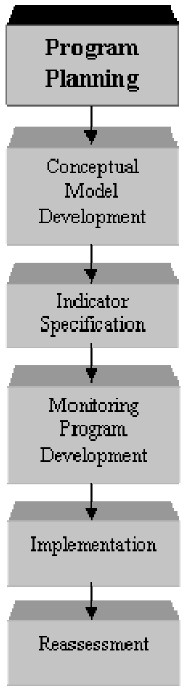
This document contains information on Planning the Program, Conceptual Model Development, and Indicator Specification for the Indicator Development for Estuaries report. EPA-842-B-07-004. The remainder of the document can be downloaded from: http://www.epa.gov/owow/estuaries/indicators/

Indicator Development for Estuaries

February 2008



PLANNING THE PROGRAM

For groups to be successful in their mission to improve or protect the ecosystems within their regions, programs must be created with a set of goals and the result in mind. Therefore, each program must be designed around a clear purpose. For example, a purpose might be to collect data that will inform scientists and managers about important aspects of a region they are working to protect.

Programs such as the NEPs, CZMPs, and NERRs were designed as partnerships between the Federal government and states working toward protecting, restoring, and sustaining development of the nation's coast through joint resources, funds, and management authorities. These programs also work to provide research, data, and education to sustain conservation and development of the coasts. When these collaborative efforts begin, a management plan is created to focus a program's efforts toward its goals.

In accordance with EPA Section 320 of the CWA (EPA, 2000a) requirement, NEPs develop a CCMP to document the partnership's plan for improving the estuary (see the callout box on the next page for more information on developing a CCMP). During development of the CCMP, the NEPs conduct a comprehensive review of the key management issues for their estuary. The CCMP identifies the estuary's priority problems, causes, and linkages to changes in the estuary. It also identifies the environmental quality goals and objectives of the program and explains the actions the NEP plans to take to abate or correct the problem. Background information on the estuary is included, such as "the status and trends of the estuary's water quality, natural resources, and uses" (EPA, 1992). The CCMP is not the indicator plan, but indicators are developed based on CCMP and monitoring plan management questions.

Similar steps are also followed when developing monitoring programs. In *Managing Troubled Waters,* the National Research Council (NRC) developed a seven-step process for developing and implementing monitoring programs:

1. Define program expectations and goals—This includes identifying public concerns along with current regulations and focusing the objectives on pertinent environmental and health regulations.
2. Define the strategy of the study—Developed by addressing specific questions to be answered. Scientists and managers must focus the questions being asked on the monitoring that is to be conducted, which will deliver the information required. These focus questions will vary from program to program.
3. Conduct relevant studies and research—Provide the groundwork for the construction of the monitoring design through development of methods, models, and techniques.

4. Develop a sampling and measurement program—The purpose of this step is to produce a sampling design that identifies what measurements should be monitored and where and when the measurements should be taken.
5. Implement the study—The implementation of the study will provide information and data for scientists and managers; however, the data will need to be analyzed and converted into useful information for managers and decision-makers to utilize.
6. Synthesize the data.
7. Report the results of a monitoring program to a varied audience consisting of managers, decision-makers, and the public (NRC, 1990).

The most important aspect of the process is that each step builds upon the previous steps. Therefore, when developing a program, it is important to revisit and rethink the steps in the process. Over time, the objectives and goals, monitoring techniques, and data available may change, as well as many other aspects of the process. When these changes occur, the plan should be updated to reflect the most current concerns.

The most important aspect of the process is that each step builds upon the previous steps.

Steps to Develop a CCMP, Monitoring Plan, and Indicators

The CCMP encompasses the management objectives established by the program. There are four phases to follow when developing a CCMP:

- **Phase 1:** Convening a management conference and establishing a structure of committees and procedures for conducting the group's work.
- **Phase 2:** Characterizing the estuary to determine its health, reasons for its decline, and trends for future conditions; assessing the effectiveness of existing efforts to protect the estuary; and defining the highest priority problems to be addressed in the CCMP.
- **Phase 3:** Specifying action plans in the CCMP to address priority problems identified through characterization and public input. The CCMP should build on existing Federal, state, and local programs as much as possible.
- **Phase 4:** Monitoring the implementation of the CCMP, reviewing progress, and redirecting efforts where appropriate.

Once the CCMP is developed, the NEP will draft a monitoring plan in accordance with its CCMP. The monitoring plan implements the management objectives and carries out action plans. Indicators are developed to address the specific estuary needs defined in the monitoring plan. NEPs work through a long process to develop and implement priority corrective actions and compliance to restore and maintain the health of an estuary. (EPA, 1993)

The following five steps are helpful when beginning the indicator development process and are discussed in more detail below:

- Determine the spatial scale of the program
- Convene a steering committee
- Identify the purpose and need for indicators
- Identify the issues
- Conduct a baseline assessment of each issue

For NEPs, the CCMP should be used for Steps 1, 3, 4, and 5; therefore, only Step 2 is required to start the indicator development process.

STEP 1: DETERMINE THE SPATIAL SCALE OF THE PROGRAM

The assessment of the nation's coasts occurs on a number of different levels. Local programs assess one or more specific issues for their local area (*e.g.*, NERRs); regional programs assess differences over a slightly larger area (*e.g.*, NEPs, Gulf of Mexico Program, Southern California Coastal Water Research Project [SCCWRP]); and national programs assess changes in the overall coastal condition throughout the nation (*e.g.*, NCA). The first step in the process is to determine the level at which the group is interested in interacting. This will determine who will be included in discussions regarding program development.

For example, a local group may be interested in tracking efforts to restore wetlands throughout a town or county. In this instance, the group will include representatives from the local agencies working to solve this problem but may also include representatives from the state level to get a perspective on how other groups throughout the state are handling this issue, or how the state agency itself is addressing the issue. Other programs, such as the NEPs and NERRs, need to track issues on a local, state, and national level. These groups would need to consider including local monitoring groups, state agencies, and people involved at the national level.

Whenever possible, it is always best to try to align local and regional programs with programs at a higher (*i.e.*, national) spatial scale. This allows for future comparisons with data collected over the larger area. If the group is interested only in local issues, it may not feel it needs to consider regional initiatives, so some convincing may be necessary.

> Whenever possible, it is always best to try to align local and regional programs with programs at a higher (*i.e.*, national) spatial scale.

The benefit of aligning a program with a larger effort can been seen when unexpected problems or changes arise. For instance, maybe the local group is interested only in studying invasive species in the local area. Aligning the program with a regional program may come in handy when a sudden unexpected change in species counts occurs with no apparent direct cause. Groups aligned with the regional sampling can then compare their local data with data collected on the regional level. This assists the program with determining whether the change was a local phenomenon that needs to be studied further or a regional issue experienced by other programs.

STEP 2: CONVENE A STEERING COMMITTEE

Steering committees should be formed during the initial phases of the indicator development process so that they can be a part of the entire process. The earlier in the process the steering committee is involved, the more efficient and effective the indicator development process will be to achieve the desired program outcomes.

Steering committees are normally formed with a mix of people from different backgrounds, agencies, and organizations. Because the committee members are an integral part of the indicator development process, it is important that each person on the committee be included for a specific reason (for example, his or her expertise in a technical area or understanding of monitoring programs in the region). Committee members also must be actively involved in each step of indicator development, not only as reviewers of the final result. Groups that have an effective steering committee have found that it is easier to establish indicators and obtain the desired outcome by the end of the process.

The most important aspect of an effective steering committee is to convene the right balance of managers, policy-makers, researchers, and the public so that all are represented. Representatives from the area’s key monitoring and management groups should be included, along with members of local environmental groups and the public. The people involved do not have to be scientists with previous indicator knowledge. Members such as managers and policy-makers should be selected for their ability to inform decision-makers on funding and regulations and should be able to provide support for the future. Researchers, scientists, and educators who possess a strong knowledge of the ecosystem and science should be included on the steering committee to make informed decisions on indicators. It is also important to include the public for several reasons. Most important, public support is critical to the success of the indicator development process by providing public opinion on the ecosystem. Ultimately, the public is the final recipient of the program’s findings on the state of the ecosystem.

Once the steering committee is formed, members should be briefed on the goals of the indicator development process. If a definition of the word “indicator” has not already been developed, the committee members should be asked to do so based on the needs of their program. The committee should also assist in developing a list of topics, questions, and conceptual models to develop indicators. The members do not need to develop all of the information themselves, but they should agree on the topic areas and review the questions and conceptual models developed to ensure that they agree on what is included. In the case of the NEPs, the steering committee should use the topics and questions from the CCMP so that indicators will be developed to answer the NEP's management questions.

Workshops have been found to be successful events where steering committee members can gather with other participants to present the indicator development information that has been prepared and to receive feedback on whether they are on the right track. Just as it is important to have the right people as members of the steering committee, it is crucial to have the appropriate workshop participants to complete the indicator development process. Although the indicator development process continues long after the workshop has ended, everyone involved in the process has a responsibility to continue the work.

The key to a successful steering committee is communication. Regular communication of information on indicator development can be accomplished through e-mail distributions, conference calls, meetings, and workshops. Members should be required to commit to the development process, which could include bi-weekly or monthly meetings, whether through conference calls or attending the meetings in person. E-mail updates on the progress of the process should be distributed promptly based on a timeframe established by all members (for example weekly, bi-weekly, or monthly).

Great Lakes Program—Steering Committee

"The process involved over 130 people that could be identified by name." "Experts, including researchers, academics, and managers, were included in each working group. They sought out individuals for inclusion in these groups based [on] expertise, rather than attempting to equally represent all sectors of the environmental world (policy, research, industry, etc…)." (Pidot, 2003)

STEP 3: IDENTIFY THE PURPOSE AND NEED FOR INDICATORS

Step 3 in the process should answer the following questions: (1) Why are we developing indicators? and (2) Why is there a need for it? The answers to these questions are the starting blocks for the rest of the program, so getting consensus on these answers is important.

Normally, the purpose and need for the program are not difficult to determine because most groups were motivated by a specific issue or group of issues that needs to be addressed. Some programs have their purpose and need specified as part of their charter. For example, the NEPs have their purpose and need specified by Section 320(b)(6) of the CWA, which states that NEPs must "…monitor the effectiveness of actions taken in pursuit of the plan." In this particular instance, "plan" refers to the CCMP developed by each NEP. Other programs have similar goals under GPRA and other statutes. The important step is agreeing on and documenting the purpose and need.

For NEPs: the purpose and need for indicator development is to track progress towards the goals outlined in their CCMP.

The actual purpose of the program will depend on the complexity and scope of the issues the group is attempting to address. If the group is addressing only a single issue, then the purpose and need statement will focus on just that issue. For example, maybe the group is focused on lowering the concentration of fecal coliform throughout the estuary. In that case, the purpose and need statement for the program might be:

> **Purpose:** To monitor the change in fecal coliform levels throughout the estuary.
>
> **Need:** At present, the amount of fecal coliform entering the estuary is causing a health hazard to the local population that is exposed to the water. This program is needed to track changes in fecal coliform levels throughout the estuary to determine whether levels are increasing or decreasing based on recent efforts to prevent fecal coliform contamination.

The following is an example of a purpose and need statement developed for a program aimed at monitoring more than one issue.

> **Purpose—**To give the region the ability to compare data, assess the regional status of the environment, and provide early warning of potential problems.
>
> **Need—**To track the status and trends in ecosystem integrity throughout the region through collaborative partnerships. To provide information for policy, management and advocacy decisions at regional and local scales.

The more focused the purpose and need statements are, the more focused the resulting program will be. In addition, it is important that all parties involved in the program development understand the purpose and need statements clearly and are reminded of them throughout the process, so that a program can be developed to meet these goals.

Great Lakes Program—SOLEC Goal

"The goal of [SOLEC] is to assemble a basin-wide suite of scientifically valid indicators that will be most useful and understandable in determining the health of the Great Lakes ecosystem to the interested public." (Bertram and Stadler-Salt, 2000)

STEP 4: IDENTIFY THE KEY ISSUES

Step 4 in the process uses the purpose and need statements to identify the issues, management objectives, and questions the program will address. For many programs, this was addressed when their management plans (*i.e.*, NEP CCMPs) were developed. Critical attributes for issue identification are:

1. The issues must directly link to the purpose and need statements;

2. Consider public, scientific, and management concerns in a measurable fashion; and
3. Details on the issues should be stated in terms of management objectives and questions that point to the critical information needs (EPA, 1993).

For NEPs: the key issues for indicator development should be the same as those identified in their CCMP.

The process of identifying issues can be simple or intricate, depending on the program goals. If the program has only one goal, such as eliminating hypoxia events from occurring within the estuary, then it will develop management objectives around this one issue. For more complex programs, the number of issues addressed will depend on the key issues affecting the ecosystem and what the program plans to cover. In this instance, the steering committee will need to define the priority issues within the estuary along with the coinciding management objectives. The document *Successful Coastal Management Solutions* outlines seven key management issues that estuaries should consider (EPA, 2003c):

1. Habitat
2. Pathogens
3. Freshwater in flow
4. Nutrients
5. Fish and wildlife
6. Introduced species (invasive species)
7. Toxics

Develop Management Objectives

Management objectives are specific actions designed to quantify/qualify the changes intended by the program for each priority issue. For example, if the issue is coliform contamination within the estuary, the management objectives for that issue might be:

- To decrease the number of boats discharging their holding tanks within the boundaries of the estuary by 70 percent within the next 3 years.
- To decrease the number of failing septic systems throughout the estuary's watershed by 50 percent within the next 15 years.
- To decrease the number of overflow instances from municipal sewer plants in the area by 25 percent within the next 10 years.
- To decrease the amount of runoff containing animal waste entering the estuary by 25 percent within the next 10 years.

Each of these management objectives has a specific goal and time period against which progress can be measured. In some instances, a quantitative value may not be associated with an issue. In these instances, it is important to be as specific as possible in order to ensure the program has some baseline condition to measure against.

These management objectives are then used to form questions that the selected indicators will address. The goal of the NEP is to determine the effectiveness of its CCMP and the implementation of the management objectives. Both the Barataria-Terrebonne and New Hampshire NEPs developed indicators based on questions formed from their CCMP management objectives; details on this process are provided in Appendix A-1 and Appendix A-2.

Basic Steps for Action Plan Development

- State the problem, identifying the probable causes and sources.
- State the program goals related to the problem and its sources.
- Set specific, measurable objectives to attain the goals.
- Determine the universe of possible management activities, both new and existing, for consideration.
- Select the activity that will work, that the public will support, and that can be implemented within a reasonable time and with reasonable resources.
- Establish specific action plans needed to abate and control the problem or to protect the resources.
- Implement and monitor results, collecting data on measurable indicators of progress.
- Report on progress, costs, and results.
- Review, re-evaluate, and redirect efforts as needed (EPA, 2005c).

Define Questions to be Answered by Indicators

Under each management objective, a question or series of questions is used to answer whether the management objective has been met or how much progress has been made toward accomplishing the objective. The questions can be developed by simply turning the management objective into a question or a series of questions that look at different aspects of the objective.

For NEPs: Management objectives and question definitions should have been conducted in the CCMP. If not, these should be connected with issues identified in the CCMP.

Question development is an important task because the selected indicators must answer the questions. Therefore, the questions must be specific enough that someone can look at a series of data and develop an answer to that question.

For example, the management objective might be:

To determine the health of fisheries with regard to ecosystem integrity.

The associated questions could be:

1. What are the trends in and the status of commercially important fisheries stocks?
2. What are the effects of fishing on non-commercial species and their associated communities?
3. What are the effects of fishing and non-fishing activities on marine habitat and fisheries productivity?
4. What are the trends in the socioeconomic characteristics of fishing?

If the indicators being developed will be used at more than one level (i.e., nationally and locally), then there may be separate questions for each level of use of the indicator.

It is important that each question be clear and understandable. This will allow an appropriate indicator to be selected—*i.e.*, one that will answer the question. That answer will then be used with information from the other questions to answer whether the management objective was met.

New Hampshire Estuaries Project—Goals and Objectives

“Those charged with developing indicators for the New Hampshire Estuaries began by considering the goals and objectives written into the estuary management plan. Each objective was rephrased as a monitoring question – for which one or more indicators were selected based on their ability to appropriate answers. The hypothetical data required to track each of those indicators was then described and compared with actual data sets produced by existing monitoring programs.” (Pidot, 2003)

STEP 5: CONDUCT A BASELINE ASSESSMENT OF EACH ISSUE

Once the management issues and objectives are selected and outlined, the next step in the process is conducting a baseline assessment of each issue. Mature programs have normally already accomplished this task, but should review the information to make sure it is up to date. For new programs, how well this task can be accomplished will depend on how well the issue has been studied in the area.

A baseline assessment of an issue compiles and analyzes all available information on that subject for that area. It defines the present conditions of that issue for that particular area. If the issue is a new one, then an initial monitoring program might need to be conducted to determine the starting point; for others, the baseline assessment may only need to consist of a review of the most recent reports on the issue. It is important to understand current conditions so that trends can be identified. For example, if the group were concerned about changing dissolved oxygen (DO) levels within the estuary from year to year, the baseline assessment would need to include information on DO levels throughout the estuary over the past year and, if possible, from previous years, so that it can be determine how levels have changed over time.

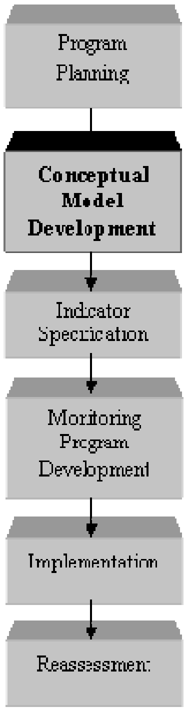
The baseline assessment should also include information on current monitoring being conducted, including what is measured; when, where and how often it is measured; how it is measured; and who conducts the monitoring. It is also helpful to know how often the monitoring programs report their data. When choosing an indicator, it is important to understand whether current monitoring conducted in the area will adequately answer the objectives. A number of programs have focused their indicator development on parameters currently measured through mandatory monitoring programs. The reason for this approach is that the baseline data are already available and the organization or agency already has a mandate to conduct the sampling, sample analysis, and data analysis. Other programs choose their indicators based on best scientific knowledge, then determine whether monitoring occurs in the area for that parameter. If the parameter was not monitored and was determined to be a priority, a monitoring plan could then be developed for it.

A high-profile baseline assessment was conducted by the Massachusetts Water Resources Authority (MWRA) in conjunction with the construction of a sewage treatment plant outfall in Massachusetts Bay. The outfall, which was brought on-line in September 2000, discharges secondary-treated effluent into Massachusetts Bay. MWRA has been monitoring the bay and Boston Harbor since 1992. The monitoring conducted prior to September 2000 was part of the baseline assessment of Massachusetts Bay and Boston Harbor. The baseline monitoring conducted allowed managers and scientists to gain vast knowledge about water quality, nutrients, benthos, sediment quality, and fish and shellfish in Massachusetts Bay and Boston Harbor. The extensive baseline assessment that MWRA conducted, which led to the comparison of pre- and post-outfall conditions within Massachusetts Bay and Boston Harbor, enabled scientists, managers, and decision-makers to make informed decisions on regulatory issues and responses needed.

There is a strong national push to establish a consistent effort in conducting baseline assessments and monitoring. Establishing a national monitoring effort would allow data to be easily compared and provide practical value for scientists and managers. To be fully effective, monitoring data collected by state, territorial, tribal, and local governments, non-governmental organizations (NGOs), and volunteers will need to be coordinated with the national monitoring network (U.S. Commission on Ocean Policy, 2004). Currently, the responsibility for monitoring and assessing marine resources is divided among a number of Federal, state, and local agencies, and other NGOs. A more unified approach with comprehensive monitoring can provide scientists and managers with the knowledge to facilitate ecosystem change and understand whether their goals and objectives are effectively being met.

San Juan Bay NEP—Baseline Information

"The proposed study will concentrate on establishing detailed Long-Term Environmental Indicators for the SJBE (LTEI-SJBE) by initially collecting baseline information from the system, establishing the indicators, and further enabling the analysis of achieved programmatic goals." (Otero, 2002)



CONCEPTUAL MODEL DEVELOPMENT

The purpose of an indicator is to summarize complex information into a simplified and useful manner and facilitate the identification of status and trends. In a common analogy to the field of medicine, the patient represents a system or phenomenon of interest. Indicator development is conducted by linking a complex collection of subsystems with many compartments and interactions, just like the multitude of physiological systems of the human body. Indicators act as “vital signs” used to measure the state of the system, just as temperature and pulse are used to assess the overall health of a patient.

Indicators are used to convey information, quantify responses, and simplify information about complex ideas. They are assumed to be a cost-effective and accurate alternative to monitoring individual components of a system. Indicators can be quantitative or qualitative in nature and are useful at many scales, both temporally and spatially. When tracked over time, an indicator can provide information on trends in the condition of a system.

Perhaps the most well-known indicators are those describing the condition of the U.S. economy, such as the Dow Jones Industrial Average. To capture the complexity of a system, multiple relevant indicators can be aggregated into an “index.” The Dow Jones Industrial Average, for example, serves as a measure of the entire U.S. market, covering a diverse mix of businesses in each market sector – financial services, technology, retail, entertainment, and consumer goods (Figure 4).

To be useful, indicators must answer the questions being asked (see page 24) while being grounded within a conceptual framework that conveys not only what is being measured, but why and in what context. The Dow Jones, for instance, is an index within the framework of the U.S. stock market. In general, the higher the value of the Dow Jones index, the better the U.S. stock market is doing.

Following up on the management goals/objectives/questions developed under the previous section—this section focuses on the use and development of conceptual models in indicator identification and development.

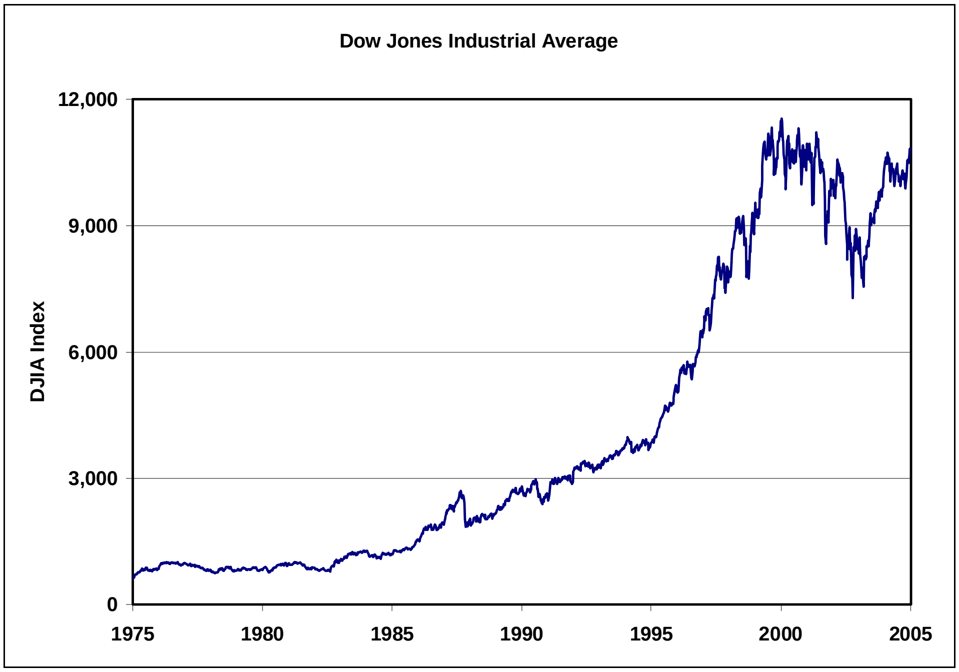


Figure 4. Example of a Common Economic Indicator—Dow Jones Industrial Average from 1975 to 2005 (weekly mean index data compiled from http://www.djindexes.com)

USE OF CONCEPTUAL MODELS IN INDICATOR DEVELOPMENT

Conceptual models interpret systems by organizing information on the structure and interactions of the system into an easily understood and sometimes visual format, which simplifies the process of identifying appropriate indicators. These models identify key ecological compartments and linkages between those compartments. Within the conceptual model, the various perturbations (Pressures) are put into context with system ecology and potential responses. Several types of conceptual models can be used to organize and identify environmental indicators. These models run the gamut from simple text describing an ecological system to complex, multifaceted flow charts that detail many of the compartmentalized aspects and interactions occurring within a particular ecosystem (see Figure 5 for an example).

New York/New Jersey Harbor Estuary Program—Indicator Development

"There is no program that monitors habitat function directly. However, one indirect way to determine whether habitats are functioning properly is to examine the population sizes of organisms that those habitats support." (Steinberg, Suszkowski, Clark, and Way, 2004)

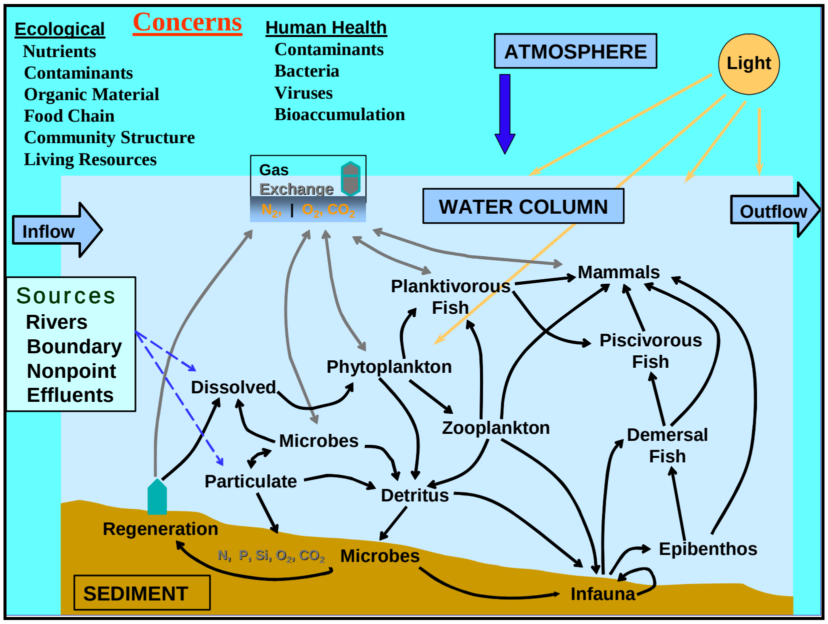


Figure 5. Conceptual Model of Estuarine Ecosystem with Multiple Stressors and Responses

DEVELOPMENT OF CONCEPTUAL MODELS

Several different types of frameworks have been created for developing conceptual models. One of the more prominent frameworks categorizes (1) environmental indicators as pressures and stressors that degrade ecological condition, (2) the state of ecological conditions, and (3) society's responses at improving ecological condition. As seen in this categorization, environmental indicators can be used to measure ecological condition, but may be used to measure progress towards meeting goals, milestones, and objectives. These indicators are often referred to as "programmatic indicators," measuring implementation of actions, funding milestones, and changing laws, policies, and regulations. The following section presents several frameworks that can be used to organize environmental—both programmatic and ecological—indicators to monitor and track estuarine health and restoration efforts. As noted previously, this manual focuses on ecological indicators, but similar frameworks and processes apply to the development of other types of indicators.

Pressure-State-Response (PSR) and Pressure-State-Response-Effect (PSR/E) Frameworks

Used internationally and nationally, the PSR framework is a conceptual framework developed by the OECD for environmental monitoring. The PSR framework (see Figure 6) represents the associations among the pressures exerted by human activities on the environment (Pressure); the changes in the quality and quantity of natural resources (State); and the societal responses to these changes through environmental and other polices (Response) (OECD, 1993).

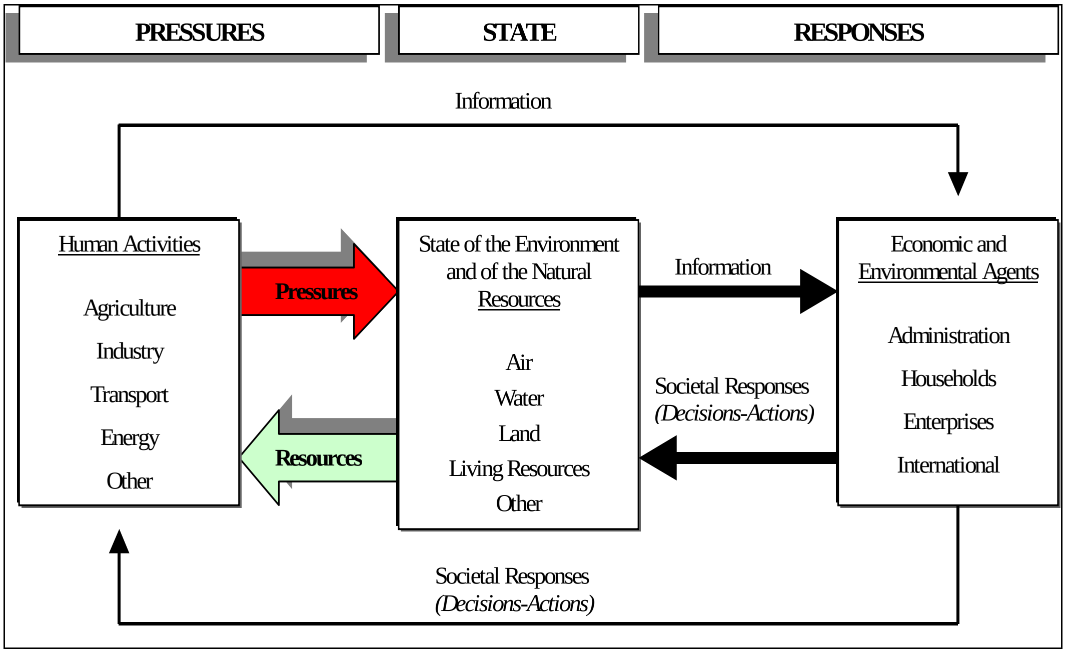


Figure 6. The PSR Conceptual Model (OECD, 1993)

Pressure indicators are measurements of the pressures exerted on the environment by human activity, whether direct (*i.e.*, proximate pressures) or indirect (*i.e.*, indirect pressures). Examples of pressure indicators include emissions from cars, discharges from municipal wastewater treatment plants, and runoff from agricultural operations. State indicators describe the quality of the environment and the quality and quantity of natural resources. State indicators generally are measurable quantities, such as water quality parameters, concentrations of air or water toxicants, the extent of viable wetlands, or the functionality or productivity of wetlands. Response indicators relate how society is responding to environmental changes and concerns by protecting and restoring the environment and preventing environmental damage. Societal responses may range from economic incentives such as taxation and subsidies to enforcement with legislative and management programs. The framework assumes that there is a causal relationship between each of the components that links human activity to environmental impacts.

Building on the existing PSR framework, the EPA Office of Policy, Planning and Evaluation modified the PSR framework to include interactions among pressure, state, and response indicators, called “effects” indicators (PSR/E) (EPA, 1995). The principles of the PSR/E framework have been adopted by EPA’s ORD, which focuses its indicator research on the state and effects components of the PSR framework. ORD’s indicators are science-based, rather than policy-based, and the guidance document *Evaluation Guidelines for Ecological Indicators* presents examples of three different types of indicators (EPA, 2000b).

With regard to the PSR and PSR/E approaches, the models can be relatively simple, focusing on only primary or secondary effects/interactions, or they may be more complex, including many factors influencing and being impacted within a system. The simpler the model, the more clearly defined the relationship between PSR and PSR/E. The main drawback in using a simple model is that a component of the real ecosystem that is not taken into account may play a critical role in how the ecosystem responds to or is affected by pressures or response actions.

It is important that conceptual models be easily understandable by both scientists and managers and that the models include enough information to make educated choices on what might be used as an indicator. For example, nutrients are a crucial ingredient in the biogeochemical functioning of an estuarine system. However, too much of a good thing, in this case anthropogenic nutrient inputs, could drive the system toward eutrophication with elevated biomass (organic material) and, eventually, lower bottom-water DO levels or even hypoxic conditions. This is just one example of the interactions of pressures on the state of an estuarine system, but it conveys the simple idea that additional input of nutrients could lead to low DO. In this case, the annual point source nutrient load may be a useful indicator of the pressures on the system. The annual or seasonal phytoplankton biomass or DO minima would be an indicator of the state of the system. If the management response is to decrease point source loading, then all three might be useful in understanding the success of the action both directly (nutrient loading) and indirectly on the effect on the system (biomass and DO).

It is important that conceptual models be easily understandable by both scientists and managers and that the models include enough information to make educated choices on what might be used as an indicator.

Tillamook Bay Estuary Program (TEP)—State Indicators

"TEP made a conscious decision to focus on "state" indicators. State indicators were selected because they best describe the quality of the environment, and integrates the effects of pressures and responses over time." (TEP, n.d.)

This example is presented in Figures 7 and 8 within the more formal PSR and PSR/E frameworks. The primary difference between these frameworks is that the PSR/E framework formalizes the effects of the response actions into the conceptual model. Although it is not a specified component in the PSR framework, continued monitoring of pressure or state variables/indicators is implicit and serves to provide an understanding of the effect of management responses. In Figure 7, the management actions result in some change in both pressures and state as signified by the returning arrows. In Figure 8, the impact of these actions is specified as expected effects to both pressure and state variables (bottom box). A more complex version using multiple variables would follow the same process but would have many more interconnections between pressures, states, responses, and effects. At some point, the model becomes less useful and it would be preferable to use an ecological framework to describe the conceptual model, as discussed in the next section.

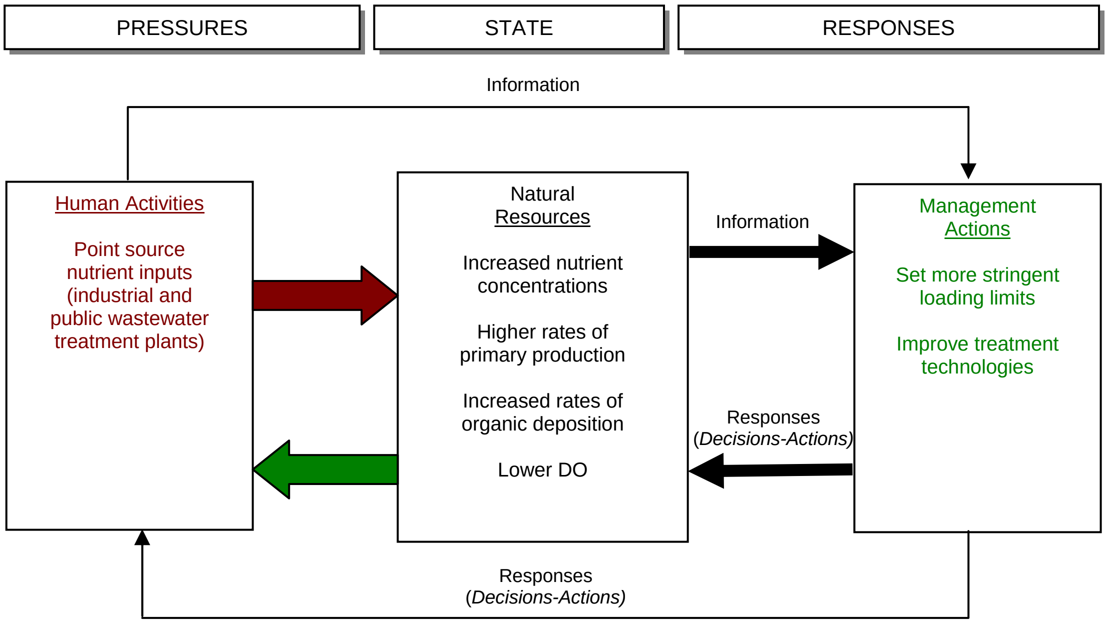


Figure 7. Example of a PSR Conceptual Model for Nutrient Inputs and Aspects of Eutrophication.

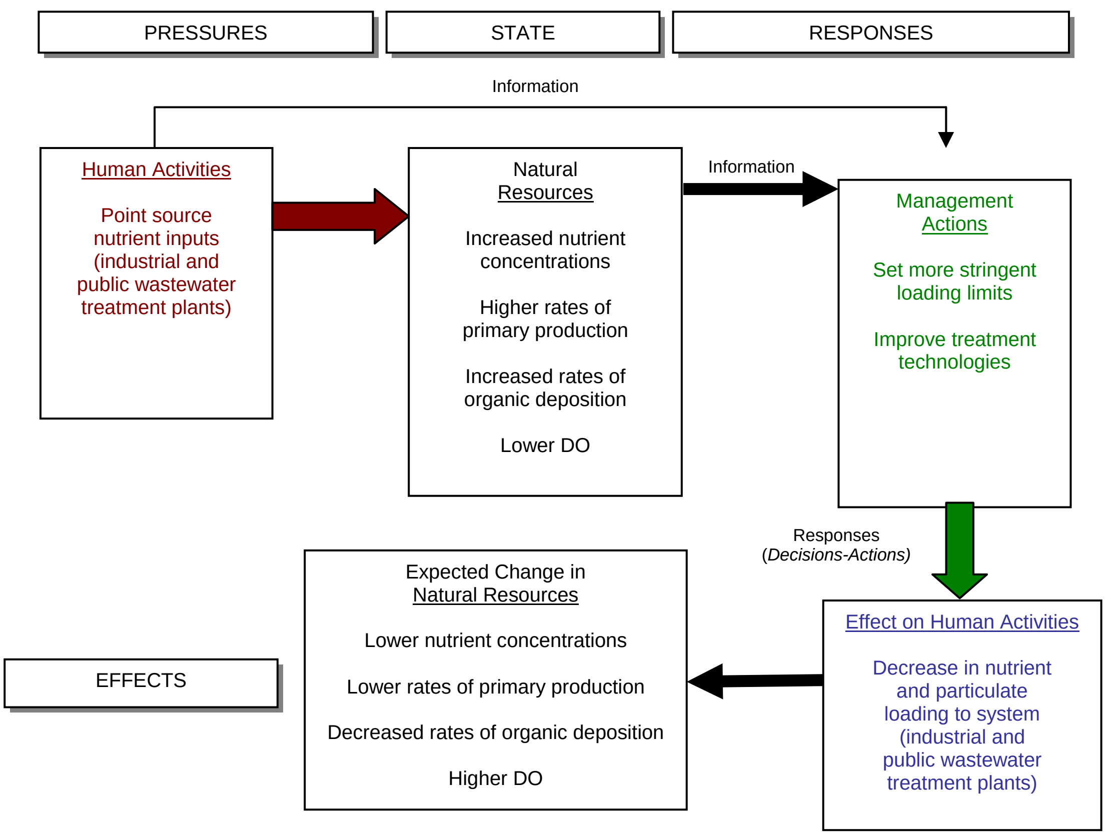


Figure 8. Example of a PSR/E Conceptual Model for Nutrient Inputs and Aspects of Eutrophication.

Note: Figures 7 and 8 were developed for this manual using example indicators.

Ecological Framework

Another environmental indicator framework that is related to the PSR/E framework is presented in the NRC's guidance document *Ecological Indicators for the Nation* (NRC, 2000). The NRC proposes national indicators of ecological condition that are influenced by multiple stressors. These indicators may be used to estimate the ability of a nation's ecosystems to continue to provide goods (*e.g.*, food and building materials) and services (*e.g.*, flood protection and recreation) for the survival of the society. These indicators fall into three categories:

1. Indicators of ecosystem extent and status;
2. Indicators of ecological capital;
3. Indicators of ecosystem functioning.

Indicators of ecosystem extent and status include measurements of land cover and land use. Indicators of ecological capital measure the biotic and abiotic natural capital, or raw materials, of the nation. Biotic raw materials include the number and distribution of native species, and the number of introduced or exotic and invasive species, while abiotic raw materials include soil and nutrients. Indicators of ecosystem functioning measure ecosystem processes or end results of processes, such as productivity and nutrient-use efficiency and nutrient balance. The interactions between raw materials and the ecosystem process are initially developed in a conceptual model of the estuarine ecosystem in order to develop relevant indicators to model the system.

In order to develop an appropriate environmental indicator, it must be directly linked to the cause, effect, or action it is tracking. Ideally, indicator development should be preceded by the development of an assessment question. An example assessment question relevant to the objective of this report is "What percent of the estuary is hypoxic?" The next critical step is the development of a framework or model of the system relevant to the assessment question. In the example, the estuary may be exhibiting hypoxic conditions due to lack of oxygen from algae growth, loss of seagrass, industrial pollutant discharges, invasive species changing ecosystem dynamics, or nutrient overloading.

Ideally, a conceptual model should be developed based on the current understanding of the structure and function of the system in question (an estuarine ecosystem example is provided in Figure 5). The model considers temporal and spatial dynamics, evaluates recuperative capacities of the resource to combat stressors, and identifies where stressors are introduced to the system and may potentially impact resources. The model should present a thorough understanding of the inputs and outputs of the system that will lead to a selection of indicators in which to perform the research. Common mistakes encountered while developing indicators include

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selecting indicators that are not linked to the assessment questions, developing indicators prior to posing an assessment question, and settling for indicators based on the currently available data.

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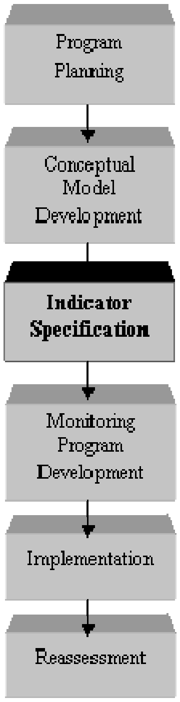
INDICATOR SPECIFICATION



Once the management goals/questions have been defined and at least one conceptual model has been developed, the process focuses on selecting appropriate indicators for addressing each question and model compartment. These indicators can be either quantitative measures (*e.g.*, DO levels) or qualitative measures (*e.g.*, aesthetics; see the *Sneaker Index* callout box below). Indicators can also be direct measurement indicators, index indicators, or complex multi-metric indicators. Direct measurement indicators, such as DO or nutrient concentrations, directly correlate the measurements of the indicator (DO) to the effect on the environment (hypoxia). Index indicators (multiple indicators), such as the index of benthic condition, integrates measures of community composition and diversity and discriminates between impacted and unimpacted areas. Complex, multi-metric indicators are a composite index, which integrates various structural and functional attributes of an ecosystem and provides an overall assessment of ecosystem condition (EPA, 2000b). An example of a multi-metric indicator is the characterization of a stream fish assemblage that measures the effects of a variety of stressors across different time scales and levels of ecological organization and evaluates the impact of fish consumption by the general public. The development of this type of indicator is based on the multi-metric Index of Biotic Integrity originally developed by Karr (Karr, 1981; Karr *et al.*, 1986). Therefore, each of these indicator types varies by the type of information and extent of analysis involved in its development.

> "The symbolic value of an indicator may outweigh its value as a literal measure."
> (Cobb and Rixford, 1998)

Sneaker Index

"The name *Sneaker Index* was originally coined by Sen. C. Bernard (Bernie) Fowler, around 1988. Sen. Fowler was deeply concerned about the future of Maryland's Patuxent River. To evaluate the condition of the river water, he began to measure how deep he could wade into the water and still see his sneakers—thus came the name 'Sneaker Index'. People understood this form of assessment very easily. Consequently, the public accepted it." (Price and Huerta, 2001)

A range of possible indicators stemming from eutrophication issues is presented in Figure 9. In this case, the input of nutrients to a system can have a variety of impacts that range from primary, to secondary, to even tertiary symptoms. Each level of symptoms in Figure 9 carries with it additional effects from other stressors. These indicators integrate impacts not only across multiple stressors, but often across wide spatial areas, over time, due to cumulative effects. A number of factors must be considered for the selection of indicators suitable for each area/region of interest (parameters and metrics).

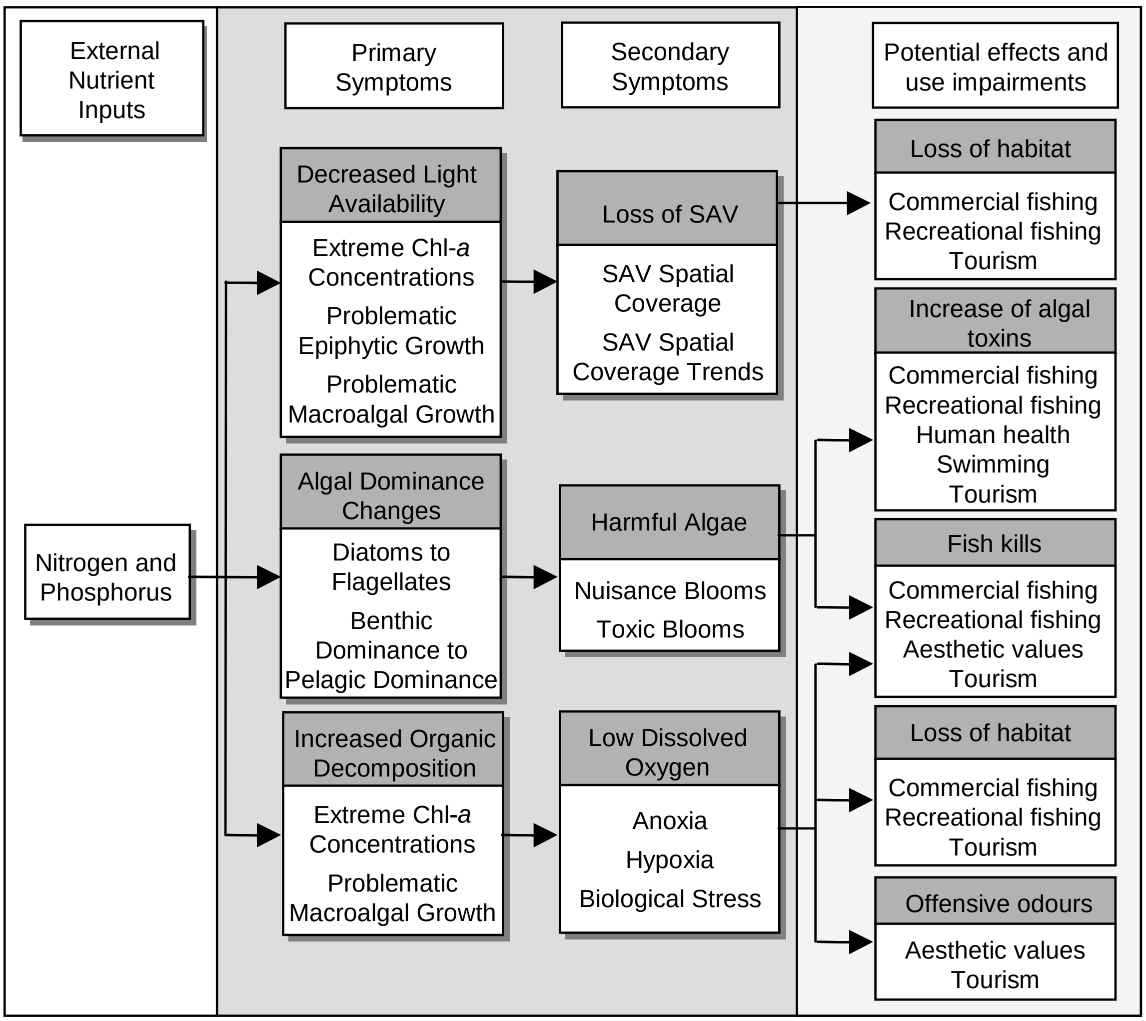


Figure 9. Example of Multiple Levels of Indicators Associated with Eutrophication and the Inputs of Nutrients (Bricker, Ferreira, and Simas, 2003)

Great Lakes Program SOLEC 1996—Science Based Indicators

At SOLEC 1996, constituents decided to create "a basin-wide, systematic framework using science-based indicators." "Small working groups of experts were assembled and asked to both 'extract' indicators from Great Lakes studies pertinent to their topic, and to identify new indicators to fill crucial gaps. According to the interviewees, breaking the indicator development process into manageable topic areas, and assigning each piece to a separate working group, made for a fairly efficient process." (Pidot, 2003)

To determine whether an indicator provides consistent information for evaluating both short- and long-term conditions and supporting management decisions, EPA has established guidelines using a four-phase approach for evaluating potential and acknowledged indicators (EPA, 2000b). The four-phase criteria are as follows:

1. ***Conceptual Relevance or Soundness***
   Is the indicator relevant to the assessment question and to the resource at risk? The choice of indicators is dependent upon initial questions and conceptual models for the relevant area.

2. ***Feasibility of Implementation (Current and Future)***
   Are the methods for long-term sampling and measuring the environmental variables technically feasible, appropriate, and efficient for use in a monitoring program? Evaluation of the indicators must focus on both the short- and long-term feasibility of monitoring, the associated costs, and the complexity of analysis and data interpretation.

3. ***Response Variability***
   Are human errors of measurement and natural variability over time and space sufficiently understood and documented? Indicators will likely integrate both anthropogenic and natural factors—can the spatial and temporal variability of each factor be determined (regional vs. local, short-term or long-term, etc.)?

4. ***Interpretation and Utility***
   Will the indicator convey information on resource conditions that is meaningful to environmental decision-makers? In addition, is the indicator currently monitored or likely to be easily monitored in the future?

These phases describe an idealized progression for indicator development that flows from fundamental concepts, to methodology, to examination of data from pilot or monitoring studies, and finally to consideration of how the indicator serves the program objectives. The guidelines are presented as sequential steps that can be used iteratively to refine the selected indicator.

Both the NRC and EPA's Environmental Monitoring and Assessment Program (EMAP) have put forth their own sets of criteria for evaluating the appropriateness of indicators for environmental systems (EMAP, 1994; NRC, 2000). Table 1 compares indicator evaluation criteria recommended by these two programs with those suggested in EPA (2000b) guidelines. Although some of the individual criteria vary between the three sets of guidelines, all of the criteria share the four phases described above, with several of the criteria in these groups overlapping across programs. The essential elements for evaluating the suitability of an indicator are whether the indicator is measurable using available technology, is relevant and responds to the assessment question, and provides information for management decision-making. Additionally, the best indicators are able to quantify information so its significance is more readily apparent and simplify information about complex phenomena to improve communication between researchers, managers, and ultimately the public.

Long Island Sound Study—Indicator Development

Indicator development began with a review of monitoring programs already collecting data in the Long Island Sound region. First, developers exclusively looked at existing programs and did not consider which information might be most useful to managers or scientists. LISS also reviewed the work of other groups that had completed indicator-based State of the Environment Reports to gain a sense of what choices were made by others with similar projects. A list of approximately 100 potential indicators was created from the review. Indicators were selected from this list based on the extent and quality of data immediately available, as well as their relevance to Long Island Sound management objectives. (Pidot, 2003)

Tillamook Bay—Indicator Selection Criteria

In addition to the selection criteria noted above, Tillamook Bay applied the following criteria:

1. Correlated to environmental conditions and/or responses
2. Representative of system-wide conditions
3. Understandable and relevant to audience
    a. Directly applicable to resource management
    b. Linked to public concern or interest
4. "Monitorable"
    a. Quantifiable
    b. Repeatable
    c. Affordable
    d. Practical

(TEP, n.d.)

Table 1. Examples of Various Indicator Evaluation Guidelines[1]

General Criteria Group	EPA (2000b)	NRC (2000)	EMAP (1994)
Conceptual relevance or soundness	*Relevance to the assessment*	*General importance*	*Unambiguously interpretable*
	Relevance to ecological function	*Conceptual basis*	
Feasibility of implementation (current and future)	*Data collection methods*	*Necessary skills*	*Available method* *Minimal environmental impact*
	Logistics		*Amendable to synoptic survey*
	Information management	*Data archiving*	
	Quality assurance		
	Monetary costs	*Cost, benefits, and cost-effectiveness*	*Cost effective*
		Data requirements	
Response variability	Estimation of measurement error		
	Temporal variability – within the field season *Temporal variability – across years* *Spatial variability*	*Temporal and spatial scales of applicability*	*Index period stability*
	Discriminatory ability	*Robustness* *Statistical properties*	*High signal-to-noise ratio* *Ecologically responsive*
Interpretation and utility	*Data quality objectives*	*Data quality*	
	Assessment thresholds		*Nominal-subnominal criteria*
	Linkage to management action		
			Retrospective
			Anticipatory
		Reliability	*Historical record*
			New information
		International compatibility	

[1]Criteria that are common to more than one program are italicized.

Indicator Specification

CONCEPTUAL RELEVANCE

The indicator must provide information that is relevant to societal concerns about ecological condition. The indicator should clearly pertain to one or more identified assessment questions. These, in turn, should be germane to a management decision and clearly relate to ecological components or processes deemed important in ecological condition. Often, the selection of a relevant indicator is obvious from the assessment question and from professional judgment. However, a conceptual model can be helpful to demonstrate and ensure an indicator's ecological relevance, particularly if the indicator measurement is a surrogate for measurement of the valued resource. This phase of indicator evaluation does not require field activities or data analysis. Later in the process, however, information may come to light that necessitates re-evaluation of the conceptual relevance, and possibly indicator modification or replacement. Likewise, new information may lead to a refinement of the assessment question. (EPA, 2000b)

The first step in indicator identification and development flows directly from the appropriate conceptual models identified for the specific estuary, ecosystem, or regional area of concern. These models may be specific to a particular segment of the ecosystem or more detailed, including multiple trophic levels and habitats. The suite of possible indicators also covers a wide range from parameter-specific to integrations of multiple metrics/parameters. In all cases, however, the indicator needs to be directly relevant to the resources at risk or the management questions being addressed. A compendium of indicators is included in Appendix B. This list, although quite comprehensive, is not necessarily complete; additional indicators may be valid in a particular system.

The strategies for selecting indicators based on conceptual models are as varied as the programs themselves, but most focus on some form of brainstorming. This activity can occur internally with NEP or other groups, externally utilizing the experience and knowledge of area scientists who are brought together as a Technical Advisory Committee (TAC) or similar types of advisory groups, or publicly with a wide range of stakeholders participating. Each level of involvement has benefits and drawbacks. Internal staff discussions can be focused, expedient, and driven by knowledge of the next three steps in the process. Expanding discussions to include a TAC will likely extend the timeframe of the process; however, it will also expand the knowledge base and may provide a more comprehensive list of indicators. Public workshops are certain to take the most time, but in addition to the benefit of likely producing a more comprehensive list of indicators that will be easily communicated, workshops also provide a mechanism of public education and a buy-in to the process.

FEASIBILITY OF IMPLEMENTATION

Adapting an indicator for use in a large or long-term monitoring program must be feasible and practical. Methods, logistics, cost, and other issues of implementation should be evaluated before routine data collection begins. Sampling, processing and analytical methods should be documented for all measurements that comprise the indicator. The logistics and costs associated with training, travel, equipment and field *and laboratory work should be evaluated and plans for information management and quality assurance developed*. (EPA, 2000b)

The factors that determine the feasibility of indicator implementation fall into two general categories—available infrastructure/expertise and costs. The availability of the infrastructure necessary for sample/data collection, analysis, and management is directly related to costs, but such costs likely have been covered by previous budgets. If existing monitoring program infrastructure is not present, then the feasibility of implementing a wide variety of indicators is limited. It is expected that most systems will have a modicum of ongoing monitoring activities and that the current system in place not only provides data relevant to some of the selected indicators, but also has the capacity to be modified to implement additional monitoring efforts. Again, the cost/benefits of each indicator will need to be evaluated based on available funding sources, both current and with an eye to the future for any long-term metrics.

RESPONSE VARIABILITY

It is essential to understand the components of variability in indicator results to distinguish extraneous factors from a true environmental signal. Total variability includes both measurement error introduced during field and laboratory activities and natural variation, which includes influences of stressors. Natural variability can include temporal (within the field season and across years) and spatial (across sites) components. Depending on the context of the assessment question, some of these sources must be isolated and quantified in order to interpret indicator responses correctly. It may not be necessary or appropriate to address all components of natural variability. Ultimately, an indicator must exhibit significantly different responses at distinct points along a condition gradient. If an indicator is composed of multiple measurements, variability should be evaluated for each measurement as well as for the resulting indicator. (EPA, 2000b)

There are two primary sources of variability in environmental data—analytical and natural. Although it is important to understand the variability inherent in specific analyses/measurements, that variability is not described herein. EPA (2000b) provides a detailed discussion of analytical variability and its context in indicator development. For this manual, it is expected that the variability from most methods of data/sample collection and analysis can be minimized or at least quantified by following explicit quality assurance/quality control (QA/QC) protocols. To this end, it is critical to have a QA/QC plan in place for any monitoring activity. Not only will it allow for assessment of field and laboratory variability, but the data quality objectives outlined in a typical QA/QC plan will also be useful during subsequent interpretation activities.

Natural variability occurs over many temporal and spatial scales, and a comprehension of natural variability is crucial to both understanding the system and selecting appropriate indicators. Ecosystem characteristics vary over time scales from hourly to interannual; selection of the optimal time scale is important in developing monitoring approaches and interpreting the data.

In most cases, the spatial scale that is of most concern to managers is their local area, but this may be as small as a localized area within an embayment, an entire embayment, a larger bay, or a large regional coastal area. Not only is the scale of the area of concern important, but important factors influencing localized areas are also often regional (*e.g.,* coastal currents), hemispheric (*e.g.,* North Atlantic Oscillation, El Niño/Southern Oscillation), or even global (*e.g.,* climate change) in scale.

In these contexts, the expectation is that the natural variability over time and space is such that an anthropogenic signal can be discerned. The natural variability either has to be relatively small or well-defined in comparison to expected changes due to human pressures. To this end, when selecting indicators to track ecosystem health and response to management actions, numerous questions should be considered concerning the temporal and spatial scale variability of environmental data. For example:

1. Are there natural seasonal patterns in the data?
2. What is the most representative time period from which to measure or average data?
3. Is the local expression of the indicator indicative of localized impacts or driven by larger regional forces?

INTERPRETATION AND UTILITY

A useful ecological indicator must produce results that are clearly understood and accepted by scientists, policy makers, and the public. The statistical limitations of the indicator's performance should be documented. A range of values should be established that defines ecological condition as acceptable, marginal, and unacceptable in relation to indicator results. Finally, the presentation of indicator results should highlight their relevance for specific management decisions and public acceptability. (EPA, 2000b)

In this last step for indicator evaluation, the expected needs that the indicator must fulfill become a bit more diverse (see Table 1). The main need is for an *a priori* understanding or establishment of a threshold level or range of values that is considered 'good' or 'bad' with which to evaluate current conditions or trends based on a particular indicator. In the best-case scenario, this level or range of values would be based on a long-term data set—baseline or historical.

In the absence of data specific to the system of interest, comparisons to other systems may suffice. These comparative systems could be impaired or pristine or likely somewhere in between, but should have enough similarities to be germane to the system of interest. Best professional judgment can also be a valid source when no other data are available. Regulatory levels or management goals could also serve as a threshold for many quantitative indicators.

The selection of indicators will always be site-specific, but the process by which indicators are selected is nearly always the same and more or less follows the four steps described above.

Table 2 lists a sampling of potential indicators and their relevance, feasibility, expected variability, and interpretation utility. Although the details in the table are limited, these examples provide a starting point and model for this approach.

For example, DO is a key indicator and integrator of water quality in coastal waters. As a basic necessity for aquatic life, DO levels directly affect ecosystem health. Diaz and Rosenberg (1995) state that no other environmental variable of such ecological importance to coastal marine ecosystems has changed so drastically in such a short period of time as DO. These authors argue that while hypoxic environments have existed through geological time, their occurrence in shallow coastal and estuarine areas appears to be increasing and the cause seems most likely to be accelerated by human activities (Nixon, 1995; Bricker *et al.*, 1999). Thus, DO is obviously relevant to understanding human impacts on our coastal ecosystems.

The measurement of DO is straightforward for both *in situ* sensors and water samples (Winkler titrations), and the methods are quite accurate. DO is typically measured as part of coastal water quality monitoring programs and is relatively inexpensive in comparison to other data-gathering efforts. Historic data are often available, current monitoring programs are normally measuring DO, and data will continue to be easily and economically obtained into the future. All these factors indicate that DO is a very feasible indicator.

As mentioned, the analytical variability in DO analysis is tightly constrained, as methods are quite accurate and precise. The amount of DO contained in marine waters at saturation is a function of physical, chemical, and biological conditions. Cold waters hold more DO than warm waters at a given salinity. Seawater at equilibrium at a given temperature contains substantially less DO than freshwater. Thus, DO concentrations naturally follow a seasonal pattern of winter maxima and summer minima that is directly related to temperature but is influenced by biological processes. This aspect of natural variability in DO concentrations, and the fact that historic and present data monitoring programs further describe these trends or provide a baseline, suggests that it is likely that an anthropogenic signal in this indicator could be observed.

Biological production and utilization of DO in coastal waters has a well-known theoretical relationship to nutrient supplies. Increased nutrient supplies often lead to increased photosynthetic production of organic matter by phytoplankton or other algae. This increase in production often results in super-saturated DO levels in the upper water column. Alternatively, a dominance of heterotrophic activity, especially microbial respiration, can lead to greatly under-saturated conditions. Highly productive waters may experience super-saturated conditions during the day and under-saturated conditions at night, especially just before sunrise as respiration has been occurring for maximum duration.

Table 2. Sampling of Indicators and their Respective Aspects under the Four Criteria—Relevance, Feasibility, Variability, and Utility

Indicator	Relevance	Feasibility	Variability	Utility
Nutrient loading	Point and non-point source inputs are one of the primary factors in eutrophication.	Point sources are required to measure nutrients by permits, and most monitoring programs include these relatively inexpensive measures.	Analytical variability is minimal and known. The inputs are also well-constrained (large natural variability in ambient waters, but not loading).	One of the responses of management is to set loading limits. Thus, baseline and post-action changes can be measured and changes in the ambient waters measured.
Dissolved oxygen	Integrator of many water quality processes and directly relevant to marine species (and fishermen).	Easily measured and among normal suite of measurements.	Analytical variability is minimal and known. Natural variability can be large, but seasonality of signal is typically known and changes in seasonal DO minima could be detected.	Given the understanding of this parameter, interpretation of the data is relatively straightforward (though ancillary information on physical current structure and bathymetry is very helpful).
Frequency of toxic/nuisance phytoplankton blooms	Public health and aesthetic issue. Shellfish closures also a monetary incentive for monitoring these species.	Often part of state monitoring programs (*e.g.*, Maine Department of Marine Resources). Local researcher with experience – otherwise can be very expensive.	Little analytical variability, assuming counts and identifications are made by experienced personnel. Natural variability can be large, but often well-known due to historical data and shellfish closures or other public health records.	Frequency of these blooms has increased—unclear from literature whether due to increase monitoring effort or as a result of anthropogenic impacts.

Table 2 (continued). Sampling of Indicators and their Respective Aspects under the Four Criteria—Relevance, Feasibility, Variability, and Utility

Indicator	Relevance	Feasibility	Variability	Utility
Acres of existing seagrass and habitat restored	Importance to fisheries and sensitive to nutrients. Integrator of eutrophication processes (decreased light, increased epiphyte growth) and other anthropogenic pressures (trawling, development, increased sedimentation, etc.).	Established direct (divers) and indirect (*in situ* instruments and remote sensing) methods exist for mapping the density and extent of seagrass beds. Can be expensive, but can be conducted on a cyclical basis to minimize annual costs.	Increased variability with the indirect measurements that quantify over a larger range, but can be minimized by ground truthing sampling. Interannual variability a direct indicator of habitat loss or gain.	Necessary for establishing baseline conditions and to monitoring the effectiveness of restoration programs. Once a baseline distribution map is available, can revisit at 3- to 5-year intervals to gauge changes in this valuable habitat resource.
Benthic indices (health, abundance, taxonomic identification and diversity)	Benthos is an integral part of the ecosystem and tends to be the repository of much of the organic material and contaminants from anthropogenic inputs. Need to develop linkages between stressors and benthic impacts.	As with the phytoplankton, this type of indicator can be very expensive if not part of an ongoing monitoring plan. Unlike plankton, the benthos could be monitored less frequently if appropriate and still provide a clear indication of improvement or degradation.	The benthos is a highly variable environment, and this is reflected in the data. This variability can be minimized by implementing a QC program, by understanding the relative temporal and spatial variability across the system. and by tailoring the sampling schema to capture only the specific time and area of interest to both focus the effort and minimize these sources of variability.	Many types of indices listed in the literature. The more effort taken in selecting an appropriate index, the more useful the results will be. Critical in establishing 'baseline' conditions and for managers tasked with both assessing ecological condition and mitigating impacts caused by anthropogenic inputs.

Table 2 (continued). Sampling of Indicators and their Respective Aspects under the Four Criteria—Relevance, Feasibility, Variability, and Utility

Indicator	Relevance	Feasibility	Variability	Utility
Fish/shellfish consumption warnings	Designed to protect public health—usually using a risk-based approach to contaminant levels. Directly impact public's perception of water quality and toxics.	Typically issued by a state agency—the monitoring, analysis and assessment of risk all conducted by the state. Data publicly available (historic and into the future).	Primary sources of variability are controlled or at least taken into account in the risk-based system. State-to-state variability may exist, but relative numbers will likely be comparable over time.	One of the end-of-the-line type indicators—if warnings increase or decrease, a clear message is understood by the public. The more localized the range of the animals, the more pertinent to individual estuaries or locations.

Another factor that affects DO concentration in estuarine and coastal waters is mixing (or lack thereof). Deeper waters, where vertical density differences exist (especially sub-pycnocline waters), may become hypoxic during the summer when DO solubility is lowest and ample supplies of labile organic carbon are available (due to sinking of senescent phytoplankton) to support microbial respiration and benthic respiration in the bottom waters. DO utilization in deeper stratified waters may outpace DO replenishment through transport of atmospheric DO and mixing and any potential net gains of DO from photosynthesis. DO concentration in coastal waters is a dynamic property that varies spatially and temporally, depending on physical, seasonal, biotic, and anthropogenic influences. Thus, the foundation for interpreting the DO indicator is sound and readily available. Not surprisingly, DO is one of the most widespread indicators in use for water quality objectives.