Canadian Water Quality Guidelines for the Protection of Aquatic Life

PHOSPHORUS: CANADIAN GUIDANCE FRAMEWORK FOR THE MANAGEMENT OF FRESHWATER SYSTEMS

Phosphorus (P; CAS No. 7723-14-0, atomic mass 30.97376) is a highly reactive, multivalent, non-metal of the nitrogen group in the period table that is never found free in nature. Phosphate rock, which contains the mineral apatite, an impure tri-calcium phosphate, is an important source of phosphorus. Phosphorus is an essential nutrient for all living organisms; living matter contains about 0.3 percent dry weight phosphorus (Horne and Goldman 1994). It plays a major role in biological metabolism, and when compared to other macronutrients required by biota, phosphorus is the least abundant and commonly the first nutrient to limit biological productivity (Wetzel 2001). Water bodies containing low phosphorus concentrations (i.e., unimpacted sites) typically support relatively diverse and abundant aquatic life that are self-sustaining and support various water uses. However, elevated phosphorus concentrations can adversely affect aquatic ecosystems (Chambers et al. 2001).

The phosphorous guideline follows a framework-based approach that accommodates the non-toxic endpoints associated with phosphorus and can be incorporated into existing management strategies. The framework offers a tiered approach where phosphorus concentrations should not (i) exceed predefined ‘trigger ranges’; and (ii) increase more than 50% over the baseline (reference) levels. The trigger ranges are based on the range of phosphorus concentrations in water that define the reference trophic status for a site. If the upper limit of the range is exceeded, or is likely to be exceeded, further assessment is required. When assessment suggests the likelihood of undesired change in the system, a management decision must be made.

Phosphorus in the Aquatic Environment

Phosphorus in aquatic systems occurs in three forms: inorganic phosphorus, particulate organic phosphorus, and dissolved (soluble) organic phosphorus. Aquatic plants require inorganic phosphate for nutrition, typically in the form of orthophosphate ions (PO_4^{3-}). This is the most significant form of inorganic phosphorus, and is the only form of soluble inorganic phosphorus directly utilized by aquatic biota. This form of phosphate is transferred to consumers and decomposers as organic phosphate. Most of the phosphorus (up to 95%) in fresh water occurs as organic phosphates, cellular constituents of organisms, and within or adsorbed to inorganic and dead particulate organic matter (Wetzel 2001). This is subsequently made available for recycling via mineralization and decomposition.

Phosphate concentrations tend to increase with increases in total phosphorus (TP), but the proportion of phosphate declines with increasing TP (Hudson et al. 2000). The turnover rate of PO_4^{3-} in phosphorus limited systems is extremely rapid, thus making its measurement difficult. Filtration of the water sample prior to analysis for PO_4^{3-} can overestimate biologically available phosphorus (Fisher and Lean 1992) and conventional methods for measuring PO_4^{3-} generally overestimate phosphate concentrations (Hudson et al. 2000). Based on these limitations, TP is generally recommended as a meaningful measurement of phosphorus in surface waters (Wetzel 2001).

In the majority of lakes, phosphorus is normally the limiting nutrient for algal growth. However, in some areas (prairie lakes and rivers) nitrogen is increasingly being found to be the most important nutrient. TP concentrations in non-polluted natural waters extend over a very wide range from <1 $\mu g \cdot L^{-1}$ in ultra-oligotrophic waters, to >200 $\mu g \cdot L^{-1}$ in highly eutrophic waters; however, most uncontaminated freshwaters contain between 10 and 50 $\mu g \cdot L^{-1}$ of TP (Wetzel 2001). Phosphorus levels of freshwaters are generally lowest in mountainous regions of bedrock geomorphology (e.g., Boreal and Pre-Cambrian Shields), and increase in lowland waters derived from sedimentary rock deposits (e.g., the Boreal Plains of Alberta). Lakes rich in organic matter, and bogs, tend to exhibit high TP concentrations.

Sedimentation of particulate phosphorus results in a slow but continuous loss from the water column. Phosphate is precipitated as insoluble iron, calcium, or aluminium phosphate and then released slowly. Exchange of phosphorus across the sediment/water interface is regulated by oxidation-reduction (redox) interactions, which are dependent on oxygen supply, mineral solubility and sorptive mechanisms (Stumm and Morgan 1996), the metabolic activities of bacteria and fungi, and turbulence from physical and biotic activities (Wetzel 2001). Lake sediments contain much higher concentrations of phosphorus than water. Under aerobic conditions, the exchange equilibria are largely unidirectional toward the sediments; however, under anaerobic conditions, inorganic exchange at the sediment-water interface is strongly influenced by redox conditions. Sediment phosphorus release (internal loading) can be an important source of phosphorus and can maintain high phosphorus concentrations in the water column, even in the absence of significant external loading (Marsden 1989; Holz and Hoagland 1999).

The first response of an aquatic system to phosphorus additions is increased plant and algal productivity and biomass. Although this may be desirable in some cases, beyond a certain point, further phosphorus additions to phosphorus-limited systems can cause undesirable effects, such as: (i) decrease in biodiversity and changes in dominant biota; (ii) decline in ecologically sensitive species and increase in tolerant species; (iii) increase in plant and animal biomass; (iv) increase in turbidity; (v) increase in organic matter, leading to high sedimentation; and (vi) anoxic conditions (Mason 1991; Environment Canada 2004). When the excessive plant growth includes certain species of cyanobacteria, toxins may be produced, causing increased risk to aquatic life, livestock, and human health (Chambers et al. 2001).

The potential human quality of life concerns that may relate to eutrophication are: (i) treatment of potable water may be difficult and costly; (ii) the supply may have an unacceptable taste or odour problem; (iii) the water may be injurious to health; (iv) the aesthetic/ recreational value of the water may decrease; (v) macrophyte growth may impede water flow and navigation; (vi) commercially important species (such as salmonoids and coregonids) may disappear (Mason 1991; Environment Canada 2004).

Water Quality Guideline Derivation

Currently, no national environmental quality guidelines exist for phosphorus, although individual provinces may have guidelines or objectives (Environment Canada 2004). 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. Phosphorus does not fit this model because it is 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, it is neither feasible nor desirable to establish a single guideline value for phosphorus. Some of the effects of phosphorus 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, guidelines for phosphorus are not derived; rather a guidance framework (Figure 1) that is consistent with CCME guideline principles is developed. The framework accommodates the non-toxic endpoints associated with phosphorus loading and permits site-specific management of phosphorus.

The framework provides a tiered approach where water bodies are marked for further assessment by comparing their trophic status to predefined 'trigger ranges'. The trigger ranges are based on a range of phosphorus concentrations in water that define the reference status for a site. Using such a scheme, sites with similar characteristics are classified together irrespective of whether they might possess these features naturally or as a result of human influence. Since the reference condition for the water body in question is defined at the onset of the framework, this problem is readily overcome; predefined states, whether determined through hindcasting or by using best available data, are always used to set the trigger range.

Steps in Guidance Framework

Set Ecosystem Goals and Objectives

As a first step, it is crucial to set ecosystem goals and objectives (e.g., enhance, protect, or restore). The objective can be set for a healthy aquatic ecosystem, with the goals being unimpaired human uses, and a diverse and functioning aquatic ecosystem. By setting the diverse aquatic ecosystem as a goal, a desire to prevent the loss of species is established. Similarly, the desire for a functioning aquatic ecosystem recognizes that ecosystems do things that are both inherently of value and of value for human uses and desires. These objectives are important because they will guide management decisions made later.

Define Reference/ Baseline Conditions

Establishing the reference condition is the most important step in the framework because it determines the trigger range that is used for comparison. In some cases, historical data may be available, but in most cases there will be a need to estimate reference (baseline) phosphorus

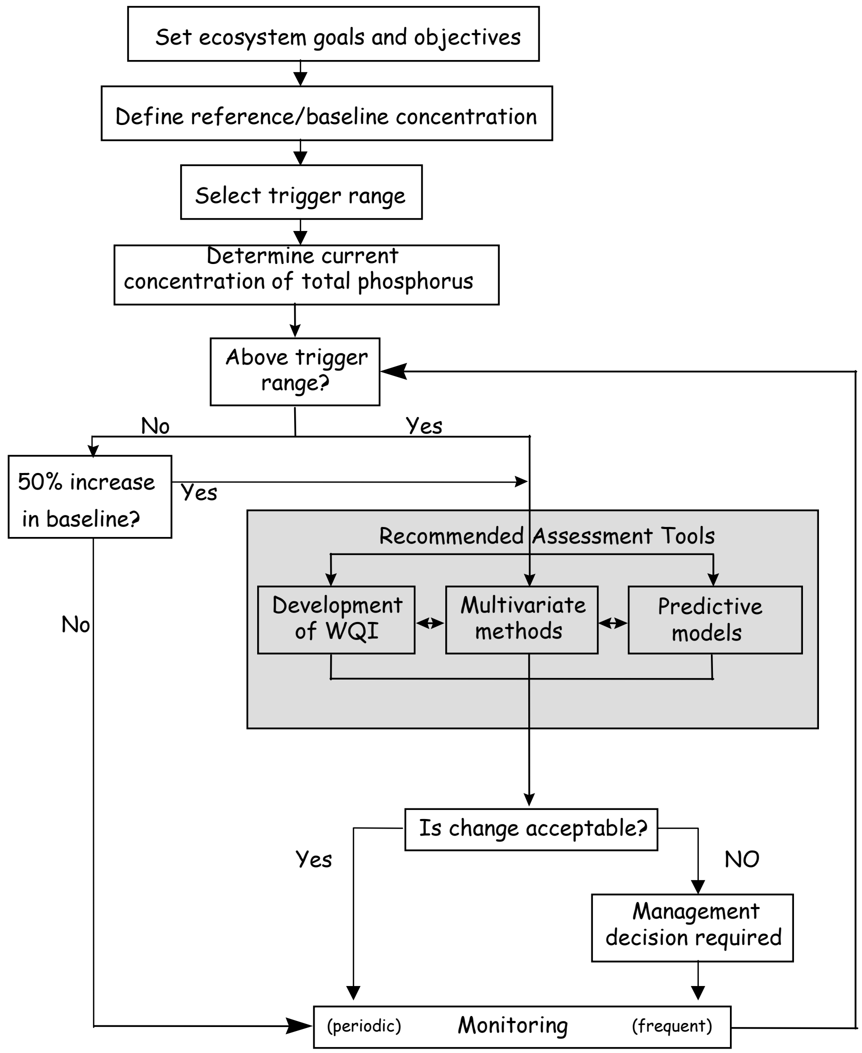

Figure 1. Canadian Guidance Framework for the management of phosphorus in freshwater systems.

concentrations. Several options are available for this, ranging from use of available historical data to derivation and application of predictive models to hindcast pre-development phosphorus values (Environment Canada 2004). Many jurisdictions (e.g., British Columbia and Ontario) which are actively managing phosphorus, have already established reference conditions that could be used in the framework. In addition, reference conditions will be relatively simple to determine in areas with little or no development. In geographical areas where there is a high density of water bodies, a single reference condition may be established for the entire area.

Select Trigger Ranges

Australia, New Zealand (NWQMS 1999), and the USEPA (EPA 2000) consider ecosystem classification in setting their nutrient guidelines. In the Canadian framework, trigger ranges are based on the trophic classification of the baseline condition or the status of reference sites.

Internationally accepted OECD (Organisation for Economic Co-operation and Development) trophic status values (Vollenweider and Kerekes 1982) are the recommended trigger ranges (Table 1). The only proposed variation is that the OECD meso-eutrophic category (10-35 $\mu g \cdot L^{-1}$) is subdivided into mesotrophic (10-20 $\mu g \cdot L^{-1}$) and meso-eutrophic (20-35 $\mu g \cdot L^{-1}$). This subdivision was necessary because considerable variation in community composition and biomass exist in Canadian waters over the OECD range of 10-35 $\mu g \cdot L^{-1}$. These trigger ranges are recommended for both rivers and lakes.

A trigger range is a desired concentration range for phosphorus; if the upper limit of the range is exceeded, it indicates a potential environmental problem, and therefore, "triggers" further investigations. Natural physical and chemical water quality variables (e.g., salinity, pH, nutrients) inherently vary within and between ecosystem types, and so the preferred method for determining the trigger ranges is to use similar, high quality reference sites to determine natural levels. These ranges are then categorised according to the trophic status of the reference site (Table 1). This approach provides a trigger range that is relevant to the ecosystem type and locality. These phosphorus limits allow management to define where their water bodies lie, and define a trigger range for that water body.

Table 1. Total phosphorus trigger ranges for Canadian lakes and rivers.

Trophic Status	Canadian Trigger Ranges Total phosphorus ($\mu g \cdot L^{-1}$)
Ultra-oligotrophic	< 4
Oligotrophic	4-10
Mesotrophic	10-20
Meso-eutrophic	20-35
Eutrophic	35-100
Hyper-eutrophic	> 100

The selection of appropriate trigger ranges and reference conditions can potentially benefit from the development and application of an ecoregional approach (Environment Canada 2004). Ecoregions provide a means of classifying ecologically distinct areas, where each region can be viewed as a discrete system made up of areas of similar geographical landform, soil, vegetation, climate, wildlife, water, etc. The use of ecoregions can improve predictability of nutrient enrichment effects. They can help differentiate between natural and anthropogenic contributions to nutrient enrichment, reduce variability in trigger ranges within a class and among classes, and contribute to improved assessment and development of trigger ranges.

Determine Current Phosphorus Concentration

Under normal conditions, TP is the only meaningful measurement of phosphorus for water (Wetzel 2001). TP can be expressed as a single measurement taken at spring turnover or as an average of several observations made on a seasonal basis; it may be an estimate for a specific zone (e.g., euphotic zone), or as a whole lake approximation. It is important that an appropriate number of samples are collected to accurately reflect TP concentrations in a system. Specific attention should be given to sites that are receiving variable phosphorus loads or exhibiting marked morphological and hydrological differences (Environment Canada 2004).

Compare Current or Predicted Concentration to Trigger Range

The upper concentration of the trigger range represents the maximum acceptable concentration of phosphorus within each of the trophic categories. If the upper limit of the trigger range is exceeded, or is likely to be exceeded, there is a risk of an impact either occurring or having occurred. At this stage, additional information on local environmental factors needs to be considered, and thus further assessment is recommended. The assessment could potentially lead to remedial advice and the restoration of a degraded water body. If the trigger range is not exceeded, the risk of an impact is regarded as low.

Compare Current or Predicted Concentration to Baseline Condition

Due to the general nature of the trigger values and the size of some of the phosphorus ranges defined, a second precaution is taken in the assessment of possible effects of phosphorus. In the event that the trigger value has not been exceeded, the question is now raised as to the degree of increase in phosphorus levels from the baseline. Up to a 50% increase in phosphorus concentrations above the baseline level is deemed acceptable (OMOE 1997). In large lakes, the 50% increase should be applied to the most sensitive areas (e.g., river mouth, point sources, or the littoral zone) rather than averaged over the whole lake. The 50% increase check is also applied to river systems. It is important to recognize that the 50% increase limit in lakes that already have high phosphorus baseline (up to 12 $\mu g \cdot L^{-1}$) may not protect against decreases in dissolved oxygen. However, in the absence of empirical data to recommend an alternative, the 50% increase limit is deemed preferable to no limit. If a 50% increase from the baseline is not observed, then there is considered a low risk of adverse effects, and only monitoring is required for these sites. If the increase from the baseline is greater than 50%, the risk of observable effects is considered to be high, and further assessment is recommended.

Recommended Assessment Tools

The recommended assessment options currently in use in Canada, the US, and other parts of the world are presented in detail in Environment Canada (2004). In summary, the tools fall into the following three categories:

i. A water quality index can be used as a surrogate for phosphorus as it can provide a single value that identifies the current state of the ecosystem, including the percent change from the reference/baseline condition (e.g., Johnes et al. 1994).

ii. Multivariate methods can also assist in comparing current conditions to baseline conditions, and the degree of impairment can be identified both spatially and temporally (Reynoldson and Day 1998; Kilgour et al. 1998; OMOE 1999).

iii. Predictive models can be applied for the management of phosphorus. For example, Lakeshore Capacity (Dillon and Rigler 1975) and paleoecology based phosphorus reconstruction (Dixit et al. 1999) models have been successfully used to estimate baseline phosphorus concentrations and to assess the magnitude and the rate of change.

These assessment tools should be viewed with the caveat that many of them were developed for specific water types or for specific areas with underlying topographic and geological assumptions. Although many of these methods can be adapted to the specific user's situation/need, care must be taken in selecting an approach that is both technically feasible and realistic to the user's needs. Furthermore, the application of any assessment tool in defining phosphorus concentration may not be exclusive, and it may be necessary to adapt a combination of approaches.

Management Decisions

Once the potential increases in phosphorus concentrations have been assessed, the results are compared to the original goals (i.e., reference or baseline conditions) set at the beginning of the framework. The degree of change is then assessed on a management level, and the question raised, "are these changes acceptable?".

Management decisions are a critical step in the framework that links back to the objectives and outcomes of the program via monitoring. Management of phosphorus should include both short-term management strategies and options, which primarily focus on operational activities; and long-term management strategies, which focus on nutrient reduction, flow management, education, monitoring, and research.

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