanford University, California

Overview: This report is a decision guide to help in the selection of spatially explicit decision-support tools for marine planning. The guide is the result of a series of workshops by the Center for Ocean Solutions and presents a selection of available marine planning spatial decision support tools.

Key insights: The guide describes 9 decision support tools which can support marine planning. The tools are classified based on their functions as they relate to the cycle of marine spatial planning (e.g., mapping and visualization, alternative scenario development and analysis, stakeholder participation, adaptive management and assessment, etc.). The authors argue that better accessibility for these tools is needed to promote their use in marine planning and assessment processes.

Some of these tools can support the assessment of cumulative effects. One of the tools discussed is the Cumulative Impacts model; a tool developed by the National Center for Ecological Analysis and Synthesis (NCEAS) which uses spatial data and weighted expert opinion to predict cumulative impact scores across a region.

Reference: **Greig, L., C. Wedeles and S. Beukema. 2013. Evaluation of Tools Available for Cumulative Effects Assessment for the Northwest Territories – Literature Reviews: Models and Management. Prepared for Government of the Northwest Territories, Department of Environment and Natural Resources Wildlife Research and Management, Wildlife Division. 101 pp.**

Description: This review evaluates 12 models for the assessment of cumulative effects to caribou herds in the Northwestern Territories (Canada). The models were reviewed against nine questions, including considerations such as data needs, ease of use, interpretation of results, etc. Greig et al. (2013) also provide a comprehensive literature review of the variety of factors contributing to cumulative effects on the four caribou ecotypes in the NWT.

Key insights: Model selection is linked to the management questions that the cumulative study seeks to answer. The best strategy to address questions related to cumulative effects on caribou in the NWT is a multi-tool/model approach that combines as necessary the best elements of models appropriate to a specific question.

Reference: **IFC (International Finance Corporation). 2013. Good Practice Handbook Cumulative Impact Assessment and Management: Guidance for the Private Sector in Emerging Markets**

Description: This guidebook proposes a six-step approach for conducting cumulative effects assessments according to best practice in developing countries. The guide is not exhaustive and acknowledges that CEA is an evolving field. Rather than prescriptive, the authors describe each step and provide case studies, literature and resources to help users with the implementation of their studies.

Key insights: According to this guide, assessment of cumulative impacts involves predicting the future state of the valued components as a result of the impacts from current, past and reasonably foreseen future developments. This assessment requires understanding the thresholds of the valued components; limits in their condition beyond which impacts can compromise the sustainability or survival of the components. In terms of types of assessment approaches, the authors identify four distinct groups: impact models, numerical models, spatial analysis using geographical information systems (GIS), and indicator-based approaches.

Reference: Canter L.W. 2008. Conceptual Models, Matrices, Networks, and Adaptive Management – Emerging Methods for CEA. Presented at Assessing and Managing Cumulative Environmental Effects, Special Topic Meeting, International Association for Impact Assessment, November 6-9, 2008, Calgary, Alberta, Canada.

Overview: Canter (2008) discusses four types of methods (i.e., conceptual models, modified matrices, networks and adaptive management) that can assist with cumulative effects assessment (CEA). The author argues for the use of these methods as part of the CEA process and describes case studies in which these approaches have been used and the lessons learned from these examples.

Key insights: The author distinguishes two broad categories of CEA methods according to their main purpose: identification and prediction methods. Identification methods are useful for scoping VCs, setting spatial and temporal boundaries, selecting VC-related indicators, and in communicating the results of the assessment. Prediction methods are critical to actually assessing the effects and determining their significance. The outcomes of these two processes (i.e., identification and prediction) can be integrated within a decision-making framework. A typical CEA study requires the selection of one or more methods to meet the study needs.

Reference: Council on Environmental Quality, "Considering Cumulative Effects under the National Environmental Policy Act", January 1997, Executive Office of the President, Washington, D.C., pp. 49-57

Overview: This guide discusses cumulative effects assessment under the United States National Environmental Policy Act. This reference provides guidance on how to conduct cumulative effects assessment, from scoping, describing the affected environment, and determining the consequences of the effects.

Key insights: One of the sections of the guide discusses the methods, tools and techniques used for cumulative effects analysis. The authors group the methods into three functional groups: those that describe the cause-effect relationships between stressors and components (e.g., matrices, flow diagrams); those that analyze the trends in resources or stressors over time; and those that overlay landscape features to identify sensitive areas, distribution of components or features, etc.

Appendix C: Additional Insights from the Technical Workshop

This section captures additional detailed feedback and comments shared by some participants after the Technical Workshop hosted by Transport Canada on 20-21 February 2019 in Ottawa. These additional insights complement the review presented in this report and can inform next steps of the initiative.

Challenges for Marine Cumulative Effects Assessment and a Potential Framework

Mike Elliott – Professor at the Institute of Estuarine and Coastal Studies (IECS), University of Hull, Hull, UK

Roland Cormier – Institute for Coastal Research, *Helmholtz-Zentrum Geesthacht*, Centre for Materials and Coastal Research (HZG), Germany

Challenges

The biggest challenges, and perhaps the greatest drawback with current methods, are a set of 10 aspects – as a checklist will the chosen CEA cope with these:

1. Increasing our poor ability to measure the spatial and temporal effects-footprints of pressures from named activities
2. Determining the extent, duration and frequency of the pressures from an activity, not just the activity itself in a place at a given time (not assuming an activity = a pressure)
3. Determining the relative effects of endogenic managed pressures overlaid by exogenic unmanaged ones
4. Giving a weighting to the different effects-footprints in space and time, not just assuming they are added linearly and arithmetically (may be antagonistic or even exponential)
5. Knowing what is in an area, what activities, what receptors or relevance (at which area, when)
6. Tackling the effects-footprints on the mobile receptors (mostly species) not just the sedentary ones (habitats and species)
7. Accepting the assumption that CEA relates to 'all impacts of all activities' not just 'all impacts of one activity/sector' (the latter is just an EIA carried out properly – if we say 'a CEA or offshore wind' then this is a misnomer)
8. Determining if there is a tipping point or threshold when all impacts are taken together and effects-footprints overlap
9. Moving from an impact on the natural receptors to those on the human receptors (thus moving along the continuum from ecosystem structure and functioning, to ecosystem services, to societal goods and benefits)
10. Tackling the conceptual difficulties in the continuum from EIA to CEA to SEA

Recipe for Cumulative Impacts/Effects Assessment

1. Define the vision for the water body and the objectives of the CEA and ensure they are SMART
2. Define the activity (extent, duration and frequency) and pressures in the area and determine the effects footprints; allow a buffer zone as necessary
3. Map the spatial and temporal effects-footprints for the activities and pressures (use the generic lists for activities and pressures and edit for a site-specific approach)
4. Determine and apply the rules for weighting the different pressures based on severity; accommodate the high probability, low risk vs low probability, high risk (using risk analysis)
5. Prioritise tackling the activities and pressures but do not assume an activity automatically leads to a pressure (it would ignore any mitigation in place)
6. Determine which receptors lie within the effects-footprints using risk assessment methodologies, indicate how and when they are overlapping; use available tools - GIS, models, prediction, best expert judgement
7. Define the indicators to be used to detect change in the receptors; determine the baseline or reference conditions (using a control area, hindcasting, modelling or best expert judgement – acknowledge all of these methods have drawbacks)
8. Determine the significance of changes to the receptors, the action points/thresholds and link to predetermined management actions to be taken if these are breached (i.e. determine change against a baseline or indicator value)
9. Ensure that the CEA builds on the EIA for individual projects and merges into SEA as an integral part of MSP
10. Cross check that the EIA-CEA-SEA-MSP continuum fulfils the 10 tenets
11. Indicate the prevention and the mitigation/compensation measures in a risk management approach (on the given receptors from the given effects-footprints)
12. Carry out an RIA (Regulatory Impact Assessment) – what synergies/conflicts are there with other implementation of regulation – include transboundary/transnational influences
13. Ensure stakeholder input at all stages, include the categories of the stakeholder typology and consider whether any group of stakeholders (e.g. Indigenous groups) carry an additional weighting
14. Ensure the impact links to societal importance via the Ecosystems Services and Societal Goods & Benefits approaches
15. Check the outputs, triangulate across methods, ensure feedback loops and give an audit trail to ensure the methods and outputs are defendable; follow the Quality Assurance principles in environmental decision-making
16. Indicate the confidence in the outputs at each step, if necessary, only at the H, M and L level

Considerations for a National Framework on Cumulative Effects of Marine Shipping

Edward Gregr – Nuu-chah-nulth Nation

Structure of the National Framework

1. I recommend adoption of a tiered approach similar to that used by the InVEST tool (and also, apparently adopted by MaPP for the Skeena assessment). This is critical for a number of reasons including:
    a. Getting to the end is critical, at a "Tier 1" level, there is a chance of getting to the end. In my experience, "frameworks" are notoriously difficult to operationalize because of unforeseen complications. Working thru a high-level overview will help avoid getting caught in the details at any particular step.
    b. Iteration in any modelling effort is really useful to understanding the methods and results, and to communicating same to partners. It is important because the overall assessment will often be only as good as its weakest piece. By iterating, a Tier 1 assessment can then be used to prioritize data gaps and determine where there might be enough information (it is tempting but distracting and unnecessary to work on what is tractable instead of facing the harder questions head on).
    c. By helping ensure a more even analysis (i.e., one that has a similar level of complexity/detail across all components), or by identifying a minimum necessary complexity, it will be easier to understand and present the uncertainties associated with the analysis. This will be critical, in my view, to developing a credible CEA.
2. I recommend a more thorough consideration of adaptive management. My understanding is that this is fundamentally how traditional knowledge is developed (i.e., Berkes et al. 2000), and will thus likely generate the most buy-in from community groups. You will likely need to distinguish the true Adaptive Management methodology (see e.g., Williams & Brown 2016 for a recent review) from the co-option of the term to describe an approach to mitigation used by proponents of development projects.

    There are a variety of frameworks (e.g., re adapting to a changing climate, Tanner-McAllister 2017) and efforts to addressing inequalities (e.g., Specht et al. 2019) that you could mine to build a pretty solid bridge between the 'Newtonian' science perspective and the more holistic FN view on cumulative impacts.
3. The framework will need to address how benefits to people are impacted, not just the things that produce the benefits (the ecosystem service literature distinguishes between services to people, and the underlying ecosystem service providers). Natural scientists tend to give this part of the analysis a wide berth, because it involves messy questions around values and prioritization of benefits. I realize this is verging towards risk assessment, but it will not be enough, in my view, to stop at impacts on 'things'. Because this is hard and depends on local context, I would recommend co-developing this piece regionally, with impacted communities, but providing space for it in the National Framework.
4. Technically, I would suggest you consider the differences in interpretation of raster vs. vector representations of the various analyses and results. Many of the tools in your toolbox are raster-based. This makes sense technically, as it facilitates data processing. However, people will want to see how

their local areas of interest are impacted. And if these areas are described by grid cells that are 2 kilometers in size, it will cause confusion and raise questions, particularly for coastal areas.

Polygons and points seem to be the primary method whereby FNs are collecting their local ecological data. I would strongly suggest that any analysis - even if conducted in raster space - be translated and presented in vector space (points and polygons) for ease of communication and understanding.

Collection and representation of Indigenous Knowledge

There was a general feeling among the FN representatives in the room that the Framework will need to be bolstered with rigorous social science methods (which may include qualitative, quantitative or participatory methods) to support FN/community perspectives on social and ecological impacts.

In the interests of efficiency and effectiveness, I would recommend contracting the services of a social scientist with demonstrated expertise in this area to do the necessary literature review. Dr. Nathan Bennett is a colleague from UBC who may be willing to write a companion report/section from a social science perspective. Nathan is a marine conservation social scientist who has been thinking a lot in recent years about the measurement and management of the types of social impacts that were discussed at the meeting (e.g., access to resources, social benefits from marine systems, etc.). Examples of Nathan's work includes Bennett (2019), Bennett et al. 2018, and Kaplan-Hallam et al. (2017).

General challenges and comments

Baselines and reference points

I suspect the regional CEAs will have trouble settling on values for baselines and reference points. While I understand why TC is focused on shipping, the fact remains that shipping typically takes place in already heavily impacted seascapes is inescapable.

While it is reasonable from TC's perspective to begin by estimating the effects of stressors related to shipping in isolation, the question of *what baseline* cumulative effects will be assessed against is likely to be contentious. Consider how people may react to additional stress applied to killer whale or herring populations in BC. Or to the cumulative effect of ice-breaking and ice loss due to climate change in the Arctic. People are unlikely to be happy if the effects of shipping are considered in isolation.

It may be worthwhile for the National Framework to provide some guidance here instead of punting it all to the regions. Some form of co-development is the only way forward I can see for baselines and thresholds.

TC needs to ask itself if there is space here to say 'no more'? This may lead to questions about whether shipping in heavily impacted areas might be prioritized? (e.g., you could run a lot more ships through the Strait of Georgia if they were all quieter; or Canada could choose to restrict shipments of say, US coal to Asia, making space for traffic that is more in line with Canada's national interest

Modelling methods

One of the key challenges here will again be the clash between the Newtonian view of a world that can be decomposed and analysed, and the common FN perspective that all things are connected.

The typical 'Western' approach to CEA and other types of models is to take systems apart to examine and understand the components, and then re-assemble them in a model of the system of interest. By definition, building a model means including only those pieces thought to be the 'most important'.

My sense is that while FNs may have come to terms with the taking apart activity, they are much less comfortable with the re-assembly of things in a way that is both conceptually and analytically incomplete. The most common questions I hear at review meetings, especially from FNs, begin with "What about ... ".

The CEA framework will need to address the question of sufficiency. The degree to which the assessments are co-developed with impacted communities will be a key determinant of both this sufficiency and the subsequent relevance of the results

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Governance Considerations for a Regional Cumulative Effects Framework

To understand the context from which methods are selected, the following references provide guidance to Indigenous, federal, and provincial governments on establishing more collaborative, shared, or joint ***governance arrangements*** to set terms of engagement around a regional cumulative effects assessment for shipping:

- **Tsleil Watuth EA Report**, using UVic's Indigenous law methodology (Val Napolean's group) to develop appropriate framework from which to develop criteria for assessment, then used secondary sources and TK to collate data for assessment. https://twnsacredtrust.ca/assessment-report-download/

- Overview of the **Indigenous-led EA model** – report from the Gwich'in Council on Impact Assessment in the Arctic – Emerging Practices of Indigenous-Led Review: https://gwichincouncil.com/sites/default/files/Firelight%20Gwich%27in%20Indigenous%20led%20review_FINAL_web_0.pdf

Any long-term, established G2G approach is the likely preferred collaborative approach in this context, given that when any new governance arrangement is established for a project, it takes a very long time and lots of resources to develop and implement.

- BC EAO is emerging with collaborative EAs, but these are very new (e.g. Taku River Tlingit Shared Decision-Making agreement with BC on EAs (attached, you can download it online).

- Canada's new IA legislation, now in Senate, creates option for agreements with other governments, including Indigenous and Provincial governments, to establish a collaborative EAs process. Similarly, Canada has established a new Indigenous Advisory Committee, but focused on project-specific EA https://www.canada.ca/en/environmental-assessment-agency/advisory/advisory-groups/Indigenous-advisory-committee.html and the workshop participants were more interested in seeing longer-term, regional cumulative assessment that would inform project-specific CEAs.

- MVEIRB, NIRB, YESAB, and James Bay Cree, etc. are established through modern treaties and create long-standing EA co-management boards and some? Have parallel cumulative effects programs (e.g. https://www.enr.gov.nt.ca/en/services/cumulative-impact-monitoring-program-cimp)

Appendix D: Technical Workshop (February 20-21, 2019) Backgrounder

Introduction

As part of the national Oceans Protection Plan, Transport Canada is currently leading the Cumulative Effects of Marine Shipping (**CEMS**) initiative with the goal of developing a Cumulative Effects Assessment Framework focused on current and potential marine vessel activity. This initiative, which is being implemented through a collaborative process with Indigenous peoples, local stakeholders, and coastal communities in six pilot sites[14] covering all three of Canada's coasts, involves the following phases:

- **Phase 1** (2017-2018) *Understand the National Context*: The first year of the initiative involved scoping the concerns related to marine vessel activities as well as identifying the **stressors**[1] of concern for each pilot site.
- **Phase 2** (2018-2020) *Understand the Regional Context*: This ongoing phase includes the selection of **valued components**[2] (VCs) for each site and the identification of the linkages between stressors and VCs (i.e., pathways of effect). It also involves the collection of existing regional data and the identification of the preferred methodology for cumulative effects assessment.
- **Phase 3** (2020-2021) *Conduct the Regional Assessments*: The selected assessment methodology will be implemented in the six pilot sites. The Cumulative Effects Assessment Framework, which encompasses this assessment, will be finalized based on these pilot experiences.
- **Phase 4** (2021-2022) *Identify actions needed*: Based on the results of implementing the Cumulative Effects Assessment Framework, regional management strategies and actions and tools to mitigate the potential effects of marine shipping will be identified.

The purpose of this evaluation process was to evaluate and compare potential assessment methodologies relevant for the assessment of **cumulative effects**[3] associated to marine shipping (Phase 2). This workshop backgrounder provides a summary of the evaluation. Detailed information and discussion can be found in the full report which includes eight sections and two appendices:

- Section 1 provides important background context which clarifies the nature of this report.
- Section 2 describes our approach to completing the evaluation.
- Section 3 describes the screening phase of our evaluation.
- Section 4 provides the detailed evaluation, including a description of possible methods and associated tools and an evaluation of their relevance, rigour, and feasibility.

[14] Northern, British Columbia; Southern, British Columbia; St. Lawrence River, Quebec; Bay of Fundy, New Brunswick; Placentia Bay, Newfoundland; Cambridge Bay, Nunavut

- Section 5 presents a comparative analysis across methods and introduces a number of case studies that illustrate the application of these methods and how they could be used in the context of the Cumulative Effects of Marine Shipping initiative.
- Section 6 discusses supporting methods frequently applied in CEA, including: Indigenous knowledge, expert elicitation and decision support tools.
- Section 7 introduces examples of CEA frameworks and how the assessment step fits into the broader context.
- Section 8 provides overall conclusions, including insights from the evaluation, how to use the assessment toolkit, and next steps for the CEMS.
- Appendix A describes additional context that has informed our evaluation. In particular, we provide a brief summary of the: status of marine shipping pathways of effects model development, regional context in the pilot sites, and data availability.
- Appendix B provides a summary of key review papers on cumulative effects assessment methods and tools.

What is cumulative effects assessment?

The Canadian Council of Ministers of the Environment (CCME) defines cumulative effects assessment (CEA) as the *systematic process of identifying, analyzing, and evaluating cumulative effects*. Ideally, CEA involves a series of methods that assess the condition of the environment, describe the causal pathways that link stressors and cumulative effects, and predict the risks and benefits associated with alternative scenarios (Jones 2016). Although there is consensus on the general steps of the CEA process (Jones 2016), there is debate in terms of the methods that should be used at each of these stages (Jones 2016, Stelzenmüller et al. 2018). It is important to understand the structure of the overall cumulative effects framework within which the method will be applied (Greig et al. 2013). In other words, what is the scope of the assessment and what management strategies are being informed by the outcome of the assessment?

We created a diagram that displays important elements in a CEA framework in order to show our understanding of how the assessment step supports the broader framework in the context of the Transport Canada led CEMS initiative. While there is a natural sequence to the generic CEA framework described in Figure D.1., implementation in practice is iterative.

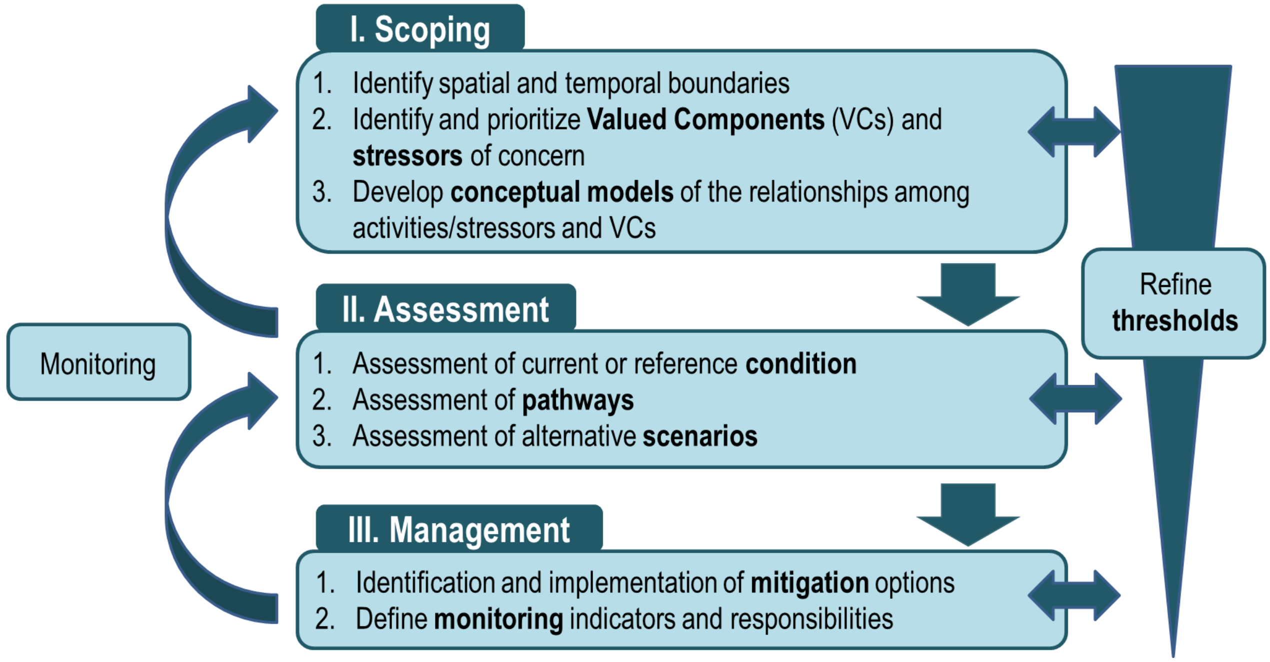

Figure D.1.: This figure shows how the assessment step fits within a broader CEA framework. The Scoping step is underway concurrently, led by Transport Canada and informed by regional workshops. This report focuses on potential methods for the Assessment step. The Management step is will be addressed in Phase 4 of the CEMS initiative.

Methods

The evaluation process (*Figure D.*) followed a tiered approach. **Tier 1** consisted of a broad screening of potential assessment methodologies. This was followed by a detailed review of the most promising methods (**Tier 2**). Concurrently, we summarized relevant context for the evaluation including: potential management levers; pathways of effects for marine shipping; concerns in each of the six pilot regions; and potential data sources. A series of interviews with key experts complemented this information.

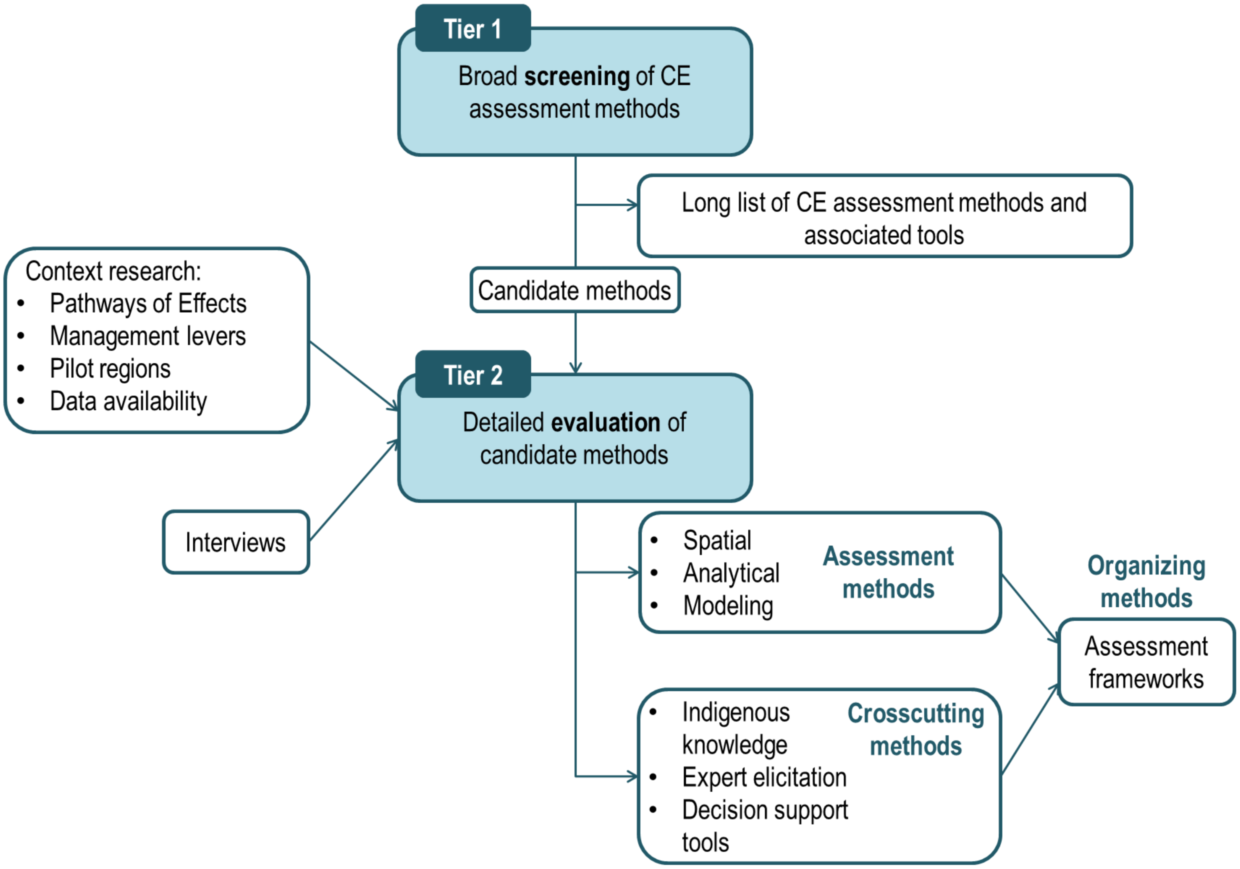

Figure D.2: Evaluation framework showing the flow of information and key outputs.

The suite of candidate assessment methodologies we were asked to consider included a combination of methods, tools, and case studies, making it difficult to compare directly. For the purpose of this report we defined these terms as follows:

Methodology: The collective body of methods employed by a particular field, in this case cumulative effects assessment.

Method: A procedure or process for attaining an object, in this case the assessment of cumulative effects. In some cases, tools may exist to support the method, but a method may exist in absence of a tool.

Tool: A means to an end, an instrument or apparatus used in performing an operation. In this case tools are designed to support one or more cumulative effects assessment methods. Tools range in specificity from specific applications (e.g., ECCC's Marine Emission Inventory Tool) to generic software (e.g., ArcGIS).

Case study: The specific application of one or more methods and associated tools. These tend to be one-off examples which employ a combination of the methods discussed in this report to achieve a particular end.

As part of the screening phase, we reviewed over 200 references including papers about specific methods and tools, review papers, assessment frameworks, key background documents, etc. Besides an overall understanding of the range and types of existing cumulative effects assessment methodologies and tools, several important insights emerged from this review:

- Methods as opposed to specific tools were identified as the most appropriate evaluation unit for the detailed review (Tier 2).
- Different assessment methods provide different functions and a combination of methods and associated tools is likely going to be necessary for the CEMS.
- Review papers group the methods according to either their methodological nature (e.g., spatial analysis, numerical models, risk assessment, etc.) or the function that they provide in the assessment process (e.g., visualization, assessment of scenarios, etc.)

Based on these findings, we identified three categories of methods: spatial, analytical and modeling for detailed review. Within each category, we organized methods depending on the part of the system they focus on; stressors, VCs, or pathways (Figure D.). While methods do not divide perfectly into mutually exclusive categories (e.g., many methods incorporate a spatial component); we found this a useful organizing structure for the Tier 2 evaluation.

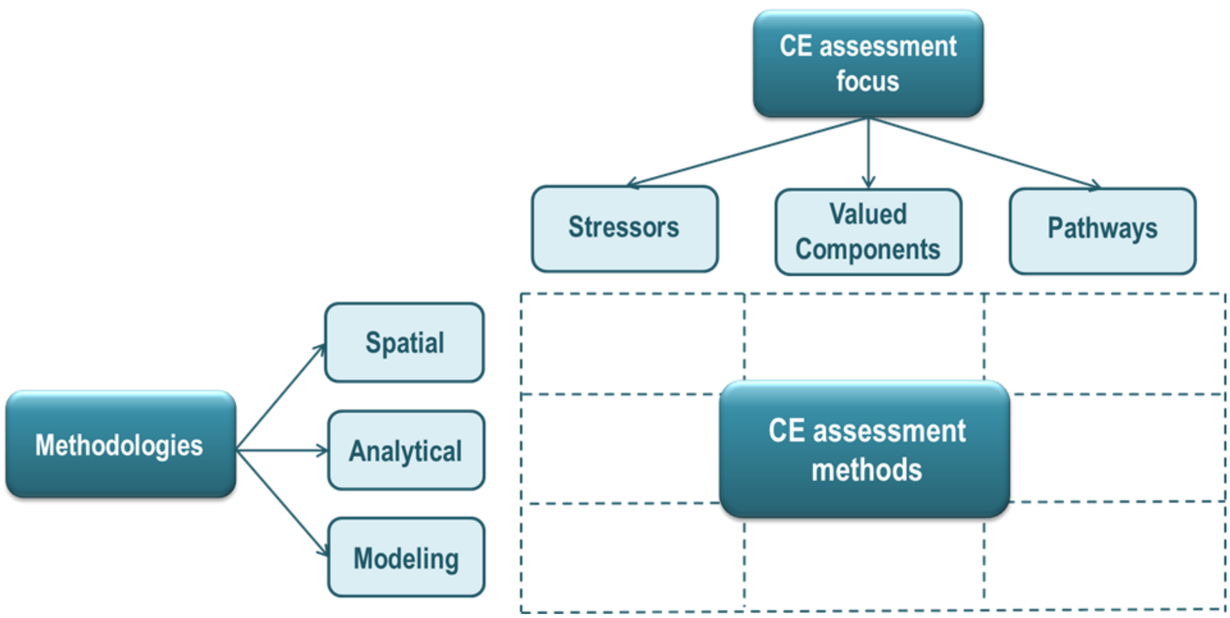

Figure D.3: Organizational structure for the evaluation of cumulative effects assessment methods.

The Tier 2 evaluation provides an overview and evaluation for each of the three categories of methods (*Section 4*[15]).

- **Overview:** A detailed description of specific methods and associated tools as applied to: stressors, VCs, and pathways

[15] Italicized section references refer to the full report

- **Evaluation:** An evaluation of the methodologies against a fixed set of criteria. These criteria inform about attributes of the methods which are especially important in selecting an approach: the **relevance** of the method in relation to the CEMS initiative; the **rigour** of the approach in terms of how well established it is in CE practice, the level of information supporting the assessment and the treatment of uncertainty; and its **feasibility** as a general estimation of how easy it would be to implement the assessment approach.

In order to help determine which methods might be appropriate under different scenarios, the Tier 2 evaluation also:

- Provides a qualitative ranking (high, medium, low) for each of the methods x criteria (*Section 5.2*).
- Documents the generic application of the methods, provides hypothetical examples of their use under the CEMS initiative and identifies specific methods and tools relevant for each method category (*Section 5.3*).
- Describes 30 cases studies (*Section 5.4*) that illustrate the application of the assessment methods in a context relevant for Transport Canada. In general, the case studies use more than one method or tool in combination to achieve their study objectives. These case studies are not included in this workshop backgrounder.

Detailed evaluation of candidate methods

Spatial methods

Overview

Spatial methods to assessing cumulative effects involve identifying the locations of stressors and VCs to understand how VCs are being exposed to stressors (i.e., geographical overlap) and the way that exposure results in different levels of effect. Spatial approaches can entail simply mapping locations to understand where there are different types of stressors and VCs as well as using characteristics about the stressors and VCs along with analytical approaches or modeling to better understand the magnitudes of effect. In this way, spatial approaches are not distinct from analytical and modeling methods but rather complementary.

The most relevant characteristics of spatial methods include the following:

- Spatial methods are **one of the most common approaches** observed in our evaluation and are expected to be a key method for the CEMS initiative.
- Spatial assessments may be particularly **useful during early iterations** to refine scope (e.g., identify geographical hotspots) and to identify information gaps.
- Although there are many ways to collect spatial data, and many ways resulting spatial information can be used, at the foundation of spatial approaches is **a single conceptually simple method**: Mapping locations and characteristics of activities/stressors and VCs.
- Inferences should not be made at **spatial scales** that are finer than the datasets allow.
- Data related to activities/stressors are often easier to gather/collect than data related to VCs, which can result in **greater uncertainties for inferences related to VCs**.

- In light of large data requirements, assessments often require **assumptions where little or no information is available**. When spatial assessment involves complementary analytical or modeling approaches, assumptions related to those methods also apply.

Application to CEMS

Type and intensity of vessel traffic differs spatially along Canadian coasts. Identifying and mapping the suites of stressors occurring in different spaces allows for identifying hotspots of concern or areas where management efforts can be focused (Ban et al. 2010). Further identifying and mapping suites of VCs allow for highlighting spaces where specific management actions may be applied to reduce effects on specific values. In the context of the CEMS initiative, spatial methods can support (Table D.) mapping the location and intensity of shipping stressors and mapping the location of VCs of interest. Overlapping these two sets of spatial information allows the identification of hotspots or areas of concern.

Table D.1: Generic application of spatial methods

Category	Generic application	Specific example of how the CEMS initiative might use methods in each category	Methods and associated tools
Stressor	Map the location and intensity of marine shipping stressors	Using AIS data, vessel density information can be used to identify in a spatially explicit way the magnitude of various stressors associated with movement underway. By connecting this spatially explicit data with models related to stressors, estimated stressor magnitudes can then be examined along with locations of VCs to identify geographical areas of concern. For example, underwater noise could be modeled based on the density of traffic, and that information can then be overlaid with information about the distribution of marine mammals.	Tools: ArcGIS, QGIS, SeaSketch
Valued component	Map the location of observations	Related to the stressor example in the row above, maps of locations of marine mammal observations and marine mammal critical habitat (as identified by DFO) could be overlaid with vessel density information to identify geographical areas of concern. This information can then inform where further work may be needed to monitor and/or model effects.	Tools: ArcGIS, QGIS

Evaluation

Table D.2: Evaluation of spatial methods

Category	Method	Evaluation criteria		
		Relevance	Rigour	Feasibility
Stressors	Mapping	Useful for understanding the spatial variability of different types of stressors, especially given that the type and intensity of vessel traffic differs spatially in Canadian waters.	Methods for mapping stressors are well documented in peer-reviewed papers. High	The method is intuitive in application and interpretation. It can incorporate multiple types of data, which are relatively easy to collect. Compilation of data

Category	Method	Evaluation criteria		
		Relevance	Rigour	Feasibility
		Can use Indigenous knowledge with this method. High		requires skills and tools that are widely used. High
Valued components	Mapping	Useful for understanding the spatial condition of VCs, and along with stressor information, the exposure of VCs to different stressors. Can use Indigenous knowledge with this method. High	Methods for mapping stressors are well documented in peer-reviewed papers. High	The method is intuitive in application and interpretation. It can incorporate multiple types of data, and compilation of data requires skills and tools that are widely used. Data collection can be costly if they do not already exit. High
Pathways	Cumulative impact mapping	A spatially explicit way to connect stressors to effects on the underlying ecosystem using limited data. May be useful depending on the assessment need. Although not common with other applications, could use Indigenous knowledge with this method. Medium	Cumulative impact mapping has been applied in many places with an approach that is well documented in peer-reviewed papers. Data needs are high, which result in data limitations that require assumptions to draw conclusions. Medium	There are multiple documented applications to follow in applying it. However, with high data requirements requiring assumptions, there is complexity in the nuance of the application. It also requires conducting expert elicitation. Medium

Analytical methods

Overview

The key characteristic of these methods is the use of **empirical data**[4] (i.e., data from observations). In the context of the CEMS analytical methods are would be used to identify spatial distributions of VCs and to evaluate the nature of the relationships between stressors and VCs (i.e., pathways).

Analytical methods for identifying the spatial distribution of VCs include home-range estimation and Habitat Suitability Models (HSM). These methods are simple in concept, although HSM requires a slightly more involved analysis, and there are multiple freely available software tools to support them. A combination of GIS and moderate statistical expertise are required.

The report describes a wide range of analytical methods for assessing pathways including: risk assessment, regression analysis, classification and regression trees and forests, principal component analysis and weight of evidence approaches. These methods vary in their complexity, rigour, and data requirements.

The key insights from the evaluation of analytical methods include:

- Assessment of the functional relationships between stressors and VCs using **empirical evidence is a critical component of cumulative effects assessment**. This step is essential to: validate the nature of hypothesized pathways, refine the scope by identifying the most important pathways, improve the accuracy of models used to evaluate alternative scenarios, inform development of meaningful thresholds, prioritize mitigation activities, and quantify uncertainty.
- These methods are data intensive and their applicability depends on **data availability and data quality**.
- **Risk assessment** is anticipated to be a useful scoping method for the CEMS initiative to help refine the priorities in each region.

- **Weight of evidence** is anticipated to be a useful method for the CEMS initiative to evaluate the relative importance of different pathways in each region. This is particularly expected to be the case in early iterations of the initiative assuming that the data are limited and varied in nature as is typical for any new initiative.
- More **complex and data rich methods** should be invested in for priority pathways where uncertainties and potential benefits are high. This includes supporting monitoring to address critical data gaps.
- **R statistical software** is freely available, well documented, accepted in academic setting, and has readily available tools to support most of the analytical methods discussed.

Application to CEMS

Analytical methods can support the CEMS initiative in various ways (Table D.):

- Determine the spatial distribution of VCs of interest.
- Develop habitat suitability models so distributions can be predicted based on habitat characteristics.
- Complete risk assessments to identify high priority areas or pathways where the exposure and consequence are high.
- Quantify the magnitude and nature of the functional relationships between stressors and VCs (i.e., pathways).
- Identify the relative importance of different pathways (i.e., the drivers of the system).

Table D.3: Generic application of analytical methods

Category	Generic application	Specific example of how the CEMS initiative might use methods in each category	Methods and associated tools
Valued Component	Determine the spatial distribution of VCs of interest. Develop habitat suitability models so distributions can be predicted based on habitat characteristics.	Observations on sea otters could be used to identify their home ranges during different times of the year and during different times in their life-cycle. This information could be used to inform vessel movement decisions/restrictions temporally during the most vulnerable periods. If data allowed or funding could be secured for monitoring, additional habitat information could be used to generate a habitat suitability model. This would allow researchers to make predictions about spatial distributions in locations without direct observations or under alternative future scenarios.	Methods: Utilization distribution, Habitat Suitability Modeling Tools: R programming language, USGS HSI software
Single Pathway	Complete risk assessments to identify high priority areas or pathways where the exposure and consequence are high.	The CEMS initiative could undertake risk assessments for priority VCs in each region to identify the stressor-VC pathways where the risk is the greatest. This would enable regions to focus more extensive monitoring and modeling efforts on a smaller subset of priority VCs which are most vulnerable to the stressors observed in each region. For example: • In the Arctic a risk assessment could be used to determine which of the concerns (e.g., increased vessel traffic impacts to food security) raised by Indigenous peoples and stakeholders are most at risk due to current or increased shipping activity.	Methods: Risk assessment Tools: EcoFate

Category	Generic application	Specific example of how the CEMS initiative might use methods in each category	Methods and associated tools
		• In the Bay of Fundy, risk assessment could be used to determine which species of concern are most at risk to oil spill events, a leading cause for concern in this region.	
Single Pathway	Quantify the magnitude and nature of the functional relationships between stressors and VCs (i.e., pathways).	Quantifying the impact of movement underway on breeding bird colonies would help to inform decisions around how much is too much. In many cases the functional relationship between a stress and an observed response in a VC is non-linear, i.e., there may be tipping points. In this example, it is possible that there is a certain number of disruptions that are tolerated before a nest is abandoned. Once these functional relationships are quantified they can be incorporated into simulation models which relate alternative stressor scenarios to population or ecosystem level responses.	Methods: Regression Tools: R programming language
Multiple Pathways	Identify the relative importance of different pathways (i.e., the drivers of the system).	A weight of evidence approach could be used to identify the pathways of greatest concern to beluga populations in the Saint Lawrence River. This would involve collecting the best available data on potential stressors (e.g., noise, collisions, oil spills, tourism, vessel wastewater, climate change) and beluga populations. If one or two stressors stand out, these can then be prioritized in future monitoring and modeling efforts. In addition, any information about the magnitude and nature of the functional relationship could be incorporated into future modeling or mitigation efforts as described in the single pathway example.	Methods: Regression, CART, Forests, PCA, WoE Tools: R programming language

Evaluation

Table D.4: Evaluation of analytical methods

Category	Method	Evaluation criteria		
		Relevance	Rigour	Feasibility
Valued components	Home-range estimation	Identify critical habitats. Medium	Well documented use in academic papers. Can account for uncertainty. High	The method is intuitive in application and interpretation. It is relatively flexible in terms of data requirements and can incorporate a variety of sources of varying degrees of precision. At a minimum the method requires georeferenced observations for the VC of interest. There are a variety of freely available software tools to support this method. High
	Habitat Suitability Modeling	Identify critical habitats and predict species distributions. High	Well documented use in academic papers. Can account for uncertainty. High	The method is intuitive in application and interpretation. The analysis and data requirements are more intensive than for home-range studies. In addition to georeferenced observations of the VC, data are also required for habitat at locations with and without the

Category	Method	Evaluation criteria		
		Relevance	Rigour	Feasibility
				VC present. Users require moderate statistical knowledge. Medium
Pathways	Risk Assessment	Useful for identifying high priority pathways where the exposure and consequence are high. As a scoping and prioritization tool, this method is highly relevant. It is not well suited to quantifying the actual functional response of a VC to an activity or stressor. Medium - High	Well documented use in academic papers, however the method is less standardized and less quantitative than many of the other analytical methods. Ad-hoc methods are sometimes used to address uncertainty. Medium	The method is intuitive in application and interpretation. It is relatively flexible in terms of data requirements and can incorporate a variety of sources of varying degrees of precision. High
	Regression analysis	Assess magnitude and nature of functional relationships between stressors and VCs as well as identify the relative importance of different pathways (i.e., the drivers of the system). High	The most established analytical method discussed in this report. Well documented use in academic papers. Can account for uncertainty. Given sufficient data this is the preferred method to quantify relationships. High	Data intensive. Implementation and interpretation are challenging. Users require significant statistical knowledge. Application to a single pathway is less challenging (i.e., requires less data and is easier to implement and interpret) than trying to evaluate the relative importance of many stressors on a particular VC. Low
	Classification and Regression Trees or Forests	Assess magnitude and nature of functional relationships between stressors and VCs. High	A more recent development in the literature but this approach is still well documented in academic papers. Bootstrap methods are used to account for uncertainty. Medium	This approach is more data intensive than regression analysis. The method is relatively easy to implement and interpret through use of freely available software tools. It may be useful when there are a relatively large number of potential stressors and uncertainty in terms of the nature of the relationships. There are a variety of freely available software tools to support this method. Users require moderate statistical knowledge. Medium
	Principle Components Analysis	Identify the relative importance of different pathways (i.e., the drivers of the system). Primarily useful in this context to help refine scope. Medium	Well documented use in academic papers. Can account for uncertainty. High	Data intensive. Implementation and interpretation can be intimidating without statistical expertise. Low or medium?
	Weight of Evidence	Identify the relative importance of different pathways (i.e., the drivers of the system). High	Well documented use in academic papers, however the method is less standardized and less quantitative than many of the other analytical methods. Uncertainty may be addressed quantitatively or using ad-hoc approaches within some lines of evidence and not others. Medium	This method has intuitive appeal and is conceptually simple yet can incorporate more rigorous information where available. The method can incorporate a variety of data sources varying in quality and quantity. High

Modeling methods

Overview

Models are tools that enable the abstraction and representation of natural systems and the prediction of their behavior. In this sense, a key characteristic of modeling approaches is that they can be used to test alternative scenarios or management options. By adjusting the model parameters, we can investigate how the system reacts to changes in the stressors or to the implementation of mitigation measures.

Specifically, for the marine environment, a broad range of modeling approaches have been used to model cumulative effects (Clarke Murray et al. 2014); from conceptual models describing the system and the interactions among stressors and VCs to complex quantitative predictive models assessing the effects of specific pathways or stressors.

Unlike analytical methods, models can be developed in absence of empirical data. This usage can test alternatives using expert knowledge and current hypotheses about the system. Sensitivity analysis can help to bound the problem and identify the most sensitive parts of the system. Pathways with the greatest influence or uncertainty in terms of their impact on the VC can then be prioritized in terms of data collection.

Single-stressor models, such as underwater noise or oil spill models, are extremely useful in predicting the intensity of a specific stressor in a region. These models are well established by decades of research and case studies and applications can be found for different geographic contexts. For instance, noise propagation models have been developed for the Pacific region (Erbe et al. 2012, O'Neill et al. 2017, Cominelli et al. 2018), the Arctic (Aulanier et al. 2017, Halliday et al. 2017), and the Saint Lawrence estuary (Chion et al. 2017).

Ecological models, focusing on a single-species, multiple species on a whole ecosystem, have been mostly applied to fisheries management. There are single species models, such as Population Viability Analysis, which can be combined with information about anthropogenic stressors to assess how human activities can impact a species at the population level (Lacy et al. 2017). Trophic ecosystem modeling frameworks, such as Ecosim with Ecopath (EwE) are increasingly being applied to environmental and management problems other than fisheries. Harvey (2018) has recently studied the effects of underwater noise on cetacean populations off the coast of Scotland using a EwE modeling framework.

Single pathway models provide an opportunity to gain a more in-depth understanding of a pathway of interest (i.e., effects of given stressor on a priority VC). Most importantly, they can be used to test alternative scenarios or management actions and their effects on the interactions between stressors and valued components. For instance, Chion et al. (2017) used the 3MTSim model to estimate how shipping restriction measures affect the beluga population in the St. Lawrence.

Multiple pathways models are problem-structuring frameworks and can be applied to any combination of stressors and valued components (Patrício et al. 2016). These models vary in their complexity from simple conceptual models (e.g., pathways of effects) to spatially-explicit models which combine multiple modeling techniques under a spatially explicit predictive framework enables a holistic assessment of the system and facilitates evaluation of alternative monitoring and management actions (Bastos et al. 2017).

General insights about modeling methods emerging from the evaluation include the following:

- A key distinction of modeling methods is that they can be used to test **alternative scenarios** or management options, the third component of the assessment step (*Figure D.*).
- Unlike analytical methods, **models can be developed in absence of empirical data**. This usage can test alternatives using expert knowledge and current hypotheses about the system. Sensitivity analysis can help to bound the problem and identify the most sensitive parts of the system. Pathways with the greatest influence or uncertainty in terms of their impact on the VC can then be prioritized in terms of data collection.

- **Spatially explicit simulation models which relate stressors to VCs and enable evaluation of alternative scenarios are the ultimate CEA method**. However, the level of data, effort, and expertise required for their implementation, makes spatially explicit models best suited at regional scales for a sub-set of highest priority VCs and pathways of greatest impact and potential for improvement.

Application to CEMS

Our review has identified a wide range of modeling methods that could support the CEMS initiative. These methods can assist in articulating hypotheses and scoping (i.e., conceptual models), quantifying the intensity of stressors (stressor models), assessing the state and interactions among the components of the environment (valued component models), linking the stressors with their effects on valued components (single pathway models) and in studying how multiple pathways can have impacts on one or more valued components (multiple pathways models).

Table D.5: Generic application of modeling methods

Category	Generic application	Specific example of how the CEMS initiative might use methods in each category	Methods and associated tools
Stressor	Modeling the magnitude or distribution of the stressor associated with a particular activity.	The impact of anchoring in Northern BC could be investigated by first modeling the substrate disturbance or 'anchoring footprint' for individual boats under different conditions (e.g., tide, wind, current) and then using this to assess the current disturbance as well as alternative future scenarios. This information could later be overlaid with VC or habitat distribution information to inform the magnitude of the impact (i.e., single pathway assessment).	Noise models: RAM, RANDI, NONM, NEMES Oil spills modeling: MOTHY, MEDSLIK, MEDSLIK-II, POSEIDON-OSM, SAMSON, H3D, SPILLCALC Emissions: MEIT
Valued Component	Simulate how a stressor or multiple stressors can affect an ecological component of the environment at the species, habitat or ecosystem scale.	A life cycle model for salmon could be generated to inform population viability analyses. In other words, various life cycle parameters (e.g., juvenile survival) could be adjusted to evaluate the long-term impacts on the population. This model could later be linked to stressor models to evaluate population level responses to alternative management scenarios (i.e., single or multiple pathway models).	Method: Population Viability Analysis (PVA) Method/tools: ECOPATH with ECCOSIM (EwE), Atlantis
Single Pathway	Link stressors to specific components by simulating the process by which effects occur from one linkage to the next along a particular pathway.	A single stressor model could be generated which describes the position and movement of tankers at different times of the year in order to identify areas which are effectively no-longer available for fishing. This could then be related to a second model which describes theoretical fishing opportunity (i.e., spatial and temporal openings or traditional use areas). The combination of these two models could be used to assess current lost fishing opportunities and possible future scenarios under different mitigation options. Similarly, a pathway model can combine an underwater noise propagation model with a distribution model of sensitive cetaceans to assess the potential impacts of increased noise due to marine traffic. Vessel strike models operate in a similar way, combining traffic data with the distribution of certain species to assess the risk of collisions.	Method: linkage of single stressor and VC models Tools: 3MTSim model, Spill Impact Model Application Package (SIMAP)

Category	Generic application	Specific example of how the CEMS initiative might use methods in each category	Methods and associated tools
Multiple Pathway	Problem-structuring frameworks that can be applied to any combination of stressors and valued components to understand the combined effect of multiple pathways and their relative importance	Under a DPSIR or BBN framework, multiple shipping impact pathways (noise, risk of strikes, discharge, etc.) could be conceptualized and study to assess their relative importance and test various management options.	Methods: DPSIR, BBN, PoE, Spatially explicit models

Evaluation

Table D.6: Evaluation of modeling methods

Category	Method	Evaluation criteria		
		Relevance	Rigour	Feasibility
Stressors		Highly relevant for studying the intensity of specific stressors (noise, oil spills) and explore management scenarios. Models exist for a few stressors associated to marine shipping. High	These models are the outcome of well-established research. They are well documented. Explicitly address uncertainty. High	Extensive and specific data requirements. Users need quantitative skills and subject knowledge. Costs may include purchase of specific software. Medium
Valued components	Single species	Useful for exploring scenarios and understand the response to stressors of a species of special importance (priority VC). Medium	Well documented use in academic papers. High	Requires extensive knowledge and data of the target species. Users need quantitative/statistical skills. Medium
	Multiple species	These models focus on simulation trophic/predation interactions. Unclear link to anthropogenic pressures. Low	There are multiple case studies and academic papers documenting the applications of these models. Rigorous data treatment and explicit consideration of uncertainty. High	Requires extensive knowledge and data of the target species. Users require significant statistical knowledge to model the species interactions. Low
	Ecosystems	Primarily used for fisheries management, these models are starting to be applied to account for other human activities. However, it is unclear how it would apply to CEMS initiative unless the VC itself is an ecosystem. Medium	Extensive literature on these models. Many tools and methods available with specific documentation. Uncertainties are usually documented. High	In general, these are data intensive models requiring large data sets to calibrate and run the simulations. Low
Single pathway		These models establish the interactions between stressors and VCs and can be used to evaluate alternative scenarios. High	Well documented in the literature. Uncertainties (in the knowledge base and the predictions of the model) are well documented. High	Extensive and specific data requirements. Multi-disciplinary teams with expert knowledge. Costs may include purchase of specific software. Medium

Category	Method	Evaluation criteria		
		Relevance	Rigour	Feasibility
Multiple pathway	PoE	An explicit understanding of the cause-effect linkages between stressors and components should underlie any model. High	PoEs are considered best practice. The quality of the evidence supporting the links determines the level of uncertainty of the model. Medium	PoE models can be developed by a range of stakeholders based on the data and knowledge available. High
	DPSIR	Flexible problem-structuring approach that can be applied to a variety of contexts. Policy-oriented model. High	Limited practical application; most assessments are semi-quantitative. Medium	This model is data flexible and it can be adapted to the available resources. High
	BBN	Limited application to marine problems but these models are emerging as a solution in data-limited contexts. High	Uncertainty explicitly addressed. High	BBN models can combine empirical data and expert knowledge. High
	Spatially explicit	Holistic modeling approach that assesses the implications of cumulative effects over space. High	Case studies well documented in the literature. Uncertainty usually documented. High	These models require specific skills (spatial and stochastic modeling) and are more data-intensive than other multiple pathways models. Medium

Supporting and organizing methods

Apart from the three categories of assessment methods (i.e., spatial, analytical and modeling) evaluated in detail, we identified and summarized several other methods that may be useful for the CEMS initiative.

Supporting methods

Indigenous knowledge and **expert elicitation** methods can support the assessment of cumulative effects in various ways, especially in terms of complementing limited data on the socio-ecological systems under study. For example, Indigenous knowledge held by individuals within coastal communities includes a wealth of information that can be useful for better understanding the dynamics of complex systems, provide insights the connections between traditional management practices and cultural beliefs, inform marine management decisions, and support resilience in the face of changing ecosystems.

Similarly, different methods have used expert elicitation to identify components important for inclusion in assessment, including what human activities should be included, what stressors result from which activities, and what components of the socio-ecological system are important to include. Expert elicitation has also been used to quantify the relationship between the different components within the system. For example, the cumulative impact mapping approach developed by Halpern et al. (2008) involves eliciting expert judgement to estimate ecosystem-specific levels of impact for multiple anthropogenic drivers of ecological change.

Organizing methods

Our evaluation also identified organizing frameworks that integrate a suite of assessment methods and tools in a way that allows decision-makers to utilize the information generated through the assessment process (Figure D.).

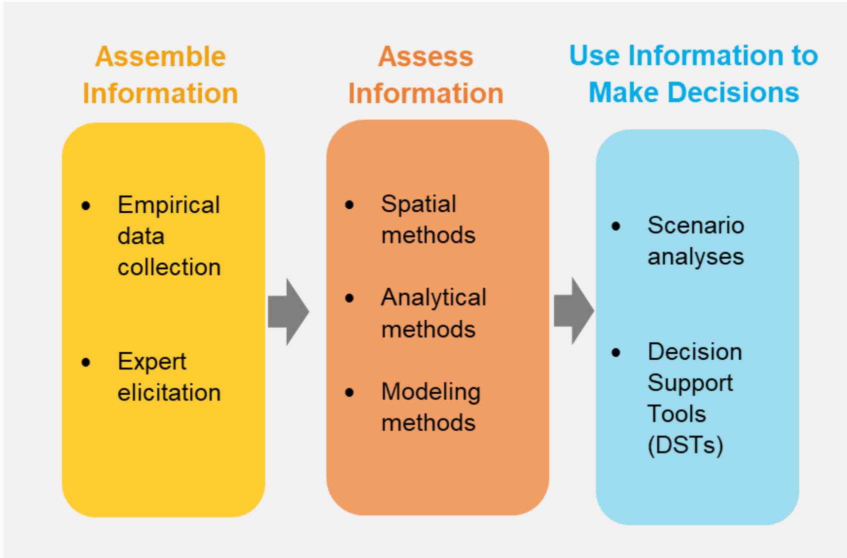

Figure D.4: A conceptual diagram, highlighting how a framework can help organize how we assemble information, assess information, and use information to arrive at management decisions

Risk assessment frameworks provide a means of qualitatively and quantitatively evaluating the exposure of a valued component to a stressor, and its sensitivity. The framework can utilize spatial and analytical assessments, Indigenous knowledge, expert elicitation, causal relationships, and model outputs to assess the relative impact of various stressors on valued components.

Frameworks such as the **EU Marine Strategy Framework** and the **BC Cumulative Effects Framework** permit CEA's to explicitly address management concerns by clearly defining objectives and thresholds (i.e., what is considered "good environmental status"), and allow analyses to occur at broad or fine scale resolution by introducing scale-specific objectives. These and other existing examples may provide useful templates for the CEMS.

Conclusions

Overarching insights

Assessing cumulative effects as part of the CEMS initiative will require a combination of assessment methods. On their own, most of the methods evaluated are insufficient to complete a full assessment. However, they each can perform important roles through the assessment process, specifically:

- Spatial methods are most useful for evaluating the reference condition of either activities/stressors or VCs as well as understanding how VCs are spatially exposed to activities/stressors;
- Analytical methods based on empirical data are useful for interpreting spatial data to inform our understanding of key habitat requirements, evaluating risk, and quantifying the relationships between stressors and VCs (i.e., pathways);
- Modeling methods build on the previous two categories and are necessary for evaluating alternative scenarios.

Examples addressing social VCs were less prevalent in the evaluation however insights generally apply to both ecological and social VCs.

Marine shipping activities are relevant nationally, whereas VCs and impact pathways differ by region. It may be possible to select a single modeling tool for stressors of concern (e.g., oil or noise) and replicate these across multiple regions. This would improve efficiency, build capacity, and enable results to be more easily compared across regions. However, it is likely that different methods and associated tools will be required to assess VCs and impact pathways in each region depending on the nature of the VCs, the intensity of stressors, the local data availability and capacity.

Preliminary guiding principles

The following list of guiding principles emerged from the evaluation.

Table D.7: Guiding principles for implementation of the assessment step of the CEMS initiative.

Principle	Description
Identify management objectives early in the process	Identifying management decisions up front will help to characterize alternative **scenarios** of interest. Identifying mitigation opportunities which are within control of the CEMS initiative will also help to focus assessment efforts.
Focus on the essential	It is not possible to assess everything. Scoping to a manageable set of **priority VCs** (e.g., less than 10), **stressors of concern**, and most important pathways is critical to successful implementation of the assessment step. The CEMS initiative is currently in the process of collaboratively refining the scope in each region. The process for prioritization and resulting decisions should be documented. Scope refinement is expected to continue iteratively as the assessment progresses.
Build on existing work	Where possible leverage existing work rather than starting from scratch. There are a number of related initiatives which could be employed to support different aspects of the CEMS initiative. This can include everything from: CEA frameworks, existing modeling tools, analyses quantifying pathways, thresholds, monitoring and data management systems.
Explicitly identify uncertainties	This may include model assumptions, data gaps or data uncertainty. Uncertainty may be expressed quantitatively or qualitatively.
Keep it simple	Models are complex assessment methods and this complexity increases as the scope of the model increases (e.g., pathways instead of single stressors or VCs). To avoid unnecessary complications, the simplest model that achieves the objectives of the assessment should be selected. We recommend coupling several smaller and simpler models rather than creating a single all-encompassing model (e.g., linking a stressor model for noise to a separate life cycle model for beluga populations). This approach is better able to leverage existing work, builds upon the strengths of subject matter experts, and reduces complexity. In general, we recommend only considering one VC at a time, although multiple stressors and pathways should be considered simultaneously. The added complexity of modeling multiple VCs simultaneously is not expected to be fruitful except perhaps in cases where there are clear trophic level interactions between VCs (e.g. marine mammals and forage fish). Even so, these would likely be questions for later iterations as specific uncertainties are identified.

Selection of assessment method

Selecting specific methods and associated tools within each category depends on the: relevance (e.g., priority VCs), rigour (e.g., credibility of the method and quality of the outputs), and feasibility (e.g., capacity/funding) of different options within the category. In general, early iterations of the assessment step tend to use simpler less data intensive methods and are more focused on refining scope and identifying knowledge gaps. Whereas later iterations involve more complex methods applied to a narrower scope (e.g., the most important pathways).

We propose a series of guiding questions for consideration when selecting assessment method(s) to be used along with the detailed summary tables of the report (*Tables 5.2 and 5.3*):

- **Relevance**
    - *What stage of the assessment process are you in?*
    - *Have the most important pathways been identified?*
    - *What management decisions are informed by the CEA?*
- **Rigour**
    - *What level of information is available for priority VCs and stressors?*
    - *Is it possible to supplement the available information with Indigenous or expert knowledge?*
    - *Is it possible to collect new data?*
- **Feasibility**
    - *What is the general knowledge and skill level of the team conducting the CEA?*
    - *What are the resources (e.g., time, money) available for conducting the CEA?*
    - *Are there existing applications of methods or tools for priority VCs, stressors of concern, or impact pathways?*
    - *Who are the key stakeholders and what is the best way to communicate the results?*

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[1] **Stressor** is any physical, chemical, or biological means that, at some given level of intensity, has the potential to negatively affect a valued component. [Thornborough et al. 2018 (DFO)]

[2] **Valued components** refer to environmental features that may be affected by an activity and that have been identified to be of concern by the proponent, government agencies, Indigenous peoples, or the public. The value of a component not only relates to its role in the ecosystem, but also to the value people place on it. For example, it may have been identified as having scientific, social, cultural, economic, historical, archaeological, or aesthetic importance. [Definition is adapted from CEAA 2012]

[3] **Cumulative effect** is a change in the environment caused by multiple interactions among human activities and natural processes that accumulate across space and time

[4] **Empirical** "originating in or based on observation or experience" Merriam-Webster [https://www.merriam-webster.com/dictionary/empirical]