NUTRIENTS: CANADIAN GUIDANCE FRAMEWORK FOR THE MANAGEMENT OF NEARSHORE MARINE SYSTEMS

Nutrient enrichment of coastal waters is one of the greatest threats to the integrity of coastal ecosystems (NRC 1994; Pelley 1998). Cultural eutrophication of marine systems dramatically increased around the world beginning in the 1950s and 60s and has been related to increase in consumption of chemical fertilizers, burning of fossil fuels, land use changes, and wastewater discharges in coastal areas (CCME 2007).

Consequences of Nutrient Over-Enrichment

The consequences of nutrient over-enrichment to marine systems are numerous and include changes in both structure (biological communities) and function (ecological processes) of aquatic ecosystems (Bricker et al. 1999; NRC 2000; USEPA 2001). An initial consequence of nutrient over-enrichment is increased plant growth which is often accompanied by changes in species composition such as a shift from a primarily diatom based plankton community to small flagellates. This may also be accompanied by an increase in the development of harmful algal blooms such as red and brown tides, which can be toxic to shellfish, fish, marine mammals resulting in changes in biodiversity, and in some cases, become a direct threat to humans (Hallegreaff 1993).

In shallow marine environments and intertidal zones where sufficient light reaches the bottom, fast growing macroalgae (e.g., *Enteromorpha*, *Ulva*, *Cladophora*) may increase, eliminating slower growing macroalgae and sea grasses (e.g., *Zostera*). In deeper environments, high phytoplankton concentrations may reduce bottom light levels to the point where sea grasses and other benthic plants are completely eliminated (CCME 2007).

One of the most serious consequences of nutrient over-enrichment to marine ecosystems is the decreased level of dissolved oxygen (DO) within the water column. Increased plant growth results in increased sedimentation of organic matter. Bacterial decomposition of this material may result in the depletion of DO, causing either hypoxic or anoxic conditions. In shallow systems, excessive macroalgal growth can result in anoxic conditions within the water column, especially during periods of warm water temperatures and during night time. This can result in death and the subsequent decomposition of macrophytes causing further depletion of DO that may in turn result in the death and elimination of aerobic benthic organisms and, in severe cases, fish kills (Rabalais et al. 1996).

Nutrients of Concern

In contrast to freshwater systems, where phosphorus is usually the limiting nutrient, temperate marine systems are thought to be nitrogen limited. This is based on considerable evidence from nutrient ratio data, bioassays and large-scale nutrient enrichment experiments (Ryther and Dunstan 1971; Nixon 1995; Oviatt et al. 1995; Howarth and Marino 1998). This difference in nutrient limitation between fresh and marine waters may be due to differences in rates of nitrogen fixation and denitrification as well as differences in nutrient loading ratios.

Phosphorus may be limiting to phytoplankton in marine systems during periods of high freshwater inflows, such as those that occur during the spring snow melt, but this is thought to be only temporary, as during summer and fall these systems become nitrogen limited (Fisher et al. 1982; D'Elia et al. 1986; Malone et al. 1996). Phosphorus may also be limiting in systems that have exceptionally high nitrogen inputs combined with stringent phosphorus input controls (Howarth 1998). This suggests that under some conditions, both phosphorus and nitrogen must be considered in plans designed to manage nutrient over-enrichment (Chapelle et al. 1994).

Although less intensively studied than phytoplankton, marine macroalgae growth in temperate systems appears to be limited primarily by nitrogen (Valiela et al. 1990).

Nutrient over-enrichment with nitrogen and phosphorus is thought to result in a decrease in silicate within the water column as a result of excessive diatom growth followed by the settling of diatoms where silicate then becomes sequestered within the sediments (Conley et al. 1993). In coastal systems having high nutrient inputs, this decline in silicate is often responsible for shift from a diatom based phytoplankton community to one in which flagellates dominate (Officer and Ryther 1980).

Iron is an important trace element for primary producers and nitrogen fixing organisms and has been shown to be a limiting nutrient in some oceanic marine systems (Martin et al. 1991). Its importance as a major limiting factor in estuaries, however, is generally considered to be minor in most instances (NRC 2000).

Sources of Nutrients

Since pre-industrial times, the amount of biologically available nitrogen entering the biosphere each year has roughly doubled (Galloway et al. 1995; Howarth 1998) and there is a strong relationship between nitrogen inputs to a coastal system and the human population density within its watershed (Cole et al. 1993). The most important sources of anthropogenic nutrient inputs to coastal systems are wastewater discharges, fertilizers and atmospheric deposition (Valiela 1995).

Of particular importance is chemical fertilizer use since nitrogen, unlike phosphorus, is not retained to any large degree in soils. Although surface runoff from the land is usually considered to be the major path by which non-point sources of nitrogen enter waterways, there is considerable evidence that groundwater inputs may be equally or more important in areas where aquifers are hydraulically connected to the sea through permeable soils (Valiela et al. 1990; Paerl 1997).

Wastewater discharges assume greater importance in heavily urbanized watersheds, especially if they contain high levels of organics, which could increase the potential for decreased DO levels. Aquaculture operations, especially finfish farms where feed is added, can be important sources of nutrients inputs in coastal areas (Merceron et al. 2002). It is estimated that about 40% of the nitrogen contained in fish foods is incorporated into fish biomass, the rest being released to the environment as metabolic wastes, feces and uneaten food fragments (Strain and Hargrave 2005). Fish and seafood processing plants are also considered as one of the potential sources of nutrients in coastal waters (Fisheries and Oceans Canada 2003).

When scaled over the entire watershed, even small nutrient losses per unit area of the watershed can be quite large (NRC 2000; Sowles 2003). In some cases it may be important to consider not the total annual loading rate, but rather the seasonal loading rate and how this correlates with the time at which the system is most susceptible to eutrophication, for example, in the summer when freshwater inputs and flushing rates are lowest (Vallino and Hopkinson 1998).

In some coastal areas, the transport of nitrogen into coastal areas from offshore water can be greater than land-based inputs (Howarth 1998). This is true for many coastal areas, such as Halifax Harbour (Petrie and Yeats 1990) and the Juan de Fuca Straight/Straight of Georgia/ Puget Sound system (Harrison et al. 1983), where nutrient-rich, deep-oceanic water upwells along the coast.

Trophic Status and Susceptibility to Nutrient Enrichment

The prevention, control and management of eutrophication require an ability to determine the trophic status and assimilation capacity of aquatic systems. Only with this information can criteria be developed to serve as guidelines for the degree of nutrient enrichment permissible before the harmful effects of eutrophication become evident in coastal waters. These criteria would also serve as targets to restore water quality in degraded systems.

Numerous approaches to determine trophic status have been developed. These are based largely on sets of indicators. In the USA, the National Oceanographic and Atmospheric Administration under the National Estuarine Eutrophication Assessment has developed an extensive set of indices of nutrient over-enrichment for estuaries (Bricker et al. 1999), and within Europe member states of the European Union have developed indicators for a diversity of coastal systems (OSPAR 1997, 2001). Australia and New Zealand have also been active in development of indicators of nutrient over-enrichment (ANZECC 2000).

Since the diversity among coastal systems, in terms of both structure and function, is great, it is important that the approach used to characterize the trophic status of a system be chosen carefully, and that the indicators used are specific and appropriate for the environmental conditions present within the system being evaluated (CCME 2007).

The assimilation capacity of a coastal system depends on a number of factors related to how it processes nutrients once they enter the system. In general, primary factors include: the extent to which the nutrients become diluted; the amount of time the nutrients remain in the system; and the natural ability of the system to process the nutrients in terms of transforming them into forms that may or may not be available to primary producers (USEPA 2004). These factors, in turn, depend on a number of coastal system characteristics such as physiographic setting, morphology, hydrodynamics, water column stratification, turbidity and the biological communities present. Many of these characteristics are related to one another either directly or indirectly.

In contrast to the numerous approaches developed to assess the degree to which a coastal system exhibits symptoms of nutrient over-enrichment, comparatively few approaches assess the assimilation capacity of a coastal system. Several of these focus largely on dilution and flushing characteristics (Bricker et al. 1999, 2003; Druon et al. 2002; Ferreira 2000). Since some estuaries are light rather than nutrient limited, Cloern (1999) has developed a simple index of susceptibility that includes factors related to both nutrient and light availability.

Water Quality Guideline Derivation

The Protocol for the Derivation of Guidelines for the Protection of Aquatic Life (CCME 1991) is intended to deal specifically with toxic substances, and provide numerical limits or narrative statements based on the most current, scientifically defensible toxicological data. Nutrients do not fit this model because they are, in general, non-toxic to aquatic organisms at levels and forms present in the environment. However, secondary effects, such as eutrophication and oxygen depletion are serious concerns. Because aquatic communities are generally adapted to ambient conditions and the factors that determine the assimilation capacity of a coastal system and its response to nutrient inputs are not well understood, it is neither feasible nor desirable to establish generic nutrient criteria that are applicable to all types of coastal systems. Some of the effects of nutrients are aesthetic and thus include an element of subjectivity. What is considered nuisance plant growth to some may be desirable to others. Based on these realities, a framework based approach that is consistent with CCME guideline principles is recommended.

Nutrient Guidance Framework for Canadian Nearshore Waters

The U.S. (USEPA 2001), Europe (OSPAR 1997, 2001) and Australia and New Zealand (ANZECC 2000) have engaged in developing guidelines for establishing nutrient criteria for particular coastal systems. Due to a limited understanding of the factors that determine a coastal system's assimilation capacity and response to nutrient inputs, these agencies have each determined that the reference condition approach (RCA) is the most practical approach, at present. The RCA is essentially an empirically-based approach that compares the state of a number of similar systems, or historical differences in a single system, in order to recognise the differences between waterbodies, or over time, in terms of their response to nutrient inputs.

The review of available approaches determined that the USEPA (2001) approach is suitable for use in determining nutrient criteria in Canada. The details and procedures for applying the reference condition approach were extensively developed and documented in a technical guidance manual prepared by the USEPA (2001). The USEPA document contains a comprehensive guidance framework that progresses from data collection to nutrient criteria development. The USEPA document also provides details on how one may go about developing estuarine classification systems, direction on how to establish monitoring systems in those instances where sufficient data are not available, and suitable field sampling designs and laboratory methodologies for development of the required databases. Also included are suggestions for the design of remediation programs for impacted systems.

Although the USEPA guidelines were developed for U.S. estuaries, the approach is generic enough to be applied to Canadian coastal waters without any severe restrictions. Another important advantage to adopting the USEPA approach is that it presents alternative procedures for developing nutrient criteria in those instances where no undisturbed sites exist. It is strongly recommended that the approach be carried out by a multidisciplinary team of experts to ensure that the best effort is made in establishing nutrient guidelines. It is possible to apply the approach on a more limited scale in cases where time and resources are limited and that the interim guidelines would be subject to revision once adequate data are available.

The basic approach described in the USEPA guidance is illustrated in Figure 1 and discussed in detail in CCME (2007). A general overview of each of the major steps is provided here and it is recommended that the USEPA (2001) guidance document should be consulted while establishing nutrient criteria for a particular nearshore system.

Steps in Guidance Framework

Establish Regional Technical Advisory Group

The application of the reference condition approach relies on the combined effort of a multidisciplinary team. The disciplines to be represented on the task force depend on the objectives, but should include experts in physical, chemical and biological oceanography. If a remediation program is included in the objectives, it may also be necessary to include individuals with expertise in hydrology, water resource management, agriculture and land-use planning. Whenever possible, these experts should be drawn from the federal, provincial and municipal agencies, academics, local community groups and private sector.

Develop Regional Classification Scheme

Coastal systems that are structurally and functionally similar may differ greatly in their response to nutrient inputs based solely on their geographic location as a result of differences in climate and geology. This requires that an appropriate ecoregion classification system be developed (if not already available) and used. It is also important to develop a classification system for coastal systems within the same ecoregion. This is typically done on the basis of the physical characteristics that are considered to be most important in determining the response to nutrient over-enrichment.

The RCA is strongly based on the ability to classify coastal marine environments into categories based on their susceptibility to nutrient over-enrichment. Although a number of classification systems for coastal systems have been developed, most are based on morphological and stratification characteristics (Pritchard 1955; Dyer 1973; Biggs and Cronin 1981; Gregory et al. 1993; Gregory and Petrie 1994) with little focus on ecological processes, and there is a real need for a classification system focused more strongly on susceptibility to nutrient over-enrichment (Livingston 2001; Jay 2000). The USEPA reviewed a number of classification systems for estuaries based on geomorphology, physical/hydrodynamic factors and biological habitats, and has developed an extensive system for classification of coastal waters based on their response to stressors, including nutrient over-enrichment (USEPA 2004). This document should be consulted for developing a classification scheme in those instances where no suitable classification scheme currently exists.

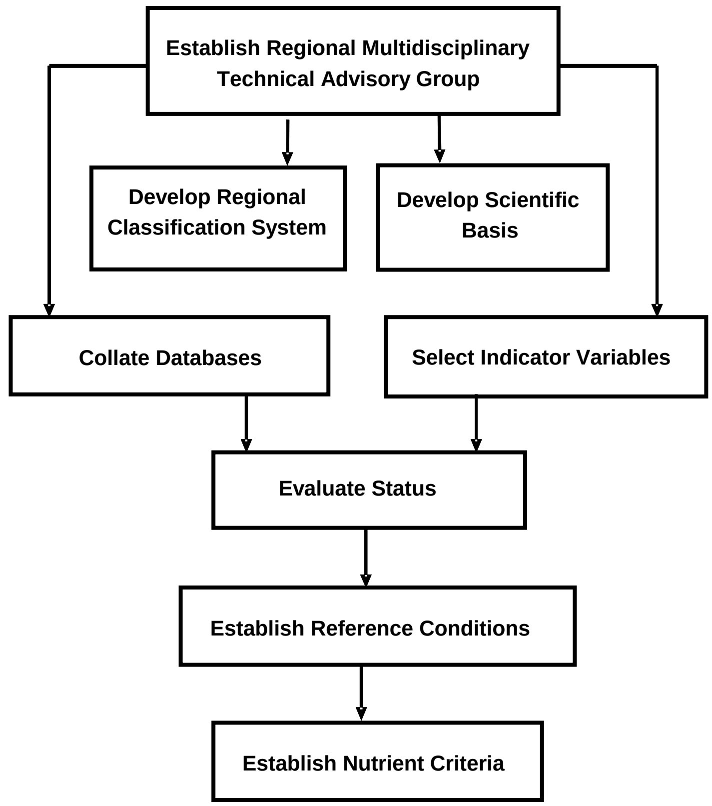

Figure 1. The USEPA's nutrient criteria development process (USEPA 2001).

The importance of having a well developed typology for a particular region cannot be over-emphasized as this is essentially the basis for classifying systems according to their assimilation capacity. Classifications based on trophic state or level of human impact that focus on symptoms of nutrient over-enrichment should be avoided since the objective of the classification scheme is to assess susceptibility to nutrient inputs rather than the response to nutrient inputs. The scheme developed for Canadian marine systems (Harding 1997), which classifies Canada's marine areas according to ecozones, ecoprovinces, ecoregions and ecodistricts, is a good beginning. The system characteristics suggested for use in this classification are morphology, water residence time, freshwater-saltwater exchanges, salinity, general water chemistry characteristics, depth, and grain size or bottom type. For estuaries, it may be important to sub-classify a system according to salinity zones. Some coastal systems may not fit well into any classification scheme due to unusually unique characteristics and this may require the development of criteria specific to that site and will require an historical database that includes data on pre-impacted conditions.

The general approach used in Bricker et al. (1999) for determining susceptibility to nutrient over-enrichment is an excellent framework for classifying coastal systems. The multivariate analysis approach employed by Strain and Yeats (1999), which employed common factor analysis procedures to classify a number of coastal systems in Nova Scotia, may also provide useful guidance. Nearshore coastal systems not associated with freshwater inflows are generally quite different both structurally and functionally than coastal lagoons and estuaries. In addition to being deeper and more influenced by longshore water circulation patterns, the biological communities present are more characteristic of shelf ecosystems. Algal macrophytes such as rockweeds and kelps replace the seagrasses common to estuaries and the greater depths result in weaker benthic-pelagic couplings. With respect to nutrient inputs, they are more subject to offshore upwelling of nutrient rich water (Harrison et al. 1983; Townsend 1998).

Develop Scientific Basis

Determining the scientific basis for criteria development involves establishing the particular approach (e.g., undisturbed sites, hindcasting, using historical data, paleoecology, etc.) and the type of data (e.g., ambient nutrient concentration, nutrient loading rates, Secchi depth, light attenuation, etc.) that will be required to develop the nutrient criteria.

Select Key Indicator Variables

The parameters used to assess the current status of the coastal system for which nutrient criteria are being sought need to be well defined, not only for assessing the need for remediation, but also to determine if they are suitable for establishing reference conditions.

Examples of indicators of causal variables include total nitrogen (TN) and total phosphorus (TP). Although TN and TP are preferred, historical data on these may be limited, making it necessary to use other forms, such as
nitrate, ammonia and phosphate. Although nitrogen is considered to be the nutrient most often responsible for creating the adverse conditions associated with nutrient over-enrichment, a number of studies have shown phosphorus to be important in some systems, particularly in temperate zone estuaries during periods of high freshwater inflows (Fisher et al. 1992; Malone et al. 1996).

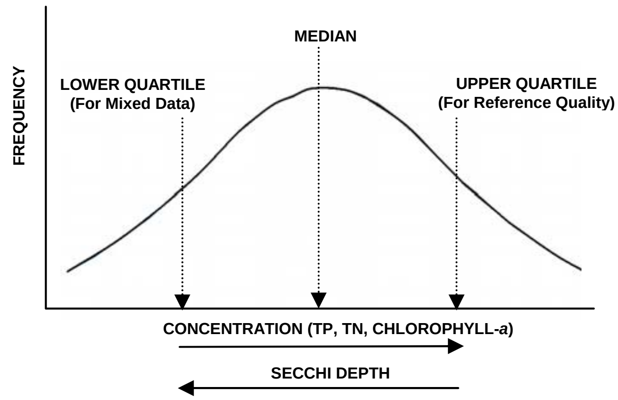

Figure 2. Frequency distribution of nutrient-related variables showing quartiles for reference high-quality and mixed data (from USEPA 2001).

Indicators of the response to nutrient inputs include phytoplankton chlorophyll *a*, water clarity and DO. Other indicators of response may include loss of seagrasses/ submerged aquatic vegetation and benthic macro fauna, increased growth of intertidal algae and other changes within the intertidal community.

Collate Databases

Existing databases are located and assessed with respect to the data requirements for determining the status of each coastal system. Efforts should be made to obtain historical data that allows an evaluation of the degree to which the system has changed over time with respect to its trophic status, as well as how much variability or stability it exhibits. Data pertaining to changes in land use in the watershed should be also collected. Historical data are essential in those instances where no undisturbed sites exist.

Determine Trophic Status and Establish Reference Conditions

Once the coastal systems of interest are classified into categories, according to ecoregion and physical characteristics, the trophic status of each site is determined. This information is then used to determine which sites fall within the undisturbed or nearly undisturbed category and are suitable for establishing reference conditions. The various approaches for setting reference conditions are as follows:

Approaches based on in situ observations

In establishing nutrient criteria, either the median, the 25th or 75th percentile value is typically used by the USEPA (Fig. 2). The median is recommended when the reference sites are considered to be relatively unimpacted by anthropogenic nutrient inputs. If the reference sites exhibit some evidence of anthropogenic impact, but exhibit little evidence of degradation, it is suggested that the value of the 75th percent quartile be used. If the data also includes sites that may be only nearly undisturbed, it may be appropriate to use the 25th percentile in place of the 75th.

It may also be possible to summarize the existing historical data as a frequency distribution for past and current data (Fig. 3). In this case the reference condition can be established at the median between the historical median and the median for present day data. In those cases where no undisturbed or nearly undisturbed sites exist, it may be possible to arrive at reference conditions based on either an historical or empirical analysis of the available data. The database would have to cover the period prior to evidence of symptoms associated with nutrient over-enrichment and be extensive enough to represent the spatial and temporal variability. One potentially serious problem in using this approach is that some symptoms of nutrient over-enrichment may be due to factors other than nutrient inputs. An example is the loss of submersed aquatic vegetation as a result of increases in turbidity due to excessive erosion within a watershed, or increased nutrient retention as a result of barriers to flushing such as causeways. Figure 4 illustrates one way of how nutrient criteria can be arrived at using this approach.

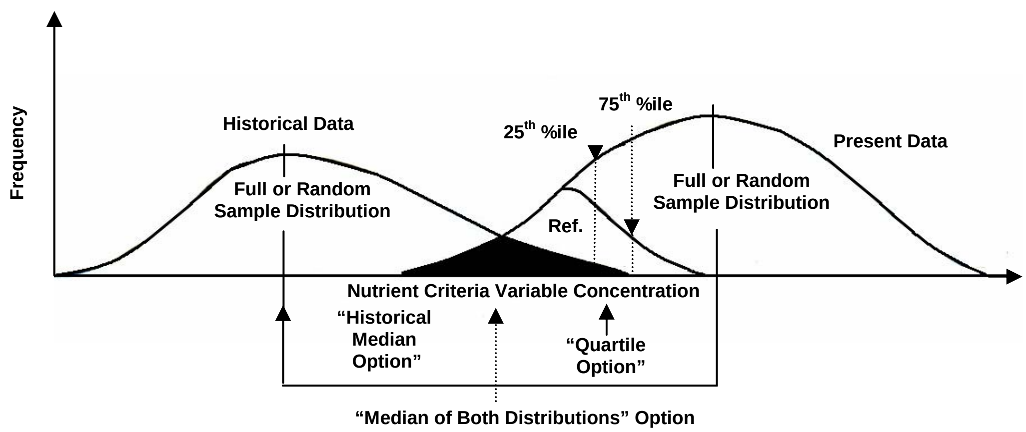

Figure 3. Illustration of the comparison of past and present nutrient data to establish a reference condition for intensively degraded estuaries (from USEPA 2001).

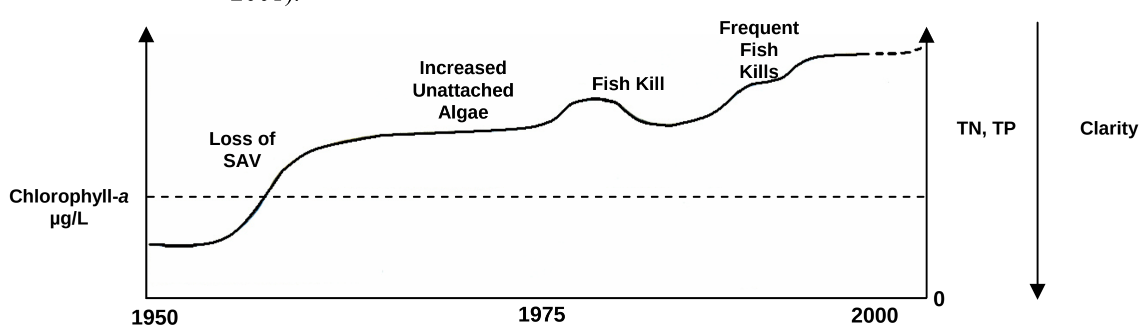

Figure 4. Hypothetical example of load/concentration response of estuarine biota to increased enrichment. The dashed line represents conditions prior to degradation that can be used to establish reference conditions and associated criteria for causal and response variables (from USEPA 2001).

Watershed-Based Approach

In the watershed approach an attempt is made to locate a tributary, or a segment thereof, which is representative of the estuary and is not nutrient enriched. If the drainage basin characteristics of the tributary, other than those associated with anthropogenic activities, are similar to other tributaries within the estuary, the nutrient load from this tributary can be extrapolated to the rest of the estuary either empirically or with a model. The total nutrient load is then related empirically using appropriate models to the response parameters. In this case nutrient criteria may be based on nutrient load rather than nutrient concentration (USEPA 2001).

Coastal Reference Conditions

The coastal approach relies on knowledge of changes in the nutrient characteristics of estuarine plumes and offshore water. Considerable information is required on the mixing and dispersive capacity of the shelf area and this typically involves the development and use of hydrodynamic circulation models. This approach has not been particularly well developed largely because nutrient over-enrichment problems are much less common in the more offshore coastal environments.

Paleoecological Approach

This approach has been suggested as potentially useful in establishing past conditions by analyzing information obtained from sediment core data. Although the time scale resolution using this technique can be relatively large, it can provide some information as to what conditions were like during periods when anthropogenic impacts are unlikely to have occurred. Examples include natural periods of hypoxic or anoxic conditions and, through analysis of diatom remnants, an indirect indication of past nutrient conditions.

Establish Nutrient Criteria

Once reference conditions are established, setting nutrient criteria may also require consideration of what is acceptable in terms of the level of deviation from reference conditions based on the anticipated human uses of the coastal system. These are essentially value judgements that must be made in consultation with all stakeholders.

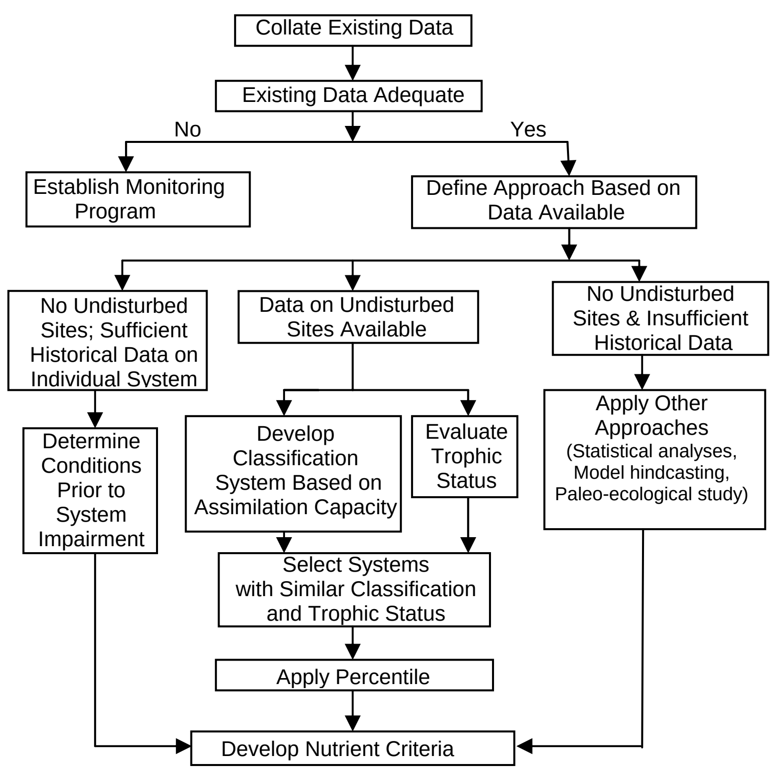

Figure 5. Overview of procedures for establishing nutrient criteria.

It is also important that the initial criteria be calibrated and verified. This is done by applying the criteria to water bodies of known trophic status. Failure of the criteria requires that they be re-evaluated and may involve consideration of factors not originally considered (e.g., turbidity, water colour, toxins). Once the criteria are validated they can be used to determine the status of a particular system based on the causal variables (e.g., nitrogen and phosphorus) and the response variables (e.g., chlorophyll *a*, water clarity, DO). Figure 5 provides an overview of the Canadian guidance framework for developing nutrient criteria.

Application of Guidance Framework

Nova Scotia Case Study

The Atlantic shoreline of Nova Scotia contains a large number of coastal bays and inlets that are subject to various levels and types of anthropogenic impacts. The 17 sites chosen for this case study are located along the mainland Atlantic nearshore coastal region (Strain and Yeats 1999) within a single ecoregion (CCME 2007). Summaries of the hydrological and chemical data are contained in Tables 1 and 2.

Approach

The reference condition approach was selected in this case study because the data required for classifying the systems in terms of their susceptibility to nutrient over-enrichment and trophic status where available.

An index of susceptibility to nutrient over-enrichment was developed based on the parameters that reflect the system's capacity to dilute nutrients entering the system from land-based sources. The parameters used in the evaluation were tidal/freshwater volume ratio, flushing time and degree of water column stratification. The trophic status of each site was based on water column nutrient and bottom-water DO concentrations. Once evaluated, an appropriate subset of reference sites was selected from the 17 sites on the basis of relatively undisturbed trophic state and a similar index of susceptibility. The selected reference sites were then used to establish criteria for causal and response variables using a frequency distribution approach.

Evaluation of Trophic Status

The trophic status of each site was evaluated based on nutrient and DO concentrations. The nutrients used were dissolved inorganic nitrogen-N and phosphate-P. These represent the causal variables. The average nutrient concentration of surface (1 m) and bottom (ca. 1 m above maximum depth) water samples were used. For DO, the response variable, bottom water concentrations were used. The chlorophyll *a* and Secchi depth could not be used as response variables because data were not available.

Trophic state (low, medium and high) was assigned for nutrients and bottom DO concentration (Table 3) according to Bricker et al. (1999). An overall index, based on all three factors was calculated by first assigning a value of 1, 2 or 3 for low, medium and high, respectively, and then summing these (Table 4).

The trophic ranking, based on nitrogen and DO, varied considerably among sites, whereas the ranking based on phosphorus did not, presumably because of naturally high phosphorus input from offshore waters. Based on the overall ranking, 12 sites (values <5) were considered to exhibit little evidence of anthropogenic nutrient over-enrichment; three sites (values ≥5 and <7) were considered to be moderately enriched, and the remaining two sites (values ≥7) were considered to be over-enriched.

Table 1. Morphological and physical characteristics of each site. A: Watershed Area (sq km); B: High Water Area (sq km); C: Volume (10^6 cu m); D: Maximum Depth (m); E: Mean Tidal Range (m); F: Tidal Prism (10^6 cu m); G: Tidal/Freshwater Volume Ratio; H: Flushing Time (hrs).

Site	A	B	C	D	E	F	G	H
Beaver Hbr	14	14	121	21	1.4	18	723	88
Bedford Bay	17	17	510	71	1.5	25	109	261
Chezzetcook Inl.	14	14	9	6	1.4	13	165	14
Country Hbr	10	10	89	22	1.2	11	40	104
Halifax-NW Arm	93	93	1759	71	1.6	146	373	155
Indian Hbr	11	11	116	21	1.4	15	300	103
Jeddore Hbr	21	21	83	18	1.4	28	178	42
LaHave Inlet	20	20	77	27	1.6	29	27	39
Liscomb Hbr	20	20	106	14	1.4	27	54	54
Mahone Bay	218	217	2227	62	1.5	319	345	171
Necum Teuch	4	4	12	15	1.3	5	29	38
Petpeswick Inlet	14	14	30	11	1.4	15	186	32
Popes Hbr	11	11	57	22	1.4	15	717	53
Sheet Hbr	18.	18.	106	22.	1.5	27	35	54
Shelburne Hbr	23	23	140	13	1.7	37	68	53
Ship Hbr	7	7	47	25	1.4	10	24	66
St. Margaret Bay	142	142	5191	91	1.6	224	416	294

Table 2. Chemical characteristics of sites.

Site	Depth (m)	Salinity (psu)	Temp (°C)	DO (mg/L)	Dissolved P (mg/L)	Dissolved Inorganic N (mg/L)
Beaver Hbr	1	29.8	18.1	8.2	0.008	0.008
"	7	29.0	17.4	8.3	0.023	0.014
Bedford Bay	1	30.0	11.1	8.9	0.023	0.035
"	13	30.8	7.3	6.4	0.046	0.103
Chezzetcook Inlet	1	29.8	19.0	8.4	0.021	0.009
"	2	29.9	18.8	7.8	0.020	0.012
Country Hbr	1	29.0	18.0	8.1	0.013	0.011
"	19	30.3	14.7	6.5	0.042	0.058
Hfx-NW Arm	1	30.6	10.1	9.7	0.017	0.029
"	18	32.0	7.6	8.8	0.025	0.039
Indian Hbr	1	29.7	17.3	8.7	0.012	0.007
"	8	29.7	17.3	8.0	0.014	0.015
Jeddore Hbr	1	29.7	18.7	7.7	0.023	0.008
"	17	29.8	17.2	4.4	0.139	0.348
LaHave Inlet	1	27.8	19.6	7.8	0.037	0.010
"	8	29.1	18.1	5.2	0.076	0.078
Liscomb Hbr	1	29.4	18.7	8.0	0.035	0.052
"	14	29.6	17.4	7.0	0.035	0.037
Mahone Bay	1	30.4	17.6	8.1	0.012	0.006
"	13	30.5	12.1	8.4	0.019	0.010
Necum Teuch Inlet	1	29.6	18.2	8.2	0.014	0.006
"	3	29.7	12.1	7.8	0.013	0.005
Petpeswick Inlet	1	28.6	20.0	8.3	0.041	0.012
"	24	28.9	17.3	0.0	0.356	1.131
Popes Hbr	1	29.8	18.4	7.9	0.013	0.008
"	20	30.3	12.2	5.1	0.063	0.241
Sheet Hbr	1	17.3	19.0	8.6	0.002	0.011
"	14	30.1	13.9	5.3	0.053	0.204
Shelburne Hbr	1	30.5	17.6	8.1	0.012	0.010
"	13	30.7	17.0	7.0	0.032	0.062
Ship Hbr	1	26.9	18.9	8.2	0.011	0.008
"	23	30.6	7.3	0.4	0.109	0.866
St. Margarets Bay	1	30.2	17.9	7.8	0.012	0.005
"	14	30.5	13.2	8.4	0.016	0.014

Table 3. Criteria for evaluating degree of nutrient over enrichment (Bricker et al. 1999).*

Parameter	Low	Medium	High
N (mg/L)	≤0.1	>0.1 - <1.0	≥1.0
P (mg/L)	<0.01	>0.01 - <0.1	≥0.1
DO (mg/L)	≥5	>2 - ≤ 5	0 - ≤ 2

*The guidelines for nutrients proposed by Bricker et al. (1999) are based on surface water concentrations. However, in this case study the average value of surface and bottom water concentrations was used because of the significant offshore nutrient input that enters the inlets as bottom water.

Table 4. Ranking of nutrient over-enrichment status.

Site	Parameter N	Parameter P	Parameter DO	Overall
Beaver Hbr	1	2	1	4
Bedford Bay	1	2	1	4
Chezzetcook Inlet	1	2	1	4
Country Hbr	1	2	1	4
Hfx - NW Arm	1	2	1	4
Indian Hbr	1	2	1	4
Jeddore Hbr	2	2	2	6
LaHave Inlet	1	2	1	4
Liscomb Hbr	1	2	1	4
Mahone Bay	1	2	1	4
Necum Teuch Hbr	1	2	1	4
Petpeswick Inlet	2	2	3	7
Popes Hbr	2	2	1	5
Sheet Hbr	2	2	1	5
Shelburne Hbr	1	2	1	4
Ship Hbr	2	2	3	7
St. Margarets Bay	1	2	1	4

Evaluation of Susceptibility to Nutrient Over-enrichment

Susceptibility to nutrient over-enrichment was based on an assessment of those factors that result in nutrients entering from upstream being either diluted or flushed out of the system. The parameters used in the assessment were tidal/freshwater volume ratio, flushing time, and degree of water column stratification for each site. An index for each parameter (Table 5) similar to that proposed by Bricker et al. (1999) was employed to assess the susceptibility. This was then quantified using a similar procedure to that used for quantifying trophic status. This resulted in seven sites being classified as having low susceptibility, nine sites being classified as having moderate susceptibility, and one site as having high susceptibly (Table 6).

Table 5. Criteria for determining susceptibility to nutrient over-enrichment.

Parameter	Low	Medium	High
Tidal Prism/FW Ratio	≥200	≥100 - 200<	100<
Flushing Time (days)	3<	≥3 - 10<	≥10
Stratification (sigma-*t*)	<5	>5 - ≤10	≥ 10

Table 6. Susceptibility to nutrient over-enrichment.

Site	Tidal/ FW		Flushing Time		Mixing		Overall Rating
	Ratio	Rating	Day	Rating	Sigma -*t*	Rating	
Beaver Hbr	723.1	1	3.7	2	0.4	1	4
Bedford Bay	109.4	2	10.9	3	1.1	1	6
Chezzetcook Inlet	165.2	2	0.6	1	0.0	1	4
Country Hbr	39.5	3	4.3	2	2.4	1	6
Hfx - NW Arm	109.8	2	6.5	2	1.0	1	5
Indian Hbr	299.9	1	4.3	2	0.1	1	4
Jeddore Hbr	177.6	2	1.8	1	0.3	1	4
LaHave Inlet	27.1	3	1.6	1	1.5	1	5
Liscomb Hbr	53.5	3	2.3	1	0.2	1	5
Mahone Bay	344.5	1	7.1	2	1.3	1	4
Necum Teuch Hbr	29.1	3	1.6	1	0.2	1	5
Petpeswick Inlet	186.3	2	1.3	1	0.1	1	4
Popes Hbr	716.5	1	2.2	1	1.9	1	3
Sheet Hbr	35.2	3	2.3	1	10.6	3	7
Shelburne Hbr	68.3	3	2.2	1	0.2	1	5
Ship Hbr	23.9	3	2.8	1	5.2	2	6
St. Margarets Bay	416.3	1	12.3	3	1.1	1	5

The degree of stratification was determined as the density difference between surface and bottom water (based on temperature and salinity) and is expressed as sigma- *t* values.

Selection of Reference Sites

The final selection of sites suitable to serve as reference condition sites was made by choosing those that showed little evidence of nutrient over-enrichment (low rating) and had similar indices of susceptibility to nutrient over-enrichment. Of the 17 sites, twelve were rated as having a low trophic status. Of these twelve sites, four had a low susceptibility to nutrient over-enrichment and eight had a moderate susceptibility. In order to maximize the number of reference sites used for establishing nutrient criteria, the eight sites having a low trophic status and a moderate susceptibility to nutrient over-enrichment were chosen as reference sites (Table 7).

Table 7. Suitability of sites to serve as reference sites.

Site	Trophic Status	Susceptibility to Nutrient Over-enrichment	Reference Site
Beaver Hbr	LOW	LOW	N
Bedford Bay	LOW	MED	Y
Chezzetcook Inlet	LOW	LOW	N
Country Hbr	LOW	MED	Y
Hfx-NW Arm	LOW	MED	Y
Indian Hbr	LOW	LOW	N
Jeddore Hbr	MED	LOW	N
LaHave Inlet	LOW	MED	Y
Liscomb Hbr	LOW	MED	Y
Mahone Bay	LOW	LOW	N
Necum Teuch Inlet	LOW	MED	Y
Petpeswick Inlet	HIGH	LOW	N
Popes Hbr	MED	LOW	N
Sheet Hbr	MED	HIGH	N
Shelburne Hbr	LOW	MED	Y
Ship Hbr	HIGH	MED	N
St. Margarets Bay	LOW	MED	Y

Nutrient Criteria

The general procedure for establishing nutrient criteria using the reference condition approach is based on data from coastal systems that show little evidence of nutrient over-enrichment and involves a frequency distribution analysis of causal and response variables.

Table 8 lists the values of the 25th, median and 75th percentile and other basic statistics of each of the casual and response variables. As discussed earlier, since all of the sites used to establish reference conditions in this case study have human populations in their watersheds, it is suggested that the 25th percentile be adopted for nutrients and the 75th percentile for DO. For DO, the 25th and 75th percentiles are reversed since high concentrations (oxia) are better than low levels (anoxia). The final decision for which criteria to adopt, however, depends on management goals (i.e., level of water quality considered to be acceptable) for reducing nutrient inputs in situations where nutrient over-enrichment is a problem.

Table 8. Summary statistics for reference sites.

Statistics	Dissolved Inorganic- N (mg/L)	Dissolved Phosphorus (mg/L)	Dissolved Oxygen (mg/L)
Minimum	0.005	0.013	6.5
Maximum	0.069	0.057	9.3
Mean	0.035	0.028	7.7
SD	0.020	0.020	0.8
25th %ile	0.020	0.015	6.8
Median	0.035	0.025	7.6
75th %ile	0.045	0.035	7.8

Boughton River Estuary (PEI) Case Study

The Boughton River Estuary is located along the eastern shoreline of PEI (Prince Edward Island). The estuary contains a number of aquaculture sites for blue mussels and oysters and supports commercial harvests of soft shell clams, quahogs, American oysters, eels and smelt. It is also used for recreational boating and fishing. Over the last few decades water quality monitoring programs have revealed that portions of the estuary experience periods of hypoxia (DO levels $\leq$50% saturation). These events appear to be associated with phytoplankton blooms that originate in the lower, freshwater portion of the river. The general description of the Boughton River Estuary and its watershed are provided in Lane and Associates (1991) and CCME (2007).

Approach

Because no reference sites similar to the Boughton River Estuary exist within PEI, it was not possible to use the reference condition approach to establish nutrient criteria. There are also no data on nutrient concentrations available prior to the period when algal blooms and hypoxic incidents are known to have occurred, so nutrient criteria could not be established based on historical data. As a result, the approach employed was to use a statistical analysis of *in situ* data on causal and response variables to determine the conditions when the indicators of nutrient over-enrichment were minimal. The rationale for this approach was that, if nutrient levels could be kept below the levels experienced when bottom waters became hypoxic, it would lead to the elimination of hypoxic events.

The three response variables used were Secchi depth, phytoplankton chlorophyll *a* concentration, and percent DO saturation. The potential causal variables examined were TN and TP. If significant relationships could be shown to exist between the causal and response variables, it would then be possible to determine the nutrient concentrations below which the response variables would be at acceptable levels.

Frequency and Times of Hypoxic Events

The data analysis indicated that hypoxic conditions occur mainly in bottom waters during the late summer-early fall. No hypoxic events were observed during the spring and the number of hypoxic events each year appears to be increasing. In addition, most hypoxic events occur within the inner section of the estuary.

Relationship between Response and Causal Variables

The data collected within the estuarine sampling sites (Fig. 6) showed significant ($p<0.05$) relationships between the three response variables and TP (positive correlation with chlorophyll *a* and negative correlation with Secchi depth and DO saturation). In contrast, no significant relationship was observed for nitrate or TN. As a result, it was determined that the nutrient criteria for this estuary should be based on TP.

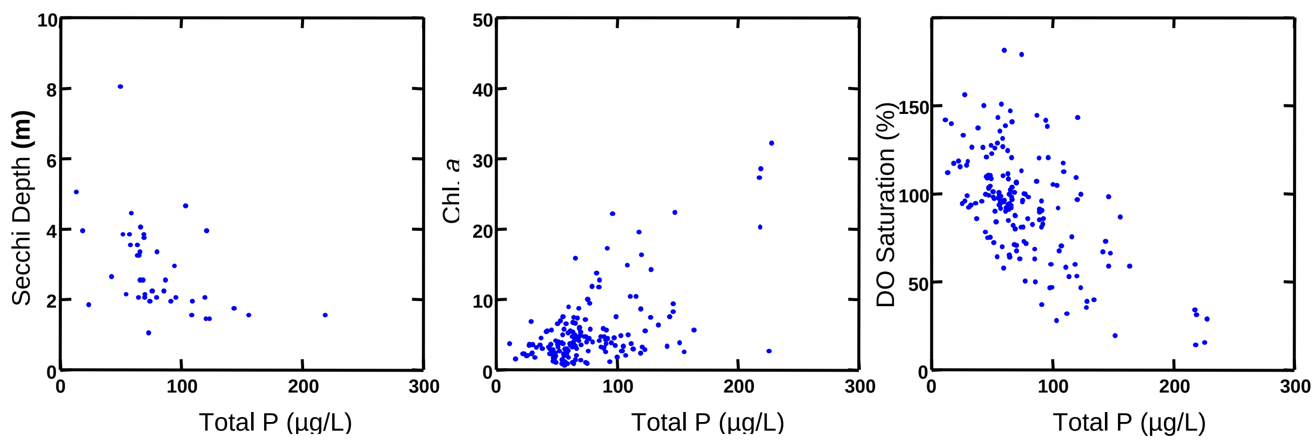

Figure 6. Relationship between response variables and total phosphorous concentration.

Table 9. Statistics for response and causal variables for DO saturation ≤50 % and >50 % in bottom waters.

Statistic	DO Saturation ≤50%				DO Saturation >50%			
	Secchi (m)	Chl *a* (µg/L)	TP (µg/L)	%DO Sat.	Secchi (m)	Chl *a* (µg/L)	TP (µg/L)	%DO Sat.
N	2	21	18	21	48	183	181	196
Minimum	1.5	2	68	1	1.0	1	13	51
Maximum	2.2	45	230	49	8.0	22	165	181
Mean	1.9	13	141	32	2.9	4	73	101
Median	1.9	8	127	34	2.9	5	66	99
25th %ile	-	4	100	28	1.9	2	50	75
75th %ile	-	20	190	42	3.3	5	80	110

Nutrient Criteria

Nutrient criteria for TP were established by examining the TP values when hypoxic events occurred within the estuary. These values, as well as those when no hypoxia events occurred are listed in Table 9. Figure 7 is a frequency plot of TP concentration when DO saturation levels are ≤50% and >50%.

In order to minimize the occurrence of hypoxic events, it is suggested that TP concentrations within the estuary not exceed 50 µg/L during the late summer-early fall period, a value that approximates the 25th percentile for conditions when DO saturation values are >50%. If TP levels are maintained below this level during the most critical periods, it should reduce the occurrence of hypoxic events.

This case study illustrates the application of an alternative approach to developing nutrient criteria in those situations where the data are inadequate for applying the more typical reference condition approaches.

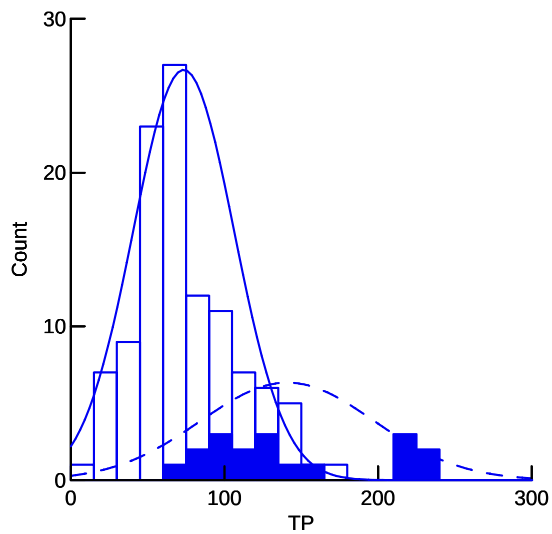

Figure 7. Frequency plot of TP concentration (µg/L) for periods when DO saturation levels are ≤50% (solid bars) and >50% (open bars).

The Special Case of Fjords

Fjords are coastal embayments characterized by having a sill at their seaward extension. They are usually formed as a result of glacial activity that scours the mouth of the embayment and, during retreat, deposits glacial debris that forms a sill. The presence of an outer sill results in a water column that typically becomes strongly stratified into two distinct layers: a surface layer that exchanges freely with offshore water, and a deeper layer landward of the sill that has a much more restricted exchange with offshore water. Whereas the surface waters of a fjord may have flushing times on the order of days, depending on the depth of the sill the deeper basin water may have exchange rates on the order of weeks, months and, in some cases, years. As a consequence of the restricted flushing of the deeper basin water, the bottom waters of fjords are much more susceptible to the accumulation of nutrients and organic materials which results in a greater likelihood of the development of hypoxic conditions.

There is no reason to believe that the same approaches used to develop nutrient criteria for other nearshore systems can not be applied to fjords (CCME 2007). The difficulty, however, may arise when attempting to apply the reference condition approach based on percentiles because of the limited number of fjords that may be present in a particular coastal ecoregion, and the greater variability in assimilation capacity among fjords as a result the effect that sill depth has on both stratification and flushing rates. For this reason, it is likely that the most appropriate method for setting nutrient criteria for a fjord would be to use the historical data approach which does not require that a classification system be developed.

Conclusions

This factsheet provides an overview of environmental problems associated with nutrient over-enrichment and approaches for dealing with nutrient over-enrichment in nearshore marine waters. Among the approaches reviewed for setting nutrient criteria, the USEPA approach is the most developed and documented approach. It is recommended that a framework-based approach be adopted for Canadian waters. This science-based approach should address nearshore marine eutrophication to establish site-specific guidelines for managing nearshore marine eutrophication.

It is also important to realize that other approaches, not specifically described in the USEPA approach, can be used in establishing nutrient criteria when data limitations prevent the use of the more typical approaches. This may be the case for sites that are unique and/or for which no reference condition data can be found. An example of this situation is clearly presented in the PEI case study.

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