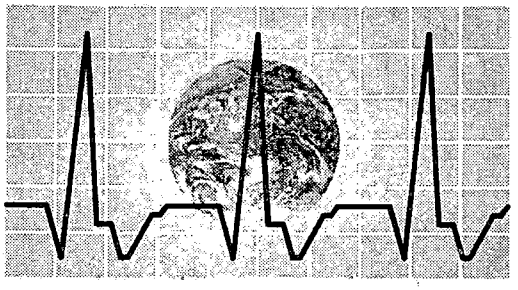
STATE OF THE ENVIRONMENT REPORTING

Selecting Indicators of Marine Ecosystem Health: A Conceptual Framework and an Operational Procedure



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State of the Environment Reporting

Selecting Indicators of Marine Ecosystem Health: A Conceptual Framework and an Operational Procedure

Occasional Paper Series No. 9

Prepared for:

The National Marine Indicators Working Group

Environment Canada and Fisheries and Oceans Canada

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Note to reader

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EXECUTIVE SUMMARY

Indicators are a means of translating and communicating scientifically credible information about trends in environmental health in a manner that is concise, easily understood, and easily used by decision-makers, nonspecialists, and the public. This report lays out both a framework and a procedure for selecting indicators to track trends related to marine ecosystem health. It offers proven concepts and methods, such as:

- a multilevel conceptual framework using an ecosystem approach;
- criteria for selecting linkages and indicators;
- an operational procedure; and
- application of the procedure to the example of pathogens in the marine environment.

Five elements represent a required "short list" of measurements for the assessment of marine ecosystem health:

- *Contaminants*—the presence of harmful synthetic or natural chemicals that have been released by human activity
- *Pathogens, biotoxins, and disease*—which may harm marine biota and human populations
- *Species diversity and size spectrum*—a core measure of ecosystem structure
- *Primary productivity and nutrients*—a core measure of ecosystem function
- *Instability*—the ability of the ocean "climate" to have different states.

The development of indicators to measure marine ecosystem health involves several steps. The focus of this report is the step of selecting indicators. It is particularly important to use a suite of different types of indicators. These should be selected from diverse environmental components (air, water, land, biota), as well as from a wide range of social and economic factors.

The framework for indicator selection can be translated into key ecosystem health questions:

1. What is happening to the environment? [CONDITION]
2. Why is it happening? [STRESS]
3. Why is it significant or important? [EFFECT]
4. What are we doing about it? [RESPONSE]
5. Is sustainability being achieved?

Indicators that answer these questions serve to gauge progress towards preserving ecosystem health. However, the simple cycle of stress, condition, effect, and response needs to be expanded. The expanded framework shows the greater levels of detail usually required by practitioners. Such a hierarchy, with successive levels of detail, allows for refinements necessary for selecting specific indicators. For example, environmental conditions can be divided into such categories as upper atmosphere, marine water, birds, and mammals.

A step-by-step operational procedure is presented to apply the framework in selecting indicators. An example is given for each step, using the issue of *pathogens in the marine ecosystem.*

There are five steps to the procedure:

- Generate an issue statement.
- Understand and refine the framework.

- Draw and validate the linkages.
- Select the indicators.
- Summarize the information.

The contribution of this paper is its consolidation of a wide variety of concepts into a single, operationally oriented package that will assist in the selection of marine indicators for future State of the Environment reporting.

SOMMAIRE

Les indicateurs offrent un moyen de traduire et de communiquer des données crédibles sur le plan scientifique au sujet des tendances de l'état de l'environnement, d'une manière concise, tout en étant faciles à comprendre et à utiliser pour les décideurs, les non-spécialistes et le public. Le présent rapport décrit donc un cadre et une marche à suivre pouvant servir à sélectionner des indicateurs qui permettront de suivre les tendances de l'état des écosystèmes marins. Il présente des concepts et des méthodes éprouvés, par exemple :

- un cadre conceptuel à plusieurs niveaux utilisant une approche écosystémique;
- des critères de sélection des liens d'interdépendance et des indicateurs;
- une procédure opérationnelle;
- l'application de la procédure à l'exemple des pathogènes dans les écosystèmes marins.

Cinq éléments constituent la « courte liste » requise de mesures en vue de l'évaluation de l'état des écosystèmes marins :

- *Contaminants*— présence de produits chimiques naturels ou synthétiques nuisibles résultant d'une activité humaine
- *Pathogènes, biotoxines et maladies* — qui pourraient nuire au biote marin et aux populations humaines
- *Diversité et spectre de taille des espèces* — mesure fondamentale de la structure des écosystèmes
- *Production primaire et nutriants*— mesure fondamentale de la fonction des écosystèmes
- *Instabilité* — la capacité du « climat » océanique d'avoir différents états.

L'établissement d'indicateurs pour mesurer l'état des écosystèmes marins comporte plusieurs étapes. Le présent rapport est axé sur celle de la sélection des indicateurs. Il est particulièrement important d'utiliser un ensemble d'indicateurs de différents types. Ceux-ci devraient être choisis dans les diverses composantes de l'environnement (air, eau, terre, biote) et parmi un large éventail de facteurs sociaux et économiques.

Le cadre de sélection des indicateurs peut être traduit en quelques questions fondamentales sur l'état de l'environnement :

1. Qu'arrive-t-il à l'environnement? [ÉTAT]
2. Quelle est la cause? [STRESS]
3. Pourquoi est-ce important ou significatif? [EFFET]
4. Que faut-il faire? [RÉACTION]
5. La durabilité est-elle assurée?

Les indicateurs qui répondent à ces questions servent à mesurer les progrès réalisés pour la préservation de l'environnement. Cependant, le simple cycle des éléments stress, état, effet et réaction doit être étendu. Le cadre élargi montre les niveaux détaillés habituellement requis par les praticiens. Une telle hiérarchie, avec ses niveaux de détail successifs, permet d'arriver au niveau de raffinement nécessaire pour choisir des indicateurs précis. Par exemple, l'état de l'environnement peut être divisé en catégories telles que la haute atmosphère, l'eau de mer, les oiseaux et les mammifères.

Une procédure opérationnelle est présentée, étape par étape, pour l'application du cadre de sélection des indicateurs. Chaque étape inclut un exemple basé sur le problème des *pathogènes dans les écosystèmes marins*.

La procédure comporte cinq étapes :

- Produire un énoncé du problème.
- Comprendre et raffiner le cadre.
- Établir et valider les liens d'interdépendance.
- Sélectionner les indicateurs.
- Résumer l'information.

Le présent document a pour but de consolider divers concepts en un ensemble axé sur le contexte opérationnel qui aidera à la sélection d'indicateurs de l'état du milieu marin pour de futurs rapports sur l'état de l'environnement.

PREFACE[1]

An indicator is a statistic or parameter that, tracked over time, provides information on trends in the condition of a phenomenon and has significance extending beyond that associated with the properties of the statistic itself. Environmental indicators are selected statistics that represent or summarize key aspects of the state of the environment, natural resource assets, and related human activities. They focus on trends in environmental changes, the stresses causing them, how the ecosystem and its components are responding to these changes, as well as the societal responses to them.

The Indicators and Assessment Office of Environment Canada leads the development of a national set of environmental indicators that gives a representative snapshot of the state of the environment and helps measure progress towards sustainable development. Research and development to improve these indicators have been ongoing through cooperative work with other federal government agencies and an extensive consultation process with stakeholders in both public and private sectors and with nongovernment organizations.

The Indicators and Assessment Office also promotes conceptual work into sustainable development indicators and their linkages as well as the development of implementation tools.

[1] Adapted from Neimanis and Kerr 1996

INTRODUCTION

Indicators are a means of translating and communicating scientifically credible information about trends in environmental health in a manner that is concise, easily understood, and easily used by decision-makers, nonspecialists, and the public (Neimanis and Kerr 1996). Indicators can be developed in a number of ways (e.g., Environment Canada Indicators Task Force 1991; MacGillivray 1995; Indicators for Evaluation Task Force 1996; Rump 1996; Water Quality Guidelines Task Group 1996). The concept of a framework to develop indicators is not new. For example, frameworks have been proposed in literature published by Environment Canada and the Organisation for Economic Co-operation and Development (OECD). Moving from conceptual frameworks to operational procedures, however, is not as well documented.

This report lays out both a framework and a procedure for selecting indicators to track trends related to marine ecosystem health. It offers proven concepts and methods, such as:

- a multilevel conceptual framework using an ecosystem approach;
- criteria for selecting linkages and indicators;
- an operational procedure; and
- application of the procedure to the example of pathogens in the marine environment.

The methods are designed to be of use to many practitioners: biologists studying animal populations, sociologists looking at community patterns, science writers preparing reports, regulators monitoring industrial problems, and developers of national- and ecosystem-level indicators.

ECOSYSTEM APPROACH

This report takes the ecosystem approach (see, for example, Larkin 1996). The ecosystem approach recognizes that progress in human societies and economies must not take place at the expense of the environment. It views the basic structures of the environment—air, water, land, and biota (including humans)—and their interrelating functions in a broad context. It integrates environmental, social, and economic concerns.

In our view, the concept of "ecosystem health" should not be defined by narrow, anthropocentric aspirations for ecosystem use, but rather by the more objective concept of ecosystem integrity. An ecosystem demonstrating aspects of "wholeness," "robustness," or "pristine conditions" would be considered to have good ecosystem integrity. By incorporating the philosophy of ecosystem integrity, marine ecosystem health can be defined as the maintenance of structure (types of species present, population size and composition) and function (movement of materials in the food web, energy sources) within the bounds of natural fluctuations.

Five elements represent a required "short list" of measurements for the assessment of marine ecosystem health:

- *Contaminants*—the presence of harmful synthetic or natural chemicals that have been released by human activity
- *Pathogens, biotoxins, and disease*—which may harm marine biota and human populations
- *Species diversity and size spectrum*—a core measure of ecosystem structure
- *Primary productivity and nutrients*—a core measure of ecosystem function
- *Instability*—the ability of the ocean "climate" to have different states.

ECOSYSTEM HEALTH INDICATORS

In our experience, the development of indicators to measure marine ecosystem health generally involves the following key steps:

- Scope the issues.
- Evaluate the knowledge base.
- Select indicators.
- Conduct targeted research and monitoring of the indicators.

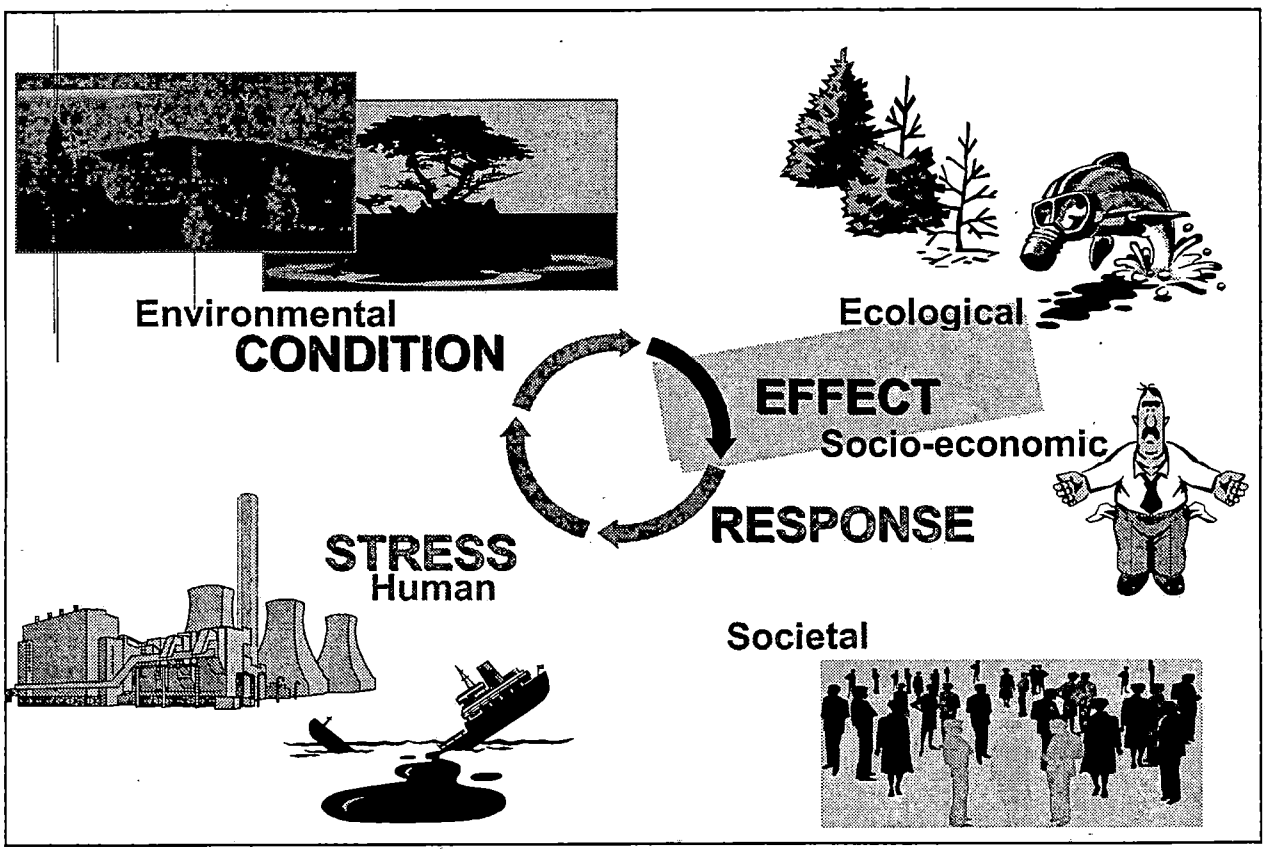
The focus of this report is the step of selecting indicators. In selecting indicators, there are some basic "ABCs"—largely common-sense practices—to follow:

- Some of the indicators should be related to ecosystem structure and function.
- Indicators should be selected in combinations (linked) rather than singly.
- Indicators should be selected using the guidance of criteria acceptable to all parties involved.

It is particularly important to use a suite of different types of indicators. These should be selected from diverse environmental components (air, water, land, biota), as well as from a wide range of social and economic factors. It is very useful to relate indicators to quantitative and qualitative targets or thresholds that are scientifically based. It is difficult, however, to obtain these "trigger" values for a given indicator. Also, the process of selection must be rigorous enough to provide meaningful and understandable indicators for measuring marine ecosystem health.

FRAMEWORK FOR INDICATOR SELECTION

Figure 1 A Framework for Indicator Selection.



GENERAL ASPECTS

Frameworks for indicator selection have been in use for some time. For example, Canada's National Environmental Indicators Program uses a cycle diagram similar to the one in Figure 1, which shows the general links between stress, condition, effect, and response. Stresses are human activities that place pressure on the environment. Conditions are subsequent changes in the state of physical and biological components of the ecosystem. Effects are the socioeconomic and ecological outcomes of these changes. Responses are society's activities to mitigate or eliminate the stress.

The framework embodies linkages between stress, conditions, effects, and response. Understanding these linkages allows hypotheses to be described and evaluated. Adequacy and relevance of the existing data are crucial. If the processes (arrows) are well enough understood, then monitoring can be conducted. If there is incomplete understanding of the processes, then research may be warranted.

The diagram can be translated into four key ecosystem health questions used by Environment Canada and others:

1. What is happening to the environment? [CONDITION]
2. Why is it happening? [STRESS]
3. Why is it significant or important? [EFFECT]
4. What are we doing about it? [RESPONSE]

These questions are at the heart of State of the Environment reporting. To them may be added another:

5. Is sustainability being achieved?

Indicators that answer these questions serve to gauge progress towards preserving ecosystem health. Indicators of environmental conditions will answer the first question ("What is happening to the environment?"). The second question ("Why is it happening?") is answered by indicators of human activities and stress agents (human *activities* such as urban development can produce stress *agents* such as contaminants). The third question ("Why is it significant or important?") is addressed by indicators of environmental effects. The fourth question ("What are we doing about it?") is answered by indicators of societal responses. The fifth question ("Is sustainability being achieved?") can be measured by comparing the indicator value to a stated target, threshold, or objective for sustainability.

There are numerous benefits derived from employing such an indicator framework, as it:

- demands an ecosystem approach;
- identifies categories for proposing candidate indicators;
- provides hierarchical levels of category detail;
- allows the identification and testing of linkages;
- offers a context for interdisciplinary analyses by multistakeholders; and
- provides a vehicle for communicating with and educating people at all levels of society.

Several papers reinforce the benefits of the framework presented here (e.g., Ecosystem Objectives Work Group 1992; Freedman et al. 1992; OECD 1993; Rapport 1993; and others). While useful, the cycle diagram is not detailed enough for practitioners who must actually conduct and defend their selection of indicators. An expanded version is required.

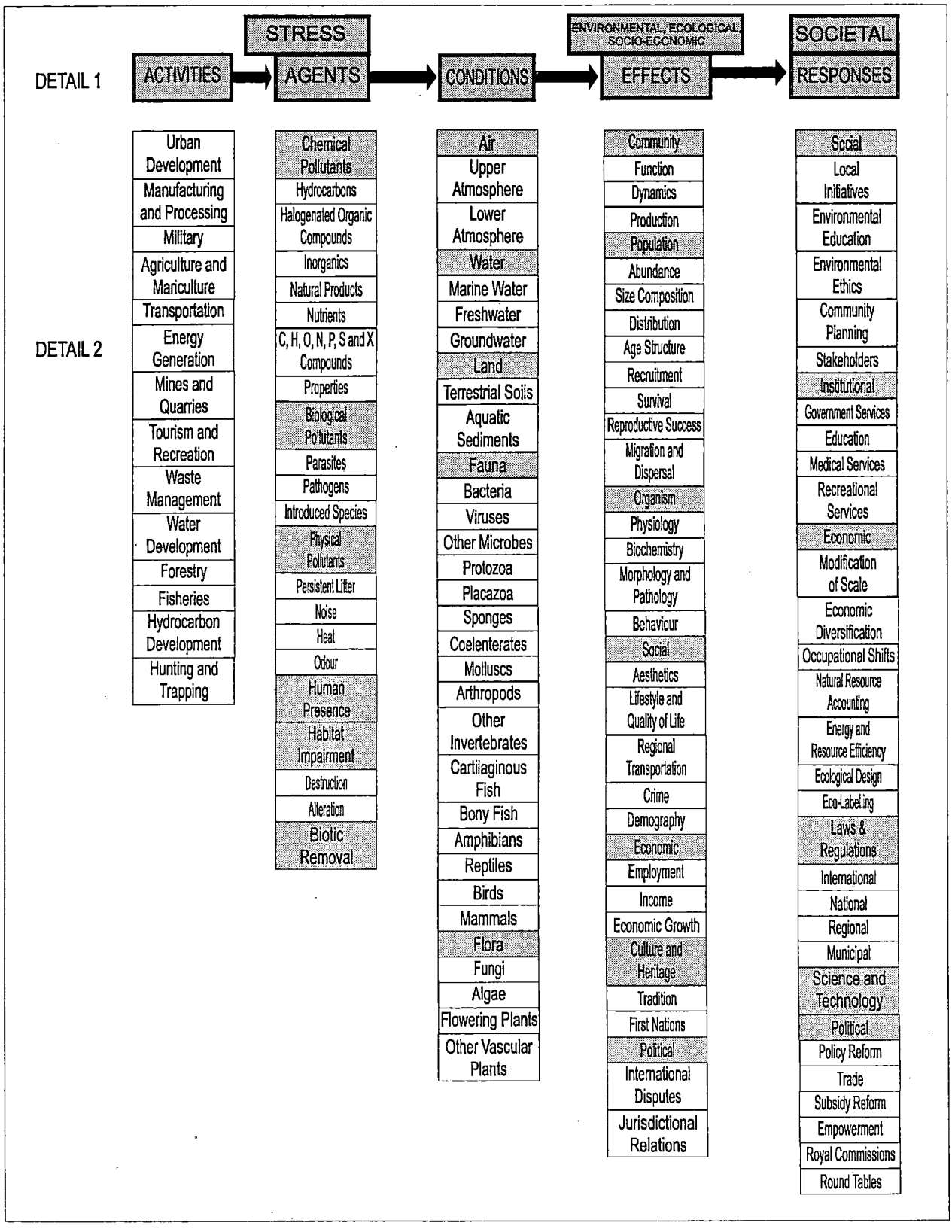
A MORE DETAILED VIEW

The expanded indicator framework presented in Figure 2 also takes an ecosystem health approach. It clearly encompasses and links social and economic values with environmental needs. However, the simple cycle of stress, condition, effect, and response is modified and expanded. The framework now also shows the greater levels of detail usually needed by practitioners. Such a hierarchy, with successive levels of detail, allows for refinements necessary for selecting specific indicators. For example, human activities are further categorized as water development, fisheries, urban development, and so on. Stress agents range from biological pollutants to habitat impairment. Environmental conditions are divided into categories such as upper atmosphere, marine water, birds, and mammals. Environmental, ecological, and socio-economic effects include social, economic, population, and organism categories. Categories of societal responses include social, economic, laws and regulations, and institutional.

Most important at the first level of detail of the framework is to link the categories together, especially responses back to stresses, so as to ensure selection of a complete suite of indicators for ecosystem health. Commonly, a single human activity may ultimately cause numerous changes in environmental conditions and have multiple environmental effects. Conversely, a single environmental effect may result from numerous human activities and stress agents. The framework is sufficiently flexible to account for such multiple linkages.

Further development of the framework could take advantage of recent advances in hypertext and hypermedia communications / computer technology, thereby enabling practitioners to examine successive levels of detail, draw appropriate linkages, and make revisions/adaptations with ease.

Figure 2 **An Expanded Framework for Indicator Selection.**



OPERATIONAL PROCEDURE—PATHOGENS IN THE MARINE ECOSYSTEM EXAMPLE

This section presents a step-by-step operational procedure to apply the framework in selecting indicators. An example is given for each step, using the issue of *pathogens in the marine ecosystem.*

There are five steps to the procedure:

- Generate an issue statement.
- Understand and refine the framework.
- Draw and validate the linkages.
- Select the indicators.
- Summarize the information.

GENERATE AN ISSUE STATEMENT

This step involves clearly defining the reason for concern. In other words, what is the valued ecological or societal feature to be "protected" from damage or alteration by a human activity, and why is a change in it significant? An issue statement relates some human action (i.e., human activity) to a change in environmental condition, which in turn causes an environmental effect.

The wording for an issue statement may seem intuitively obvious while at the same time being difficult to defend in an objective manner. A good issue statement usually reflects the concern of a broad segment of society, rather than the view of one particular special interest group. Consultations with specialists and interested stakeholders; analysis of journals, news clippings, and opinion polls; and a review of government policy statements and regulations regarding the environment can all lead to a firmer base for creating an issue statement.

Different elements of an issue statement should be able to clearly answer some basic questions, such as:

- What is causing the problem?
- How do you know there is a problem?
- Does this human activity seem sustainable?

An example of an issue statement is provided in Box 1.

Box 1 Example of an Issue Statement

"Pathogens from cities' and municipalities' sewage discharges/effluents are causing the closure of polluted shellfish growing areas and thus are adversely affecting the commercial and recreational harvesting of marine shellfish."

In this example:

- The valued ecosystem feature is "marine shellfish resources" because of the social and economic values.
- Stress is "pathogens from cities' and municipalities' sewage discharges/effluents."
- Condition is "polluted shellfish growing areas."
- Effect is "impaired commercial and recreational harvesting of marine shellfish."
- Response is "closures of shellfish growing areas."

UNDERSTAND AND REFINE THE FRAMEWORK

To be generally applicable, the framework should be readily understood and should retain a substantial degree of flexibility. While the framework shown in Figure 2 will be applicable to some exercises, finer detail levels will be warranted to select indicators (see Appendix A for an example). The practitioner should customize and refine categories for preparing a framework that is tailored to each issue statement.

DRAW AND VALIDATE THE LINKAGES

In this step, the practitioner translates the issue statement generated in Step One into a series of linkages. This is perhaps the most challenging task in the entire operational procedure, because an issue statement is often complex and can involve a dozen or more linkages.

The concept of issue statements and links was originally used as part of the Adaptive Environmental Assessment and Management (AEAM) approach of Holling (1978). Issue statements and links have been used extensively to define research and monitoring requirements associated with hydrocarbon development in the Beaufort Sea, as part of the Beaufort Environmental Monitoring Project (BEMP) and Beaufort Region Environmental Assessment and Monitoring (BREAM).

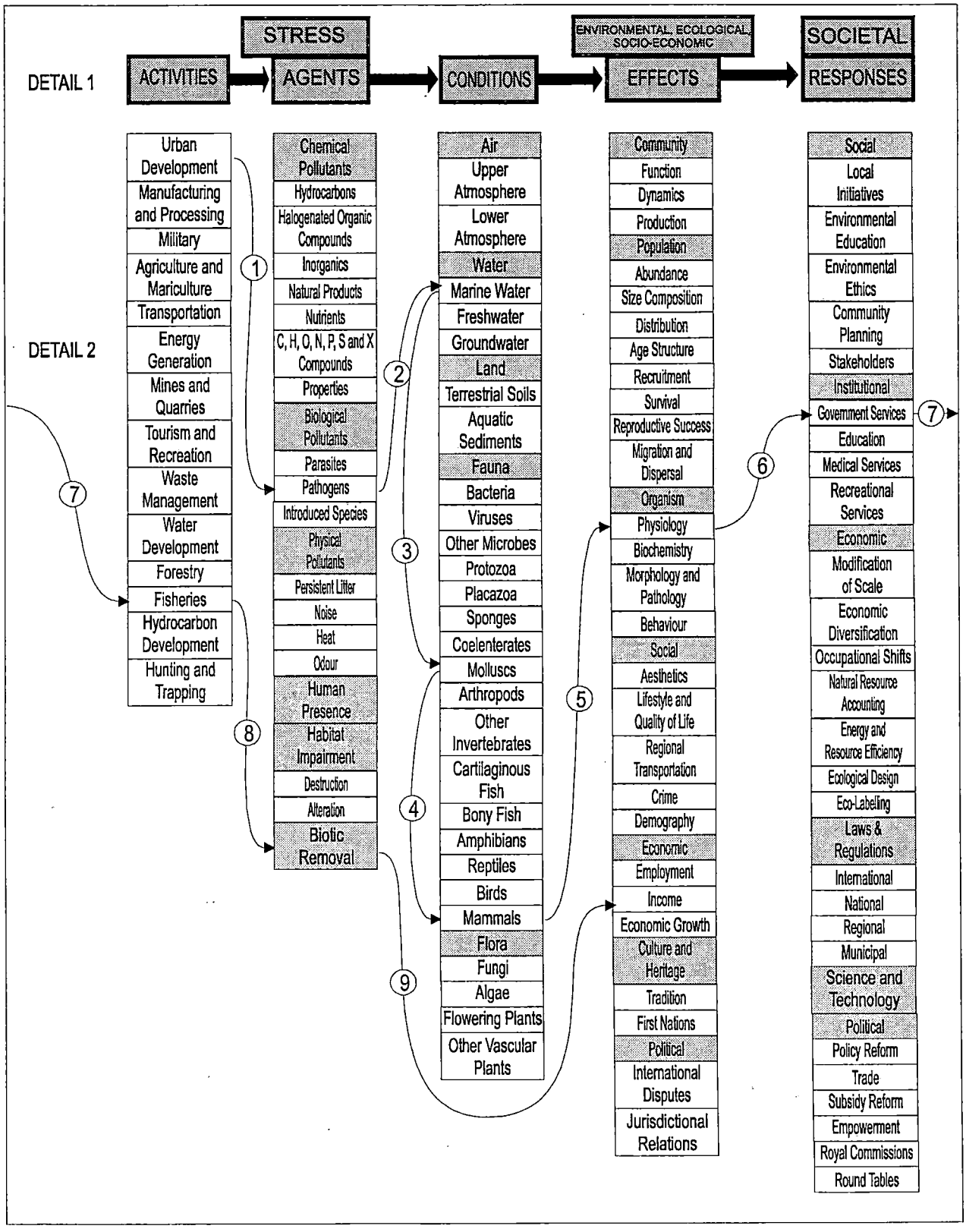
On the framework diagram, the practitioner depicts the linkages by drawing arrows between categories through various levels of detail. The result takes on the appearance of a wiring diagram. The schematic representation serves as a tool to focus evaluation of potential indicators.

An important concept to understand in making these linkages is **ecosystem structure and function**. It is essential to clearly define what we mean by ecosystem structure and function before discussing this conceptual framework further. Using marine ecosystems as an example, "structure" includes trophic composition, population abundance, biodiversity, size composition, and age structure. In the schematic diagram shown in Figure 3, structure is represented by the boxes. The "function" of an ecosystem refers to the processes that can lead to ecosystem change. Examples of function for a marine ecosystem include nutrient recycling, bioaccumulation, and reproduction. In the example presented in this report, function is represented by the arrows joining the structure boxes.

Figure 3 shows some key linkages for the example issue of pathogens in the marine ecosystem. Because of graphical limitations, this figure does not reflect the more thorough refinement of detail necessary to select actual indicators. Instead, examples of these levels of detail are given in Appendix A.

After tracing the linkages schematically, the practitioner should fully describe each. Doing this takes time and effort, but the result begins to serve as an excellent audit trail both for the practitioner and for others. An example of this linkage description for pathogens in the marine ecosystem is shown in Box 2.

Figure 3 **Framework Linkages for the Issue of "Pathogens in the Marine Ecosystem"**



Box 2 Example of Linkage Descriptions for Pathogens in the Marine Ecosystem

Linkage 1: Urban development (human activity) results in discharge of sewage containing pathogens such as bacteria (stress agent) into receiving marine waters.

Linkage 2: Sewage pathogens are accumulating in marine waters (environmental condition).

This linkage captures the absorption of the discharged pathogens from surrounding marine waters into the tissues of molluscs, such as oysters and mussels.

Linkage 4: Pathogens pass from molluscs to mammals (environmental condition).

This linkage identifies the transference of discharged pathogens up the food chain from molluscs to mammals.

Linkage 5: Pathogens affect the health of organisms (ecological effect).

This linkage hypothesizes that pathogens concentrated in the tissues of organisms will cause sickness in some species (e.g., gastroenteritis in humans), which further affects their physiology.

Linkage 6: Government monitoring programs (societal responses) are initiated to monitor pathogens in marine waters, in order to safeguard human health.

Linkage 7: Shellfish harvesting areas are closed by national monitoring agencies (societal response) because of pathogenic pollution.

Linkage 8: Closure of shellfish harvesting areas results in reduced harvest of marine shellfish (human activity).

Linkage 9: Income is adversely affected by reduced harvest of marine shellfish (socioeconomic effect).

Having traced and described the linkages, the practitioner should attempt to validate each by finding answers to the following questions:

- Is the linkage VALID and TESTABLE with existing knowledge?
- Is the linkage PROBABLY VALID but NOT YET TESTABLE with existing knowledge (e.g., use weight of evidence)?
- Is the linkage PROBABLY VALID but PROBABLY NEVER TESTABLE with existing or future knowledge?
- Is the linkage PROBABLY INVALID and/or NOT TESTABLE with existing knowledge?

Not only should linkage validation lead to indicator selection in the following step, but it should also highlight any data and information gaps for each linkage. These gaps could then direct future monitoring and research activities. For example, if a linkage is found to be "probably valid but not yet testable with existing knowledge," appropriate research or monitoring could provide the necessary knowledge to make the linkage "valid and testable."

Box 3 displays a model linkage validation form, including the issue statement and all linkages, numbered as in Figure 3. Each linkage in the form should have a validation note giving a rationale or explanation; this again serves as a defensible audit trail. Only two notes are provided here as illustration.

Box 3 Model Form for Validating Linkages and Notes for Selecting Potential Indicators

Issue statement: "Pathogens from cities' and municipalities' sewage discharges/effluents are causing the closure of polluted shellfish growing areas and thus are adversely affecting the commercial and recreational harvesting of marine shellfish."

Linkage #	Linkage	Validation	Notes
1	Urban development is a source of pathogens.	Valid and testable	1.1
2	Pathogens from urban development are present in marine waters.	Valid and testable	1.2
3	Pathogens in marine waters are accumulated by filter-feeding molluscs.	Valid and testable	etc.
4	Pathogens pass from molluscs to mammals.	Valid and testable	etc.
5	Pathogens affect the health of organisms.	etc.	etc.
6	National monitoring programs are initiated to pathogens in marine waters.	etc.	etc.
7	Shellfish harvesting areas are closed by national monitoring agencies because of pathogenic pollution from urban development.		
8	Closure of shellfish harvesting areas results in reduced harvest of marine shellfish.		
9	Income is adversely affected by closure of shellfish harvesting areas.		

Note 1.1—Selection of potential indicators

Pathogens exist in the ecosystem naturally or as a result of bacterial contamination. Bacteria from human and animal feces (fecal bacteria) may be associated with disease-causing organisms that threaten the health of marine animals and humans. Pathogenic contaminants are discharged into the marine ecosystem by stress agents of human activities, such as urban development. The amount of discharge and its treatment could be an indicator for this link.

Note 1.2—Selection of potential indicators

In this linkage, we are selecting potential indicators of the environmental condition of pathogens in marine waters. Therefore, we will screen data on indicators for the presence of pathogens in marine waters. However, we will not focus on trends in pathogen levels in fauna, because these will be addressed in other linkages, such as linkages 3, 4, and 5.

The best **indicators** of the presence of disease-causing organisms from fecal sources should have the following properties:

- present in fecal-contaminated water when pathogens are present, but in greater numbers;
- incapable of growth in the aquatic ecosystem, but capable of surviving longer than pathogens;
- more resistant to disinfection than pathogens;
- easily and accurately enumerated;

- applicable to all types of natural recreational waters;
- absent from nonpolluted waters, and exclusively associated with animal and human fecal wastes;
- density of indicator directly correlated with the degree of fecal contamination;
- density of indicator quantitatively related to swimming-associated illnesses.

The fecal coliform group of bacteria, which includes Escherichia coli (E. coli), fits most of the above criteria for selection as an **indicator of bacterial contamination in the marine ecosystem.** Although other groups or species of bacteria better meet the criteria, there are complications inherent in their use, such as expensive or onerous laboratory analyses or the risk of false negatives (not detecting the bacteria when they are present). Therefore, at present, fecal coliform bacteria are widely used by Canadian jurisdictions as indicators of bacterial contamination in the marine ecosystem.

The fate of bacterial contaminants in coastal marine waters and sediment depends on a large number of factors, including water depth, tides, currents, waves, and water structure (temperature and salinity characteristics). The flow of bacteria into the coastal waters surrounding urban areas generally reflects the range of diseases present in the human population, unless the waste discharged is adequately treated.

Evidence (validation)—example for the Strait of Georgia, west coast of British Columbia:

A review of marine monitoring data for the Capital Regional District of Victoria, B.C., has provided evidence for the accumulation of E. coli in the waters and sediments of the Strait of Georgia (Seakem Group Ltd. et al. 1990). Fecal coliform occurred at surface offshore stations at a median value of 30 per 100 mL. At nearshore stations, the median value was 28 per 100 mL. The data also showed that sediment coliform concentrations were greatest near the sewage discharge point at the Clover Point and Macaulay Point outfalls. The concentrations decreased to median values of 200 per 100 mL within 1 to 2 km of the outfall. These results are typical of the distribution of fecal coliform contamination in the water and sediments near sewage outfalls (UNESCO 1982; GESAMP 1990).

SELECT THE INDICATORS

Having formulated the concern as an issue statement and explicitly drawn and validated the linkages in the framework, the next step is to select indicators from some or all of those suggested by the linkages. Indicator selection has been discussed in literature published by a wide variety of agencies, including Environment Canada, Health Canada, the OECD, the Great Lakes International Joint Commission, and the U.S. Environmental Protection Agency (EPA). The Department of Fisheries and Oceans in Canada has championed systematic marine data evaluation using available metadata, as part of the Arctic and West Coast Data Compilation and Appraisal programs. In the literature, there are numerous criteria and methods (such as ranking and weighting) offered for selecting the indicators. They all have pros and cons. Box 4 lists some indicator selection criteria that have proven practical and valuable in past selection exercises.

Box 4 Criteria for Selecting Indicators

Data reliability

- Timeliness: Data are provided within a time frame consistent with decision-making requirements.
- Cost-effectiveness: Data are relatively easy and inexpensive to measure and use.
- Geographic scope: Data are provided for a geographic and temporal scale appropriate to the issue.
- Data adequacy: Data are both accurate and precise.
- Data availability: The data required to support the indicator should be available, or it should be reasonable to assume that the data could be acquired. The indicator should be supported by sufficient data over more than one time period, to show trends over time. The security of data monitoring programs should be reasonably stable to ensure future comparable data.

Issue relevance

- Scientific validity: The indicator is technically sound and consistent with scientific understanding of the system or element being described, and its attributed significance is defensible. There should be general consensus among credible experts that the indicator is valid.
- Representative: The information that the indicator conveys about a phenomenon should be representative of the condition as a whole.
- Responsive to change: The indicator should show changes or trends in the environment or in an environment-related human activity.

Usefulness to decision-makers

- Understandable: The indicator must be simple and clear; its significance should be fairly obvious and easily understood by those nonspecialists who will use it, particularly in the context of the issue to which it is related. The wording used to describe the indicator must also be understandable.
- Relevance/utility: The indicator should provide information that can be used (i.e., information that is relevant to the needs of potential users). The indicator should be relevant to stated goals and objectives, as well as policies or issues of concern.
- Target/threshold: Ideally, an indicator should have a target or threshold with which to compare it so that users are able to assess the significance of the values associated with it.
- Potential for comparison: The indicator is used by other institutions or jurisdictions.

Of course, there will probably be more than one candidate indicator, especially of environmental condition or human activity, and several may prove to be of equal value. Partnerships and consultations are an absolutely essential part of the selection process and all aspects of indicator development. It is up to the practitioner to consult with other specialists and potential users to decide how to qualitatively select the most appropriate indicator(s). Formal alliances such as working groups, task groups, or advisory groups with binding terms of reference are definite assets in the process of consultation.

Although the method is subjective, the summary record of decisions presented in Box 5 provides a sieve or filter with which to screen and propose final indicators. It also shows reasons for eliminating other candidate indicators.

As shown in Box 5, Candidate Indicator A—Fecal coliform levels in coastal marine waters (measured as geometric mean fecal coliform/100 mL per year)—meets all the indicator selection criteria. Explanatory notes on linkages, caveats, data sources, etc. should be documented. For example, the data for this sample indicator are collected as part of numerous municipal monitoring programs in the provinces; marine

waters at shellfish harvesting areas are routinely surveyed as part of a national program by Environment Canada.

Box 5 Completed Standard Form for Selecting Candidate Indicators

Linkage #: *2*
Linkage Description: Pathogens from urban development discharges accumulate in marine waters.
Indicator Category: *Condition*
Rating against criteria: 4 = Meets X = Fails ? = Uncertain

Criteria	**Indicator A:** (Bacterial contamination) *Fecal coliform levels in coastal marine waters (geometric mean fecal coliform/100 mL per year)*	**Indicator B:**
DATA RELIABILITY		
Timeliness	✔	
Cost-effectiveness	✔	
Geographic scope	✔	
Data adequacy	✔	
Data availability	✔	
ISSUE RELEVANCE		
Scientific validity	✔	
Representative	✔	
Responsive to change	✔	
USEFULNESS TO DECISION-MAKERS		
Understandable	✔	
Relevance/utility	✔	
Target/threshold	✔	
Potential for comparison	✔	

SUMMARIZE THE INFORMATION

In the first four steps, the practitioner has generated an issue statement, refined the framework, drawn and validated the linkages that suggested potential indicators, and then selected indicators. The critical remaining step is to summarize the information in report form and complete reviews and revisions of the documents. Three types of documents are suggested:

I) An Indicator Selection Summary Report, which should include:

- the purpose and scope;
- a list of all linkages (and their validation) for each issue;
- a list of all candidate indicators, highlighting the selected ones for each linkage;
- preliminary data graphs or tabled data for each indicator; and

- a completed framework, with selected indicators and numbered linkages for each issue.

II) A Supporting Rationale Document, including:

- all completed forms for selecting indicators and validating linkages;
- data coverage, reliability, and sources for each indicator; and
- a glossary of key terms.

III) A Monitoring and Research Overview, including:

- recommended monitoring plans for each "valid and testable" linkage; and
- recommended research plans for each "valid but not yet testable" linkage.

Together, this set of report products will provide practitioners with a concise and informative package useful for different operations and diverse exercises such as regulatory planning, environmental reporting, educational training, research focusing, and regional planning.

SUMMARY AND CONCLUSIONS

Our intention has been to provide the reader with a concise, practical manual for selecting indicators of marine ecosystem health. We have codified our experiences rather than performing an extensive literature review. You are encouraged to examine the literature and develop your own thoughts on the subject.

The contribution of this paper is its consolidation of a wide variety of concepts into a single, operationally oriented package that will assist in the selection of marine indicators for future State of the Environment reporting.

The operational procedure for selecting indicators has been divided into five main steps. First, generate an "issue statement" that captures the reason for concern within a general stress–condition–effect–response framework.

Second, expand upon that framework, filling in the details that are relevant to understanding and supporting the claims made in the issue statement. This portion of the exercise tends to flesh out aspects of the structure of the ecosystem under scrutiny.

Third, explore aspects of ecosystem function by drawing linkages from one detailed section of the framework, such as a "human activity," to another section of the framework that would be logically connected to it, such as an "environmental condition." By drawing these linkages, potential indicators begin to suggest themselves.

Fourth, carefully screen the "long list" of potential indicators against defensible criteria in order to generate your final "short list" of indicators. The final selection of indicators should be performed in consultation with technical experts and potential users of the information.

Fifth, summarize your deliberations in report form. A package of three different types of reports is recommended.

Whatever the application, the procedure outlined here can assist in the making of informed decisions regarding the health of Canada's marine ecosystems.

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GLOSSARY

These are terms practitioners may come across in seeking to develop indicators.

Behavioural effect	alteration of normal conduct of an organism (e.g., locomotion, feeding).
Biochemical effect	effect on biochemical processes of an organism (e.g., enzyme activity, protein induction).
Biotic removal	removal of biological resources from their natural habitat for human uses (e.g., fish or timber harvesting).
Contaminant	any human-made physical, chemical, or biological substance that is introduced into the ecosystem. The presence of a contaminant, however, does not necessarily imply an effect (Wells and Rolston 1991).
Eco-labelling	certification of consumer products to indicate that they meet environmental standards (e.g., energy-saving light bulbs); a market instrument promoting environmentally sound practices.
Ecological design	product design taking into consideration all environmental implications of manufacture, use, and disposal.
Ecosystem	the physical and chemical environment of a community of organisms and all the interactions between those organisms, as well as between organisms and their environment.
Ecosystem approach	an ecological approach to environmental planning and management that recognizes the interrelationships of environmental media and regards humans as key components of ecological systems (Water Quality Guidelines Task Group 1996).
Ecosystem-based management	the integrated management of ecological systems and human activities to maintain or enhance the health and integrity of an ecosystem (Ecosystem Management Task Force 1992; Environment Canada, Quebec Region 1993).
Ecosystem goals	broad, narrative statements describing the desired state of an ecosystem (Bertram and Reynoldson 1992).
Ecosystem health	an ecosystem state in which the environment is viable and livable; the economy is equitable, sustainable, and adequately prosperous; and the community is livable and convivial.
Ecosystem integrity	a state of ecosystem condition that is optimized for its geographic location, including gross energy input, available water, site nutrient capital, and colonization history.
Ecosystem objectives	narrative statements describing a desired condition for an ecosystem through a set of parameters, taking into account ecological characteristics and uses (UN Economic Commission for Europe 1993).
Environmental conditions	the biological, physical, and chemical state of air, land, water, and biota.
Environmental effect	alteration of ecological systems by human actions.
Environmental ethics	a set of principles to guide humanity's relationship with nature.

Framework	in the present context, a structure that describes the bounds for indicator selection and development. The framework is based on levels of detail of human activities, stress agents, environmental conditions, ecological/socioeconomic effects, and societal responses.
Habitat	a geographic area that provides for key activities of life.
Habitat impairment	the destruction or alteration of pristine habitat.
Human activity	human activity that can biologically, chemically, or physically alter environmental conditions.
Indicator	a statistic or parameter that, tracked over time, provides information on trends in the condition of a phenomenon and has significance extending beyond that associated with the properties of the statistic itself (Neimanis and Kerr 1996).
Indicator practitioner	a person or group involved in the selection and development of indicators for reporting, managerial, or scientific purposes.
Indicator selection criteria	standards or judgments used to select an indicator.
Introduced species	species intentionally or accidentally introduced by humans to an environment in which it is not normally found (e.g., purple loosestrife, zebra mussel).
Issue statement	statement describing a valued ecosystem component (societal or ecological feature) at risk because of human action(s).
Linkage	hypothesis statement of connections between one or more details in the framework.
Linkage validation	process of testing and validating a linkage in the framework.
Mariculture	cultivation and harvesting of marine resources in enclosed areas.
Monitoring	testing on a routine basis, with some degree of control, to ensure that the quality of the ecosystem has not exceeded a prescribed criteria range.
Morphological effect	change to the normal body structure of an object, such as an organism.
Natural resource accounting	the integration of values for environmental goods and services into conventional national accounts systems.
Pathological effect	alteration to the normal structure of organisms as a result of disease (e.g., deformation, tumours).
Persistent litter	human-made objects lost or discarded in the environment that take a long time to break down (e.g., plastics, metals).
Physiological effect	alteration in the normal functioning of major biological systems (e.g., circulation, respiration).
Pollutant	a substance directly or indirectly introduced by humans into the ecosystem, harming biota or impairing the chemical or physical quality of air, water, or land.
Societal response	a societal action elicited because of an observed or perceived effect on ecosystem health.
Stress agent	mechanism of alteration in environmental conditions; mechanisms can include actions (e.g., biotic removal) and pollutants (e.g., dioxins).

APPENDIX A

MORE DETAILED CATEGORIES OF THE FRAMEWORK SHOWN IN FIGURE 2

Examples of detail for levels 2 to 4 are provided in this appendix for each of the following categories:

- Human Activities (for mines and quarries)
- Stress Agents
- Environmental Conditions
- Environmental, Ecological, and Socioeconomic Effects
- Societal Responses

As mentioned in "Step Two" of this report, you, the practitioner, should refine the framework through successive levels of detail for each issue statement. At greater levels of detail, the placement of a particular item within a particular "box" becomes more subjective. You may disagree with the placement of items in the examples provided in this appendix. You may find that an item fits better in level 3 when we have placed it in level 4. Aim for consistency with your own refinements, rather than adopting our version directly.

The next step is to select the appropriate candidate indicators of Human Activities, Stress Agents, Environmental Conditions, Environmental, Ecological, and Socioeconomic Effects, and Societal Responses, **which can then be evaluated against the selection criteria.** Again, it is only the specific linkages you identify between structure and function that you will pursue.

Example of levels of detail for HUMAN ACTIVITIES—Mines and Quarries (Level 2)

Level 3	Level 4
Site Investigation and Preparation	Access Roads Site Surveying Soil Testing Hydrological Testing Environmental Survey Site Clearing Excavation Drainage Alteration Stream Crossing Equipment Pest Control Utilities Waste Disposal and Recovery Project Storage
Construction	Access Roads Site Clearing Excavation Blasting and Drilling Demolition Building Relocation Cut and Fill Tunnel, Underground Structures Erosion Control Drainage Alteration Stream Crossing Channel Dredging and Straightening Channel Revetments Piers, Seawalls Offshore Structures Equipment Pest Control Utilities Labour Force Waste Disposal and Recovery Product Storage Abandonment Reclamation Reforestation Fertilization Ancillary Transmission Lines and Pipelines

continued on next page.

Example of levels of detail for HUMAN ACTIVITIES—Mines and Quarries (Level 2) continued

Level 3	Level 4
Operation and Maintenance	Forest Clearing Excavation Spoil Overburden Blasting and Drilling Dredging Equipment Operation Operational Failures Energy Requirements Energy Generation Automobile, Aircraft, Vessel Movement Pedestrian Movement Utilities Waste Disposal and Recovery Product Storage Spills and Leaks Explosions De-icing, Snow Removal and Disposal Pest Control Dust Control Abandonment
Future and Related Activities	Urbanization Industrial Development Transportation Energy Requirement

Example of levels of detail for STRESS AGENTS

Level 2		Level 3
Chemical Pollutants	Hydrocarbons	Aromatic Hydrocarbons Polycyclic Hydrocarbons Hydrocarbon Materials
	Halogenated Organic Compounds	Halogenated Pesticides Polycyclic Halogenated Compounds Dioxins and Furans Halogenated Phenolic Compounds
	Inorganics	Metals Nonmetals
	Natural Products	
	Nutrients	Nitrogen Phosphorus Silicon
	Carbon, Hydrogen, Oxygen, Nitrogen, Phosphorus, Sulphur, and Halogenated Compounds	Phenolic Compounds Phthalates Resins and Fatty Acids Organophosphates Carbonates Triazines Herbicides and Fungicides Antisapstains Others
	Properties	Stable Isotopes Radionuclides Derived Quantities
Biological Pollutants	Parasites	
	Pathogens	Bacteria Viruses
	Introduced Species	Flora Fauna
Physical Pollutants	Persistent Litter	
	Suspended Matter	
	Noise	
	Heat	
	Odour	
Human Presence		
Habitat Impairment	Destruction	
	Alteration	Physical or Chemical
Biotic Removal	Harvest	

Example of levels of detail for ENVIRONMENTAL CONDITIONS

	Level 2	Level 3	Level 4
Air	Upper Atmosphere Lower Atmosphere	Stratospheric Ozone Air Quality	
Water	Marine Water Fresh Water Groundwater	Inorganic Contaminants Organic Contaminants	
Land	Terrestrial Soils Aquatic Sediments	Inorganic Contaminants Organic Contaminants	
Fauna	Bacteria		
	Viruses		
	Other Microbes		
	Protozoa	Phylum Sarcomastigophora	Class Phytomastigophora Class Zoomastigophora Class Lobosa Class Filosa Class Granuloreticulosa Class Acantharia Class Polycystina Class Phaeodaria Class Heliozoa
		Phylum Apicomplexa	Class Sporozoa Class Piroplasma
		Phylum Microspora	
		Phylum Ciliophora	Class Kinetofragminophora Class Oligohymenophora Class Polyhymenophora
		Phylum Platyhelminthes	Class Turbellaria Class Monogena (flukes) Class Trematoda (flukes) Class Cestoda (tapeworms)
		Phylum Mesozoa	
		Phylum Rotifera	Class Seisonidea Class Bdelloidea Class Monogonata
		Phylum Acanthocephala (endoparasites)	
		Phylum Knorhycha	
		Phylum Lorcifera	
		Phylum Priapulida	
		Phylum Sipuncula (marine worms)	
	Placazoa (Phylum Placazoa)		
	Sponges (Phylum Porifera)		

continued on next page.

Example of levels of detail for ENVIRONMENTAL CONDITIONS continued

	Level 2	Level 3	Level 4
Fauna cont'd	Coelenterates	Phylum Cnidaria	Class Hydrozoa Class Scyphozoa Class Anthozoa
		Phylum Ctenophora	Class Tentaculata Class Nuda
	Molluscs (Phylum Mollusca)	Class Gastropoda	Subclass Prosobranchia Order Archaeogastropoda (limpets, abalone) Order Mesogastropoda Order Stenoglossa (whelks) Subclass Opisthobranchia Order Pleurocoela Order Sacoglossa (sea slugs) Order Acoela (sea slugs) Subclass Pulmonata Order Basommatophora Order Stylommatophora
		Class Bivalvia	Order Protobranchia Order Filibranchia (mussels, scallops) Order Eulamellibranchia (oysters, cockles) Order Septibranchia
		Class Cephalopoda	Order Tetrabranchia Order Dibranchia Suborder Decapoda (squid, cuttlefish) Suborder Octopoda (octopus)
	Arthropods (Phylum Arthropoda)	Class Merostomata (horseshoe crab) Class Arachnida (spiders) Class Pycnogonida (sea spiders)	
		Subphylum Crustacea	Class Branchiopoda Class Ostracoda Class Copepoda Class Mystacocarida Class Branchiura Class Cirripedia (barnacles)

continued on next page.

Example of levels of detail for ENVIRONMENTAL CONDITIONS continued

	Level 2	Level 3	Level 4
Fauna cont'd	Arthropods (Phylum Arthropoda) cont'd	Class Malacostaca	Super-Order Peracarida Order Amphipoda (shrimp) Super-Order Hoplocarida (shrimp) Super-Order Eucarida Order Euphausiacea (krill) Order Decapoda (crab, shrimp, crayfish)
		Subphylum Uniramia	Class Insecta Class Diplopoda (millipedes) Class Pauropoda Class Symphyla Class Chilopoda (centipedes)
	Other Invertebrates	Phylum Pentastomida	
		Phylum Phoronida	
		Phylum Bryozoa	Class Phylactolaemata Class Stenolaemata Class Gymnolaemata
		Phylum Entoproca	
		Phylum Brachiopoda (lamp shells)	
		Phylum Chaetognatha (arrow worms)	
		Phylum Echinodermata	Class Crinoidea Class Stellaroidea Subclass Asteroidea (sea stars) Subclass Ophiuroidea (brittle and basket stars) Class Holothuroidea (sea cucumbers)
		Phylum Hemichordata	Class Enteropneusta Class Pterobranchia
	Cartilaginous Fish	Class Marsipobranchii	Subclass Cyclostomata (lamprey, hagfish)
		Class Selachii	Subclass Euselachii Order Pleurotremata (sharks) Order Hypotremata (rays)
		Class Bradyodonti	
	Bony Fish (Class Pisces)	Subclass Palaeopterygii Subclass Neopterygii Order Isospondyl Suborder Clupeoidea (sardine, herring) Suborder Salmonidae (salmon, trout, char, smelt)	

continued on next page.

Example of levels of detail for ENVIRONMENTAL CONDITIONS continued

	Level 2	Level 3	Level 4
Fauna cont'd	Amphibians (Class Amphibia)	Order Caudata (salamander, newt) Order Salientia (frog, toad) Order Gymnophiona	
	Reptiles (Class Reptilia)	Order Phyncholephalia Order Testudines (tortoise, turtle) Order Crocodylia (crocodiles, alligators) Order Squamata Suborder Sauria (lizards) Suborder Serpentes (snakes)	
	Birds (Class Aves)	Order Gaviiformes (divers) Order Podicipediformes (grebes) Order Procellariiformes (petrel, albatross) Order Pelecaniformes (cormorant, pelican, gannet) Order Ciconiiformes (ibis) Order Anseriformes (duck, goose, swan) Order Galliformes (fowl) Order Gruiformes (rail) Order Charadriiformes (skua, gull) Order Columbiformes (pigeon) Order Strigiformes (owls) Order Apodiformes (swifts) Order Coraciiformes (kingfisher) Order Piciformes (woodpecker) Order Passeriformes (songbirds) Order Falconiformes (hawks, osprey, falcon)	

continued on next page.

Example of levels of detail for ENVIRONMENTAL CONDITIONS continued

	Level 2	Level 3	Level 4
Fauna cont'd	Mammals (Class Mammalia)	Subclass Prototheria	Infra-Class Metatheria Order Marsupialia Infra-Class Eutheria Order Insectivora Order Dermoptera Order Chiroptera (bats) Order Primates (humans, gorillas, apes) Order Edentata Order Pholidota Order Lagomorpha (rabbits) Order Rodentia Order Cetacea Suborder Odontoceti (toothed) Order Mysticeti (baleen) Order Carnivora Suborder Fissipedia Order Pinnipedia Order Tubulidentata Order Proboscidea Order Hyracoidea Order Sirenia (dugong, manatee) Order Perissodactyla (horse) Order Artiodactyla Suborder Artiodactyla Suborder Tylopoda Suborder Ruminantia (deer, elk, cows)
Flora	Fungi and Lichens (Division Mycota)	Class Chytridiomycetes Class Oomycetes Class Zygomycetes	Order Ascomycetes Order Lichens
	Algae	Division Chlorophyta (green algae)	
		Division Rhodophyta (red algae)	
		Division Chrysophyta	Class Bacillariophyceae (diatoms) Class Chrysophyceae (blue-green algae)
		Division Xanthophyta	
		Division Pyrrophyta	Class Dinophyceae (dinoflagellates)
		Division Euglenophyta	
	Flowering Plants (Subdivision Spermatophytina)	Class Angiospermae	Subclass Dicotyledonae Subclass Monocotyledonae

continued on next page.

Example of levels of detail for ENVIRONMENTAL CONDITIONS continued

	Level 2	Level 3	Level 4
Flora cont'd	Other Vascular Plants		

Example of levels of detail for ENVIRONMENTAL, ECOLOGICAL, AND SOCIOECONOMIC EFFECTS

	Level 2	Level 3
Community	Function	Nutrient Flow Energy Flow
	Dynamics	Species Diversity Phenotypic Diversity Genotypic Diversity Colonization Species Loss Species Interactions Succession
	Production	Primary Production Decomposition Respiration Nutrient Recycling
Population	Abundance Size Composition Distribution Age Structure Recruitment Survival Reproductive Success Migration and Dispersal	
Organism	Physiology	Respiration Circulation Hematology Digestion Excretion Growth Reproduction Osmoregulation Locomotion Nervous and Sensory Systems
	Biochemistry	Protein Induction and Inhibition Enzyme Activity Genetic Induction and Inhibition EndocrInology Genotoxicity Metabolism

continued on next page.

Example of levels of detail for ENVIRONMENTAL, ECOLOGICAL, AND SOCIOECONOMIC EFFECTS continued

	Level 2	Level 3
Organism cont'd	Morphology and Pathology	Deformation Body Indices Histology Tumours Lesions Immunology Hematological Disorders
	Behaviour	Locomotion Feeding Reproduction Aggression Orientation Migration Preference-Avoidance
Social	Aesthetics	Noise Odour Visual Pleasure Consonance with Nature Spirituality Biotic Diversity
	Lifestyle and Quality of Life	Human Mental Health Health Services Availability Life Expectancy Infant Mortality Fertility Rate Educational Enrolment Educational Attainment Literacy Affordable Housing Gender Equality Leisure Time
	Regional Transportation	Accidents Efficiency Infrastructure Maintenance Energy Use
	Crime	Crime Rate Incarceration Prosecution Public Safety Recidivism (Repeated Criminal Activity)

continued on next page.

Example of levels of detail for ENVIRONMENTAL, ECOLOGICAL, AND SOCIOECONOMIC EFFECTS continued

	Level 2	Level 3
Social cont'd	Demography	Age Structure Birth Rate Death Rate Density Emigration Immigration Rural–Urban Migration Urbanization
Economic	Employment	Unemployment
		Underemployment
	Income	Poverty Savings Personal Debt Wages Social Security Environmental Litigation Costs Liability Insurance and Bonds
	Resource Consumption	Resource Value Commodity Prices Damage to Market Goods
	Inter-generational Equity Community Development	
	Contributions to GDP, National Debt, Trade Balance, Inflation	
Culture and Heritage	Tradition First Nations	
Political	International Disputes Jurisdictional Relations	

Example of levels of detail for SOCIETAL RESPONSES

	Level 2	Level 3	Level 4
Social	Local Initiatives Environmental Education Environmental Ethics Community Planning Stakeholder Involvement		
Institutional	Government Services	Science Welfare Environmental Protection Defence Employment Resource Management Immigration	
	Education		
	Medical Services		
	Recreational Services		
Economic	Modification of Scale Economic Diversification Occupational Shifts Natural Resource Accounting Energy and Resource Efficiency Ecological Design Eco-labelling		
Laws and Regulations	International	Agreements Conventions Protocols	Investigation Safeguards Measures Immunities Privileges Exemptions Arbitration Mediation
	National	Acts Legislation Standards Regulations Policy, Monitoring, and Compliance Procedures Implementation and Management Privileges and Exemptions Amendments Codes of Practice Criminal Court System Criminal Legislation Judicial Review	

continued on next page.

Example of levels of detail for SOCIETAL RESPONSES continued

	Level 2	Level 3	Level 4
Laws and Regulations cont'd	Regional	Statutes Acts Legislation Regulations Policy Standards Monitoring and Compliance Procedures Implementation and Management Regulations Legal Suits Liability Exemptions Tickets Fines Criminal Court System Criminal Legislation Criminal Prosecution	
	Municipal	Bylaws Regulations Policy Liabilities Safeguards Tickets Fines	
Science and Technology			
Political	Policy Reform		
	Trade		
	Subsidy Reform		
	Empowerment		
	Royal Commissions		
	Round Tables		